Technical Summary

The Emissions Gap Report

Are the Copenhagen Accord Pledges Sufficient to Limit Global Warming to 2° C or 1.5° C?

A Preliminary Assessment

The Copenhagen Accord declared that deep cuts in global emissions are required *"so as to hold the increase in global temperature below 2 degrees Celsius".* The Accord called for an assessment that would consider strengthening the long-term goal including *"temperature rises of 1.5 degrees".* Since December 2009, 140 countries[1] have associated themselves with the Copenhagen Accord. Of these, 85 countries have pledged to reduce their emissions or constrain their growth up to 2020.

The question remains, however, whether these pledges are sufficient to achieve the Accord's temperature limits, or if there will be a gap between what is needed and what is expected as a result of the pledges.

Many scientific groups have identified global emission pathways[2], or emissions trajectories, that are consistent with various temperature limits, while others have estimated global emissions in 2020 based on the Copenhagen Accord pledges. Some groups have calculated both. Not surprisingly, different groups have come up with different estimates. The range of estimates is caused, for example, by the fact that some of the pledges have conditions attached, such as the provision of finance and technology or ambitious action from other countries. This leads to a range of potential outcomes rather than a single estimate.

To understand and interpret the range of results coming from different studies, the United Nations Environment Programme (UNEP), in conjunction with the European Climate Foundation and the National Institute of Ecology, Mexico, convened a six-month preliminary assessment of these studies. This assessment aims to provide policy-makers with an overview of results from various studies, as well as their areas of agreement and disagreement. Individuals from twenty-five groups have contributed to the assessment and co-authored this publication. This report is a summary of that work.

Notably, the 2020 emissions reduction pledges analysed in this report were not decided under a quantitative top-down approach to emissions management — one that starts with temperature limits for which the mitigation effort is distributed among countries by

[1] As of 12 November 2010.

[2] An "emission pathway" shows how emissions change into the future

negotiation. Therefore, at this time we are only analysing the effect of the offers brought forward by countries in the form of pledges under the Copenhagen Accord.[3]

This assessment addresses four main questions:

- What 2020 emission levels are consistent with the 2° C and 1.5° C limits[4]?
- What are the expected global emissions in 2020?
- How big is the "emissions gap"?
- How can the gap be reduced?

Key findings

- Studies show that emission levels of approximately 44 gigatonnes of carbon dioxide equivalent ($GtCO_2e$) (range: 39-44 $GtCO_2e$*) in 2020 would be consistent with a "likely" chance of limiting global warming to 2° C.
- Under business-as-usual projections, global emissions could reach 56 $GtCO_2e$ (range: 54-60 $GtCO_2e$) in 2020, leaving a gap of 12 $GtCO_2e$.
- If the lowest-ambition pledges were implemented in a "lenient" fashion**, emissions could be lowered slightly to 53 $GtCO_2e$ (range: 52-57 $GtCO_2e$), leaving a significant gap of 9 $GtCO_2e$.
- The gap could be reduced substantially by policy options being discussed in the negotiations:
  - By countries moving to higher ambition, conditional pledges
  - By the negotiations adopting rules that avoid a net increase in emissions from (a) "lenient" accounting of land use, land-use change and forestry activities and (b) the use of surplus emission units
- If the above policy options were to be implemented, emissions in 2020 could be lowered to 49 $GtCO_2e$ (range: 47-51 $GtCO_2e$), reducing the size of the gap to 5 $GtCO_2e$. This is approximately equal to the annual global emissions from all the world's cars, buses and transport in 2005 – But this is also almost 60 per cent of the way towards reaching the 2° C target.
- It will also be important to avoid increasing the gap by "double counting" of offsets.
- Studies show that it is feasible to bridge the remaining gap through more ambitious domestic actions, some of which could be supported by international climate finance.

[3] We note that this is a technical report that explores possible outcomes associated with the implementation of the Copenhagen Accord. It is not intended to legitimize the Accord, nor does it constitute an endorsement of a pledge-and-review architecture vis-à-vis a target-based approach for emission reductions. In addition this report is not intended to advocate any particular policy or emissions pathway.

[4] Although the Copenhagen Accord is not explicit about the baseline against which temperature increase should be measured, we have assumed that it is pre-industrial levels.

– With or without a gap, current studies indicate that steep emission reductions are needed post 2020 in order to keep our chances of limiting warming to 2° C or 1.5° C.

** Range here refers to the "majority of results", i.e. their 20th and 80th percentile.*
*** "Lenient" in this report is used to refer to the situation in which LULUCF accounting rules and the use of surplus emission units result in a net increase in emissions*

What 2020 emission levels are consistent with the 2° C and 1.5° C limits?

Box 1: Method for assessing emission levels consistent with temperature limits

In this assessment we examine two groups of pathways: (1) pathways produced by integrated assessment models (IAM), which simulate the energy-economic system including the turnover of energy infrastructure; and (2) "stylized" pathways, produced by other models that do not explicitly model the change in the energy system or feasibility of emission reduction rates. We focus on results from IAMs because they are able to actually describe the system's response to different policies and measures and emission-related targets (see Box 2). However, we also draw on "stylized" scenarios in order to better understand the theoretical rates of emission reduction and magnitude of negative emissions needed to be consistent with particular temperature limits.

A total of 223 emission pathways produced by 15 modelling groups have been analysed[5]. We account for many, but not all, sources of the uncertainty of models and data by compiling results from a number of studies and identifying conclusions that appear robust.

1. The level of human-induced global warming is primarily determined by the cumulative emissions over time, i.e. when emissions peak, at what level, and how fast they decline thereafter.

The total stock of greenhouse gases in the atmosphere has a strong effect on climate forcing related to climate change. This stock is determined by the accumulated emissions of greenhouse gases in the atmosphere. It follows that cumulative emissions have a profound influence on the long-term increase of global temperature[6].

An important point is that several different emission pathways can result in the same cumulative emissions over a period of time. But not all pathways are considered equally feasible; some are thought to be constrained by an upper ceiling on the rate of emission reductions due to technological, economic, social and political factors. Hence, the feasibility of reduction rates plays a central role in determining which 2020 emission levels are consistent with temperature limits. Also important are assumptions about the feasibility of "negative emissions", i.e. the net removal of carbon dioxide (CO_2) from the atmosphere through, for example, planting forests or capturing CO_2 from biomass (see Box 3).

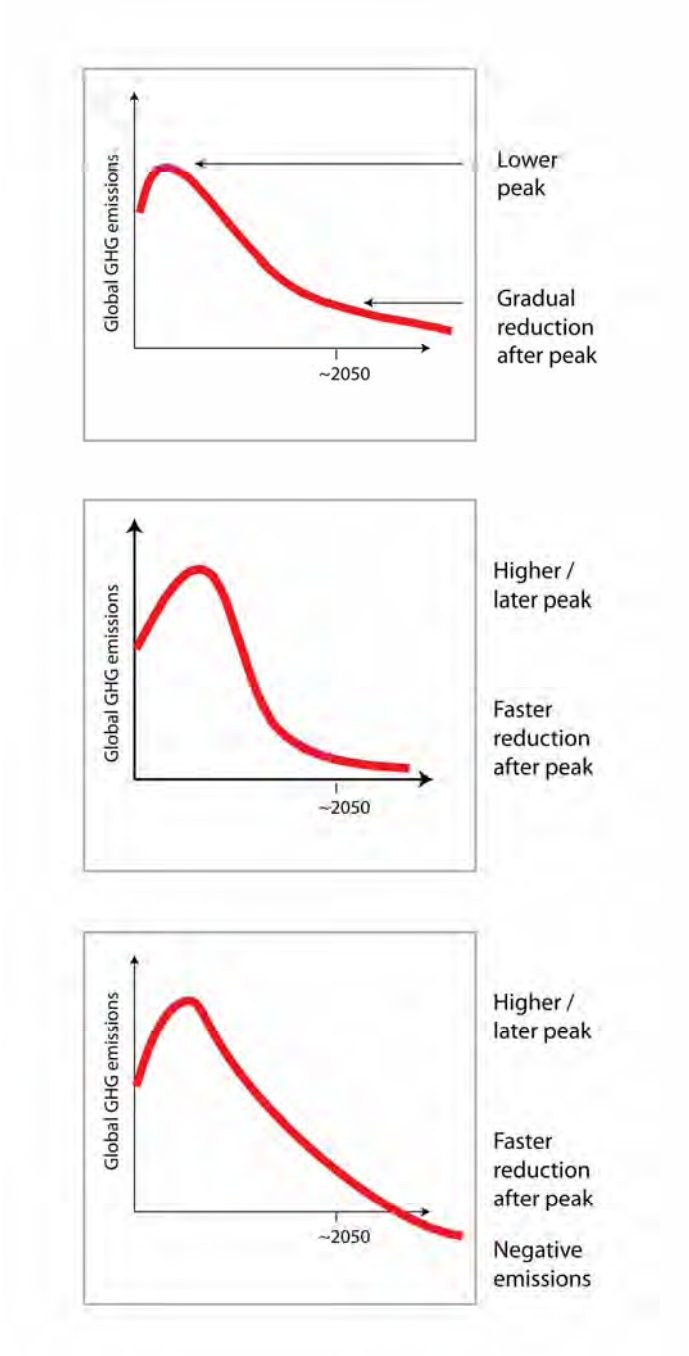
Studies show that there is a trade-off between the timing of the peak and the rate of decrease in emissions afterwards – the sooner and lower the peak, the slower the rate of decrease can be afterwards. Conversely, the longer the peak is delayed and the higher it is, the faster emissions must decline afterwards, and/or the stronger the negative emissions over the long term, in order to stay within the temperature limit (see Figure A).

Many recent modelling studies have assumed that it would be unrealistic for global emissions to immediately start decreasing (because of political and economic factors) and therefore have focused on scenarios in which global emissions continue to increase for a few years and then decrease sharply afterwards.

[5] Detail on the studies reviewed can be found in Chapters 2 and 3 of the full report.

[6] It is important to note that a number of other factors, such as the level of sulphate aerosols and the shape of the pathway, also have a significant influence on the maximum temperature increase.

Figure A: Illustration of different pathway types for the same temperature increase. See Point 1 for explanation.



Box 2: Understanding temperature limits

A temperature increase of 2° C or 1.5° C represents an increase in global average near surface temperature compared with pre-industrial times. This is meant to be an indicator of local climate changes. Importantly, a 2° C or 1.5° C global average increase can translate into much higher temperature changes locally.

There are significant uncertainties in the relationship between temperature, emission pathways, cumulative emissions, and atmospheric concentrations. Therefore, in this assessment, each emission pathway is associated with a range of probabilities for temperature, reflecting uncertainties in the carbon cycle and many other aspects of the climate system. Hence, an emission pathway is associated with probabilities of staying within a range of different temperature changes.

To illustrate, an emission pathway that has a 50 per cent chance of limiting warming to under 2° C, may also have a 5 per cent probability that warming will exceed 3° C and, say, a 10 per cent probability of staying below 1.5° C. Similarly, an emission pathway that has a 66 per cent chance of staying under 2° C, may also have a probability of less than 3 per cent that warming will exceed 3° C and, say, a 20 per cent probability of staying below 1.5° C.

In this assessment we focus on emission pathways that lead to a global average temperature increase of less than 2° C over this century with a "likely" chance (greater than 66 per cent probability) and then explain how they would be different for a "medium" chance (50-66 per cent probability). In addition we examine pathways in which the temperature changes are below 1.5° C by the end of the century, but "overshoots" this value for part of the century.

2. Emission pathways consistent with a "likely" chance of meeting the 2° C limit generally peak before 2020, have emission levels in 2020 around 44 $GtCO_2e$ (range: 39-44 $GtCO_2e$[7]), have steep emission reductions afterwards and/or reach negative emissions in the longer term.

Emission pathways assessed in this report that provide a "likely" (greater than 66 per cent) chance of staying within the 2° C limit, have the following characteristics:

- A peak in global annual emissions[8] before 2020.
- 2020 global emission levels of around 44 $GtCO_2e$ (range: 39-44 $GtCO_2e$).[9]
- Average annual reduction rates of CO_2 from energy and industry between 2020 and 2050 of around 3 per cent (range: 2.2 to 3.1 per cent)[10].
- 2050 global emissions that are 50-60 per cent below their 1990 levels.
- In most cases, negative CO_2 emissions from energy and industry starting at some point in the second half of the century.

[7] All ranges given in this report represent the 20th and 80th percentiles of results, unless otherwise stated. This range has been chosen to reflect the majority of results of the analysis.

[8] Global annual emissions consist of emissions of the "Kyoto basket of gases" coming from energy, industry and land use.

[9] These are rounded numbers. If numbers with one decimal place were shown it would be clear that the upper end of the range is slightly greater than 44 $GtCO_2e$ and the median slightly smaller than 44. The fact that both the median and upper end of the range are 44 indicates that many of the estimates were close to 44.

[10] Throughout this report emission reduction rates are given for carbon dioxide emissions from energy and industry and expressed relative to 2000 emission levels except when explicitly stated otherwise

Accepting a "medium" (50-66 per cent) rather than "likely" chance of staying below the 2° C limit relaxes the constraints only slightly: emissions in 2020 could be 1 $GtCO_2e$ higher, and average rates of reduction after 2020 could be 2.5 per cent per year (range 2.2-3.0 per cent). Nevertheless, global emissions still need to peak before 2020 in the majority of cases.

3. It turns out that the 2020 emission levels with a *"likely"* chance of staying within the 2° C limit can be about the same as those with a *"medium" or lower* chance of meeting the *1.5 °C* target. However, to have a higher chance of meeting the 1.5° C target the emission reduction rates after 2020 would have to be much faster.

In this assessment we have identified some emission pathways that keep the increase in temperature below 1.5° C by 2100, but "overshoot" this limit by a small amount for a few decades prior to 2100. However, the chance of doing so is low (range: 27-35 per cent probability). The emission levels in 2020 of these pathways are about the same as those in Point 2 above, i.e. they are consistent with a likely chance of staying below the 2° C limit throughout the twenty-first century.[11]

In addition, the most ambitious "stylized" pathways show that staying within the 1.5° C limit with overshoot (and with a "medium" or "likely" chance) have emission reduction rates after 2020 that are at the high end or faster than presently found in the IAM literature. Lower emission levels in 2020 would allow slower emission reduction rates after 2020.

These findings should be considered preliminary, however, as few studies have explicitly looked at the question of achieving the 1.5° C target.

4. The range in results stems from uncertainties of assumptions and models used for calculations.

The range in estimates of emission levels comes from model uncertainties including the omission of feedback phenomena in the climate system and (in some models) the impact of aerosols on climate forcing. The uncertainty of key assumptions, such as baseline emissions, also has an influence on calculations.

Box 3. What are feasible emission reduction rates? What are negative emissions?

The behaviour of the climate system dictates that future temperatures will be strongly influenced by emissions throughout the coming decades. Hence, the consistency of 2020 emissions with a given temperature limit can only be judged if emissions after 2020 are taken into account. For that reason it is important to know the feasible rates of emission reductions after 2020. Feasibility refers to whether a particular emission pathway is considered achievable. It depends upon technical, economic, political and social constraints and the extent of mitigation policy. Some of these factors, in particular technological and economic feasibility, can be represented in models such as integrated assessment models (IAM). These include assumptions about the maximum feasible rate of introducing technology, maximum costs of technologies, feasibility of specific system configurations, and limits regarding behavioural changes. Another important factor determining the maximum emissions reduction rate is the typical lifetime of machinery and infrastructure. These lifetimes are important if mitigation strategies aim to avoid premature replacement of capital, which is often considered to be very expensive. Other factors, such as political or social attitudes, might also influence the rate of emission reductions, but they are usually not taken into account by IAMs.

[11] One IAM pathway has been identified that has a "medium" chance of complying with the 1.5° C limit by 2100 (with some overshoot for a few decades) and shows emission reduction rates considered feasible in the IAM literature. See Chapter 2, full report.

There are different views about feasible emission reduction rates. The highest average rate of emission reductions over the next four to five decades found in the IAM literature is around 3.5 per cent per year. This would imply a decarbonisation rate (the rate of decrease in emissions per unit of GDP) of more than 6 per cent per year. Historically (1969-2009), a decarbonisation rate of about 1% has been seen globally. However, it is important to note that expectations about feasibility can change with future developments in technology, attitudes, and economics.

One of many important elements related to the feasibility of emission pathways is negative emissions. Many of the scenarios compiled in this assessment show global negative carbon dioxide (CO_2) emissions (from energy and industry) from mid-century onwards in order to achieve the temperature limits examined here[12].

Global negative CO_2 emissions would occur if the removal of CO_2 from the atmosphere is greater than the emissions into it. This might be achievable through large-scale afforestation efforts, for example. Many models assume a large deployment of bioenergy combined with carbon-capture-and-storage (BECCS) technology in order to achieve negative emissions. The feasibility of large scale bioenergy systems is related to its sustainability, including the availability of sufficient land and water, its impact on biodiversity, and the productivity of biomass.

If negative CO_2 emissions at a significant scale are not possible, then the options for meeting the limits are substantially constrained.

What are the expected global emissions in 2020?

5. Global emissions in 2020 will depend on the pledges implemented and the rules surrounding them. On one hand, emissions in 2020 could be as low as 49 $GtCO_2e$ (range: 47-51 $GtCO_2e$) when countries implement their conditional pledges with "strict" accounting rules. On the other hand, they could be as high as 53 $GtCO_2e$ (range: 52-57 $GtCO_2e$) when countries implement unconditional pledges with "lenient" accounting rules.

As a reference point, without pledges global greenhouse gas emissions may increase from 45 $GtCO_2e$ in 2005 to around 56 $GtCO_2e$ in 2020 (range: 54-60 $GtCO_2e$) according to business-as-usual projections. These results come from thirteen studies that have been reviewed in this assessment.

Results show that the pledges, if implemented, are expected to reduce global emissions in 2020 compared to business-as-usual projections. How much lower will depend on:

i. Whether countries implement their unconditional (lower ambition) or conditional (higher ambition) pledges. Conditions attached to the pledges include, for example, the provision of adequate climate finance and ambitious action from other countries.

ii. The extent to which accounting rules for land use, land-use change and forestry (LULUCF) can be used to weaken the mitigation targets of industrialized countries. This could occur if credit is given for LULUCF activities that would have happened in any case without further policy intervention.

iii. The extent to which surplus emissions units, particularly those that could be carried over from the current commitment period of the Kyoto Protocol, are used to meet industrialized country targets.

[12] In this assessment, seventy-five per cent of scenarios with a "likely" chance of staying below 2° C and fifty per cent of the scenarios that have a "medium" chance of staying below 2° C.

For the purposes of this report, we have developed four cases that provide a range of plausible outcomes from the UNFCCC negotiations, each with different combinations of the factors mentioned above. We use the term "lenient rules" to refer to cases in which countries maximise the use of surplus emission units and "lenient LULUCF credits", and thereby weaken mitigation targets.[13] We use "strict rules" for the cases in which they do not[14].

> *Case 1 – "Unconditional pledge, lenient rules"*: If countries implement their unconditional pledges and are subject to "lenient" accounting rules (as explained in the paragraph above), global emissions are expected to be about 53 $GtCO_2e$ in 2020 (range: 52-57 $GtCO_2e$), or about 3 $GtCO_2e$ lower than business-as-usual projections.
>
> *Case 2 – "Unconditional pledge, strict rules"*: If countries implement their unconditional pledges and are subject to "strict" accounting rules (as explained in the paragraph above), global emissions are expected to drop to 52 $GtCO_2e$ (range: 50-55 $GtCO_2e$).
>
> *Case 3 – "Conditional pledge, lenient rules"*: If countries implement their higher ambition, conditional pledges and are subject to "lenient" accounting rules, global emissions are expected to drop to 51 $GtCO_2e$ (range: 49-53 $GtCO_2e$)
>
> *Case 4 – "Conditional pledge, strict rules"*: If countries implement their higher ambition, conditional pledges, and are subject to "strict" accounting rules, global emissions are expected to drop to 49 $GtCO_2e$ in 2020. (range: 47-51 $GtCO_2e$).

Thus, under the most ambitious outcome, the pledges could result in 2020 emissions that are 7 $GtCO_2e$ lower than business-as-usual.

6. Emissions could be lower or higher than these estimates, as a result of other factors. Emissions could be higher if offsets were to be "double-counted" towards both industrialized and developing country pledges or if pledges were to be ineffectively implemented. Emissions could be lower as a result of international climate finance for further mitigation efforts, or if countries were to strengthen their pledges, or if domestic activities went beyond their pledges.

The estimates reflected in the four cases do not take into account all factors that could affect emissions in 2020.

Two factors could increase emissions and lessen the impact of the pledges. If industrialized countries were to use offsets to meet their targets, and the developing countries that supplied the offsets also counted them towards their pledges, then emissions would be higher than estimated in Point 5. This "double counting" of offsets could increase emissions in 2020 by up to 1.3 $GtCO_2e$ in 2020. Similarly, if domestic policies were to be ineffective in meeting the pledges, emissions could be higher in 2020.

There are also factors that could further decrease emissions in 2020. If substantial international funds were to become available as agreed to in the Copenhagen Accord, emissions could be as much as 2.5 $GtCO_2e$ lower in 2020 than in the four cases above.

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[13] Credits given for carbon removals from existing forests or other sinks that would have occurred without policy intervention. See Chapter 3, full report for more detail on the "lenient" and "strict" definitions.

[14] Note that surplus emission units and credits given for LULUCF activities do not necessarily weaken mitigation targets.

Similarly, if domestic policies went beyond international pledges or if pledges were strengthened, emissions could be substantially lower.

7. A number of uncertainties lead to a significant range in estimates of expected 2020 emissions.

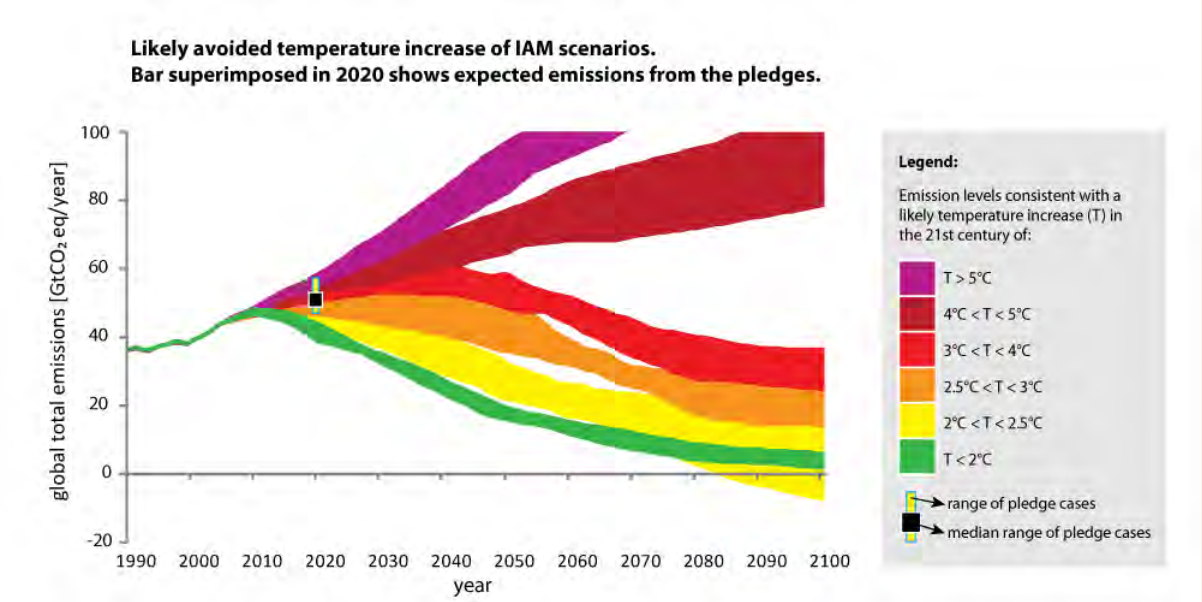
There is a large range between different groups' estimates for 2020 emission levels, even under the same assumptions regarding conditionality of pledges and accounting rules (range: -4 to +8 $GtCO_2e$ around the median estimate, depending on the case). The range of estimates is caused, for example, by differences in the underlying data sets, the treatment of emissions from LULUCF, the estimates of emissions from international transport, and the assumptions made about business-as-usual emissions growth of developing countries.

Box 4. What are the temperature implications of present pledges?

It is not possible to precisely answer the above question because the trend in temperature will strongly depend on the pathway of emissions after 2020. But results from integrated assessment models give us a hint at the range of pathways that could occur between 2020 and 2100. If we start at the level of emissions expected from the Copenhagen Accord pledges in 2020 and then follow the range of these pathways through to 2100, we find that they imply a temperature increase of between 2.5 to 5°C before the end of the century (see Figure B). The lower bound is the case in which emissions are fairly stringently controlled after 2020, and the upper in which they are more weakly controlled. In other words, emission levels in 2020 implied by current pledges do not seem to be consistent with 2° C or 1.5° C temperature limits. To stay within these limits, emission levels would have to be lower in 2020 and then be followed by considerable reductions.

Figure B – Temperature increases associated with emission pathways and compared to the expected emissions from the pledges: Coloured bands show groups of IAM emission pathways that have approximately the same "likely" avoided temperature increase in the twenty-first century. Specifically the coloured bands show the 20th to 80th percentile range of the IAM pathways associated with those temperature increases[15]. Superimposed on top of the pathways is the range of estimated emissions resulting from the Copenhagen Accord pledges. The small black bar shows the range of median estimates from the four pledge cases. The thin blue bar represents the wider range of estimates associated with those four cases (the 20th to 80th percentile range).

[15] The gaps between the coloured bands come about because this report mainly compiled pathways from low greenhouse gas stabilisation scenarios



How big is the "emissions gap"?

8. A "gap" is expected in 2020 between emission levels consistent with a 2° C limit and those resulting from the Copenhagen Accord pledges. The size of the gap depends on the likelihood of a particular temperature limit, and how the pledges are implemented. If the aim is to have a "likely" chance (greater than 66 per cent) of staying below the 2° C temperature limit, the gap would range from 5-9 $GtCO_2e$, depending on how the pledges are implemented.

As a reference point, we saw in Point 2 that to have a "likely" chance of staying below the 2° C temperature limit, global emissions should be around 44 $GtCO_2e$ (range: 39-44 $GtCO_2e$). But according to business-as-usual projections global emissions in 2020 may be around 56 $GtCO_2e$ (range: 54-60 $GtCO_2e$). This leaves a gap of about 12 $GtCO_2e$ (range: 10-21 $GtCO_2e$).

The four pledge cases, each with different assumptions about the future outcome of the UNFCCC negotiations, result in different gaps as follows[16]:

> *Case 1 – "Unconditional pledges, lenient rules"*. The gap would be reduced down to 9 $GtCO_2e$ (range: 8-18 $GtCO_2e$) or about 3 $GtCO_2e$ below business-as-usual.

[16] All cases refer to emission levels consistent with a "likely" chance of staying below 2° C.

Case 2 – "Unconditional pledges, strict rules". The gap would be about 8 $GtCO_2e$ (range: 6-16 $GtCO_2e$), or about 4 $GtCO_2e$ below business-as-usual.

Case 3 – "Conditional pledges, lenient rules". The gap would be about 7 $GtCO_2e$ (range: 5-14 $GtCO_2e$) or about 5 $GtCO_2e$ below business-as-usual.

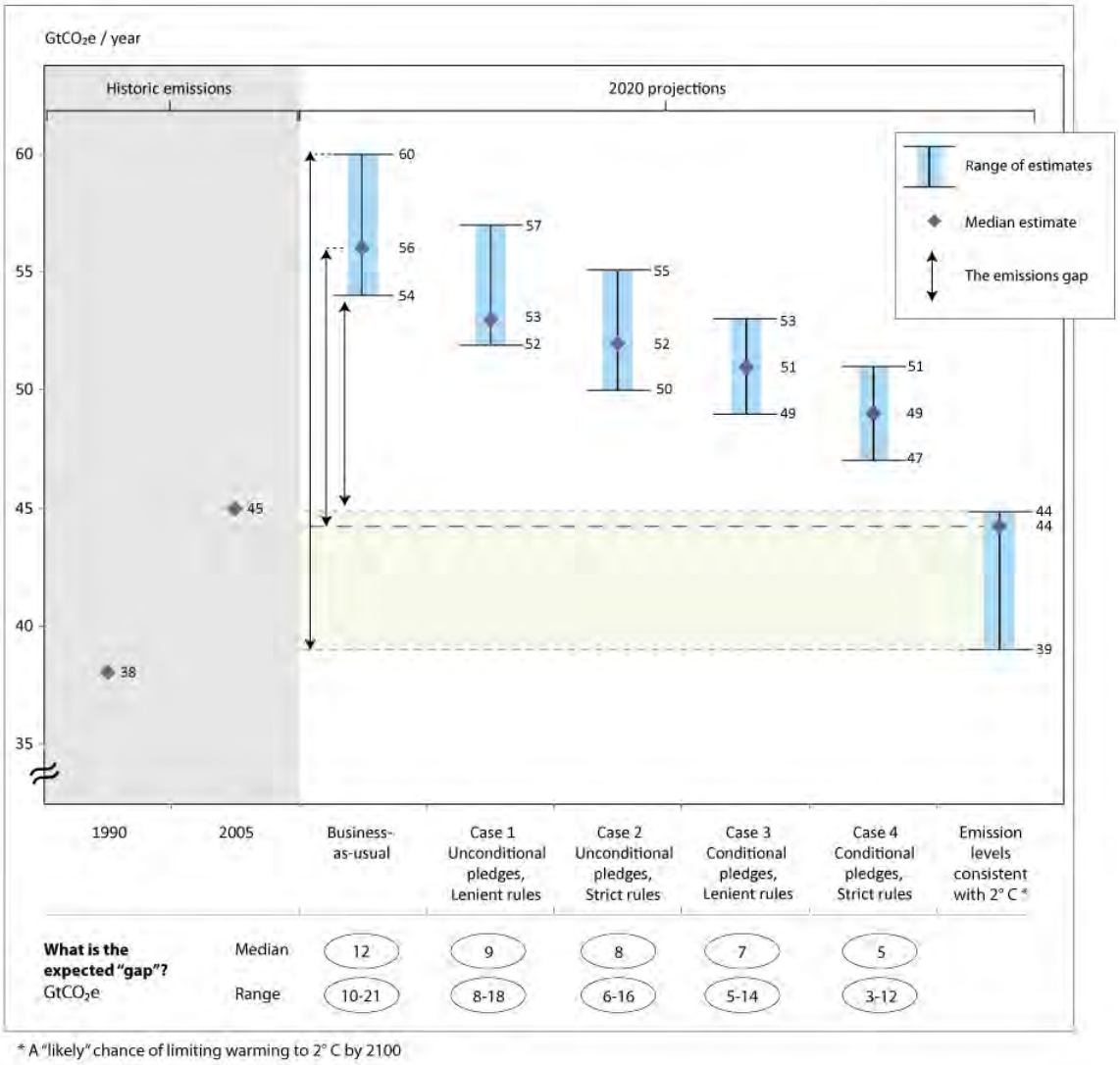
Case 4 – "Conditional pledges, strict rules". The gap would be about 5 $GtCO_2e$ (range: 3-12 $GtCO_2e$). This is about 7 $GtCO_2e$ lower than business-as-usual, and almost 60 per cent of the way to the 2° C levels. Although the gap would be considerably narrower than the business-as-usual case, it would still be as large as the total greenhouse gas emissions from the European Union in 2005 or from global road transport emissions in that year.

These results can be seen in Figure C.

Double-counting of international emission offsets could also increase the gap up to 1.3 $GtCO_2e$. This is a real risk since the Copenhagen Accord does not include rules regarding the use of international offsets.

As a final point here, to have a *"medium"* rather than a *"likely"* chance of staying within the 2° C limit, global emissions in 2020 can be about 1 $GtCO_2e$ higher and the gap also narrows by about 1 $GtCO_2e$.

Figure C: Comparison of expected emissions in 2020 with the emission levels consistent with a "likely" chance of meeting the 2° C limit. The figure compares the expected emissions in 2020 resulting from the four pledge cases with the emission levels consistent with a "likely" chance of meeting the 2° C limit. The median estimates and range of estimates (20th to 80th percentile) are shown. The gap between expected emissions and the 2° C levels is given below in each case.



9. There are considerable uncertainties around the estimates of the gap.

Since the emissions gap is the difference between emission levels for different temperature targets and expected emissions in 2020, the gap also inherits the uncertainties of these two components. The reader will note that the range around median estimates (Figure C) is not symmetric; the lower bound extends about 1-2 $GtCO_2e$ below the median, whereas the upper bound rises 7-9 $GtCO_2e$ above it (for a "likely" chance of staying below 2^oC). One way

to interpret this skewed range is that the gap may turn out to be higher rather than lower than the median.

This assessment focuses on the majority (20th – 80th percentile) of emission pathways. But there are obviously also results outside of this range. In the extreme case, if we combine the highest $2^{o}C$ emission levels with the lowest estimate of expected emissions, the gap disappears. At the opposite extreme, if we combine the lowest $2^{o}C$ emission levels with the highest estimate of expected emissions, the gap would be greater than 20 $GtCO_2e$.

How can the gap be reduced?

10. Various international policy actions are available to close the gap.

a) Reducing the gap through higher ambition pledges.

The gap can be reduced by around 2-3 $GtCO_2e$ (with a range of estimates from 2 to 5 $GtCO_2e$) by moving from the unconditional (lower ambition) pledges to the conditional (higher ambition) pledges.

- Industrialized countries: The majority of this reduction would come from industrialized countries, whose pledges are sometimes conditional on the ambitious action of other countries or on domestic legislation.
- Developing countries: A smaller, but still important, part of the reduction would come from developing countries, whose pledges are sometimes conditional on the adequate provision of international climate finance or technology transfer.

b) Reducing the gap by tightening the rules

The gap can be reduced by around 1-2 $GtCO_2e$ by ensuring that "strict" rules apply to the use of LULUCF credits and surplus emission units.

- LULUCF accounting: If industrialized countries apply "strict" accounting rules to minimise the use of what we refer to as 'lenient LULUCF credits'[17] , they would strengthen the effect of their pledges and thus reduce the emissions gap by up to 0.8 $GtCO_2e$.
- Surplus emission units: Likewise, if the rules governing the use of surplus emission units under the Kyoto Protocol were designed in a way that would avoid the weakening of mitigation targets, the gap could be reduced by up to 2.3 $GtCO_2e$. These include units carried over from the current commitment period and any potential new surpluses created in the next.

We note that policy options (a) and (b) are interdependent and so their benefits cannot necessarily be added together. But we estimate that the two options combined could reduce

[17] Credits given for carbon removals from existing forests or other sinks that would have occurred without policy intervention

emissions by around 4 $GtCO_2e$ in 2020 (with a range of estimates of 4-6 $GtCO_2e$) compared with the least ambitious case (case 1).

In addition, the risk of the gap increasing in size can be avoided if the negotiations set rules regarding international offsets to prevent them from being counted towards both industrialized and developing country pledges. “Double-counting” would increase the gap by up to 1.3 $GtCO_2e$.

11. It is feasible to close the remaining gap through further mitigation actions by countries, some of which could be supported by international climate finance.

If the above measures were to be taken, there might still be a gap of 5 $GtCO_2e$ compared with a 2° C limit. This gap could be closed if countries were to adopt more ambitious actions or pledges. The results from integrated assessment models (IAM) suggest that it is possible to reach emission levels where there is no gap, using mitigation measures that are economically and technologically feasible. .

Analysis also shows that international climate finance in line with the Copenhagen Accord could help achieve some of these reductions in developing countries.

12. Studies show that laying the groundwork for steep rates of emissions reduction from 2020 onwards would be necessary for staying within a limit of 2° C and even more so for 1.5° C, whatever the outcome of the pledges.

The results of the IAM pathways that have a “likely” (greater than 66 per cent) or even “medium” (50-66 per cent) chance of limiting temperature increase to 2° C show average annual emission reduction rates of greater than 2 per cent per year after 2020. Achieving this over the long-term would be unprecedented because, on the contrary, global emissions have almost continuously grown since the industrial revolution.

The higher the emissions in 2020, the faster the rate of decline required thereafter to meet temperature targets. Therefore, if targets are to be met, it will be essential to lay the groundwork now for such rates of reduction. This can be done, for example, by avoiding lock-in of high carbon infrastructure with long life-spans and developing and introducing advanced clean technologies.

1. Introduction

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1.1. COPENHAGEN, TEMPERATURE LIMITS AND PLEDGES

Following the 15th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change, forty-two[18] industrialized countries submitted quantified economy-wide emission targets for 2020. In addition, forty-three[19] developing countries submitted nationally appropriate mitigation actions for inclusion in the Appendices to the 2009 Copenhagen Accord.[20] These pledges[21] have since become the basis for analysing the extent to which the global community is on track to meet long-term temperature goals as outlined in the Copenhagen Accord:

> *(Para 1)…To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change.*
>
> *(Para 2)…We agree that deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective consistent with science and on the basis of equity.*
>
> *(Para 12)…We call for an assessment of the implementation of this Accord to be completed by 2015, including in the light of the Convention's ultimate objective. This would include consideration of strengthening the long-term goal referencing various matters presented by the science, including in relation to temperature rises of 1.5 degrees Celsius.*

This publication aims to assess the following questions: are countries' pledges of action collectively consistent with and, if implemented, likely to achieve the 2° C and 1.5° C temperature goals? If not, how big is the gap between emission levels consistent with these temperature goals and the emissions expected as a result of the pledges?

Notably, the 2020 emission reduction pledges were not decided through a quantitative top-down approach to emissions management, i.e. one that would begin with agreed-upon temperature limits and then be followed by negotiation to distribute the burden of emission reductions necessary to meet these limits. Therefore, at this time we can only analyse the

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[18] http://unfccc.int/home/items/5264.php

[19] http://unfccc.int/home/items/5265.php

[20] http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf#page=4

[21] For the purposes of this report, pledges include Annex I targets and non-Annex I actions.

emerging "global deal" on climate change by summing pledges from the bottom up—in other words, based on offers already brought forward voluntarily by countries.

Box 1a: Understanding temperature limits

A warming limit of 2° C or 1.5° C refers to the increase in global annual average near surface temperature compared with pre-industrial times. This temperature is intended to be an indicator for local changes in a wide range of observable quantities, such as precipitation. It is important to note that a 2° C global average rise can translate into much larger (or smaller) temperature changes in different latitudes and elevations. Moreover, undesirable impacts will generally be driven by local climate changes (e.g. changes in rainfall patterns) and often by changes in extremes in different seasons rather than by annual average temperature values.

There are significant uncertainties in the relationship between temperature, emission pathways, cumulative emissions, and atmospheric concentrations. Therefore, in this assessment, each emission pathway is associated with probabilities of staying within a range of temperature limits. These probabilities reflect the uncertainties in the carbon cycle as well as many other aspects of the climate system. To illustrate, an emission pathway that has a 50 per cent chance of limiting warming to under 2° C may also have a 5 per cent probability that warming will exceed 3° C and, say, a 10 per cent probability of staying below 1.5° C. If we then consider an emission pathway that has a 66 per cent chance of being under 2° C, it may also have a probability of less than 3 per cent that warming will exceed 3° C, and, say, a 20 per cent probability of staying below 1.5° C.

Therefore, it is not possible to guarantee that a particular emission pathway will achieve a temperature limit of 2° C or 1.5° C, and probabilities of achievement are used instead. In this assessment we focus on two temperature limits, 2° C and 1.5° C; and two probabilities of meeting them – a "likely" chance (probability greater than 66 per cent) and a "medium" chance (probability between 50-66 per cent).

1.2. SCOPE OF THE REPORT

This report addresses many of the key issues raised by the Copenhagen Accord. For example, the emission pathways consistent with temperature limits and the expected emissions in 2020 based on current pledges. Furthermore, it examines whether there is a gap between emission levels consistent with temperature limits and expected emissions, and furthermore, the increases in temperature consistent with such a gap in emissions. Outside the scope of the report are issues related to the comparability and equity of pledges.

1.3. A MULTI-DIMENSIONAL CHALLENGE

In assessing these issues we are confronted with a series of highly complex issues, which result from both scientific and political factors.

In **Chapter 2**, we focus on the likelihood of various emission pathways staying within temperature limits. For these pathways we identify the period in which emissions peak, the level of emissions in 2020, and the corresponding emission reduction rates after 2020. Results include emission pathways from integrated assessment models (IAM) and carbon cycle and climate models. Also discussed are current views about the feasibility of emission reductions and negative emissions, as well as factors determining long-term temperature, including cumulative emissions.

Chapter 3 reviews estimates of global emission levels in 2020 based on country emission pledges. Among the factors influencing these estimates are whether pledges are

independent of, or conditional on, other countries' actions, financing or technological support. For industrialized countries, key factors include: the accounting procedures for emissions or uptake of carbon from land use, land-use change and forestry (LULUCF); the potential for international climate finance, as agreed in the Copenhagen Accord to enable further emission reductions; the carry-over of emission reduction units from the first commitment period of the Kyoto Protocol (2008-2012); and the potential double counting of offsets with emission reductions from non-Annex I countries' actions. Emission estimates are also influenced by the uncertainty of base year emissions and by assumptions needed for filling in sectoral or other gaps in the emission estimates of various groups.

The pledges of industrialized countries are fairly easy to convert into emission estimates because they are usually related to historic emissions. However, more assumptions are needed to make this conversion for developing countries because their pledges have usually been pegged to economic, demographic or other projections.

Chapter 4 builds upon the previous two chapters by examining a possible "emissions gap" in 2020 between emission levels consistent with temperature limits and expected emissions resulting from the pledges. It then goes on to explore policy options for narrowing the size of the gap.

Chapter 5 goes a step further by reporting on possible long-term temperature changes following from current pledges.

The online version of the report[22] contains three appendices with additional information about emission pledge calculations in this report. Appendix 1 provides detail on the differences between the four pledge cases described in Chapter 3 and the uncertainties around them. Appendix 2 provides a country-by-country analysis of the pledges of the largest emitting countries. Appendix 3 compares the findings of modelling groups that have assessed country pledges.

[22] www.unep.org/publications/ebooks/emissionsgapreport

2. Which emission pathways are consistent with a 2° C or 1.5° C temperature limit?

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2.1 INTRODUCTION

This chapter identifies future emission pathways that are consistent with a 2° C or 1.5° C temperature limit. Many scenarios and pathways for annual global emissions of greenhouse gases have been published in the scientific literature to explore possible long-term trends in climate change. This literature has been used in this report to understand the kind of pathways consistent with the goal of limiting global temperature increase to less than 2° C or 1.5° C above pre-industrial levels.

Among the different studies of future emission pathways, two main types can be identified. The first type is produced by integrated assessment models (IAM), which simulate both future climate and future socio-economic systems, including the emissions of greenhouse gases from industry and power generation, agriculture, forestry and other land use activities (see for example Clarke et al. 2009, Edenhofer et al. 2010, van Vuuren et al. 2007). IAMs take into account assumptions about technological and economic constraints and so, to some extent, provide a view on what are "feasible" emission reductions. The second type of pathway, described here as "stylized", explores more directly the relationship between emissions and temperature, for example by making assumptions about the timing and magnitude of peak emissions and rates of reduction[23] following the peak. These are pathways produced by models that do not explicitly simulate change in the energy system or feasibility of emission reduction rates. "Stylized" pathways are designed to better understand the temperature outcomes resulting from emission pathways computed by carbon cycle and climate models, without making assumptions about how those emissions are produced (see for example Lowe et al. 2009, Meinshausen et al. 2009).

Although both approaches provide important insights and findings, only results from IAMs are used here for quantitative analysis, unless otherwise stated.

Scenarios published by IAMs in the literature mostly look into optimal pathways to achieve a certain long-term target and not into the question of what emission range in 2020 would achieve a temperature limit. For this reason, we have assembled a large set of scenarios computed with various objectives in mind, and have tested them to see if they are consistent with temperature limits. The combination of these scenarios provides insight into the full range of 2020 emissions consistent with long-term temperature limits. It is possible that other feasible pathways will be identified by modelling groups, once they begin to run their models to explore the full 2020 emissions range.

[23] Throughout this report emission reduction rates are given for carbon dioxide emissions from energy and industry and expressed relative to 2000 emission levels except when explicitly stated otherwise.

Although IAM studies have paid little explicit attention to the question of the range of 2020 emissions consistent with temperature limits, there are some studies of stylized pathways that have done this (Bowen and Ranger 2009, Meinshausen et al. 2009).

In our quantitative assessment of IAM results we have attempted to take the differences between studies (in terms of uncertainties of various input assumptions and different approaches) into account by re-analysing the results of these studies using a common set of assumptions about base year emissions, coverage of non-CO_2 gases, carbon cycle assumptions and interpretation of climate goals (as explained in Box 2a). These re-analysed pathways have been evaluated in terms of their consistency with a 2° C and 1.5° C limit. An important factor here is that projections of the future climate all contain uncertainty (Meehl et al. 2007). This means that when discussing the possibility of satisfying a particular temperature limit, it is necessary to express the result in terms of a probability. As explained in Box 2a, the MAGICC model (Meinshausen et al. 2008) has been used here to take into account some of this uncertainty.

2.2 WHAT DETERMINES LONG-TERM TEMPERATURE?

Many greenhouse gases emitted by human activities have long atmospheric residence times and alter the Earth's energy balance. In addition, the average temperature of the Earth typically adjusts only slowly to changes in the energy balance (Lowe et al. 2009, Solomon et al. 2009). These slow-change processes imply that decision makers need to take into account long-term effects of current and near term emissions (National Research Council 2009). This is even more important as many impacts of climate change are potentially adverse and/or irreversible (at least on time scales of relevance to society).

A number of recent studies have shown that one of the strongest predictors of temperature increase within the twenty-first century is the cumulative emissions of greenhouse gases[24], especially CO_2 (Allen et al. 2009, IPCC 2007b, Matthews and Caldeira 2008, Matthews et al. 2009, Meinshausen et al. 2009, Van Vuuren et al. 2008). Cumulative emissions are determined by the annual emissions over time. In ambitious mitigation scenarios, the following factors play an important role in determining the cumulative emissions:

- the year in which global emissions peak
- the emission level at the peak
- the pathway of global annual emissions after the peak.

For the same cumulative emissions, a higher and/or later emissions peak means faster reductions after the peak than for earlier and/or lower peaks in emissions.

However, all three factors are bounded by feasibility considerations, including economic and/or technological constraints (see Section 2.3). For instance, there are constraints on how fast high-carbon energy infrastructure can be replaced with low-carbon infrastructure (for example, coal-fired power plants with renewable energy production).

[24] The shape of the emission pathway of short-lived greenhouse gases and forcing agents has more influence on the degree of temperature change than long-lived agents. Different emission pathways of short-lived gases (even if they have similar cumulative emissions) influence the temperature increase in different ways (Shine et al. 2005). The assessments in this study include the combined effects of both short and long-lived greenhouse gases and forcing agents.

As a consequence, there is a limited range of 2020 emissions that are consistent with a 2° C or 1.5° C limit, given current assumptions about the feasibility of emission pathways post 2020.

In addition, the probability of exceeding a particular temperature level varies according to the cumulative emissions level—for a higher degree of confidence in staying within a particular temperature limit, a lower cumulative emissions level is required. Pathways with later or higher peaks also reduce, or even eliminate, the "margin of error", should future advances in climate science or additional evidence of the risks of climate change convince citizens and policymakers that more ambitious targets for limiting climate change are needed (Lowe et al. 2009).

2.3 CURRENT ESTIMATES OF FEASIBILITY

The implications of 2020 emission levels for long-term temperature outcomes depend importantly on how much and how fast it is considered feasible to reduce emissions before, and particularly beyond 2020. Feasibility (i.e. considerations on whether a particular emission pathway is possible to achieve) is a subjective concept that has to take into account several factors: technological, economic, political and social. Technological feasibility refers to whether technologies exist, and can be scaled-up fast enough, to produce enough low-carbon energy to meet demand. Economic feasibility refers to whether or not the cost of doing so is considered prohibitively high. Political feasibility includes factors, such as whether the assumed extent of participation in emission reduction efforts across countries (or economic sectors) is plausible and whether the time required to develop institutions that would facilitate this participation is reasonable. Finally, social feasibility refers to whether measures to control emissions would be acceptable to society, for example after taking into account their implications for equity or for non-climate environmental consequences.

IAMs can account for several of these factors by representing inertia of technological and social systems. Examples include assumptions about the maximum feasible technology penetration rates, maximum cost, feasibility of specific system configurations, and maximum speed of behavioural changes.

The results of IAMs are, therefore, helpful in informing our view on feasibility and, hence, are the primary source of quantitative information used in this assessment. However, it should be noted that they do not set "hard laws" on feasibility. On the one hand, they are based on our *current* understanding of technological and economic constraints, which could change; therefore the range of emission pathways considered feasible could shrink or expand over time. For instance, the models do not include the possibility of the development of "game-changing" new technologies currently unforeseen. On the other hand, feasibility also depends on societal and political factors that are not typically considered in IAMs (Bosetti et al. 2010, Ha-Duong et al. 1997, Ha-Duong and Treich 2004). Recently, IAM studies have explored the influence of participation of different countries in model comparison studies (Clarke *et al.* 2009) and this could reduce the range of pathways considered feasible.

One important factor determining the maximum emission reduction rate is the lifetime of machinery and infrastructure: this can be decades or even centuries for building stock and urban infrastructure; around 40 years for power stations; 20 to 40 years for manufacturing equipment; up to 20 years for heating devices; and 10 to 20 years for passenger vehicles, but much longer for transport infrastructure (Philibert 2007). These lifetimes are critically important, if mitigation strategies aim to avoid premature replacement of capital and the high

costs associated with it. For illustration, carbon dioxide emissions from energy and industry would decline by about 3 per cent per year if no new emission-producing infrastructure were to be built (adapted from Davis et al. 2010). In the assessed IAM literature on mitigation scenarios, the highest average rate of total emission reduction over the next 4 to 5 decades is about 3.5 per cent per year (den Elzen et al. 2010)[25].

To put this in context, a global CO_2 emission reduction rate of 3 per cent would require a rate of decrease in emissions per unit of GDP (or decarbonization rate) of almost 6 per cent for an assumed annual rate of global GDP growth of 3 per cent. Ranger et al. (2010) show that there is very little precedent for such high rates of emission reductions amongst the top 25 emitters. The global decarbonization rate over the 1969-2009 period was 1 per cent on average, although this was in the absence of strong international climate policies. In a society that places the highest possible priority on reducing emissions, the normal capital turnover rate could possibly be increased. However, some studies suggest that higher annual reduction rates of up to about 6 per cent per year are possible for a limited time in certain circumstances, but only when the conditions have been put in place for rapid investment in decarbonization of the energy sector (e.g. Edenhofer et al. 2009). The feasibility of achieving emission reduction rates of 3 per cent or more per year for CO_2 emissions from energy and industry is highly uncertain, given political and societal constraints and the fact that emission reductions are not likely to be distributed evenly across nations.

Lastly, it should be noted that most of the pathways consistent with the temperature limits in this report include negative global emissions of CO_2 from energy and industry beginning in the 2060s and 2070s. Understanding the feasibility of negative emissions is therefore crucial for assessing the chances of meeting the 2° C and 1.5° C temperature limits: if negative emissions of a significant scale are not possible, then our options for meeting the targets are significantly constrained. Global net negative emissions occur when the removal of CO_2 from the atmosphere due to anthropogenic activities is greater than the anthropogenic emissions into it. One way to achieve this (and assumed by many IAMs) is through the implementation of bioenergy combined with carbon capture and storage (BECCS). This involves using large amounts of biomass to generate energy, and then capturing and safely storing underground or elsewhere CO_2 released by combustion. Since biomass takes up CO_2 from the atmosphere in the course of its growth, and since the CO_2 taken up is stored underground, BECCS in effect removes CO_2 from the atmosphere (Azar et al. 2010). Direct air capture of CO_2 and other technologies may also lead to negative emissions, but are currently not included in IAMs. The feasibility of large scale bioenergy systems, whether used in conjunction with CCS or not, is related to factors such as availability of land and water, impacts on biodiversity, and biomass productivity.

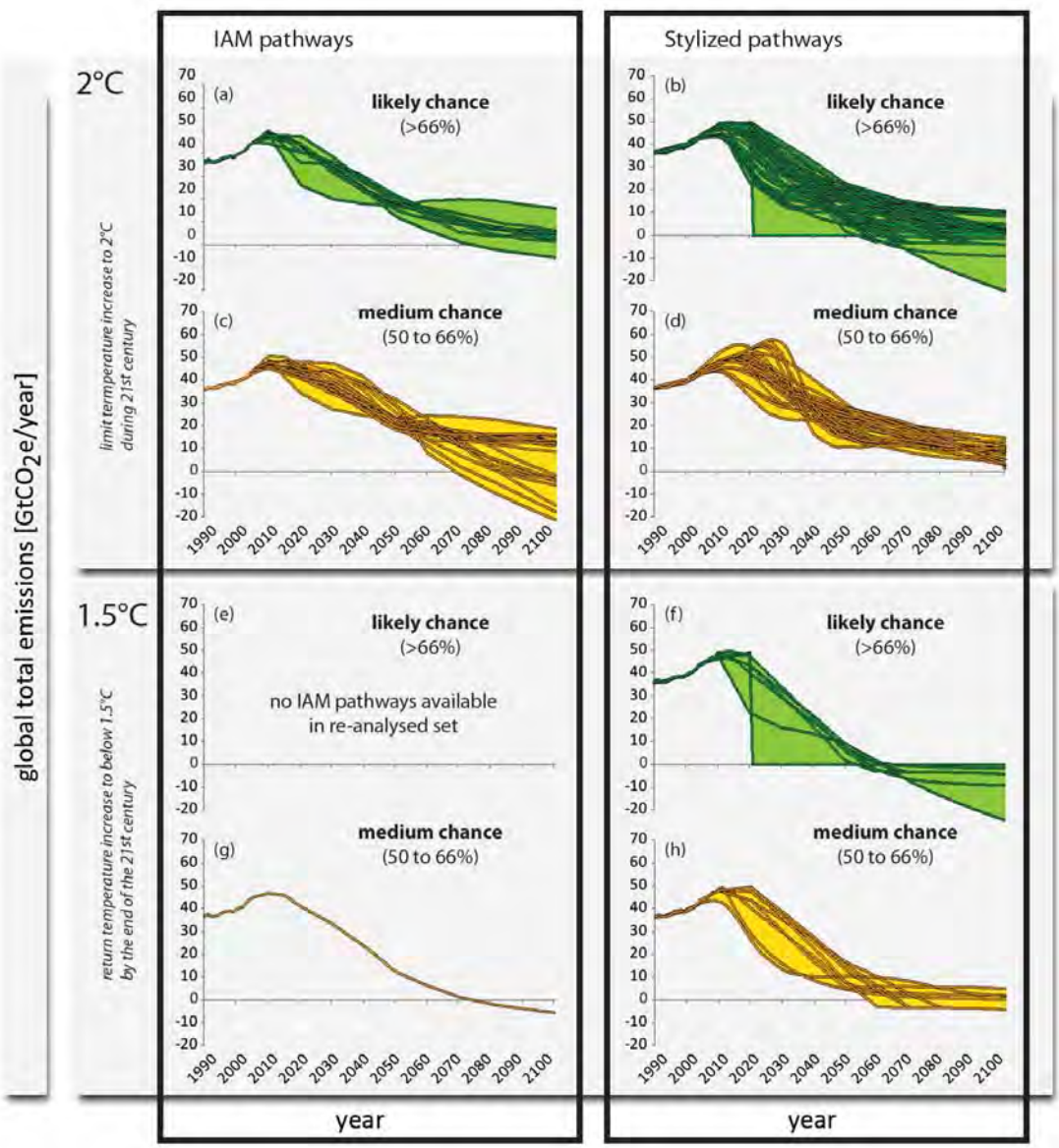
2.4 WHAT EMISSION PATHWAYS AND EMISSION LEVELS IN 2020 ARE CONSISTENT WITH 2° C AND 1.5° C LIMITS?

This section explains how the re-analysed IAM pathways relate to 2020 emission levels, and how these levels relate to the subsequent evolution of pathways that are consistent with the 2° C and 1.5° C temperature limits. Findings from “stylized” pathways are also discussed, because they add to our understanding of emission pathways consistent with temperature

[25] In our set of re-analysed IAM pathways, the fastest reduction rate of energy and industrial emissions is 3.6 per cent (O’Neill et al. 2009). In this report, we usually refer to reduction rates of energy and industrial carbon dioxide emissions, rather than *total* emission reduction rates.

limits. It is shown that expected levels of global emissions in 2020 carry important information for policymakers about the feasibility, scale and magnitude of actions required afterwards to limit global temperature increase.

Figure 1: Overview of global greenhouse gas emissions in $GtCO_2e$/year of IAM emission pathways (panels a, c, e and g at the left) and "stylized" emission pathways (panels b, d, f and h at the right). These are pathways that have been re-analysed in this assessment and that meet the 1.5° and 2° C temperature limits with a particular probability. The area in between the pathways is shaded for clarity. Green pathways meet the temperature limits with a "likely" chance (greater than 66 per cent) (panels a, b, e and f) and orange/yellow pathways with a "medium" chance (50 to 66 per cent) (panels c, d, g and h). The methods used to produce the Figure are detailed in Box 2a. Note that these are global *total* emissions (land use, energy and industry). Later in the chapter we refer to negative emissions of CO_2 from energy and industry only, hence the discrepancy between the number of pathways showing negative emissions in this chart and in Table 1



Box 2a: Method for identifying emission pathways

For the purpose of this assessment we collected a total of 223 emission pathways. Of these 126 were IAM emission pathways published by 15 modelling groups[26], of which 113 explored low greenhouse gas concentration targets while taking into account some assumptions about technological and socio-economic inertia, whereas the remaining 13 represent scenarios without strong mitigation policy. These IAM pathways had varied rates of emission reductions across regions, sectors and gases in order to minimise costs. Of the 223 pathways, 97 were "stylized" pathways[27] which did not make assumptions about technological and economic feasibility, but identified the emission pathways that corresponded to particular temperature targets based on carbon cycle and climate models.

We have evaluated the probability of each of the pathways meeting a 2° C and 1.5° C limit. In order to make results more comparable, we have adjusted the pathways so that they have the same emission levels in 2000 and 2005. Emissions for these years were taken from the multi-gas emissions inventory developed as part of the "Representative Concentration Pathways" (RCPs) scenario exercise (Granier et al. submitted, Meinshausen et al. submitted). When a particular pathway lacked the emissions of a particular substance (e.g. sulphate aerosols, organic carbon, black carbon or atmospheric ozone precursors), these data were taken from the RCP3-PD scenario (van Vuuren et al. submitted). It should be noted that the RCP-3PD scenario assumes strong environmental policies and this is consistent with the aim of this report to identify mitigation pathways that stay within a 2° C or 1.5° C limit. Ozone depleting substances controlled by the Montreal Protocol are assumed to follow a gradual phase-out during the twenty-first century.

The temperature calculations of the harmonised emission pathways were made more comparable by using a single model MAGICC 6.3 (Meinshausen et al. 2009, Meinshausen et al. 2008) to calculate the probabilistic temperature outcome up to 2100 for each emission pathway.

A joint probability distribution of the most important climate response uncertainties has been used, with climate sensitivity uncertainties closely reflecting the estimate provided by the IPCC (IPCC 2007c)[28].This distribution gives the probability of a particular response of temperature to emissions. Because a probability distribution rather than a single number is used for the climate sensitivity factor, temperature outcomes are expressed in terms of probabilities, for example, "emission pathways with a medium chance of staying below a 2° C limit". The emission pathways were put into different categories according to temperature limits (1.5° and 2° C), their probability of meeting the limit (50-66 per cent, greater than 66 per cent), the assumed technologies (e.g. negative emissions or not), and whether they are "stylized" or IAM pathways.

We also performed a sensitivity analysis by analysing 11 recalibrated versions of the climate model to explore alternative values of the climate sensitivity distribution that have been published (see Meinshausen et al. 2009). For emission pathways that give around a "medium" chance of meeting a 2° C limit during the twenty-first century, the sensitivity studies lead to a spread in the median projected temperature of only ±0.2° C.

It is important to note that although we have harmonised the pathways for comparability, some uncertainties remain, for example, about future levels of anthropogenic aerosols, soot and organic carbon.

[26] Studies underlying the IAM emission pathways can be found in the literature (Clarke et al. 2007, Clarke et al. 2009, Edenhofer et al. 2009, Edenhofer et al. 2010, Fujino et al. 2006, IPCC 2007a, O'Neill et al. 2009, Riahi et al. 2007, Smith and Wigley 2006, van Vuuren et al. 2007, Wise et al. 2009).

[27] Studies underlying the "stylized" pathways are found in the literature (Bowen and Ranger 2009, den Elzen et al. 2007, Lowe et al. 2009, Meinshausen et al.2009, Ranger et al. 2010, Rogelj et al. 2010a, Rogelj et al. 2010b, Schaeffer and Hare 2009), as well as the methodology used in this report for possible complementary pathways (Meinshausen et al. 2006).

[28] The climate sensitivity distribution used for the analysis throughout this report is the "illustrative default" case as described in Meinshausen et al. (2009).

The climate model used in this study has previously been validated and shown to credibly reproduce observed climate changes when driven by historic emissions or forcings. However, like other climate models it does not include all of the physical processes that could affect the real climate in future. For instance, there is no treatment of extra carbon release from melting permafrosts.

Our quantitative assessment of IAM pathways found a notable number and range of emissions that are consistent with the temperature limits of interest in this report, even after re-analysis. In the text we focus on the median and range of the "majority of results", with the range corresponding to the 20th to 80th percentile of outcomes. Results at either end of this range are not necessarily invalid or incorrect, and are also discussed in the text.

Assessment of the pathways consistent with 2° C

Of all IAM emission pathways that were included in our quantitative assessment, 9 were found to have a "likely" chance (greater than 66 per cent) of limiting warming to less than 2° C above pre-industrial levels. The results of our quantitative assessment (Table 1) show that the majority of emission pathways with a "likely" chance of meeting the 2° C limit show the following characteristics:

- A peak in global greenhouse gas emissions before 2020 and in general earlier in the decade;
- 2020 global greenhouse gas emission levels of 44 $GtCO_2e$ (median), with a range[29] of 39-44 $GtCO_2e$[30];
- Average annual reduction rates of CO_2 emissions from energy and industry between 2020 and 2050 of around 3 per cent (range of 2.2-3.1 per cent)
- 2050 global emissions that are 50-60 per cent below their 1990 levels; and
- In most cases, negative CO_2 emissions from energy and industry beginning in the 2060s to 2070s[31].

A further 18 IAM pathways were found to have a "medium" chance (50-66 per cent) of staying below a temperature increase of 2° C. The 2020 emission levels are similar (median 45 $GtCO_2e$, range 42-46), while the emission reduction rate between 2020 and 2050 is lower (2.5 compared with 3 per cent per year), Half of these "medium" chance pathways involve net negative CO_2 emissions from energy and industry, beginning between the mid-2050s and mid-2070s[32].

[29] Ranges here, and in the following text, refer to the "majority of results", that is, between the 20th and 80th percentile of results, unless otherwise specified.

[30] Note, these are rounded numbers. If numbers with one decimal place were shown it would be apparent that the upper end of the range is above slightly above 44 and the median slightly below. The fact that both the median and the upper end of the range round to 44 indicates that many of the estimates were close to 44.

[31] 2 of the 9 scenarios do not rely on negative CO_2 emissions from energy and industry to meet the 2° C limit and are associated with low 2020 emission levels of 26 and 36 $GtCO_2e$. Note that Figure 1 does not depict this level of negative emissions since that figure shows global *total* emissions rather than CO_2 emissions from energy and industry, which are described here.

[32] Note that Figure 1 does not depict this level of negative emissions since that figure shows global *total* emissions rather than CO_2 emissions from energy and industry, which are described here.

In general, "medium" chance pathways for 2° C differ from "likely" chance pathways either by having higher emission levels in 2020 but the same rates of emission reductions afterwards, or having the same emission levels in 2020 but slower reduction rates afterwards. "Likely" chance pathways also rely more often on negative emissions.

The re-analysed set of "stylized" pathways (not included in Table 1) shows that, if emissions ranged up to 50 $GtCO_2e$ in 2020, average reduction rates of up to 4 per cent per year would be needed in the 2020-2050 period to meet the 2° C limit (Rogelj et al. 2010b, Schaeffer and Hare 2009)[33]. The high end of these reduction rates is currently not found in the IAM literature. These pathways also require large negative emissions in the second half of this century to meet the temperature limit.

Another important message from analysing IAM emission pathways is that they suggest that it is economically and technologically feasible to achieve substantial emission reductions. This implies that it is possible to reach emission levels consistent with a 2° C target (i.e. approximately 44 $GtCO_2e$ in 2020).

To have a higher confidence of staying below a 2° C limit, it seems essential to deploy negative emission technologies (to reduce CO_2 from energy and industry) in the second half of the century, that is, unless emission levels are significantly below 44 $GtCO_2e$ in 2020.

Assessment of the pathways consistent with 1.5° C

None of the IAM or "stylized" pathways in this assessment lead to temperature increases below 1.5° C throughout this century. One IAM study published by Magné et al. (2010) depicts an emission pathway with a "medium" chance of achieving the 1.5° C target by the end of the century and has 2020 emissions of 41 $GtCO_2e$. These results suggest that after a small (0.1° C) transient overshoot of the temperature limit of about half a century, the temperature increase by the end of the twenty-first century could be brought back to below 1.5° C with a "medium" chance. In general, the IAM pathways that meet the 2° C limit with a "likely" chance also meet the 1.5° C target by 2100 but with a lower probability of 30 per cent (range 27-35 per cent for the 20th-80th percentile) and with a median temperature peak at some point in the twenty-first century of between 1.6° C and 1.7° C.

A few studies have used stylized pathways to explore the achievement of a 1.5° C limit in more detail (Ranger et al. 2010, Schaeffer and Hare 2009). The stylized pathways included in this assessment suggest that limiting warming to 1.5° C by 2100 (with a "medium" to "likely" chance) means 2020 emission levels of 40 to 48 $GtCO_2e$ (20th-80th percentile range), and reduction rates of 3 to 5 per cent per year in the 2020-2050 period (Schaeffer and Hare 2009). These pathways would also employ negative CO_2 emissions in the second half of this century. As discussed in Section 2.3, the feasibility of achieving such high emission reduction rates is difficult to assess and they are not found in the current literature of IAM results.

[33] In the literature, two studies of "stylized pathways" have explicitly focused on the question of emission pathways consistent with the 2° C limit (Bowen and Ranger 2009 and Meinshausen et al. 2009).

Table 1: Re-analysis results of IAM pathways with 2° C characteristics.

2° C pathways	**Number of pathways**	**Peak year period***	**2020 total emission levels** ($GtCO_2e$)**		**Average energy and industry CO_2 reduction rate from 2020 to 2050** (% of 2000 levels / yr)		**Decade in which global energy and industry CO_2 emissions turn negative**	
			Median	Range***	**Median**	Range***	**Median**	Range***
"Likely" chance (greater than 66 per cent) of staying below 2° C during twenty-first century								
Without negative CO_2 emissions from energy and industry	2	2010-20	**31**	26-36	**0.9**	0.6-1.2	**N/A**	N/A
With negative CO_2 emissions from energy and industry	7	2010-20	**44**	41-{44-44}-48	**3.0**	2.8-{2.9-3.2}-3.2	**2070**	2050-{*2060-2070*}-2080
Full IAM set	9	2010-20	**44**	26-{39-44}-48	**3.0**	0.6-{2.2-3.1}-3.2	**N/A**	N/A
"Medium" chance (50 to 66 per cent) of staying below 2° C during twenty-first century								
Without negative CO_2 emissions from energy and industry	9	2010-20	**44**	34-{42-45}-48	**2.4**	0.8-{2.2-2.7}-3.1	**N/A**	N/A
With negative CO_2 emissions from energy and industry	9	2010-20	**45**	41-{42-46}-48	**2.5**	1.3-{2.3-3.2}-3.6	**2060**	2050-{*2050-2060*}-2070
Full IAM set	18	2010-20	**45**	34-{42-46}-48	**2.5**	0.8-{2.2-3.0}-3.6	**N/A**	N/A

* Because IAM pathways provide emissions data only for 5-year or 10-year increments, the encompassing period in which the peak in global emissions occurs is given. The peak year period given here reflects the 20th-80th percentile range. Note that pathways with a "likely" chance show peaks earlier in the decade, whilst those with a 'medium' chance are spread across the whole decade.
** For comparison: the median of current (2010) emissions in the harmonised IAM set is 48 $GtCO_2e$.

*** Range is presented as the (minimum value - {20th percentile - 80th percentile} - maximum value). Only minimum, maximum and median values are given for the subsets with very few pathways

Results from low and high ends of emissions range in 2020

In the text we have focused on the "majority of results" of the re-analysed IAM pathway set (the median and 20th to 80th percentile range). However, results outside this range are also valid and provide useful information.

We first consider the *high end* of the range of expected emissions in 2020 represented by results from van Vuuren et al. 2007 for a "likely" chance to stay below a 2°C limit, and O'Neill et al. 2009 for a "medium" chance. At this end of the range emissions are 48 $GtCO_2e$. For a "likely" chance to achieve the temperature target, average reduction rates between 2020 and 2050 (of CO_2 emissions from energy and industry) are 3.2 per cent per year, and for a medium chance 3.6 per cent per year[34]. These set the upper range of emissions and reduction rates.

[34] The seemingly counterintuitive difference in reduction rates is explained by the different shape of the post 2020 emission pathways. Van Vuuren et al. (2007) show emissions declining shortly after 2020 and hence have a lower rate of reduction with a high likelihood of limiting temperature increase than O'Neill et al. (2009), which decline later but faster and deeper.

The *low end* of the range shows that relatively low emission reduction rates between 2020 and 2050 are sufficient to reach the temperature limit, if 2020 emission levels are at the low end of the range. Some pathways, for example in Barker and Scrieciu (2010) and Clarke et al. (2009), indicate 2020 emission levels of 26-36 $GtCO_2e$. These results suggest that it may be technologically and economically feasible to reduce global emissions by 2020 by substantially more than the majority of IAM pathways assume.

Box 2b. Overshooting of 2° C Temperature limits

Model results show that temperature trends could overshoot and then drop again below temperature limits as a result of natural "sinks" acting to gradually reduce the atmospheric burden of the greenhouse gases over time. However, since this process occurs slowly, it is expected that once temperatures overshoot a target, they will take decades to drop below the target (Lowe et al. 2009). This process could be accelerated if negative CO_2 emissions were achieved as discussed earlier (Azar et al. 2006, Azar et al. 2010).

Overshoot pathways often arise in three different contexts: (1) deliberate policy choice to minimise mitigation costs; (2) failure to meet certain emission targets or goals; or (3) late participation by all major emitters in global mitigation efforts (Clarke et al. 2009, van Vliet et al. 2009). While deliberate overshoot may minimise mitigation costs over time, it does run the risk of lock-in of further fossil fuel use and thereby limiting the rate at which emissions can decline in subsequent years.

In the assessed IAM pathway set, four pathways have a temporary temperature overshoot before dropping below 2° C again. [35]. All of these pathways have global negative CO_2 emissions to help achieve the target. In these pathways the constraint on 2020 emissions is relaxed slightly, and the peak is postponed to 2020 and beyond.

Delayed action may have economic benefits (as noted above), but also has risks associated with the higher, albeit temporary, temperatures. These include higher mitigation costs over the long term and later and larger damages from climate change impacts. Huntingford and Lowe (2007) argue that there are significant risks from exceeding temperature limits during overshoot scenarios, due to uncertainty about so-called tipping points. An additional risk of overshooting temperature limits is that positive feedbacks, not known in advance, might result in a larger temperature increase than anticipated.

2.5 GAPS IN KNOWLEDGE AND FURTHER WORK

The ability to assess pathways consistent with specific temperature limits depends on understanding both the climate system and the global energy system, as well as the ways in which each responds to change over time.

Important uncertainties exist in our understanding of the climate system. We have accounted for some of this uncertainty by examining the probability of meeting particular temperature limits. Future shifts in the underlying probability distributions, as a result of improved understanding of parameters and/or feedbacks in the climate system, could change the expected probability with which a certain pathway would meet a specified temperature limit. There is also much uncertainty around the issue of how rapidly temperatures may be reduced after overshooting, and the reversibility of associated climate system changes.

[35] In addition to the 27 of the 126 IAM pathways that are able to meet the 2° C limit during the twenty-first century without a temperature overshoot and with a probability higher than 50 per cent.

Our understanding of the feasibility of pathways is also incomplete. Many of the pathways assessed here were not designed to specifically investigate the limits to feasible emission reductions, and none of the studies were designed explicitly to explore the full range of emissions in 2020 that would be consistent with long-term temperature limits. Research specifically targeted to address these questions would improve our understanding of which pathways can feasibly achieve temperature targets.

In addition, emission pathways now considered infeasible could become feasible if variables such as population growth rate, consumption of energy, aerosol emissions, economic growth and technological developments turn out to be different from the assumptions used in current studies. Other factors could also make emission pathways feasible such as the willingness of society to take “extreme” action by retiring energy infrastructure before the end of its useful lifetime, or by making significant lifestyle changes. Similarly, the pathways thought to be feasible in this report could in practice be unachievable, if, for example, participation in mitigation efforts was limited across sectors and countries, or if technological and socio-economic barriers were more severe than expected.

Given these uncertainties, it will be crucial over time to re-evaluate the emission pathways consistent with particular temperature limits and to inform the policy community accordingly.

3. What are the expected global emissions in 2020?

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3.1 INTRODUCTION

Nearly 140 countries have associated themselves with the Copenhagen Accord and over 80 countries, representing about 80 per cent of global emissions, have appended targets (Annex I countries) and/or mitigation actions (non-Annex I countries). The aim of this chapter is to assess the published analyses and to explore what these targets and actions (collectively referred to as "pledges")[36] are likely to lead to in terms of 2020 emissions[37]. Three appendices to this Chapter are available online[38]. Appendix 1 provides detail on the differences between the four cases and the uncertainties around them. Appendix 2 provides a country-by-country analysis of the pledges of the largest emitting countries. Appendix 3 compares the modelling groups' findings and details the adjustments made to their data to ensure consistent comparisons. Chapter 4 then goes on to combine these results with those of the previous chapter on emission pathways in order to assess the extent to which these pledges are consistent with a 2° C or 1.5° C pathway.

Estimating 2020 emissions, based on countries' pledges or submissions to the Copenhagen Accord, is not a simple task. This Chapter explains in detail that it involves *inter alia*: information on the historical, current and future growth of countries' emissions; interpretations in the cases in which countries have submitted a range of pledges; assumptions on the precise meaning of those pledges where countries have not been specific; and uncertainties in the underlying data used by modelling groups.

Therefore, we separate the emission estimates that are driven by distinct policy choices, either nationally or in the negotiations, from what is driven by different modelling assumptions. We first present the results of this analysis and then move on to explore the modelling uncertainties around them.

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36 Please note that the pledges incorporated in the Copenhagen Accord in early 2010 have not changed through the 2010 negotiations' cycle

37 Whilst this assessment focuses on the pledges submitted to the Copenhagen Accord, in one instance, for Indonesia, modelling groups have analysed a conditional pledge announced by the President but not included in the Copenhagen Accord submission. The impact of that pledge is included in the two conditional pledge cases presented in this Chapter.

38 www.unep.org/publications/ebooks/emissionsgapreport

3.2 GLOBAL AGGREGATE EMISSIONS RESULTING FROM THE PLEDGES

For this assessment, the analyses of 13 modelling groups have been reviewed[39]. Of these, nine groups have performed a global analysis and four have focused on either Annex I or a subset of other countries. These groups have made different assumptions about how the conditionality of pledges plays out in global emissions. Hence, adjustments have been made to the various estimates, in order to facilitate a meaningful comparison. The adjustments made are briefly explained in Box 3a and detailed in the appendices available online[40]. The aim has been to construct a set of pledge cases with estimates of different 2020 emission levels.

Box 3a: Explanation of the four pledge cases and calculation method

In this chapter we have constructed four distinct pledge cases that could result from different policy choices of Governments or from different outcomes of the negotiations. These four cases are combinations of the following two interdependent factors:

Unconditional versus conditional pledges: We have distinguished between countries' unconditional and conditional pledges. Several industrialized countries have made pledges conditional on actions from other countries or the passing of domestic legislation, and developing countries' pledges are often conditional on finance or technology transfer. We have made common assumptions as to whether a country's pledge is deemed conditional or not (detailed in Appendix 2) and applied that to all modelling groups' estimates. We have then summed the estimates to create a global total, which also includes international transport emissions. Note that where a country does not have an unconditional pledge (e.g. Canada, Japan, US and South Africa) the business-as-usual estimate for that country is assumed for the unconditional case reflected in Figure 2. [41]

"Lenient" versus "strict" rules: We have adjusted these results to take into account the maximum[42] impact of two unresolved issues in the negotiations: LULUCF accounting and the use of surplus emissions units. These issues have the potential to displace mitigation action in other sectors and thus lead to higher global emissions in 2020. The adjustments made are based on a review of existing literature and are reflected in the two "lenient" pledge cases (the "strict rules" cases do not include any impact from these issues). Specifically, for LULUCF accounting we have applied a maximum expected impact of 4.2 per cent of 1990 Annex I emissions annually in 2020 (approximately 0.8 $GtCO_2e$). We assumed that credits of this magnitude would be given for carbon removals from existing forests or other sinks that would have occurred without further policy interventions (see Box 3b). For surplus emissions units, we have made two adjustments: the first for the expected impact of surplus emissions units "carried over" or "banked" from the first commitment period and used in the next. We have applied the maximum expected impact of 1.3 $GtCO_2e$ on 2020 emissions. The second adjustment is to account for any new surplus units that are expected to be generated in the next commitment period as a result of the pledges from Russia, Ukraine and Belarus remaining above business-as-usual. The expected impact of these depends on the modelling assumptions of each

[39] Namely: Climate Action Tracker (CAT) by Ecofys, Climate Analytics and PIK; Climate Interactive (the C-ROADS model); Climate Strategies; FEEM (the WITCH model); IIASA (the GAINS model); Grantham Research Institute (LSE); OECD (the ENV-linkages model); PBL Netherlands Environmental Assessment Agency (the FAIR model); Peterson Institute for International Economics (PIIE); Project Catalyst; the AVOID research programme (led by the Met Office Hadley Centre); UNEP Risoe; and the World Resources Institute (WRI).

[40] www.unep.org/publications/ebooks/emissionsgapreport

[41] Given that these countries are implementing and/or planning some domestic policies, this is a very cautious assumption (e.g. for the USA see Bianco and Litz (2010)).

[42] A maximum impact is taken in order to show an upper bound for what 2020 emissions could be under these cases.

group and ranges up to 1 $GtCO_2e$ in 2020.[43] A more detailed description of these issues and adjustments is available in Appendix 1.

In order to make consistent comparisons across modelling groups, we have had to adjust the global emission estimates of some groups to ensure that all sectors and countries are covered. In the case where data were missing (e.g. international transport emissions), we have added the median value of other modelling groups' data. In addition, in order to ensure a consistent comparison with the results from Chapter 2 we have harmonised the data for the same 2005 emissions used in that chapter. These adjustments result in slightly different emission levels for each of the groups compared with those included in their publications. Appendix 3 provides more detail on the differences between modelling groups' findings and the adjustments made.

In Figure 2 we show median results for each case to reflect the clustering of results from modelling groups. In the text we report the 20th and 80th percentile range to reflect the majority of the results.

To estimate emissions expected in 2020 we have to make assumptions about the policy choices of governments. Since these choices are uncertain we specify four different cases, each giving a different combination of choices (Box 3a). The results for emissions are as follows (and are summarised in Figure 2):

As a reference point, without pledges global greenhouse gas emissions may increase from 45 $GtCO_2e$ in 2005 to around 56 $GtCO_2e$ in 2020 (with a range[44] of 54-60 $GtCO_2e$) according to business-as-usual projections.

- *Case 1 – "Unconditional pledges, lenient rules"*: this case would occur if countries stick to their lower-ambition pledges and are subject to "lenient" accounting rules. By this we mean that Annex I countries maximise the use of surplus emission units and "lenient LULUCF credits" (see Box 3b) to meet their targets.. In this case, the median estimate of emissions in 2020 is 53 $GtCO_2e$ per year, with a range of 52-57 $GtCO_2e$.
- *Case 2 – "Unconditional pledges, strict rules"*: This case would occur if countries stick to their lower-ambition pledges and are subject to "strict" accounting rules. By this we mean that the use of surplus units and "lenient LULUCF credits" is assumed to be zero. In this case, the median estimate of emissions in 2020 is 52 $GtCO_2e$, with a range of 50-55 $GtCO_2e$.
- *Case 3 – "Conditional pledges, lenient rules"*: This case would occur if countries moved to their higher-ambition pledges (as conditions are either met or relaxed), but are subject to "lenient" accounting rules (as explained in case 1 above). This case was included because some of the more ambitious pledges of Annex I countries are conditional on some use of these credits or carry-over of surplus units (e.g. European Union, Russia). In this case, the median estimate of emissions in 2020 is 51 $GtCO_2e$, with a range of 49-53 $GtCO_2e$.
- *Case 4 – "Conditional pledges, strict rules"*: This case would occur if countries moved to their higher-ambition pledges, and are subject to "strict" accounting rules

[43] Note that in computing the emissions for the "lenient" cases we have applied the adjustments noted in this box for LULUCF accounting and surplus emission units. H owever, if those adjustments resulted in Annex I emissions being higher than their business-as-usual projections then we capped emissions at that level. Hence the adjustments noted in this box are not additive.

[44] Henceforth, in this chapter all ranges refer to the 20th-80th percentile, unless otherwise specified.

(as explained in case 2 above). In this case, the median estimate of emissions in 2020 is 49 $GtCO_2e$, with a range of 47-51 $GtCO_2e$.

It is worth noting that there is the possibility of higher global emissions if international offsets are counted towards both industrialized and developing countries' pledges (the so-called "double counting" of offsets). It should also be noted that in some countries the impact of existing domestic policies or national plans could lead to lower emissions than the conditional pledges submitted to the Copenhagen Accord. International climate finance could also leverage further mitigation and lower emissions. All these issues have been analysed and found to have a significant effect on 2020 emissions. However, they are not included in any of these cases but are discussed as additional factors in Section 3.4 below.

From the analysis of these four cases it is interesting to note that the international policy options being discussed in the UNFCCC negotiations, and inherent in these cases, can significantly reduce the level of emissions in 2020. The most ambitious of the cases (case 4) is expected to be 7 $GtCO_2e$ lower than business-as-usual emissions (range of 6-9 $GtCO_2e$ lower).

For Annex I countries, in the least ambitious case ("unconditional pledges, lenient rules"), emissions are estimated to be 6 per cent above 1990 levels (range of 1-12 per cent above) or equivalent to business-as-usual emissions in 2020. In fact, in many cases the use by Annex I countries of surplus units and "lenient LULUCF credits" provides more overall emission units than needed. This could result in higher emissions after 2020 if those units were to be banked for use in the following period.

In the most ambitious case ("conditional pledges, strict rules"), Annex I emissions in 2020 are expected to be 16 per cent below 1990 levels (range of 15-18 per cent below) and 20 per cent below business-as-usual emissions (range of 17-26 per cent).

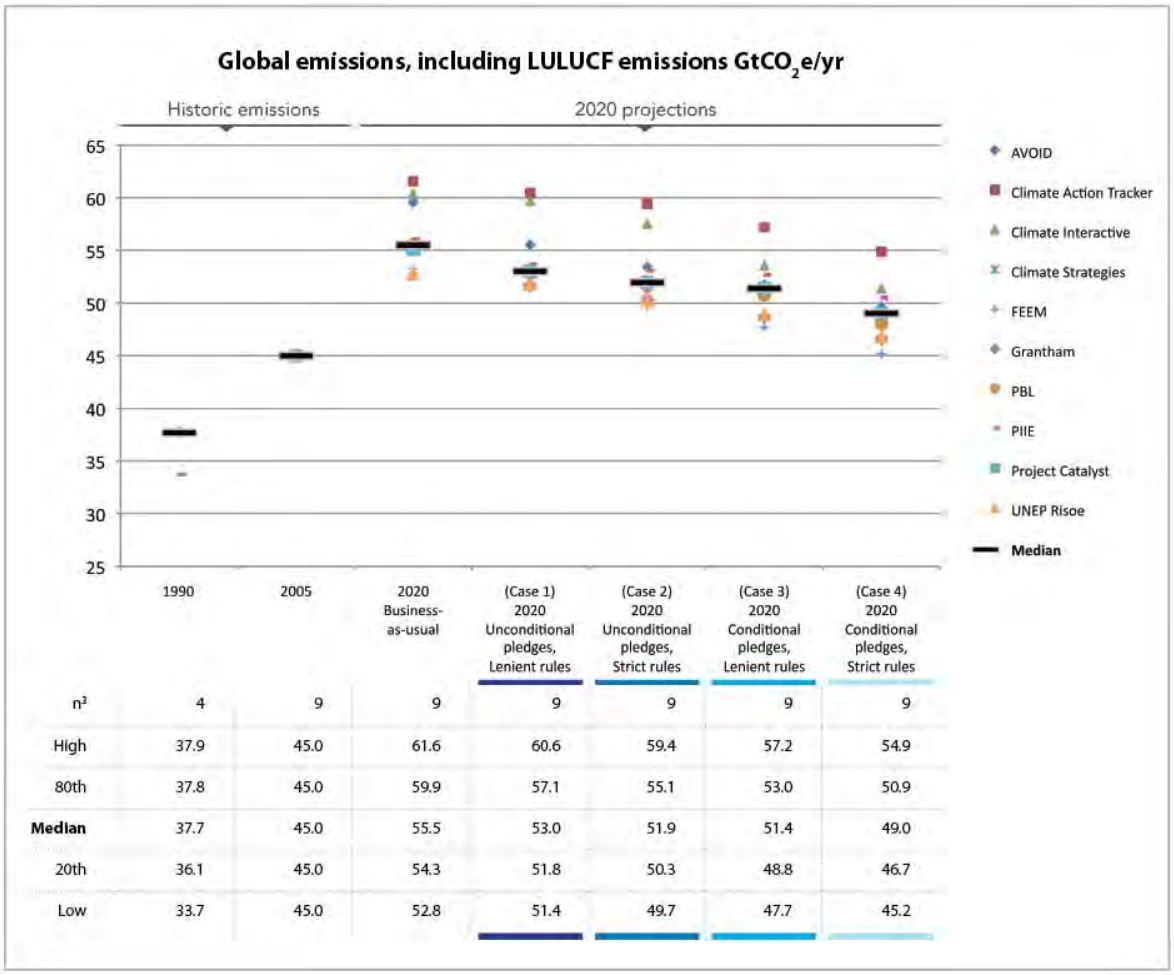
For non-Annex I countries, in the least ambitious case ("unconditional pledges") emissions are estimated to be 7 per cent lower than business-as-usual emissions (range of 6-8 per cent lower). In the most ambitious case ("conditional pledges"), non-Annex I emissions are 9 per cent lower than business-as-usual (range of 8-9 per cent lower).

This implies that the aggregate Annex I countries' emission goals are less ambitious than the 25-40 per cent reduction by 2020 (compared with 1990) suggested in the IPCC Fourth Assessment Report (IPCC 2007a). Collectively the non-Annex I countries' goals are less ambitious than the 15-30 per cent deviation from business-as-usual which is also commonly used as a benchmark (den Elzen and Höhne 2008, 2010). Whilst these values are helpful as a benchmark, it should be noted that, as described in chapters 2 and 4, various other emission pathways are consistent with the 2° C and 1.5° C temperature limits.

The cases presented in Figure 2 will be taken forward into the next chapter, which compares global emissions projections for 2020 with the emission pathways associated with limiting temperature rise to 2° C or 1.5° C. There are many possible combinations of the uncertainties considered in the preceding section that may lead to different 2020 emissions. However, the four cases presented above represent a reasonable summary of the potential low and high ambition outcomes that may be associated with the pledges.

Several options exist for policymakers to influence the final global 2020 emission level by delivering on their highest announced ambition and ensuring that accounting rules do not displace mitigation, and by finding ways to deliver further ambition either domestically, through finance or in sectors not currently covered.

Figure 2. Global emissions resulting from the four pledge cases, as found by different modelling groups



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

All emissions in this figure and chapter refer to $GtCO_2e$ (gigatonnes or billion tonnes of carbon dioxide equivalent)—the global warming potential-weighted sum of the six Kyoto greenhouse gases, that is, CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, including LULUCF CO_2 emissions.
n = number of studies; High = maximum of full range; Low = minimum of full range; 20th-80th = 20th and 80th percentile values of the range
1. The data presented in the table have been harmonised to a common emissions level in 2005 (45 $GtCO_2e$) in order to make these data more comparable to results in Chapter 2.
2. The range in 1990 emissions stems from the use of different data sources and assumptions especially for non-Annex I countries.
3. In the set of studies examined in this report, nine modelling groups have analysed the impact of pledges at the global level, while four have analysed only a subset of countries.

3.3 ANALYSIS OF DIFFERENCES BETWEEN ESTIMATES

The range between modelling groups' estimates can be split into three categories:

1) Differences between the four pledge cases,
2) Differences between estimates for the same pledge case, and
3) Other factors that could affect emissions

More detail on each of these issues and, where appropriate, the sources of estimates can be found online[45] in Appendix 1. Figure 3 summarises the impact of these differences on the emissions of the four pledge cases, together with the further uncertainties described in the next section.

1) Differences between the four pledge cases

The four cases presented in Figure 2 are characterised by different assumptions on the conditionality of both Annex I and non-Annex I countries' pledges, LULUCF accounting rules and on the use of surplus units from the first commitment period and the possible creation of new surplus in the future. An overview of the impact of these assumptions is provided below – Appendix 1 has more details:

Unconditional versus conditional pledges

If countries were to move from unconditional to conditional pledges global emissions would be around 2-3 $GtCO_2e$ lower (with a range of estimates of 2-5 $GtCO_2e$). This breaks down as follows (numbers in parentheses show the annual 2020 emission reductions associated with moving from case 1 to 3 or from case 2 to 4 in Figure 2):

- Conditionality of Annex I (industrialized) countries (0 to -2.7 $GtCO_2e$)[46]: A significant number of Annex I countries have made pledges that are conditional on the actions of others or on the passing of domestic legislation. In some instances, countries also have unconditional pledges that will be implemented even if those conditions are not met.
- Conditionality of non-Annex I (developing) countries (0 to -0.7 $GtCO_2e$)[47]: As was the case for the Annex I countries, some non-Annex I countries have included a range in their submissions, with the upper end of the range often being conditional on climate finance.

"Lenient" versus "strict" rules

If the rules in the negotiations regarding the use of LULUCF credits and surplus emission units were to be set in a "strict" rather than "lenient" manner, emissions could be around 1-2 $GtCO_2e$ lower. This breaks down as follows (numbers in parentheses show the maximum possible increase in annual 2020 emissions reflected in the "lenient" cases)

- LULUCF accounting rules (0 to +0.8 $GtCO_2e$): The accounting rules that determine the extent to which LULUCF activities in Annex I countries could be used to meet their respective targets for the period after 2012 are still being negotiated. Most proposals in the negotiations would limit the number of "lenient LULUCF credits" by using historical or reference level baselines (see Box 3b).

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[45] www.unep.org/publications/ebooks/emissionsgapreport

[46] 2.7 $GtCO_2e$ is the median estimate of the studies. It does not exactly match the 2-3 $GtCO_2e$ reflected in the median estimate of Figure 2 due to the distribution of the sample for global emissions. See Appendix 1 for details.

[47] 0.7 $GtCO_2e$ is the median estimate of the studies. It does not exactly match the 1-2 $GtCO_2e$ reflected in the median estimate of Figure 2 due to the distribution of the sample for global emissions. See Appendix 1 for details.

– Surplus emission units

- Carry-over of surplus units from the first commitment period (0 to +1.3 $GtCO_2e$): Surplus emission units can arise due to some countries exceeding their targets in the first commitment period. Countries with surplus units can also "bank" them and use them for meeting their target in a following commitment period post-2012, or sell them to other countries for their compliance.

- Creation of new surplus units in a possible second commitment period: (0 to +1.0 $GtCO_2e$)[48]: Further surplus emission units can occur through some countries being allocated emission units significantly above the estimated business-as-usual level in a possible second commitment period. These units can be used by countries to meet their targets, or sell to other countries for their compliance.

It should be noted that the above issues are interdependent and will result in different emission reductions depending on the order in which they are implemented. Hence the numbers presented above cannot simply be added together and are, therefore, not easily traceable to the median results reflected in Figure 2 above[49]. In the reviewed studies, the total impact from these options (if taken together) would be a reduction in global emissions of 4 $GtCO_2e$ (reflected in the move from Case 1 to 4 in the table), with a full range across studies of 3-8 $GtCO_2e$.

Box 3b: Further explanation of LULUCF accounting in "lenient" and "strict" rules

LULUCF accounting systems should provide credits for proven CO_2 removals from new or enhanced sinks as a result of further policy intervention. Credits for such activities would result in CO_2 removals from the atmosphere that could contribute to meeting, and thus should be counted towards, targets[50].

The "strict" rules cases developed in this chapter reflect situations in which LULUCF credits such as those described above are provided. For calculation purposes, the quantity of LULUCF credits is set to zero in these cases – although some credits could occur. This is accurate because the resulting target emission level is the same and therefore it is not necessary to estimate the possible quantity of these LULUCF credits.

In the "lenient" case, on the other hand, we assume that credits are given for CO_2 removals by sinks that are expected to occur anyway in the absence of additional policy (e.g. from forests existing prior to 1990). Given that these direct-human induced emission removals are anyway part of the baseline emissions,[51] the use of such credits would increase the estimate of 2020 global emissions. In this assessment we call such credits *"lenient LULUCF credits"*. Specifically, we assume that "lenient LULUCF credits" of up to 0.8 $GtCO_2e$ per year in 2020 could be generated in the "lenient" cases shown in Figure 2. See Appendix 1 for details.

[48] Note that only some modelling groups have analyzed this, so for many groups the assumed impact of this is zero. These groups assume that no extra units are assigned for targets above business-as-usual. However, of the six modelling groups that did analyse this, estimates suggest that it could have as much as a +1 $GtC0_2e$ impact in 2020 (in the conditional pledge cases) – see Appendix 1 for more detail.

[49] The distribution of the sample also complicates this, making it difficult to trace the numbers back to Figure 2.

[50] For the same emission target these credits would allow correspondingly higher emissions in other sectors compared to the situation in which such LULUCF credits were not used to meet the target. In this case, from a global accounting sense, the final net emission level would be the same, assuming that target is met (i.e. would have a "net-zero" effect on the target)

[51] Or are considered by carbon cycle models as CO_2-uptake by the terrestrial biosphere in response to elevated CO_2 concentrations

2) Differences between estimates for the same pledge case

Figure 2 shows that there is sometimes a large difference between modelling groups' estimates of the same cases. The main reasons for these differences are described below and, where possible, the uncertainty that each implies for 2020 global emissions. Numbers in parentheses give the range of 2020 emission estimates in Figure 2 that could be attributed to each of these reasons.

- LULUCF emissions (±4 $GtCO_2e$): Global emissions from LULUCF are subject to a high level of uncertainty, which the IPCC estimates to be ±4 $GtCO_2e$. There is particular uncertainty around anthropogenic emissions from peat lands. Lastly there is an uncertainty around how modelling groups treat the LULUCF emissions from Annex I countries, in particular. LULUCF emission uncertainty may be partially reflected in the range of estimates from different modelling groups.

- Baseline emissions (-3.4 to +2.4 $GtCO_2e$): Modelling groups have used different assumptions regarding non-Annex I countries' business-as-usual emission projections and Annex I countries' base year emissions (e.g. whether LULUCF CO_2 is included or not). Moreover, the quantification of emission reductions due to carbon intensity targets (measured as improvement in emissions per unit of GDP) poses additional uncertainties.

- Non-covered sectors and countries (-1.1 to +2.7 $GtCO_2e$): There is often a significant range in the emissions estimates for sectors not included under national pledges, such as emissions from international aviation and maritime transport (bunkers) and for countries without pledges. The results from different studies will vary, since some have explored the impact of mitigation policies of only a subset of countries.

3) Other factors that could affect emissions

There are a number of other factors not reflected in the range of estimates under each of these cases, but which could have a large impact on 2020 emissions. Modelling groups have generally not factored these issues into their central estimates for emissions resulting from the pledges—although many of the groups have estimated the impact of these issues separately. These factors include the following. Numbers in parentheses give the maximum annual 2020 emissions impact on the four cases:

- Double counting of offsets (0 to +1.3 $GtCO_2e$): The potential for double counting of offsets towards both industrialized and developing country pledges, is a major source of uncertainty not reflected in Figure 2. This could occur if industrialized countries use offsets to meet their targets and that these same offsets also counted towards developing country pledges. A simple estimate of the risk of double counting can be made by assuming that 33 per cent of the deviation of Annex I emissions from business-as-usual is covered by offsets and that all of those are also counted towards

non-Annex I goals. This would lead to emissions being around 1.3 $GtCO_2e$ higher (as compared to the "conditional pledge, strict rules" case)[52]

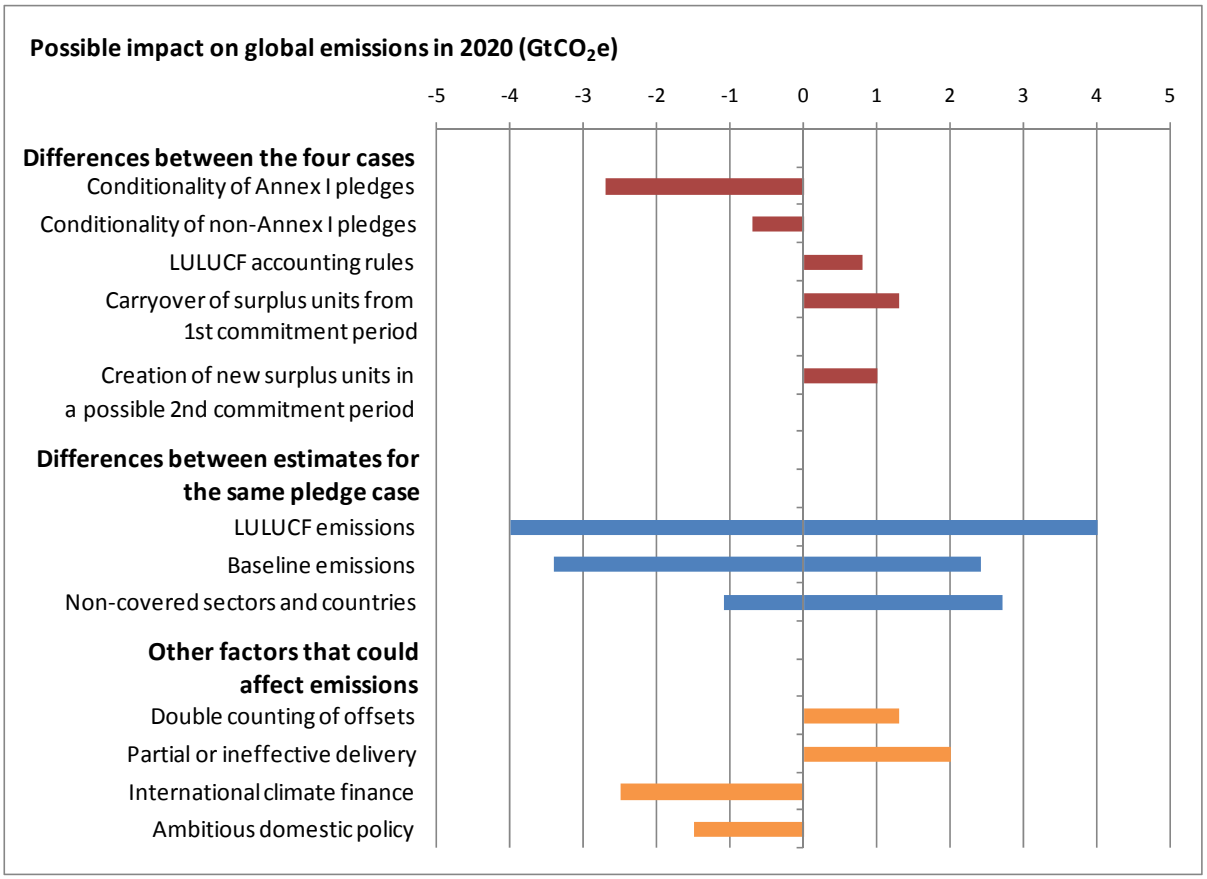
– Partial or ineffective delivery (0 to +2.0 $GtCO_2e$): Any failure to carry out policies would undermine national efforts and lead to higher 2020 emissions; this would push countries' emissions back towards business-as-usual. Conversely, well-designed policies that spur innovation and investment could mean that goals are exceeded. All analyses covered in Figure 2 assume that countries will meet their targets. A crude assessment of the risk of partial implementation can be made by assuming that a certain proportion of the deviation from global business-as-usual is not delivered. Using 25 per cent would lead to estimates of 2020 emissions around 2.0 $GtCO_2e$ higher than in Figure 2 (as compared to the "conditional pledge, strict rules" case).

– International climate finance (0 to -2.5 $GtCO_2e$): International climate finance could leverage further emission reductions beyond the conditional pledges of countries or in countries that have not yet specified mitigation actions. The upper bound of -2.5 $GtCO_2e$ is found by a study that assumes that 25 per cent of Copenhagen Accord financing in 2020 will be used for additional mitigation actions (Carraro and Massetti, 2010).

– Ambitious domestic policy (0 to -1.5 $GtCO_2e$): Certain countries have domestic plans that include mitigation actions that some analysts estimate to be more ambitious than the Copenhagen Accord pledges. The three modelling groups that have analysed this issue estimate that this could lead to emissions being up to 1.5 $GtCO_2e$ lower than the Copenhagen Accord pledges would suggest.

[52] Note also that if offset credits are provided for activities that are not "additional" to expected baselines, even higher total emissions would result.

Figure 3: Summary of the maximum impact of differences and uncertainties on global 2020 emissions. There is a strong interaction between these factors and the effects are therefore not additive. Hence, no estimate of their total impact is given.



Box 3c: Under what circumstances would the Copenhagen Accord pledges lead to a peak in global emissions before 2020?

Most of the emission pathways consistent with a likely chance of meeting the 2º C limit show emissions peaking before 2020 (see Chapter 2). Hence, peaking is an important indicator of whether pledges are consistent with the 2º C limit.

Making an assessment of whether global emissions peak between now and 2020 requires understanding of where the emissions will be in 2020, as well as their trajectory in the interval between now and then. If the emissions in 2020 are close to or below current levels, then it is possible that emissions will peak over this period. Estimates of current (2009) emission levels are around 48 $GtCO_2e$ (Manning et al. 2010). Since only the most ambitious of the pledge cases comes close to current levels, we expect that this pledge case is the one most likely to result in a peak in emissions before 2020. By contrast, the least ambitious pledge case ("unconditional pledges, lenient rules") results in a strong increase in emissions and is therefore the least likely to peak before 2020.

It should be noted that, it is also possible that emissions could peak before 2020, but still remain significantly above current levels in 2020. This could occur, for example, if the emission reduction policies are only introduced or start to take significant effect towards the end of this decade. However, it is difficult to assess the likelihood of this from the pledges alone.

4. What is the emissions gap?

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4.1 INTRODUCTION

This section assesses the potential "emissions gap" between expected emissions based on country pledges and emission levels in 2020 consistent with 2° and 1.5° C limits. For this purpose, we build upon the results in chapters 2 and 3.

As pointed out in Chapter 2, the emission levels consistent with temperature limits depend on the desired likelihood of meeting particular limits, the feasible pace of emission reductions post 2020, and the availability of technology to achieve, for example, negative emissions (Chapter 2, Table 1).

It was explained in Chapter 3 that expected emissions in 2020 depend on whether unconditional or conditional pledges are followed and on the outcome of a number of issues under negotiation, in particular that of LULUCF accounting and surplus emission units (Chapter 3, Figure 2). Given the uncertainty of both expected emissions and emission levels consistent with temperature limits, we do not make a single estimate of the potential gap. Instead, we assess the likely range of the gap based on combinations of assumptions about both expected emissions and emission levels corresponding to temperature targets[53].

4.2 FINDINGS FOR 2° C

Table 2 summarises the gaps that result from four different interpretations of how the pledges are followed, and for a "likely" (greater than 66 per cent) and a "medium" (50-66 per cent) chance of staying below 2° C.

In Chapter 2 it was shown that emission levels of 44 $GtCO_2e$ in 2020 (range of 39-44 $GtCO_2e$)[54] are consistent with a "likely" chance of limiting global warming to 2° C.

In Chapter 3, four pledge cases or possible negotiation outcomes were identified. Here we compare the gap in 2020 between expected emissions based on these cases and emission levels identified in Chapter 2. As a reference point, business-as-usual emissions in 2020 would result in a gap of 12 $GtCO_2e$ (range of 10-21 $GtCO_2e$).

– *Case 1 – "Unconditional pledges, lenient rules"*. Countries implement their lower-ambition pledges and maximise the use of "lenient LULUCF credits"[55] and surplus emissions units to meet their goals. In this case, the gap is 9 $GtCO_2e$ with a range of

[53] However, it is important to note that the results in Chapter 2 do not take into account some other important sources of uncertainty, such as the effects in the future of different potential levels of anthropogenic aerosols—these may also affect the assessment of the gap.

[54] As in previous chapters, this and following ranges refer to the 20th and 80th percentile of results, unless otherwise specified.

[55] Credits given for carbon removals from existing forests or other sinks that would have occurred without policy intervention and are likely to be included in the baseline of models.

8-18 $GtCO_2e$. The unconditional pledges would thus reduce the gap by about 20 per cent compared to business-as-usual.

– *Case 2 – "Unconditional pledges, strict rules".* Countries implement their lower-ambition pledges but do not use "lenient LULUCF credits" and surplus emission units to meet their goals. In this case, the gap narrows to 8 $GtCO_2e$ (range of 6-16 $GtCO_2e$). Compared to business-as-usual, this is equivalent to achieving about 30 per cent of the overall mitigation effort towards 2° C by 2020.

– *Case 3 – "Conditional pledges, lenient rules".* Countries implement their higher-ambition pledges and make maximum use of "lenient LULUCF credits" and surplus emissions units. In this case, the gap is reduced to 7 $GtCO_2e$ (range of 5-14 $GtCO_2e$). Compared to business-as-usual, this is equivalent to achieving about 35 per cent of the overall mitigation effort towards 2° C by 2020.

– *Case 4 – "Conditional pledges, strict rules".* Countries not only implement their higher-ambition pledges, but also do not use "lenient LULUCF credits" and surplus emission units to meet their goals. The result is a further narrowing of the gap to 5 $GtCO_2e$ (range of 3-12 $GtCO_2e$). This corresponds to the smallest gap assessed in Table 2, and is equivalent to reducing the overall mitigation effort towards 2° C by almost 60 per cent compared to business-as-usual in 2020. As a point of reference, the remaining gap is about the level of emissions in the European Union in 2005 or from the world's road transport in that same year.

Hence, moving from (lower-ambition) unconditional pledges to (higher-ambition) conditional pledges narrows the gap by about 2 to 3 $GtCO_2e$—the majority of this reduction would come from industrialized countries, whose pledges are sometimes conditional on the ambitious action of other countries or on domestic legislation. A smaller, but still important, part of the reduction would come from developing countries, whose pledges are sometimes conditional on the adequate provision of international climate finance or technology transfer.

In addition, the gap can be reduced by around 1 to 2 $GtCO_2e$ by ensuring that "strict" rules apply to the use of LULUCF credits and surplus emission units. If industrialized countries apply "strict" accounting rules to minimise the use of what we refer to as "lenient LULUCF credits", they would strengthen the effect of their pledges and thus reduce the emissions gap by up to 0.8 $GtCO_2e$. Likewise, if the rules governing the use of surplus emission units under the Kyoto Protocol were designed in a way that would avoid the weakening of mitigation targets, the gap could be reduced by up to 2.3 $GtCO_2e$. These include units carried over from the current commitment period and any potential new surpluses created in the next. See Chapter 3 for more details[56].

There are also a number of important factors, mentioned in Chapter 3, that could increase or decrease the gap and that are not included in these cases. The double counting of international offsets towards both industrialized and developing countries' goals could reduce the overall amount of mitigation and thus increase the gap by up to 1.3 $GtCO_2e$. Conversely, the implementation of ambitious existing national plans, beyond what is included in the Copenhagen Accord, could narrow the gap by up to 1.5 $GtCO_2e$ (as compared to the fourth pledge case).

[56] Note that the 0.8 and 2.3 $GtCO_2e$ numbers indicate the maximum possible impact expected from these issues and cannot simply be added together. The median impact of moving from "lenient" to "strict" accounting rules is found to be 1-2 $GtCO_2e$. See Chapter 3 for more details.

To have a *"medium"* rather than a *"likely"* chance of staying below 2° C, the emission levels for the pledge cases can be about 1 $GtCO_2e$ higher, and the corresponding gap 1 $GtCO_2e$ lower for all pledge cases (Table 2).

Explanation of the range of results of the emissions gap for 2° C

The range of the gap presented for the different cases in Table 2 is based on the "majority of results" (20th to 80th percentile) across both the pledges and the 2° C emission levels. The upper bound estimate of the gap combines low 2° C emission levels (20th percentile) with high emissions from pledges (80th percentile). As explained in Chapter 2, emission levels consistent with the 2° C limit tend to be lower in 2020 when followed by comparatively slower emission reduction rates thereafter, or when negative emissions are not achieved over the long run.

Conversely, at the low end of the gap range we find a combination of higher 2° C emission levels in 2020 and low expected emissions as a result of the pledges. Emission levels that are consistent with 2° C tend to be higher in 2020 when reduction rates are comparatively high after 2020 (3.1 per cent per year) and/or it is assumed that negative emissions take effect over the long run. Under these conditions, emissions can afford to be higher in 2020, since they will be reduced more quickly afterwards.

The size of the gap is therefore strongly dependent on expectations about emission reduction rates after 2020 and the prospects for negative emissions later in the century. Both depend, of course, on the rate of technological development.

In addition, the reader will note that the range around median estimates is not symmetric; the lower bound extends by about 1-2 $GtCO_2e$ below the median, whereas the upper bound rises 7-9 $GtCO_2e$ above it (for a "likely" chance). This is found for all the pledge cases examined and arises because of the skewed distribution of pledge estimates with a more pronounced tail on the upper bound. One interpretation of this skewed range is that the gap may in reality tend to be on the higher side of the median.

This chapter has so far focused on the "majority of results" (20th to 80th percentile of estimates). Results outside this range indicate that emission levels for a "likely" chance of staying below 2° C could be as high as 48 $GtCO_2e$ (Chapter 2), while at the same time expected emissions under case 4 ("conditional pledges, strict rules") could, according to one estimate, be as low as 45 $GtCO_2e$ in 2020. Under these conditions, no gap exists. On the other hand, looking at the other end of the range, we find 2° C emission levels for a "likely" chance of staying below the 2° C limit can range as low as 26 $GtCO_2e$, while the highest estimate of emissions under case 1 of the pledge cases ("unconditional pledges, lenient rules") is 61 $GtCO_2e$, resulting in a gap as high as 35 $GtCO_2e$.

4.3 FINDINGS FOR 1.5° C

There is no emission pathway in the assessed IAM literature of Chapter 2 that achieves the 1.5° C limit with a "likely" (greater than 66 per cent) chance and only one study in this literature depicts an emission pathway consistent with a medium (50-66 per cent) chance of meeting the 1.5° C limit (Magné et al. 2010). The IAM pathways assessed that meet the *2° C* limit with a "likely" chance suggest, however, that after a small (0.1-0.2° C) transient overshoot of the 1.5° C target, the temperature increase by the end of the twenty-first century could drop below 1.5° C, *but with a lower probability.* These pathways reach the 1.5° C target in the long-term with a median probability of 30 per cent (range of 27-35 per cent).

Reaching 1.5° C with these lower probabilities would thus leave a similar emissions gap in 2020 as the one for a "likely" chance for 2° C. However, having a "likely" chance of reaching the 1.5° C target would require higher rates of emission reductions after 2020 (and correspondingly high rates of technological development and deployment) than those reported in the IAM literature.

Table 2. The global gap (in $GtCO_2e$ per year) between emission levels for staying below 2° C (with a "likely" (greater than 66 per cent) and a "medium" (50-66 per cent) chance) and expected emissions as a result of the Copenhagen Accord pledges. All estimates in this table are derived from the results of chapters 2 and 3. Values in bold correspond to medians, and numbers in brackets correspond to 20th to 80th percentile of estimates. Numbers in italics give the adjusted 2020 emission levels for expected emissions from the pledges and emission levels from the pathways.

Pledge case	"Likely" chance (>66%) to stay below 2°C *(2020 emissions: 44 [39-44])*		"Medium" chance (50 to 66%) to stay below 2°C *(2020 emissions: 45 [42-46])*	
Business as usual *2020 emissions: 56 [54-60])*	**12**	[10-21]	**11**	[8-18]
Unconditional pledge, Lenient rules *(2020 emissions: 53 [52-57])*	**9**	[8-18]	**8**	[6-15]
Unconditional pledge, Strict rules *(2020 emissions: 52 [50-55])*	**8**	[6-16]	**7**	[4-13]
Conditional pledge, Lenient rules *(2020 emissions: 51 [49-53])*	**7**	[5-14]	**6**	[3-11]
Conditional pledge, Strict rules *(2020 emissions: 49 [47-51])*	**5**	[3-12]	**4**	[1-9]

4.4 CONCLUSIONS

We have seen in this chapter that a global emissions gap is likely between expected emissions as a result of the pledges and emission levels consistent with the 2° C limit in 2020. But our analysis of options for implementing the Copenhagen Accord pledges has also shown that this gap could be narrowed through any of the following policy options[57]:

1. *Implement conditional pledges:* If all countries were to move to their conditional (high ambition) pledges, it would significantly narrow the 2020 emissions gap towards 2° C. The gap would be reduced by about 2 to 3 $GtCO_2e$, with most of the emission reductions coming

[57] Note that options 1 and 2 are non-additive as their impact depends on the order in which they are implemented. We find that the median impact of these two options together is 4 $GtCO_2e$ in 2020 (shown by moving from the "unconditional pledges, lenient rules" case to the "conditional pledges, strict rules" case) with a 20th to 80th percentile range across groups of 4-6 $GtCO_2e$

from industrialized countries and a smaller, but important, share coming from developing countries. This would require that conditions on those pledges be fulfilled. These conditions include expected actions of other countries as well as the provision of adequate financing, technology transfer and capacity building. Alternatively it would imply that conditions are relaxed or removed.

2. *Minimise the use of "lenient LULUCF credits" and surplus emission units*: If industrialized countries applied strict accounting rules to minimise the use of "lenient LULUCF credits" and avoided the use of surplus emissions units for meeting their targets, they would strengthen the effect of their pledges and thus reduce the emissions gap in 2020 by about 1 to 2 $GtCO_2e$ (with up to 0.8 $GtCO_2e$ coming from LULUCF accounting and up to 2.3 $GtCO_2e$ from surplus emissions units[58]).

3. *Avoid double-counting of offsets:* Double-counting of offsets could lead to an increase of the gap of up to 1.3 $GtCO_2e$, depending on whether countries implement their unconditional or conditional pledges (there is likely to be greater demand for offsets in the higher-ambition, conditional case). Hence avoiding double-counting could be an important policy option.

4. *Implement measures beyond current pledges:* The scenarios assessed in Chapter 2 indicate that it is technically possible to reduce emissions beyond present national plans in 2020. These scenarios show that the gap could be closed, and that emission levels consistent with 2° C could be achieved through the implementation of a wide portfolio of mitigation measures, including energy efficiency and conservation, renewables, nuclear, carbon capture and storage, non-CO_2 emissions mitigation, hydro-electric power, afforestation and avoided deforestation.

5. *Lay the groundwork for faster emission reduction rates after 2020:* Emission pathways consistent with a 2° C temperature limit are characterized by rapid rates of emission reductions post 2020 (of greater than 2.2 per cent per year). Such reduction rates on a sustained time-scale would be unprecedented historically. Therefore it is critical to lay the groundwork now for faster post 2020 emission reductions, for example, by avoiding lock-in of high-carbon infrastructure with long lifespans, or by developing and demonstrating advanced clean technologies.

[58] Note that the 0.8 and 2.3 $GtCO_2e$ numbers indicate the maximum possible impact expected from these issues and cannot simply be added together. The median impact of moving from "lenient" to "strict" accounting rules is found to be 1-2 $GtCO_2e$. See Chapter 3 for more details.

5. Twenty-first century temperature projections associated with the pledges

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5.1 INTRODUCTION

In the previous chapter (Chapter 4), it has been shown that, in the majority of cases, there is a gap between the 2020 emission levels expected as a result of the current pledges and the emission levels that would be consistent with either a 2° C or 1.5° C limit. For a "likely" chance of meeting the 2° C limit, the size of the gap can range between 5 and 9 $GtCO_2e$ (range of 3-18 $GtCO_2e$) depending on the pledge case under consideration.

There is also widespread interest in the implications of 2020 pledges for long-term temperature change. Because future temperature increase is highly dependent upon cumulative emissions after 2020, it is not possible to link unambiguously current pledges with a future temperature outcome or likelihood without making assumptions about post 2020 emission levels. However, it is possible to compare 2020 emissions with IAM scenarios associated with different levels of future warming. Each of these IAM scenarios result in an emission pathway consistent with assumptions about technological and economic development. These emission pathways then lead to different levels of temperature increase in the twenty-first century. Superposition of the 2020 pledge estimates on the IAM pathways provides insight into possible long term temperature trends consistent with the pledges.

5.2 PLEDGES IN 2020 AND TWENTY-FIRST CENTURY TEMPERATURES

In Figure 4, a set of 126 IAM emission pathways (see Box 2a) have been assembled that give rise to a range of likely future temperatures from below 2° C to more than 5° C. Since the emission pathways have all been generated by IAM models, the rates of decline in annual emissions in each of these scenarios are constrained by assumptions about technological and/or economic feasibility embedded in these models. Superimposed on these pathways is a bar representing the range of 2020 expected emissions derived from the pledge cases in Chapter 3.

Figure 4 shows that the range of 2020 emission levels resulting from the pledges tends to be consistent with the IAM pathways that have a likely temperature increase ranging from 2.5° C to 5° C. This is consistent with the findings in chapters 2, 3 and 4. This broad range of temperatures results from a variety of assumptions about post 2020 policy, technological and economic development.

As discussed in previous chapters, this does not mean that current pledges preclude meeting the 2° C limit. However, achieving this goal from the level of emissions resulting from the pledges would involve faster rates of decline, or greater negative emissions than included in most of the scenarios in Chapter 2. This could involve factors not assumed in the

IAM scenarios considered in this report such as development of new technologies or higher economic expenditures.

One clear implication of Figure 4 is that a "likely" chance of meeting a 2° C or 1.5° C limit will require attention to two factors:

- Implementing and strengthening 2020 emissions pledges: Implementation of the "conditional pledges, strict rules" case would bring emissions in 2020 to about 49 $GtCO_2e$ (range of 47-51 $GtCO_2e$) compared with the 44 $GtCO_2e$ (range of 39-44 $GtCO_2e$) that would give a "likely" chance of meeting the 2° C limit. Hence, strengthening the pledges would be needed in order to close the gap when considering the majority of results.

- Laying the policy and investment groundwork for faster and deeper reductions in post 2020 emissions: Since all the pathways that have a "likely" chance of achieving temperature limits show strong declines in emissions after 2020 it will be important to achieve faster and deeper emission reductions post 2020.

These conclusions also hold for a "medium" chance of meeting the 2° C limit.

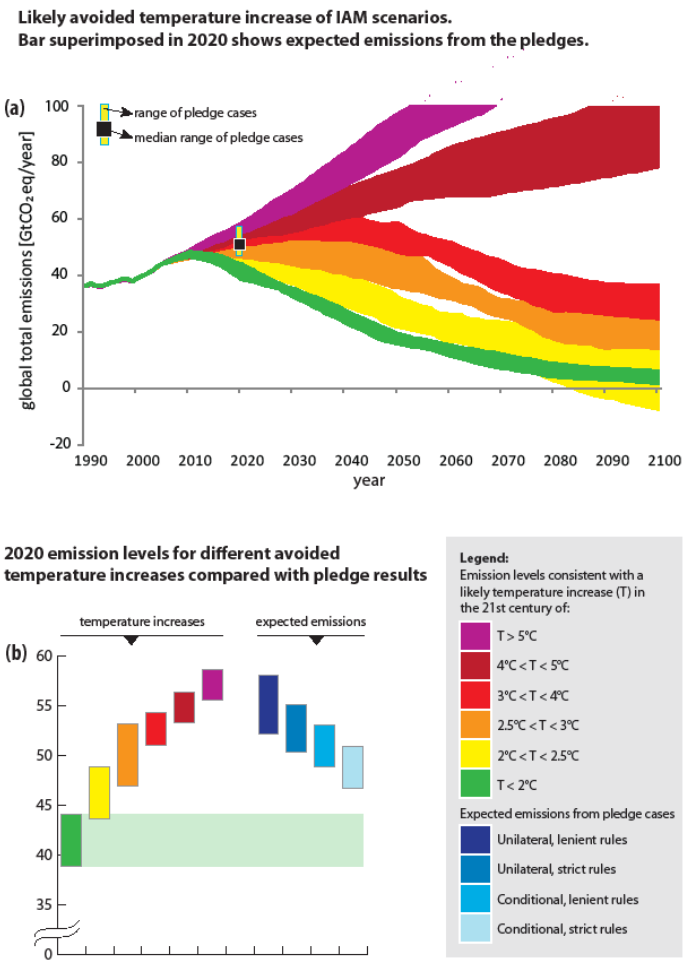

Figure 4: Temperature increases associated with emission pathways and compared to the expected emissions from the pledges
(a) Coloured bands show IAM emission pathways over the twenty-first century. The pathways were grouped based on ranges of "likely" avoided temperature increase in the twenty-first century. Emission corridors were defined by, at each year, identifying the 20th to 80th percentile range of emissions and drawing the corresponding coloured bands across the range. Wide gaps are visible between the coloured bands because most of these scenarios aim for low greenhouse gas emission targets and because only the 20th to 80th percentile of results are shown. The small black bar represents the range of the median estimates of the pledge cases from Chapter 3 in 2020. The thin blue bar represents the range from the 80th percentile of the "unconditional pledges, lenient rules" case to the 20th percentile of the "conditional pledges, strict rules" case.
(b) The coloured bars on the left hand side of this panel show the range (20th to 80th percentile) of 2020 emission levels from the IAM pathways consistent with a "likely" chance of avoiding different temperature increases—as shown in panel (a). The right hand side of panel (b) compares these emissions corridors with the 20th to 80th percentile ranges of expected emissions resulting from the four pledge cases developed in Chapter 3.

5.3 CONCLUSIONS

The majority of results in this report show that emissions in 2020 expected from the Copenhagen Accord pledges are higher than emission levels consistent with a “medium” or “likely” chance of staying below 2° C and 1.5° C. At the same time they also show that the range of 2020 emission levels from the Copenhagen Accord pledges tends to be consistent with the IAM pathways that have “likely” temperature increases of 2.5° C to 5° C up to the end of the twenty-first century.

However, this does not mean that a 2° C goal is infeasible. The IAM literature shows that it remains possible to meet the temperature limits reviewed here, but the emission reduction rates required post 2020 are at the high end of what is currently assumed in the IAM literature to be technologically and economically feasible. The IAM literature also shows that options might be limited after 2020: a full range of low-emission technologies would have to be available and broad participation in global efforts to reduce emissions would be needed (Calvin et al. 2009, Clarke et al. 2009, Krey and Riahi 2009, van Vliet et al. 2009). Pathways capable of meeting the 2° C and 1.5° C limits require significant effort to develop technologies for achieving negative CO_2 emissions from energy and industry starting shortly after mid-century.

Commencing with such fast rates of emission reduction in 2020 and maintaining them for decades will require significant changes in underlying infrastructure and policy. Thus, if it is desired to meet temperature targets, two things appear to be required: first, countries would have to increase the ambition of their 2020 pledges; and second, society would have to put in place the policy, research, and investment processes to support and sustain such a rapid decline in emissions. Rapid rates of emission reduction will also require sustained global effort and cooperation, since action by only a small subset of countries will not be enough to reach temperature targets (Calvin et al. 2009, Clarke et al. 2009, Clarke and Weyant 2009, Krey and Riahi 2009, van Vliet et al. 2009).

In order to bring emissions in line with IAM pathways that meet a 2° C limit, there is a need to not only implement current pledges fully, but also to raise the ambition of those pledges and lay the groundwork for faster and deeper reductions of post 2020 emissions. Going further in the short term and achieving stronger cuts to lower levels in 2020 would leave open more possibilities to meet temperature limits and would allow more flexibility in choosing a post 2020 pathway for global emissions.

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EDITORIAL

Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets

An editorial comment

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Abstract The IPCC Fourth Assessment Report, Working Group III, summarises in Box 13.7 the required emission reduction ranges in Annex I and non-Annex I countries as a group, to achieve greenhouse gas concentration stabilisation levels between 450 and 650 ppm CO_2-eq. The box summarises the results of the IPCC authors' analysis of the literature on the regional allocation of the emission reductions. The box states that Annex I countries as a group would need to reduce their emissions to below 1990 levels in 2020 by 25% to 40% for 450 ppm, 10% to 30% for 550 ppm and 0% to 25% for 650 ppm CO_2-eq, even if emissions in developing countries deviate substantially from baseline for the low concentration target. In this paper, the IPCC authors of Box 13.7 provide background information and analyse whether new information, obtained after completion of the IPCC report, influences these ranges. The authors concluded that there is no argument for updating the ranges in Box 13.7. The allocation studies, which were published after the writing of the IPCC report, show reductions in line with the reduction ranges in the box. From the studies analysed, this paper specifies the "substantial deviation" or "deviation from baseline" in the box: emissions of non-Annex I countries as a group have to be below the baseline roughly between 15% to 30% for 450 ppm CO_2-eq, 0% to 20% for 550 ppm CO_2-eq and from 10% above to 10% below the baseline for 650 ppm CO_2-eq, in 2020. These ranges apply to the whole group of non-Annex I countries and may differ substantially per country. The most important factor influencing these ranges above, for non-Annex I countries, and in the box, for Annex I countries, is new information on higher baseline emissions (e.g. that of Sheehan, Climatic Change, 2008, this issue). Other factors are the assumed global emission level in 2020 and assumptions on

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land-use change and forestry emissions. The current, slow pace in climate policy and the steady increase in global emissions, make it almost unfeasible to reach relatively low global emission levels in 2020 needed to meet 450 ppm CO_2-eq, as was first assumed feasible by some studies, 5 years ago.

1 Introduction

The level of ambition for reductions by developed countries (Annex I countries) and developing countries (non-Annex I countries), in a future international agreement on climate change, is one very important element in the current climate negotiations. The Ad-Hoc Working Group on Further Commitments for Annex I countries under the Kyoto Protocol (AWG-KP), agreed on the wording of the level of its ambition. At a preparatory meeting in August 2007, it noted the usefulness of the contribution of Working Group III to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), which states that emissions need to peak within the next 10 to 15 years and that emissions must be reduced to well below half of the 2000 level by the middle of the twenty-first century, in order to stabilise their concentrations in the atmosphere at the lowest level assessed by the IPCC. In addition, AWG-KP recognised that Annex I countries need to reduce their emissions within a range of 25% to 40% below 1990 levels in 2020, in order to reach the lowest stabilisation levels assessed by the IPCC. The reduction range of −25% to −40% refers to Box 13.7 of the Working Group III report of the IPCC AR4 (Table 1) (Gupta et al. 2007). Agreement on this formulation was possible under the Kyoto Protocol because (1) it is only a recognition of this range and not a decision on it and (2) the USA did not take part in this agreement, as it has not ratified the Kyoto Protocol.

At the Conference of the Parties (COP) 13 in Bali in December 2007, the issue of the reduction range for the Annex I was discussed again, this time with all countries, including the USA. Initial drafts by the EU called for the same wording as already agreed to under the Kyoto Protocol. The Box 13.7 of the IPCC report received large attention, including by the media. But in the end, agreement could not be reached on the reduction percentages in the negotiations under the Convention and, instead, it called for "deep cuts in global emissions" and a reference to the IPCC AR4 was included in a footnote.

The conference also agreed to complete the negotiation process on comparable mitigation commitments or actions by all developed countries and nationally appropriate mitigation actions by developing countries by the end of 2009.

In this paper the authors of Box 13.7 provide more details on the studies that were used to prepare the ranges and they analyse whether new information, obtained after completion of the IPCC report, influences these ranges. A first question is how the ranges were derived and whether new allocation studies would change the results (Section 2). A second question concerns the possibility of quantifying what is termed as "substantial deviation from the baseline" for non-Annex I countries and what the important determinants are. One important assumption is the reductions by the Annex I countries, but an even more important assumption is the baseline that was chosen (Section 3). Different baselines were tested, including those with rapid growth in emissions, in particular in the developing countries, as presented by

Table 1 IPCC Box 13.7: The range of the difference between emissions in 1990 and emission allowances in 2020/2050 for various GHG concentration levels for Annex I and non-Annex I countries as a group

Scenario category	Region	2020	2050
A—450 ppm CO_2-eq[a]	Annex I	−25% to −40%	−80% to −95%
	Non-Annex I	Substantial deviation from baseline in Latin America, Middle East, East Asia and Centrally-Planned Asia	Substantial deviation from baseline in all regions
B—550 ppm CO_2-eq	Annex I	−10% to −30%	−40% to −90%
	Non-Annex I	Deviation from baseline in Latin America and Middle East, East Asia	Deviation from baseline in most regions, especially in Latin America and Middle East
C—650 ppm CO_2-eq	Annex I	0% to−25%	−30% to −80%
	Non-Annex I	Baseline	Deviation from baseline in Latin America, Middle East, and East Asia

Source: Gupta et al. (2007, Section 13.3.3.3). The aggregate range is based on multiple approaches to apportion emissions between regions (contraction and convergence, Multi-Stage, Triptych and intensity targets, among others). Each approach makes different assumptions about the pathway, specific national efforts and other variables. Additional extreme cases—in which Annex I or non-Annex I undertake all reductions—are not included. The ranges presented here do not imply political feasibility, nor do the results reflect cost variances.

[a]Only the studies aiming at stabilisation at 450 ppm CO_2-eq assume a (temporary) overshoot of about 50 ppm (see den Elzen and Meinshausen 2006b).

Sheehan (2008). Also important are assumptions on the required global emission level and on CO_2 emissions from land use, land-use change and forestry (LULUCF).

2 Main assumptions underlying the studies quoted in the IPCC report

Several studies have analysed the level of commitment of different regions and countries and the timing of participation, which are required to ensure meeting the long-term concentration stabilisation targets, using different post-2012 regimes for differentiation of future commitments (allocation schemes). This has been summarised in Box 13.7 by IPCC AR4 (Gupta et al. 2007). Table 2 presents the main assumptions of the sixteen studies used and quoted in the IPCC analysis and two additional unquoted studies (i.e. Höhne et al. 2003; Leimbach 2003), which influence the results:

- *Allocation calculations for CO_2 only or all greenhouse gases (GHGs):* Some calculations were based on all GHGs and some only on CO_2. The share of non-CO_2 gases is usually higher in developing counties
- *Baseline:* The baseline emissions are a major determinant for the results, as more reductions are necessary if baseline emissions are higher
- *Kyoto implementation:* For the short term it is important whether studies have assumed that the Kyoto protocol targets are implemented or not.

Table 2 Main assumptions of the studies quoted by the IPCC and more recent studies (in chronological order) underlying Box 13.7

	Allocation calculations	Baseline scenario[a]	Assumptions on meeting Kyoto targets in 2008–2012	Allocation schemes covered[b]	Global emission target (excl. LULUCF CO_2) in 2020/2050 (%-compared to 1990 levels), for CO_2-eq concentration (ppm), IPCC categories		
					A—450	B—550	C—650
Studies used quoted in IPCC report							
Berk and den Elzen (2001)	CO_2	IPCC* A1	Annex I incl. USA	MS, CC, HR	+10/−20		
Blanchard et al. (2002)	CO_2	IPCC** A1	Annex I excl. USA; FSU BAU[c]	CC, HR, EI			+50/NI
Winkler et al. (2002)	CO_2	IPCC B1	Not considered; base-year 2000	HR, AP, EI	0		
Criqui et al. (2003)	CO_2-eq	CPI 2003	Annex I excl. USA & Australia	MS, CC		+35/−20	+50/+35
Höhne et al. (2003) *(not quoted)*	CO_2-eq	IPCC A2	Annex I incl. USA; FSU BAU[c]	MS, CC, EI, TY, other		+27/NI	
Leimbach (2003) *(not quoted)*	CO_2	Own	Not included; base-year 2000	CC			[40; 75]/+25
WBGU (2003)	CO_2	IPCC**	Annex I incl. USA	CC	+20/−60	+30/+5	
Bollen et al. (2004)	CO_2	IPCC A1	Annex I excl. USA & Australia	CC		+30/NI	+50/NI
Groenenberg et al. (2004)	CO_2	IPCC A1	Not included; base-year 1995	TY	+15/NI	[20; 30]/+5	[35; 60]/+50
Böhringer and Löschel (2005)	CO_2	DOE ref.	Annex I excl. USA & Australia	Other			+50
den Elzen and Lucas (2005)	CO_2-eq	CPI 2003	Annex I excl. USA & Australia	MS, CC, EI, TY, other		+35/−20	+50/+35
den Elzen et al. (2005b)	CO_2-eq	CPI 2003	Annex I excl. USA & Australia	MS, CC, HR		+35/−20	+50/+35
Höhne et al. (2005) (Höhne 2005)	CO_2-eq	IPCC all*	Annex I incl. USA; FSU BAU[c]	MS, CC, EI, TY, other	+10/−40	+30/−10	+50/+45
Michaelowa et al. (2005)	CO_2	Own	Annex I excl. USA & Australia	MS			+30[d]/NI
Böhringer and Welsch (2006)	CO_2	IPCC** A1	Not included; base-year 2000	CC		[30; 35]/−15	

den Elzen and Meinshausen (2006a, b)[e]	CO_2-eq	CPI 2003	Annex I excl. USA & Australia	MS, CC	[20; 30]/ [−30;−50]	+40/[−10; 10]	
Persson et al. (2006)	CO_2	IPCC A1	Annex I excl. USA	CC		+36	
Studies published after IPCC AR4							
den Elzen et al. (2007a)[e,f]	CO_2-eq	CPI 2003	Annex I excl. USA & Australia	Other	[20; 30]/ [−30;−50]	+40/[−10; 10]	
den Elzen et al. (2008b)[e]	CO_2-eq	IPCC B2***	Annex I excl. USA & Australia	MS, CC	+20/−35	+35/−5	
den Elzen et al. (2008a)[e]	CO_2-eq	IPCC B2***	Annex I excl. USA & Australia	TY	+20/−35	+35/−5	
Höhne et al. (2006)[f]	CO_2-eq	IPCC* all	Annex I excl. USA; FSU BAU[c]	Other, CC		+35/−25	+50/+35
Vaillancourt and Waaub (2006)	CO_2	Own	Not included; base-year 2000	Other			+57/+65
Höhne et al. (2007)[f]	CO_2-eq	IPCC* all	Annex I excl. USA; FSU BAU[c]	MS, CC, HR, TY, other	+10/−40	+30/−10	+50/+45
Baer et al. (2008)	CO_2	WEO 2007[g]	Annex I excl. USA	Other	+10/−80		
Timilsina (2008)	CO_2	Own	Annex I excl. USA; FSU BAU[c]	EI			+46/NI
Number of studies					11	16	14

NI Not included

[a]Own: scenario based on own assumptions; IPCC*: IMAGE implementation of IPCC SRES 2001 scenarios (IMAGE-team 2001); IPCC**: IIASA (1998) implementation; CPI: common POLES-IMAGE baseline (van Vuuren et al. 2003, 2006); DOE reference scenario (DOE 2003); Update IPCC B2***: updated IMAGE/TIMER implementation of the IPCC-SRES B2 scenario (van Vuuren et al. 2007), which roughly follows the reference scenario of the World Energy Outlook (WEO) 2004 (IEA 2004)

[b]The abbreviations of the schemes are given in Table 3

[c]The emissions of the former Soviet Union (FSU) and Eastern European countries are assumed to equal the baseline or business-as-usual (BAU) emissions (which are far below their Kyoto targets)

[d]For the period 2013–2017

[e]Assuming a (temporary) overshoot of about 50 ppm

[f]Uncertainty ranges presented in this study also include uncertainties in scenarios, but this effect is limited, and not included in Fig. 1

[g]Reference scenario of the WEO 2007 (IEA 2007)

- *The assumed allocation scheme covered:* Some studies in Table 2 focus on one scheme, whereas others include a wide range of about ten schemes (see for example, den Elzen and Lucas 2005).
- *Global emission limits:* Many global emission pathways can lead to the same long-term concentration stabilisation level. Pathways with higher emissions in the earlier part of the century have lower emissions in the later part of the century. Therefore, it is important which global emission level in 2020 and 2050 was chosen from a possible range that represents one long-term stabilisation level (i.e. 450, 550 and 650 ppm CO_2-eq).

Table 2 (bottom part) also shows the seven new allocation studies that became available after the finalisation of the IPCC report. In fact, the first four of these studies were already included in the calculations of the presented reduction ranges, but at the last moment of publication of the IPCC AR4 report, their citations were excluded, as these studies were still unpublished, at the time.

Figure 1 presents the resulting emission reduction targets for the Annex I and non-Annex I countries as a group, which are mainly based on information provided by the authors of the studies or, for some studies, are derived from detailed information in the papers themselves. The figure also presents the adopted IPCC AR4 reduction ranges (Gupta et al. 2007). The IPCC AR4 based these ranges on the outcomes of all studies mentioned in Table 2 (except for Leimbach 2003; Vaillancourt and Waaub 2006; Höhne et al. 2007; Baer et al. 2008; Timilsina 2008). We listed all studies that were available to us. Outliers that provide substantially different results compared to other studies were excluded and more weight was given to the more recent multi-gas studies. We did not make judgements on the way the studies allocated emission reductions across regions and countries.

A brief overview of the studies is given below.

The study by Berk and den Elzen (2001) is one of the first, quantifying post-2012 CO_2 emission allocations for meeting long-term concentration stabilisation targets, based on three regimes, i.e. Multi-Stage, Contraction & Convergence (C&C) and Berk and den Elzen's implementation of the Brazilian proposal (see Table 3). The study assumed that all Annex I countries would meet their Kyoto targets (the USA had not rejected ratification), a low global emission target of only 10% above 1990 levels, by 2020, and 20% below 1990 levels, by 2050. Based on its low short-term emission this study is clustered under the lowest IPCC 450 ppm CO_2-eq category (Table 2).The Annex I countries, as a group, need to reduce their emissions from about 30% to 45% below 1990 levels, which is at the lower end of the IPCC AR4 range (see Fig. 1). The reductions for the non-Annex I countries, as a group, range from 15% to 35% below the baseline emissions. Later, den Elzen (2002) also included Triptych regime calculations and an extensive sensitivity analysis. Similar work has been done by Blanchard (2002), focussing on stabilisation at 550 ppm CO_2 concentration (about 650 ppm CO_2-eq). Winkler et al. (2002) also calculated the CO_2 emission allowances of the key developing countries, using three allocation schemes, and assuming global CO_2 emissions returning to 1990 levels by 2020, and using the lowest IPCC SRES B1 scenario.

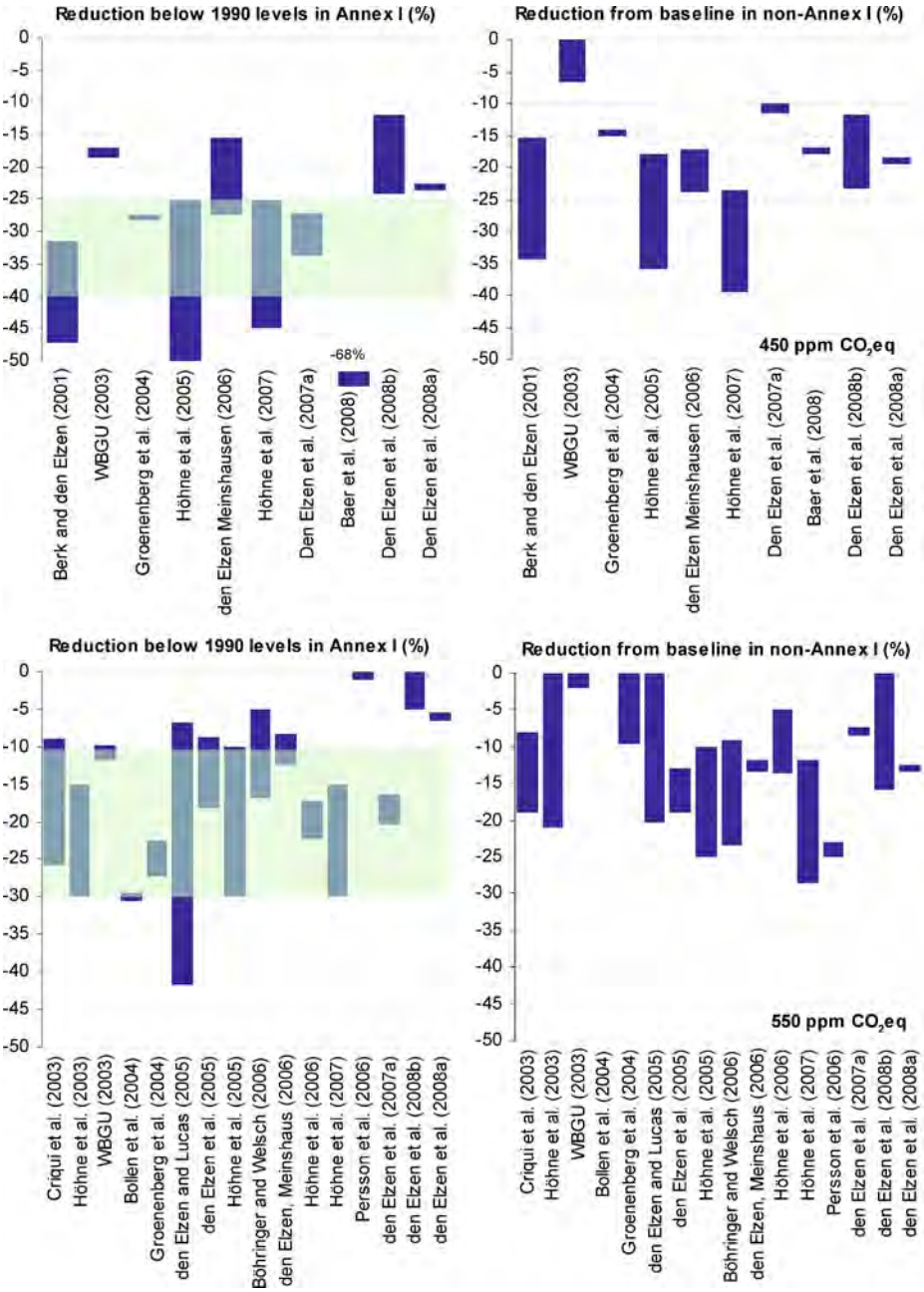

Fig. 1 Reductions in Annex I (below 1990 level) and non-Annex I countries (below baseline) as a group in 2020 for the studies quoted by the IPCC and more recent studies. Uncertainty ranges indicated here, are based on the outcomes of different post-2012 regimes. The figure also depicts the reduction ranges for Annex I countries as reported in IPCC Box 13.7

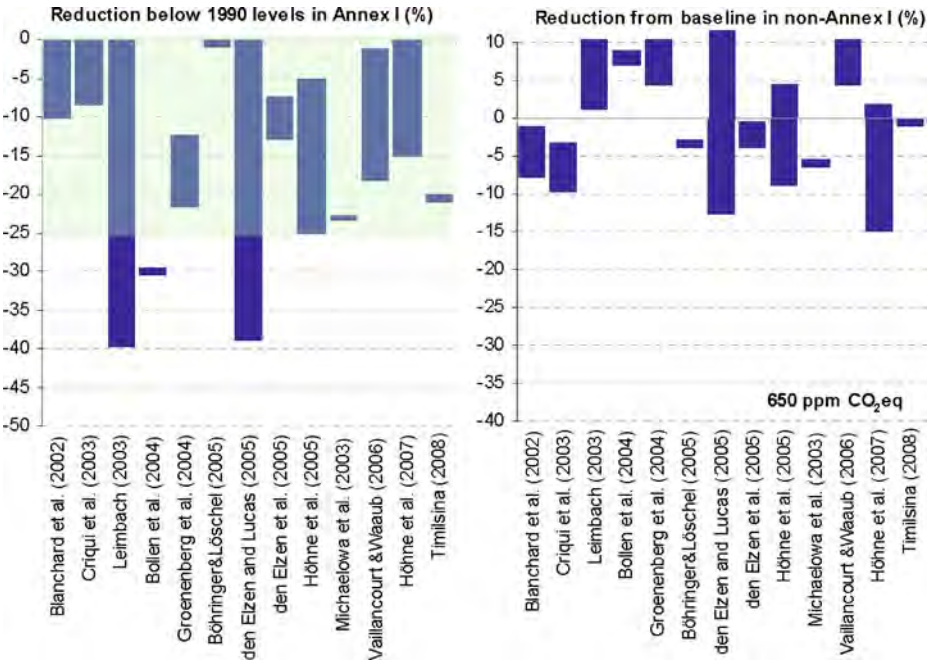

Fig. 1 (continued)

Most studies in Table 2 focussed on CO_2 only, instead of all GHGs. Criqui et al. (2003) and Höhne et al. (2003) were among the first to calculate emission allowances for all GHGs, i.e. CO_2-equivalent emissions, including the anthropogenic emissions of six Kyoto greenhouse gases (fossil CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 (using the 100-year GWPs of IPCC 2001)). These studies, as did all earlier studies, excluded LULUCF CO_2 emissions, as these were too uncertain. Criqui et al. (2003) presented reduction targets for two C&C variants (convergence years 2050 and 2100) and three Multi-Stage variants for regions, and focused on stabilising GHG concentration targets at 550 and 650 ppm CO_2-eq (see also den Elzen et al. 2006). Den Elzen and Lucas (2005) extended this analysis, using ten very different emission allocation schemes, varying from grandfathering to a convergence in per capita emissions before 2015, leading to a wide range of reductions in Annex I countries, below 1990 levels. Another follow-up study, den Elzen et al. (2005b), focused on less regimes, but also presented abatement costs.

Höhne et al. (2003) focussed on a wide range of post-2012 regimes (all variants of those mentioned in Table 3) for a global emission target in 2020 (roughly corresponding with 550 ppm CO_2-eq), and was the first to present the reduction targets for individual countries.[1] The reductions for Annex I countries in 2020 are, in general, more stringent than those in Criqui et al. (2003), due to their assumed lower

[1]They used baseline scenarios for population, GDP and emissions at the level of countries, based on applying the regional downscaling method for the IPCC SRES emission scenarios from the four IPCC SRES regions to countries.

Table 3 Short description of the various post-2012 regimes for differentiation of future commitments (allocation schemes)

Approach	Abbreviation	Operational rule for allocation of emission allowances
Multi-Stage approach	MS	An incremental but rule-based approach, which assumes a gradual increase in the number of parties taking on mitigation commitments and in their level of commitment as they move through several stages according to participation and differentiation rules (Berk and den Elzen 2001; den Elzen 2002).
Historical responsibility (Brazilian Proposal)	HR	Reduction targets based on countries' contribution to temperature increase (UNFCCC 1997; den Elzen et al. 2005a).
Ability to Pay	AP	Emission reduction allocation and participation based on per capita income thresholds (Jacoby et al. 1999).
Contraction & Convergence (C&C)	CC	Emission targets based on a convergence of per capita emission levels of all countries under a contraction of the global emission profile (Meyer 2000).
Emission Intensity	EI	Emission reductions related to improvements in the emission per unit GDP output (Baumert et al. 1999).
Triptych	TY	Emission allowances based on various differentiation rules to different sectors for all Parties (Phylipsen et al. 1998).

2010 emissions in Annex I countries (the starting point of the calculations), from stronger Kyoto reduction assumptions. Höhne et al. (2003) assumed that all Annex I countries (including USA) implement the Kyoto targets, except for the former Soviet Union (FSU) and Eastern European States, which start from their baseline emissions (far below the Kyoto target). Criqui et al. (2003), however, assumed that all Annex I countries meet the Kyoto targets (this is for FSU and Eastern European States well above their baseline), except for the USA, which are assumed to meet their national target (about 25% above 1990 levels in stead of −7% below 1990 emissions under Kyoto in 2010).

Besides these studies, there are also CO_2-only studies with macro-economic or energy-system models, which focus primarily on the C&C regime for global CO_2-only emissions targets, as was done by Bollen et al. (2004), Leimbach (2003), Persson et al. (2006) and WBGU (2003). These studies mainly vary the convergence year

between 2025 and 2100, showing stringent reductions for Annex I countries for an early convergence. WBGU (2003) (identical to Nakicenovic and Riahi 2003) focuses on C&C 2050 and 2100 for 400 ppm CO_2 concentration stabilisation under the IPCC B1 and B2 baseline scenarios, and 450 ppm CO_2 under the IPCC A1T scenario. The first group of 400 ppm CO_2,corresponding with the lowest 450 ppm CO_2-eq target, and the lower baseline scenarios (B1 and B2), in particular, lead to low reductions targets for Annex I and non-Annex I countries (well above the IPCC AR4 range) (Fig. 1). Bollen et al. (2004) and Leimbach (2003) focus on global emission targets, in 2020, as high as 50–75% above 1990 levels (within 650 ppm CO_2-eq) and show high reduction targets for Annex I countries (30% to 40% below 1990 levels)—well below the IPCC AR4 range. In contrast, they have surplus emission allowances (emissions above the baseline) for non-Annex I countries. Compared to the other results, these studies seem outliers. Böhringer and Welsch (2006) used emission allocations from current emissions, based on equal-per-capita emission.

Groenenberg et al. (2004) has extended the Triptych approach for all GHGs and also presented an extensive sensitivity analysis, showing a wide range of reduction targets for Annex I and non-Annex I countries in 2020. As Kyoto targets were not considered, the reduction targets are somewhat higher, but still within the IPCC AR4 ranges. Den Elzen et al. (2008a) further improved the Triptych approach by, for example, a differentiated participation for developing countries that, together with accounting for the Kyoto targets (excluding the USA), lead to reduction targets which are somewhat lower than the IPCC AR4 reductions.

Böhringer and Löschel (2005) use another approach that differs from the rule-based allocation schemes used in all previous studies. They interviewed experts about their judgment on four key aspects of a possible Post-Kyoto scenario, until 2020: the targeted global emission reduction, USA participation, the inclusion of developing countries, and the allocation rule for abatement duties. In general, this approach leads to a high global emission limit by 2020 and rather low reduction targets for the Annex I and non-Annex I countries (Table 1 and Fig. 1).

Vaillancourt and Waaub (2006) proposed a dynamical multi-criterion method to compare various alternative allocation rules and found a compromise solution, although this led to global emissions as high as 50% above 1990 levels in 2020.

Höhne et al. (2005) updated the calculations of in their study of 2003, again for a wide range of regimes. For the lowest concentration category, a non-overshoot 400 ppm CO_2 concentration stabilisation (about 450 ppm CO_2-eq) is assumed. This, combined with the stronger Kyoto reduction assumptions (all Annex I countries including the USA implement Kyoto), leads to emission reductions in Annex I countries, up to 45% below 1990 levels in 2020, for 450 ppm CO_2-eq. In general, their reduction range exceeds the IPCC AR4 range on the lower end. Höhne et al. (2007) further updated the analysis with very similar reduction ranges, although they now assumed that the USA follows its national target, leading to a less ambitious range for Annex I countries. In Höhne et al. (2006) a variant of the per capita convergence ('common but differentiated convergence') is presented, in which the per capita emissions of all countries converge to a low level. The per capita emissions in non-Annex countries, however, start to converge later, but end up at the same level. This leads to slightly more ambitious 2020 I reduction targets for Annex I countries.

Den Elzen and Meinshausen (2006b) focused on Multi-Stage and C&C, and GHG concentration targets 400–550 ppm CO_2-eq. For 400 and 450 ppm CO_2-eq they

assumed an overshoot in the concentration targets. This overshoot, combined with a lower baseline and less stringent Kyoto reduction assumption (all Annex I countries, except for the USA and Australia, implement their Kyoto targets by 2010), lead to less ambitious reduction targets for Annex I countries. Similar assumptions have been made in den Elzen et al. (2008b), presenting in detail the required abatement options and costs. As they excluded the 400 ppm scenario and used a lower baseline (update of IPCC B2), the reductions for Annex I and non-Annex I countries were less ambitious, although the USA still has to return to its 1990 levels by 2020. In den Elzen et al. (2007a) a variant of the Multi-Stage type regime, i.e. the 'South–North Dialogue' Proposal (Ott et al. 2004) was analysed. This proposal is based on the criteria of responsibility, capability and potential to mitigate, and include deep cuts in industrialised (Annex I) countries and differentiated mitigation commitments for developing countries.

Another very recent allocation study came from Baer et al. (2008), called the Greenhouse Development Rights Framework. This framework calculates national shares of the global mitigation requirement based on an indicator that combines capacity (per capita income over a $7,500 threshold) and responsibility (cumulative per capita emissions since 1990) in a way that is sensitive to intra-national income distribution. National allocations are then calculated by subtracting each country's share of the global mitigation requirement from its national baseline emissions trajectory. This approach leads to very high Annex I emission reductions of about −70% below 1990 levels in 2020.

The following findings can be drawn from Table 2 and Fig. 1:

- A wide range of studies cover the different stabilisation levels; most have studied 550 ppm CO_2-eq.
- The number of multi-gas studies that analysed the lowest concentration category, published at the time of writing the IPCC AR4, was limited, i.e. den Elzen and Meinshausen (2006b) and Höhne et al. (2005), but about four of these studies were in press at the time of writing the IPCC AR4 (see Table 1). In general, the studies of Höhne assume a lower global emission limit in 2020 (10%, 30% and 50% above 1990 levels for stabilisation at 450, 550 and 650 ppm CO_2-eq) and stronger Kyoto reduction assumptions (the USA follows Kyoto and FSU starts in 2010 with baseline emissions), whereas the studies of den Elzen assume a higher global emission limit (25%, 40% and 50% for stabilisation at 450, 550 and 650 ppm CO_2-eq by 2020) and lower Kyoto reduction targets (the USA follows national policy by 2010, and FSU starts in 2010 at their Kyoto targets). Therefore, the studies of Höhne et al. lead to more stringent reduction targets in the presented ranges for 2020, whereas those by den Elzen et al. lead to less stringent reduction targets for 2020. However, less stringent reductions in the short term require more stringent reductions in the long term, to reach the same long-term stabilisation level. Hence, the targets presented by Höhne for the long term, are less stringent than those presented by den Elzen.
- There is no argument for updating the ranges in Box 13.7 of the IPCC report based on the new studies published after its completion, as all studies show reductions that are in line with the reduction ranges in the box.
- As has been explained in the IPCC report, the reductions in Annex I and non-Annex I countries in the Box largely depend on the regime assumptions, the

global emissions target (and related to the concentration stabilisation target) and depend on the assumptions on the initial 2010 emission levels. This issue is also further analysed in the next chapter.

- As was also concluded by Sheehan, most of these studies use baseline emission scenarios, mostly the IPCC SRES scenarios, that are developed before 2003 and do not account for the recent rapid growth in emissions. More specifically, in all studies the reference cases are within the SRES marker scenario range, and hence subject to the critique outlined in Sheehan (2008). The impact of new baseline scenarios will be discussed in the next section.
- The studies that were analysed show that emissions in the group of non-Annex I countries deviate from the baseline roughly between 15% to 30% for 450 ppm CO_2-eq, between 0% to 20% for 550 ppm CO_2-eq and from 10% above to 10% below the baseline for 650 ppm CO_2-eq, in 2020. Quantitative estimates per regional group for non-Annex I countries are not possible, as all studies used different regional groupings.

3 Assessing the emission reductions in Annex I and non-Annex I

One particular issue of interest is: if Annex I countries reduce their domestic emissions to a certain extent, then how far do the emissions in non-Annex I countries have to be reduced, to achieve the stabilisation of the climate at a certain level? In the previous sections it is described which Annex I reductions have been calculated by the different studies, as well as what these studies assumed to be a "substantial deviation from the baseline" for non-Annex I countries. This section further analyses which factors are important in this trade-off and it assesses their influence, using simple calculations to quantify this influence. The analysis concentrates on 2020 as this is the timeframe of major interest in the negotiations. The most important factors in the reductions of greenhouse gas emissions in Annex I and non-Annex I countries, in order of descending influence, are:

1. *Baseline emissions*: These are particularly uncertain for non-Annex I countries, but so is the historical emission trend, which is not always the same in the models.
2. *The assumed global emission level in 2020 for a long-term concentration stabilisation target*: As the long-term concentration stabilisation level depends also on the cumulative emissions, a certain stabilisation level can only be translated into an emission *range* in 2020. This range is particularly large if one assumes that concentrations may temporarily overshoot the desired level.
3. *Land-use CO_2 emission projections*: Current land-use related CO_2 emissions and projections are particularly uncertain and, mostly, they are not or only indirectly considered in the studies cited above.

Below, a brief description is given of the assumptions for the first two points, followed by an analysis of each of these points, in Section 3.3.

3.1 Baseline

Current and historical emission levels vary by a few percentage points, depending on the data source, but all data sources report an increase in global emissions. Table 4

Table 4 GHG emissions (excluding LULUCF CO_2 and international transport emissions) for the Annex I and non-Annex I countries as a group and the world, for the period 1990–2006 (upper) and 2020 projection (lower)

	Emission (million tonnes CO_2-eq)			Change compared to 1990 levels		
	Annex I	Non-Annex I	World	Annex I (%)	Non-Annex I (%)	World (%)
1990	18,531	12,847	31,378	0	0	0
1995	18,123	14,294	32,417	−2	11	3
2000	17,986	16,866	34,852	−3	31	11
2005	18,414	20,609	39,023	−1	60	24
2006	18,460	21,548	40,008	0	68	25
2020 scenario[a]						
IPCC A1 2001	23,558	34,732	57,616	27	170	84
IPCC A2 2001	23,110	29,752	52,434	25	132	67
IPCC B1 2001	19,334	28,435	47,222	4	121	50
IPCC B2 2001	20,520	31,234	51,114	11	143	63
IPCC A1F 2001	24,066	35,126	58,521	30	173	87
IPCC A1T 2001	33,408	23,034	55,812	24	160	78
CPI 2003	21,108	31,779	52,243	14	147	66
Update IPCC B2	22,345	27,530	49,370	21	114	57
Sheehan (2008)[b]	22,215	40,575	61,726	20	216	97

Source: GHG emissions for the period 1990–2005: IEA (2008); CO_2 emissions in 2006: BP (2007) and non-$CO_2$and process CO_2 emissions in 2006: using the trend of 2004–2005.

[a]IPCC: IMAGE implementation of IPCC SRES 2001 scenarios (IMAGE-team 2001); CPI: common POLES-IMAGE baseline (van Vuuren et al. 2003, 2006); Update IPCC B2: updated IMAGE/TIMER implementation of the IPCC-SRES B2 scenario (van Vuuren et al. 2007)

[b]As the Sheehan baseline does not include the non-CO_2 GHG emissions, we have estimated these based on the IMAGE IPCC SRES A1b scenario.

gives the historical trend in the global GHG emissions (excluding land-use related CO_2 emissions and international transport emissions) for one very recent data source. In 2005, global CO_2-eq emissions were about 24% above 1990 emission levels (IEA 2008). The 2006 figures are based on a preliminary estimate by the Netherlands Environmental Assessment Agency, using recently published BP [British Petroleum (BP 2007)] energy data and cement production data. From 2005 to 2006, global CO_2 emissions from fossil fuel use increased by about 2.6%, which is less than the 3.3% increase the year before.[2] The 2.6% increase is mainly due to a 4.5% increase in global coal consumption. In the 1990–2006 period, global fossil-fuel related CO_2 emissions increased over 35%, which is an increase of 25% for the overall GHG emissions (excluding LULUCF CO_2 emissions), assuming an ongoing linear trend over the past 5 years, for the non-CO_2 GHG emissions in 2006.

Even if the Kyoto Protocol is implemented by those countries that have ratified it, it is very likely that global emissions will continue to rise until 2012, when a new international climate agreement can start to be effective. The approximate stabilisation of emissions by Annex I countries will be more than counterbalanced by an ongoing and strong rise in emissions in non-Annex I countries.

[2]http://www.mnp.nl/en/dossiers/Climatechange/moreinfo/Chinanowno1inCO2emissionsUSAinsecondposition.html.

Table 4 also shows the projections of future emissions from various sources. The standard set of emission scenarios, IMAGE implementation (IMAGE-team 2001) of the IPCC special report on emission scenarios (Nakicenovic et al. 2000) was prepared already in 2001 and, therefore, does not reflect the recent changes in emissions.[3] Still, its large range covers most of the scenarios that were produced afterwards. Already in 2020, the spread will be high: global emissions could be as low as 50% below, or as high as 92% above 1990 level, according to the recent projection of Sheehan (2008) (for a discussion of this scenario, see van Vuuren and Riahi 2008). The impact of the various baselines on the reductions in Annex I and non-Annex I countries, will be analysed in Section 3.3.

3.2 Global emission level in 2020 necessary for a long-term concentration stabilisation target

A second, very important assumption is the global emission level in 2020, necessary for a long-term concentration stabilisation target. The long-term stabilisation level depends also on the cumulative emissions. A long-term stabilisation level can only be translated into an emission *range* in 2020. This range is particularly large if one assumes that concentrations may temporarily overshoot the desired level. In earlier studies, this emission level is lower, as they assumed that reductions would start earlier and would not be postponed, in the way they are in the current trends.

Höhne et al. (2005) were rather optimistic about the Kyoto implementation and early action by developing countries and did not allow for overshooting. They, therefore, used very low global emission levels of 10% and 30%, compared to 1990 levels in 2020, for 450 and also 550 ppm CO_2-eq, based on stabilisation paths from various sources that were available at that time. Given that today's global GHG emission level (excluding LULUCF CO_2) is already 25% above 1990, and that it will further increase until 2010, the chosen values are very ambitious and reaching +10% may have become unrealistic.

Den Elzen and Meinshausen (2006a, b) also presented emission pathways to stabilise CO_2-eq concentrations at 550 and 450 ppm. The 450 ppm pathway allows overshooting, i.e., concentrations peak before stabilising at lower levels, rising to 500 ppm CO_2-eq, before dropping to the 450 ppm CO_2-eq, later on. Allowing an overshoot also relaxes the global emission targets in the short term (2020), but increases the necessary effort afterwards (up to 2050 and beyond), shifting the burden into the future. The GHG emissions (excluding LULUCF CO_2) may increase to 30%, compared to 1990 levels in 2020, for 450 ppm CO_2-eq.

To illustrate the impact of the first three elements (baseline, 2020 global emission level and land-use CO_2 emissions) on the emission reduction in Annex I and non-Annex I, we use the global emission targets of den Elzen et al. (2007b), presenting the global GHG emission pathways for the three concentration stabilisation levels, and their ranges (see Table 5). The numbers of this study are in line with den Elzen and Meinshausen (2006b) and another study of Meinshausen et al. (2006), using the EQW methodology, and are within the 2020 and 2050 ranges of the IPCC AR4 (Fisher

[3]The IMAGE IPCC SRES scenarios are used here, as this set is used by many allocation studies in Table 2, for reasons of consistency (one single model is used for all scenarios) and regional detailed information.

Table 5 Assumptions for global emission target (excl. LULUCF CO_2) in 2020 and 2050 (%-compared to 1990 emission levels) for the different multi-gas pathways for stabilising at 450, 550 and 650 ppm CO_2-eq concentration of this study and Höhne et al

CO_2-equivalent concentration	This study (based on den Elzen et al. 2007b)		Höhne et al. (2005)
	Central estimate (%)	Range[a] (%)	(%)
2020			
450 ppm (no overshoot)			+10
450 ppm (overshoot)	+25	[+15; +30]	
550 ppm	+40	[+30; +45]	+30
650 ppm	+50	[+40; +60]	+50
2050			
450 ppm (no overshoot)			−40
450 ppm (overshoot)	−35	[−45;−25]	
550 ppm	−5	[−10; 0]	−10
650 ppm	+35	[+20; +60]	+45

Numbers are rounded off to the nearest decimal or half-decimal.

[a]The uncertainty range presented here needs to be considered carefully in the context of the envelope. Choosing lower reductions in the beginning needs to be compensated by higher reductions later on and vice versa.

et al. 2007). These estimates do not account for possible higher carbon releases from the terrestrial biosphere (such as carbon cycle feedbacks, or continuing high deforestation).

3.3 Analysis

Figure 2 shows the trade-off between deviations from baseline in non-Annex I countries in 2020 (left to right) and the change in GHG emissions for Annex I countries, compared to 1990 (top to bottom) for the stabilisation levels, as shown in Table 5 for den Elzen et al. (2007b). The Annex I reduction range of the AWG of −25% to −40% is also shown.

Note that these reductions are assumed to occur independently by domestic reductions in Annex I and non-Annex I countries. If Annex I countries decide to achieve some of these reductions outside of the group (through CDM or any other future mechanisms), additional reductions have to occur in developing countries.

The calculations behind these figures are very straightforward. First, a simple calculation can be made of the total overall global allowable emissions to meet the various concentration stabilisation targets, by combining the global GHG emission targets of Table 5 with the global GHG emissions of Table 4. In the second step, the allowable emissions of the Annex I countries can be calculated, by combing the allowable emissions of the non-Annex I countries (calculated as the reduction from their baseline emissions, see Table 4) and the global allowable emissions of step 1.

Figure 2 provides the average outcome over separate calculations for each of the six IMAGE IPCC SRES scenarios (IMAGE-team 2001) (A1B, A1Fl, A1T, A2, B1, B2) (*the IPCC SRES average*), for 2020 and 2050 to capture a wide spread of possible future baseline emission developments.

To exemplify the figure, an example is given for the average over the six IPCC SRES scenarios. Figure 2a shows that the emission reductions for Annex I countries, as a group, of 25% relative to 1990 in 2020 (top range of the green shaded area),

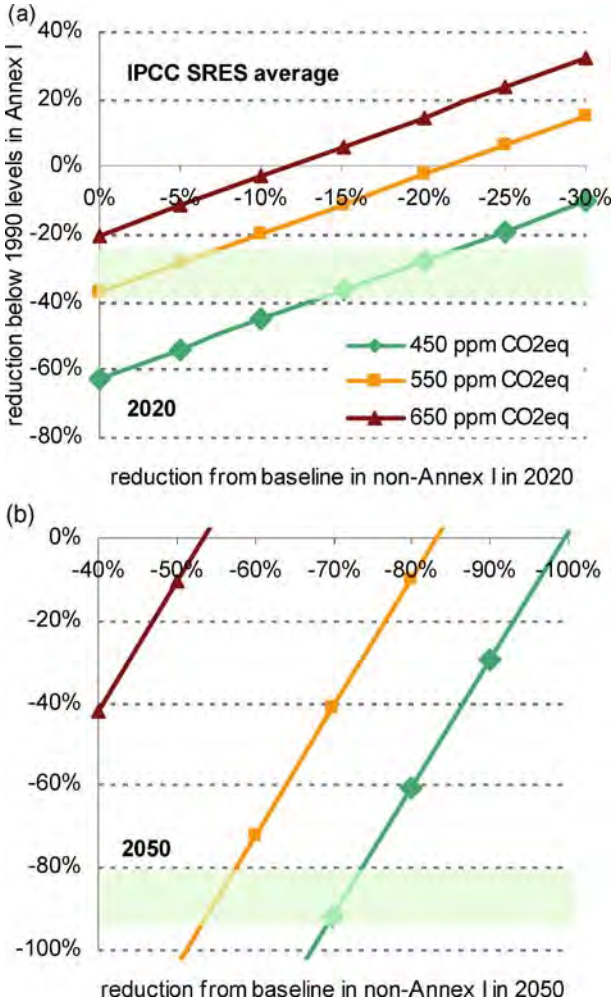

Fig. 2 The trade-off in reductions in 2020 (**a**) and 2050 (**b**), in Annex I and non-Annex I countries as a group, for three concentration stabilisation levels. The *numbers* represent the averaged outcome over separate calculations for each of the six IPCC SRES baselines (IPCC SRES average). The figure also depicts the reduction ranges for Annex I countries for 450 ppm CO_2-eq as reported in IPCC Box 13.7

and deviation from the baseline by non-Annex I countries, as a group, of around 7% is consistent with a 550 ppm CO_2-eq stabilisation level (intersection of the middle yellow line for 550 ppm with the top range of the green shaded area). For meeting 450 ppm CO_2-eq stabilisation, the non-Annex I countries' deviation, compared to the baseline, becomes around 22% (intersection of the bottom green line for 450 ppm with the top range of the green shaded area). If non-Annex I countries do not deviate from the baseline, then even if Annex I countries cut their emissions by about 40% in 2020, stabilisation of only slightly less than 550 ppm CO_2-eq is possible. Figure 2b also shows the results for 2050, for example, showing that for 550 ppm CO_2-eq a 80% emission reduction in Annex I countries corresponds with about 55% reduction from the baseline for non-Annex I countries. Note that this is viable only for the average of the IPCC SRES baseline scenarios. The outcome for individual IPCC SRES scenarios is different (see below).

3.3.1 Baseline emissions

The outcomes of the calculations heavily depend on the assumed baseline scenario (see also Section 3.1), as can be seen in Fig. 3. It shows the same picture for only one stabilisation level at a time (using the central estimate as shown in Table 5), but for various baseline scenarios (the IPCC scenarios and their updates as mentioned in Table 2 and the baseline of Sheehan), i.e. the average of the IPCC SRES baseline, as well as the minimum and maximum outcome, the common POLES-IMAGE (CPI) baseline (van Vuuren et al. 2003, 2006) and the update of IPCC B2 (van Vuuren et al. 2007). The figure shows that if Annex I countries as a group reduces with 30% below 1990 level, non-Annex I need to reduce about 10–25% below baseline for meeting 450 ppm CO_2-eq under the IPCC SRES emission scenarios. For the baseline of Sheehan (2008), which reports much higher growth in emissions in non-Annex I countries compared to the growth under the IPCC scenarios, the reduction becomes as high as 35% for non-Annex I (Table 4).

For all stabilisation levels, the choice of the baseline has significant implications for the required reductions in Annex I and non-Annex I countries. For example, 450 ppm CO_2-eq and 40% reduction of emissions in Annex I countries (top left figure, lower border of the green shaded area) would not require any deviation from the lowest baseline (minimum of the IPCC SRES), but a 20% deviation from the highest baseline for developing countries (maximum of the IPCC SRES). For the baseline of Sheehan this would even mean a deviation as high as 30%. In this scenario, the very high emission growth in non-Annex I countries, leads to much higher reductions in the Annex I and non-Annex I countries as the figure shows. Much less emission space is left for the Annex I countries when we fix the reduction below baseline in non-Annex I, or much higher deviation from the baseline in the non-Annex I countries is necessary when we fix the reduction for the Annex I countries.

3.3.2 The assumed global emission level in 2020 for a long-term concentration stabilisation target

So far, the central estimates have been assumed for the global emission limits in 2020. The uncertainty ranges of the global emission limits of 2020 have been used (see Table 5), and the effects of using the minimum and maximum have been analysed (see Fig. 4). For example, the figure shows that for 450 ppm CO_2-eq and a 40% emission reduction for Annex I countries would require a 7% to 22% deviation from the baseline, for a maximum and minimum global emission limit, compared to a 12% deviation for the default global limit.

3.3.3 Land-use CO_2 emission projections

The next important factor is the assumption of emissions from land use, land-use change and forestry (LULUCF).

The allocation studies by Höhne assume that CO_2 emissions from LULUCF need to decline at the same speed as emissions from all other sectors. However, while most baseline scenarios assume an increase in emissions in other sectors (in particular in the developing countries with the highest LULUCF emissions), all baseline scenarios assume that these emissions will decline over the course of the century. This is due

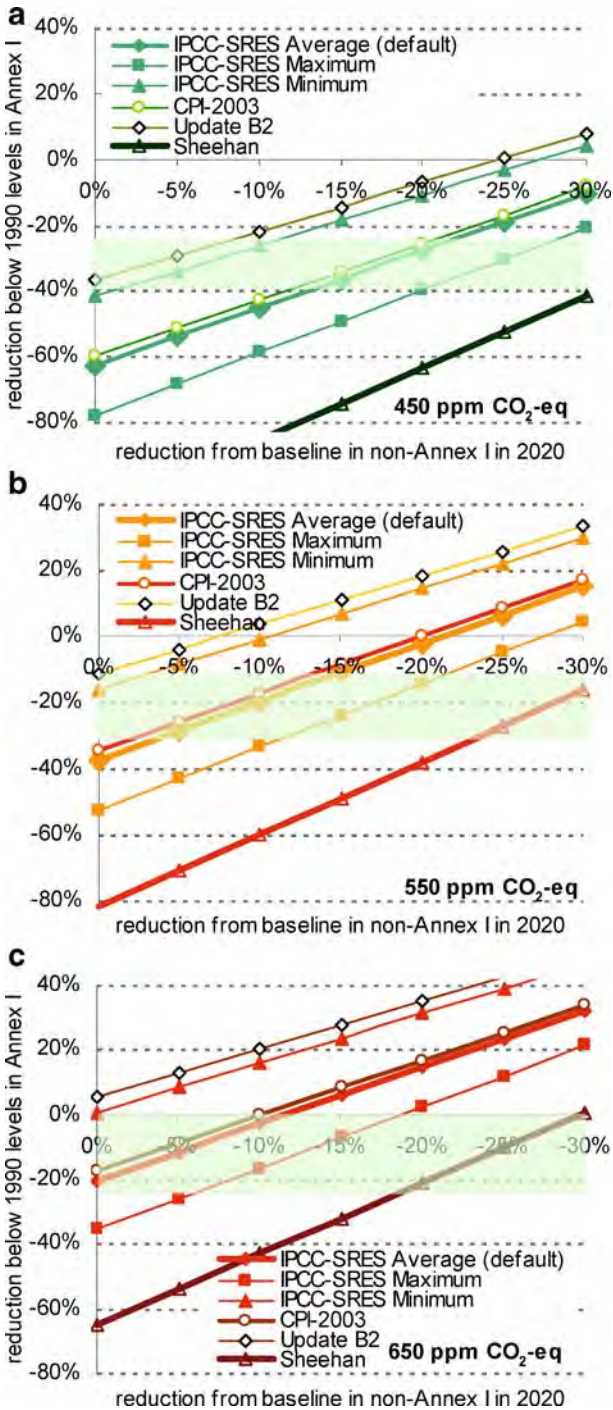

Fig. 3 The trade-off in reductions in 2020, in Annex I and non-Annex I countries as a group, for various baseline emissions (incl. baseline of Sheehan), for concentration stabilisation at 450 (**a**), 550 (**b**) and 650 (**c**) ppm CO_2-eq**.** The figure also depicts the reduction ranges for Annex I countries for the concentration stabilisation levels as reported in IPCC Box 13.7

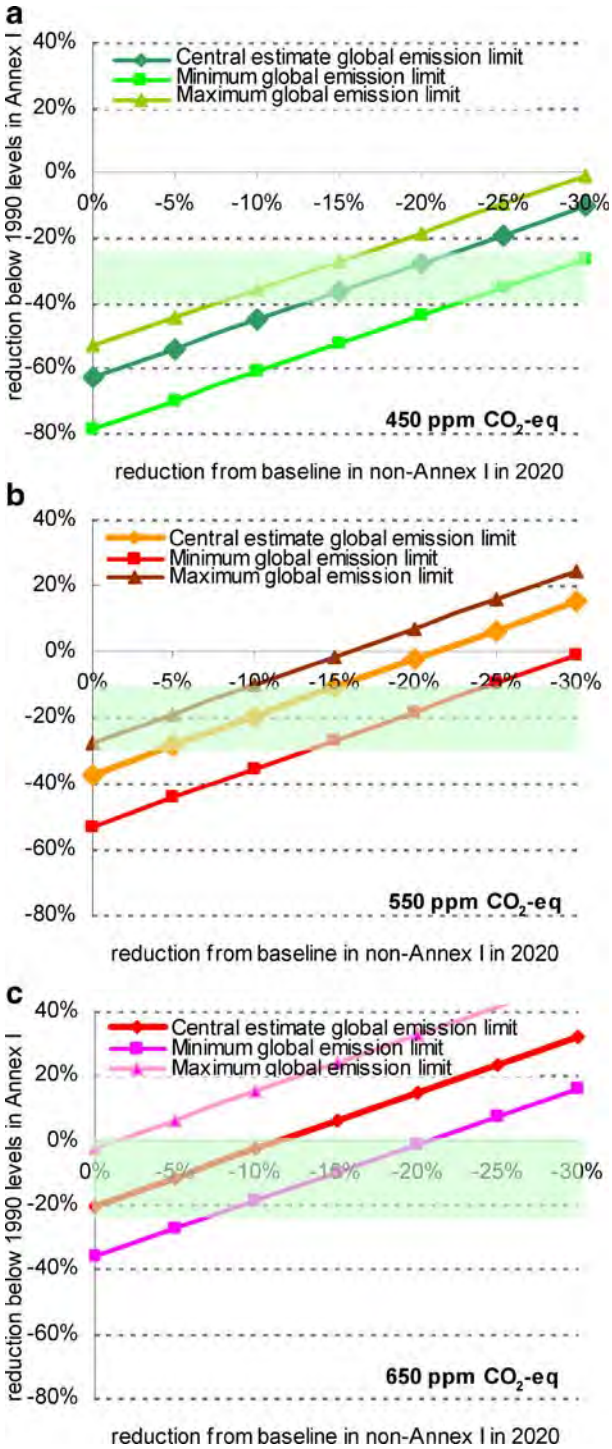

Fig. 4 The trade-off in reductions in 2020, in Annex I and non-Annex I countries as a group, for various global emission limits in 2020, for concentration stabilisation at 450 (**a**), 550 (**b**) and 650 (**c**) ppm CO_2-eq**.** The *numbers* represent the averaged outcome over separate calculations for each of the six IPCC SRES baselines. The figure also depicts the reduction ranges for Annex I countries for the concentration stabilisation levels as reported in IPCC Box 13.7

Table 6 Assumptions for global emission target (excl. LULUCF CO_2) in 2020 (%-compared to 1990 emission levels) for the different multi-gas pathways for stabilising at 450, 550 and 650 ppm CO_2-eq concentration for various assumptions on avoiding deforestation (affecting the LULUCF CO_2 emissions)

CO_2-equivalent concentration	Baseline deforestation (this study)	Avoiding deforestation 2020 (%)	Avoiding deforestation 2030 (%)
	Central estimate (%)		
2020			
450 ppm	25	35	30
550 ppm	40	50	45
650 ppm	50	55	52

to the fact that, at a certain point, all forest is depleted (stopping the emission) and reforestation occurs (increasing the terrestrial carbon uptake).

The allocation studies by den Elzen assume that CO_2 emissions from LULUCF follow the baseline, so there will be no policy intervention against deforestation, and emissions will be ongoing until at least 2020, after which they will decline. This is also assumed in the calculations presented in the figures of this paper. The other allocation studies in Table 2 are not very clear about what they have assumed for the LULUCF emissions.

Separate policy interventions are currently discussed under the UNFCCC to avoid deforestation as early as possible. One could, therefore, assume that emissions from LULUCF, due to policy interventions against deforestation, are declining much faster than all other emissions. This means, in turn, that all other emissions could decrease slightly slower. To illustrate this influence of different intervention policies against deforestation, two cases have been tested (see Table 6). The first case is assuming a strong policy to avoid deforestation on the short-term, leading to zero emission by 2020, in the second case a medium policy is assumed, which leads to zero emission by 2030. The latter roughly corresponds with reducing the baseline LULUCF CO_2 emissions by 50% in 2020. Consequently, global emission levels of *all other sectors* could be higher (higher values in Table 6 compared to the central case).

Note that, again, the reductions in the sectors are treated independently, so they are not linked with the carbon market. If the avoiding of deforestation should be induced by the carbon market through a new emission credits transfer mechanism, then reduction targets of Annex I countries (buyers) would have to be more stringent.

Figure 5 shows the results in terms of reductions in Annex I countries below 1990 (top to bottom) and in non-Annex I countries below the baseline (left to right). Avoiding deforestation by 2020 eases the efforts of developing countries in all other sectors from −22% to −12% below baseline in 2020 for the 450 ppm CO_2-eq case.

3.3.4 Influence of all factors

What does the "substantial deviation from baseline" mean for non-Annex I countries in box 13.7? The answer depends on a number of factors, which are summarised in Fig. 6. It is assumed (a priori) that the group of Annex I countries reduce emissions

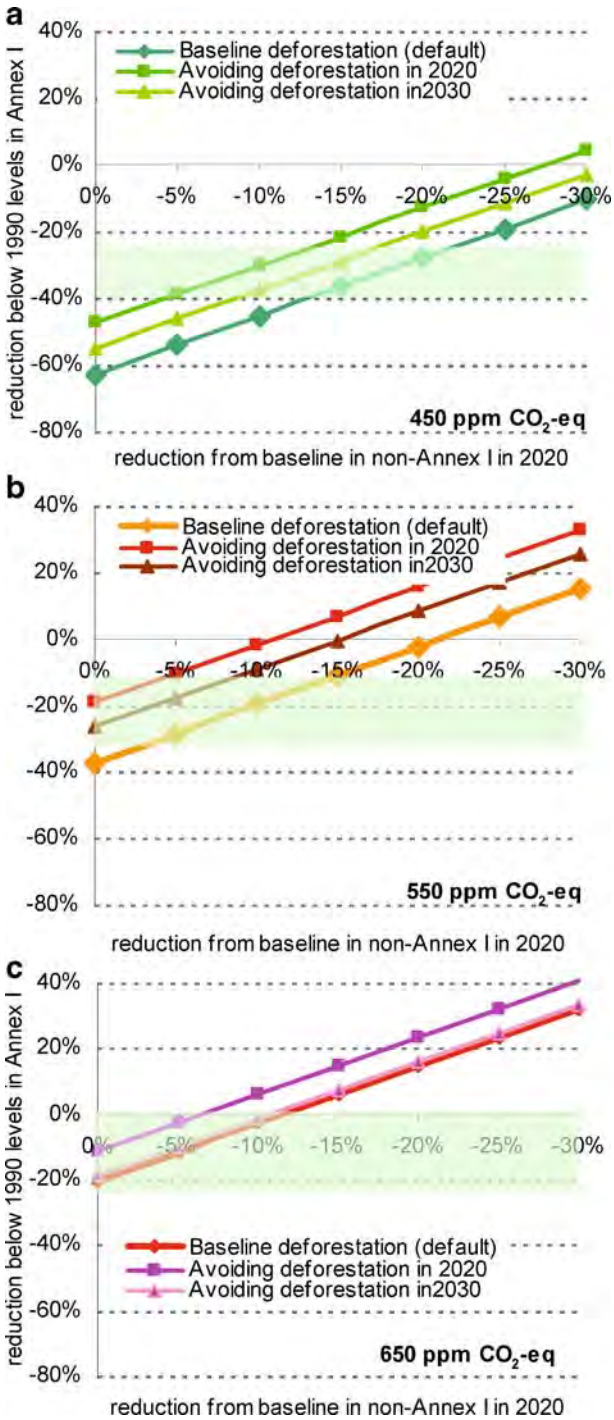

Fig. 5 The trade-off in reductions in 2020, in Annex I and non-Annex I countries as a group, for various assumptions on avoiding deforestation, for concentration stabilisation at 450 (**a**), 550 (**b**) and 650 (**c**) ppm CO_2-eq**.** The *numbers* represent the averaged outcome over separate calculations for each of the six IPCC SRES baselines. The figure also depicts the reduction ranges for Annex I countries for the concentration stabilisation levels as reported in IPCC Box 13.7

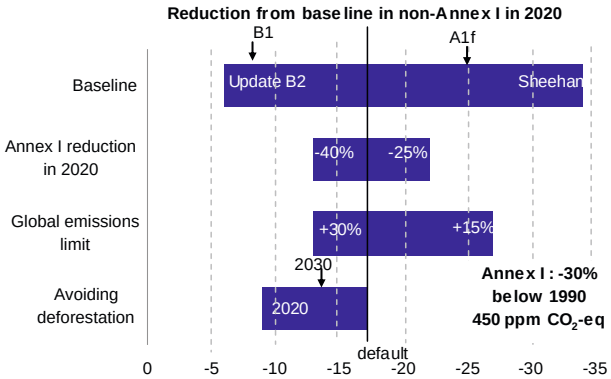

Fig. 6 The impact in the reduction from the baseline in non-Annex I countries as a group in 2020 of all factors assuming a 30% reduction in Annex I countries, below 1990 levels (default)

by a certain percentage and then analyse which reductions from baseline will be required in the non-Annex I countries. In this case, a 30% emission reduction below the 1990 emissions level in the Annex I countries was assumed, as this is roughly in the middle of the AWG reduction range of 25% to 40%. The substantial deviation for reaching 450 ppm CO_2-eq is very roughly around 17% below the baseline, in 2020.

The most important factor is the assumption on the baseline. Varying the baseline and keeping all other parameters constant, the reduction in the non-Annex I countries is between −5% and −35% below the baseline, in 2020. The baseline by Sheehan is the most ambitious, because it assumes the largest growth in non-Annex I emissions. Varying the assumed reductions in Annex I countries, means that the reduction in the non-Annex I countries could vary between −13% and −22%. Varying the global emission level in 2020 to still be consistent with 450 ppm CO_2 eq, the reduction in non-Annex I countries could vary between −13% to −27%. Varying assumptions on avoiding deforestation, means that the reduction in the non-Annex I countries could vary between −9% and −17%.

4 Conclusions

This paper provides background information on Box 13.7 of the IPCC Forth Assessment Report, Working Group III, which shows reduction ranges for Annex I and non-Annex I countries, for 2020 and 2050, consistent with stabilising the climate at various levels. In this paper, the authors of the box give more details on the studies used to prepare the ranges and analyse whether new information, obtained after completion of the IPCC report, influences these ranges. This analysis includes all studies that were available to us. We did not make judgements on the way the studies allocated emission reductions across regions and countries.

A first question was how the ranges were derived and whether these new allocation studies would change the results.

The conclusion is that there is no argument for updating the ranges in Box 13.7 of the IPCC report. The new studies that were published after the publication of the IPCC report show reductions that are in line with the reduction ranges in the box. The more recent allocation studies, published after the IPCC report came out, were

accounted for in the calculations of the presented reduction ranges. However, the studies themselves were not referred to in the IPCC report, due to the fact that they were still in press or submitted at the time of its publication.

The ranges given in the box and in this paper are assumed to be achieved domestically by both groups of countries. If Annex I countries plan to achieve a part of their emission targets outside of their territory, through credit transfer mechanisms such as the CDM, then first the ranges presented in the box and in this paper would have to be achieved and the credit transfers would have to occur in addition.

From the studies analysed, this paper specifies "substantial deviation" and "deviation" from baseline in the Box: emissions in the group of non-Annex I countries may deviate from the baseline roughly between 15% to 30% for 450 ppm CO_2-eq, 0% to 20% for 550 ppm CO_2-eq and from 10% above to 10% below the baseline for 650 ppm CO_2-eq, in 2020, in addition to the stated reductions for Annex I countries. Quantitative estimates per regional group for non-Annex I countries are not possible, as all studies used different regional groupings.

A second question is what are the important determinants for the "substantial deviation from the baseline" in non-Annex I countries. Simple and transparent calculations were used to illustrate the impact of different assumptions.

The substantial deviation from baseline in the non-Annex I countries for reaching 450 ppm CO_2 eq for the default settings in our calculations is around 17% below the baseline, in 2020. The most important factor for this value is the assumption on the baseline. The reduction in non-Annex I countries is between −5% and −35% below the baseline, in 2020, with the baseline of Sheehan lying leading to the lower end of this range. When the assumed reductions in Annex I countries vary, then the reduction in non-Annex I countries could vary between −13% and −22%. With varying the global emission levels in 2020, the reduction in non-Annex I countries could vary between −13% to −27%. Varying assumptions on avoiding deforestation, means that the reduction in non-Annex I countries could vary between −9% and −17%.

As was also concluded by Sheehan, most of the allocation studies use baseline emission scenarios, mostly the IPCC SRES scenarios, which were developed before 2003, and do not account for the recent rapid growth in emissions. This paper shows that if higher baselines are used, such as the one of Sheehan, then reductions in Annex I and/or non-Annex I countries have to be more ambitious.

The analysis by this paper reconfirms that stabilising the climate at safe levels is a serious challenge. The current slow pace in climate policy and steadily increasing global emissions mean that it is almost unfeasible to reach relatively low global emission levels, in 2020, as was assumed to be possible by some studies of 5 years ago (e.g. +10% above 1990 level compared to +26% today). Newer studies assume higher global emission levels in the short term, but also assume more stringent emission reductions in the longer term, to reach the same stabilisation levels. Amplified efforts are needed to be able to turn around the trend in global greenhouse gas emissions.

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Target Atmospheric CO_2: Where Should Humanity Aim?

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Abstract: Paleoclimate data show that climate sensitivity is ~3°C for doubled CO_2, including only fast feedback processes. Equilibrium sensitivity, including slower surface albedo feedbacks, is ~6°C for doubled CO_2 for the range of climate states between glacial conditions and ice-free Antarctica. Decreasing CO_2 was the main cause of a cooling trend that began 50 million years ago, the planet being nearly ice-free until CO_2 fell to 450 ± 100 ppm; barring prompt policy changes, that critical level will be passed, in the opposite direction, within decades. If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that. The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects.

Keywords: Climate change, climate sensitivity, global warming.

1. INTRODUCTION

Human activities are altering Earth's atmospheric composition. Concern about global warming due to long-lived human-made greenhouse gases (GHGs) led to the United Nations Framework Convention on Climate Change [1] with the objective of stabilizing GHGs in the atmosphere at a level preventing "dangerous anthropogenic interference with the climate system."

The Intergovernmental Panel on Climate Change [IPCC, [2]] and others [3] used several "reasons for concern" to estimate that global warming of more than 2-3°C may be dangerous. The European Union adopted 2°C above pre-industrial global temperature as a goal to limit human-made warming [4]. Hansen *et al.* [5] argued for a limit of 1°C global warming (relative to 2000, 1.7°C relative to pre-industrial time), aiming to avoid practically irreversible ice sheet and species loss. This 1°C limit, with nominal climate sensitivity of ¾°C per W/m^2 and plausible control of other GHGs [6], implies maximum CO_2 ~ 450 ppm [5].

Our current analysis suggests that humanity must aim for an even lower level of GHGs. Paleoclimate data and ongoing global changes indicate that 'slow' climate feedback processes not included in most climate models, such as ice sheet disintegration, vegetation migration, and GHG release from soils, tundra or ocean sediments, may begin to come into play on time scales as short as centuries or less [7]. Rapid on-going climate changes and realization that Earth is out of energy balance, implying that more warming is 'in the pipeline' [8], add urgency to investigation of the dangerous level of GHGs.

A probabilistic analysis [9] concluded that the long-term CO_2 limit is in the range 300-500 ppm for 25 percent risk tolerance, depending on climate sensitivity and non-CO_2 forcings. Stabilizing atmospheric CO_2 and climate requires that net CO_2 emissions approach zero, because of the long lifetime of CO_2 [10, 11].

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We use paleoclimate data to show that long-term climate has high sensitivity to climate forcings and that the present global mean CO_2, 385 ppm, is already in the dangerous zone. Despite rapid current CO_2 growth, ~2 ppm/year, we show that it is conceivable to reduce CO_2 this century to less than the current amount, but only *via* prompt policy changes.

1.1. Climate Sensitivity

A global climate forcing, measured in W/m^2 averaged over the planet, is an imposed perturbation of the planet's energy balance. Increase of solar irradiance (So) by 2% and doubling of atmospheric CO_2 are each forcings of about 4 W/m^2 [12].

Charney [13] defined an idealized climate sensitivity problem, asking how much global surface temperature would increase if atmospheric CO_2 were instantly doubled, assuming that slowly-changing planetary surface conditions, such as ice sheets and forest cover, were fixed. Long-lived GHGs, except for the specified CO_2 change, were also fixed, not responding to climate change. The Charney problem thus provides a measure of climate sensitivity including only the effect of 'fast' feedback processes, such as changes of water vapor, clouds and sea ice.

Classification of climate change mechanisms into fast and slow feedbacks is useful, even though time scales of these changes may overlap. We include as fast feedbacks aerosol changes, e.g., of desert dust and marine dimethylsulfide, that occur in response to climate change [7].

Charney [13] used climate models to estimate fast-feedback doubled CO_2 sensitivity of 3 ± 1.5°C. Water vapor increase and sea ice decrease in response to global warming were both found to be strong positive feedbacks, amplifying the surface temperature response. Climate models in the current IPCC [2] assessment still agree with Charney's estimate.

Climate models alone are unable to define climate sensitivity more precisely, because it is difficult to prove that models realistically incorporate all feedback processes. The Earth's history, however, allows empirical inference of both fast feedback climate sensitivity and long-term sensitivity to specified GHG change including the slow ice sheet feedback.

2. PLEISTOCENE EPOCH

Atmospheric composition and surface properties in the late Pleistocene are known well enough for accurate assessment of the fast-feedback (Charney) climate sensitivity. We first compare the pre-industrial Holocene with the last glacial maximum [LGM, 20 ky BP (before present)]. The planet was in energy balance in both periods within a small fraction of 1 W/m^2, as shown by considering the contrary: an imbalance of 1 W/m^2 maintained a few millennia would melt all ice on the planet or change ocean temperature an amount far outside measured variations [Table **S1** of 8]. The approximate equilibrium characterizing most of Earth's history is unlike the current situation, in which GHGs are rising at a rate much faster than the coupled climate system can respond.

Climate forcing in the LGM equilibrium state due to the ice age surface properties, i.e., increased ice area, different vegetation distribution, and continental shelf exposure, was -3.5 ± 1 W/m^2 [14] relative to the Holocene. Additional forcing due to reduced amounts of long-lived GHGs (CO_2, CH_4, N_2O), including the indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor (Fig. **S1**) was -3 ± 0.5 W/m^2. Global forcing due to slight changes in the Earth's orbit is a negligible fraction of 1 W/m^2 (Fig. **S3**). The total 6.5 W/m^2 forcing and global surface temperature change of 5 ± 1°C relative to the Holocene [15, 16] yield an empirical sensitivity ~¾ ± ¼ °C per W/m^2 forcing, i.e., a Charney sensitivity of 3 ± 1 °C for the 4 W/m^2 forcing of doubled CO_2. This empirical fast-feedback climate sensitivity allows water vapor, clouds, aerosols, sea ice, and all other fast feedbacks that exist in the real world to respond naturally to global climate change.

Climate sensitivity varies as Earth becomes warmer or cooler. Toward colder extremes, as the area of sea ice grows, the planet approaches runaway snowball-Earth conditions, and at high temperatures it can approach a runaway greenhouse effect [12]. At its present temperature Earth is on a flat portion of its fast-feedback climate sensitivity curve (Fig. **S2**). Thus our empirical sensitivity, although strictly the mean fast-feedback sensitivity for climate states ranging from the ice age to the current interglacial period, is also today's fast-feedback climate sensitivity.

2.1. Verification

Our empirical fast-feedback climate sensitivity, derived by comparing conditions at two points in time, can be checked over the longer period of ice core data. Fig. (**1a**) shows CO_2 and CH_4 data from the Antarctic Vostok ice core [17, 18] and sea level based on Red Sea sediment cores [18]. Gases are from the same ice core and have a consistent time scale, but dating with respect to sea level may have errors up to several thousand years.

We use the GHG and sea level data to calculate climate forcing by GHGs and surface albedo change as in prior calculations [7], but with two refinements. First, we specify the N_2O climate forcing as 12 percent of the sum of the CO_2 and CH_4 forcings, rather than the 15 percent estimated earlier [7] Because N_2O data are not available for the entire record, and its forcing is small and highly correlated with CO_2 and CH_4, we take the GHG effective forcing as

$$Fe\ (GHGs) = 1.12\ [Fa(CO_2) + 1.4\ Fa(CH_4)], \qquad (1)$$

using published formulae for Fa of each gas [20]. The factor 1.4 accounts for the higher efficacy of CH_4 relative to CO_2, which is due mainly to the indirect effect of CH_4 on tropospheric ozone and stratospheric water vapor [12]. The resulting GHG forcing between the LGM and late Holocene is 3 W/m^2, apportioned as 75% CO_2, 14% CH_4 and 11% N_2O.

The second refinement in our calculations is to surface albedo. Based on models of ice sheet shape, we take the horizontal area of the ice sheet as proportional to the 4/5 power of volume. Fig. (**S4**) compares our present albedo forcing with prior use [7] of exponent 2/3, showing that this

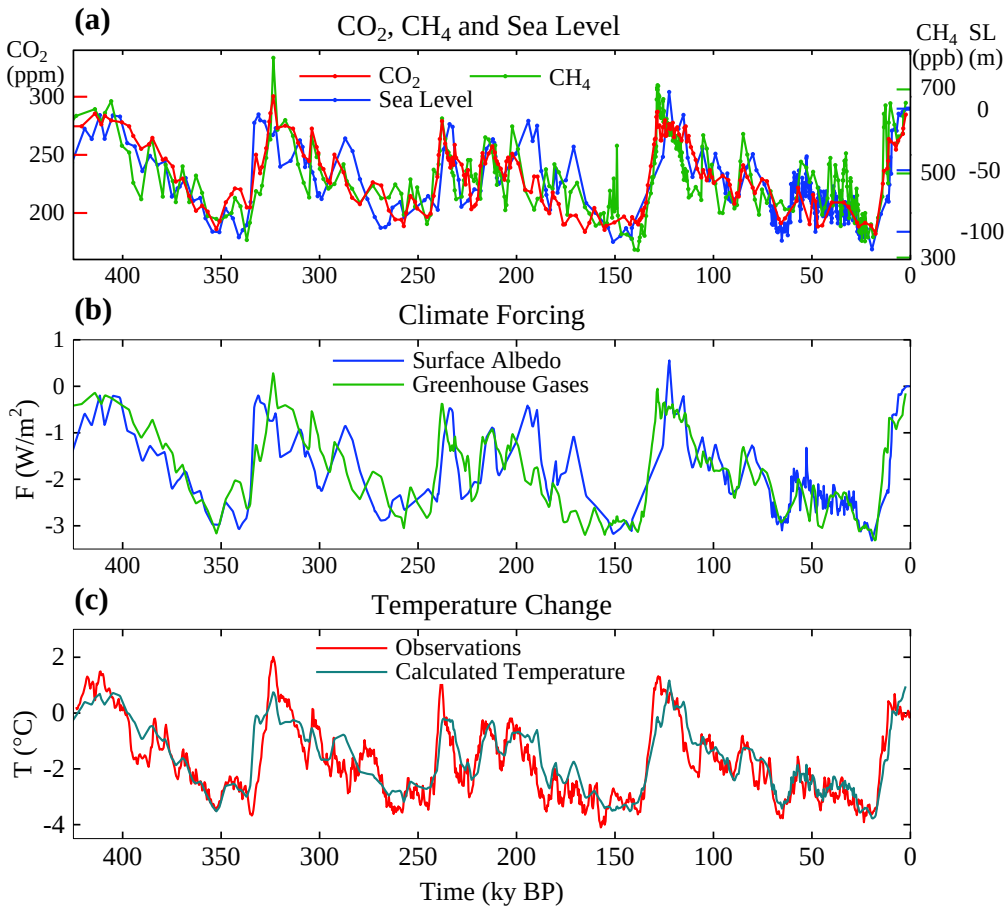

Fig. (1). (**a**) CO_2, CH_4 [17] and sea level [19] for past 425 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from sea level change. (**c**) Calculated global temperature change based on climate sensitivity of ¾°C per W/m^2. Observations are Antarctic temperature change [18] divided by two.

choice and division of the ice into multiple ice sheets has only a minor effect.

Multiplying the sum of GHG and surface albedo forcings by climate sensitivity ¾°C per W/m^2 yields the blue curve in Fig. (**1c**). Vostok temperature change [17] divided by two (red curve) is used to crudely estimate global temperature change, as typical glacial-interglacial global annual-mean temperature change is ~5°C and is associated with ~10°C change on Antarctica [21]. Fig. (**1c**) shows that fast-feedback climate sensitivity ¾°C per W/m^2 (3°C for doubled CO_2) is a good approximation for the entire period.

2.2. Slow Feedbacks

Let us consider climate change averaged over a few thousand years – long enough to assure energy balance and minimize effects of ocean thermal response time and climate change leads/lags between hemispheres [22]. At such temporal resolution the temperature variations in Fig. (**1**) are global, with high latitude amplification, being present in polar ice cores and sea surface temperature derived from ocean sediment cores (Fig. **S5**).

GHG and surface albedo changes are mechanisms causing the large global climate changes in Fig. (**1**), but they do not initiate these climate swings. Instead changes of GHGs and sea level (a measure of ice sheet size) lag temperature change by several hundred years [6, 7, 23, 24].

GHG and surface albedo changes are positive climate feedbacks. Major glacial-interglacial climate swings are instigated by slow changes of Earth's orbit, especially the tilt of Earth's spin-axis relative to the orbital plane and the precession of the equinoxes that influences the intensity of summer insolation [25, 26]. Global radiative forcing due to orbital changes is small, but ice sheet size is affected by changes of geographical and seasonal insolation (e.g., ice melts at both poles when the spin-axis tilt increases, and ice melts at one pole when perihelion, the closest approach to the sun, occurs in late spring [7]. Also a warming climate causes net release of GHGs. The most effective GHG feedback is release of CO_2 by the ocean, due partly to temperature dependence of CO_2 solubility but mostly to increased ocean mixing in a warmer climate, which acts to flush out

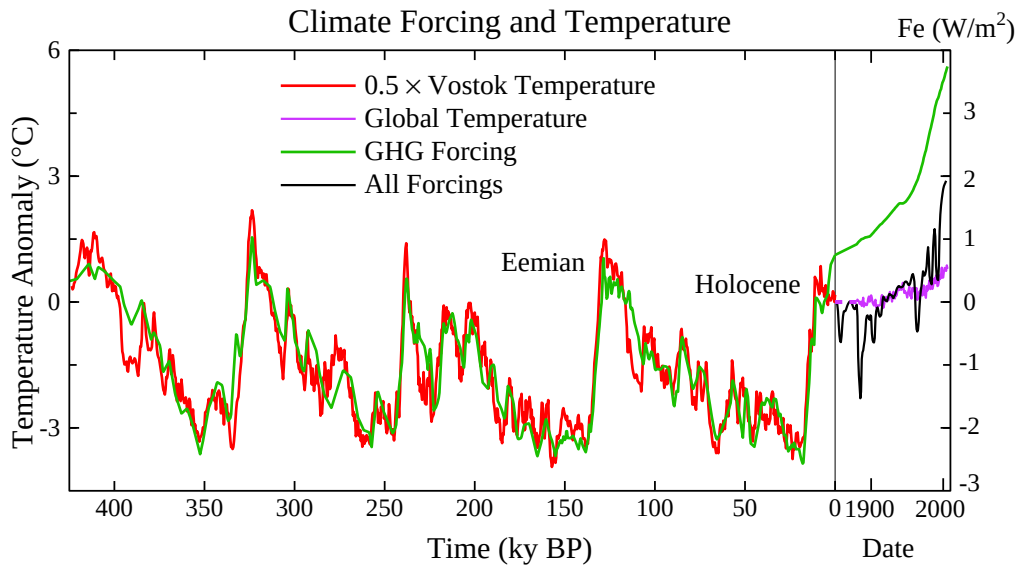

Fig. (2). Global temperature (left scale) and GHG forcing (right scale) due to CO_2, CH_4 and N_2O from the Vostok ice core [17, 18]. Time scale is expanded for the industrial era. Ratio of temperature and forcing scales is 1.5°C per W/m^2, i.e., the temperature scale gives the expected equilibrium response to GHG change including (slow feedback) surface albedo change. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky BP (Fig. **S6**). Zero point of modern temperature and net climate forcing was set at 1850 [5], but this is also the zero point for 10-8 ky BP, as shown by the absence of a trend in Fig. (**S6**) and by the discussion of that figure.

deep ocean CO_2 and alters ocean biological productivity [27].

GHG and surface albedo feedbacks respond and contribute to temperature change caused by any climate forcing, natural or human-made, given sufficient time. The GHG feedback is nearly linear in global temperature during the late Pleistocene (Fig. **7** of [6, 28]). Surface albedo feedback increases as Earth becomes colder and the area of ice increases. Climate sensitivity on

Pleistocene time scales includes slow feedbacks, and is larger than the Charney sensitivity, because the dominant slow feedbacks are positive. Other feedbacks, e.g., the negative feedback of increased weathering as CO_2 increases, become important on longer geologic time scales.

Paleoclimate data permit evaluation of long-term sensitivity to specified GHG change. We assume only that, to first order, the area of ice is a function of global temperature. Plotting GHG forcing [7] from ice core data [18] against temperature shows that global climate sensitivity including the slow surface albedo feedback is 1.5°C per W/m^2 or 6°C for doubled CO_2 (Fig. **2**), twice as large as the Charney fast-feedback sensitivity. Note that we assume the area of ice and snow on the planet to be predominately dependent on global temperature, but some changes of regional ice sheet properties occur as part of the Earth orbital climate forcing (see Supplementary Material).

This equilibrium sensitivity of 6°C for doubled CO_2 is valid for specified GHG amount, as in studies that employ emission scenarios and coupled carbon cycle/climate models to determine GHG amount. If GHGs are included as a feedback (with say solar irradiance as forcing) sensitivity is still larger on Pleistocene time scales (see Supplementary Material), but the sensitivity may be reduced by negative feedbacks on geologic time scales [29, 30]. The 6°C sensitivity reduces to 3°C when the planet has become warm enough to lose its ice sheets.

This long-term climate sensitivity is relevant to GHGs that remain airborne for centuries-to-millennia. The human-caused atmospheric GHG increase will decline slowly if anthropogenic emissions from fossil fuel burning decrease enough, as we illustrate below using a simplified carbon cycle model. On the other hand, if the globe warms much further, carbon cycle models [2] and empirical data [6, 28] reveal a positive GHG feedback on century-millennia time scales. This amplification of GHG amount is moderate if warming is kept within the range of recent interglacial periods [6], but larger warming would risk greater release of CH_4 and CO_2 from methane hydrates in tundra and ocean sediments [29]. On still longer, geological, time scales weathering of rocks causes a negative feedback on atmospheric CO_2 amount [30], as discussed in section 3, but this feedback is too slow to alleviate climate change of concern to humanity.

2.3. Time Scales

How long does it take to reach equilibrium temperature with specified GHG change? Response is slowed by ocean thermal inertia and the time needed for ice sheets to disintegrate.

Ocean-caused delay is estimated in Fig. (**S7**) using a coupled atmosphere-ocean model. One-third of the response occurs in the first few years, in part because of rapid response over land, one-half in ~25 years, three-quarters in 250 years, and nearly full response in a millennium. The ocean-

caused delay is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of surface water and deep water [31], as discussed in the Supplementary Material Section.

Ice sheet response time is often assumed to be several millennia, based on the broad sweep of paleo sea level change (Fig. **1a**) and primitive ice sheet models designed to capture that change. However, this long time scale may reflect the slowly changing orbital forcing, rather than inherent inertia, as there is no discernable lag between maximum ice sheet melt rate and local insolation that favors melt [7]. Paleo sea level data with high time resolution reveal frequent 'suborbital' sea level changes at rates of 1 m/century or more [32-34].

Present-day observations of Greenland and Antarctica show increasing surface melt [35], loss of buttressing ice shelves [36], accelerating ice streams [37], and increasing overall mass loss [38]. These rapid changes do not occur in existing ice sheet models, which are missing critical physics of ice sheet disintegration [39]. Sea level changes of several meters per century occur in the paleoclimate record [32, 33], in response to forcings slower and weaker than the present human-made forcing. It seems likely that large ice sheet response will occur within centuries, if human-made forcings continue to increase. Once ice sheet disintegration is underway, decadal changes of sea level may be substantial.

2.4. Warming "in the Pipeline"

The expanded time scale for the industrial era (Fig. **2**) reveals a growing gap between actual global temperature (purple curve) and equilibrium (long-term) temperature response based on the net estimated climate forcing (black curve). Ocean and ice sheet response times together account for this gap, which is now 2.0°C.

The forcing in Fig. (**2**) (black curve, Fe scale), when used to drive a global climate model [5], yields global temperature change that agrees closely (Fig. **3** in [5]) with observations (purple curve, Fig. **2**). That climate model, which includes only fast feedbacks, has additional warming of ~0.6°C in the pipeline today because of ocean thermal inertia [5, 8].

The remaining gap between equilibrium temperature for current atmospheric composition and actual global temperature is ~1.4°C. This further 1.4°C warming still to come is due to the slow surface albedo feedback, specifically ice sheet disintegration and vegetation change.

One may ask whether the climate system, as the Earth warms from its present 'interglacial' state, still has the capacity to supply slow feedbacks that double the fast-feedback sensitivity. This issue can be addressed by considering longer time scales including periods with no ice.

3. CENOZOIC ERA

Pleistocene atmospheric CO_2 variations occur as a climate feedback, as carbon is exchanged among surface reservoirs: the ocean, atmosphere, soils and biosphere. The most effective feedback is increase of atmospheric CO_2 as climate warms, the CO_2 transfer being mainly from ocean to atmosphere [27, 28]. On longer time scales the total amount of CO_2 in the surface reservoirs varies due to exchange of carbon with the solid earth. CO_2 thus becomes a primary agent of long-term climate change, leaving orbital effects as 'noise' on larger climate swings.

The Cenozoic era, the past 65.5 My, provides a valuable complement to the Pleistocene for exploring climate sensitivity. Cenozoic data on climate and atmospheric composition are not as precise, but larger climate variations occur, including an ice-free planet, thus putting glacial-interglacial changes in a wider perspective.

Oxygen isotopic composition of benthic (deep ocean dwelling) foraminifera shells in a global compilation of ocean sediment cores [26] provides a starting point for analyzing Cenozoic climate change (Fig. **3a**). At times with negligible ice sheets, oxygen isotope change, $\delta^{18}O$, provides a direct measure of deep ocean temperature (T_{do}). Thus T_{do} (°C) ~ -4 $\delta^{18}O$ + 12 between 65.5 and 35 My BP.

Rapid increase of $\delta^{18}O$ at about 34 My is associated with glaciation of Antarctica [26, 40] and global cooling, as evidenced by data from North America [41] and Asia [42]. From then until the present, ^{18}O in deep ocean foraminifera is affected by both ice volume and T_{do}, lighter ^{16}O evaporating preferentially from the ocean and accumulating in ice sheets. Between 35 My and the last ice age (20 ky) the change of $\delta^{18}O$ was ~ 3‰, change of T_{do} was ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Given that a 1.5‰ change of $\delta^{18}O$ is associated with a 6°C T_{do} change, we assign the remaining $\delta^{18}O$ change to ice volume linearly at the rate 60 msl per mil $\delta^{18}O$ change (thus 180 msl for $\delta^{18}O$ between 1.75 and 4.75). Equal division of $\delta^{18}O$ between temperature and sea level yields sea level change in the late Pleistocene in reasonable accord with available sea level data (Fig. **S8**). Subtracting the ice volume portion of $\delta^{18}O$ yields deep ocean temperature T_{do} (°C) = -2 ($\delta^{18}O$ -4.25‰) after 35 My, as in Fig. (**3b**).

The large (~14°C) Cenozoic temperature change between 50 My and the ice age at 20 ky must have been forced by changes of atmospheric composition. Alternative drives could come from outside (solar irradiance) or the Earth's surface (continental locations). But solar brightness increased ~0.4% in the Cenozoic [43], a linear forcing change of only +1 W/m^2 and of the wrong sign to contribute to the cooling trend. Climate forcing due to continental locations was < 1 W/m^2, because continents 65 My ago were already close to present latitudes (Fig. **S9**). Opening or closing of oceanic gateways might affect the timing of glaciation, but it would not provide the climate forcing needed for global cooling.

CO_2 concentration, in contrast, varied from ~180 ppm in glacial times to 1500 ± 500 ppm in the early Cenozoic [44]. This change is a forcing of more than 10 W/m^2 (Table **1** in [16]), an order of magnitude larger than other known forcings. CH_4 and N_2O, positively correlated with CO_2 and global temperature in the period with accurate data (ice cores), likely increase the total GHG forcing, but their forcings are much smaller than that of CO_2 [45, 46].

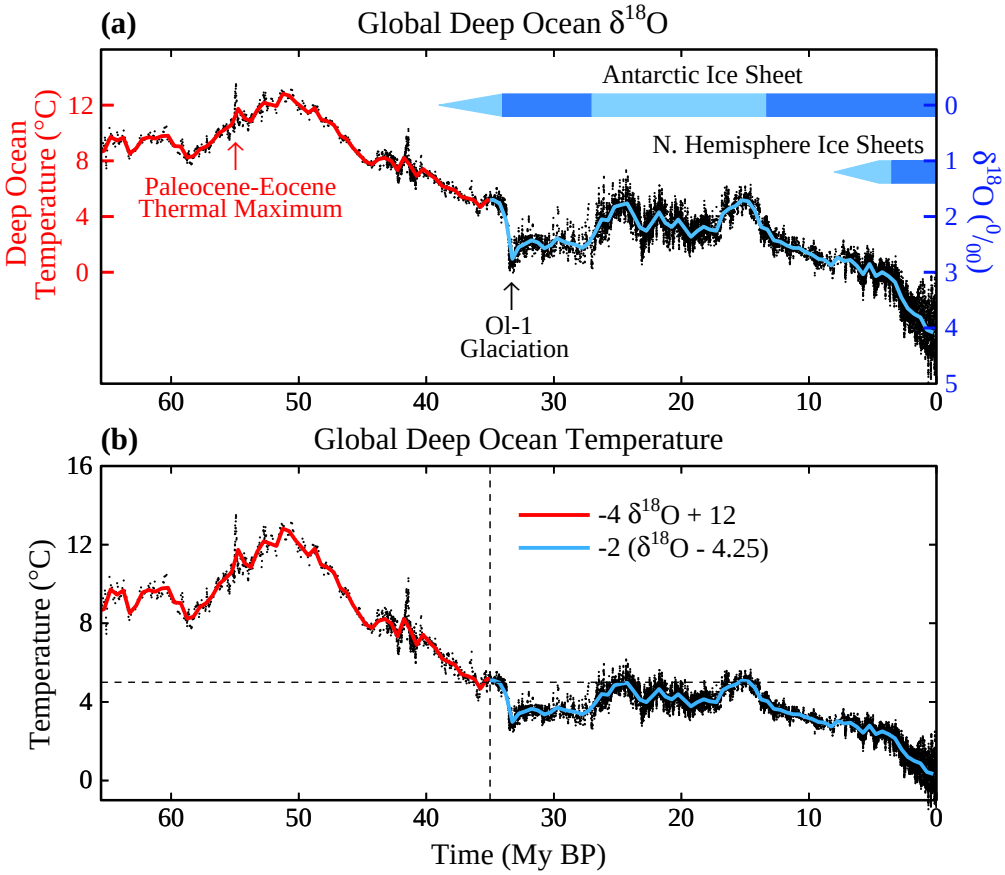

Fig. (3). Global deep ocean (**a**) $\delta^{18}O$ [26] and (**b**) temperature. Black curve is 5-point running mean of $\delta^{18}O$ original temporal resolution, while red and blue curves have 500 ky resolution.

3.1. Cenozoic Carbon Cycle

Solid Earth sources and sinks of CO_2 are not, in general, balanced at any given time [30, 47]. CO_2 is removed from surface reservoirs by: (1) chemical weathering of rocks with deposition of carbonates on the ocean floor, and (2) burial of organic matter; weathering is the dominant process [30]. CO_2 returns primarily *via* metamorphism and volcanic outgassing at locations where carbonate-rich oceanic crust is being subducted beneath moving continental plates.

Outgassing and burial of CO_2 are each typically 10^{12}-10^{13} mol C/year [30, 47-48]. At times of unusual plate tectonic activity, such as rapid subduction of carbon-rich ocean crust or strong orogeny, the imbalance between outgassing and burial can be a significant fraction of the one-way carbon flux. Although negative feedbacks in the geochemical carbon cycle reduce the rate of surface reservoir perturbation [49], a net imbalance ~10^{12} mol C/year can be maintained over thousands of years. Such an imbalance, if confined to the atmosphere, would be ~0.005 ppm/year, but as CO_2 is distributed among surface reservoirs, this is only ~0.0001 ppm/year. This rate is negligible compared to the present human-made atmospheric CO_2 increase of ~2 ppm/year, yet over a million years such a crustal imbalance alters atmospheric CO_2 by 100 ppm.

Between 60 and 50 My ago India moved north rapidly, 18-20 cm/year [50], through a region that long had been a depocenter for carbonate and organic sediments. Subduction of carbon-rich crust was surely a large source of CO_2 outgassing and a prime cause of global warming, which peaked 50 My ago (Fig. **3b**) with the Indo-Asian collision. CO_2 must have then decreased due to a reduced subduction source and enhanced weathering with uplift of the Himalayas/Tibetan Plateau [51]. Since then, the Indian and Atlantic Oceans have been major depocenters for carbon, but subduction of carbon-rich crust has been limited mainly to small regions near Indonesia and Central America [47].

Thus atmospheric CO_2 declined following the Indo-Asian collision [44] and climate cooled (Fig. **3b**) leading to Antarctic glaciation by ~34 My. Antarctica has been more or less glaciated ever since. The rate of CO_2 drawdown declines as atmospheric CO_2 decreases due to negative feedbacks, including the effect of declining atmospheric temperature and plant growth rates on weathering [30]. These negative feedbacks tend to create a balance between crustal outgassing and drawdown of CO_2, which have been equal within 1-2 percent over the past 700 ky [52]. Large fluctuations in the size of the Antarctic ice sheet have occurred in the past 34 My, possibly related to temporal variations of plate tectonics [53] and outgassing rates. The relatively constant atmos-

pheric CO_2 amount of the past 20 My (Fig. **S10**) implies a near balance of outgassing and weathering rates over that period.

Knowledge of Cenozoic CO_2 is limited to imprecise proxy measures except for recent ice core data. There are discrepancies among different proxy measures, and even between different investigators using the same proxy method, as discussed in conjunction with Fig. (**S10**). Nevertheless, the proxy data indicate that CO_2 was of the order of 1000 ppm in the early Cenozoic but <500 ppm in the last 20 My [2, 44].

3.2. Cenozoic Forcing and CO_2

The entire Cenozoic climate forcing history (Fig. **4a**) is implied by the temperature reconstruction (Fig. **3b**), assuming a fast-feedback sensitivity of ¾°C per W/m^2. Subtracting the solar and surface albedo forcings (Fig. **4b**), the latter from Eq. S2 with ice sheet area *vs* time from $\delta^{18}O$, we obtain the GHG forcing history (Fig. **4c**).

We hinge our calculations at 35 My for several reasons. Between 65 and 35 My ago there was little ice on the planet, so climate sensitivity is defined mainly by fast feedbacks. Second, we want to estimate the CO_2 amount that precipitated Antarctic glaciation. Finally, the relation between global surface air temperature change (ΔT_s) and deep ocean temperature change (ΔT_{do}) differs for ice-free and glaciated worlds.

Climate models show that global temperature change is tied closely to ocean temperature change [54]. Deep ocean temperature is a function of high latitude ocean surface temperature, which tends to be amplified relative to global mean ocean surface temperature. However, land temperature change exceeds that of the ocean, with an effect on global temperature that tends to offset the latitudinal variation of ocean temperature. Thus in the ice-free world (65-35 My) we take $\Delta T_s \sim \Delta T_{do}$ with generous (50%) uncertainty. In the glaciated world ΔT_{do} is limited by the freezing point in the deep ocean. ΔT_s between the last ice age (20 ky) and the present

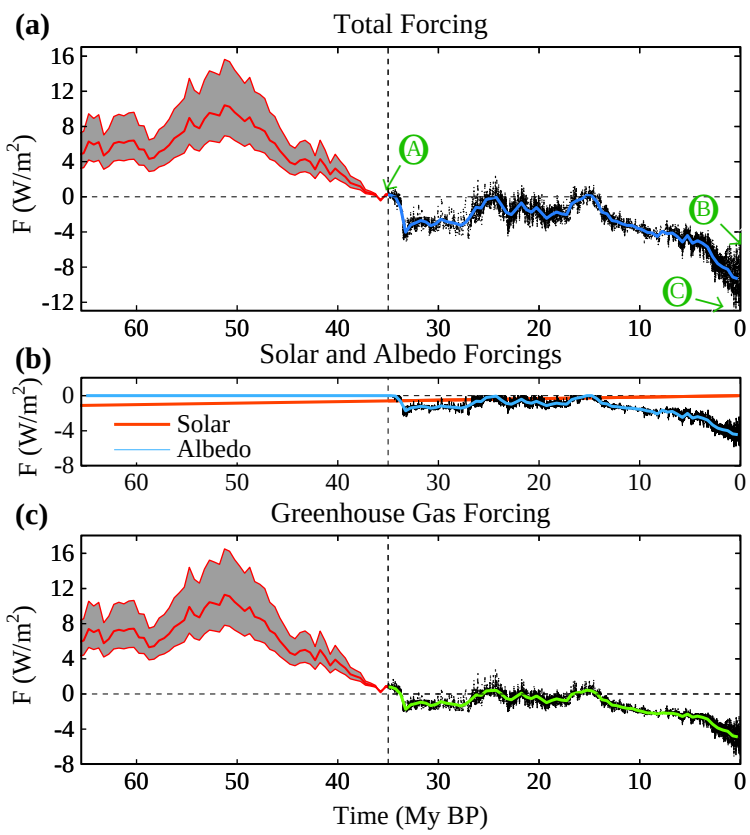

Fig. (4). (**a**) Total climate forcing, (**b**) solar and surface albedo forcings, and (**c**) GHG forcing in the Cenozoic, based on T_{do} history of Fig. (**3b**) and assumed fast-feedback climate sensitivity ¾°C per W/m^2. Ratio of T_s change and T_{do} change is assumed to be near unity in the minimal ice world between 65 and 35 My, but the gray area allows for 50% uncertainty in the ratio. In the later era with large ice sheets we take $\Delta T_s/\Delta T_{do} = 1.5$, in accord with Pleistocene data.

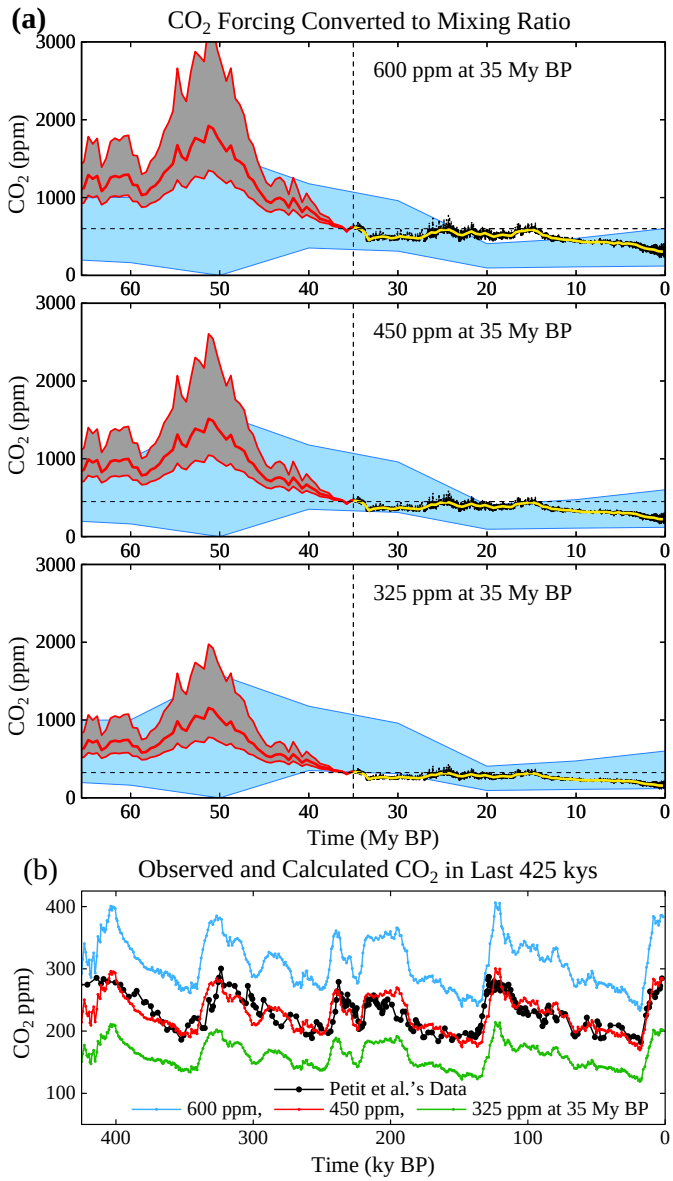

Fig. (5). (**a**) Simulated CO_2 amounts in the Cenozoic for three choices of CO_2 amount at 35 My (temporal resolution of black and colored curves as in Fig. (**3**); blue region: multiple CO_2 proxy data, discussed with Fig. (**S10**); gray region allows 50 percent uncertainty in ratio of global surface and deep ocean temperatures). (**b**) Expanded view of late Pleistocene, including precise ice core CO_2 measurements (black curve).

interglacial period (~5°C) was ~1.5 times larger than ΔT_{do}. In Fig. (**S5**) we show that this relationship fits well throughout the period of ice core data.

If we specify CO_2 at 35 My, the GHG forcing defines CO_2 at other times, assuming CO_2 provides 75% of the GHG forcing, as in the late Pleistocene. CO_2 ~450 ppm at 35 My keeps CO_2 in the range of early Cenozoic proxies (Fig. **5a**) and yields a good fit to the amplitude and mean CO_2 amount in the late Pleistocene (Fig. **5b**). A CO_2 threshold for Antarctic glaciation of ~500 ppm was previously inferred from proxy CO_2 data and a carbon cycle model [55].

Individual CO_2 proxies (Fig. **S10**) clarify limitations due to scatter among the measurements. Low CO_2 of some early Cenozoic proxies, if valid, would suggest higher climate

sensitivity. However, in general the sensitivities inferred from the Cenozoic and Phanerozoic [56, 57, 58] agree well with our analysis, if we account for the ways in which sensitivity is defined and the periods emphasized in each empirical derivation (Table **S1**).

Our CO_2 estimate of ~450 ppm at 35 My (Fig. **5**) serves as a prediction to compare with new data on CO_2 amount. Model uncertainties (Fig. **S10**) include possible changes of non-CO_2 GHGs and the relation of ΔT_s to ΔT_{do}. The model fails to account for cooling in the past 15 My if CO_2 increased, as several proxies suggest (Fig. **S10**). Changing ocean currents, such as the closing of the Isthmus of Panama, may have contributed to climate evolution, but models find little effect on temperature [59]. Non-CO_2 GHGs also could have played a role, because little forcing would have been needed to cause cooling due to the magnitude of late Cenozoic albedo feedback.

3.3. Implication

We infer from Cenozoic data that CO_2 was the dominant Cenozoic forcing, that CO_2 was ~450 ± 100 ppm when Antarctica glaciated, and that glaciation is reversible. Together these inferences have profound implications.

Consider three points marked in Fig. (**4**): point A at 35 My, just before Antarctica glaciated; point B at recent interglacial periods; point C at the depth of recent ice ages. Point B is about half way between A and C in global temperature (Fig. **3b**) and climate forcings (Fig. **4**). The GHG forcing from the deepest recent ice age to current interglacial warmth is ~3.5 W/m^2. Additional 4 W/m^2 forcing carries the planet, at equilibrium, to the ice-free state. Thus equilibrium climate sensitivity to GHG change, including the surface albedo change as a slow feedback, is almost as large between today and an ice-free world as between today and the ice ages.

The implication is that global climate sensitivity of 3°C for doubled CO_2, although valid for the idealized Charney definition of climate sensitivity, is a considerable understatement of expected equilibrium global warming in response to imposed doubled CO_2. Additional warming, due to slow climate feedbacks including loss of ice and spread of flora over the vast high-latitude land area in the Northern Hemisphere, approximately doubles equilibrium climate sensitivity.

Equilibrium sensitivity 6°C for doubled CO_2 is relevant to the case in which GHG changes are specified. That is appropriate to the anthropogenic case, provided the GHG amounts are estimated from carbon cycle models including climate feedbacks such as methane release from tundra and ocean sediments. The equilibrium sensitivity is even higher if the GHG feedback is included as part of the climate response, as is appropriate for analysis of the climate response to Earth orbital perturbations. The very high sensitivity with both albedo and GHG slow feedbacks included accounts for the huge magnitude of glacial-interglacial fluctuations in the Pleistocene (Fig. **3**) in response to small forcings (section 3 of Supplementary Material).

Equilibrium climate response would not be reached in decades or even in a century, because surface warming is slowed by the inertia of the ocean (Fig. **S7**) and ice sheets. However, Earth's history suggests that positive feedbacks, especially surface albedo changes, can spur rapid global warmings, including sea level rise as fast as several meters per century [7]. Thus if humans push the climate system sufficiently far into disequilibrium, positive climate feedbacks may set in motion dramatic climate change and climate impacts that cannot be controlled.

4. ANTHROPOCENE ERA

Human-made global climate forcings now prevail over natural forcings (Fig. **2**). Earth may have entered the Anthropocene era [60, 61] 6-8 ky ago [62], but the net human-made forcing was small, perhaps slightly negative [7], prior to the industrial era. GHG forcing overwhelmed natural and negative human-made forcings only in the past quarter century (Fig. **2**).

Human-made climate change is delayed by ocean (Fig. **S7**) and ice sheet response times. Warming 'in the pipeline', mostly attributable to slow feedbacks, is now about 2°C (Fig. **2**). No additional forcing is required to raise global temperature to at least the level of the Pliocene, 2-3 million years ago, a degree of warming that would surely yield 'dangerous' climate impacts [5].

4.1. Tipping Points

Realization that today's climate is far out of equilibrium with current climate forcings raises the specter of 'tipping points', the concept that climate can reach a point where, without additional forcing, rapid changes proceed practically out of our control [2, 7, 63, 64]. Arctic sea ice and the West Antarctic Ice Sheet are examples of potential tipping points. Arctic sea ice loss is magnified by the positive feedback of increased absorption of sunlight as global warming initiates sea ice retreat [65]. West Antarctic ice loss can be accelerated by several feedbacks, once ice loss is substantial [39].

We define: (1) the *tipping level*, the global climate forcing that, if long maintained, gives rise to a specific consequence, and (2) the *point of no return*, a climate state beyond which the consequence is inevitable, even if climate forcings are reduced. A point of no return can be avoided, even if the tipping level is temporarily exceeded. Ocean and ice sheet inertia permit overshoot, provided the climate forcing is returned below the tipping level before initiating irreversible dynamic change.

Points of no return are inherently difficult to define, because the dynamical problems are nonlinear. Existing models are more lethargic than the real world for phenomena now unfolding, including changes of sea ice [65], ice streams [66], ice shelves [36], and expansion of the subtropics [67, 68].

The tipping level is easier to assess, because the paleoclimate quasi-equilibrium response to known climate forcing is relevant. The tipping level is a measure of the long-term climate forcing that humanity must aim to stay beneath to avoid large climate impacts. The tipping level does not define the magnitude or period of tolerable overshoot. However, if overshoot is in place for centuries, the thermal per-

turbation will so penetrate the ocean [10] that recovery without dramatic effects, such as ice sheet disintegration, becomes unlikely.

4.2. Target CO_2

Combined, GHGs other than CO_2 cause climate forcing comparable to that of CO_2 [2, 6], but growth of non-CO_2 GHGs is falling below IPCC [2] scenarios. Thus total GHG climate forcing change is now determined mainly by CO_2 [69]. Coincidentally, CO_2 forcing is similar to the net human-made forcing, because non-CO_2 GHGs tend to offset negative aerosol forcing [2, 5].

Thus we take future CO_2 change as approximating the net human-made forcing change, with two caveats. First, special effort to reduce non-CO_2 GHGs could alleviate the CO_2 requirement, allowing up to about +25 ppm CO_2 for the same climate effect, while resurgent growth of non-CO_2 GHGs could reduce allowed CO_2 a similar amount [6]. Second, reduction of human-made aerosols, which have a net cooling effect, could force stricter GHG requirements. However, an emphasis on reducing black soot could largely off-set reductions of high albedo aerosols [20].

Our estimated history of CO_2 through the Cenozoic Era provides a sobering perspective for assessing an appropriate target for future CO_2 levels. A CO_2 amount of order 450 ppm or larger, if long maintained, would push Earth toward the ice-free state. Although ocean and ice sheet inertia limit the rate of climate change, such a CO_2 level likely would cause the passing of climate tipping points and initiate dynamic responses that could be out of humanity's control.

The climate system, because of its inertia, has not yet fully responded to the recent increase of human-made climate forcings [5]. Yet climate impacts are already occurring that allow us to make an initial estimate for a target atmospheric CO_2 level. No doubt the target will need to be adjusted as climate data and knowledge improve, but the urgency and difficulty of reducing the human-made forcing will be less, and more likely manageable, if excess forcing is limited soon.

Civilization is adapted to climate zones of the Holocene. Theory and models indicate that subtropical regions expand poleward with global warming [2, 67]. Data reveal a 4-degree latitudinal shift already [68], larger than model predictions, yielding increased aridity in southern United States [70, 71], the Mediterranean region, Australia and parts of Africa. Impacts of this climate shift [72] support the conclusion that 385 ppm CO_2 is already deleterious.

Alpine glaciers are in near-global retreat [72, 73]. After a one-time added flush of fresh water, glacier demise will yield summers and autumns of frequently dry rivers, including rivers originating in the Himalayas, Andes and Rocky Mountains that now supply water to hundreds of millions of people. Present glacier retreat, and warming in the pipeline, indicate that 385 ppm CO_2 is already a threat.

Equilibrium sea level rise for today's 385 ppm CO_2 is at least several meters, judging from paleoclimate history [19, 32-34]. Accelerating mass losses from Greenland [74] and West Antarctica [75] heighten concerns about ice sheet stability. An initial CO_2 target of 350 ppm, to be reassessed as effects on ice sheet mass balance are observed, is suggested.

Stabilization of Arctic sea ice cover requires, to first approximation, restoration of planetary energy balance. Climate models driven by known forcings yield a present planetary energy imbalance of +0.5-1 W/m^2 [5]. Observed heat increase in the upper 700 m of the ocean [76] confirms the planetary energy imbalance, but observations of the entire ocean are needed for quantification. CO_2 amount must be reduced to 325-355 ppm to increase outgoing flux 0.5-1 W/m^2, if other forcings are unchanged. A further imbalance reduction, and thus CO_2 ~300-325 ppm, may be needed to restore sea ice to its area of 25 years ago.

Coral reefs are suffering from multiple stresses, with ocean acidification and ocean warming principal among them [77]. Given additional warming 'in-the-pipeline', 385 ppm CO_2 is already deleterious. A 300-350 ppm CO_2 target would significantly relieve both of these stresses.

4.3. CO_2 Scenarios

A large fraction of fossil fuel CO_2 emissions stays in the air a long time, one-quarter remaining airborne for several centuries [11, 78, 79]. Thus moderate delay of fossil fuel use will not appreciably reduce long-term human-made climate change. Preservation of a climate resembling that to which humanity is accustomed, the climate of the Holocene, requires that most remaining fossil fuel carbon is never emitted to the atmosphere.

Coal is the largest reservoir of conventional fossil fuels (Fig. **S12**), exceeding combined reserves of oil and gas [2, 79]. The only realistic way to sharply curtail CO_2 emissions is to phase out coal use except where CO_2 is captured and sequestered.

Phase-out of coal emissions by 2030 (Fig. **6**) keeps maximum CO_2 close to 400 ppm, depending on oil and gas reserves and reserve growth. IPCC reserves assume that half of readily extractable oil has already been used (Figs. **6**, **S12**). EIA [80] estimates (Fig. **S12**) have larger reserves and reserve growth. Even if EIA estimates are accurate, the IPCC case remains valid if the most difficult to extract oil and gas is left in the ground, *via* a rising price on carbon emissions that discourages remote exploration and environmental regulations that place some areas off-limit. If IPCC gas reserves (Fig. **S12**) are underestimated, the IPCC case in Fig. (**6**) remains valid if the additional gas reserves are used at facilities where CO_2 is captured.

However, even with phase-out of coal emissions and assuming IPCC oil and gas reserves, CO_2 would remain above 350 ppm for more than two centuries. Ongoing Arctic and ice sheet changes, examples of rapid paleoclimate change, and other criteria cited above all drive us to consider scenarios that bring CO_2 more rapidly back to 350 ppm or less.

4.4. Policy Relevance

Desire to reduce airborne CO_2 raises the question of whether CO_2 could be drawn from the air artificially. There are no large-scale technologies for CO_2 air capture now, but

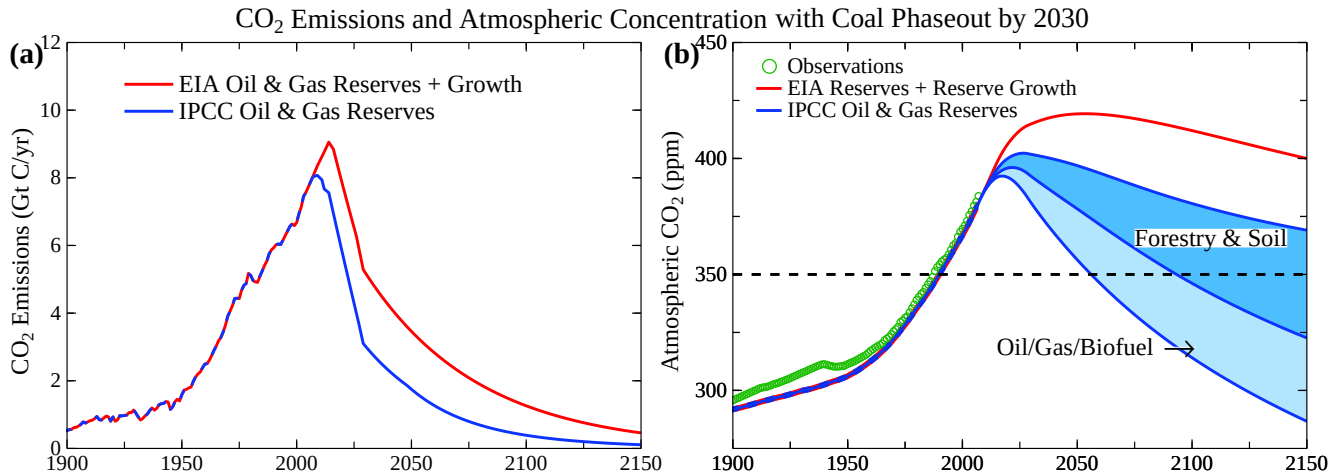

Fig. (6). (**a**) Fossil fuel CO_2 emissions with coal phase-out by 2030 based on IPCC [2] and EIA [80] estimated fossil fuel reserves. (**b**) Resulting atmospheric CO_2 based on use of a dynamic-sink pulse response function representation of the Bern carbon cycle model [78, 79].

with strong research and development support and industrial-scale pilot projects sustained over decades it may be possible to achieve costs ~$200/tC [81] or perhaps less [82]. At $200/tC, the cost of removing 50 ppm of CO_2 is ~$20 trillion.

Improved agricultural and forestry practices offer a more natural way to draw down CO_2. Deforestation contributed a net emission of 60±30 ppm over the past few hundred years, of which ~20 ppm CO_2 remains in the air today [2, 83] (Figs. (**S12**, **S14**). Reforestation could absorb a substantial fraction of the 60±30 ppm net deforestation emission.

Carbon sequestration in soil also has significant potential. Biochar, produced in pyrolysis of residues from crops, forestry, and animal wastes, can be used to restore soil fertility while storing carbon for centuries to millennia [84]. Biochar helps soil retain nutrients and fertilizers, reducing emissions of GHGs such as N_2O [85]. Replacing slash-and-burn agriculture with slash-and-char and use of agricultural and forestry wastes for biochar production could provide a CO_2 drawdown of ~8 ppm or more in half a century [85].

In the Supplementary Material Section we define a forest/soil drawdown scenario that reaches 50 ppm by 2150 (Fig. **6b**). This scenario returns CO_2 below 350 ppm late this century, after about 100 years above that level.

More rapid drawdown could be provided by CO_2 capture at power plants fueled by gas and biofuels [86]. Low-input high-diversity biofuels grown on degraded or marginal lands, with associated biochar production, could accelerate CO_2 drawdown, but the nature of a biofuel approach must be carefully designed [85, 87-89].

A rising price on carbon emissions and payment for carbon sequestration is surely needed to make drawdown of airborne CO_2 a reality. A 50 ppm drawdown *via* agricultural and forestry practices seems plausible. But if most of the CO_2 in coal is put into the air, no such "natural" drawdown of CO_2 to 350 ppm is feasible. Indeed, if the world continues on a business-as-usual path for even another decade without initiating phase-out of unconstrained coal use, prospects for avoiding a dangerously large, extended overshoot of the 350 ppm level will be dim.

4.5. Caveats: Climate Variability, Climate Models, and Uncertainties

Climate has great variability, much of which is unforced and unpredictable [2, 90]. This fact raises a practical issue: what is the chance that climate variations, e.g., a temporary cooling trend, will affect public recognition of climate change, making it difficult to implement mitigation policies? Also what are the greatest uncertainties in the expectation of a continued global warming trend? And what are the impacts of climate model limitations, given the inability of models to realistically simulate many aspects of climate change and climate processes?

The atmosphere and ocean exhibit coupled nonlinear chaotic variability that cascades to all time scales [91]. Variability is so large that the significance of recent decadal global temperature change (Fig. **7a**) would be very limited, if the data were considered simply as a time series, without further information. However, other knowledge includes information on the causes of some of the temperature variability, the planet's energy imbalance, and global climate forcings.

The El Nino Southern Oscillation (ENSO) [94] accounts for most low latitude temperature variability and much of the global variability. The global impact of ENSO is coherent from month to month, as shown by the global-ocean-mean SST (Fig. **7b**), for which the ocean's thermal inertia minimizes the effect of weather noise. The cool anomaly of 2008 coincides with an ENSO minimum and does not imply a change of decadal temperature trend.

Decadal time scale variability, such as predicted weakening of the Atlantic overturning circulation [95], could interrupt global warming, as discussed in section 18 of the Supplementary Material. But the impact of regional dynamical effects on global temperature is opposed by the planet's energy imbalance [96], a product of the climate system's thermal inertia, which is confirmed by increasing ocean heat

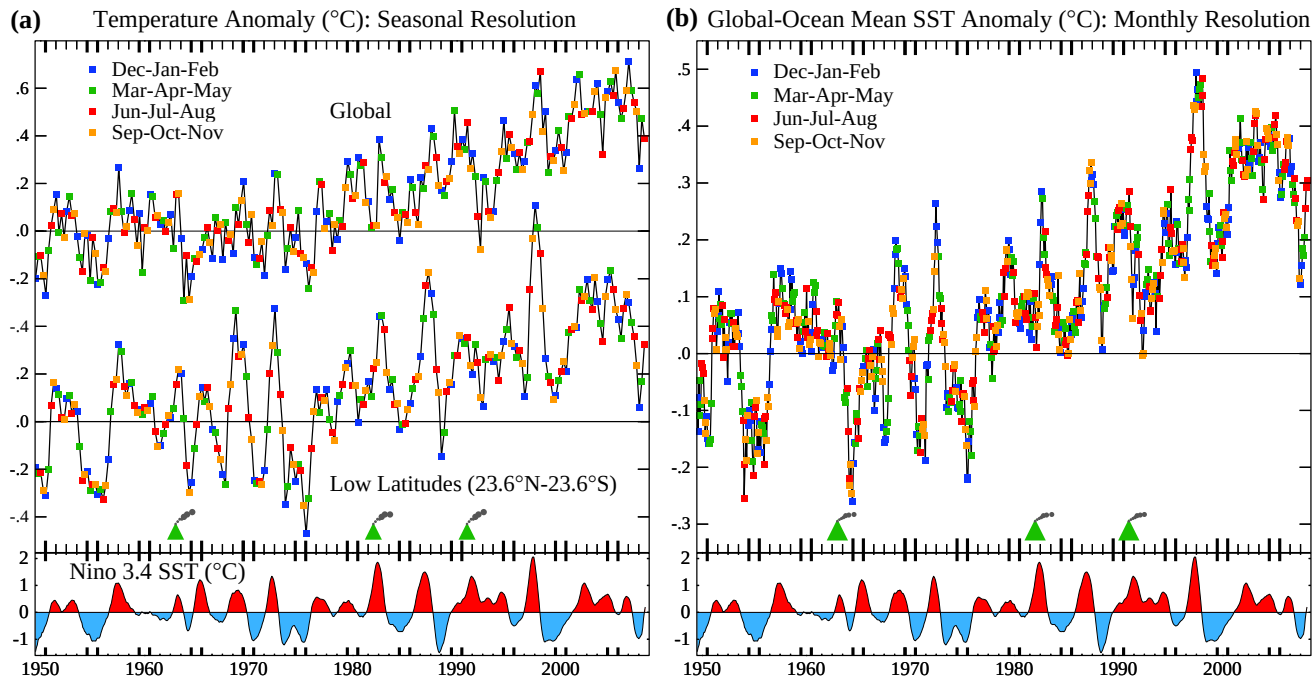

Fig. (7). (**a**) Seasonal-mean global and low-latitude surface temperature anomalies relative to 1951-1980, an update of [92], (**b**) global-ocean-mean sea surface temperature anomaly at monthly resolution. The Nino 3.4 Index, the temperature anomaly (12-month running mean) in a small part of the tropical Pacific Ocean [93], is a measure of ENSO, a basin-wide sloshing of the tropical Pacific Ocean [94]. Green triangles show major volcanic eruptions.

storage [97]. This energy imbalance makes decadal interruption of global warming, in the absence of a negative climate forcing, improbable [96].

Volcanoes and the sun can cause significant negative forcings. However, even if the solar irradiance remained at its value in the current solar minimum, this reduced forcing would be offset by increasing CO_2 within seven years (Supplementary Material section 18). Human-made aerosols cause a greater negative forcing, both directly and through their effects on clouds. The first satellite observations of aerosols and clouds with accuracy sufficient to quantify this forcing are planned to begin in 2009 [98], but most analysts anticipate that human-made aerosols will decrease in the future, rather than increase further.

Climate models have many deficiencies in their abilities to simulate climate change [2]. However, model uncertainties cut both ways: it is at least as likely that models underestimate effects of human-made GHGs as overestimate them (Supplementary Material section 18). Model deficiencies in evaluating tipping points, the possibility that rapid changes can occur without additional climate forcing [63, 64], are of special concern. Loss of Arctic sea ice, for example, has proceeded more rapidly than predicted by climate models [99]. There are reasons to expect that other nonlinear problems, such as ice sheet disintegration and extinction of interdependent species and ecosystems, also have the potential for rapid change [39, 63, 64].

5. SUMMARY

Humanity today, collectively, must face the uncomfortable fact that industrial civilization itself has become the principal driver of global climate. If we stay our present course, using fossil fuels to feed a growing appetite for energy-intensive life styles, we will soon leave the climate of the Holocene, the world of prior human history. The eventual response to doubling pre-industrial atmospheric CO_2 likely would be a nearly ice-free planet, preceded by a period of chaotic change with continually changing shorelines.

Humanity's task of moderating human-caused global climate change is urgent. Ocean and ice sheet inertias provide a buffer delaying full response by centuries, but there is a danger that human-made forcings could drive the climate system beyond tipping points such that change proceeds out of our control. The time available to reduce the human-made forcing is uncertain, because models of the global system and critical components such as ice sheets are inadequate. However, climate response time is surely less than the atmospheric lifetime of the human-caused perturbation of CO_2. Thus remaining fossil fuel reserves should not be exploited without a plan for retrieval and disposal of resulting atmospheric CO_2.

Paleoclimate evidence and ongoing global changes imply that today's CO_2, about 385 ppm, is already too high to maintain the climate to which humanity, wildlife, and the rest of the biosphere are adapted. Realization that we must reduce the current CO_2 amount has a bright side: effects that had begun to seem inevitable, including impacts of ocean acidification, loss of fresh water supplies, and shifting of climatic zones, may be averted by the necessity of finding an energy course beyond fossil fuels sooner than would otherwise have occurred.

We suggest an initial objective of reducing atmospheric CO_2 to 350 ppm, with the target to be adjusted as scientific understanding and empirical evidence of climate effects accumulate. Although a case already could be made that the eventual target probably needs to be lower, the 350 ppm target is sufficient to qualitatively change the discussion and drive fundamental changes in energy policy. Limited opportunities for reduction of non-CO_2 human-caused forcings are important to pursue but do not alter the initial 350 ppm CO_2 target. This target must be pursued on a timescale of decades, as paleoclimate and ongoing changes, and the ocean response time, suggest that it would be foolhardy to allow CO_2 to stay in the dangerous zone for centuries.

A practical global strategy almost surely requires a rising global price on CO_2 emissions and phase-out of coal use except for cases where the CO_2 is captured and sequestered. The carbon price should eliminate use of unconventional fossil fuels, unless, as is unlikely, the CO_2 can be captured. A reward system for improved agricultural and forestry practices that sequester carbon could remove the current CO_2 overshoot. With simultaneous policies to reduce non-CO_2 greenhouse gases, it appears still feasible to avert catastrophic climate change.

Present policies, with continued construction of coal-fired power plants without CO_2 capture, suggest that decision-makers do not appreciate the gravity of the situation. We must begin to move now toward the era beyond fossil fuels. Continued growth of greenhouse gas emissions, for just another decade, practically eliminates the possibility of near-term return of atmospheric composition beneath the tipping level for catastrophic effects.

The most difficult task, phase-out over the next 20-25 years of coal use that does not capture CO_2, is Herculean, yet feasible when compared with the efforts that went into World War II. The stakes, for all life on the planet, surpass those of any previous crisis. The greatest danger is continued ignorance and denial, which could make tragic consequences unavoidable.

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Supplementary Material

1. ICE AGE CLIMATE FORCINGS

Fig. (**S1**) shows the climate forcings during the depth of the last ice age, 20 ky BP, relative to the Holocene [14]. The largest contribution to the uncertainty in the calculated 3.5 W/m^2 forcing due to surface changes (ice sheet area, vegetation distribution, shoreline movements) is due to uncertainty in the ice sheet sizes [14, S1]. Formulae for the GHG forcings [20] yield 2.25 W/m^2 for CO_2 (185 ppm → 275 ppm), 0.43 W/m^2 for CH_4 (350 → 675 ppb) and 0.32 W/m^2 for N_2O (200 → 270 ppb). The CH_4 forcing includes a factor 1.4 to account for indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor [12].

The climate sensitivity inferred from the ice age climate change (~¾°C per W/m^2) includes only fast feedbacks, such as water vapor, clouds, aerosols (including dust) and sea ice. Ice sheet size and greenhouse gas amounts are specified boundary conditions in this derivation of the fast-feedback climate sensitivity.

It is permissible, alternatively, to specify aerosol changes as part of the forcing and thus derive a climate sensitivity that excludes the effect of aerosol feedbacks. That approach was used in the initial empirical derivation of climate sensitivity from Pleistocene climate change [14]. The difficulty with that approach is that, unlike long-lived GHGs, aerosols are distributed heterogeneously, so it is difficult to specify aerosol changes accurately. Also the forcing is a sensitive function of aerosol single scatter albedo and the vertical distribution of aerosols in the atmosphere, which are not measured. Furthermore, the aerosol indirect effect on clouds also depends upon all of these poorly known aerosol properties.

One recent study [S2] specified an arbitrary glacial-interglacial aerosol forcing slightly larger than the GHG glacial-interglacial forcing. As a result, because temperature, GHGs, and aerosol amount, overall, are positively correlated in glacial-interglacial changes, this study inferred a climate sensitivity of only ~2°C for doubled CO_2. This study used the correlation of aerosol and temperature in the Vostok ice core at two specific times to infer an aerosol forcing for a given aerosol amount. The conclusions of the study are immediately falsified by considering the full Vostok aerosol record (Fig. **2** of [17]), which reveals numerous large aerosol fluctuations without any corresponding temperature change. In contrast, the role of GHGs in climate change is confirmed when this same check is made for GHGs (Fig. **2**), and the fast-feedback climate sensitivity of 3°C for doubled CO_2 is confirmed (Fig. **1**).

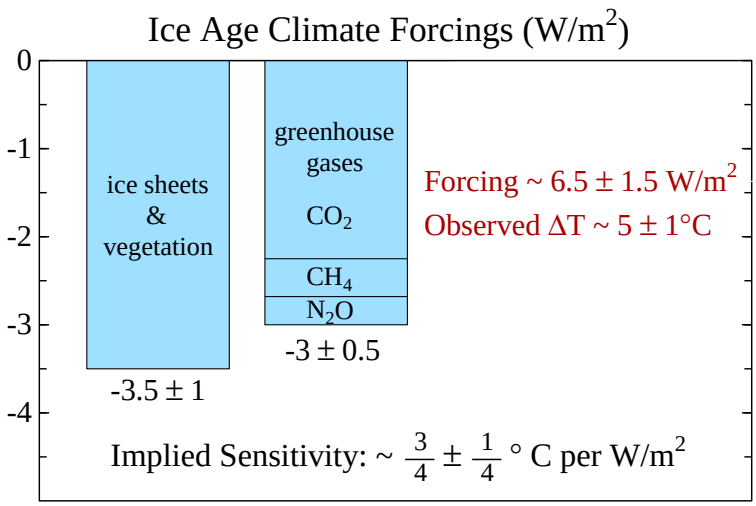

Fig. (S1). Climate forcings during ice age 20 ky BP, relative to the present (pre-industrial) interglacial period.

All the problems associated with imprecise knowledge of aerosol properties become moot if, as is appropriate, aerosols are included in the fast feedback category. Indeed, soil dust, sea salt, dimethylsulfide, and other aerosols are expected to vary (in regional, inhomogeneous ways) as climate changes. Unlike long-lived GHGs, global aerosol amounts cannot be inferred from ice cores. But the effect of aerosol changes is fully included in observed global temperature change. The climate sensitivity that we derive in Fig. (**S1**) includes the aerosol effect accurately, because both the climate forcings and the global climate response are known. The indirect effect of aerosol change on clouds is, of course, also included precisely.

2. CLIMATE FORCINGS AND CLIMATE FEEDBACKS

The Earth's temperature at equilibrium is such that the planet radiates to space (as heat, i.e., infrared radiation) the same amount of energy that it absorbs from the sun, which is ~240 W/m^2. A blackbody temperature of ~255°K yields a heat flux of 240 W/m^2. Indeed, 255°K is the temperature in the mid-troposphere, the mean level of infrared emission to space.

A climate forcing is a perturbation to the planet's energy balance, which causes the Earth's temperature to change as needed to restore energy balance. Doubling atmospheric CO_2 causes a planetary energy imbalance of ~4 W/m^2, with more energy

coming in than going out. Earth's temperature would need to increase by ΔT_O = 1.2-1.3°C to restore planetary energy balance, if the temperature change were uniform throughout the atmosphere and if nothing else changed.

Actual equilibrium temperature change in response to any forcing is altered by feedbacks that can amplify or diminish the response, thus the mean surface temperature change is [14]

$$\begin{aligned}\Delta T_{eq} &= f\,\Delta T_O \\ &= \Delta T_O + \Delta T_{feedbacks} \\ &= \Delta T_O + \Delta T_1 + \Delta T_2 + \ldots,\end{aligned}$$

where f is the net feedback factor and the ΔT_i are increments due to specific feedbacks.

The role of feedback processes is clarified by defining the gain, g,

$$\begin{aligned}g &= \Delta T_{feedbacks}/\Delta T_{eq} \\ &= (\Delta T_1 + \Delta T_2 + \ldots)/\Delta T_{eq} \\ &= g_1 + g_2 + \ldots\end{aligned}$$

g_i is positive for an amplifying feedback and negative for a feedback that diminishes the response. The additive nature of the g_i, unlike f_i, is a useful characteristic of the gain. Evidently

$$f = 1/(1 - g)$$

The value of g (or f) depends upon the climate state, especially the planetary temperature. For example, as the planet becomes so warm that land ice disappears, the land ice albedo feedback diminishes, i.e. $g_{land\ ice\ albedo} \rightarrow 0$.

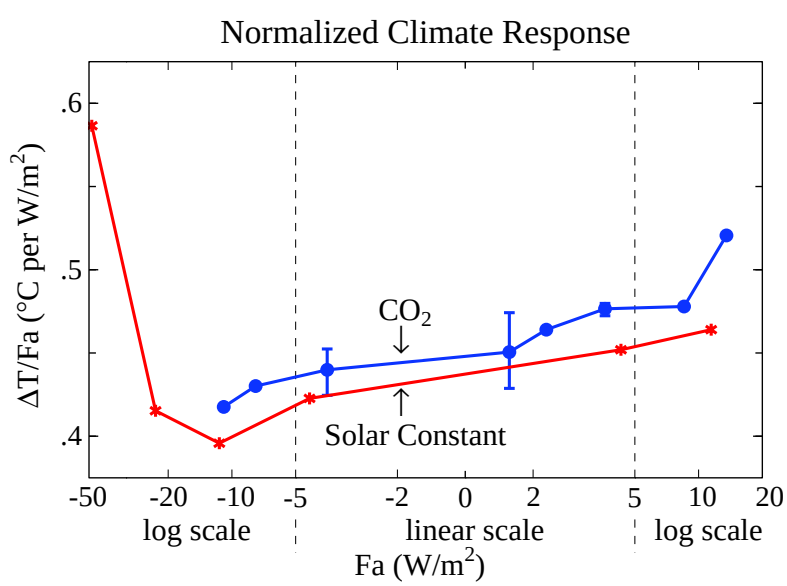

Fig. (S2). Global surface air temperature change [12] after 100 years in simulations with the Goddard Institute for Space Studies modelE [S3, 5] as a function of climate forcing for changes of solar irradiance and atmospheric CO_2. Fa is the standard adjusted climate forcing [12]. Results are extracted from Fig. (**25a**) of [12]. Curves terminate because the climate model 'bombs' at the next increment of forcing due to failure of one or more of the parameterizations of processes in the model as extreme conditions are approached.

'Fast feedbacks', such as water vapor, clouds and sea ice, are the mechanisms usually included in the 'Charney' [13] climate sensitivity. Climate models yield a Charney (fast feedback) sensitivity of about 3°C for doubled CO_2 [2, 12], a conclusion that is confirmed and tightened by empirical evidence from the Pleistocene (Section 2.1). This sensitivity implies

$$g_{fast\ feedbacks} \sim 0.5\text{-}0.6.$$

This fast feedback gain and climate sensitivity apply to the present climate and climate states with global temperatures that are not too different than at present.

If g approaches unity, $f \rightarrow \infty$, implying a runaway climate instability. The possibility of such instability is anticipated for either a very warm climate (runaway greenhouse effect [S4]) or a very cold climate (snowball Earth [S5]). We can investigate how large a climate forcing is needed to cause $g \rightarrow 1$ using a global climate model that includes the fast feedback processes, because both of these instabilities are a result of the temperature dependence of 'fast feedbacks' (the water vapor and ice/snow albedo feedbacks, respectively).

Fig. (**S2**) suggests that climate forcings ~10-25 W/m^2 are needed to approach either runaway snowball-Earth conditions or the runaway greenhouse effect. More precise quantification requires longer simulations and improved parameterizations of physical processes as extreme climates are approached. The processes should include slow feedbacks that can either amplify or diminish the climate change.

Earth has experienced snowball conditions [S5], or at least a 'slushball' state [S6] with ice reaching sea level in the tropics, on at least two occasions, the most recent ~640 My BP, aided by reduced solar irradiance [43] and favorable continental locations. The mechanism that allowed Earth to escape the snowball state was probably reduced weathering in a glaciated world, which allowed CO_2 to accumulate in the atmosphere [S5]. Venus, but not Earth, has experienced the runaway greenhouse effect, a state from which there is no escape.

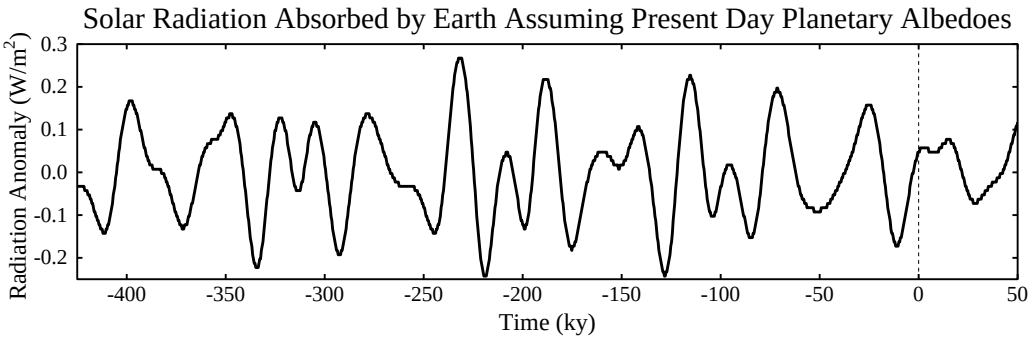

Fig. (S3). Annual-mean global-mean perturbation of the amount of solar radiation absorbed by the Earth, calculated by assuming present-day seasonal and geographical distribution of albedo.

3. PLEISTOCENE FORCINGS AND FEEDBACKS

Fig. (**S3**) shows the perturbation of solar radiation absorbed by the Earth due to changes in Earth orbital elements, i.e., the tilt of the Earth's spin axis relative to the orbital plane, the eccentricity of the Earth's orbit, and the time of year at which the Earth is closest to the sun (precession of equinoxes). This perturbation is calculated using fixed (present day) seasonal and geographical distribution of planetary albedo.

The global-mean annual-mean orbital (Milankovitch) forcing is very weak, at most a few tenths of 1 W/m^2. Our procedure in calculating the forcing, keeping ice sheet properties (size and albedo) fixed, is appropriate for 'instantaneous' and 'adjusted' radiative forcings [12].

Further, successive, definitions of the orbital 'forcing', e.g., allowing some regional response to the seasonal insolation perturbations, may be useful for the purpose of understanding glacial-interglacial climate change. For example, it may be informative to calculate the 'forcing' due to insolation-induced changes of ice-she*et al*bedo, because increased insolation can 'age' (increase snow crystal size and thus darken) an ice surface and also spur the date of first snow-melt [7]. However, one merit of the standard forcing definition is the insight that glacial-interglacial climate swings are almost entirely due to feedbacks.

Indeed, the gain during the Pleistocene is close to unity. Climate models and empirical evaluation from the climate change between the last ice age (Section 2.1 above) yield $g_{\text{fast feedbacks}}$ ~0.5-0.6 (the gain corresponding to fast feedback climate sensitivity 3°C for doubled CO_2). GHGs and surface albedo contribute about equally to glacial-interglacial 'forcings' and temperature change, with each having gain ~0.2 [14]. Thus

$$g = g_{\text{fast feedbacks}} + g_{\text{surface albedo}} + g_{\text{GHG}}$$
$$= \sim 0.5\text{-}0.6 + \sim 0.2 + \sim 0.2.$$

Thus climate gain in the Pleistocene was greater than or of the order of 0.9. It is no wonder that late Cenozoic climate fluctuated so greatly (Fig. **3b**). When substantial ice is present on the planet, g is close to unity, climate is sensitive, and large climate swings occur in response to small orbital forcings. Indeed, with g near unity any forcing or climate noise can cause large climate change, consistent with the conclusion that much of climate variability is not due to orbital forcings [S7]. In the early Cenozoic there was little ice, $g_{\text{surface albedo}}$ was small, and thus climate oscillations due to insolation perturbations were smaller.

It may be useful to divide inferences from Pleistocene climate change into two categories: (1) well-defined conclusions about the nature of the climate change, (2) less certain suggestions about the nature and causes of the climate change. The merit of identifying well-defined conclusions is that they help us predict likely consequences of human-made climate forcings. Less certain aspects of Pleistocene climate change mainly concern the small forcings that instigated climate swings. The small forcings are of great interest to paleoclimatologists, but they need not prevent extraction of practical implications from Pleistocene climate change.

Two fundamental characteristics of Pleistocene climate change are clear. First, there is the high gain, at least of the order of 0.9, i.e., the high sensitivity to a climate forcing, when the planet is in the range of climates that existed during the Pleistocene. Second, we have a good knowledge of the amplifying feedbacks that produce this high gain. Fast feedbacks, including water vapor, clouds, aerosols, sea ice and snow, contribute at least half of this gain. The remainder of the amplification is provided almost entirely by two factors: surface albedo (mainly ice sheets) and GHGs (mainly CO_2).

Details beyond these basic conclusions are less certain. The large glacial-interglacial surface albedo and GHG changes should lag global temperature, because they are feedbacks on global temperature on the global spatial scale and millennial time scale. The lag of GHGs after temperature change is several hundred years (Fig. **6** of [6]), perhaps determined by the ocean overturning time. Ice sheet changes may lag temperature by a few millennia [24], but it has been argued that there is no discernible lag between insolation forcing and the maximum rate of change of ice sheet volume [7].

A complication arises from the fact that some instigating factors (forcing mechanisms) for Pleistocene climate change also involve surface albedo and GHG changes. Regional anomalies of seasonal insolation are as much as many tens of W/m^2. The global forcing is small (Fig. **S3**) because the local anomalies are nearly balanced by anomalies of the opposite sign in either the opposite hemisphere or the opposite season. However, one can readily imagine climate change mechanisms that operate in such a way that cancellation does not occur.

For example, it has been argued [7] that a positive insolation anomaly in late spring is most effective for causing ice sheet disintegration because early 'albedo flip', as the ice becomes wet, yields maximum extension of the melt season. It is unlikely that the strong effect of albedo flip on absorbed solar energy could be offset by a negative insolation anomaly at other times of year.

A second example is non-cancellation of hemispheric insolation anomalies. A hemispheric asymmetry occurs when Earth is cold enough that ice sheets extend to Northern Hemisphere middle latitudes, due to absence of similar Southern Hemisphere land. It has been argued [7] that this hemispheric asymmetry is the reason that the orbital periodicities associated with precession of the equinoxes and orbit eccentricity became substantial about 1 million years ago.

Insolation anomalies also may directly affect GHG amounts, as well as surface albedo. One can readily imagine ways in which insolation anomalies affect methane release from wetlands or carbon uptake through biological processes.

Surface albedo and GHG changes that result immediately from insolation anomalies can be defined as climate forcings, as indirect forcings due to insolation anomalies. The question then becomes: what fractions of the known paleo albedo and GHG changes are immediate indirect forcings due to insolation anomalies and what fractions are feedbacks due to global temperature change?

It is our presumption that most of the Pleistocene GHG changes are a slow feedback in response to climate change. This interpretation is supported by the lag of several hundred years between temperature change and greenhouse gas amount (Fig. **6** of [6]). The conclusion that most of the ice area and surface albedo change is also a feedback in response to global temperature change is supported by the fact that the large climate swings are global (Section 5 of Appendix).

Note that our inferred climate sensitivity is not dependent on detailed workings of Pleistocene climate fluctuations. The fast feedback sensitivity of 3°C for doubled CO_2, derived by comparing glacial and interglacial states, is independent of the cause and dynamics of glacial/interglacial transitions.

Climate sensitivity including surface albedo feedback (~6°C for doubled CO_2) is the average sensitivity for the climate range from 35 My ago to the present and is independent of the glacial-interglacial 'wiggles' in Fig. (**3**). Note that climate and albedo changes occurred mainly at points with 'ready' [63] feedbacks: at Antarctic glaciation and (in the past three million years) with expansion of Northern Hemisphere glaciation, which are thus times of high climate sensitivity.

The entire ice albedo feedback from snowball-Earth to ice-free planet (or vice versa) can be viewed as a response to changing global temperature, with wiggles introduced by Milankovitch (orbital) forcings. The average $g_{surface\ albedo}$ for the range from today's climate through Antarctic deglaciation is close to $g_{surface\ albedo} \sim 0.2$, almost as large as in the Pleistocene. Beyond Antarctic deglaciation (i.e., for an ice-free planet) $g_{surface\ albedo} \rightarrow 0$, except for vegetation effects.

For the sake of specificity, let us estimate the effect of slow feedbacks on climate sensitivity. If we round ΔT_O to 1.2°C for doubled CO_2 and the fast feedback gain to $g_{fast\ feedbacks} = 0.6$, then for fast feedbacks alone f = 2.5 and the equilibrium warming is ΔT_{eq} = 3°C. Inclusion of $g_{surface\ albedo} = 0.2$ makes f = 5 and ΔT_{eq} = 6°C, which is the sensitivity if the GHG amount is specified from observations or from a carbon cycle model.

The feedback factor f can approach infinity, i.e., the climate can become unstable. However, instabilities are limited except at the snowball Earth and runaway greenhouse extremes. Some feedbacks have a finite supply, e.g., as when Antarctica becomes fully deglaciated. Also climate change can cause positive feedbacks to decrease or negative feedbacks to come into play.

For example, Fig. (**S2**) suggests that a cooling climate from the present state first reduces the fast feedback gain. This and reduced weathering with glaciation may be reasons that most ice ages did not reach closer to the iceball state. Also there may

be limitations on the ranges of GHG (CO_2, CH_4, N_2O) feedbacks. Empirical values g_{GHG} ~ 0.2 and $g_{surface\ albedo}$ ~ 0.2 were derived as averages relevant to the range of climates that existed in the past several hundred thousand years, and they may not be valid outside that range.

On the other hand, if the forcing becomes large enough, global instabilities are possible. Earth did become cold enough in the past for the snowball-Earth instability. Although the runaway greenhouse effect has not occurred on Earth, solar irradiance is now at its highest level so far, and Fig. (**S2**) suggests that the required forcing for runaway may be only 10-20 W/m^2. If all conventional and unconventional fossil fuels were burned, with the CO_2 emitted to the atmosphere, it is possible that a runaway greenhouse effect could occur, with incineration of life and creation of a permanent Venus-like hothouse Earth. It would take time for the ice sheets to melt, but the melt rate may accelerate as ice sheet disintegration proceeds.

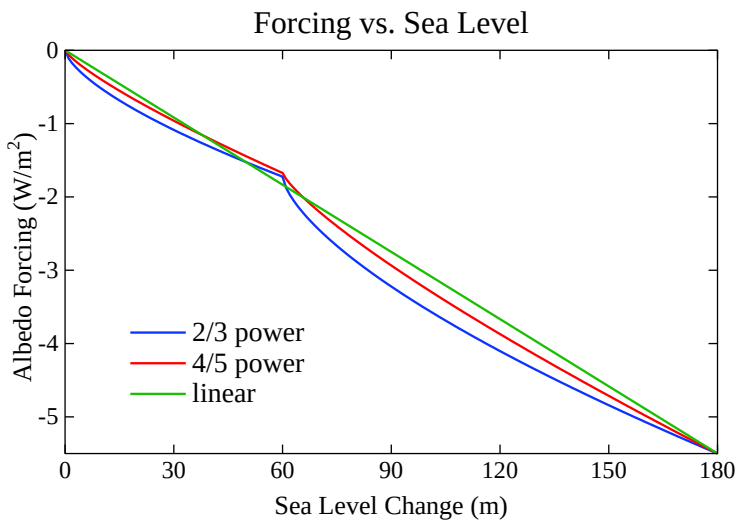

Fig. (S4). Surface albedo climate forcing as a function of sea level for three approximations of the ice sheet area as a function of sea level change, from an ice free planet to the last glacial maximum. For sea level between 0 and 60 m only Antarctica contributes to the albedo change. At the last glacial maximum Antarctica contains 75 m of sea level and the Northern Hemisphere contains 105 m.

4. ICE SHE*ET AL*BEDO

In the present paper we take the surface area covered by an ice sheet to be proportional to the 4/5 power of the volume of the ice sheet, based on ice sheet modeling of one of us (VM-D). We extend the formulation all the way to zero ice on the planet, with separate terms for each hemisphere. At 20 ky ago, when the ice sheets were at or near their maximum size in the Cenozoic era, the forcing by the Northern Hemisphere ice sheet was -3.5 W/m^2 and the forcing by the Southern Hemisphere ice sheet was -2 W/m^2, relative to the ice-free planet [14]. It is assumed that the first 60 m of sea level fall went entirely into growth of the Southern Hemisphere ice sheet. The water from further sea level fall is divided proportionately between hemispheres such that when sea level fall reaches -180 m there is 75 m in the ice sheet of the Southern Hemisphere and 105 m in the Northern Hemisphere.

The climate forcing due to sea level changes in the two hemispheres, SL_S and SL_N, is

$$F_{Albedo}\ (W/m^2) = -\ 2\ (SL_S/75\ m)^{4/5} - 3.5\ (SL_N/105\ m)^{4/5}, \qquad (S1)$$

where the climate forcings due to fully glaciated Antarctica (-2 W/m^2) and Northern Hemisphere glaciation during the last glacial maximum (-3.5 W/m^2) were derived from global climate model simulations [14].

Fig. (**S4**) compares results from the present approach with results from the same approach using exponent 2/3 rather than 4/5, and with a simple linear relationship between the total forcing and sea level change. Use of exponent 4/5 brings the results close to the linear case, suggesting that the simple linear relationship is a reasonably good approximation. The similarity of Fig. (**1c**) in our present paper and Fig. (**2c**) in [7] indicates that change of exponent from 2/3 to 4/5 did not have a large effect.

5. GLOBAL NATURE OF MAJOR CLIMATE CHANGES

Climate changes often begin in a specific hemisphere, but the large climate changes are invariably global, in part because of the global GHG feedback. Even without the GHG feedback, forcings that are located predominately in one hemisphere, such as ice sheet changes or human-made aerosols, still evoke a global response [12], albeit with the response being larger in the hemisphere of the forcing. Both the atmosphere and ocean transmit climate response between hemispheres. The deep ocean can carry a temperature change between hemispheres with little loss, but because of the ocean's thermal inertia there can be a hemispheric lag of up to a millennium (see Ocean Response Time, below).

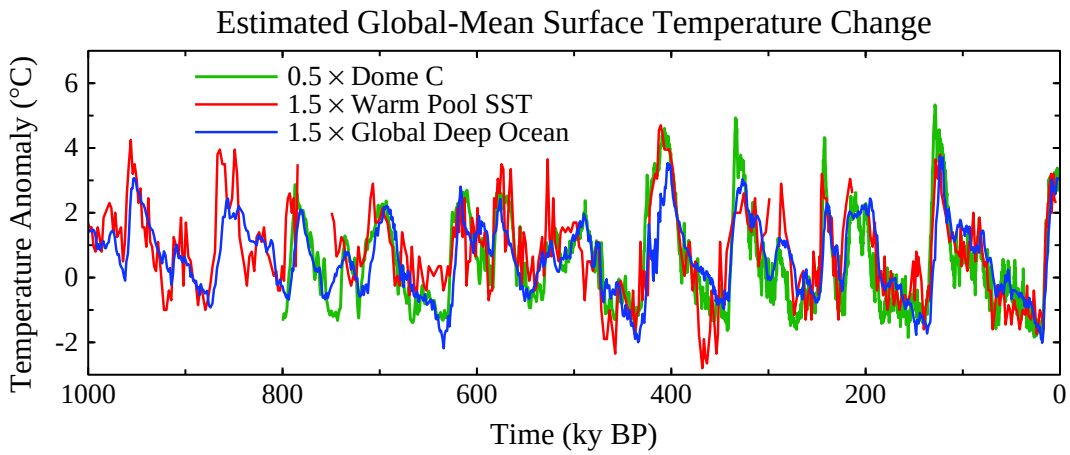

Fig. (S5). Estimated global temperature change based on measurements at a single point or, in the case of the deep ocean, a near-global stack of ocean drilling sites: Antarctica Dome C [S8], Warm Pool [S9], deep ocean [26].

Fig. (**S5**) compares temperature change in Antarctica [S8], the tropical sea surface [S9], and the global deep ocean [26]. Temperature records are multiplied by factors that convert the temperature record to an estimate of global temperature change. Based on paleoclimate records, polar temperature change is typically twice the global average temperature change, and tropical temperature change is about two-thirds of the global mean change. This polar amplification of the temperature change is an expected consequence of feedbacks [14], especially the snow-ice albedo feedback. The empirical result that deep ocean temperature changes are only about two-thirds as large as global temperature change is obtained from data for the Pleistocene epoch, when deep ocean temperature change is limited by its approach to the freezing point.

6. HOLOCENE CLIMATE FORCINGS

The GHG zero-point for the paleo portion of Fig. (**2**) is the mean for 10-8 ky BP, a time that should precede any significant anthropogenic effect on GHG amount. It has been suggested that the increase of CO_2 that began 8000 years ago is due to deforestation and the increase of CH_4 that began 6000 years ago is caused by rice agriculture [62]. This suggestion has proven to be controversial, but regardless of whether late Holocene CO_2 and CH_4 changes are human-made, the GHG forcing is anomalous in that period relative to global temperature change estimated from ocean and ice cores. As discussed elsewhere [7], the late Holocene is the only time in the ice core record in which there is a clear deviation of temperature from that expected due to GHG and surface albedo forcings.

The GHG forcing increase in the second half of the Holocene is ~3/4 W/m^2. Such a large forcing, by itself, would create a planetary energy imbalance that could not be sustained for millennia without causing a large global temperature increase, the expected global warming being about 1°C. Actual global temperature change in this period was small, perhaps a slight cooling. Fig. (**S6**) shows estimates of global temperature change obtained by dividing polar temperature change by two or multiplying tropical and deep ocean temperatures by 1.5. Clearly the Earth has not been warming rapidly in the latter half of the Holocene. Thus a substantial (negative) forcing must have been operating along with the positive GHG forcing.

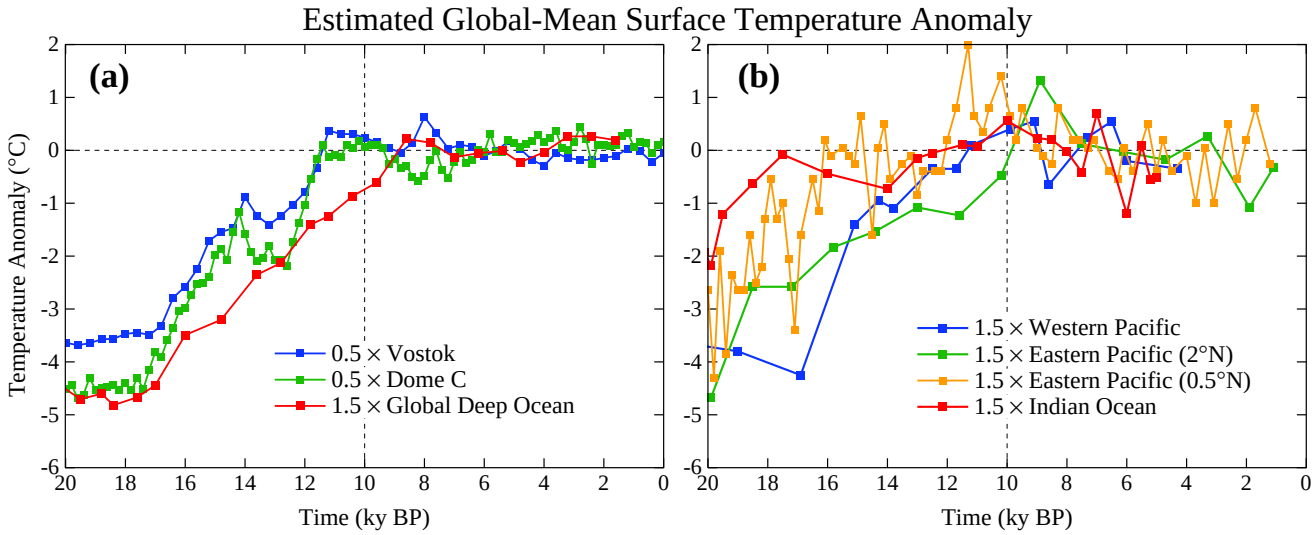

Fig. (S6). Estimates of global temperature change inferred from Antarctic ice cores [18, S8] and ocean sediment cores [S9-S13], as in Fig. (**S5**) but for a period allowing Holocene temperature to be apparent.

Deforestation causes a negative climate forcing [12], but an order of magnitude too small to balance GHG positive forcing. A much larger negative forcing is expected from human-made aerosols. Aerosol forcing is non-linear, especially the indirect effect on clouds, with aerosols added to a pristine atmosphere being more effective than those added to the current highly polluted atmosphere. Given estimates of a negative forcing of 1-2 W/m^2 for today's anthropogenic aerosols [2, 5, 12], a negative aerosol forcing at least of the order of 0.5 W/m^2 in 1850 is expected. We conclude that aerosols probably were the predominant negative forcing that opposed the rapid increase of positive GHG forcing in the late Holocene.

7. OCEAN RESPONSE TIME

Fig. (**S7**) shows the climate response function, defined as the fraction of equilibrium global warming that is obtained as a function of time. This response function was obtained [7] from a 3000-year simulation after instant doubling of atmospheric CO_2, using GISS modelE [S3, 12] coupled to the Russell ocean model [S14]. Note that although 40% of the equilibrium solution is obtained within several years, only 60% is achieved after a century, and nearly full response requires a millennium. The long response time is caused by slow uptake of heat by the deep ocean, which occurs primarily in the Southern Ocean.

This delay of the surface temperature response to a forcing, caused by ocean thermal inertia, is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of water into the deep ocean [31]. The ocean model used for Fig. (**S7**) may mix somewhat too rapidly in the waters around Antarctica, as judged by transient tracers [S14], reducing the simulated surface response on the century time scale. However, this uncertainty does not qualitatively alter the shape of the response function (Fig. **S7**).

When the climate model used to produce Fig. (**S7**) is driven by observed changes of GHGs and other forcings it yields good agreement with observed global temperature and ocean heat storage [5]. The model has climate sensitivity ~3°C for doubled CO_2, in good agreement with the fast-feedback sensitivity inferred from paleoclimate data.

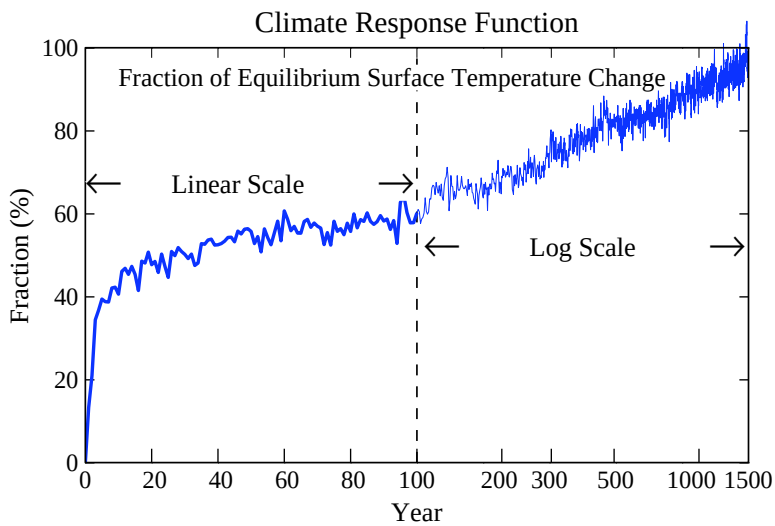

Fig. (S7). Fraction of equilibrium surface temperature response versus time in the GISS climate model [7, 12, S3] with the Russell [S14] ocean. The forcing was doubled atmospheric CO_2. The ice sheets, vegetation distribution and other long-lived GHGs were fixed.

8. SEPARATION OF $\Delta^{18}O$ INTO ICE VOLUME AND TEMPERATURE

$\delta^{18}O$ of benthic (deep ocean dwelling) foraminifera is affected by both deep ocean temperature and continental ice volume. Between 34 My and the last ice age (20 ky) the change of $\delta^{18}O$ was ~ 3, with T_{do} change ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Based on the rate of change of $\delta^{18}O$ with deep ocean temperature in the prior period without land ice, ~ 1.5 of $\delta^{18}O$ is associated with the T_{do} change of ~ 6°C, and we assign the remaining $\delta^{18}O$ change to ice volume linearly at the rate 60 msl per mil $\delta^{18}O$ change (thus 180 msl for $\delta^{18}O$ between 1.75 and 4.75).

Thus we assume that ice sheets were absent when $\delta^{18}O < 1.75$ with sea level 75 msl higher than today. Sea level at smaller values of $\delta^{18}O$ is given by

$$SL\ (m) = 75 - 60 \times (\delta^{18}O - 1.75). \qquad (S2)$$

Fig. (**S8**) shows that the division of $\delta^{18}O$ equally into sea level change and deep ocean temperature captures well the magnitude of the major glacial to interglacial changes.

9. CONTINENTAL DRIFT AND ATMOSPHERIC CO_2

At the beginning of the Cenozoic era 65 My ago the continents were already close to their present latitudes, so the effect of continental location on surface albedo had little direct effect on the planet's energy balance (Fig. **S9**). However, continental drift has a major effect on the balance, or imbalance, of outgassing and uptake of CO_2 by the solid Earth and thus a major effect on atmospheric composition and climate. We refer to the carbon in the air, ocean, soil and biosphere as the combined surface reservoir of carbon, and carbon in ocean sediments and the rest of the crust as the carbon in the 'solid' Earth. Sloshing of CO_2 among the surface reservoirs, as we have shown, is a primary mechanism for glacial-interglacial climate fluctuations. On longer time scales the total amount of carbon in the surface reservoirs can change as a result of any imbalance between outgassing and uptake by the solid Earth.

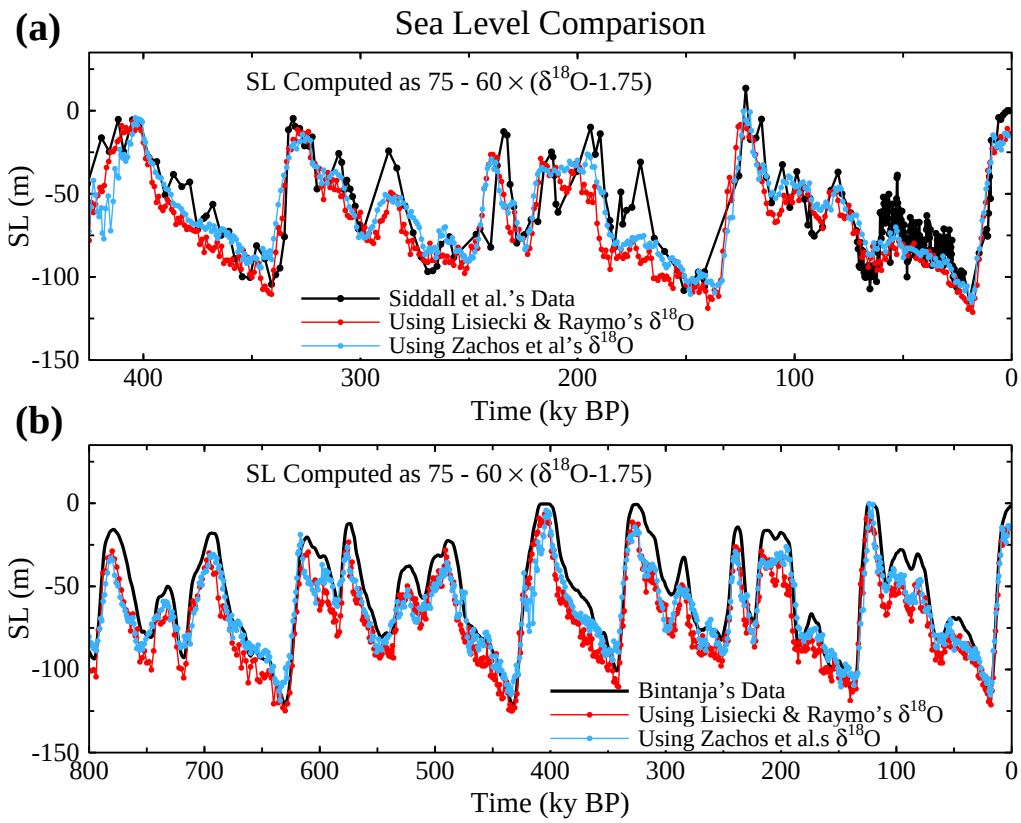

Fig. (S8). (**a**) Comparison of Siddall *et al.* [19] sea level record with sea level computed from $\delta^{18}O$ *via* Eq. S2 using two alternative global benthic stacks [26, S15]. (**b**) Comparison of Bintanja *et al.* [S16] sea level reconstruction with the same global benthic stacks as in (**a**).

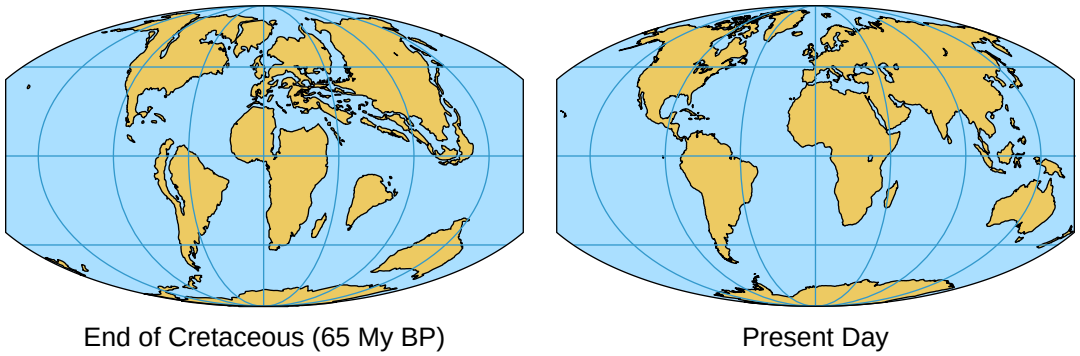

Fig. (S9). Continental locations at the beginning and end of the Cenozoic era [S17].

Outgassing, which occurs mainly in regions of volcanic activity, depends upon the rate at which carbon-rich oceanic crust is subducted beneath moving continental plates [30, 47]. Drawdown of CO_2 from the surface reservoir occurs with weathering of rocks exposed by uplift, with the weathering products carried by rivers to the ocean and eventually deposited as carbonates on the ocean floor [30] and by burial of organic matter. Both outgassing and drawdown of CO_2 are affected by changes in plate tectonics, which thus can alter the amount of carbon in the surface reservoir. The magnitude of the changes of carbon in the surface reservoir, and thus in the atmosphere, is constrained by a negative weathering feedback on the time scale of hundreds of thousands of years [30, 52], but plate tectonics can evoke changes of the surface carbon reservoir by altering the rates of outgassing and weathering.

At the beginning of the Cenozoic the African plate was already in collision with Eurasia, pushing up the Alps. India was still south of the equator, but moving north rapidly through a region with fresh carbonate deposits. It is likely that subduction of carbon rich crust of the Tethys Ocean, long a depocenter for sediments, caused an increase of atmospheric CO_2 and the early Cenozoic warming that peaked ~50 My ago. The period of rapid subduction terminated with the collision of India with Eurasia, whereupon uplift of the Himalayas and the Tibetan Plateau increased weathering rates and drawdown of atmospheric CO_2 [51].

Since 50 My ago the world's major rivers have emptied into the Indian and Atlantic Oceans, but there is little subduction of oceanic crust of these regions that are accumulating sediments [47]. Thus the collision of India with Asia was effective in both reducing a large source of outgassing of CO_2 as well as exposing rock for weathering and drawdown of atmospheric CO_2. The rate of CO_2 drawdown decreases as the CO_2 amount declines because of negative feedbacks, including the effects of temperature and plant growth rate on weathering [30].

10. PROXY CO_2 DATA

There are inconsistencies among the several proxy measures of atmospheric CO_2, including differences between results of investigators using nominally the same reconstruction method. We briefly describe strengths and weaknesses of the four paleo-CO_2 reconstruction methods included in the IPCC report [2], which are shown in Fig. (**S10**) and discussed in detail elsewhere [S18]. The inconsistencies among the different proxies constrain their utility for rigorously evaluating our CO_2 predictions. We also include a comparison of our calculated CO_2 history with results from a version of the Berner [30] geochemical carbon cycle model, as well as a comparison with an emerging CO_2 proxy based on carbon-isotope analyses of nonvascular plant (bryophyte) fossils [S19].

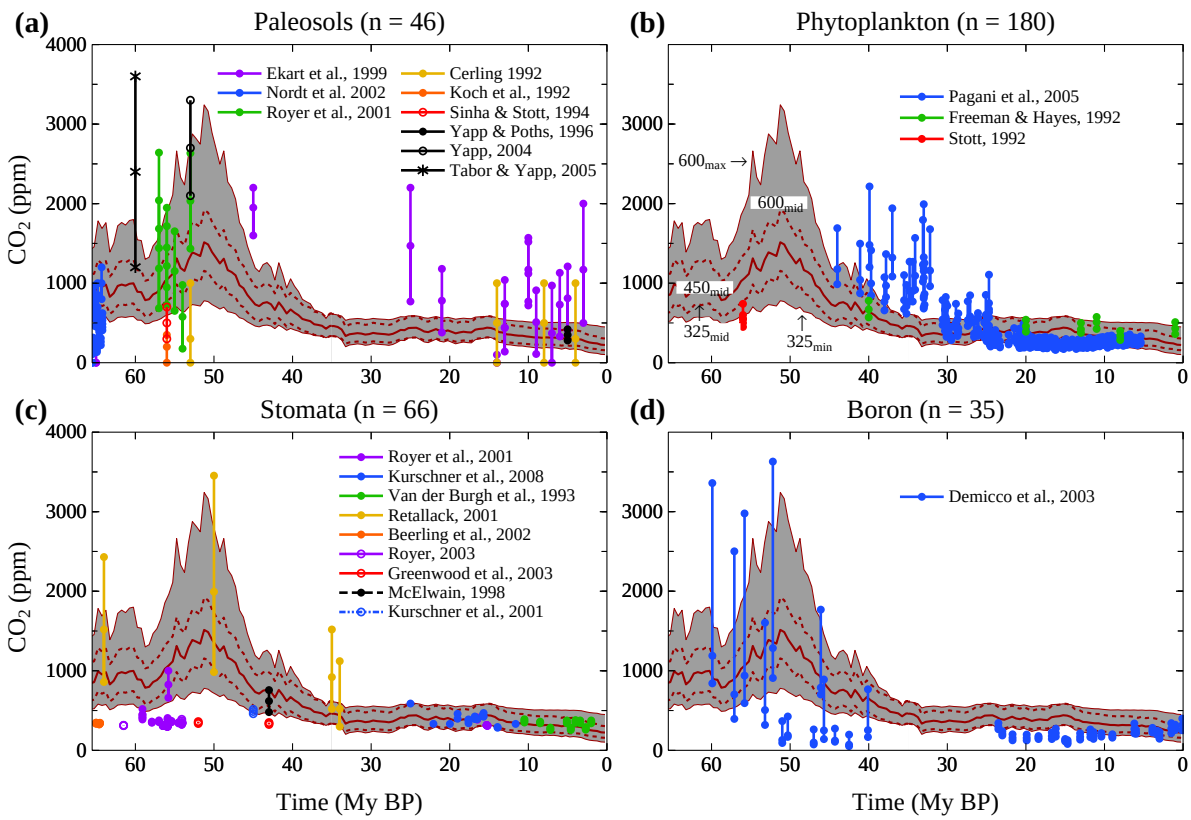

Fig. (S10). Comparison of proxy CO_2 measurements with CO_2 predictions based on deep-ocean temperature, the latter inferred from benthic $\delta^{18}O$. The shaded range of model results is intended mainly to guide the eye in comparing different proxies. The dark central line is for the standard case with CO_2 = 450 ppm at 35 My ago, and the dashed lines are the standard cases for CO_2 = 325 and 600 ppm at 35 My ago. The extremes of the shaded area correspond to the maximum range including a 50% uncertainty in the relation of ΔT_s and ΔT_{do}. Our assumption that CO_2 provides 75% of the GHG throughout the Cenozoic adds additional uncertainty to the predicted CO_2 amount. References for data sources in the legends are provided by Royer [55], except Kurshner *et al.* [S20].

The paleosol method is based on the $\delta^{13}C$ of pedogenic carbonate nodules, whose formation can be represented by a two end-member mixing model between atmospheric CO_2 and soil-derived carbon [S21]. Variables that need to be constrained or assumed include an estimation of nodule depth from the surface of the original soil, the respiration rate of the ecosystem that inhabits the soil, the porosity/diffusivity of the original soil, and the isotopic composition of the vegetation contribution of respired CO_2. The uncertainties in CO_2 estimates with this proxy are substantial at high CO_2 (±500-1000 ppm when CO_2 > 1000 ppm) and somewhat less in the lower CO_2 range (±400-500 ppm when CO_2 < 1000 ppm).

The stomatal method is based on the genetically-controlled relationship [S22] between the proportion of leaf surface cells that are stomata and atmospheric CO_2 concentrations [S23]. The error terms with this method are comparatively small at low CO_2 (< ±50 ppm), but the method rapidly loses sensitivity at high CO_2 (> 500-1000 ppm). Because stomatal-CO_2 relationships are often species-specific, only extant taxa with long fossil records can be used [S24]. Also, because the fundamental response of stomata is to the partial pressure of CO_2 [S25], constraints on paleoelevation are required.

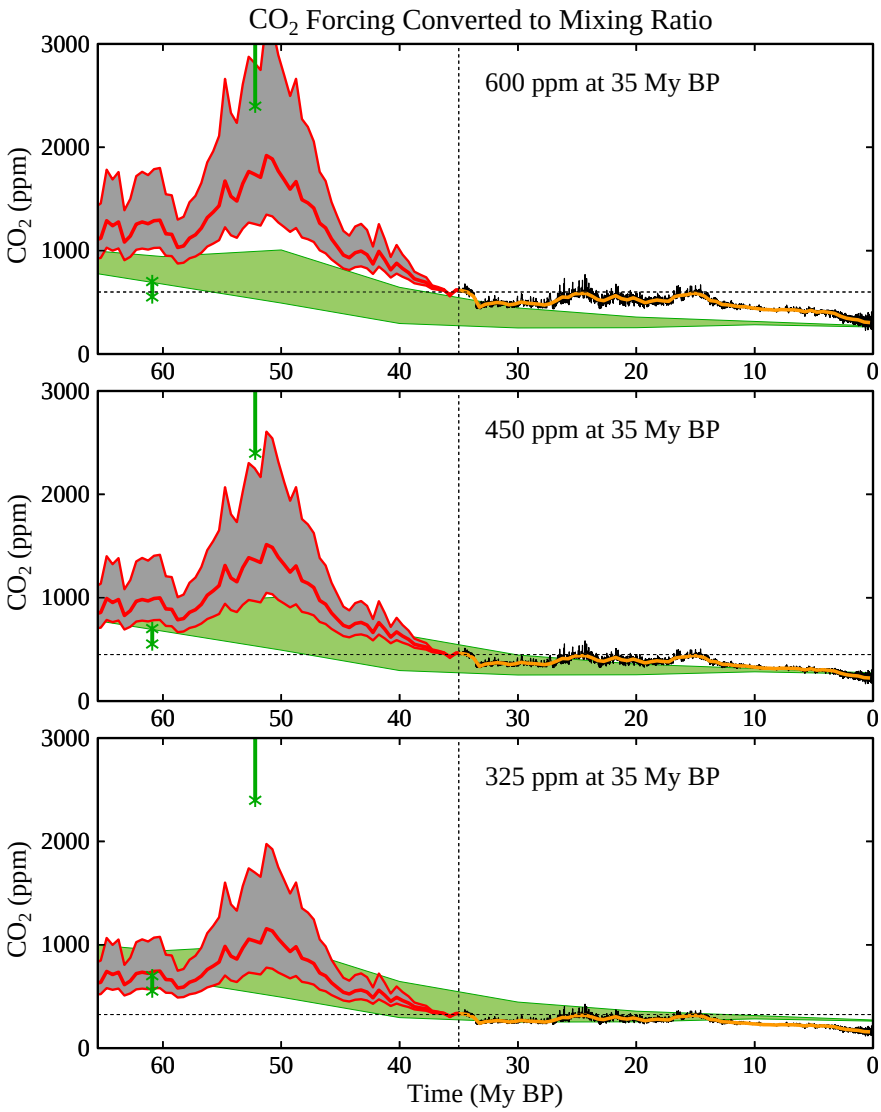

Fig. (S11). Simulated CO_2 in the Cenozoic for three choices of CO_2 amount at 35 My, as in Fig. (**5**), compared with the CO_2 history in a geochemical model [30], specifically the model version described by Fletcher *et al.* [S19]. The green vertical bars are a proxy CO_2 measure [S19] obtained from fossils of non-vascular plants (bryophytes) that is not included among the proxies shown in Fig. (**S10**).

The phytoplankton method is based on the Rayleigh distillation process of fractionating stable carbon isotopes during photosynthesis [S26]. In a high CO_2 environment, for example, there is a higher diffusion rate of CO_2 through phytoplankton cell membranes, leading to a larger available intercellular pool of $CO_{2[aq]}$ and more depleted $\delta^{13}C$ values in photosynthate. Cellular growth rate and cell size also impact the fractionation of carbon isotopes in phytoplankton and thus fossil studies must take these factors into account [S27]. This approach to reconstructing CO_2 assumes that the diffusional transport of CO_2 into the cell dominates, and that any portion of carbon actively transported into the cell remains constant with time. Error terms are typically small at low CO_2 (< ±50 ppm) and increase substantially under higher CO_2 concentrations [S27].

The boron-isotope approach is based on the pH-dependency of the $\delta^{11}B$ of marine carbonate [S28]. This current method assumes that only borate is incorporated in the carbonate lattice and that the fractionation factor for isotope exchange between boric acid and borate in solution is well-constrained. Additional factors that must be taken into account include test dissolution and size, species-specific physiological effects on carbonate $\delta^{11}B$, and ocean alkalinity [S29-S31]. As with the stomatal and phytoplankton methods, error terms are comparatively small at low CO_2 (< ±50 ppm) and the method loses sensitivity at higher CO_2 (> 1000 ppm). Uncertainty is unconstrained for extinct foraminiferal species.

Fig. (**S10**) illustrates the scatter among proxy data sources, which limits inferences about atmospheric CO_2 history. Given the large inconsistency among different data sets in the early Cenozoic, at least some of the data or their interpretations must be flawed. In the range of proxy data shown in Fig. (**5**) we took all data sources as being of equal significance. It seems likely that the low CO_2 values in the early Cenozoic are faulty, but we avoid omission of any data until the matter is clarified, and thus the range of proxy data shown in Fig. (**5**) is based on all data. Reviews of the proxy data [S19, 55] conclude that atmospheric CO_2 amount in the early Cenozoic reached values of at least 500-1000 ppm.

Fig. (**S11**) shows that geochemical carbon cycle modeling [30, S19] is reasonably consistent with our calculated long-term trend of atmospheric CO_2 for the cases with CO_2 at 34 My ago being in the range from about 325 to 450 ppm. The geochemical modeling does not yield a strong maximum of CO_2 at 50 My ago, but the temporal resolution of the modeling (10 My) and the absence of high resolution input data for outgassing due to variations in plate motions tends to mitigate against sharp features in the simulated CO_2.

Fig. (**S11**) also shows (vertical green bars) an emerging CO_2 proxy based on the isotopic composition of fossil liverworts. These non-vascular plants, lacking stomatal pores, have a carbon isotopic fractionation that is strongly CO_2 dependent, reflecting the balance between CO_2 uptake by photosynthesis and inward CO_2 diffusion [S19].

11. CLIMATE SENSITIVITY COMPARISONS

Other empirical or semi-empirical derivations of climate sensitivity from paleoclimate data (Table **S1**) are in reasonable accord with our results, when account is taken of differences in definitions of sensitivity and the periods considered.

Royer *et al*. [56] use a carbon cycle model, including temperature dependence of weathering rates, to find a best-fit doubled CO_2 sensitivity of 2.8°C based on comparison with Phanerozoic CO_2 proxy amounts. Best-fit in their comparison of model and proxy CO_2 data is dominated by the times of large CO_2 in the Phanerozoic, when ice sheets would be absent, not by the times of small CO_2 in the late Cenozoic. Their inferred sensitivity is consistent with our inference of ~3°C for doubled CO_2 at times of little or no ice on the planet.

Higgins and Schrag [57] infer climate sensitivity of ~4°C for doubled CO_2 from the temperature change during the Paleocene-Eocene Thermal Maximum (PETM) ~55 My ago (Fig. **3**), based on the magnitude of the carbon isotope excursion at that time. Their climate sensitivity for an ice-free planet is consistent with ours within uncertainty ranges. Furthermore, recalling that we assume non-CO_2 to provide 25% of the GHG forcing, if one assumes that part of the PETM warming was a direct of effect of methane, then their inferred climate sensitivity is in even closer agreement with ours.

Pagani *et al*. [58] also use the magnitude of the PETM warming and the associated carbon isotopic excursion to discuss implications for climate sensitivity, providing a graphical relationship to help assess alternative assumptions about the origin and magnitude of carbon release. They conclude that the observed PETM warming of about 5°C implies a high climate sensitivity, but with large uncertainty due to imprecise knowledge of the carbon release.

Table S1. Climate Sensitivity Inferred Semi-Empirically from Cenozoic or Phanerozoic Climate Change

Reference	Period	Doubled CO_2 Sensitivity
Royer *et al*. [56]	0-420 My	~ 2.8°C
Higgins and Schrag [57]	PETM	~4°C
Pagani *et al*. [58]	PETM	High

12. GREENHOUSE GAS GROWTH RATES

Fossil fuel CO_2 emissions have been increasing at a rate close to the highest IPCC [S34] scenario (Fig. **S12b**). Increase of CO_2 in the air, however, appears to be in the middle of the IPCC scenarios (Fig. **S12c**, **d**), but as yet the scenarios are too close and interannual variability too large, for assessment. CO_2 growth is well above the "alternative scenario", which was defined with the objective of keeping added GHG forcing in the 21st century at about 1.5 W/m^2 and 21st century global warming less than 1°C [20].

Non-CO_2 greenhouse gases are increasing more slowly than in IPCC scenarios, overall at approximately the rate of the "alternative scenario", based on a review of data through the end of 2007 [69]. There is potential to reduce non-CO_2 forcings below the alternative scenario [69].

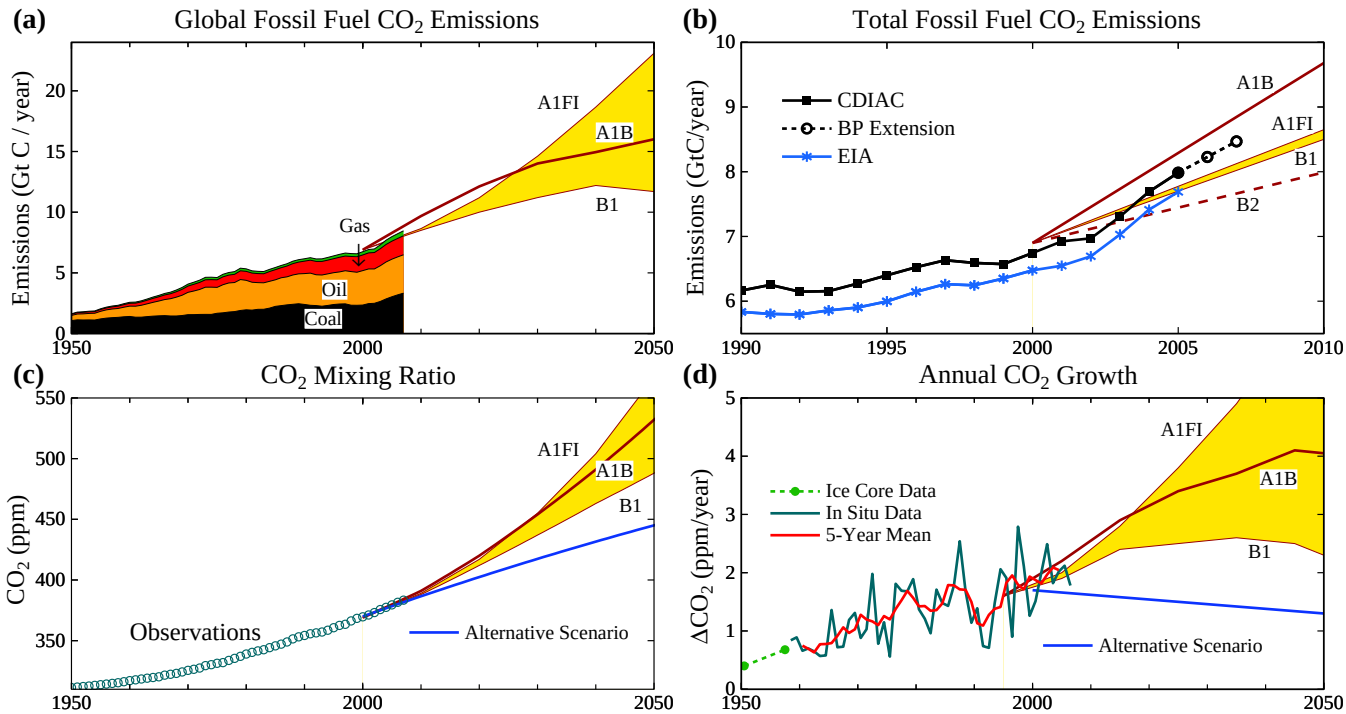

Fig. (S12). (**a**) Fossil fuel CO_2 emissions by fuel type [S32, S33], the thin green sliver being gas flaring plus cement production, and IPCC fossil fuel emissions scenarios, (**b**) expansion global emissions to show recent changes more precisely, the EIA values excluding CO_2 emissions from cement manufacture, (**c**) observed atmospheric CO_2 amount and IPCC and "alternative" scenarios for the future, (**d**) annual atmospheric CO_2 growth rates. Data here is an update of data sources defined in [6]. The yellow area is bounded by scenarios that are most extreme in the second half of the 21st century; other scenarios fall outside this range in the early part of the century.

13. FOSSIL FUEL AND LAND-USE CO_2 EMISSIONS

Fig. (**S13**) shows estimates of anthropogenic CO_2 emissions to the atmosphere. Although fossil emissions through 2006 are known with good accuracy, probably better than 10%, reserves and potential reserve growth are highly uncertain. IPCC [S34] estimates for oil and gas proven reserves are probably a lower limit for future oil and gas emissions, but they are perhaps a feasible goal that could be achieved *via* a substantial growing carbon price that discourages fossil fuel exploration in extreme environments together with national and international policies that accelerate transition to carbon-free energy sources and limit fossil fuel extraction in extreme environments and on government controlled property.

Coal reserves are highly uncertain, but the reserves are surely enough to take atmospheric CO_2 amount far into the region that we assess as being "dangerous". Thus we only consider scenarios in which coal use is phased out as rapidly as possible, except for uses in which the CO_2 is captured and stored so that it cannot escape to the atmosphere. Thus the magnitude of coal reserves does not appreciably affect our simulations of future atmospheric CO_2 amount.

Integrated 1850-2008 net land-use emissions based on the full Houghton [83] historical emissions (Fig. **S14**), extended with constant emissions for the past several years, are 79 ppm CO_2. Although this could be an overestimate by up to a factor of two (see below), substantial pre-1850 deforestation must be added in. Our subjective estimate of uncertainty in the total land-use CO_2 emission is a factor of two.

14. THE MODERN CARBON CYCLE

Atmospheric CO_2 amount is affected significantly not only by fossil fuel emissions, but also by agricultural and forestry practices. Quantification of the role of land-use in the uptake and release of CO_2 is needed to assess strategies to minimize human-made climate effects.

Fig. (**S15**) shows the CO_2 airborne fraction, AF, the annual increase of atmospheric CO_2 divided by annual fossil fuel CO_2 emissions. AF is a critical metric of the modern carbon cycle, because it is based on the two numbers characterizing the global carbon cycle that are well known. AF averages 56% over the period of accurate data, which began with the CO_2 measurements of Keeling in 1957, with no discernable trend. The fact that 44% of fossil fuel emissions seemingly "disappears" immediately provides a hint of optimism with regard to the possibility of stabilizing, or reducing, atmospheric CO_2 amount.

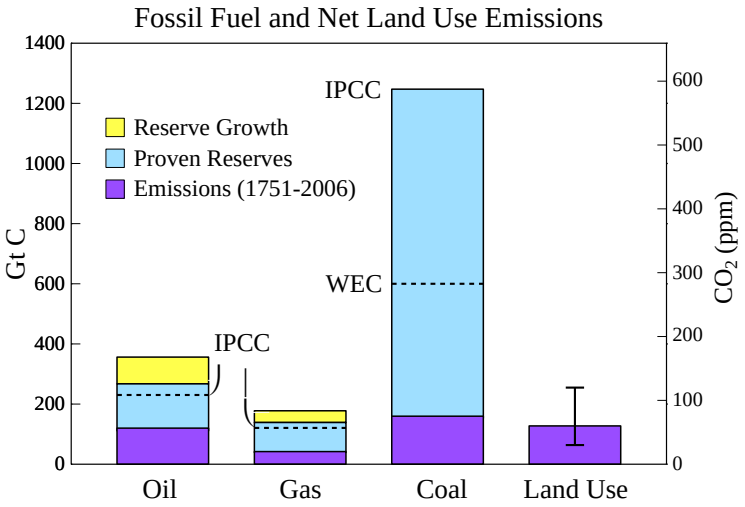

Fig. (S13). Fossil fuel and land-use CO_2 emissions, and potential fossil fuel emissions. Historical fossil fuel emissions are from the Carbon Dioxide Information Analysis Center [CDIAC, S32] and British Petroleum [BP, S33]. Lower limits on oil and gas reserves are from IPCC [S34] and higher limits are from the United States Energy Information Administration [EIA, 80]. Lower limit for coal reserves is from the World Energy Council [WEC, S35] and upper limit from IPCC [S34]. Land use estimate is from integrated emissions of Houghton/2 (Fig. **S14**) supplemented to include pre-1850 and post-2000 emissions; uncertainty bar is subjective.

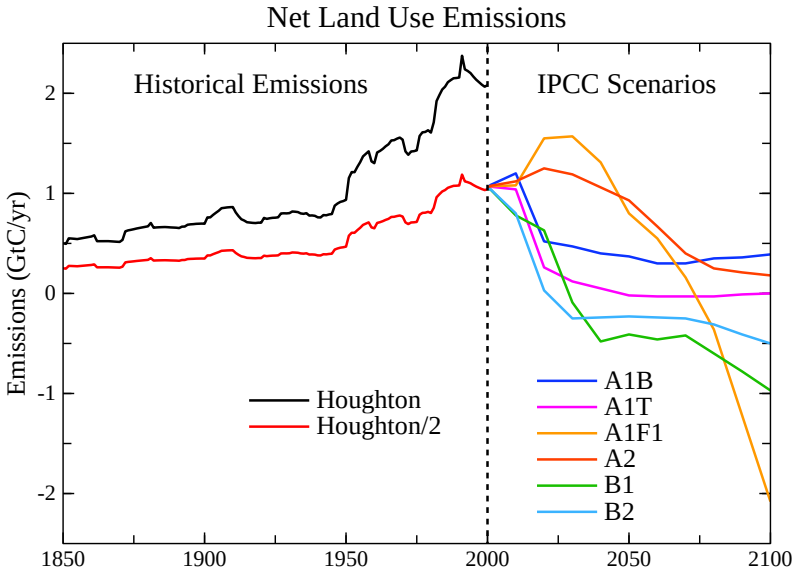

Fig. (S14). Left side: estimate by Houghton [83] of historical net land-use CO_2 emissions, and a 50 percent reduction of that estimate. Right side: IPCC [2] scenarios for land-use CO_2 emissions.

That optimism needs to be tempered, as we will see, by realization of the magnitude of the actions required to halt and reverse CO_2 growth. However, it is equally important to realize that assertions that fossil fuel emissions must be reduced close to 100% on an implausibly fast schedule are not necessarily valid.

A second definition of the airborne fraction, AF2, is also useful. AF2 includes the net anthropogenic land-use emission of CO_2 in the denominator. This AF2 definition of airborne fraction has become common in recent carbon cycle literature. However, AF2 is not an observed or accurately known quantity; it involves estimates of net land-use CO_2 emissions, which vary among investigators by a factor of two or more [2].

Fig. (**S15**) shows an estimate of net land-use CO_2 emissions commonly used in carbon cycle studies, labeled "Houghton" [83], as well as "Houghton/2", a 50% reduction of these land-use emissions. An over-estimate of land-use emissions is one possible solution of the long-standing "missing sink" problem that emerges when the full "Houghton" land-use emissions are employed in carbon cycle models [2, S34, 79].

Principal competing solutions of the "missing sink" paradox are (1) land-use CO_2 emissions are over-estimated by about a factor of two, or (2) the biosphere is being "fertilized" by anthropogenic emissions, *via* some combination of increasing atmospheric CO_2, nitrogen deposition, and global warming, to a greater degree than included in typical carbon cycle models.

Reality may include contributions from both candidate explanations. There is also a possibility that imprecision in the ocean uptake of CO_2, or existence of other sinks such as clay formation, could contribute increased CO_2 uptake, but these uncertainties are believed to be small.

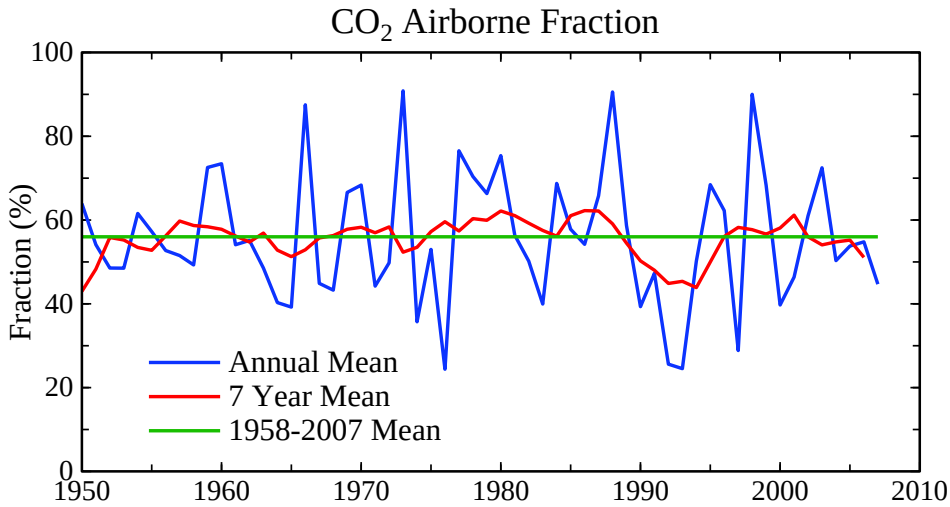

Fig. (S15). CO_2 airborne fraction, AF, the ratio of annual observed atmospheric CO_2 increase to annual fossil fuel CO_2 emissions.

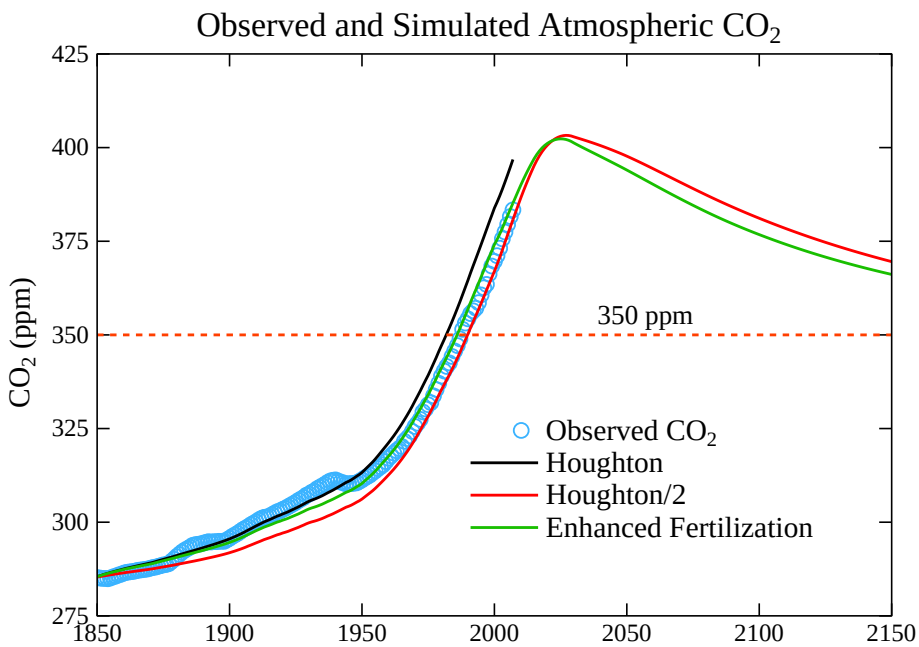

Fig. (S16). Computed and observed time evolution of atmospheric CO_2. "Enhanced Fertilization" uses the full "Houghton" land use emissions for 1850–2000. "Houghton/2" and "Enhanced Fertilization" simulations are extended to 2100 assuming coal phase-out by 2030 and the IPCC [2] A1T land-use scenario. Observations are from Law Dome ice core data and flask and in-situ measurements [6, S36, http://www.esrl.noaa.gov/gmd/ccgg/trends/].

Fig. (**S16**) shows resulting atmospheric CO_2, and Fig. (**S17**) shows AF and AF2, for two extreme assumptions: "Houghton/2" and " Enhanced Fertilization", as computed with a dynamic-sink pulse response function (PRF) representation of the Bern carbon cycle model [78, 79]. Fertilization is implemented *via* a parameterization [78] that can be adjusted to achieve an improved match between observed and simulated CO_2 amount. In the "Houghton/2" simulation the original value [78] of the fertilization parameter is employed while in the "Enhanced Fertilization" simulation the full Houghton emissions are used with a larger fertilization parameter. Both "Houghton/2" and "Enhanced Fertilization" yield good agreement with the observed CO_2 history, but Houghton/2 does a better job of matching the time dependence of observed AF.

It would be possible to match observed CO_2 to an arbitrary precision if we allowed the adjustment to "Houghton" land-use to vary with time, but there is little point or need for that. Fig. (**S16**) shows that projections of future CO_2 do not differ much even for the extremes of Houghton/2 and Enhanced Fertilization. Thus in Fig. (**6**) we show results for only the case Houghton/2, which is in better agreement with the airborne fraction and also is continuous with IPCC scenarios for land use.

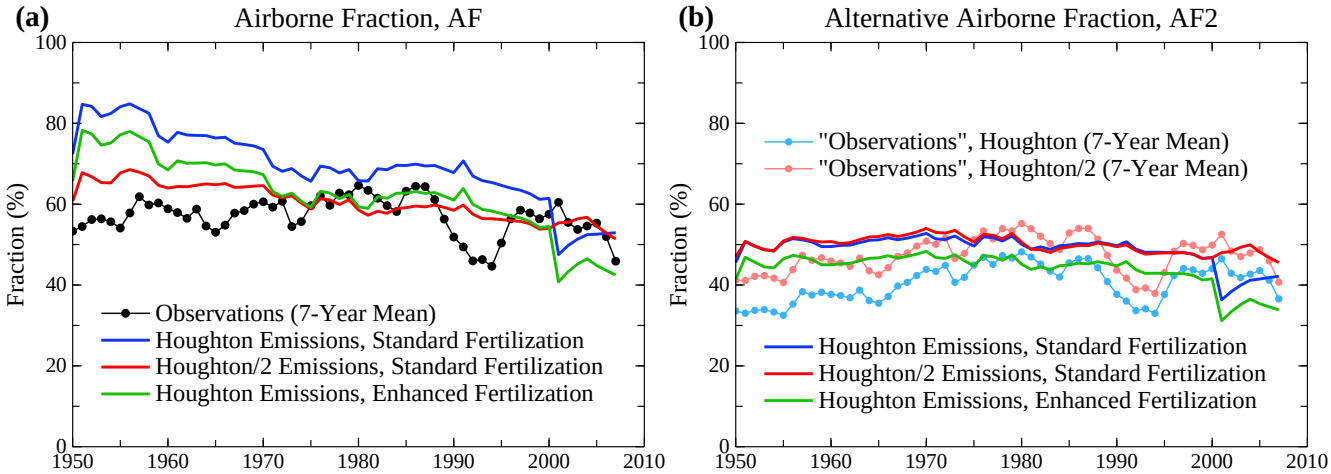

Fig. (S17). (**a**) Observed and simulated airborne fraction (AF), the ratio of annual CO_2 increase in the air over annual fossil fuel CO_2 emissions, (**b**) AF2 includes the sum of land use and fossil fuel emissions in the denominator in defining airborne fraction; thus AF2 is not accurately known because of the large uncertainty in land use emissions.

15. IMPLICATIONS OF FIG. (6): CO_2 EMISSIONS AND ATMOSPHERIC CONCENTRATION WITH COAL PHASE-OUT BY 2030

Fig. (**6**) provides an indication of the magnitude of actions that are needed to return atmospheric CO_2 to a level of 350 ppm or lower. Fig. (**6**) allows for the fact that there is disagreement about the magnitude of fossil fuel reserves, and that the magnitude of useable reserves depends upon policies.

A basic assumption underlying Fig. (**6**) is that, within the next several years, there will be a moratorium on construction of coal-fired power plants that do not capture and store CO_2, and that CO_2 emissions from existing power plants will be phased out by 2030. This coal emissions phase out is the sine qua non for stabilizing and reducing atmospheric CO_2. If the sine qua non of coal emissions phase-out is achieved, atmospheric CO_2 can be kept to a peak amount ~400-425 ppm, depending upon the magnitude of oil and gas reserves.

Fig. (**6**) illustrates two widely different assumptions about the magnitude of oil and gas reserves (illustrated in Fig. **S13**). The smaller oil and gas reserves, those labeled "IPCC", are realistic if "peak oil" advocates are more-or-less right, i.e., if the world has already exploited about half of readily accessible oil and gas deposits, so that production of oil and gas will begin to decline within the next several years.

There are also "resource optimists" who dispute the "peakists', arguing that there is much more oil (and gas) to be found. It is possible that both the "peakists" and "resource optimists" are right, it being a matter of how hard we work to extract maximum fossil fuel resources. From the standpoint of controlling human-made climate change, it does not matter much which of these parties is closer to the truth.

Fig. (**6**) shows that, if peak CO_2 is to be kept close to 400 ppm, the oil and gas reserves actually exploited need to be close to the "IPCC" reserve values. In other words, if we phase out coal emissions we can use remaining oil and gas amounts equal to those which have already been used, and still keep peak CO_2 at about 400 ppm. Such a limit is probably necessary if we are to retain the possibility of a drawdown of CO_2 beneath the 350 ppm level by methods that are more-or-less "natural". If, on the other hand, reserve growth of the magnitude that EIA estimates (Figs. **6** and **S13**) occurs, and if these reserves are burned with the CO_2 emitted to the atmosphere, then the forest and soil sequestration that we discuss would be inadequate to achieve drawdown below the 350 ppm level in less than several centuries.

Even if the greater resources estimated by EIA are potentially available, it does not mean that the world necessarily must follow the course implied by EIA estimates for reserve growth. If a sufficient price is applied to carbon emissions it will discourage extraction of fossil fuels in the most extreme environments. Other actions that would help keep effective reserves close to the IPCC estimates would include prohibition of drilling in environmentally sensitive areas, including the Arctic and Antarctic.

National policies, in most countries, have generally pushed to expand fossil fuel reserves as much as possible. This might partially account for the fact that energy information agencies, such as the EIA in the United States, which are government agencies, tend to forecast strong growth of fossil fuel reserves. On the other hand, state, local, and citizen organizations can influence imposition of limits on fossil fuel extraction, so there is no guarantee that fossil resources will be fully exploited. Once the successors to fossil energy begin to take hold, there may be a shifting away from fossil fuels that leaves some of the resources in the ground. Thus a scenario with oil and gas emissions similar to that for IPCC reserves may be plausible.

Assumptions yielding the Forestry & Soil wedge in Fig. (**6b**) are as follows. It is assumed that current net deforestation will decline linearly to zero between 2010 and 2015. It is assumed that uptake of carbon *via* reforestation will increase linearly until 2030, by which time reforestation will achieve a maximum potential sequestration rate of 1.6 GtC per year [S37]. Waste-derived biochar application will be phased in linearly over the period 2010-2020, by which time it will reach a maximum uptake rate of 0.16 GtC/yr [85]. Thus after 2030 there will be an annual uptake of 1.6 + 0.16 = 1.76 GtC per year, based on the two processes described.

Thus Fig. (**6**) shows that the combination of (1) moratorium and phase-out of coal emissions by 2030, (2) policies that effectively keep fossil fuel reserves from significantly exceeding the IPCC reserve estimates, and (3) major programs to achieve carbon sequestration in forests and soil, can together return atmospheric CO_2 below the 350 ppm level before the end of the century.

The final wedge in Fig. (**6**) is designed to provide an indication of the degree of actions that would be required to bring atmospheric CO_2 back to the level of 350 ppm by a time close to the middle of this century, rather than the end of the century. This case also provides an indication of how difficult it would be to compensate for excessive coal emissions, if the world should fail to achieve a moratorium and phase-out of coal as assumed as our "sine qua non".

Assumptions yielding the Oil-Gas-Biofuels wedge in Fig. (**6b**) are as follows: energy efficiency, conservation, carbon pricing, renewable energies, nuclear power and other carbon-free energy sources, and government standards and regulations will lead to decline of oil and gas emissions at 4% per year beginning when 50% of the estimated resource (oil or gas) has been exploited, rather than the 2% per year baseline decline rate [79]. Also capture of CO_2 at gas- power plants (with CO_2 capture) will use 50% of remaining gas supplies. Also a linear phase-in of liquid biofuels is assumed between 2015 and 2025 leading to a maximum global bioenergy from "low-input/high-diversity" biofuels of ~23 EJ/yr, inferred from Tilman *et al*. [87], that is used as a substitute for oil; this is equivalent to ~0.5 GtC/yr, based on energy conversion of 50 EJ/GtC for oil. Finally, from 2025 onward, twice this number (i.e., 1 GtC/yr) is subtracted from annual oil emissions, assuming root/soil carbon sequestration *via* this biofuel-for-oil substitution is at least as substantial as in Tilman *et al*. [87]. An additional option that could contribute to this wedge is using biofuels in powerplants with CO_2 capture and sequestration [86].

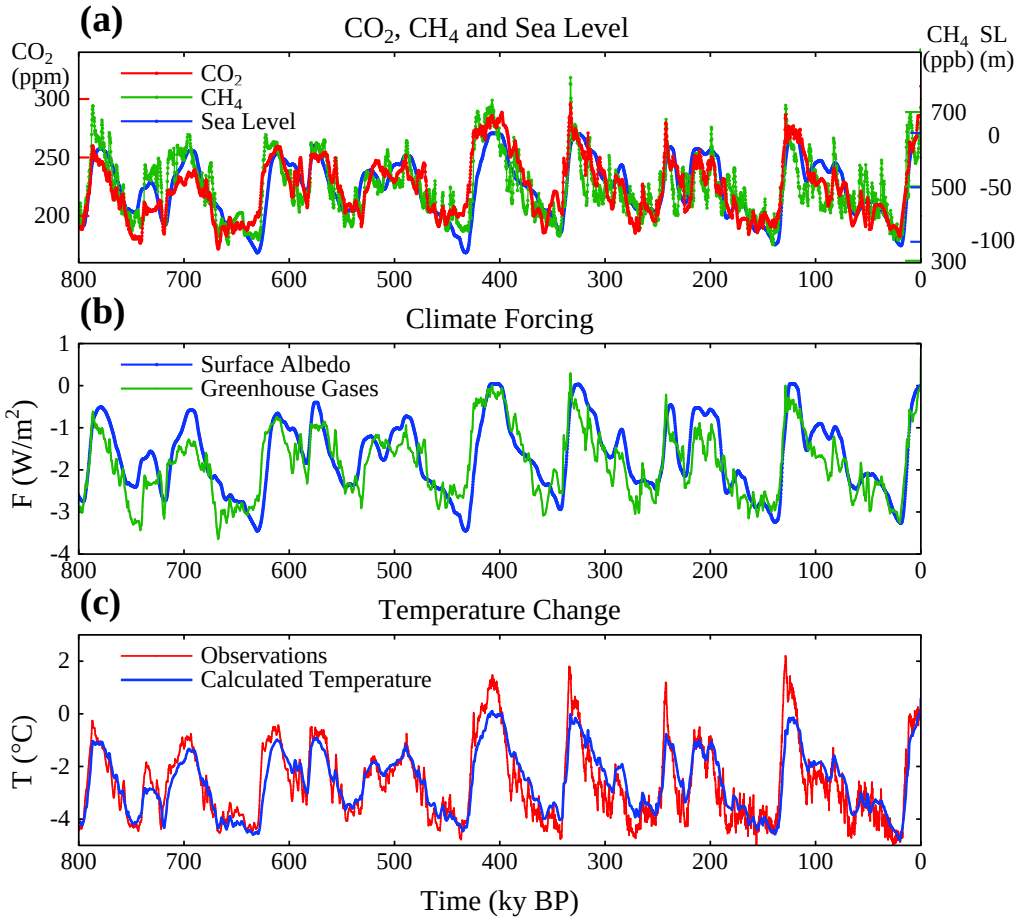

Fig. (S18). (**a**) CO_2 [S38], CH_4 [S39] and sea level [S16] for past 800 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from the sea level history of Bintanja *et al*. [S16]. (**c**) Calculated global temperature change based on the above forcings and climate sensitivity ¾°C per W/m^2. Observations are Antarctic temperature change from the Dome C ice core [S8] divided by two.

16. EPICA 800 KY DATA

Antarctic Dme C ice core data acquired by EPICA (European Project for Ice Coring in Antarctica) provide a record of atmospheric composition and temperature spanning 800 ky [S8], almost double the time covered by the Vostok data [17, 18] of Figs. (**1**) and (**2**). This extended record allows us to examine the relationship of climate forcing mechanisms and temperature change over a period that includes a substantial change in the nature of glacial-interglacial climate swings. During the first half of the EPICA record, the period 800-400 ky BP, the climate swings were smaller, sea level did not rise as high as the present level, and the GHGs did not increase to amounts as high as those of recent interglacial periods.

Fig. (**S18**) shows that the temperature change calculated exactly as described for the Vostok data of Fig. (**1**), i.e., multiplying the fast-feedback climate sensitivity ¾°C per W/m^2 by the sum of the GHG and surface albedo forcings (Fig. **S18b**), yields a remarkably close fit in the first half of the Dome C record to one-half of the temperature inferred from the isotopic composition of the ice. In the more recent half of the record slightly larger than ¾°C per W/m^2 would yield a noticeably better fit to the observed Dome C temperature divided by two (Fig. **S19**). However, there is no good reason to change our approximate estimate of ¾°C per W/m^2, because the assumed polar amplification by a factor of two is only approximate.

The sharper spikes in recent observed interglacial temperature, relative to the calculated temperature, must be in part an artifact of differing temporal resolutions. Temperature is inferred from the isotopic composition of the ice, being a function of the temperature at which the snowflakes formed, and thus inherently has a very high temporal resolution. GHG amounts, in contrast, are smoothed over a few ky by mixing of air in the snow that occurs up until the snow is deep enough for the snow to be compressed into ice. In the central Antarctic, where both Vostok and Dome C are located, bubble closure requires a few thousand years [17].

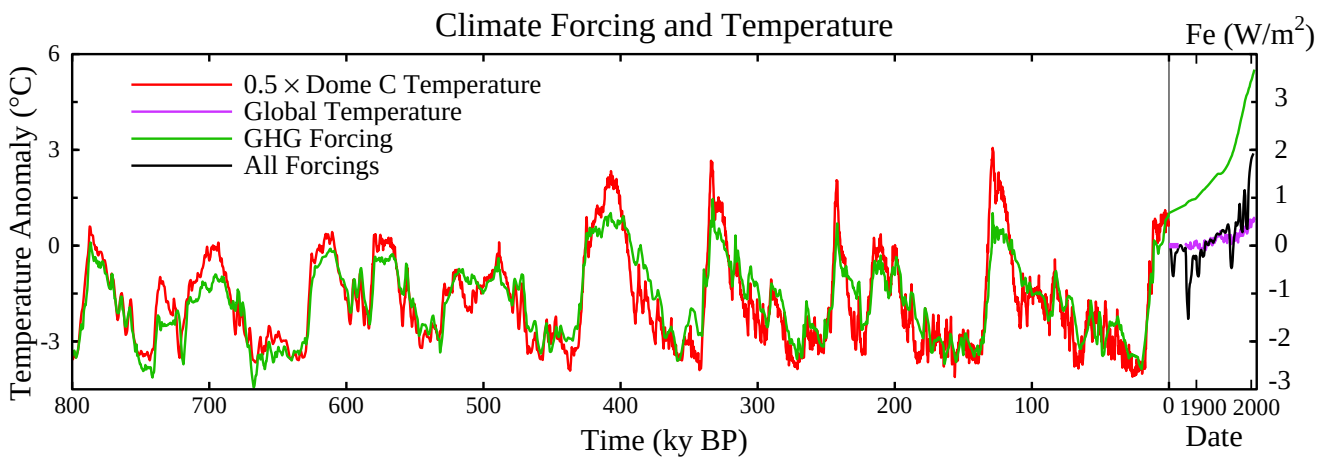

Fig. (S19). Global temperature change (left scale) estimated as half of temperature change from Dome C ice core [S8] and GHG forcing (right scale) due to CO_2, CH_4 and N_2O [S38, S39]. Ratio of temperature and forcing scales is 1.5°C per W/m^2. Time scale is expanded in the extension to recent years. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky before present. Net climate forcing and modern temperature zero points are at 1850. The implicit presumption that the positive GHG forcing at 1850 is largely offset by negative human-made forcings [7] is supported by the lack of rapid global temperature change in the Holocene (Fig. **S6**).

17. COMPARISON OF ANTARCTIC DATA SETS

Fig. (**S20**) compares Antarctic data sets used in this supplementary section and in our parent paper. This comparison is also relevant to interpretations of the ice core data in prior papers using the original Vostok data.

The temperature records of Petit *et al.* [17] and Vimeux *et al.* [18] are from the same Vostok ice core, but Vimeux *et al.* [18] have adjusted the temperatures with a procedure designed to correct for climate variations in the water vapor source regions. The isotopic composition of the ice is affected by the climate conditions in the water vapor source region as well as by the temperature in the air above Vostok where the snowflakes formed; thus the adjustment is intended to yield a record that more accurately reflects the air temperature at Vostok. The green temperature curve in Fig. (**S20c**), which includes the adjustment, reduces the amplitude of glacial-interglacial temperature swings from those in the original (red curve) Petit *et al.* [17] data. Thus it seems likely that there will be some reduction of the amplitude and spikiness of the Dome C temperature record when a similar adjustment is made to the Dome C data set.

The temporal shift of the Dome C temperature data [S8], relative to the Vostok records, is a result of the improved EDC3 [S40, S41] time scale. With this new time scale, which has a 1σ uncertainty of ~3 ky for times earlier than ~130 ky BP, the rapid temperature increases of Termination IV (~335 ky BP) and Termination III (~245 ky BP) are in close agreement with the contention [7] that rapid ice sheet disintegration and global temperature rise should be nearly simultaneous with late spring

(April-May-June) insolation maxima at 60N latitude, as was already the case for Terminations II and I, whose timings are not significantly affected by the improved time scale.

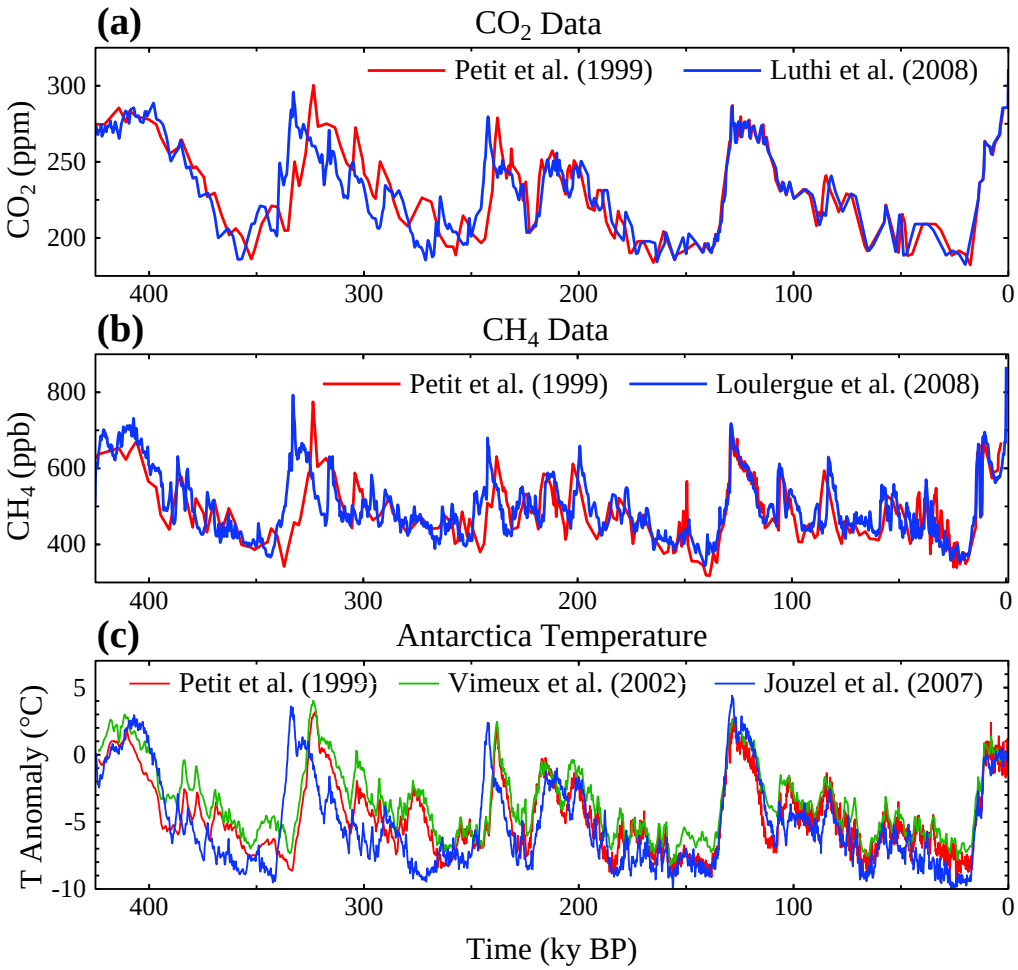

Fig. (S20). Comparison of Antarctic CO_2, CH_4, and temperature records in several analyses of Antarctic ice core data.

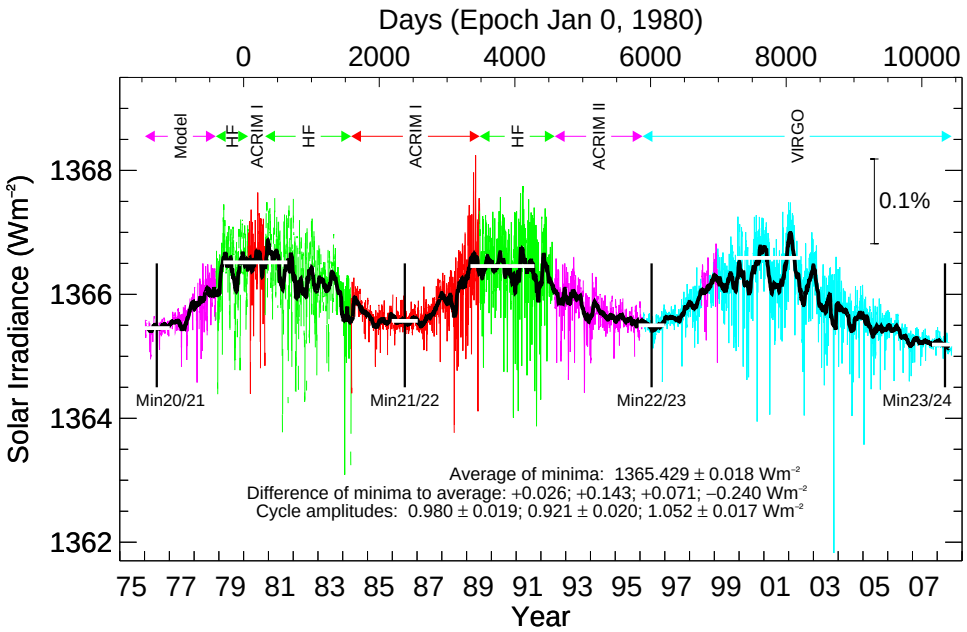

Fig. (S21). Solar irradiance from composite of several satellite-measured time series based on Frohlich and Lean [S44].