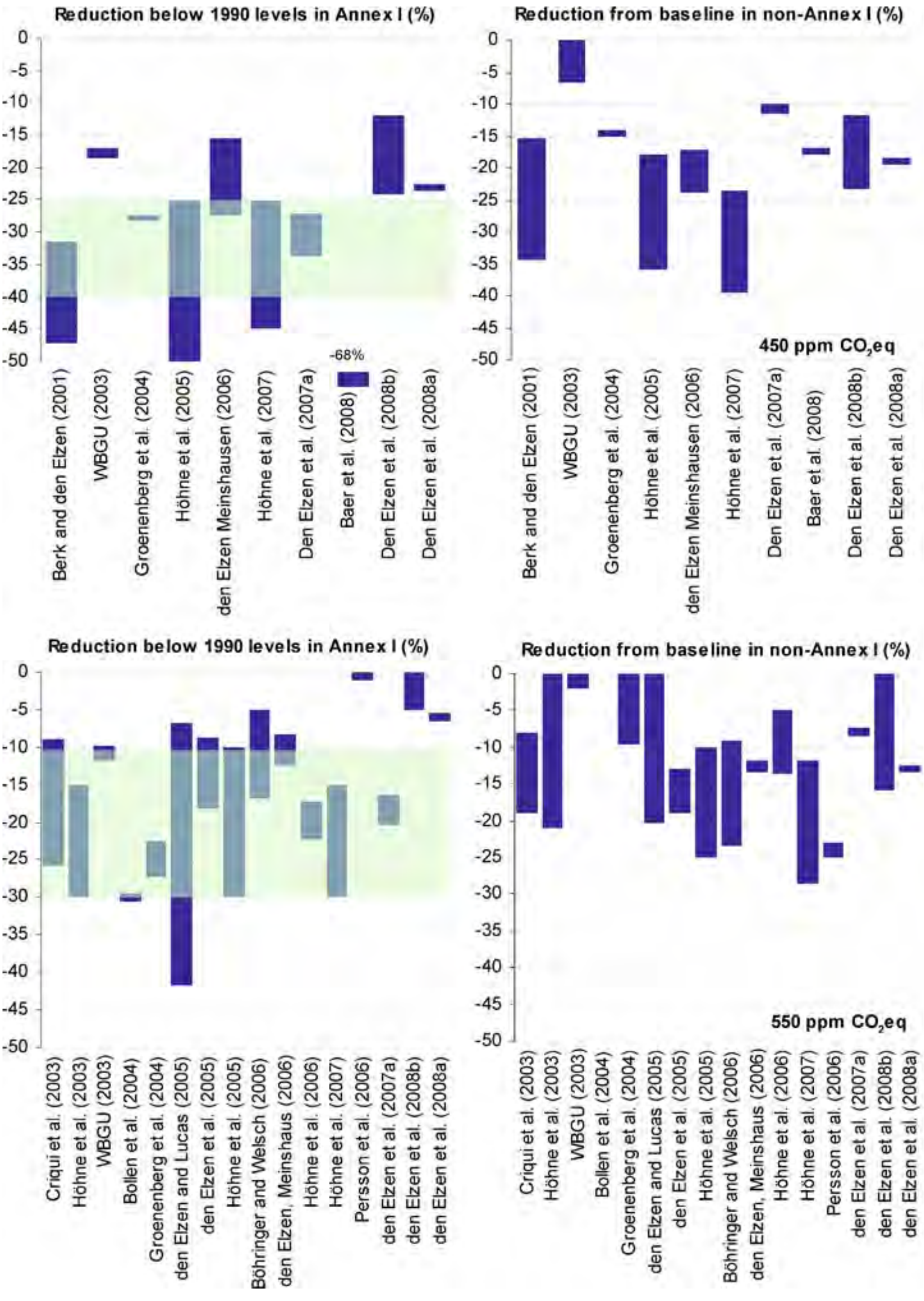


Fig. 1 Reductions in Annex I (below 1990 level) and non-Annex I countries (below baseline) as a group in 2020 for the studies quoted by the IPCC and more recent studies. Uncertainty ranges indicated here, are based on the outcomes of different post-2012 regimes. The figure also depicts the reduction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

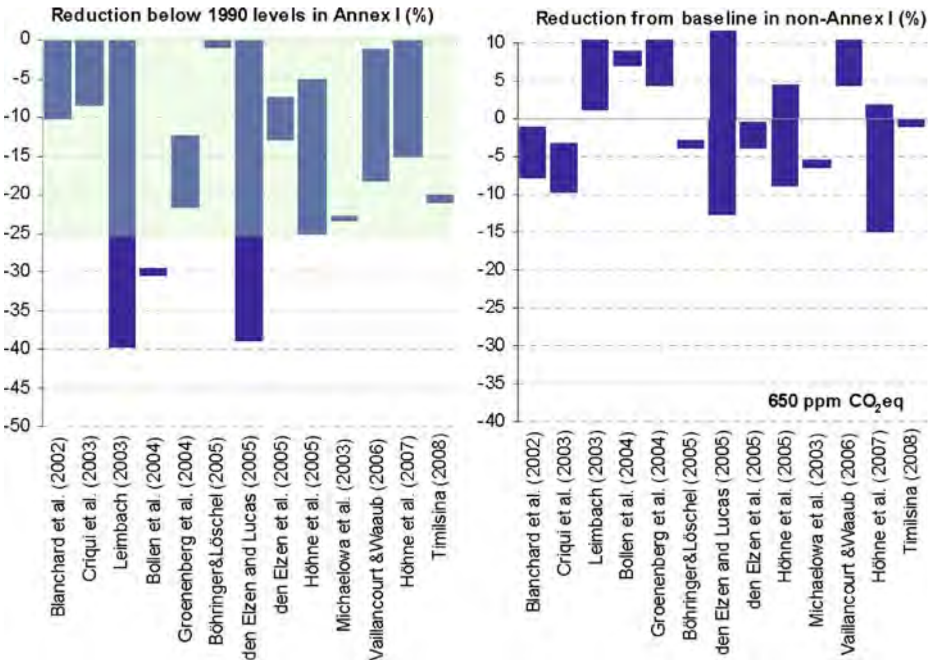


Fig. 1 (continued)

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	This study (based on den Elzen et al. 2007b)		Höhne et al. (2005)
concentration	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.

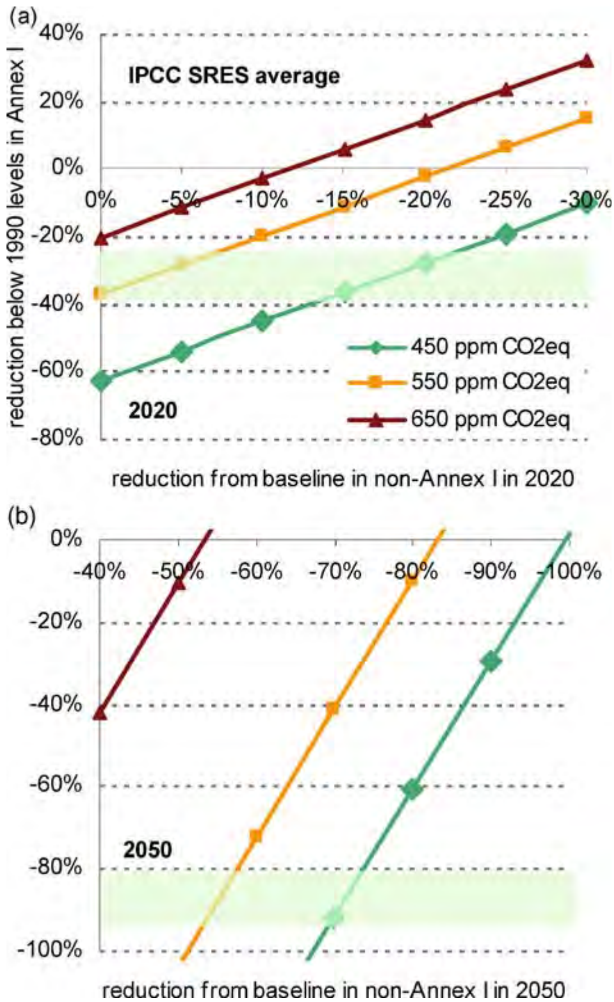
Note that these reductions are assumed to occur independently by domestic reductions in Annex I and non-Annex I countries. If Annex I countries decide to achieve some of these reductions outside of the group (through CDM or any other future mechanisms), additional reductions have to occur in developing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

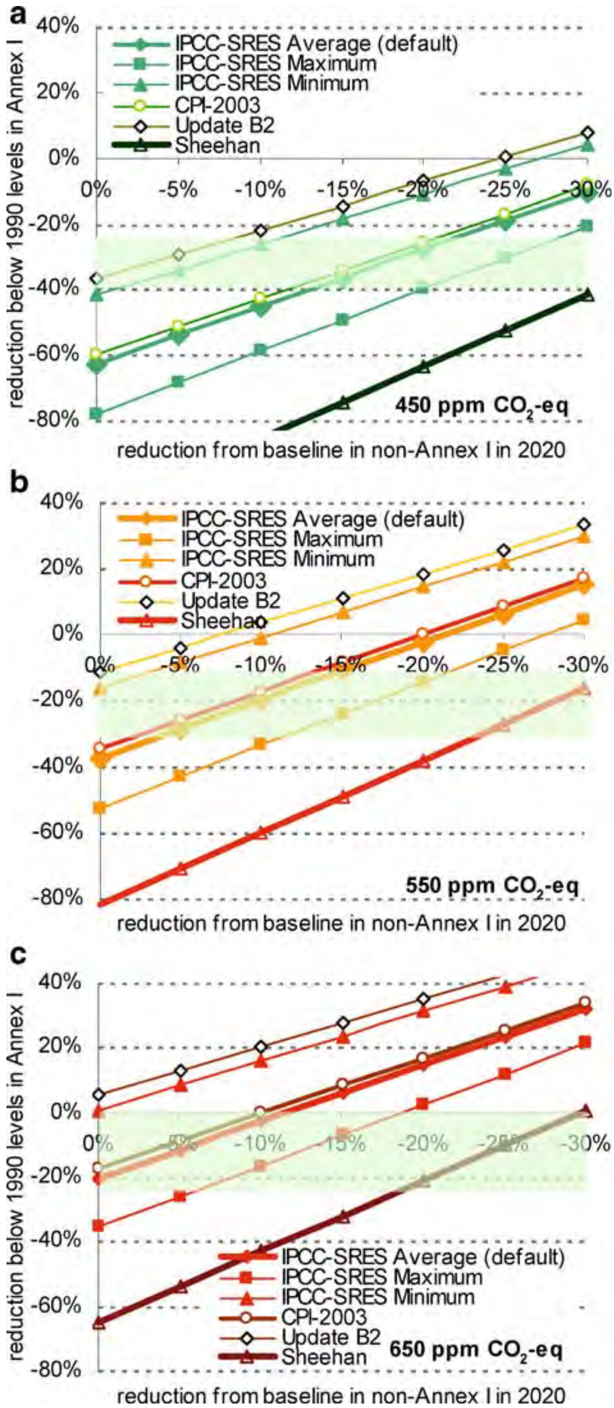


Fig. 3 The trade-off in reductions in 2020, in Annex I and non-Annex I countries as a group, for various baseline emissions (incl. baseline of Sheehan), for concentration stabilisation at 450 (**a**), 550 (**b**) and 650 (**c**) ppm CO_2-eq**.** The figure also depicts the reduction ranges for Annex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

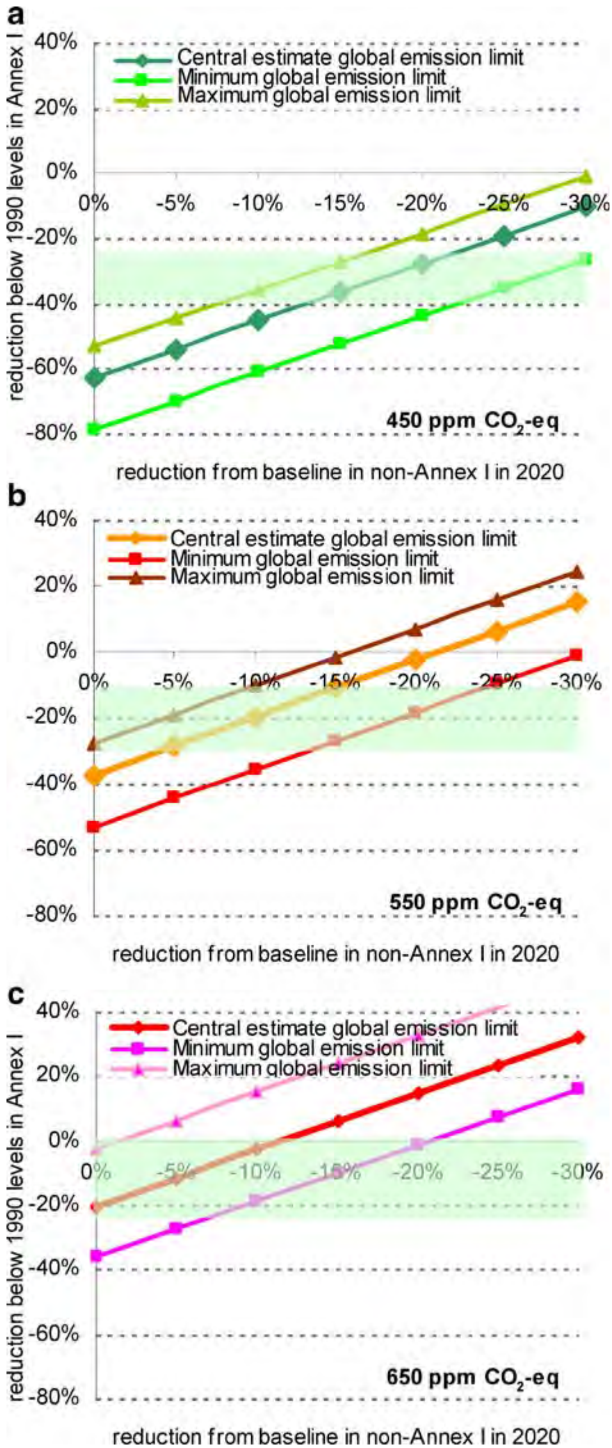


Fig. 4 The trade-off in reductions in 2020, in Annex I and non-Annex I countries as a group, for various global emission limits in 2020, for concentration stabilisation at 450 (**a**), 550 (**b**) and 650 (**c**) ppm CO_2-eq**.** The *numbers* represent the averaged outcome over separate calculations 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) Central estimate (%)	Avoiding deforestation 2020 (%)	Avoiding deforestation 2030 (%)
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

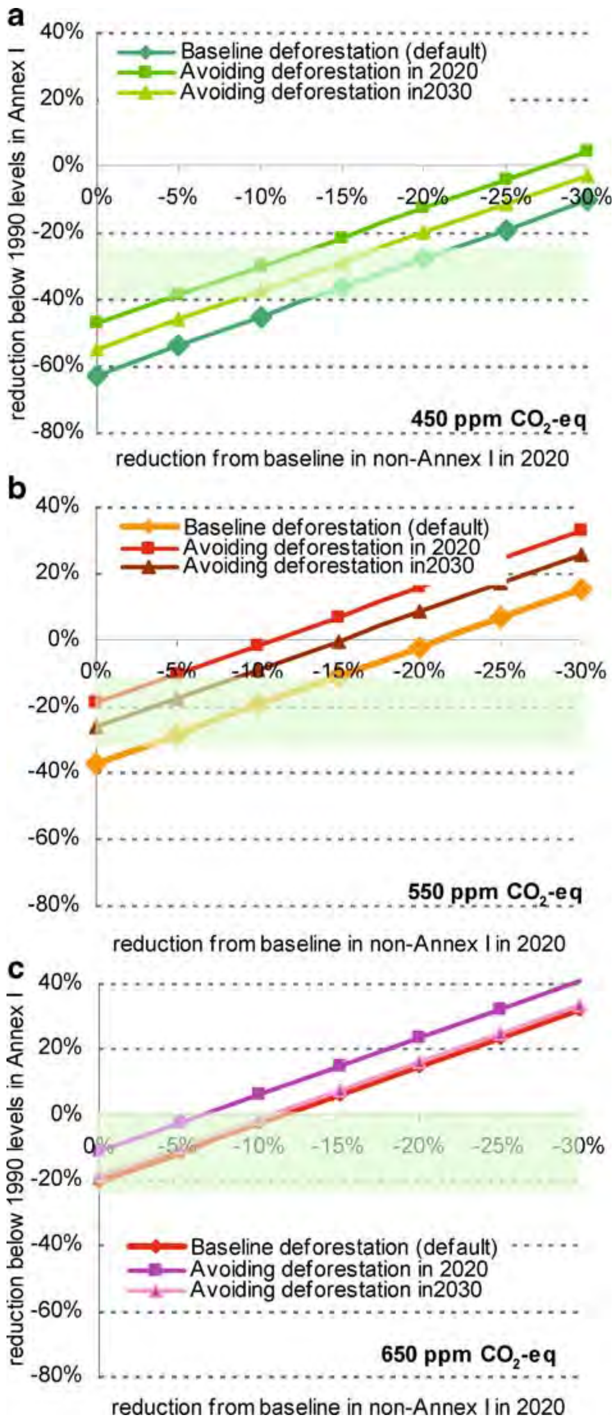
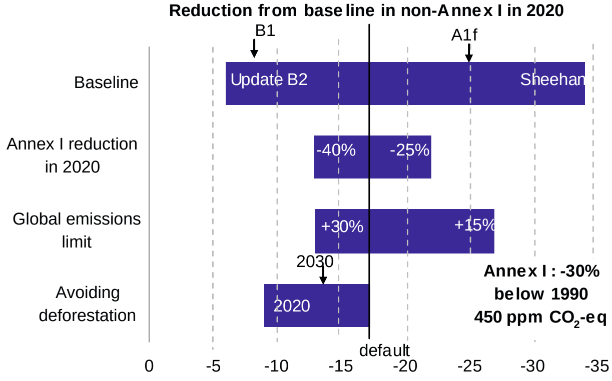


Fig. 5 The trade-off in reductions in 2020, in Annex I and non-Annex I countries as a group, for various assumptions on avoiding deforestation, for concentration stabilisation at 450 (**a**), 550 (**b**) and 650 (**c**) ppm CO_2-eq**.** The *numbers* represent the averaged outcome over separate calculations 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

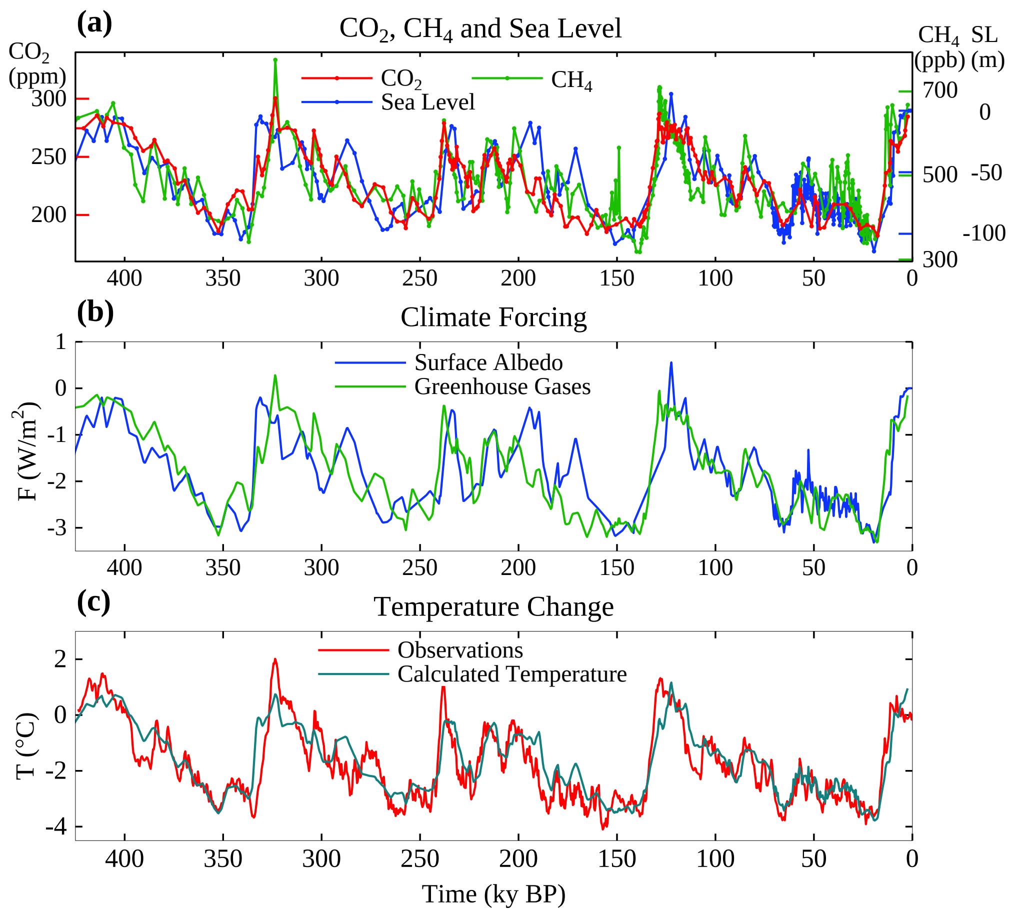

Fig. (1). (**a**) CO_2, CH_4 [17] and sea level [19] for past 425 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from sea level change. (**c**) Calculated global temperature change based on climate sensitivity of ¾°C per W/m^2. Observations are Antarctic temperature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

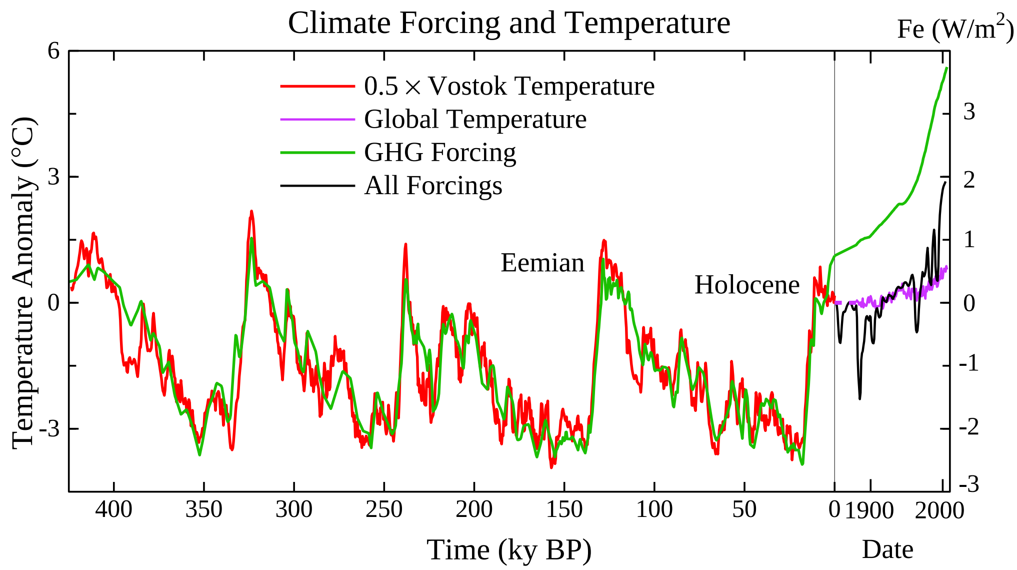

Fig. (2). Global temperature (left scale) and GHG forcing (right scale) due to CO_2, CH_4 and N_2O from the Vostok ice core [17, 18]. Time scale is expanded for the industrial era. Ratio of temperature and forcing scales is 1.5°C per W/m^2, i.e., the temperature scale gives the expected equilibrium response 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].

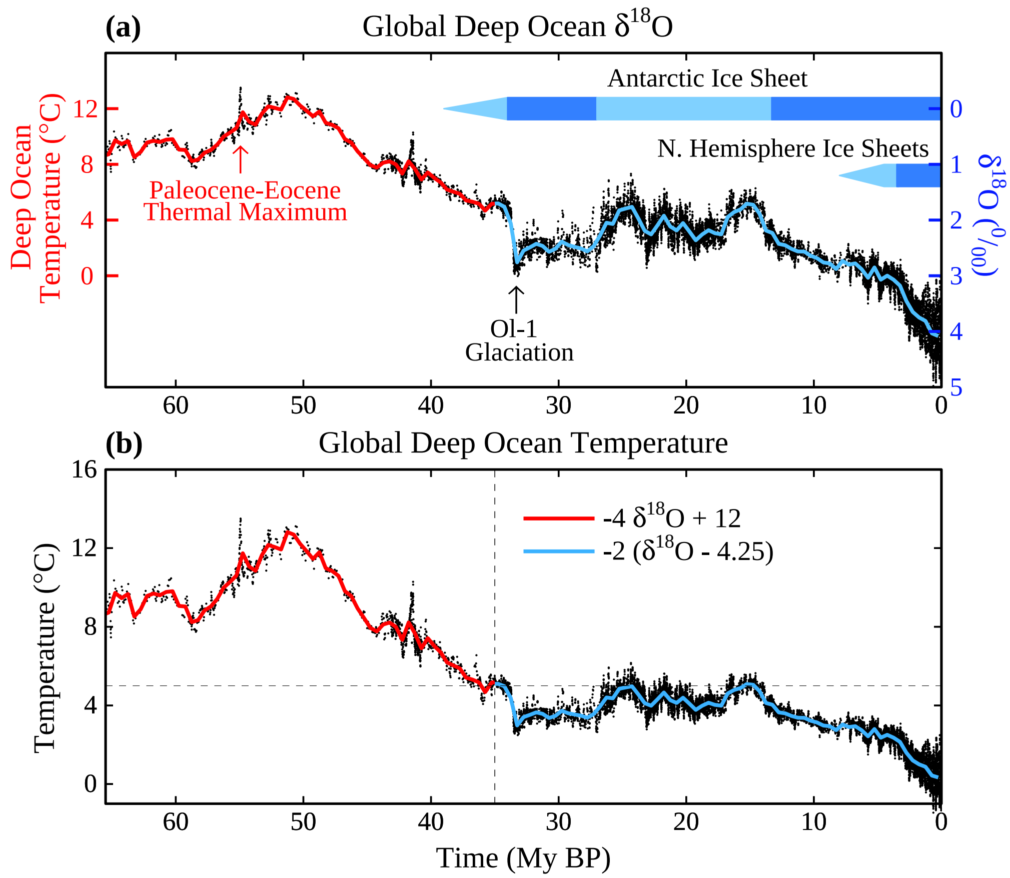

Fig. (3). Global deep ocean (**a**) $\delta^{18}O$ [26] and (**b**) temperature. Black curve is 5-point running mean of $\delta^{18}O$ original temporal resolution, while red and blue curves have 500 ky resolution.

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 atmospheric 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 δ^{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

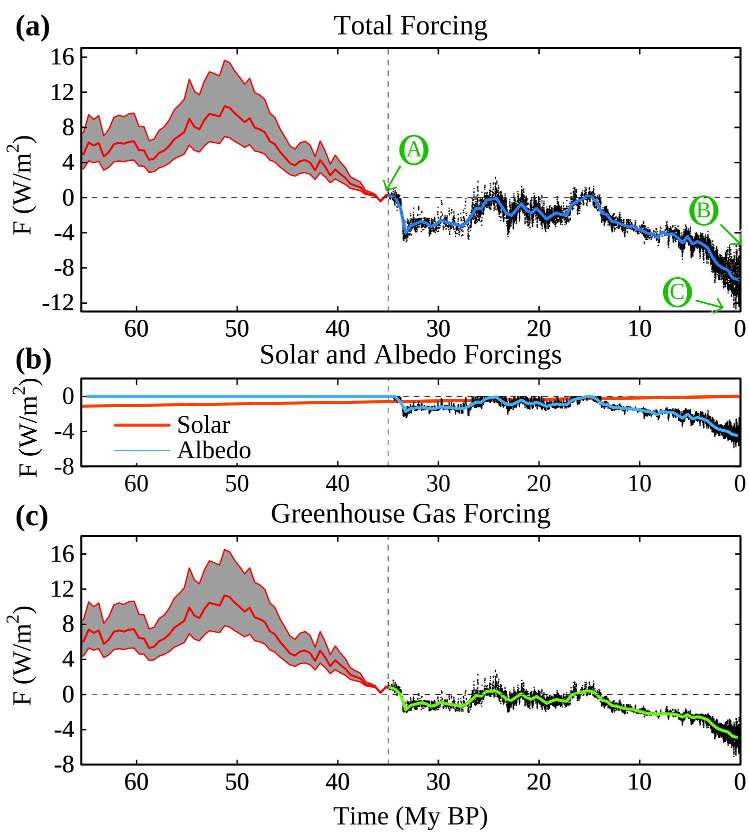

Fig. (4). (**a**) Total climate forcing, (**b**) solar and surface albedo forcings, and (**c**) GHG forcing in the Cenozoic, based on T_{do} history of Fig. (**3b**) and assumed fast-feedback climate sensitivity ¾°C per W/m^2. Ratio of T_s change and T_{do} change is assumed to be near unity in the minimal 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.

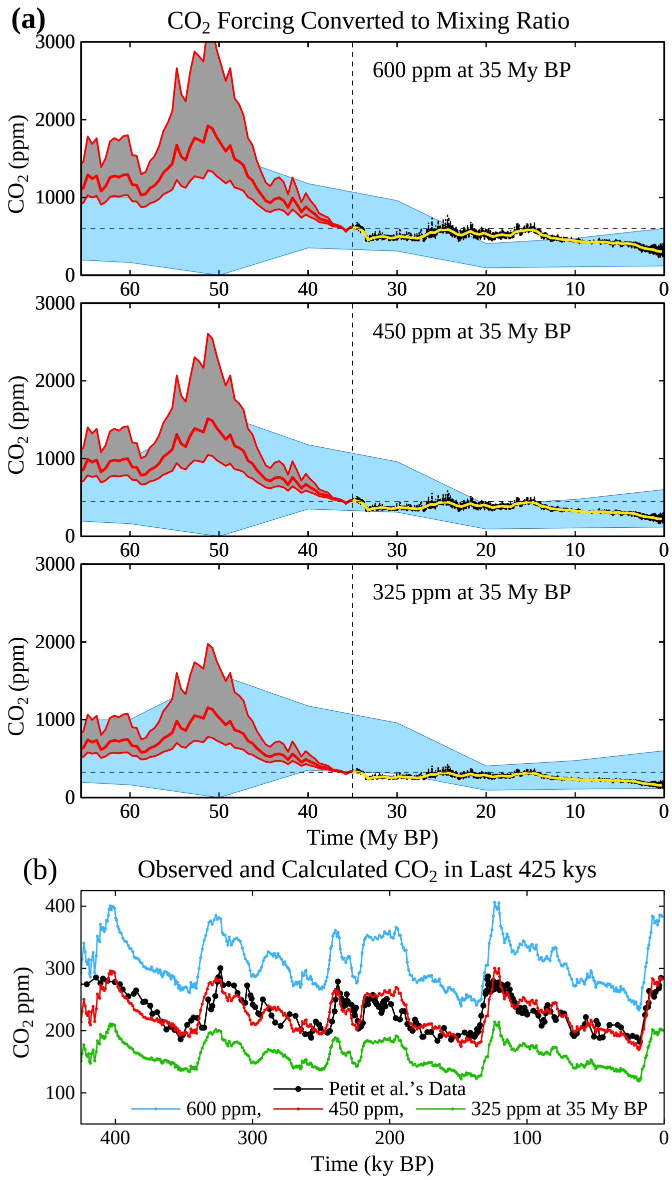

Fig. (5). (**a**) Simulated CO_2 amounts in the Cenozoic for three choices of CO_2 amount at 35 My (temporal resolution of black and colored curves as in Fig. (**3**); blue region: multiple CO_2 proxy data, discussed with Fig. (**S10**); gray region allows 50 percent uncertainty in ratio of global surface 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 perturbation 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

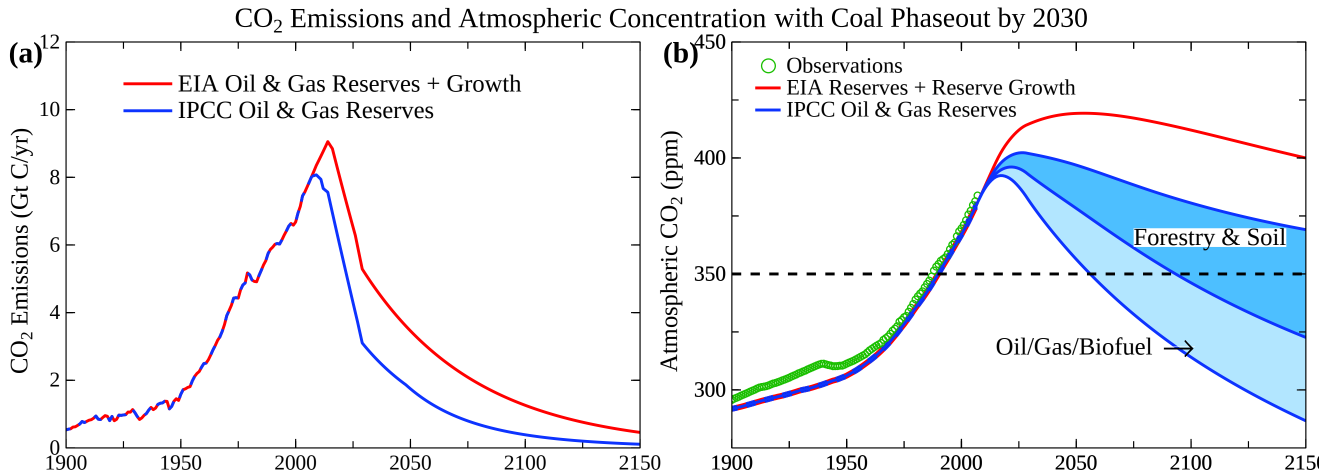

Fig. (6). (**a**) Fossil fuel CO_2 emissions with coal phase-out by 2030 based on IPCC [2] and EIA [80] estimated fossil fuel reserves. (**b**) Resulting atmospheric CO_2 based on use of a dynamic-sink pulse response function representation of the Bern carbon cycle model [78, 79].

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

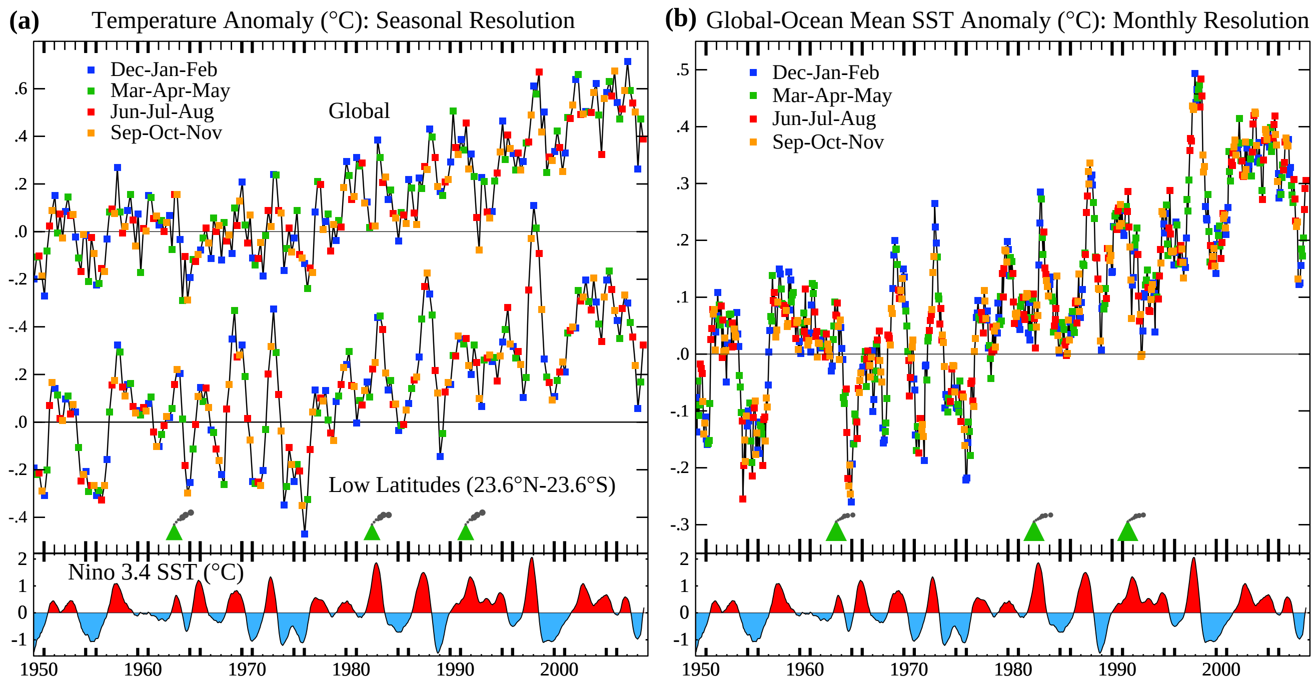

Fig. (7). (**a**) Seasonal-mean global and low-latitude surface temperature anomalies relative to 1951-1980, an update of [92], (**b**) global-ocean-mean sea surface temperature anomaly at monthly resolution. The Nino 3.4 Index, the temperature anomaly (12-month running mean) in a small part of the tropical 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**).

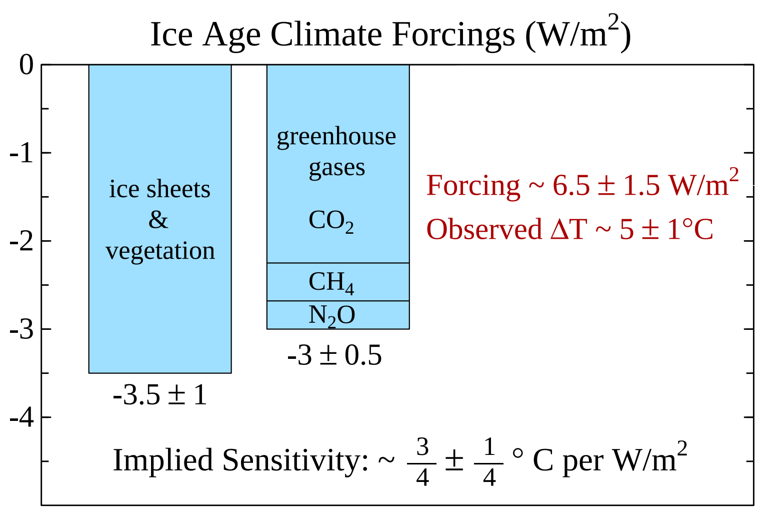

Fig. (S1). Climate forcings during ice age 20 ky BP, relative to the present (pre-industrial) interglacial period.

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]

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

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,

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

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. $g_{land\ ice\ albedo} \rightarrow 0$.

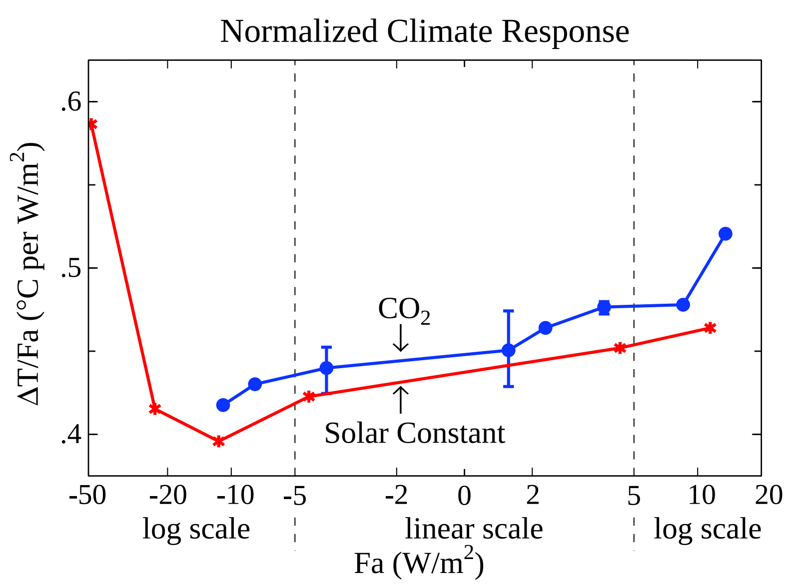

Fig. (S2). Global surface air temperature change [12] after 100 years in simulations with the Goddard Institute for Space Studies modelE [S3, 5] as a function of climate forcing for changes of solar irradiance and atmospheric CO_2. Fa is the standard adjusted climate forcing [12]. Results are extracted 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.

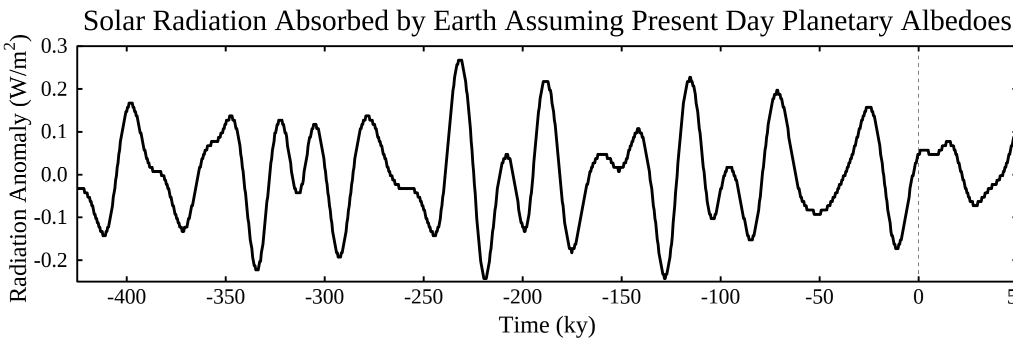

Fig. (S3). Annual-mean global-mean perturbation of the amount of solar radiation absorbed by the Earth, calculated by assuming present-day seasonal and geographical distribution of albedo.

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 $g_{fast\ feedbacks}$ ~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

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

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, $g_{surface\ albedo}$ 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.

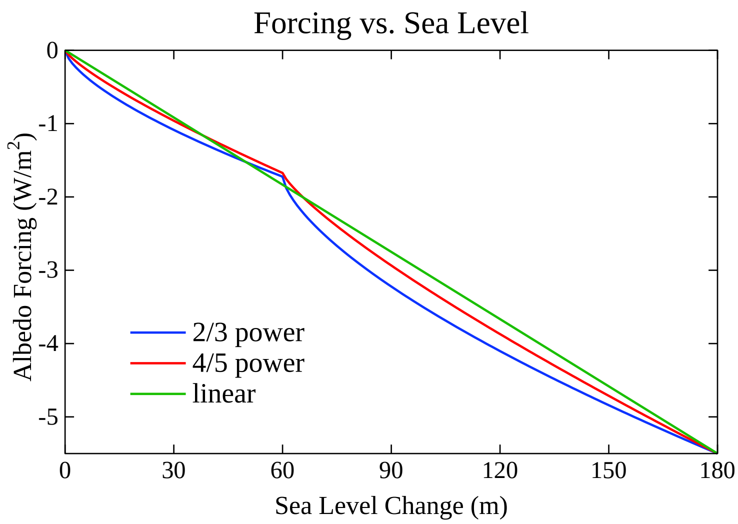

Fig. (S4). Surface albedo climate forcing as a function of sea level for three approximations of the ice sheet area as a function of sea level change, from an ice free planet to the last glacial maximum. For sea level between 0 and 60 m only Antarctica contributes to the albedo change. At the last glacial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

4. ICE SHEET ALBEDO

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).

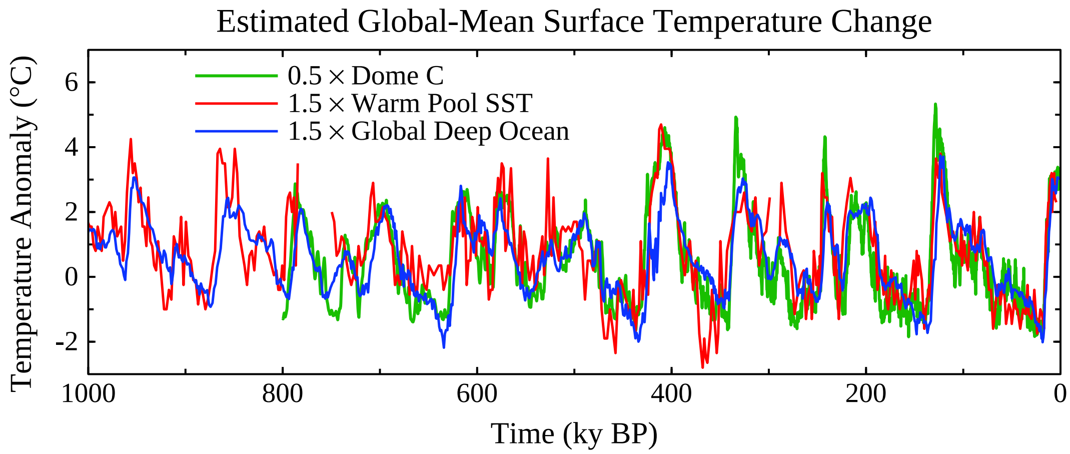

Fig. (S5). Estimated global temperature change based on measurements at a single point or, in the case of the deep ocean, a near-global stack of ocean drilling sites: Antarctica Dome C [S8], Warm Pool [S9], deep ocean [26].

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.

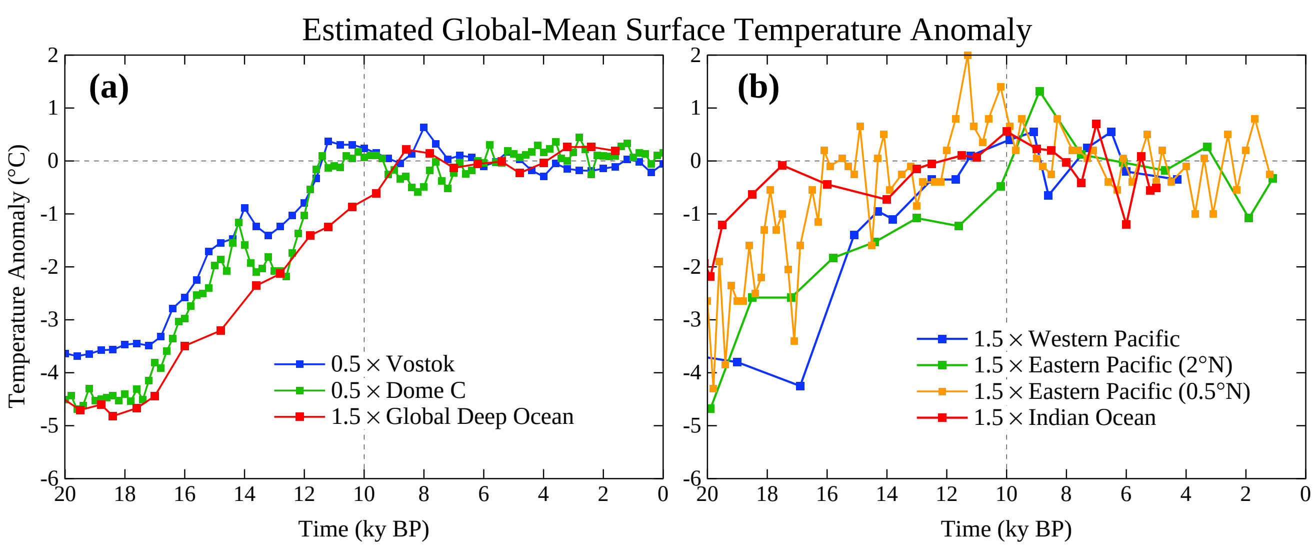

Fig. (S6). Estimates of global temperature change inferred from Antarctic ice cores [18, S8] and ocean sediment cores [S9-S13], as in Fig. (**S5**) but for a period allowing Holocene temperature to be apparent.

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.

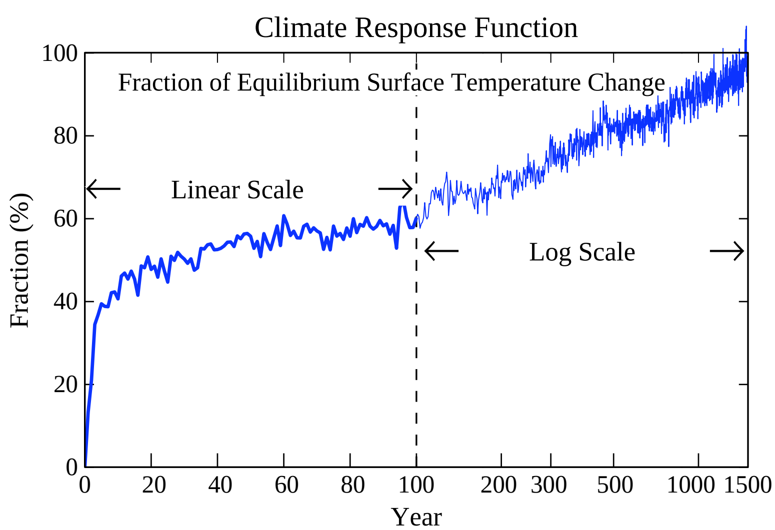

Fig. (S7). Fraction of equilibrium surface temperature response versus time in the GISS climate model [7, 12, S3] with the Russell [S14] ocean. The forcing was doubled atmospheric CO_2. The ice sheets, vegetation distribution and other long-lived GHGs were fixed.

8. SEPARATION OF Δ^{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.

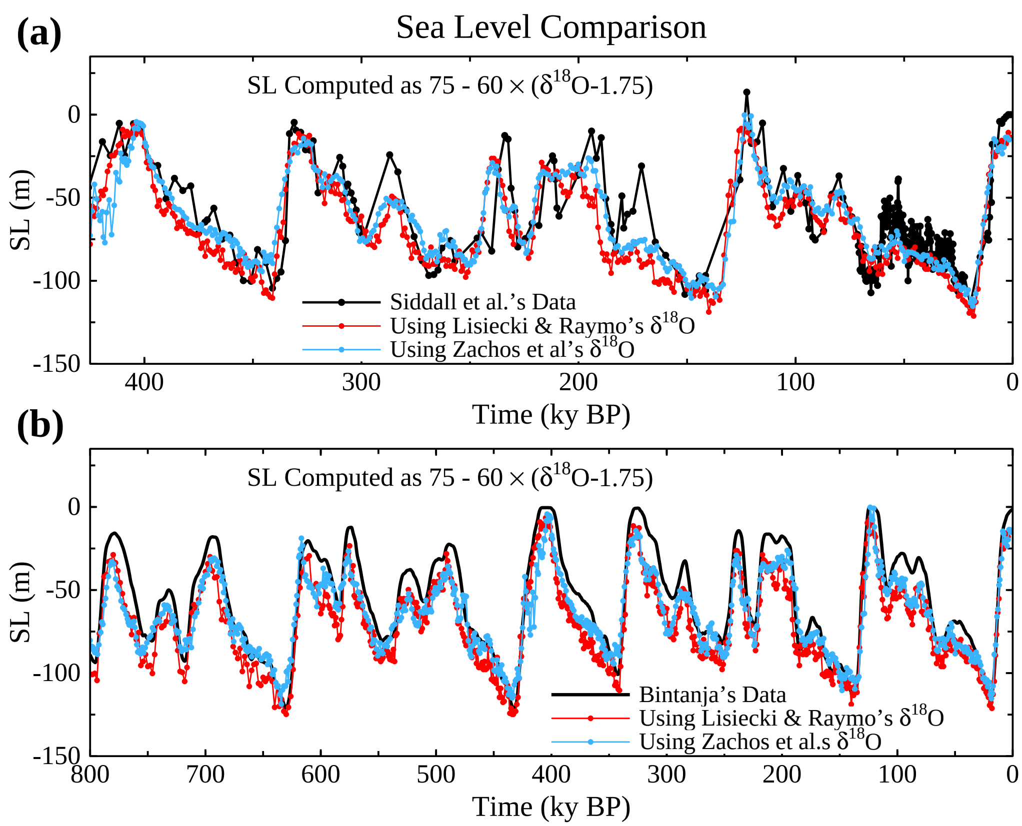

Fig. (S8). (**a**) Comparison of Siddall *et al.* [19] sea level record with sea level computed from $\delta^{18}O$ *via* Eq. S2 using two alternative global benthic stacks [26, S15]. (**b**) Comparison of Bintanja *et al.* [S16] sea level reconstruction with the same global benthic stacks as in (**a**).

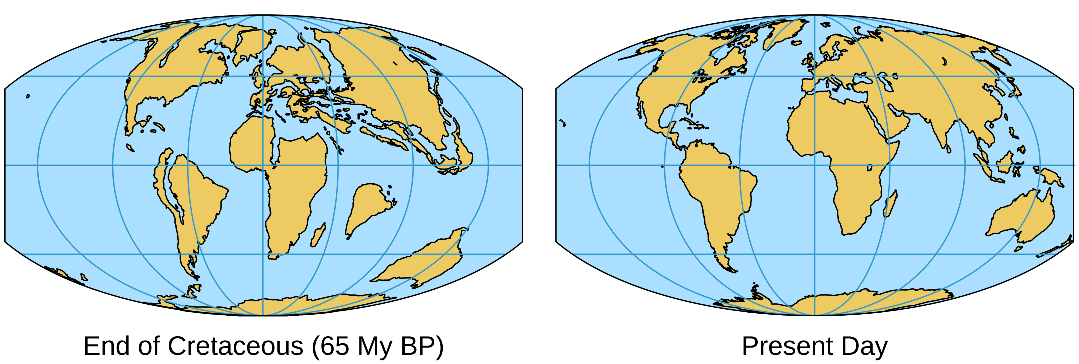

Fig. (S9). Continental locations at the beginning and end of the Cenozoic era [S17].

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].

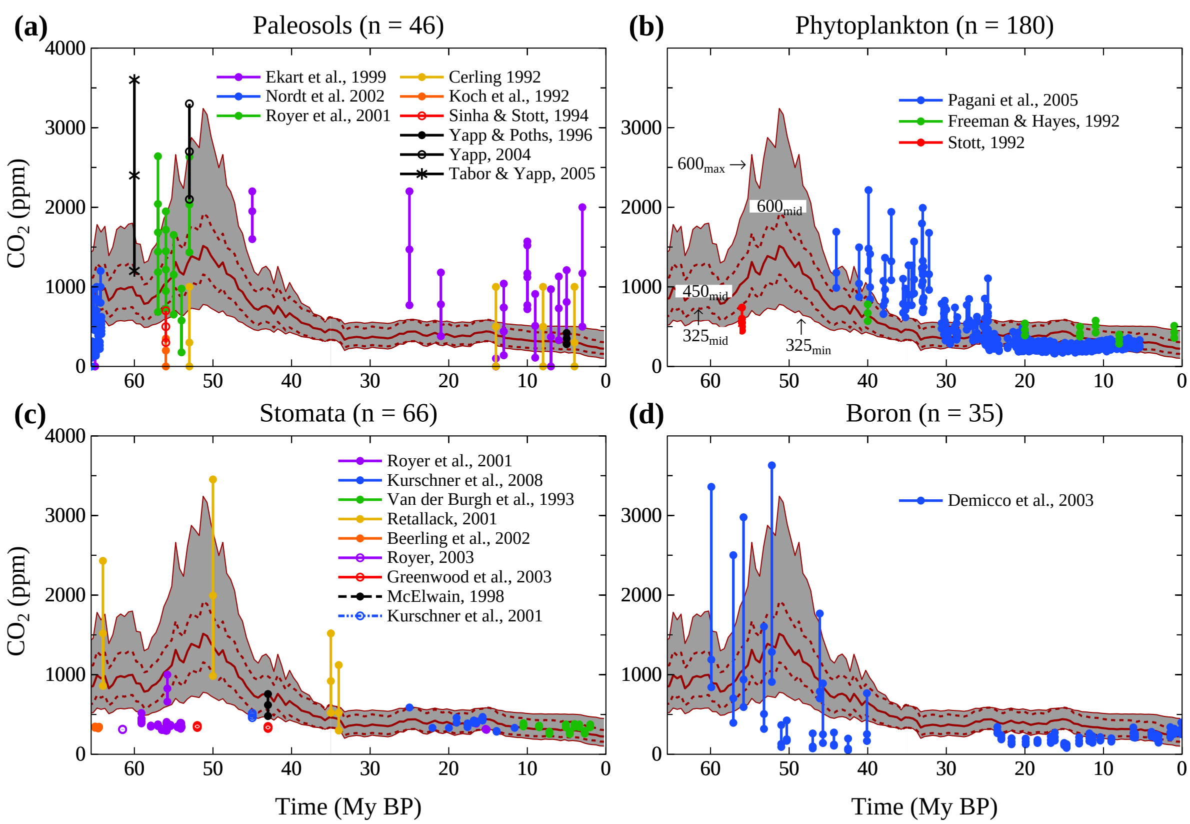

Fig. (S10). Comparison of proxy CO_2 measurements with CO_2 predictions based on deep-ocean temperature, the latter inferred from benthic $\delta^{18}O$. The shaded range of model results is intended mainly to guide the eye in comparing different proxies. The dark central line is for the standard case 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.

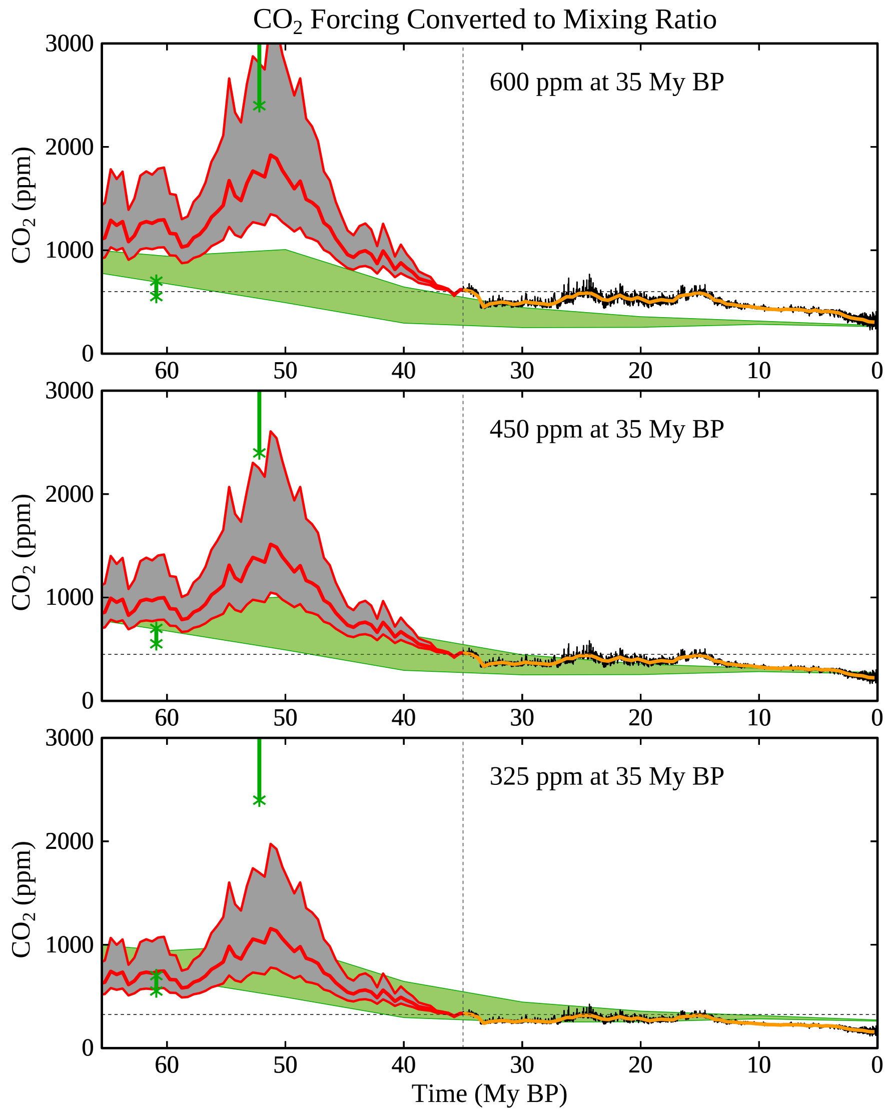

Fig. (S11). Simulated CO_2 in the Cenozoic for three choices of CO_2 amount at 35 My, as in Fig. (**5**), compared with the CO_2 history in a geochemical model [30], specifically the model version described by Fletcher *et al.* [S19]. The green vertical bars are a proxy CO_2 measure [S19] obtained from 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].

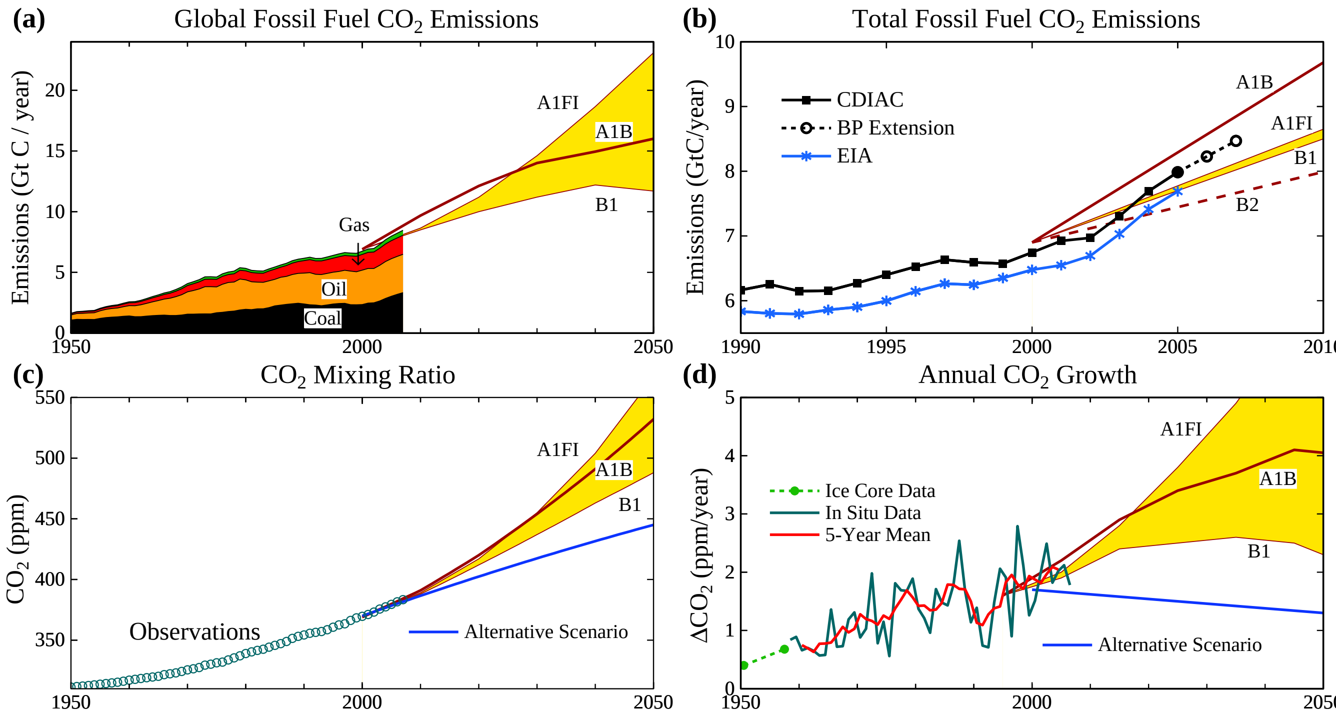

Fig. (S12). (**a**) Fossil fuel CO_2 emissions by fuel type [S32, S33], the thin green sliver being gas flaring plus cement production, and IPCC fossil fuel emissions scenarios, (**b**) expansion global emissions to show recent changes more precisely, the EIA values excluding CO_2 emissions from cement 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.

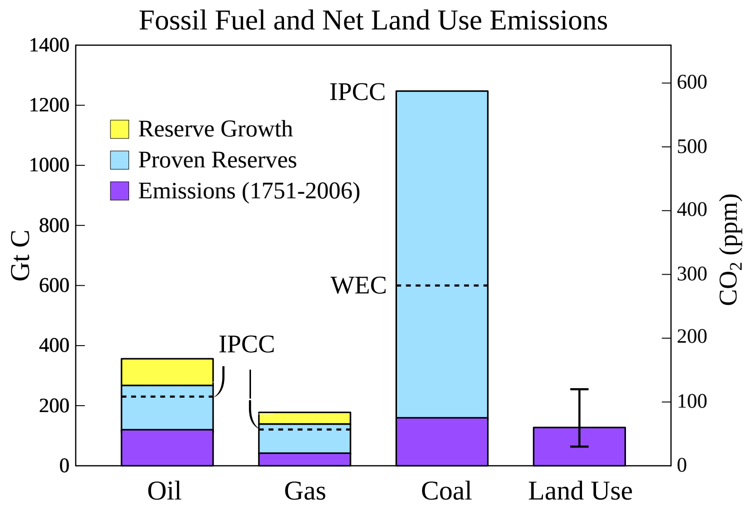

Fig. (S13). Fossil fuel and land-use CO_2 emissions, and potential fossil fuel emissions. Historical fossil fuel emissions are from the Carbon Dioxide Information Analysis Center [CDIAC, S32] and British Petroleum [BP, S33]. Lower limits on oil and gas reserves are from IPCC [S34] and higher limits are 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.

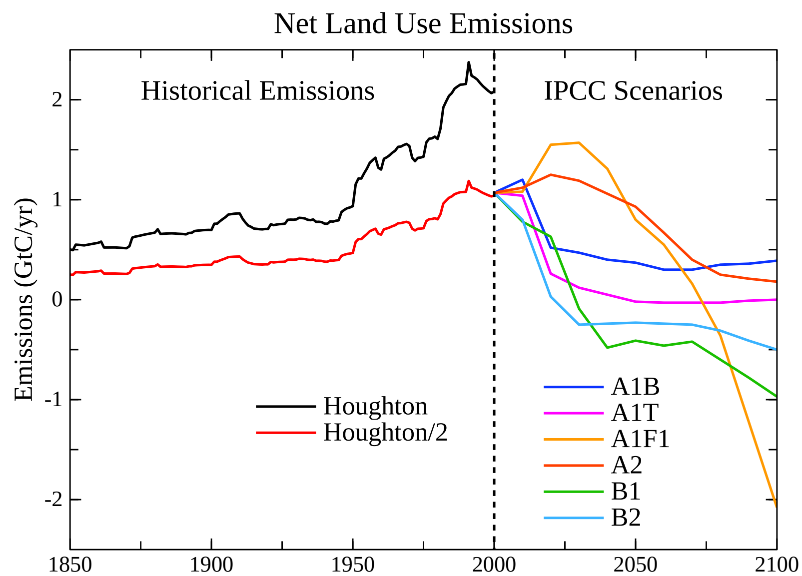

Fig. (S14). Left side: estimate by Houghton [83] of historical net land-use CO_2 emissions, and a 50 percent reduction of that estimate. Right side: IPCC [2] scenarios for land-use CO_2 emissions.

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.

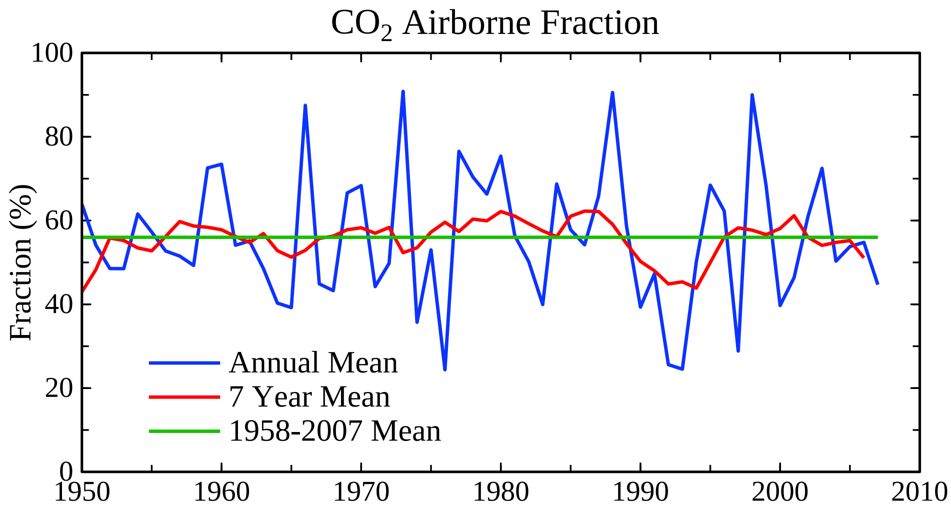

Fig. (S15). CO_2 airborne fraction, AF, the ratio of annual observed atmospheric CO_2 increase to annual fossil fuel CO_2 emissions.

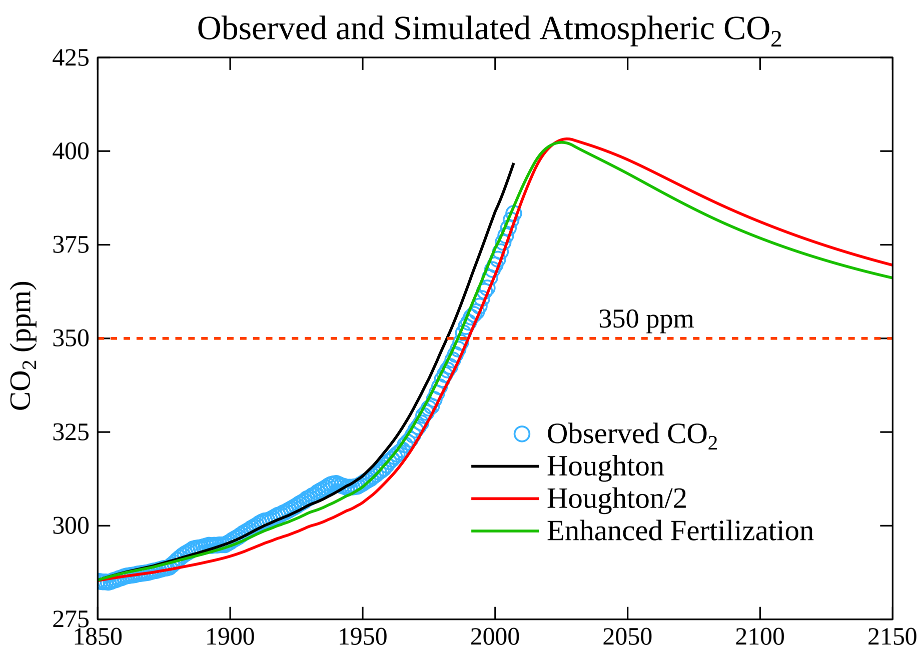

Fig. (S16). Computed and observed time evolution of atmospheric CO_2. "Enhanced Fertilization" uses the full "Houghton" land use emissions for 1850–2000. "Houghton/2" and "Enhanced Fertilization" simulations are extended to 2100 assuming coal phase-out by 2030 and the IPCC [2] A1T land-use scenario. 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.

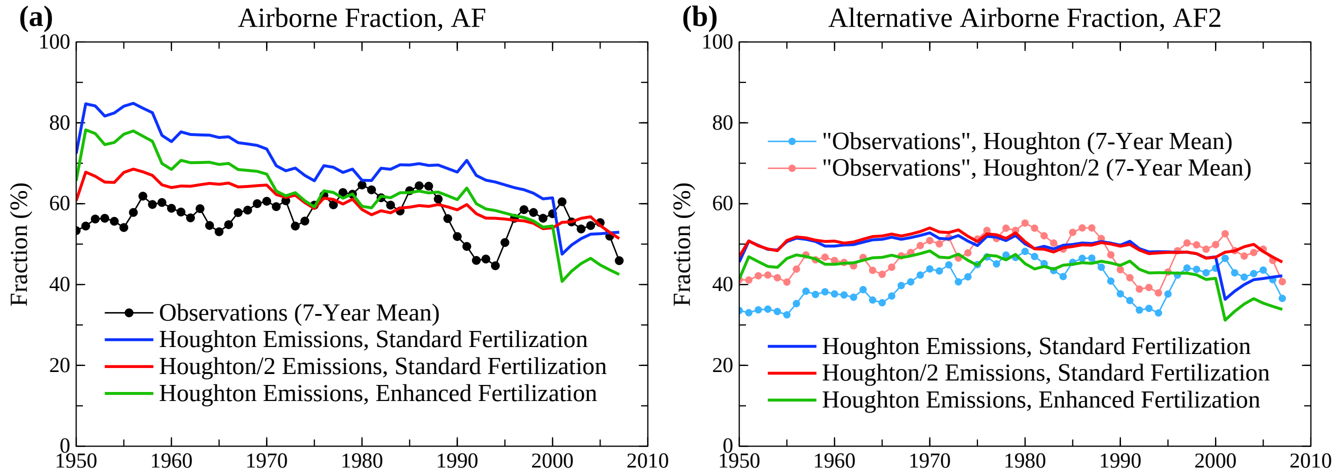

Fig. (S17). (**a**) Observed and simulated airborne fraction (AF), the ratio of annual CO_2 increase in the air over annual fossil fuel CO_2 emissions, (**b**) AF2 includes the sum of land use and fossil fuel emissions in the denominator in defining airborne fraction; thus AF2 is not accurately known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

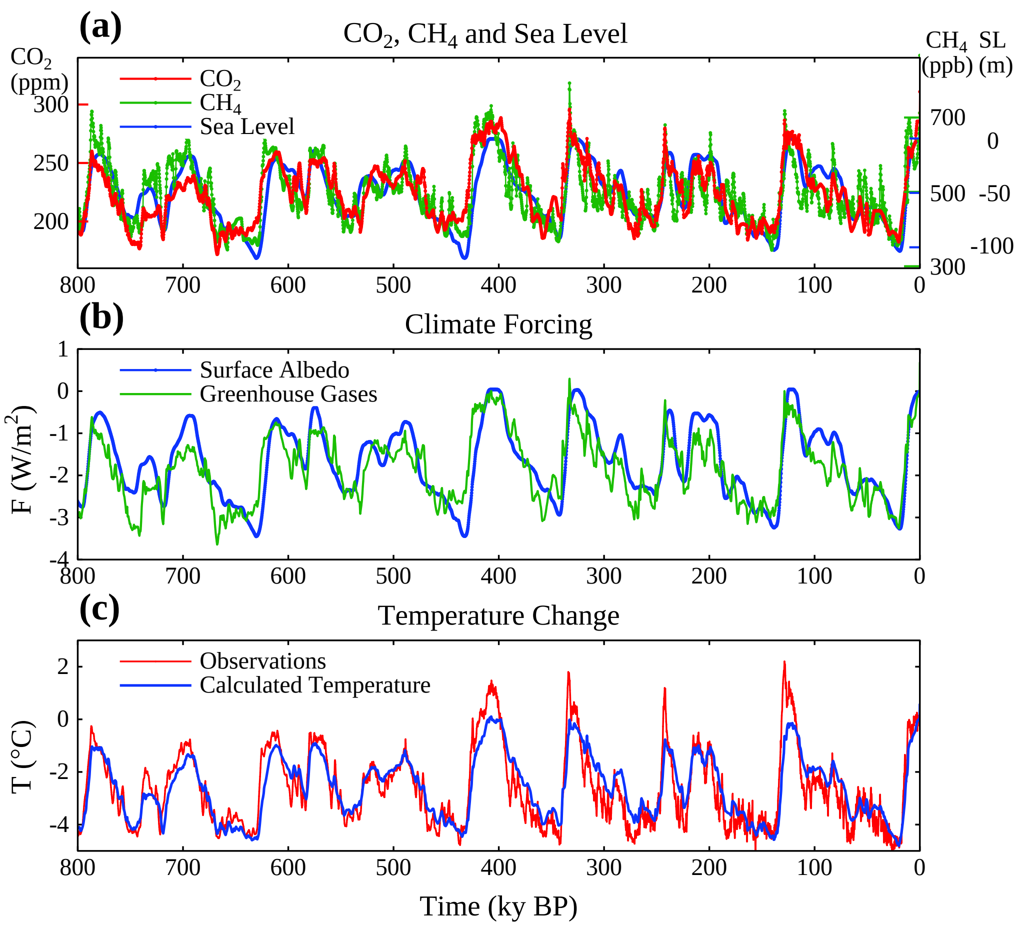

Fig. (S18). (**a**) CO_2 [S38], CH_4 [S39] and sea level [S16] for past 800 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from the sea level history of Bintanja *et al.* [S16]. (**c**) Calculated global temperature change based on the above forcings and climate 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].

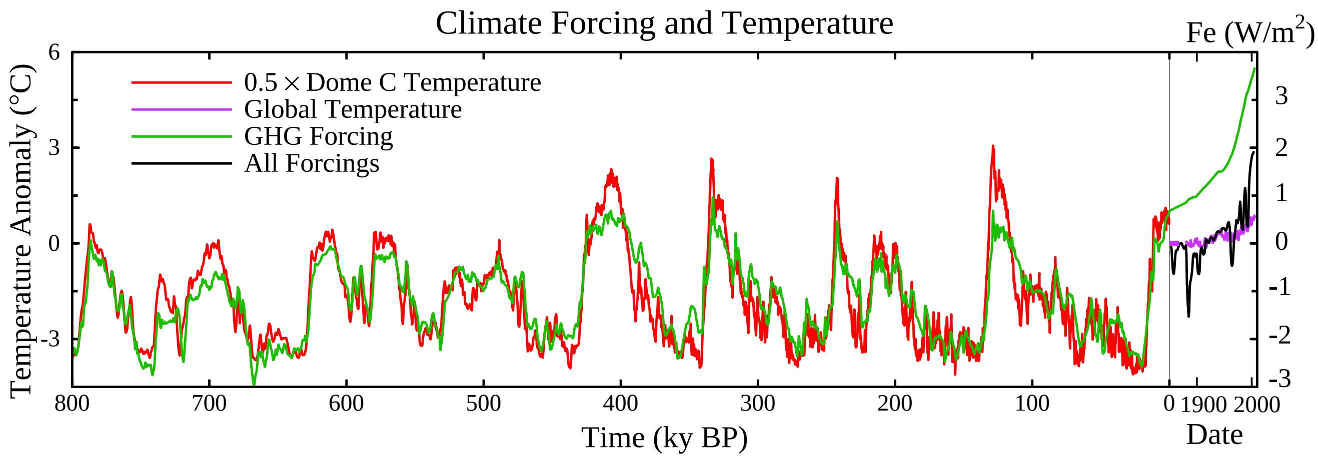

Fig. (S19). Global temperature change (left scale) estimated as half of temperature change from Dome C ice core [S8] and GHG forcing (right scale) due to CO_2, CH_4 and N_2O [S38, S39]. Ratio of temperature and forcing scales is 1.5°C per W/m^2. Time scale is expanded in the extension to recent years. 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.

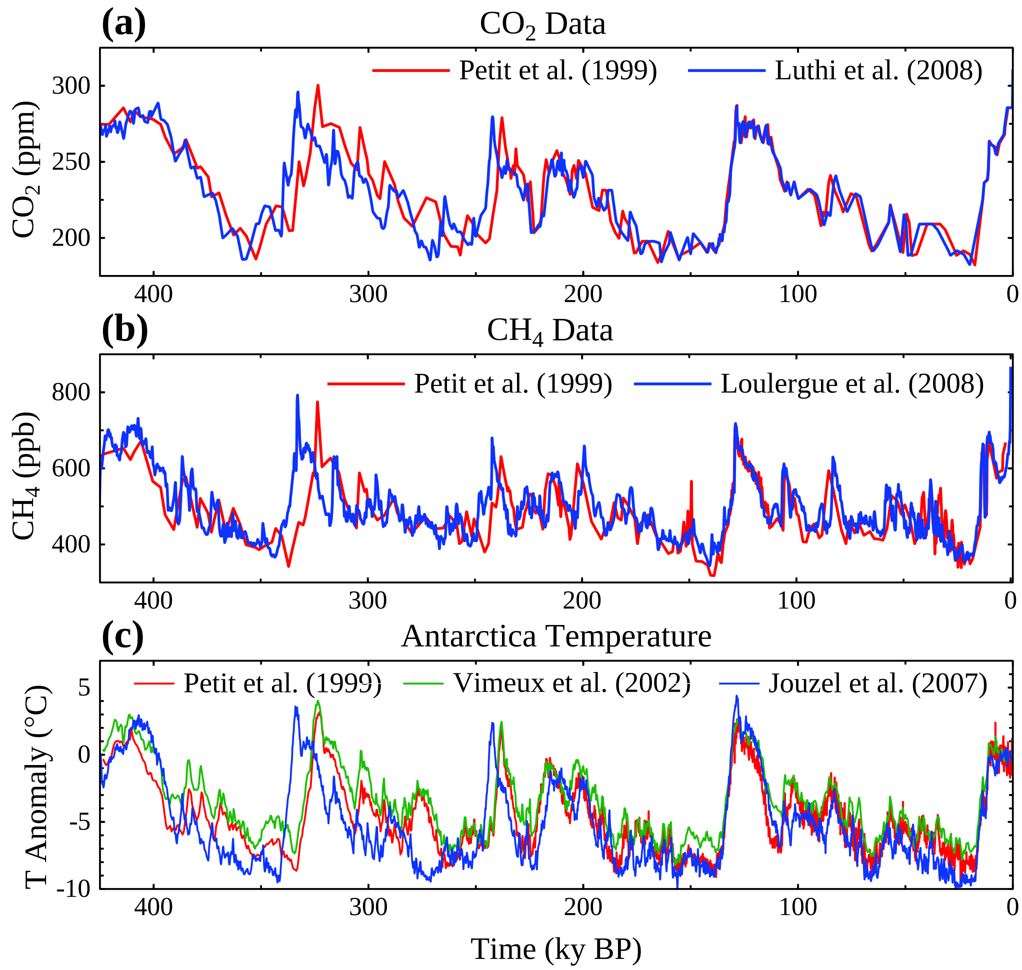

Fig. (S20). Comparison of Antarctic CO_2, CH_4, and temperature records in several analyses of Antarctic ice core data.

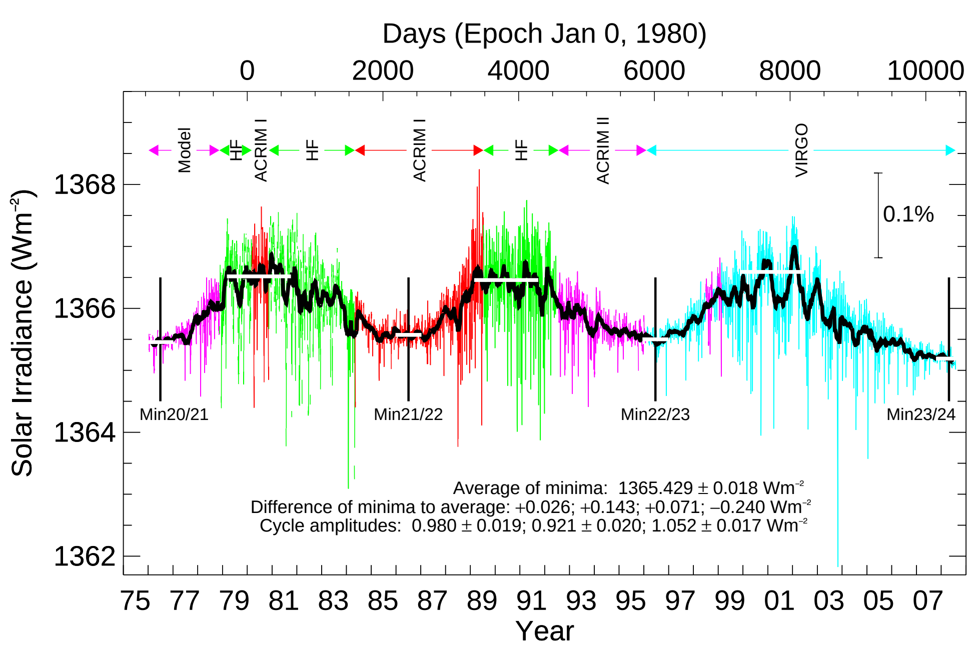

Fig. (S21). Solar irradiance from composite of several satellite-measured time series based on Frohlich and Lean [S44].

18. CLIMATE VARIABILITY, CLIMATE MODELS, AND UNCERTAINTIES

Climate exhibits great variability, forced and unforced, which increases with increasing time scale [2, 90, 91]. Increasing abilities to understand the nature of this natural variability and improving modeling abilities [S42] do not diminish the complications posed by chaotic variability for interpretation of ongoing global change.

Expectation that global temperature will continue to rise on decadal time scales is based on a combination of climate models and observations that support the inference that the planet has a positive energy imbalance [5, 8, 96]. If the planet is out of energy balance by +0.5-1 W/m^2, climate models show that global cooling on decadal time scales is unlikely [96], although one model forecast [95] suggests that the Atlantic overturning circulation could weaken in the next decade, causing a regional cooling that offsets global warming for about a decade.

The critical datum for determining the certainty of continued global warming on decadal time scales is the planet's energy imbalance. Improved evaluations of ocean heat storage in the upper 700 m of the ocean [97] yield ~0.5 x 10^{22} J/yr averaged over the past three decades, which is ~0.3 W/m^2 over the full globe. Our model has comparable heat storage in the ocean beneath 700 m, but limited observational analyses for the deep ocean [S43] report negligible heat storage.

If our modeled current planetary energy imbalance of 0.5-1 W/m^2 is larger than actual heat storage, the likely explanations are either: (1) the climate model sensitivity of 3°C for doubled CO_2 is too high, or (2) the assumed net climate forcing is too large. Our paleoclimate analyses strongly support the modeled climate sensitivity, although a sensitivity as small as 2.5 W/m^2 for doubled CO_2 could probably be reconciled with the paleoclimate data. The net climate forcing is more uncertain. Our model [8] assumes that recent increase of aerosol direct and indirect (cloud) forcings from developing country emissions are offset by decreases in developed countries.

These uncertainties emphasize the need for more complete and accurate measurements of ocean heat storage, as well as precise global observations of aerosols including their effects on clouds. The first satellite observations of aerosols and clouds with the needed accuracy are planned to begin in 2009 [98]. Until accurate observations of the planetary energy imbalance and global climate forcing are available, and found to be consistent with modeled climate sensitivity, uncertainties in decadal climate projections will remain substantial.

The sun is another source of uncertainty about climate forcings. At present the sun is inactive, at a minimum of the normal ~11 year solar cycle, with a measureable effect on the amount of solar energy received by Earth (Fig. **S21**). The amplitude of solar cycle variations is about 1 W/m^2 at the Earth's distance from the sun, a bit less than 0.1% of the ~1365 W/m^2 of energy passing through an area oriented perpendicular to the Earth-sun direction.

Climate forcing due to change from solar minimum to solar maximum is about ¼ W/m^2, because the Earth absorbs ~235 W/m^2 of solar energy, averaged over the Earth's surface. If equilibrium climate sensitivity is 3°C for doubled CO_2 (¾°C per W/m^2), the expected equilibrium response to this solar forcing is ~0.2°C. However, because of the ocean's thermal inertia less than half of the equilibrium response would be expected for a cyclic forcing with ~11 year period. Thus the expected global-mean transient response to the solar cycle is less than or approximately 0.1°C.

It is conceivable that the solar variability is somehow amplified, e.g., the large solar variability at ultraviolet wavelengths can affect ozone. Indeed, empirical data on ozone change with the solar cycle and climate model studies indicate that induced ozone changes amplify the direct solar forcing, but amplification of the solar effect is by one-third or less [S45, S46].

Other mechanisms amplifying the solar forcing have been hypothesized, such as induced changes of atmospheric condensation nuclei and thus changes of cloud cover. However, if such mechanisms were effective, then an 11-year signal should appear in temperature observations (Fig. **7**). In fact a very weak solar signal in global temperature has been found by many investigators, but only of the magnitude (~0.1°C or less) expected due to the direct solar forcing.

The possibility remains of solar variability on longer time scales. If the sun were to remain 'stuck' at the present solar minimum (Fig. **S21**) it would be a decrease from the mean irradiance of recent decades by ~0.1%, thus a climate forcing of about -0.2 W/m^2.

The current rate of atmospheric CO_2 increase is ~2 ppm/year, thus an annual increase of climate forcing of about +0.03 W/m^2 per year. Therefore, if solar irradiance stays at its recent minimum value, the climate forcing would be offset by just seven years of CO_2 increase. Human-made GHG climate forcing is now increasing at a rate that overwhelms variability of natural climate forcings.

Climate models are another source of uncertainty in climate projections. Our present paper and our estimated target CO_2 level do not rely on climate models, but rather are based on empirical evidence from past and ongoing climate change. However, the limited capability of models to simulate climate dynamics and interactions among climate system components makes it difficult to estimate the speed at which climate effects will occur and the degree to which human-induced effects will be masked by natural climate variability.

The recent rapid decline of Arctic ice [S47-S49] is a case in point, as it has been shown that model improvements of multiple physical processes will be needed for reliable simulation. The modeling task is made all the more difficult by likely connections of Arctic change with the stratosphere [S50] and with the global atmosphere and ocean [S51].

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LETTERS

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Emission pathways consistent with a 2 °C global temperature limit

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In recent years, international climate policy has increasingly focused on limiting temperature rise, as opposed to achieving greenhouse-gas-concentration-related objectives. The agreements reached at the United Nations Framework Convention on Climate Change conference in Cancun in 2010 recognize that countries should take urgent action to limit the increase in global average temperature to less than 2 °C relative to pre-industrial levels[1]. If this is to be achieved, policymakers need robust information about the amounts of future greenhouse-gas emissions that are consistent with such temperature limits. This, in turn, requires an understanding of both the technical and economic implications of reducing emissions and the processes that link emissions to temperature. Here we consider both of these aspects by reanalysing a large set of published emission scenarios from integrated assessment models in a risk-based climate modelling framework. We find that in the set of scenarios with a 'likely' (greater than 66%) chance of staying below 2 °C, emissions peak between 2010 and 2020 and fall to a median level of 44 Gt of CO_2 equivalent in 2020 (compared with estimated median emissions across the scenario set of 48 Gt of CO_2 equivalent in 2010). Our analysis confirms that if the mechanisms needed to enable an early peak in global emissions followed by steep reductions are not put in place, there is a significant risk that the 2 °C target will not be achieved.

Cumulative emissions of long-lived greenhouse gases (GHGs) approximately define the temperature response of the climate system at timescales of centuries to millennia[2–4] because a significant fraction of CO_2 emissions, the dominant anthropogenic GHG, is removed very slowly from the atmosphere[5,6]. The temperature response will therefore continue, even when global emissions return to zero, or when concentrations are stabilized[6,7]. Cumulative emissions provide very little information on the technical feasibility and cost implications of following a particular 'emissions pathway', information that is needed for policymakers who are deciding now on emissions goals for the coming decades. Path-dependent assessments, such as the United Nations Environment Programme's *The Emissions Gap Report*[8], are therefore highly policy-relevant. This work extends the pathway analysis of that report (see Supplementary Information).

The Cancun Agreements refer to holding global mean temperature increase below 2 °C. Therefore, we do not allow a temperature overshoot in this study, although concentrations may temporarily overshoot a level that in equilibrium would lead to an exceedance of the temperature limit. There is increasing evidence from recent studies[7,9,10] that a decline of temperature might be unlikely on timescales relevant to human societies in the absence of strongly negative emissions. The slow ocean mixing that delays warming due to anthropogenic radiative forcing at present would also limit the amount of cooling for many decades to centuries[9–11].

Scenarios developed by integrated assessment models (IAMs) represent analyses of how society could evolve given assumed constraints of feasibility. In general, 'feasibility' encompasses technological, economic, political and social factors. IAMs account for some of these factors by assuming a set of mitigation technologies, constraining their potential and the rate at which these technologies can be introduced, amongst other things. Examples of such constraints include assumptions about the maximum feasible technology penetration rates, maximum cost, constraints on the use of renewables based on their intermittency and a maximum speed of specific system changes. Societal and political factors have typically received only limited attention: for instance, nearly all mitigation scenarios assume full participation of all regions in global mitigation efforts.

Scenarios from different IAMs consistent with different policy targets have been compared in previous studies[12,13]. Most of these focus on optimal (least-cost) pathways to achieve GHG concentration stabilization. Only recently, modelling comparison studies[12] have started focusing on second-best scenarios, which assume limited/delayed international participation of countries and/or reduced technology availability implying delayed emission reductions. The range in IAM outcomes for similar targets is broad, and reflects prevailing uncertainties captured by different methods and underlying assumptions[12,14,15]. Considering the combined impact on mitigation targets of both climate and technical and economic constraints and uncertainties has thus far received little attention.

Here we present a scenario reanalysis focusing on temperature targets. We use the carbon-cycle and climate model MAGICC6 (ref. 16), constrained by historical observations, to obtain estimates

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Table 1 | Overview of pathway characteristics of emission pathways that limit global average temperature increase to below 2 °C relative to pre-industrial levels during the twenty-first century.

	Number of pathways	Peaking decade* (2000 + year)	Total GHG emissions in 2020 (Gt CO_2e)	Average industrial CO_2 post-peak reduction rates† (percentage of 2000 emissions per year)
'Very likely' chance (>90%) of staying below 2 °C during twenty-first century‡				
Without global net negative industrial CO_2 emissions	0	—	—	—
With global net negative industrial CO_2 emissions	3	10(—[10]—)15	41(—[43]—)44	3.2(—[3.3]—)3.3
All pathways	3	10(—[10]—)15	41(—[43]—)44	3.2(—[3.3]—)3.3
'Likely' chance (>66%) of staying below 2 °C during twenty-first century				
Without global net negative industrial CO_2 emissions	14	10(10[10]10)20	21(26[42]45)48	0(1.0[2.3]3.3)3.6
With global net negative industrial CO_2 emissions	12	10(10[10]15)15	41(41[44]46)48	1.5(1.7[3.0]3.5)3.8
All pathways	26	10(10[10]15)20	21(31[44]46)48	0(1.5[2.7]3.4)3.8
'At least fifty-fifty' chance (>50%) of staying below 2 °C during twenty-first century				
Without global net negative industrial CO_2 emissions	20	10(10[10]15)20	21(28[44]47)48	0(1.3[2.4]3.1)3.6
With global net negative industrial CO_2 emissions	19	10(10[10]20)30	41(42[45]48)50	1.2(1.7[3.0]3.6)5.9
All pathways	39	10(10[10]15)30	21(38[44]47)50	0(1.5[2.7]3.5)5.9

Data are provided for three probability options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%) or 'at least fifty-fifty' (greater than 50%) chance.
Format: minimum(15%quantile[median]85%quantile)maximum. *The year given is an indication of the middle of the decade in which the peaking occurs in the scenarios. †Being relative to constant 2000 emissions, these reduction rates differ from exponential reduction rates (see Methods). ‡Owing to the low number of pathways, only minimum, median and maximum values are given for the 'very likely' option.

of future atmospheric GHG concentrations and transient temperatures (see Methods). This approach eliminates the uncertainty due to differing climate representations within the individual IAM studies[17]. We compiled a set of 193 emissions pathways from the literature (see Methods and Supplementary Information). Of this set, roughly one third represents baseline scenarios (that is, possible developments in the absence of climate policy intervention) and the remainder represents emission mitigation scenarios.

Owing to the uncertainty in our quantitative understanding of the climate system and carbon-cycle response to emissions, the projected results can be defined in terms of a probability of staying below a given temperature target. The choice of which target and with which probability it is to be reached can be informed by science but is fundamentally a political question depending on risk and value judgements. Policymakers in Cancun did not specify such a probability, neither quantitatively nor qualitatively. To cover a range of possible choices, we evaluate pathways for three options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%) and an 'at least fifty-fifty' (greater than 50%) probability throughout the twenty-first century (see Methods). Pathways with a 'very likely' 2 °C probability are a subset of pathways with a 'likely' probability, which are in turn a subset of the pathways with an 'at least fifty-fifty' probability of limiting temperature increase to below 2 °C.

In our set, none of the baseline scenarios is able to limit the global temperature increase to below 2 °C. On the other hand, 3, 26 and 39 pathways have a 'very likely', 'likely' and 'at least fifty-fifty' chance to limit global temperature change to below 2 °C during the twenty-first century, respectively (Table 1, Fig. 1). In all pathways, emissions peak in the short term and decline later to stay below 2 °C. We start from estimated median 2010 emissions across our harmonized set (see Methods) of about 48 Gt of CO_2 equivalent (CO_2e). For pathways with a 'likely' chance of staying below 2 °C we find the following characteristics: median 2020 emissions are 44 Gt CO_2e, with a 15–85% quantile range of 31–46 Gt CO_2e. Most of these pathways (at least 85% of all cases) peak global emissions before 2020. After the peak, emissions decline. Still for the same pathways, median annual post-peak CO_2 reduction rates (see Methods) are around 2.7% (range 1.5–3.4%), and global total GHG emissions in 2050 show a median reduction of 45% (range 35–55%) below 1990 levels of 36.6 Gt CO_2e.

Besides a 2 °C limit, the Cancun Agreements furthermore include a commitment to review and consider strengthening the long-term goal, particularly in relation to a 1.5 °C limit. No ensemble member (including even the most stringent mitigation scenarios) limits warming to less than 1.5 °C throughout the entire century for any of the probability options. However, some scenarios in our set bring warming back below 1.5 °C by 2100: a first scenario (from 'POLES' in ref. 13) does so with a probability of about 50%, and a second scenario (from 'MERGE' in ref. 13) with a 'likely' chance (>66%).

An important difference[14] is noted between pathways that do not show global CO_2 emissions from energy and industry to become negative compared with those that do. Net negative emissions from the energy and industry sector may be possible through the application of a combination of capture and geological storage[18] of CO_2 (CCS) and bio-energy[19] (BECCS). In the pathways with no negative emissions, the median 2020 values for the 'likely' option are 2 Gt CO_2e lower at 42 Gt CO_2e (Table 1). Pathways that have net negative emissions (28 in total) feature higher rates of post-peak emission reductions while not exhibiting significant differences for the peak period. An in-depth analysis of the influence of BECCS on the

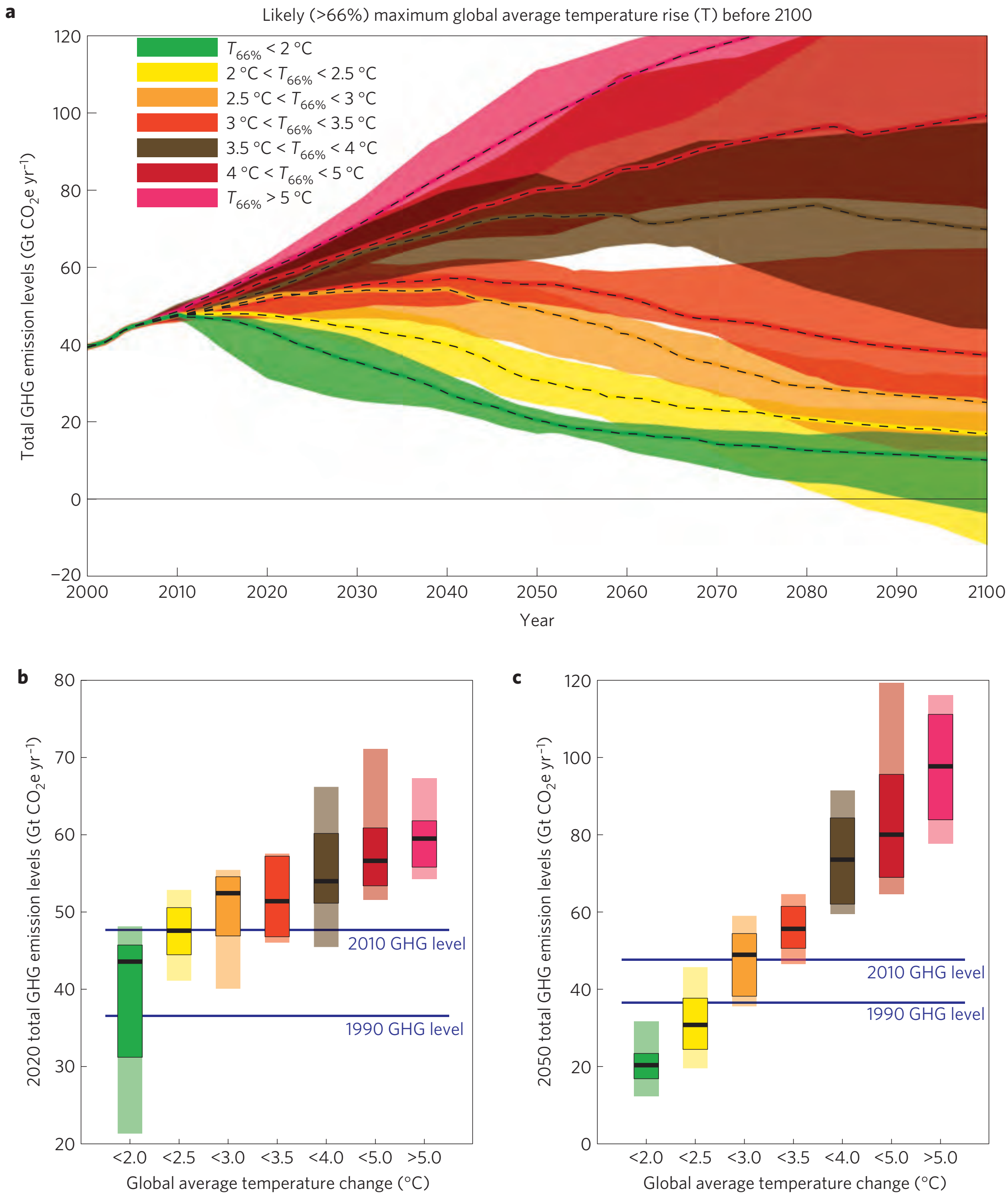

Figure 1 | Emission ranges of published IAM scenarios, colour coded as a function of the likely (greater than 66% probability) avoided global average temperature increase. a, 15–85% quantile ranges over time of global total GHG emissions of pathway sets consistent with a given temperature limit during the twenty-first century. Colour coding defines the respective temperature limit per pathway set. Black dashed lines show the median for each respective pathway set. **b**,**c**, 2020 (**b**) and 2050 (**c**) time slices of global total emissions consistent with a temperature limit during the twenty-first century. Shaded areas represent the minimum–maximum ranges; the coloured bounded rectangles the 15–85% quantile ranges and the thick black horizontal lines the median values for each temperature level, respectively. Horizontal blue lines represent median 1990 and 2010 emissions. Ranges for the other probability options (>90% and >50%) and time slices are given in Supplementary Figs S1–S5.

global peak of emissions is not possible with the available scenarios and would require specifically designed experiments that address this question.

Weakening the stringency of the 2 °C limit and accepting a lower chance of success (at least 50% instead of 66% probability), slightly shifts the 15–85% quantile range of scenarios in 2020 to 38–47 Gt CO_2e (the median remains at 44 Gt CO_2e). The peaking period remains during the present decade (precision-limited by the decadal-resolution data from the IAMs) and the median post-peak emission reduction rates are virtually the same as for the 'likely' case in more than 85% of the cases. Finally, the three pathways with a 'very likely' (greater than 90%) chance of success show a peak during this decade, 2020 emissions not exceeding 44 Gt CO_2e and post-peak reduction rates that are higher than the medians from the other cases. These three pathways have negative emissions.

Atmospheric CO_2 and CO_2e concentrations in 2100 of the pathways 'likely' consistent with 2 °C (Table 2) are around 425 ppm CO_2 (range 415–460) and 465 ppm CO_2e (range 435–475), respectively. Pathways consistent with 2 °C with a 'likely' or 'fifty-fifty' chance have peaked CO_2 concentrations during the twenty-first century (see Methods) in about 30 and 40% of the cases, respectively. CO_2-equivalent concentrations peaked in about 40% of the cases for both probability options. If scenarios do not peak concentrations, they stabilize during the twenty-first century. A

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Table 2 | Overview of 2020 emissions, 2100 atmospheric CO_2 and total GHG concentrations of pathways that hold global average temperature increase below a specific temperature limit.

	Number of pathways	Total GHG emissions in 2020 ($Gt\ CO_2e$)	Atmospheric concentrations in 2100	
			CO_2 ($ppm\ CO_2$)	Total GHG ($ppm\ CO_2e$)
Emission pathways with a 'likely' (>66%) probability to limit temperature increase to below:				
1.5 °C	Insufficient data	Insufficient data	Insufficient data	Insufficient data
2 °C	26	21(31[44]46)48	375(412[423]457)468	400(436[463]476)486
2.5 °C	46	41(44[48]51)53	376(416[490]506)542	422(472[526]554)557
3 °C	45	40(47[52]55)55	477(501[542]574)616	554(561[609]636)645
3.5 °C	22	46(47[51]57)58	540(562[602]659)709	647(649[669]751)775
4 °C	18	45(51[54]60)66	649(661[726]811)890	759(782[833]869)939
5 °C	19	52(53[57]61)71	678(746[817]958)1104	851(922[993]1101)1134
Above 5 °C	10	54(56[59]62)67	888(905[975]1046)1049	1116(1153[1207]1318)1482

Data are provided for pathways that hold temperature increase to below a given temperature limit during the twenty-first century with a 'likely' (greater than 66%) chance. Results are given for temperature bins defined by the temperature limit and its preceding limit. For example, the '3 °C' row shows characteristics for emission pathways that limit warming below 3 °C with a 'likely' chance, but above 2.5 °C. See also Fig. 1 and Supplementary Fig. S6. Data for the other probability options are presented in Supplementary Figs S3, S5, S7 and S8, and in Supplementary Tables S1 and S2. Format: minimum(15%quantile[median]85%quantile)maximum.

decline afterward is not excluded. All 'very likely' chance pathways show a peak and decline in CO_2e concentrations of GHGs. More than 70% of the 'likely' chance scenarios assume global net negative CO_2 emissions from industry and energy to achieve such peaking. Furthermore, all scenarios that would comply with a 'fifty-fifty' chance and are outside the 'likely' subset include such negative emissions.

There are a number of caveats in interpreting our results. First, by describing the 15–85% quantiles over time, the intertemporal relationship between different emission paths is masked. Although the median path can be considered as a representative evolution of emissions for 'likely' pathways, the 15 and 85% quantile paths cannot. Emissions near the 85% quantile path in the first half of the century are followed by emissions near the 15% quantile path in the second half and vice versa (see Supplementary Fig. S9).

Second, besides results from the 15–85% quantiles, results outside this range also give insights. They provide information about potential future worlds in the tails of the distributions. A few pathways[20,21] (three in total) suggest that emissions could decline globally to about 30%–40% below 1990 levels by 2020. On the other side of the spectrum, one pathway[22] peaks at 48 Gt CO_2e in 2020 owing to delayed participation and still stays below 2 °C with a 'likely' chance. Another scenario[23] shows steep emission reduction rates of 5.9% after peaking at 50 Gt CO_2e around 2030, while still having an 'at least fifty-fifty' probability to stay below 2 °C. CCS contributes massively to the mitigation portfolio in this scenario, capturing up to almost double the present global CO_2 emissions per year by 2065. For most scenarios in our set, a peak in world emissions in 2030 would be more consistent with a 'likely' chance to stay below 3 °C instead of 2 °C.

A third issue is that for many scenarios the potential for net negative global CO_2 emissions from energy and industry is a crucial factor[14]. The potential of BECCS (refs 18,19) is already included in many IAMs. However, as for other advanced technologies, BECCS has not been demonstrated on a significant scale in the real world. Concerns exist with respect to CO_2 storage potential[18] as well as with respect to competition of large-scale bio-energy systems[24] with food production, biodiversity and ecosystem services. Other negative emission technologies, such as direct air capture of CO_2, are not explicitly included in most models at present.

Fourth, our set of pathways represents scenarios that are considered feasible by IAMs. The extent to which the realization of such scenarios is plausible in the real world goes beyond techno-economic and physical constraints represented by the IAMs, and also depends highly on factors such as political circumstances and public acceptance. Our analysis of the scenario space relies on the soundness and quality of the underlying IAM studies, and does not imply any independent assessment of the feasibility of the above-mentioned factors. We also acknowledge that only a limited set of scenarios were run for the low-temperature targets discussed here, and that scenario details are often not reported when IAMs find these targets infeasible[12]. Our findings, in particular with respect to low-emissions scenarios, therefore should be interpreted as an indication of the stringency of mitigation that would need to occur to keep specific targets within reach. They should, however, not be interpreted as a comprehensive assessment of the feasibility of the required mitigation action.

Related to this, it should be noted that most of the IAM scenarios used in this study tried to find cost-effective pathways for long-term climate targets. Scenarios that would look at economically less attractive[12,25] options could feature higher and/or later peaks with steeper declines afterwards. The ensemble we used was not designed to systematically sample all possible options, but represents an 'ensemble of opportunity'[26]. Clearly, IAMs do not set 'hard laws' on the consideration of whether achieving a particular scenario is possible. They are based on modellers' assumptions about technological and economic constraints, which are subject to change. Finally, a better understanding of socio-economic impacts of regional climate change and their inclusion in IAMs might have a large influence on the medium- and long-term cost efficiency of emission pathways. As understanding evolves, it will be necessary to update assessments such as the one presented here and develop studies that address this question directly. Furthermore, the treatment of political feasibility, including the will of national governments to implement transitions to low-carbon economies, remains a big unknown.

This analysis implies that the range of published IAM scenarios in line with the goal of staying below 2 °C with a 'likely' chance would peak during this decade and have annual 2020 emissions of around 44 Gt CO_2e (range of 31–46 Gt CO_2e). Our scenario set includes hardly any scenarios that take delayed participation of regions in international carbon markets into account. However, not assuming this at present seems optimistic given the reluctance of some major emitters to join such a system. Following higher 2020 emissions and later peaking as a result of weaker early mitigation action would significantly reduce the chances of staying below 2 °C. Without a firm commitment to put in place the mechanisms to enable an early global emissions peak followed by steep reductions thereafter, there are significant risks that the 2 °C target, endorsed by so many nations, is already slipping out of reach.

Methods

We reanalysed an ensemble of 193 emission pathways from IAMs. This ensemble includes reference and mitigation pathways from model intercomparison studies (refs 12,13,27, among others, see Supplementary Table S3 for an overview of all references), as well as from other stabilization and non-intervention scenarios. All members are treated equally likely in the set.

Historical emission estimates come with a typical uncertainty range of 20–30% (ref. 28). Therefore, for each member of the ensemble, the historical emissions up to 2005 are harmonized to the historical multi-gas emission inventory developed in the framework of the representative concentration pathways[29,30] (RCPs). Emissions of each ensemble member are adjusted with a tapered scaling factor that returns to unity in 2050. This approach prevents possible amplification of negative emissions in the second half of the century[28]. When future emissions of a particular gas are missing, the multi-gas characteristics of the RCP3-PD scenario[31] are assumed, including sulphate aerosols, organic carbon, black carbon and atmospheric ozone precursors. The RCP3-PD scenario models strong environmental and climate policies. This choice is therefore consistent with our set-up to primarily analyse mitigation pathways that reduce emissions to be consistent with international temperature limits. Ozone-depleting substances controlled by the Montreal Protocol are assumed to follow a gradual phase-out during the twenty-first century.

After harmonization, six IAM pathways that show a decline or stabilization in historical emissions from 2005 to 2010 are excluded from the final ensemble. We also excluded one scenario for which insufficient detailed information about the underlying assumptions was available (as in ref. 12).

Each member of the harmonized multi-gas emission pathway ensemble is analysed probabilistically with the reduced-complexity climate system and carbon-cycle model MAGICC (ref. 16), version 6. MAGICC has been calibrated and shown to be able to reliably determine the atmospheric burden of CO_2 concentrations following high-complexity carbon-cycle models[16,32]. It is also able to project global average near-surface warming in line with estimates made by complex atmosphere–ocean general circulation models for a range of forcing scenarios, as assessed in the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change[33] (IPCC). Here it has been set up with historical constraints for observed hemispheric land/ocean temperatures and ocean heat-uptake (see Supplementary Information), emulating the C^4MIP carbon-cycle models[34] and with the same climate-sensitivity probability distribution as the ‘illustrative default case’ in ref. 2 that closely reflects IPCC estimates[33]. Herewith, the uncertainties in climate sensitivity, ocean heat-uptake and the response of the carbon-cycle to a given emissions pathway are taken into account. For each pathway, a 600-member ensemble is calculated to determine its resulting time-evolving temperature probability distribution.

We carried out a sensitivity analysis on the climate-sensitivity choice and on the assumptions regarding anthropogenic aerosols, soot and organic carbon, and found that our results are robust under those sensitivity cases (see Supplementary Information and Supplementary Table S4).

The range of results from this reanalysis of IAM pathways always refers to the median, and the 15–85% quantile range (as an approximation of the one-standard-deviation range around the mean). This provides a point of comparison with the approach in the IPCC AR4 (ref. 15). For completeness, also the minimum–maximum range is given. Total GHG emissions refer to emissions included in the Kyoto basket of GHGs, which contains carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (SF_6) (see Supplementary Information). ‘Negative CO_2 emissions’ refer to net global emissions from energy and industry, excluding land-use emissions. The ‘post-peak’ reduction rates are calculated over the period between 10 and 30 years after the peak. To allow comparison and ensure consistency with the IPCC AR4, reduction rates are computed for global CO_2 emissions from energy and industry, and relative to 2000 levels. If fewer than 10 pathways were available in a particular subset, only median, minimum and maximum values are provided. If a pathway yields atmospheric CO_2 concentrations in 2100 that are at least 5% lower than the maximum concentration during the twenty-first century, this pathway is defined to have peaked concentrations during this century. The same approach applies to the total GHG (CO_2e) concentrations.

Temperatures projections ‘relative to pre-industrial’ are calculated relative to the 1850–1875 base period.

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Author contributions

J.R., W.H., J.L., K.R., B.M., M.M. and D.P.v.V. designed the research. M.M. developed the climate model set-up. J.R. carried out the research. All authors discussed the results and contributed to writing the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.R.

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Sharing the effort under a global carbon budget

Niklas Höhne
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24 August 2009

Commissioned by:
WWF International

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PECPDE083519

WWF foreword

In order to avoid dangerous climate change there is a growing consensus among now more than 120 countries that average global temperatures should not increase by more than 2°C over pre-industrial levels. This was affirmed in July of this year by the G8+5 nations, a group of countries encompassing all major emitters from the developed and developing world. This is a giant leap forward and provides large hope for success of the ongoing negotiations for a post-2012 treaty to be agreed in Copenhagen at the Climate Summit in December this year.

How can this objective be met? WWF and other members of the Climate Action Network (CAN) are strongly promoting a legally binding mid-term target of at least 40% emissions reductions by 2020 below 1990 levels for developed countries as a group, under common but differentiated responsibilities that require nations that are rich and have high per capita emissions to 'pay back' their atmospheric debt. Globally, all countries need to have reduced their total greenhouse gas emissions by at least 80% below 1990 levels by 2050 in order for the world to stay below 2°C of warming.

The emissions trajectory between now and 2050 needs to be distributed in an equitable way with the appropriate distinctions made between 'rich' and 'poor' and between 'high' and 'low' per capita emitters. To inform the international debate, WWF asked the leading energy research consultancy ECOFYS to elaborate on the practicalities and implications of some suggested methodologies already under discussion and some that are promising and should receive consideration.

As well as the need for an 80% cut in emissions globally by 2050, another requirement taken into account by the research was the need to cut global emissions by 30% over 1990 levels by 2030 – a feasible as well as necessary target according to a recent climate action cost calculation, the McKinsey Climate Cost Curve 2.0. Also, land use factors globally need to turn from being a net source of CO_2 to becoming a net sink between 2020 and 2030, with major reductions required in emissions from deforestation and clearing in the tropics. Action at this level could ensure the entire world becomes a net emissions sink post 2060.

Although WWF has strong sympathy with the Greenhouse Gas Development Right Framework to distribute the allowable emissions in a social and equitable way in the next decades, at this point in time WWF is not promoting any particular approach to distribute the finite global greenhouse gas budget between 1990 and 2100. But whichever approach the world chooses in order to stay below 2°C, the cumulative greenhouse gas budget cannot change substantially. If we relax on the trajectory of one country, another country needs to pick up the bill. There is no carbon offset for Planet Earth as such. We know, decarbonising the economy in the next 50 years or so will be tough for most nations – and let us be very honest – particularly for many rapidly industrialising nations.

However, unabated climate change will cost much more socially, economically and environmentally. It will wreak havoc on global food security and freshwater availability, and its impacts will be disproportionately felt by poor and vulnerable communities. What WWF seeks to do with this paper is to kick-start a debate on how to globally share the carbon budget consistent with a trajectory to keep global warming below 2°C. This is not about burden sharing – this is about benefit sharing. Compared to unabated climate change, perceived economic 'hardship' is a luxury problem.

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Executive summary

Stringent global greenhouse gas emission reductions by all sectors and all countries will be necessary to keep global average temperature increase below 2°C. This report gives an overview of different methods to share the effort of reducing greenhouse gas emissions between countries to reach a given global carbon budget by 2100 in line with the 2°C limit.

First, we defined the carbon budget, which is the amount of tolerable global emissions over a period of time. Afterwards, we divided the available emission rights among countries according to different rules. To be consistent with the 2°C limit, for this report we assume CO_2eq emissions will have to be reduced by 30% compared to 1990 levels by 2030. By 2050 global emissions excluding those from land-use change and forestry (LUCF) need to be reduced by 80% compared to 1990. This leads to an emission budget of roughly 1800 $GtCO_2$eq between 1990 and 2100 excluding LUCF. Further, we assume that emissions from LUCF remain constant at about 4 $GtCO_2$ until 2010 and decline to zero by between 2010 and 2020. LUCF will become a stable net sink of emissions afterwards. By 2030 LUCF will remain at -4 $GtCO_2$. The global emission budget including LUCF will, thus, be about 1600 $GtCO_2$eq. This is the budget between 1990 and 2100. Until today and because mankind has already increased its global emissions substantively since 1990, the remaining net cumulative budget between 2009 and 2100 is limited to 870 GtCO2eq. This translates to an allowable global annual emission on average for the next 91 years of no more than 9.5 $GtCO_2$eq, or about 20% of today's annual net global emissions.

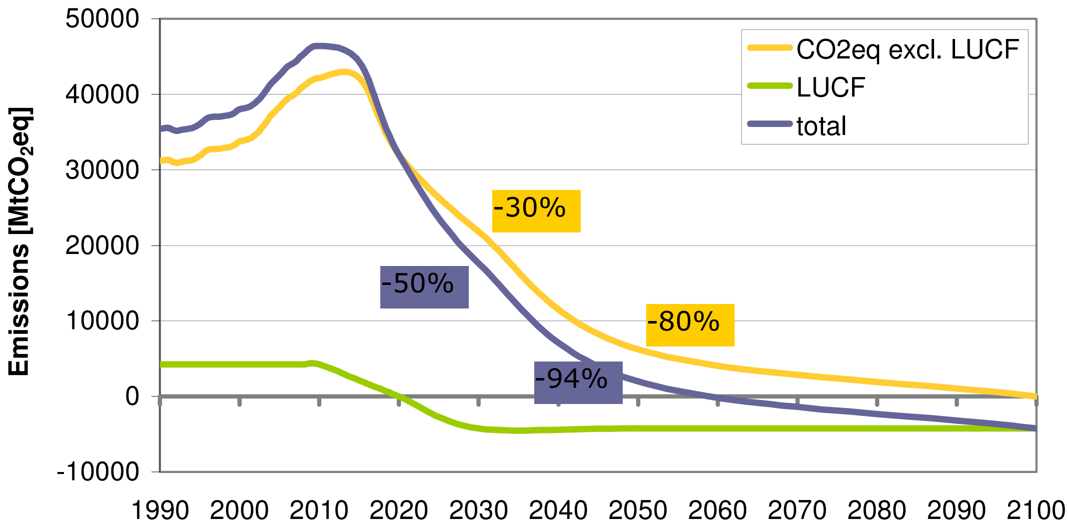

Figure 1. Possible global GHG emissions pathway between 1990 and 2100 according to a global carbon budget of about 1800 Mt CO_2eq (excl. LUCF) and 1600 Mt CO_2eq (incl. LUCF)

Under this strict emission budget, delay in reductions of only 5 years has significant consequences. Starting absolute global emission reductions around the year 2015 requires global average annual emissions reductions of about 5%, which already is very ambitious. Starting absolute global reduction in 2020 requires a global annual reduction of 8% after 2020.

The requirements to reach this are very stringent (see Figure 2). This is also reflected by the resulting target of about 0.5 tCO_2eq per capita as global average in 2050. In

2020 the average per capita emissions are around 9 tCO_2eq per capita for Annex I and 3-5 tCO_2eq per capita for non-Annex I.

We have shared the global emission budget using three methodologies, which are currently under discussion:

- Greenhouse Development Rights (GDRs): All countries need to reduce emissions below their business as usual path based on their responsibility (cumulative emissions) and capacity (GDP). Only emissions and GDP of the population above a development threshold account towards responsibility and capability.
- Contraction and Convergence (C&C): The targets for individual countries are set in such a way that per capita emission allowances converge from the countries' current levels to a level equal for all countries within a given period, here until 2050.
- Common but Differentiated Convergence (CDC): As above, targets are set so per capita emissions for all countries converge to an equal level over the period 2010 to 2050. For developed (Kyoto Protocol Annex I) countries' per capita emission allowances convergence starts immediately. For individual non-Annex I countries' per capita emissions convergence starts from the date when their per capita emissions reach a certain percentage threshold of the (gradually declining) global average.

Generally, the Greenhouse Development Rights approach (GDRs) allows negative emissions where required reductions based on capacity and responsibility are larger than business as usual emissions. Contraction and Convergence (C&C) and Common But Differentiated Convergence (CDC) allow only very low but not negative emission levels. Therefore, Annex I emission targets go to -60% in 2020 under the GDRs, while the other approaches require around -40%.

Negative emission allowances (below 100% of base year) do not mean that the respective countries have to mitigate everything domestically. This is just a method of illustrating the equitable emissions allocations under this methodology. In reality it means that industrialised countries have to substantially support reducing emissions in developing countries via the carbon market, technology and/or funding etc.

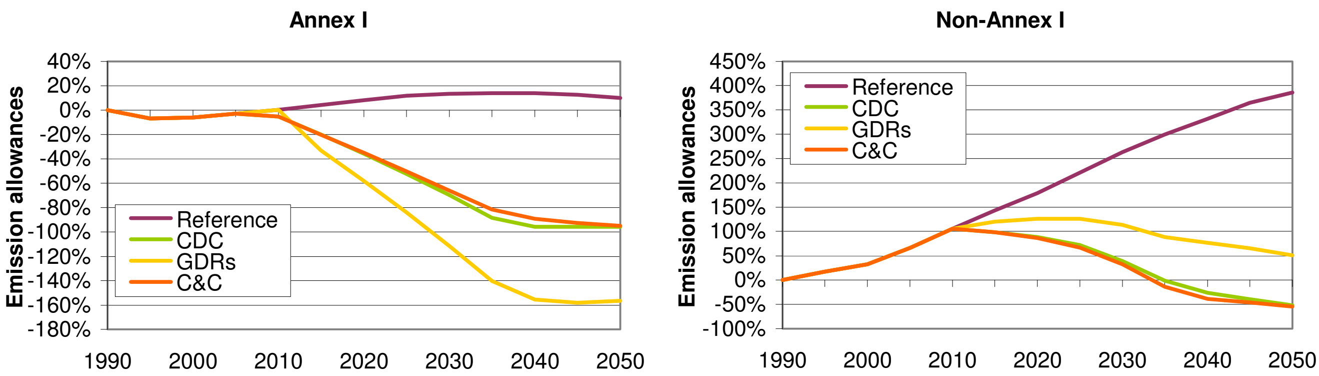

Figure 2. Development of emission allowances for Annex I countries and Non-Annex I countries between 1990 (0%) and 2050 under the effort sharing approaches CDC, GDRs and C&C

Developing countries in general and economies in transition (EITs) have more room to grow under GDRs than under the other approaches. The main reasons for this are the relatively low per capita emissions combined with limited financial capacity.

Least Developed Countries (LDCs) are almost all exempt from emission reduction requirements under GDRs, while under C&C they are granted little more allowances than their reference emissions until 2020 and face reduction obligations after 2025. Under CDC they face reductions after 2030.

Cumulative emissions per capita vary considerably under C&C and CDC for Annex I and non-Annex I. For GDRs some non-Annex I countries are even granted higher per capita cumulative emissions than some countries of Annex I.

Under GDRs, non-Annex I countries are allowed to increase their total emissions and peak until 2025 and then need to reduce them to roughly today's level in 2050 (about 50% above 1990). Under C&C and CDC there is less room for growth and their emissions need to be at a third of today's emissions (half of 1990's emissions). This is particularly reflected in the case of China and India. Both countries would be entitled under GDR to grow their emissions by 10% and even 240%, respectively, by 2050 compared to 1990, while being required to reduce by more than 70% and about 2-7% in the same period under the other two models.

Table of contents

List of Abbreviations

BAU	Business as usual
C	Capacity
C&C	Contraction and Convergence
CDC	Common but differentiated convergence
CDM	Clean development mechanism
CO_2eq	Carbon dioxide equivalents
EIT	Economies in transition
GDP	Gross domestic product
GDRs	Greenhouse Development Rights
LDC	Least developed country
LUCF	Land-use change and forestry
R	Responsibility
RCI	Responsibility Capacity Index
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar

1 Introduction

Further action is needed that goes far beyond what has been agreed so far under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol to "prevent dangerous anthropogenic interference with the climate system", the ultimate objective of the UNFCCC. It is beyond question that developed countries (Annex I countries) will have to take a leading role. They will have to commit to substantial emission reductions and financing commitments due to their historical responsibility and their financial capability. However, the stabilisation of the climate system will require global emissions to peak within the next decade and decline well below current levels by the middle of the century. It is hence a global issue and, thus, depends on the participation of as many countries as possible.

More than 120 countries, including the European Community and many developing nations particularly LDC and Small Island Nations, and numerous development, social justice and environmental NGOs have agreed that global average temperature increase should be limited to 2°C above pre-industrial levels to avoid such dangerous interference. Recent proposals, e.g. of the Alliance of Small Island States, now call for 1.5°C. The risk that a stable greenhouse gas concentration of e.g. 450 ppmv CO_2eq would result in global average temperature above 2°C in the long term is around 50%. At 400 ppmv CO_2eq, the risk is 30% (Meinshausen 2005). Consequently, global emissions have to peak in the next 15 years and decline well below the 1990 level in 2050 and further thereafter.

Under the principle of "common but differentiated responsibilities", one of the guiding principles stipulated in Article 3.1 of the UNFCCC, developed countries (so called Annex I Parties) take the lead in reducing emissions and developing countries (Non-Annex I Parties) act to protect the climate system on the basis of equity and in accordance with the common but differentiated responsibilities and respective capabilities. Current international climate negotiations center around "mitigation commitments and actions" for developed countries and "nationally appropriate mitigation actions" for developing countries.

Developing countries have a lower historical responsibility for climate change but some are already or will become important emitters. A less carbon intensive development path will have positive effects on these countries' sustainable development and on the global climate system. On the one hand, climate change action will contribute directly to achieving sustainable development objectives, such as energy security, sustainable economic development, technology innovation, job creation, local environmental protection and enhancement of capacity to adapt to climate change impacts. On the other hand, especially developing countries will benefit from a more stable global climate because they are the most vulnerable to climate change effects.

In this report for WWF International Ecofys analyses emission allowances for different groups of countries until 2050 under a given carbon budget between 1990 and 2100. The analysed approaches consider all countries but give different weight to Annex I and non-Annex I efforts.

We first describe the carbon budget and the methodology used (Chapter 2), then we briefly describe the considered effort sharing approaches (Chapter 3). Afterwards, we present the results as emission allowances per group under the different effort sharing approaches (Chapter 3.2). Finally, we give a short conclusion of this analysis. Detailed data and a description of the used calculation model (EVOC) are included in the Appendix.

2 Global carbon budget

Different approaches exist for global effort sharing of greenhouse gas emission reductions. One possibility is to define the carbon budget, which is the global amount of tolerable emissions over a period of time. Afterwards the available emission rights can be divided among countries according to different rules. To come close to 2° limit, for this report we assume CO_2eq emissions will have to be reduced by 30% compared to 1990 levels by 2030. By 2050 global emissions excluding LUCF need to be reduced by 80% compared to 1990. This leads to an emission budget of roughly 1800 Gt CO_2eq between 1990 and 2100.

As emissions from land use change and forestry (LUCF) are known only with considerable uncertainty, we took simplifying assumptions about current and future emissions from this sector. We assume that emissions from land-use change and forestry (LUCF) remain constant at about 4 $GtCO_2$ until 2010 and decline to zero by between 2010 and 2020. Due to reducing deforestation and increasing re- and afforestation LUCF will have to become a net sink of emissions afterwards (see Figure 3 and Table 1 below). We assume that after 2030 LUCF will remain at -4 $GtCO_2$. The global emission budget including LUCF will, thus, be about 1600 $GtCO_2$eq between 1990 and 2100.

Because mankind has already increased its global emissions substantively since 1990, the remaining net cumulative budget between 2009 and 2100 is limited to 870 $GtCO_2$eq. This translates to an allowable global annual emission on average for the next 91 years of no more than 9.5 $GtCO_2$eq, or about 20% of today's annual net global emissions.

In order to stay within the boundary of the global GHG budget, sometime from 2060 onwards, net global emissions must be negative (little emissions from energy use and larger sequestration of carbon from forests and other technologies).

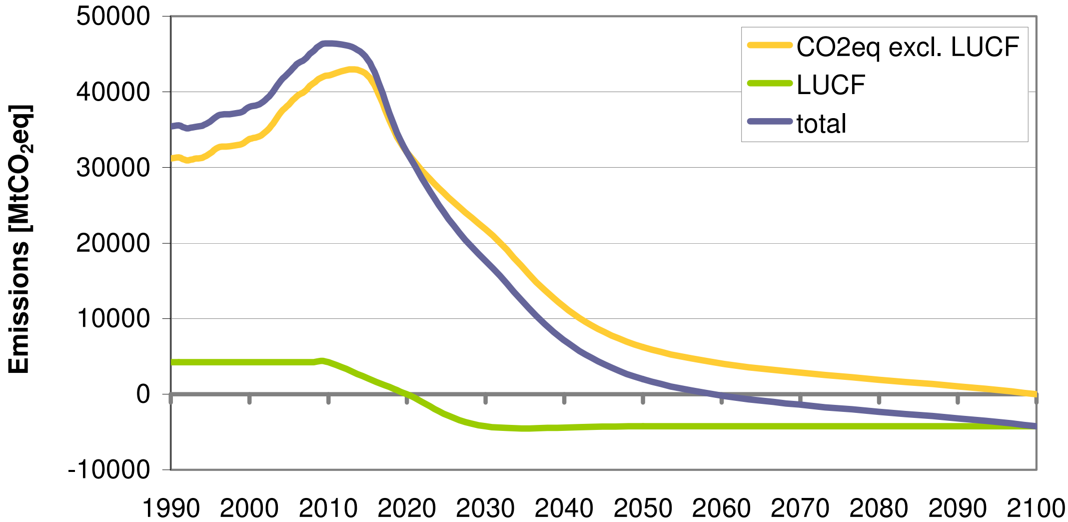

Figure 3. Possible global GHG emissions pathway between 1990 and 2100 according to a global carbon budget of about 1800 Mt CO_2eq (excl. LUCF) and 1600 Mt CO_2eq (incl. LUCF)

Table 1. Assumption on cumulative GHG emissions between 1990 and 2100

	2030 emissions [% change from 1990]	2050 emissions [% change from 1990]	Cumulative emissions				
			1990-2008	2009-2100	1990-2050	2010-2050	1990-2100
CO_2eq excl. LUCF	-30%	-80%	650	1160	1660	970	1820
LUCF	-200%	-200%	80	-290	0	-80	-210
Total emissions	**-50%**	**-94%**	**730**	**870**	**1660**	**880**	**1600**

Generally, one can imagine different pathways to reduce emissions that satisfy the same budget. Figure 4 gives an example of three different emission paths. The yellow path requires absolute global emission reduction comparatively early around the year 2015. The required average annual emissions reduction is about 5%. The medium path (dark violet) starts absolute emission reduction about 2-3 years later. The annual reduction rate is similar about 6%. The third path (light violet) requires absolute global reduction in 2020. As a result also the annual reduction of 8% after 2020 is more challenging to achieve a global carbon budget that is comparable with the yellow path of early reduction.

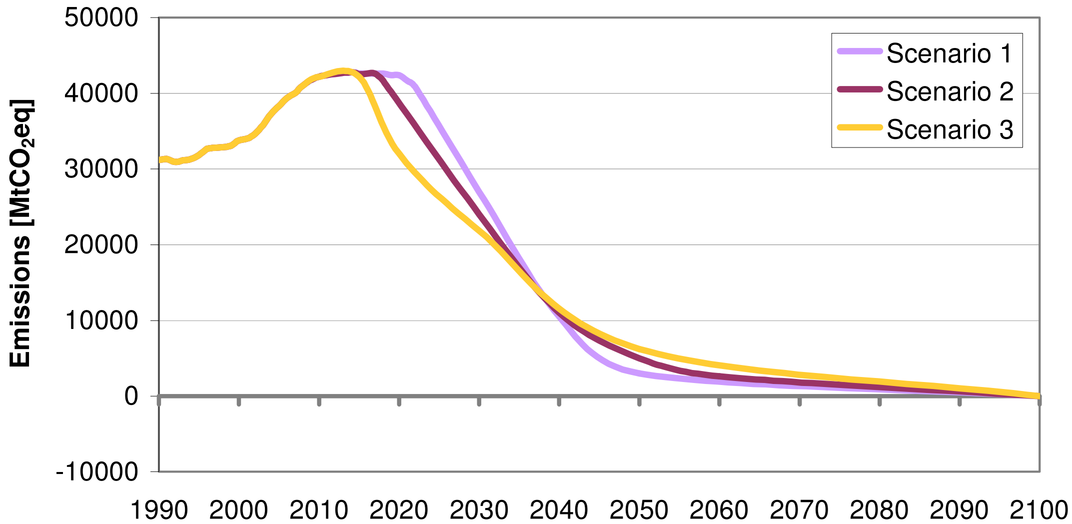

Figure 4. Sensitivity of possible global GHG emissions pathway excl. LUCF between 1990 and 2100

Table 2. Cumulative GHG emissions excl. LUCF between 1990 and 2100

Scenario	2030 emissions [% change from 1990]	2050 emissions [% change from 1990]	Cumulative emissions 1990-2050	Cumulative emissions 1990-2100
Scenario 1	-13%	-80%	~1750	~1830
Scenario 2	-30%	-80%	~1670	~1830
Scenario 3	-23%	-84%	~1700	~1830

3 Global effort sharing

3.1 Parameters

This section presents the parameters applied for three possible future methodological architectures consistent with the considered global carbon budget. This means that the calculation outcomes have to meet the global reference emissions of -30% compared to 1990 levels in 2030 and -80% in 2050 mentioned above. The following approaches are included in the calculation of emission allowances:

- Greenhouse Development Rights
- Common but Differentiated Convergence
- Contraction and Convergence by 2050

For this comparison of the emission rights under different distribution approaches in a future architecture the Evolution of Commitments tool (EVOC) is used. A detailed description of the EVOC model is included in Appendix A.

3.1.1 Greenhouse development rights (GDRs)

The Greenhouse Development Rights (GDRs) approach to share the effort of global greenhouse gas emissions reduction was developed by Baer et al. (Baer et al. 2007, 2008; cp. also Niklas Höhne and Sara Moltmann 2008). It is based on three main pillars:

The right to develop: Baer et al. assume the right to develop as the essential part for any future global climate regime in order to be successful. Therefore a development threshold is defined. Below this level individuals must be allowed to make development their first priority and do not need to contribute to the global effort of emission reduction or adaptation to climate change impacts. Those above this threshold will have to contribute regardless their nationality. This means that individuals above this threshold will have to contribute even if they live in a country that has an average per capita income below this level. The level for this development threshold would have to be matter of international debate. However Baer et al. 2008 suggest an income-level of $7,500 per capita and year. Based on this, the effort sharing of the GDRs is based on the capacity and the responsibility of each country.

Capacity: The capacity (C) of a county is reflected by its income. The income distribution among individuals is taken into account by the gini coefficient of a country. A gini coefficient close to 1 indicates low equality while a value close to 0 indicates a high equality in income distribution. As the countries capacity is needed to define per-country emission allowances the sum of income of those individuals per country above the development threshold is summed and considered to calculate each countries capacity.

Responsibility: The responsibility (R) is based on the "polluter pays" principle. For the GDRs according to Baer et al. it is measured as cumulative per capita CO_2 emissions from fossil fuel consumption since 1990. However, it should be distinguished between survival emissions and luxury emissions. Baer et al. assume that emissions are proportional to consumption, which again is linked to income. Emissions related to that share of income below the development threshold are equivalent to the part of national income that is not considered in calculating a countries capacity. Therefore, they shall be considered as survival emissions. Those emissions linked to income above the development threshold are luxury emissions and shall account for a countries responsibility.

Allocation of emission rights: The allocation of emission reduction obligations and resulting emission rights is based on each country's responsibility and capacity, combined in the Responsibility Capacity Index (RCI). This is defined as $RCI = R^a \cdot C^b$, where *a* and *b* are weighting factors. Baer et al. assume and equal weighting of 0.5 for *a* and 0.5 for *b*. This gives capacity and responsibility an equal weighting.

Two global emissions development paths are considered. First, the business-as-usual (BAU) case and second the reduction path necessary to reach the emission level in order to stabilise global emissions (see Figure 5). The difference of these two is the amount of emissions that need to be reduced globally. Each country's annual share of this reduction is determined by the relative share of its RCI compared to the sum of RCIs of all other countries.

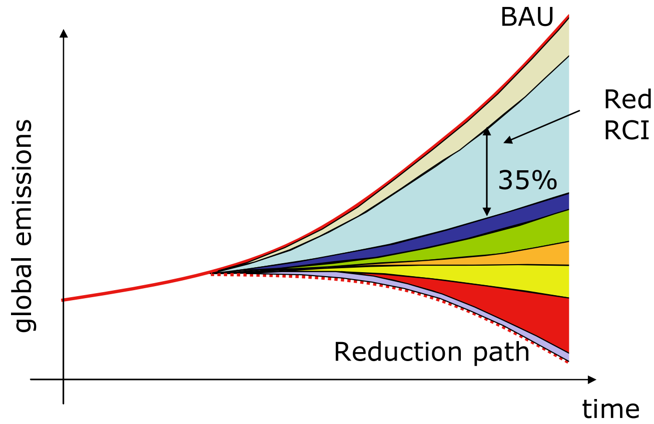

Figure 5. Effort sharing under the Greenhouse Development Rights (GDRs) approach according to the Responsibility Capacity Index (RCI)

Table 3 includes the parameters chosen for the calculations on the GDRs approach in this report.

Table 3. Parameters chosen for the Greenhouse Development Rights approach

Parameter	Unit	
Development threshold	USD (2005) / capita / year	7,500
Start year for cumulative emissions		1990
Weighting of Capacity	%	50%
Weighting of Responsibility	%	50%

3.1.2 Contraction and convergence (C&C)

Under contraction and convergence (C&C) (GCI 2005; Meyer 2000), all countries participate in the regime with quantified emission targets. As a first step, all countries agree on a path of future global emissions that leads to an agreed long-term stabilisation level for greenhouse gas concentrations ('contraction'). As a second step, the targets for individual countries are set in such a way that per capita emission allowances converge from the countries' current levels to a level equal for all countries within a given period ('convergence'). The convergence level is calculated at a level that resulting global emissions follow the agreed global emission path. It might be more difficult for some countries to reduce emissions compared to others, e.g. due to climatic conditions or resource availability. Therefore, emission trading could be allowed to level off differences between allowances and actual emissions. However, C&C does not explicitly provide for emission trading.

As current per capita emissions differ greatly between countries some developing countries with very low per capita emissions, (e.g. India, Indonesia or the Philippines) could be allocated more emission allowances than necessary to cover their emissions (some call this "tropical hot air"). This would generate a flow of resources from developed to developing countries if these emission allowances are traded.

To meet the global emission path of -30% (2030) and -80% (2050) a convergence at about 0.6 to 0.7 tCO_2eq per capita in 2050 is necessary (see Table 4). In this case the average per capita emissions will have to lie around 4.5 tCO_2eq per capita in 2020.

Table 4. Convergence levels of per capita emissions rights in tCO_2eq/cap in 2050 (the global emission level is the same but global population is different per scenario)

Scenario	Average in 2020 [tCO2eq/cap]	Convergence level in 2050 [tCO2eq/cap]
A1B	4.66	0.70
A1FI	4.67	0.70
A1T	4.61	0.73
A2	4.22	0.58
B1	4.39	0.74
B2	4.46	0.69

3.1.3 Common but differentiated convergence (CDC)

Common but differentiated convergence (CDC) is an approach presented by Höhne et al. (2006). Annex I countries' per capita emission allowances converge within, e.g., 40 years (2010 to 2050) to an equal level for all countries. Individual non-Annex I countries' per capita emissions also converge within the same period to the same level but convergence starts from the date, when their per capita emissions reach a certain percentage threshold of the (gradually declining) global average. Non-Annex I countries that do not pass this percentage threshold do not have binding emission reduction requirements. Either they take part in the CDM or they voluntarily take on positively binding emission reduction targets. Under the latter, emission allowances may be sold if the target is overachieved, but no emission allowances have to be bought if the target is not reached.

The CDC approach, similarly to C&C, aims at equal per capita allowances in the long run (see Figure 6). In contrast to C&C it considers more the historical responsibility of countries. Annex I countries would have to reduce emissions similarly to C&C, but many non-Annex I countries are likely to have more time to develop until they need to reduce emissions. Non-Annex I country participation is conditional to Annex I action through the gradually declining world average threshold. No excess emission allowances ("hot air") would be granted to least developed countries.

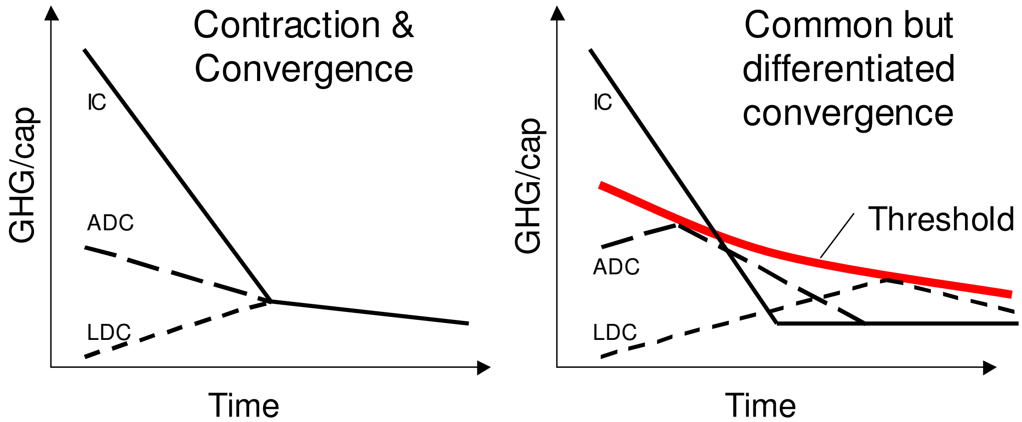

Figure 6. Schematic representation of GHG emissions per capita for three types of countries (an industrialized country (IC), an advanced developing country (ADC) and a least developed country (LDC)) under contraction and convergence (left) and under common but differentiated convergence (right)

The parameters for the convergence time, the threshold for participation and the convergence level used in this report are provided in Table 5.

Table 5. Parameters used for the Common but Differentiated Convergence approach

Parameter	Unit	A1B	A1FI	A1T	A2	B1	B2
Convergence time	Years	27	27	27	27	27	27
Threshold	% difference from world average	-35%	-35%	-35%	-31%	-22%	-24%
Convergence level	tCO_2eq/cap	0.64	0.64	0.64	0.42	0.51	0.52

3.1.4 Overview of all considered effort-sharing approaches

Table 6 below gives a short overview on strengths and weaknesses of the considered effort-sharing approaches Greenhouse Development Rights (GDRs), Contraction and Convergence (C&C) and Common but Differentiated Convergence (CDC).

Table 6. Strengths and weaknesses of the considered effort sharing approaches

	Strengths	Weaknesses
GDRs	• Uses historical emissions and GDP above a development threshold for differentiation • Uses share of wealthy population in a country as indicator for required action by that country • Assigns responsibility to reduce emissions abroad • Participation of all countries with the same rules • Includes cost-effective reduction options in developing countries through full international emissions trading	• Reduction below BAU assumes that the BAU is equitable • Possibly too simple and not considering detailed national circumstances
C&C	• Emphasis on a common endpoint: equal per capita emissions – does not require BAU • Participation of all countries with the same rules • Simple, clear concept • Includes cost-effective reduction options in developing countries through full international emissions trading • Support for least developed countries through excess emission rights	• Current per capita emissions is the only criterion for differentiation, does not consider differences in historical responsibility • National circumstances (including historical responsibility) not accommodated (optionally countries within one region can redistribute allowances to accommodate national concerns) • Substantial reduction for countries with high per capita emissions, also such developing countries • Also least developed countries need to be capable of participating in emissions trading to receive benefits (national greenhouse gas inventories and emission trading authorities)
CDC	• Emphasis on a common endpoint and equal path towards it: equal per capita emissions – does not require BAU • Applies simple rules, thus, making approach transparent • Delay of non-Annex I countries takes account of the responsibility for past emissions • Eliminates the component of "hot air" (no excess allowances for low emission countries)	• Per capita emissions is the only criterion for differentiation, but the delay of Non-Annex I countries accounts for differences in historical responsibility • National circumstances not accommodated, except per capita emissions and current membership of Annex I • Possibly too simple and not considering detailed national circumstances

3.2 Results

This chapter presents the results for emission rights for different countries and regions under the effort sharing approaches described before.

As all calculations consider six different reference scenarios based on the Special Report on Emission Scenarios from the IPCC (SRES, Nakicenovic et al. 2000). These scenarios include different assumptions concerning growth of GDP, population and other important factors. The bars in the figures indicate the median of the results from all scenarios; the error bars show the highest and lowest values.

Figure 7 shows the emission allowances in 2020 and 2050 as percentage change from 1990 for different reduction approaches. Figure 8 and Figure 9 give the same data as percentage changes from business as usual (BAU) and as emissions per capita, respectively.

Figure 10 shows cumulative emissions between 1990-2020 and 1990-2050 under different effort sharing approaches divided by the population in 2020 and 2050, respectively. Figure 11 gives the cumulative emissions between 1990-2020 and 1990-2050 under the different effort sharing methods. Figure 12 and Figure 13 show the development of national emission allowances between 1990 and 2020 under CDC, GDRs and C&C for Annex I and non-Annex I, respectively. Cumulative emissions are divided by the absolute number of people in that year. For 2020 this means for example that emissions are added from 1990 to 2020 and are then divided by the population of 2020.

All calculations and results comprise emissions *exclude* LUCF. The global emission budget described in Chapter 2 can be met, if in addition emissions from LUCF also follow the path described there (reduction to zero in 2020 and turning to a net sink in 2030 with constant level afterwards). Including LUCF would lead to changes in the distributions, which could be significant for countries with high emissions and/or removals in this sector, e.g. Brazil, USA and Russia.

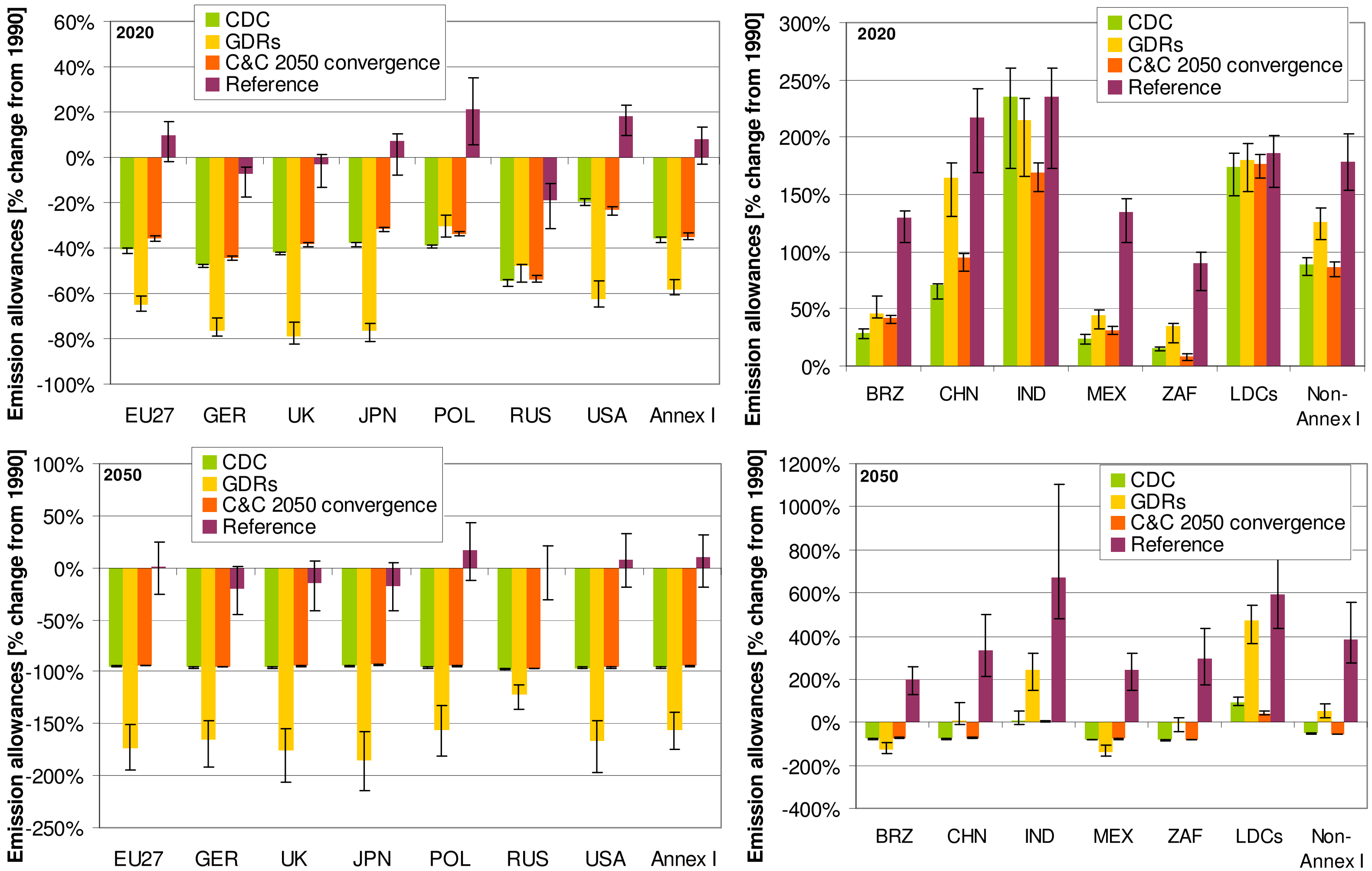

Figure 7. Emission allowances in 2020 and 2050 as percentage change from 1990 for different reduction approaches.

Note: EU27 (European Union), GER (Germany), UK (United Kingdom), JPN (Japan), RUS (Russia), POL (Poland), USA, Annex I, BRZ (Brazil), CHN (China), IND (India), MEX (Mexico), ZAF (South Africa), LDCs (least developed countries), non-Annex I. Data are included in Appendix B.

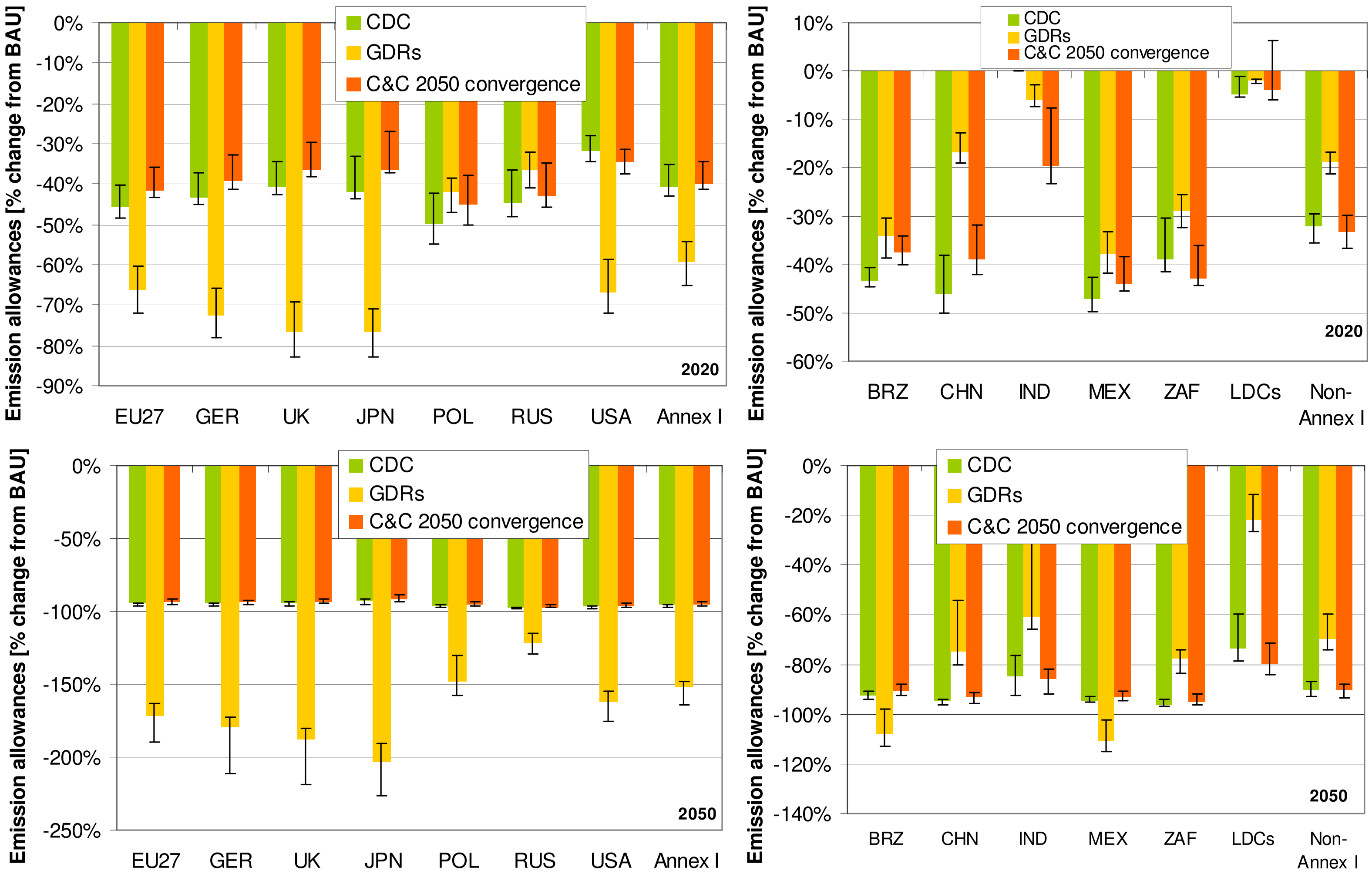

Figure 8. Emission allowances in 2020 and 2050 as percentage change from business as usual (BAU) for different reduction approaches.

Note: EU27 (European Union), GER (Germany), UK (United Kingdom), JPN (Japan), RUS (Russia), POL (Poland), USA, Annex I, BRZ (Brazil), CHN (China), IND (India), MEX (Mexico), ZAF (South Africa), LDCs (least developed countries), non-Annex I. Data are included in Appendix B.

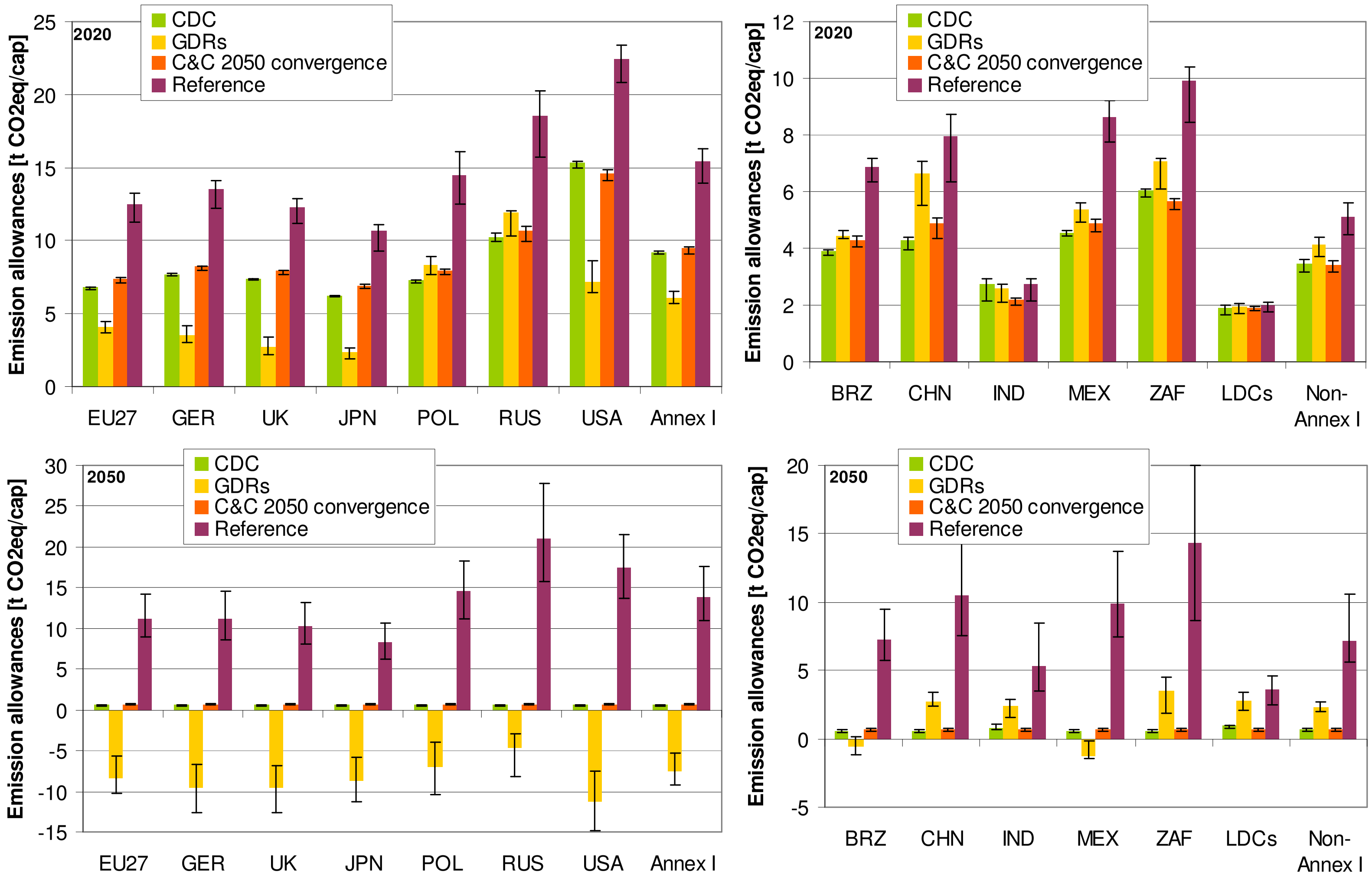

Figure 9. Emission allowances in 2020 and 2050 as emissions per capita for different reduction approaches.

Note: EU27 (European Union), GER (Germany), UK (United Kingdom), JPN (Japan), RUS (Russia), POL (Poland), USA, Annex I, BRZ (Brazil), CHN (China), IND (India), MEX (Mexico), ZAF (South Africa), LDCs (least developed countries), non-Annex I. Data are included in Appendix B.

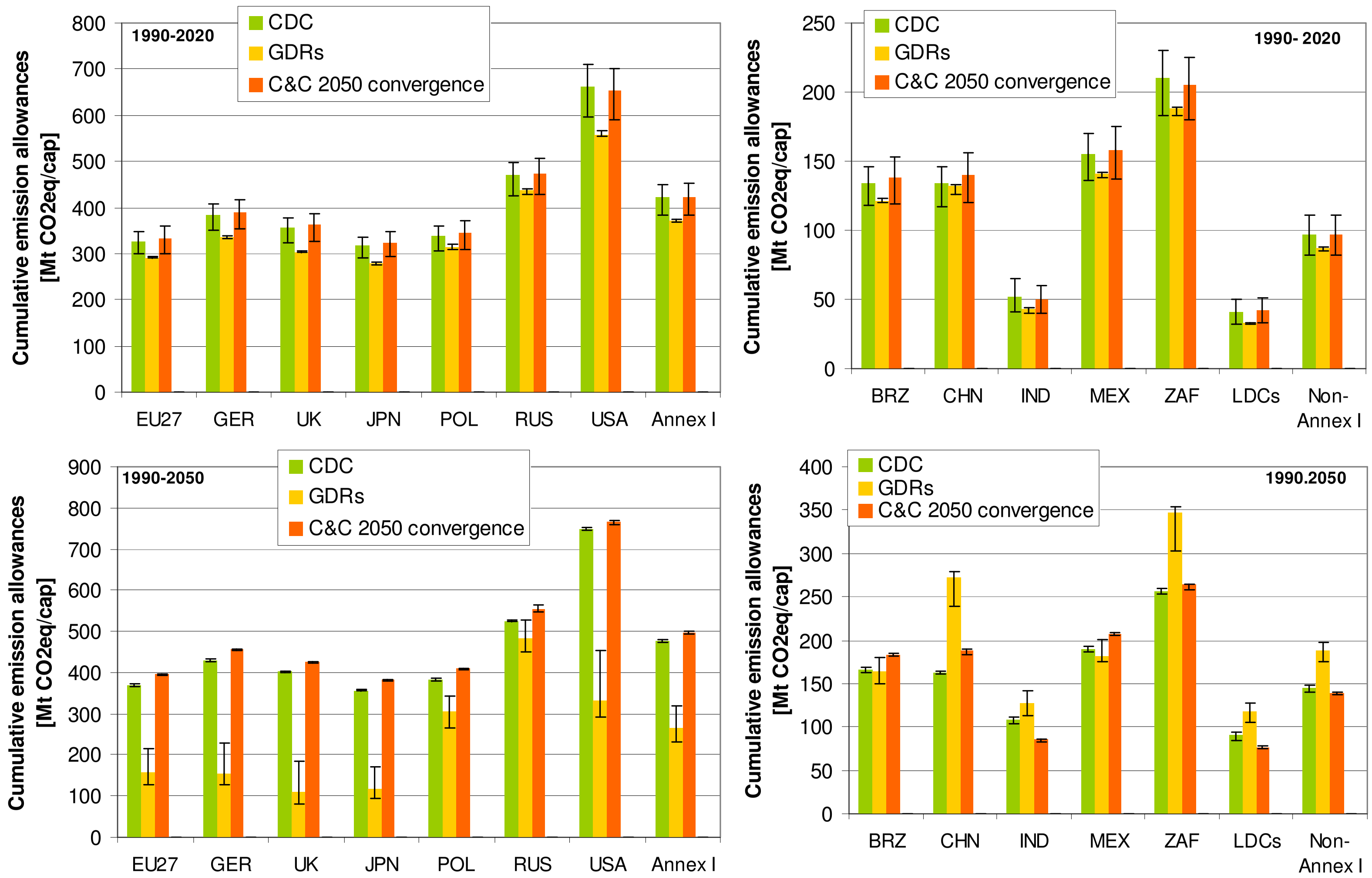

Figure 10. Cumulative emission allowances (1990-2020 and 1990-2050) per capita (2020 and 2050) different reduction approaches.

Note: EU27 (European Union), GER (Germany), UK (United Kingdom), JPN (Japan), RUS (Russia), POL (Poland), USA, Annex I, BRZ (Brazil), CHN (China), IND (India), MEX (Mexico), ZAF (South Africa), LDCs (least developed countries), non-Annex I. Data are included in Appendix B.

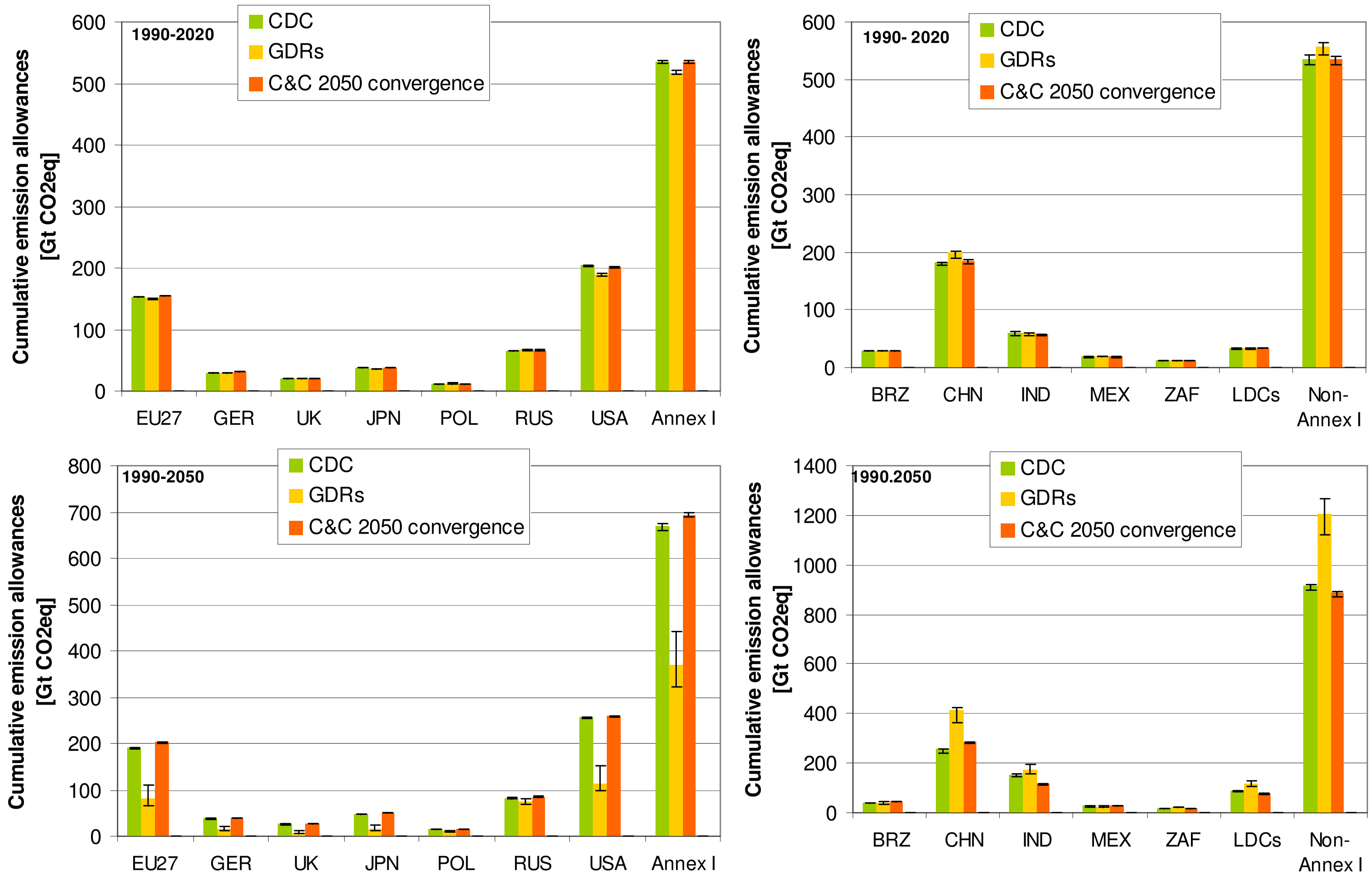

Figure 11. Cumulative emission allowances from 1990 to 2020 and 2050 for different reduction approaches.

Note: EU27 (European Union), GER (Germany), UK (United Kingdom), JPN (Japan), RUS (Russia), POL (Poland), USA, Annex I, BRZ (Brazil), CHN (China), IND (India), MEX (Mexico), ZAF (South Africa), LDCs (least developed countries), non-Annex I. Data are included in Appendix B.

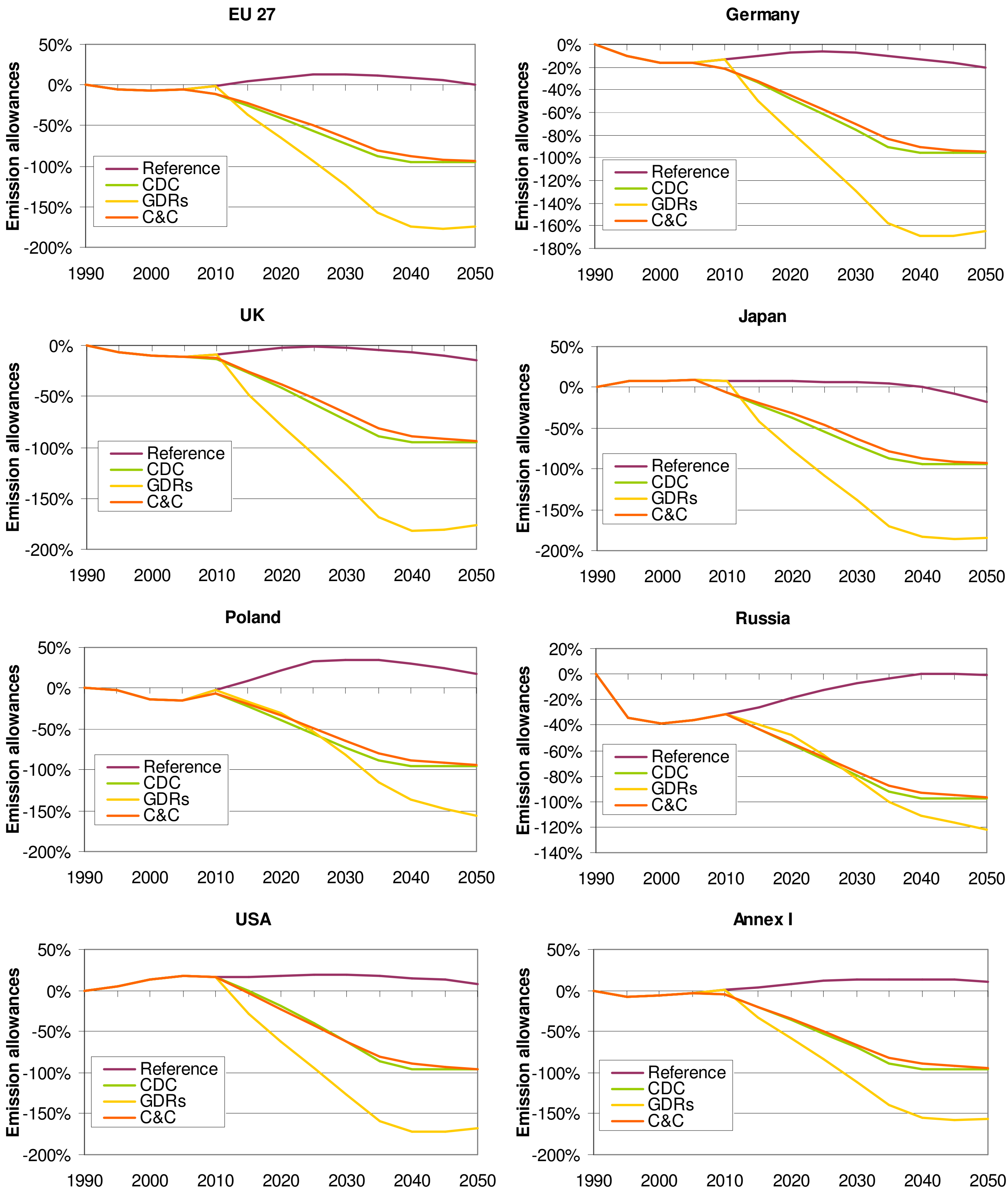

Figure 12. Development of national emission allowances as percentage change from 1990 emissions for Annex I between 1990 and 2050 under CDC, GDRs and C&C.

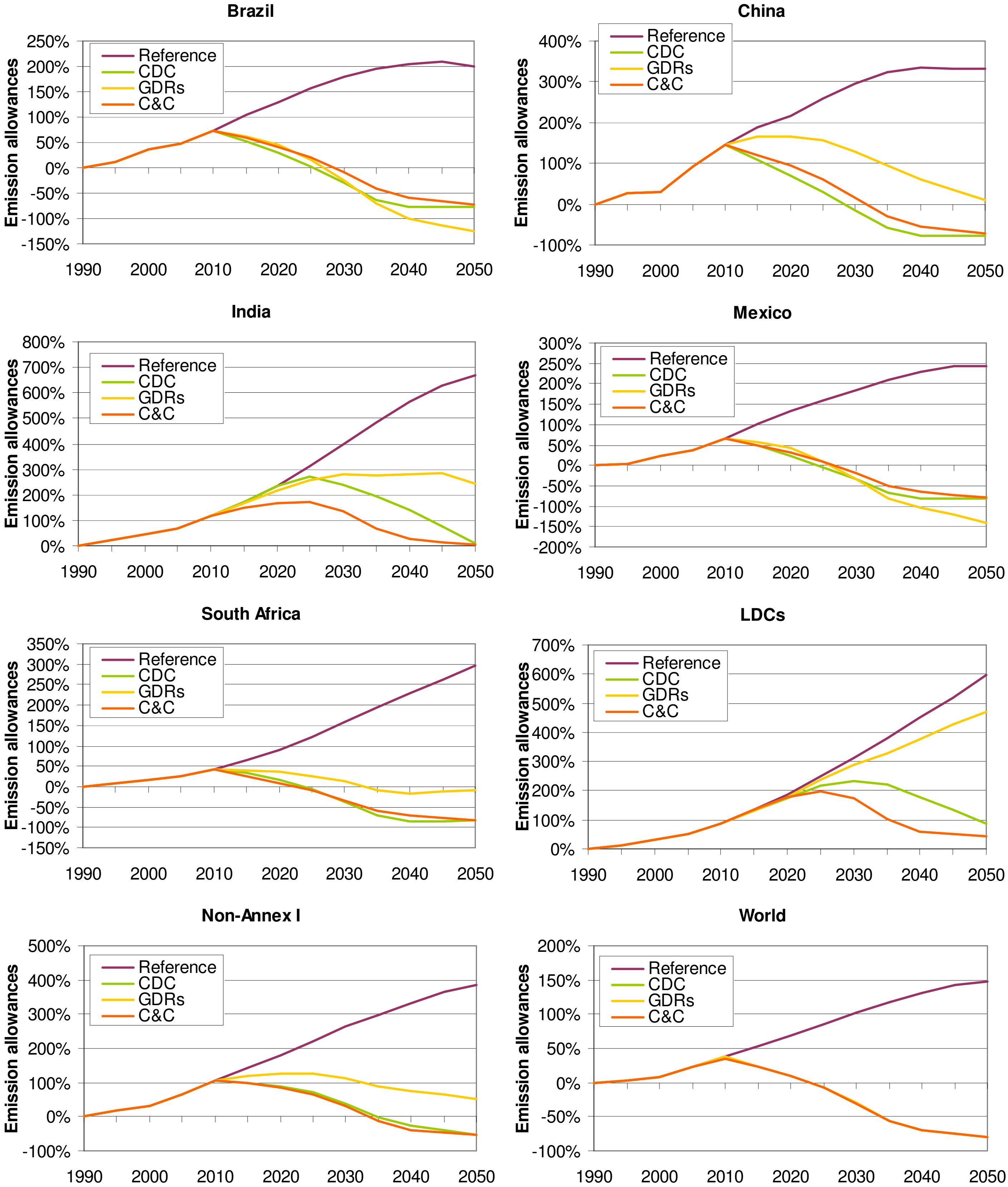

Figure 13. Development of national emission allowances as percentage change from 1990 emissions for non-Annex I and the world between 1990 and 2050 under CDC, GDRs and C&C.

4 Conclusions

The assumptions of -30% emission reduction below 1990 levels by 2020 and -80% by 2050 lead to a global GHG budget excluding LUCF of roughly 1800 Gt from 1990 to 2100. The requirements to reach this are very stringent. This is also reflected by the resulting target of about 0.5 tCO_2eq per capita as global average in 2050. In 2020 the average per capita emission lie around 9 tCO_2eq per capita for Annex I and 3-5 tCO_2eq per capita for non-Annex I.

Generally, the Greenhouse Development Rights approach (GDRs) allows negative emission where required reductions based on capacity and responsibility are larger than business as usual emissions. Contraction and Convergence (C&C) and Common but Differentiated Convergence (CDC) allow only very small but not negative emissions. Therefore, Annex I emission targets go to -60% in 2020 under the GDRs, while the other approaches require around -40%.

Hardly any differences can be seen for Annex I between C&C and CDC results. In the long term C&C leads to slightly less stringent results for high income and high emission countries.

By 2050, GDR requires Annex I countries as a group to reduce emissions by 157% and 'only' by 95% under C&C and CDC.

Developing countries and economies in transition (EITs) have more room to grow under GDRs than under the other approaches. The main reason for this is the relatively low per capita emissions combined with limited financial capacity.

LDCs are almost all exempt from emission reduction requirements under GDRs (+ >450% by 2050) , while under C&C they are granted little more allowances then their reference emissions until 2020 and face reduction obligations after 2025. Under CDC they face reductions after 2030.

Cumulative emissions per capita vary considerably under C&C and CDC for Annex I and non-Annex I. For GDRs some non-Annex I countries are granted higher per capita cumulative emissions than some countries of Annex I.

Under GDRs, non-Annex I countries are allowed to increase their total emissions and peak until 2025 and then need to reduce them to roughly today's level in 2050 (about 50% above 1990). Under C&C and CDC there is less room for growth and their emissions need to be at a third of today's emissions (half of 1990's emissions). This is reflected particular in the case of China and India. Both countries would be entitled under GDR to grow their emissions by 10% and even 240%, respectively by 2050 compared to 1990 but would be required to reduce by >70% and about 2-7% in same period under the other two models.

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Appendix A Description of the EVOC tool

This section describes the Evolution of Commitments tool (EVOC) version 8, developed by Ecofys, that is used to quantify emission allowances under the various approaches in this report. It includes emissions of CO_2, CH_4, N_2O, hydroflourocarbons (HFCs), perflourocarbons (PFCs) and sulphur hexafluoride (SF_6) for 192 individual countries. Historical emissions are based on national emission inventories submitted to the UNFCCC and, where not available, other sources such as the International Energy Agency. Future emissions are based on the IPCC Special Report on Emissions Scenarios (Nakicenovic et al. 2000). The greenhouse gas emission data for 1990 to 2006 is derived by an algorithm that combines emission estimates from various sources.

We first collected historical emission estimates by country, by gas and by sector from the following sources and ordered them in the following hierarchy:

1. National submissions to the UNFCCC as collected by the UNFCCC secretariat and published in the GHG emission database available at their web site. For Annex I countries, the latest available year is usually 2004. Most non-Annex I countries report only or until 1994 (UNFCCC 2008).
2. CO_2 emissions from fuel combustion as published by the International Energy Agency. The latest available year is 2003 (IEA 2008).
3. Emissions from land-use change as published by Houghton in the WRI climate indicator analysis tool (Houghton 2003).
4. Emissions from CH_4 and N_2O as estimated by the US Environmental Protection Agency. Latest available year is 2005 (USEPA 2006)
5. CO_2, CH_4, N_2O, HFC, PFC and SF_6 emissions from the EDGAR database version 3.2 available for 1990 and 1995 (Olivier and Berdowski 2001).[1]

Future emissions are derived from the MNP/RIVM IMAGE implementation of the SRES scenarios (IMAGE team 2001).

The datasets vary in their completeness and sectoral split. We first defined which of the sectors provided in the datasets correspond to 7 sectors. This definition is provided in Table 1. Note that CO_2 emissions from the IEA do not include process emissions from cement production. Hence, if IEA data is chosen, process emissions from cement production are not included.

For each country, gas and sector, the algorithm completes the following steps:

1. For all data sets, missing years in-between available years within a data set are linearly interpolated and the growth rate is calculated for each year step.
2. The data source is selected, which is highest in hierarchy and for which emission data are available. All available data points are chosen as the basis for absolute emissions.
3. Still missing years are filled by applying the growth rates from the highest data set in the hierarchy for which a growth rate is available.

[1] For CH_4 and N_2O, the values of EPA are largely based on the EDGAR database (1990 and 1995), but extended to the year 2000.

As future emissions are only available on a regional basis and not country-by-country, the resulting set of emissions is then extended into the future by applying the growth rates of the respective sectors and gas of the region to which the country belongs. (See Table 1 for detailed information on data sources and definition of sectors.)

For population, GDP in purchase power parities and electricity demand, the country base year data was taken from the United Nations (UN 2008), World Bank (2008) and IEA (2008), respectively. These data are extended into the future by applying the growth rates from the IMAGE model for the region to which the country belongs.

Emissions until 2010 are estimated as follows: It is assumed that Annex I countries implement their Kyoto targets by 2010. It is assumed that the reductions necessary to meet the Kyoto target are achieved equally in all sectors. In 2010, the level of the domestic sector is taken from the relevant reference scenario. The level of the other sectors are taken from the reference scenario and reduced, so that the Kyoto target is met. The years from the last available year to 2010 are linearly interpolated. All non-Annex I countries follow their reference scenario until 2010.

Table 1. Data sources and definition of sectors

	UNFCCC		Edgar 3.2 database		USEPA		LUCF Houghton		IEA		IMAGE CD	
	Regional:	country by country	**Regional:**	country by country	**Regional:**	country-by country	**Regional:**	country-by country	**Regional:**	country by country	**Regional:**	17 regions
	Temporal:	1990 to 2002 (various)	**Temporal:**	1990 and 1995	**Temporal:**	1990-2020	**Temporal:**	1950-2000	**Temporal:**	1970-2000	**Temporal:**	1970 to 2100
	Gas:	CO2, CH4, N2O, HFCs, PFCs, SF6	**Gas:**	CO2, CH4, N2O; HFCs, PFCS, SF6	**Gas:**	CH4, N2O	**Gas:**	CO2	**Gas:**	CO2	**Gas:**	CO2, CH4, N2O, HFCs, PFCs, SF6
Industry												
	1A2	Manufacturing Industries and Construction	**F10**	Industry					3T Other Energy Industries		ENERGY 01 Industry	
	2A0	Mineral Products	**F30**	Other transformation sectors					401 Iron and Steel		ENERGY 07 Other energy transformation	
	2B0	Chemical Industry	**B10CH4N2O**	Biofuel industry CH4 N2O					402 Chemical and Petrochemical		INDUS 01 Feedstocks	
	2C0	Metal Production	**B30CH4N2O**	Biofuel charcoal production CH4 N2O					403 Non-Ferrous Metals		INDUS 02 Industrial activities	
	2D0	Other Production	**I10**	Iron and steel					404 Non-Metallic Minerals			
	2G0	Other (Industrial Processes)	**I20**	Non-ferrous metals					409 Paper, Pulp and Printing			
			I30	Chemicals					405 Transport Equipment			
			I40	Building materials					406 Machinery			
			I50	Pulp and paper					407 Mining and Quarrying			
			I60	Food					408 Food and Tobacco			
			I70	Solvent use/Miscellaneous					410Wood and Wood Products			
			I80	Transport evaporation					411 Construction			
			I90	Miscellanecus industry					412 Textile and Leather			
			F60	non-energy use and feedstocks					413 Non-specified Industry			
									414 Non-Energy Use Ind/Transf/Energy			
									If the IEA data set is chosen, process emissions from industry (e.g. from cement) are not covered			
Electricity												
	1A1	Energy Industries	**F20**	Power generation					11 Public Electricity Plants		ENERGY 06 Electric power generation	
			B20CH4N2O	Biofuel power generation CH4 N2O					12 Public CHP Plants			
									13 Public Heat Plants			
									14 Own Use in Electricity, CHP and heat plants			
									21 Autoproducer Electricity Plants			
									22 Autoproducer CHP Plants			
									23 Autoproducer Heat Plants			
Domestic												
	1A3	Transport	**F40**	Residential, commercial and other sectors					5T Transport		ENERGY 02 Transport	
	1A4	Other Sectors (Fuel Combustion)	**F51**	Transport road					6T Other Sectors		ENERGY 03 Residential (households)	
	1A5	Other (Fuel Combustion)	**F54**	Transport land non-road					*MB Memo: International Marine Bunkers*		ENERGY 04 Services (commercial and public)	
	2E0	Production of Halocarbons and Sulphur Hexafluoride	**F57**	Transport air (international and domestic)					*AB Memo: International Aviation Bunkers*		ENERGY 05 Agriculture and other enduse	
	2F0	Consumption of Halocarbons and Sulphur Hexafluoride	***F58***	*Transport international shipping*							*ENERGY 09 Marine bunkers*	
	3TT	TOTAL Solvent and Other Product Use	**B40CH4N2O**	Biofuel residential CH4 N2O							FGAS	
	9TT	*TOTAL International Bunkers*	**B51CH4N2O**	Biofuel transport road CH4 N2O								
			C10	HFC-byproc.								
			C20	HFC use								
			C30	PFC-byproc.								
			C40	PFC use								
			C50	SF6 use								
	Secotors in italics are excluded when the user chooses to exclude international transport											
Fossil fuel production												
	1BT	TOTAL Fugitive Emissions from Fuels	**F70**	Coal production	02 Coal production				7T Differences due to Losses and/or Transformation		ENERGY 08 Fossil fuel production	
			F80	Oil production, transmission and handling	03 Natural gas production							
			F90	Gas production and transmission	04 Oil production							
			F95	Fossil fuel fres								
Agriculture												
	4TT	TOTAL Agriculture	**L10**	Fertiliser use	06 Manure management						LAND 10 wetland rice	
			L15	Rice cultivation	07 Enteric fermentation						LAND 11 animals	
			L20	Enteric fermentation	08 Rice production						LAND 12 animal waste	
			L30	Animal waste management (confined N2O, all CH4)	09 Agricultural soils						LAND 14 fertilizer	
			L50	Crop production							LAND 15 indirect fertilizer	
			L60	Animal waste management (deposited on soil- N2O)							LAND 16 indirect animal waste	
			L71	Atmospheric deposition							LAND 17 crop residues	
			L75	Leaching and run-off							LAND 18 biological N-fixation	
LUCF												
	5TT	TOTAL Land-Use Change & Forestry	**L41**	BB-Deforestation	10 Biomass combustion		Land-use				LAND 01 biomass burning	
			L42	BB-Savanna burning							LAND 02 burning of traditional biomass / fuelwood burning	
			L43	BB-Agricultural waste burning							LAND 03 timber pool (short lifetime)	
			L44	BB-Vegetation fires							LAND 04 timber pool (long lifetime)	
			L45	BB-deforestation post burn effects							LAND 05 carbon release by regrowing vegetation (-NEP)	
											LAND 06 agricultural waste burning	
											LAND 07 savanna burning	
											LAND 13 land clearing	
Waste												
	6TT	TOTAL Waste	**W10**	Landfills	11 Landfills						LAND 08 landfills	
			W15	Humans/pets	12 Wastewater						LAND 09 (domestic) sewage	
			W20	Waste water treatment								
			W30	Human waste disposal								
			W40	Waste incineration								
			W50	Miscelaneous waste handling (hazardous waste)								
	CO2 emissions from Biaomass buring (UNFCCC sector 1A8 and EGRAR sectors B10 to B51) are not included as they are not to be included in the national totals according to teh IPCC guidelines and the UNFCCC repsoting guidelines)											

As a default setting, all Annex I countries are assumed to reach the lower of their Kyoto target and their reference scenarios in 2010. Only the USA is assumed to follow its BAU emissions until 2010. All non-Annex I countries also follow their reference scenario until 2010. After 2010, the emission allowances per country are calculated according to the effort sharing approaches.

A limitation of the tool is the unknown future development of emissions of individual countries. Here, we have used the standard set of future emissions scenarios, the IPCC SRES scenarios, as a basis. They provide a broad range of storylines and therefore a wide range of possible future emissions. We cover this full range of possible future emissions, economic and population development in a consistent manner. But the SRES scenarios are only available at the level of up to 17 regions (as in the IMAGE implementation) and scaling them down to individual countries introduces an additional element of uncertainty. We applied the growth rates provided for 17 world regions to the latest available data points of the individual countries within the respective regions. So, on the level of regions, we cover the full-range uncertainty about future emissions. When again aggregating the regions, the effect of downscaling cancels out. But the full level of uncertainty is not covered on the national level as substantial differences may exist for expected growth for countries within one of the 17 regions.

The future reference development of emissions, economic and population is affected by the starting values (which is data available from the countries or other international sources and which can be substantially different for countries in one region) and the assumed growth rates (which are derived from the 17 regions).

The assumed growth rates may affect the results of countries to a different extent. Some countries are less affected as they dominate their regional group, such as Brazil, Mexico, Egypt, South Africa, Nigeria, Saudi Arabia, China and India. It is for second or third largest countries in a region or for members of an inhomogeneous group, for which this method may lead to an over or underestimation of the future development.

Second or third largest countries in a region are e.g. Argentina, Venezuela, United Arab Emirates and South Korea. In the Contraction and Convergence approach, the error would be small as countries follow their reference scenario only until 2010 and converge afterwards. For Common but Differentiated Convergence and Multistage, the downscaling method may influence the time of participation. But the countries listed above would all participate at the earliest possible moment, based on their already today high per capita emissions. In the Triptych approach, growth in industrial and electricity production and a reduction below reference for agriculture is used, which may be affected by the downscaling method.

Members of an inhomogeneous group would be those of South East Asia, which includes Indonesia and the Philippines as lower-income countries and Malaysia, Singapore and Thailand as higher-income countries. Here the growth is averaged over the region, probably underestimated for Indonesia and the Philippines and overestimated for Singapore. The dominant element here is the starting point. The low per capita emissions of the Philippines and Indonesia lead to their late participation, while the high per capita emissions in Malaysia, Singapore and Thailand lead to their immediate participation. In the Triptych approach, growth in industrial and electricity production and a reduction below reference for agriculture is used, which may be affected by the downscaling method.

For Annex I countries, the future reference development is not as relevant since they always participate in the regime on the highest stage and have to reduce emissions independent of the reference development. Future values are only relevant for intensity targets (GDP) or for the Triptych approach (industrial and electricity production).

A different uncertainty is introduced since our future emissions are static, meaning that emissions in non-participating developing countries do not change as a result of ambitious or relaxed emission reductions in developed countries. Stringent reductions could affect emissions of non-participating countries in two ways. There could be increased emissions through migration of energy-intensive industries or decreased emissions due to technology spill-over. Overall, we assume that this effect is small and not significantly influencing the results of this analysis.

Appendix B Emission allowances distributed with EVOC

For methodological reasons an overall carbon budget of 1600 Gt by 2050 is assumed instead of 1660 Gt by 2050 as estimated in Chapter 2.

Table 2. Emission allowances as percentage change from 1990 for 2020 and 2050 under CDC, C&C and GDRs excluding LUCF

Year	Emissions [Mt CO2 eq.] 1990	2000	2010	CDC % change from 1990 2020			GDRs % change from 1990 2020			C&C 2050 convergence % change from 1990 2020			Reference % change from 1990 2020		
Country group			BAU	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	31196	33764	43250	6%	10%	12%	6%	10%	12%	6%	10%	12%	55%	68%	83%
EU27	5802	5371	5767	-42%	-41%	-40%	-68%	-65%	-61%	-37%	-36%	-35%	-2%	9%	16%
GER	1253	1055	1086	-49%	-48%	-47%	-79%	-76%	-71%	-45%	-44%	-44%	-18%	-8%	-4%
UK	800	718	731	-43%	-42%	-42%	-83%	-79%	-73%	-39%	-38%	-37%	-13%	-3%	1%
JPN	1318	1427	1423	-39%	-38%	-38%	-81%	-76%	-73%	-33%	-32%	-31%	-8%	7%	11%
POL	456	392	445	-40%	-39%	-39%	-35%	-30%	-25%	-35%	-34%	-32%	5%	21%	35%
RUS	3361	2060	2288	-57%	-55%	-54%	-55%	-48%	-47%	-55%	-54%	-52%	-31%	-19%	-12%
USA	6341	7240	7403	-21%	-19%	-18%	-66%	-62%	-54%	-26%	-23%	-22%	10%	18%	23%
Annex I	19699	18545	19746	-37%	-36%	-35%	-60%	-58%	-54%	-37%	-35%	-33%	-3%	8%	13%
BRZ	680	931	1175	24%	29%	33%	42%	45%	61%	37%	42%	45%	108%	130%	135%
CHN	3546	4604	8703	59%	71%	73%	130%	165%	177%	82%	94%	98%	169%	218%	242%
IND	1087	1560	2343	173%	235%	261%	165%	215%	234%	152%	169%	177%	173%	235%	261%
MEX	457	562	763	19%	23%	27%	32%	44%	49%	27%	31%	34%	107%	135%	146%
ZAF	337	391	483	14%	16%	17%	21%	35%	37%	5%	8%	11%	66%	90%	99%
LDCs	682	888	1270	149%	174%	186%	152%	180%	195%	165%	176%	184%	156%	186%	202%
Non-Annex I	11263	14850	23124	79%	89%	95%	111%	126%	138%	78%	86%	91%	154%	179%	202%

	Emissions [Mt CO2 eq.] 1990	2000	2010	CDC % change from 1990 2050			GDRs % change from 1990 2050			C&C 2050 convergence % change from 1990 2050			Reference % change from 1990 2050		
			BAU	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	31196	33764	43250	-80%	-80%	-80%	-80%	-80%	-80%	-80%	-80%	-80%	90%	148%	225%
EU27	5802	5371	5767	-96%	-95%	-94%	-195%	-174%	-151%	-95%	-94%	-94%	-25%	1%	25%
GER	1253	1055	1086	-97%	-96%	-96%	-193%	-165%	-147%	-96%	-95%	-95%	-45%	-20%	1%
UK	800	718	731	-96%	-95%	-95%	-206%	-176%	-155%	-95%	-94%	-94%	-41%	-15%	6%
JPN	1318	1427	1423	-96%	-94%	-94%	-214%	-185%	-158%	-94%	-93%	-93%	-41%	-18%	5%
POL	456	392	445	-97%	-95%	-95%	-182%	-156%	-132%	-95%	-94%	-94%	-13%	17%	43%
RUS	3361	2060	2288	-98%	-97%	-97%	-136%	-122%	-112%	-97%	-97%	-97%	-31%	-1%	20%
USA	6341	7240	7403	-97%	-96%	-96%	-198%	-167%	-147%	-96%	-96%	-95%	-19%	8%	32%
Annex I	19699	18545	19746	-97%	-96%	-95%	-175%	-157%	-139%	-95%	-95%	-95%	-18%	10%	31%
BRZ	680	931	1175	-81%	-77%	-76%	-145%	-125%	-95%	-74%	-73%	-70%	131%	201%	256%
CHN	3546	4604	8703	-81%	-76%	-76%	-10%	10%	92%	-74%	-73%	-67%	209%	331%	497%
IND	1087	1560	2343	-8%	7%	51%	146%	242%	323%	1%	2%	5%	478%	669%	1108%
MEX	457	562	763	-84%	-81%	-80%	-156%	-140%	-106%	-78%	-78%	-75%	145%	243%	321%
ZAF	337	391	483	-87%	-83%	-83%	-41%	-7%	19%	-82%	-81%	-78%	173%	295%	434%
LDCs	682	888	1270	80%	88%	115%	362%	472%	544%	35%	43%	54%	433%	596%	778%
Non-Annex I	11263	14850	23124	-55%	-52%	-50%	23%	51%	85%	-56%	-54%	-53%	278%	386%	557%

Table 3. Emission allowances as percentage change from BAU for 2020 and 2050 under CDC, C&C and GDRs excluding LUCF

	Emissions [Mt CO2 eq.]			CDC % change from BAU 2020			GDRs % change from BAU 2020			C&C 2050 convergence % change from BAU 2020			Reference % change from BAU 2020		
Year	1990	2000	2010												
Country group			BAU	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	31196	33764	43250	-39%	-35%	-32%	-39%	-35%	-32%	-39%	-35%	-32%			
EU27	5802	5371	5767	-48%	-46%	-40%	-72%	-66%	-60%	-43%	-42%	-36%			
GER	1253	1055	1086	-45%	-43%	-37%	-78%	-73%	-66%	-41%	-39%	-33%			
UK	800	718	731	-43%	-40%	-35%	-83%	-77%	-69%	-38%	-36%	-30%			
JPN	1318	1427	1423	-44%	-42%	-33%	-83%	-77%	-71%	-37%	-36%	-27%			
POL	456	392	445	-55%	-50%	-42%	-47%	-42%	-38%	-50%	-45%	-38%			
RUS	3361	2060	2288	-48%	-45%	-37%	-41%	-37%	-32%	-46%	-43%	-35%			
USA	6341	7240	7403	-34%	-32%	-28%	-72%	-67%	-59%	-37%	-34%	-31%			
Annex I	19699	18545	19746	-43%	-40%	-35%	-65%	-59%	-54%	-41%	-40%	-34%			
BRZ	680	931	1175	-45%	-44%	-41%	-39%	-34%	-30%	-40%	-38%	-34%			
CHN	3546	4604	8703	-50%	-46%	-38%	-19%	-17%	-13%	-42%	-39%	-32%			
IND	1087	1560	2343				-7%	-6%	-3%	-23%	-20%	-8%			
MEX	457	562	763	-50%	-47%	-43%	-42%	-38%	-33%	-45%	-44%	-38%			
ZAF	337	391	483	-41%	-39%	-31%	-32%	-29%	-25%	-44%	-43%	-36%			
LDCs	682	888	1270	-5%	-5%	-1%	-2%	-2%	-2%	-6%	-4%	6%			
Non-Annex I	11263	14850	23124	-36%	-32%	-29%	-21%	-19%	-17%	-37%	-33%	-30%			

	Emissions [Mt CO2 eq.]			CDC % change from BAU 2050			GDRs % change from BAU 2050			C&C 2050 convergence % change from BAU 2050			Reference % change from BAU 2050		
	1990	2000	2010												
			BAU	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	31196	33764	43250	-94%	-92%	-89%	-94%	-92%	-89%	-94%	-92%	-89%			
EU27	5802	5371	5767	-96%	-95%	-94%	-190%	-172%	-164%	-95%	-94%	-92%			
GER	1253	1055	1086	-96%	-95%	-94%	-211%	-180%	-173%	-95%	-94%	-92%			
UK	800	718	731	-96%	-94%	-94%	-219%	-188%	-181%	-95%	-93%	-91%			
JPN	1318	1427	1423	-95%	-92%	-92%	-226%	-203%	-190%	-94%	-91%	-88%			
POL	456	392	445	-97%	-96%	-95%	-157%	-148%	-130%	-96%	-95%	-93%			
RUS	3361	2060	2288	-98%	-97%	-97%	-130%	-122%	-115%	-97%	-97%	-95%			
USA	6341	7240	7403	-98%	-96%	-96%	-176%	-162%	-155%	-97%	-96%	-95%			
Annex I	19699	18545	19746	-97%	-96%	-95%	-164%	-152%	-148%	-96%	-95%	-93%			
BRZ	680	931	1175	-94%	-92%	-91%	-113%	-108%	-98%	-93%	-91%	-88%			
CHN	3546	4604	8703	-96%	-95%	-94%	-80%	-75%	-54%	-96%	-93%	-91%			
IND	1087	1560	2343	-92%	-85%	-76%	-66%	-61%	-29%	-92%	-86%	-82%			
MEX	457	562	763	-95%	-95%	-93%	-115%	-111%	-102%	-95%	-93%	-91%			
ZAF	337	391	483	-97%	-96%	-94%	-84%	-78%	-74%	-96%	-95%	-92%			
LDCs	682	888	1270	-79%	-73%	-60%	-27%	-21%	-11%	-84%	-80%	-71%			
Non-Annex I	11263	14850	23124	-93%	-90%	-87%	-74%	-70%	-60%	-93%	-90%	-88%			

Table 4. Emission allowances as per capita emissions for 2020 and 2050 under CDC, C&C and GDRs excluding LUCF

Year	Emissions [t CO2eq./cap]			CDC t CO2eq./cap 2020			GDRs t CO2eq./cap 2020			C&C 2050 convergence t CO2eq./cap 2020			Reference t CO2eq./cap 2020		
Country group	1990	2000	2010 incl. Kyoto target	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	6.0	5.6	6.2	4.2	4.5	4.7	4.2	4.5	4.7	4.2	4.5	4.7	6.4	6.9	7.6
EU27	12.3	11.1	10.4	6.7	6.8	6.8	3.7	4.1	4.4	7.1	7.4	7.5	11.2	12.5	13.2
GER	15.8	12.8	11.9	7.6	7.7	7.7	3.1	3.5	4.2	8.0	8.2	8.3	12.2	13.5	14.1
UK	13.9	12.0	11.4	7.3	7.4	7.4	2.2	2.7	3.4	7.7	7.9	8.0	11.2	12.3	12.9
JPN	10.7	11.3	9.6	6.2	6.3	6.3	1.9	2.4	2.7	6.7	6.9	7.0	9.3	10.7	11.1
POL	12.0	10.2	11.2	7.1	7.2	7.3	7.7	8.3	8.9	7.7	7.9	8.0	12.5	14.5	16.1
RUS	22.7	14.1	15.9	9.9	10.2	10.5	10.3	11.9	12.0	10.0	10.7	11.0	15.7	18.5	20.2
USA	25.4	25.7	24.0	14.9	15.3	15.4	6.4	7.2	8.7	14.1	14.6	14.9	20.9	22.5	23.4
Annex I	16.5	14.9	14.2	9.1	9.2	9.3	5.7	6.1	6.5	9.1	9.4	9.6	14.0	15.4	16.3
BRZ	4.5	5.3	5.9	3.8	3.9	4.0	4.3	4.5	4.6	4.0	4.3	4.4	6.4	6.9	7.2
CHN	3.1	3.6	6.5	3.9	4.3	4.4	5.5	6.6	7.1	4.3	4.9	5.1	6.4	8.0	8.7
IND	1.3	1.5	2.0	2.2	2.7	2.9	2.1	2.6	2.7	2.0	2.2	2.3	2.2	2.7	2.9
MEX	5.5	5.7	6.9	4.4	4.5	4.7	4.9	5.4	5.6	4.6	4.9	5.0	7.7	8.6	9.2
ZAF	9.6	8.9	9.2	5.8	6.0	6.1	6.1	7.1	7.2	5.4	5.6	5.8	8.4	9.9	10.4
LDCs	1.3	1.3	1.5	1.7	1.9	2.0	1.7	1.9	2.0	1.8	1.9	2.0	1.7	2.0	2.1
Non-Annex I	2.8	3.1	4.3	3.2	3.5	3.6	3.7	4.2	4.4	3.2	3.4	3.5	4.5	5.1	5.6

	Emissions [t CO2eq./cap]			CDC t CO2eq./cap 2050			GDRs t CO2eq./cap 2050			C&C 2050 convergence t CO2eq./cap 2050			Reference t CO2eq./cap 2050		
	1990	2000	2010 incl. Kyoto target	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	6.0	5.6	6.2	0.6	0.7	0.7	0.6	0.7	0.7	0.6	0.7	0.7	6.5	8.1	11.7
EU27	12.3	11.1	10.4	0.4	0.6	0.6	-10.3	-8.4	-5.7	0.6	0.7	0.7	9.0	11.1	14.1
GER	15.8	12.8	11.9	0.4	0.6	0.6	-12.7	-9.5	-6.7	0.6	0.7	0.7	8.6	11.2	14.5
UK	13.9	12.0	11.4	0.4	0.6	0.6	-12.6	-9.6	-6.9	0.6	0.7	0.7	8.0	10.3	13.2
JPN	10.7	11.3	9.6	0.4	0.6	0.6	-11.3	-8.7	-5.9	0.6	0.7	0.7	6.2	8.3	10.7
POL	12.0	10.2	11.2	0.4	0.6	0.6	-10.5	-6.9	-4.0	0.6	0.7	0.7	11.2	14.5	18.3
RUS	22.7	14.1	15.9	0.4	0.6	0.6	-8.2	-4.6	-2.9	0.6	0.7	0.7	15.8	21.0	27.8
USA	25.4	25.7	24.0	0.4	0.6	0.6	-14.8	-11.2	-7.5	0.6	0.7	0.7	13.6	17.5	21.4
Annex I	16.5	14.9	14.2	0.4	0.6	0.6	-9.2	-7.6	-5.3	0.6	0.7	0.7	10.9	13.9	17.6
BRZ	4.5	5.3	5.9	0.4	0.6	0.6	-1.2	-0.6	0.1	0.6	0.7	0.7	5.7	7.2	9.5
CHN	3.1	3.6	6.5	0.4	0.6	0.6	2.4	2.7	3.4	0.6	0.7	0.7	7.5	10.5	16.2
IND	1.3	1.5	2.0	0.6	0.7	1.1	1.6	2.3	2.9	0.6	0.7	0.7	3.5	5.4	8.4
MEX	5.5	5.7	6.9	0.4	0.6	0.6	-1.5	-1.2	-0.2	0.6	0.7	0.7	7.4	9.8	13.7
ZAF	9.6	8.9	9.2	0.4	0.6	0.6	1.9	3.5	4.5	0.6	0.7	0.7	8.7	14.3	20.0
LDCs	1.3	1.3	1.5	0.8	1.0	1.0	2.1	2.8	3.4	0.6	0.7	0.7	2.5	3.6	4.6
Non-Annex I	2.8	3.1	4.3	0.6	0.7	0.8	1.9	2.3	2.7	0.6	0.7	0.7	5.6	7.1	10.5

Table 5. Cumulative emission allowances (1990 – 2020 and 1990 – 2050) per capita (in 2020 and 2050) under CDC, C&C and GDRs excluding LUCF

	Population million people			Cumulative emissions Mt CO2 eq./cap		CDC Mt CO2eq./cap 1990-2020			GDRs Mt CO2eq./cap 1990-2020			C&C 2050 convergence Mt CO2eq./cap 1990-2020		
Year	2000	2010	2020	1990-2000	1990-2010									
Country group	Median	Median	Median	Median	Median	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	6033	6873	7854	53	101	136	156	172	136	138	139	136	156	172
EU27	482	499	512	115	219	298	327	348	290	292	294	301	334	358
GER	82	84	86	139	261	350	384	407	334	335	340	353	389	416
UK	60	61	63	128	239	324	356	378	302	303	307	327	362	388
JPN	127	130	132	109	214	290	317	336	276	278	280	293	324	348
POL	38	38	39	114	217	307	338	360	309	315	322	310	345	371
RUS	146	145	152	168	317	427	469	498	428	438	442	428	473	506
USA	282	310	338	237	449	597	663	709	553	556	566	592	654	700
Annex I	1248	1313	1392	150	285	382	422	449	370	371	375	382	423	454
BRZ	174	203	237	44	87	118	134	146	120	121	123	119	138	153
CHN	1263	1368	1511	34	77	117	134	146	126	132	133	120	140	156
IND	1016	1186	1375	13	26	41	52	65	40	43	44	40	50	60
MEX	98	111	130	50	100	136	155	170	138	141	142	137	158	175
ZAF	44	52	67	81	149	183	210	230	183	188	189	180	205	225
LDCs	647	815	994	11	21	32	41	50	32	33	33	33	42	51
Non-Annex I	4734	5499	6390	27	56	82	97	111	85	87	88	82	97	111

	Population million people			Cumulative emissions Mt CO2 eq./cap		CDC Mt CO2eq./cap 1990-2050			GDRs Mt CO2eq./cap 1990-2050			C&C 2050 convergence Mt CO2eq./cap 1990-2050		
	2000	2010	2050	1990-2000	1990-2010									
	Median	Median	Median	Median	Median	Min	Median	Max	Min	Median	Max	Min	Median	Max
World	6033	6873	10823	53	101	201	205	208	202	204	205	201	204	205
EU27	482	499	537	115	219	367	370	372	126	157	215	392	396	398
GER	82	84	91	139	261	428	430	433	129	156	227	452	456	457
UK	60	61	67	128	239	399	402	404	81	112	185	423	427	428
JPN	127	130	134	109	214	355	357	359	95	119	172	380	384	384
POL	38	38	38	114	217	380	383	385	266	306	343	406	411	411
RUS	146	145	183	168	317	523	525	527	450	483	527	549	556	563
USA	282	310	419	237	449	746	749	752	291	331	453	759	766	768
Annex I	1248	1313	1637	150	285	474	476	479	231	266	319	495	499	501
BRZ	174	203	350	44	87	163	165	168	150	163	180	181	184	185
CHN	1263	1368	1976	34	77	161	163	165	239	273	279	183	188	189
IND	1016	1186	1871	13	26	104	108	111	114	127	142	82	86	87
MEX	98	111	193	50	100	187	190	192	175	182	200	205	208	209
ZAF	44	52	106	81	149	253	256	260	302	347	354	258	264	264
LDCs	647	815	1495	11	21	85	90	94	105	118	128	74	77	78
Non-Annex I	4734	5499	9071	27	56	141	144	148	176	189	198	137	139	140

Note: Cumulative emissions are divided by the absolute number of people in that year. E.g. for 2020 Cumulative emission from 1990 to 2020 are divided by the population of 2020.

Table 6. Cumulative emission allowances from 1990 to 2020 and 2050 under CDC, C&C and GDRs excluding LUCF

	Cumulative emissions		CDC			GDRs			C&C 2050 convergence		
	Gt CO2 eq.		Gt CO2 eq.			Gt CO2 eq.			Gt CO2 eq.		
Year	1990-2000	1990-2010	1990-2020			1990-2020			1990-2020		
Country group	Median	Median	Min	Median	Max	Min	Median	Max	Min	Median	Max
World total	319	692	1068	1081	1089	1070	1083	1092	1068	1081	1089
Figure 02 EU27	55	109	153	154	154	149	150	150	154	155	155
Figure 04 GER	11	22	30	30	30	29	29	29	30	30	31
Figure 05 UK	8	15	21	21	21	19	19	19	21	21	21
Figure 07 JPN	14	28	38	38	38	36	37	37	39	39	39
Poland	4	8	12	12	12	12	12	12	12	12	12
EVOC 05 RUS	25	46	65	66	66	65	67	67	65	66	66
Figure 01 USA	67	139	202	204	205	187	188	191	200	202	203
UNFCCC Annex I	187	375	532	535	536	515	517	521	532	535	538
EVOC 12 BRZ	8	18	28	28	28	28	29	29	28	29	29
EVOC 24 CHN	42	106	177	182	183	190	199	201	181	186	187
EVOC 25 IND	13	31	56	60	61	56	59	61	55	58	58
EVOC 13 MEX	5	11	18	18	18	18	18	19	18	18	18
EVOC 17 ZAF	4	8	12	12	12	12	13	13	12	12	12
Least Developed Countries	7	17	32	33	33	32	33	33	32	33	33
UNFCCC Non Annex I	129	311	525	536	542	541	556	564	525	535	540

	Cumulative emissions		CDC			GDRs			C&C 2050 convergence		
	Gt CO2 eq.		Gt CO2 eq.			Gt CO2 eq.			Gt CO2 eq.		
	1990-2000	1990-2010	1990-2050			1990-2050			1990-2050		
	Median	Median	Min	Median	Max	Min	Median	Max	Min	Median	Max
World total	319	692	1580	1599	1607	1583	1602	1610	1580	1599	1607
Figure 02 EU27	55	109	188	191	192	65	81	110	201	203	204
Figure 04 GER	11	22	37	37	37	11	13	20	39	39	39
Figure 05 UK	8	15	25	26	26	5	7	12	27	27	27
Figure 07 JPN	14	28	47	47	48	13	16	23	50	50	51
Poland	4	8	15	15	15	10	12	13	16	16	16
EVOC 05 RUS	25	46	79	81	82	68	73	80	83	85	86
Figure 01 USA	67	139	252	256	257	99	112	153	257	259	260
UNFCCC Annex I	187	375	659	669	673	321	370	443	689	694	698
EVOC 12 BRZ	8	18	39	40	40	36	39	43	43	44	44
EVOC 24 CHN	42	106	243	255	256	360	412	421	276	284	286
EVOC 25 IND	13	31	143	150	154	156	174	195	113	118	119
EVOC 13 MEX	5	11	24	25	25	23	24	26	27	27	27
EVOC 17 ZAF	4	8	17	17	17	20	23	24	17	18	18
Least Developed Countries	7	17	84	90	92	105	117	127	74	76	77
UNFCCC Non Annex I	129	311	898	917	919	1123	1207	1268	873	890	893

Table 7. Cumulative emission allowances from 2010 to 2020 and 2050 under CDC, C&C and GDRs excluding LUCF

Year	Cumulative emissions Gt CO2 eq.		CDC Gt CO2 eq.			GDRs Gt CO2 eq.			C&C 2050 convergence Gt CO2 eq.		
	1990-2000	1990-2010	2010-2020			2010-2020			2010-2020		
Country group	Median	Median	Min	Median	Max	Min	Median	Max	Min	Median	Max
World total	319	692	376	387	395	377	388	396	376	389	397
Figure 02 EU27	55	109	43	44	44	38	39	40	45	45	46
Figure 04 GER	11	22	8	8	8	7	7	7	9	9	9
Figure 05 UK	8	15	6	6	6	4	4	5	6	6	6
Figure 07 JPN	14	28	10	11	11	8	8	9	11	11	11
Poland	4	8	4	4	4	4	4	4	4	4	4
EVOC 05 RUS	25	46	19	19	20	19	20	21	19	20	20
Figure 01 USA	67	139	63	64	65	48	48	52	61	63	63
UNFCCC Annex I	187	375	157	160	161	139	140	144	157	161	163
EVOC 12 BRZ	8	18	10	10	11	11	11	11	10	11	11
EVOC 24 CHN	42	106	71	76	76	84	92	94	75	80	81
EVOC 25 IND	13	31	25	29	30	25	28	29	25	27	27
EVOC 13 MEX	5	11	7	7	7	7	7	7	7	7	7
EVOC 17 ZAF	4	8	4	4	5	4	5	5	4	4	4
Least Developed Countries	7	17	14	15	16	14	15	16	15	15	16
UNFCCC Non Annex I	129	311	214	224	229	231	244	252	215	224	230

	Cumulative emissions Gt CO2 eq.		CDC Gt CO2 eq.			GDRs Gt CO2 eq.			C&C 2050 convergence Gt CO2 eq.		
	1990-2000	1990-2010	2010-2050			2010-2050			2010-2050		
	Median	Median	Min	Median	Max	Min	Median	Max	Min	Median	Max
World total	319	692	888	905	913	889	906	914	888	907	915
Figure 02 EU27	55	109	79	81	83	-45	-30	0	91	94	94
Figure 04 GER	11	22	15	15	16	-11	-9	-2	17	17	18
Figure 05 UK	8	15	11	11	11	-10	-8	-3	12	12	12
Figure 07 JPN	14	28	19	20	20	-15	-12	-5	22	23	23
Poland	4	8	6	7	7	2	3	5	7	8	8
EVOC 05 RUS	25	46	33	35	36	22	27	34	37	38	39
Figure 01 USA	67	139	113	117	117	-41	-27	13	117	120	120
UNFCCC Annex I	187	375	284	294	298	-55	-7	66	314	319	323
EVOC 12 BRZ	8	18	21	22	22	18	21	25	25	26	26
EVOC 24 CHN	42	106	137	149	149	254	305	314	170	178	180
EVOC 25 IND	13	31	112	119	123	126	143	164	82	87	88
EVOC 13 MEX	5	11	13	14	14	12	12	15	16	16	16
EVOC 17 ZAF	4	8	9	9	9	12	15	16	9	10	10
Least Developed Countries	7	17	67	73	74	87	99	110	56	59	60
UNFCCC Non Annex I	129	311	587	605	607	813	895	955	562	579	582

Appendix C Comparison of data from EcoEquity and EVOC

	China	India	World	
				original data
Development threshold				roughtly calculated
EcoEquity			7,500	
Ecofys			7,500	
GDP, 2005, PPP, billion $				
Ecofys (ppp 2000)	5,333	2,441	55,588	
Word Bank (PPP 2005) (WDI, 2008)	5,333	2,441	56,265	
Word Bank	5,333	2,341	54,980	
GDP, 2020, PPP, billion $				
EcoEquity	12,971	6,623	99,708	
Ecofys (ppp 2000)	17,529	8,524	95,150	
EcoEquity, % of global	13%	7%	100%	
Ecofys, % of global	18%	9%	100%	
GDP per capita, 2010, PPP				
EcoEquity	5,899	2,818	9,929	
Ecofys (ppp 2000)	5,864	3,005	10,095	
EcoEquity, % change from global average	-41%	-72%	0%	
Ecofys, % change from global average	-42%	-70%	0%	
Population (% of global), 2010				
EcoEquity	19.7%	17.2%	100%	
Ecofys	19.7%	17.3%	100%	
RCI (share of global)				
EcoEquity (2010)	5.5%	0.5%	100%	
Ecofys (2010)				
EcoEquity (2030)	15.2%	2.3%	100%	
Ecofys (2030)	14.5%	3.5%	100%	
Emissions, roughly, GtCO2				
IEA 2000	3	1	23	
EcoEquity 2000	3	1	29	
EcoEquity 2030, BAU	12	3	50	
EcoEquity 2030, GDRs	7	3	17	
Emissions, MtCO2e				
Ecofys 2000	5	1	32	
Ecofys 2030, BAU (median)	14	5	63	
Ecofys 2030, GDRs (median)	8	4	22	
Emissions, growth rate 2000-2030				
EcoEquity, BAU	304%	520%	69%	
Ecofys, BAU	205%	313%	98%	
EcoEquity, GDRs	129%	373%	-41%	
Ecofys, GDRs	77%	216%	-31%	
Emissions, change to BAU, 2030				
EcoEquity, %	-43%	-24%	-65%	
Ecofys, %	-42%	-24%	-65%	
EcoEquity, GtCO2	5	1	32	
Ecofys, GtCO2e	6	1	41	
Gases included				
EcoEquity:	CO2 only			
Ecofys:	CO2eq (CO2, CH4, N2O, PFCs, HFCs, SF6)			

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