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<2°C Trajectories – a Brief Background Note

by
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(KyotoPlus-Papers sind Arbeitspapiere, die der inhaltlichen Begleitung der Konferenz „KyotoPlus – Wege aus der Klimafalle“ am 28. / 29. September 2006 in Berlin dienen. Die Meinung der Autoren gibt nicht unbedingt die Meinung der Veranstalter wieder, noch die Meinung der Einrichtungen, bei denen sie beschäftigt sind.)

(KyotoPlus-Papers are working papers to inform the conference „KyotoPlus – Escaping the Climate Trap“ on 28 / 29 September 2006 in Berlin. The opinions expressed in these papers do not necessarily represent those of the organisers or those of the institutions with which the author is affiliated.)

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1. Introduction

While the first commitment period of the Kyoto Protocol is starting soon, countries prepare for negotiating the second step of common but differentiated targets to reduce greenhouse gas emissions for the period after 2012. The ultimate goal agreed to by basically all nations is to "prevent dangerous anthropogenic interference with the climate system". Thus, near term action will have to be guided by long-term goals. Policy goals for the long-term have been set by various actors; e.g. the EU's established its 2°C objective first in 1996. Clearly, such a policy goal is not a "safe level" as a global mean temperature rise up to 2°C already implies serious adverse climate impacts in various regions (Smith et al., 2001; Hare, 2003; ACIA, 2004).

Despite 2°C not being a "safe level", we can derive emission trajectories for keeping global warming below 2°C. Currently, global mean temperatures are at about 0.8°C above pre-industrial levels. However, one additional decision has to be made by policymakers: How certain do we want to be not to exceed 2°C? This need for decision making under uncertainty is similar to many other policy debates, e.g. on nuclear safety: we want to prevent a meltdown, but the safety measures we envisage (ranging from multiple emergency backup generators to not using the technology at all) largely depend on how certain we want to be. Where is the uncertainty in climate science? Substantial uncertainties remain in the exact sensitivity of the climate system to human-induced perturbations, i.e. the greenhouse gas emissions. However, we do have certainty about the fact that the climate is changing due to human-induced greenhouse gas emissions and that potentially catastrophic impacts might be triggered (Smith et al., 2001). The equilibrium temperature of the earth might be 2.0°C, 3.0°C or 4.5°C in case we double CO_2 concentrations (see e.g. Gregory et al., 2002; Murphy et al., 2004; Schneider von Deimling et al., 2006; Knutti et al., in press). Deriving the necessary level of emissions reductions is therefore dependent upon how certain we want to be not to cross 2°C.

Working the cause-effect chain backwards, this background note first highlights greenhouse gas concentration levels compatible with 2°C (section 2), the issue of whether we are committed to cross 2°C because we are committed to cross 400ppm CO_2eq concentrations (section 3), the advantages of focussing on this centuries' peaking instead of long-term stabilization levels (section 4), and the global emission implications of having a likely chance to stay below 2°C (section 5). Section 6 briefly mentions uncertainties and section 7 concludes.

2. Stabilization at <400ppm CO2eq needed for a likely chance to stay below 2°C

This section explores the relationship between stabilized greenhouse gas concentration levels and global mean equilibrium temperatures. Often, this relationship is expressed in terms of "climate sensitivity", which states the equilibrium global mean surface temperature increase for a doubling of atmospheric CO_2 concentrations. Pre-industrial CO_2 concentrations were around 278 parts per million (ppm), thus a climate sensitivity of 3°C implies that the expected equilibrium surface temperature for a stabilization at 556ppm CO_2 is 3°C. Further doubling of CO_2 concentrations from 556ppm CO_2 to 1112 ppm CO_2 would imply an additional 3°C warming (6°C in total)[1].

Unfortunately, it is not clear, what the real climate sensitivity is. Early estimates range between 1.5°C and 4.5°C (IPCC, 1996, 2001), and recent studies basically confirm this range. However, higher values cannot be excluded and climate sensitivities around the lower side of 1.5°C seem less and less likely (see e.g. Forest et al., 2002; Gregory et al., 2002; Knutti et al., 2003; Murphy et al., 2004; Schneider von Deimling et al., 2006; Knutti et al., in press).

Taking those recent studies into account, our current knowledge about the climate systems suggests that only stabilization around or below 400ppm CO_2 equivalence will likely allow us to keep global mean temperature levels below 2°C in the long-term (see Table 1).

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[1] This is due to the assumed linear relationship between radiative forcing and temperature and the assumed logarithmic concentration – forcing relationship for CO2 (see for the latter Myhre et al., 1998).

Table 1 - Likelihoods to stay below different equilibrium temperature levels for different CO_2 equivalent stabilization levels. If global mean temperatures should “likely” stay below 2°C, a stabilization of greenhouse gas concentrations around or below 400ppm CO_2 equivalent were needed. This table indicates these likelihoods to stay below 2°C and other temperature levels in case that the climate sensitivity is believed to be somewhere between 2.0°C and 4.5°C with 80% confidence.[2]

	Equilibrium Warming with 3°C climate sensitivity[3]	Probability to stay below equilibrium warming level					
Stabilization concentration (CO2 equivalence)	**Degree Celsius above pre-industrial (°C)**	**1.5°C**	**2.0°C**	**2.5°C**	**3.0°C**	**3.5°C**	**4.0°C**
350 ppm	1.0°C	Very likely	Very likely	Very likely	Very likely	Very likely	Very likely
400 ppm	1.6°C	Medium	Likely				
450 ppm	2.1°C	Unlikely	Medium	Likely	Likely		
500 ppm	2.5°C	Very unlikely	Unlikely	Medium		Likely	
550 ppm	3.0°C			Unlikely	Medium likelihood		Likely
600 ppm	3.3°C		Very unlikely			Medium Likelihood	
650 ppm	3.7°C				Unlikely		Medium likelihood
700 ppm	4.0°C						

3. We cross 400ppm CO_2eq, although we don’t have to exceed 2°C.

Given the need for a 400ppm CO_2eq stabilization, a slightly disturbing fact is that we are currently already close to that level and will most likely cross the 400ppm CO_2eq level in the near future. The CO_2 concentrations alone are currently around 380ppm, rising by nearly 2ppm per year. In addition, other greenhouse gases contribute to a warming, like methane and nitrous oxide, while some human-induced aerosols have a net cooling effect. Overall, these non-CO_2 warming and cooling effects might currently approximately cancel each other, although there is a rather substantial uncertainty in regard to the cooling effect of aerosols.

Fortunately, the fact that we are most likely to cross 400ppm CO_2eq level in the near-term, does not mean that our goal to stay below 2°C is unachievable. If global concentration levels peak this century and are brought back to lower levels again, like 400ppm, the climate system’s inertia would help us to stay below 2°C.

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[2] Here the underlying calculations follow a similar procedure as applied in Wigley and Raper (2001): A 2°C to 4.5°C uncertainty range is assumed to be a 80% confidence interval for a lognormal probability distribution of climate sensitivity. For the translation of such a probability distribution into likelihoods to exceed or stay below 2°C, please see Meinshausen (2006). Legend for likelihoods: “very likely”: >90%, “likely” 66%-90%, “medium likelihood”: 33% to 66%; “unlikely” 10% to 33%; “very unlikely” <10%. Note that the “very likely” category is here only applied for illustrative purposes – assuming the lognormal pdf of climate sensitivity, and therefore does not reflect the remaining scientific uncertainty for high climate sensitivities >4.5°C.

[3] Note that global mean temperature at equilibrium is different from expected global mean temperatures in 2100 due to the inertia of the climate system. These equilibrium temperatures follow from the equivalent CO2 concentration value and the simplified expression for equilibrium temperatures (namely $dT = (\ln(CO_2eq/278ppm))/\ln(2))*S$, where CO_2eq is the equivalent concentration level, and S the climate sensitivity).

It's a bit like cranking up the control button of a kitchen's oven to 220°C (the greenhouse gas concentrations here being the control button). Provided that we are lowering the control button fast enough again, the actual temperature in the oven will never reach 220°C (see Figure 1).

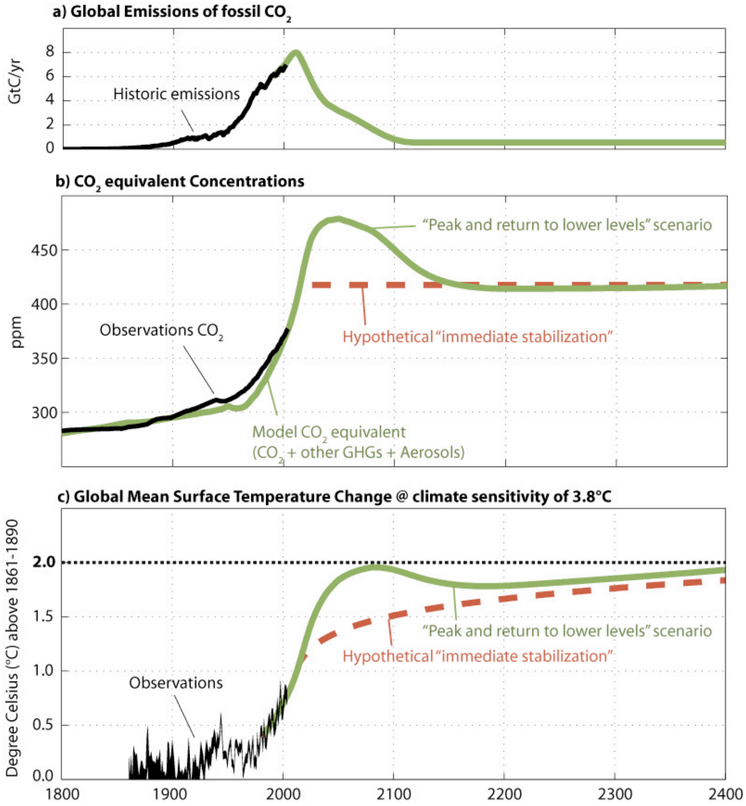

Figure 1 A schematic representation of (a) fossil CO_2 emissions, (b) CO_2-equivalent concentrations, and (c) global mean temperature for two scenarios: Firstly, an "immediate stabilization" which implies rising CO_2-equivalent concentrations up to around 415 ppm in 2015 and stable levels after that (red dashed line). This scenario is clearly hypothetical as the implied emission reductions in 2015 and beyond would hardly be economically and technically feasible. Secondly, a peaking scenario (green solid line), which temporarily exceeds and then returns to a 415 ppm stabilization level. Both scenarios manage to stay below a 2°C target – here for a climate sensitivity of 3.8°C or lower. This is roughly equivalent to a 4:1 chance of staying below 2°C[4].

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[4] The depicted peaking scenario is the EQW-S475-P400 scenarios as presented in Chapter 28 of the DEFRA report "Avoiding Dangerous Climate Change" (Schellnhuber et al., 2006). The "combined constraint" (see as well Chapter 28) has been chosen to find aerosol forcing and ocean diffusivity values for a 3.8°C climate sensitivity, which allow an approximate match to historic temperature and ocean heat uptake records. The historic fossil CO_2 emission data is taken from Marland et al.(see http://cdiac.esd.ornl.gov/trends/emis/tre_glob.htm), the CO_2 observations from Etheridge et al. and others are as given at http://www.giss.nasa.gov/data/simodel/ghgases/Fig1A.ext.txt and http://cdiac.ornl.gov/ftp/trends/co2/lawdome.combined.dat, and the temperature observations and their uncertainties are from Jones, Folland et al. as given here http://www.met-office.gov.uk/research/hadleycentre/CR_data/Annual/land+sst_web.txt. The simple climate model that was used is MAGICC 4.1 as in (Wigley and Raper, 2001). For more discussion, please see http://www.realclimate.org/index.php/archives/2006/01/can-2c-warming-be-avoided/.

4. Peaking is the key, not stabilization

Given that we are going to overshoot the required stabilization level of 400ppm in the near-term, it seems advisable not to focus on the stabilization level so much. Rather, one might want to focus on the peaking level within this century. This peaking level is the concentration at which the greenhouse gas concentrations level off and decrease again thereafter. Such a shift of the focus from stabilization to peaking scenarios would have several advantages.

Firstly, all conceivable mitigation scenarios for meeting 2°C with reasonable chances are peaking scenarios.

Secondly, focussing on the peaking level shifts the time horizon of interest closer to current times. It is somewhat easier to derive consequences for emission reduction from a 2050 peaking concentration target rather then from a 2150 stabilization concentration target.

Thirdly, the expected warming consequences of peaking scenarios have a lower uncertainty compared to the equilibrium warming of stabilization scenarios, as recently pointed out by Frame et al. (2006).

Although a comprehensive analysis of peaking levels is still subject of active research, some recent studies indicate that a peaking level around 475ppm CO_2equivalence is necessary to have a "likely" chance to meet a 2°C target (e.g. den Elzen and Meinshausen, 2006; Meinshausen, 2006); see as well Figure 1.

5. Global Emissions would need to be halved by 2050

This last section makes the step from concentrations to emissions. Thus, it sketches the emission implications of such "likely" 2°C trajectories. The default multi-gas emission pathway, as depicted in Figure 1 a, is here accompanied by a set of other pathways that peak at 475 or a bit higher and ultimately stabilize at 400ppm CO_2eq. Despite the fact that different methods[5] were used for deriving these multi-gas emission pathways the main conclusion is relatively robust: global greenhouse gas emissions need to be approximately halved by 2050 relative to 1990 emissions (see Figure 2).

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[5] Different methods exist for creating emissions scenarios, such as using bottom-up economic and technological models (see e.g. Nakicenovic and Swart, 2000; Swart et al., 2002). For our purposes, seeking a multi-gas emission pathway that stays below 2°C with a certain probability, a meta-approach has been chosen. This method, called "Equal Quantile Walk" (EQW) builds on the multi-gas emission characteristics of 54 SRES and post-SRES scenarios (see Meinshausen et al., 2006for further details). Furthermore, comparable emission pathways are shown that stabilize as well at 400ppm CO_2eq using a method based on marginal abatement cost curves (FAIR-SiMCaP pathways as described in den Elzen and Meinshausen, 2006).

Splitting up these global emissions into regional emission budgets is not a matter of solving a pure science question. The global cake can be split up in differently sized pieces – ideally depending on fairness, mitigation capacity, historical contribution, per-capita emissions, and other criteria, but undoubtedly influenced by a myriad of non-climate related political factors. In Figure 2, the depicted regional emissions of the default emission pathway are simply a reflection of regional emission evolutions of 54 SRES and post-SRES published scenarios in the literature. As the applied EQW method picks 'comparatively'[6] low emission levels for each region, the not so surprising result is that a sharp decrease of OECD emissions goes hand in hand with a more moderate decrease of non-Annex I emissions. In other words, the default scenario shows that Annex I (OECD and REF) countries are required to sharply reduce their emissions, more than the global average in relative terms (see Figure 2a) – a feature that is shared with possibly any plausible allocation scheme. Thus, while the EQW pathways derived this regional split-up of emissions from the multitude of underlying IPCC baseline and stabilization scenarios, there are many other methods, which apply explicit emission allocation schemes, such as Multi-Stage or Per Capita Convergence. The shown FAIR-SiMCaP pathways fall in this latter category.

Using median population projections by Lutz et al. (2001), the globally averaged per-capita emissions would have to decline to about 1-2 tonnes CO_2 equivalence emissions per year (tCO_2eq/yr) by the end of the century, with the Annex-I regions being currently far above this level (see Figure 2b). Currently, globally averaged per-capita emissions are about $6.1tCO_2/eq$ and $6.8tCO_2/yr/cap$, excluding and including landuse CO_2 emissions, respectively.

Table 2 - Global absolute and percapita emissions relative to 1990. Absolute global emissions would have to be reduced around 50% by 2050 (bold numbers). Given the expected increase in world population, the percapita emissions would have to be reduced around 70% by 2050. Shown are the default EQW pathway (italics – highlighted in Figure 2) as well as the mean and double standard deviations across the set of EQW and FAIR-SiMCaP pathways (in brackets). Note that the difference from the cases including and excluding landuse CO_2 emissions stems here from relatively large landuse CO_2 reductions assumed in the EQW pathways, not depicted in Figure 2. See as well text.

Absolute emissions	**2020**	**2050**	**2100**
w/o landuse CO2	*8%*(17±16%)	*-40%*(-47±14%)	*-71%*(-71±2%)
w landuse CO2	*-8%*(6±22%)	***-54%*(-60±14%)**	*-84%*(-84±2%)
PerCapita emissions			
w/o landuse CO2	*-25%*(-18±11%)	*-64%*(-68±9%)	*-82%*(-82±1%)
w landuse CO2	*-36%*(-26±15%)	*-73%*(-76±8%)	*-90%*(-90±1%)

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[6] See Meinshausen et al. (2006) for details.

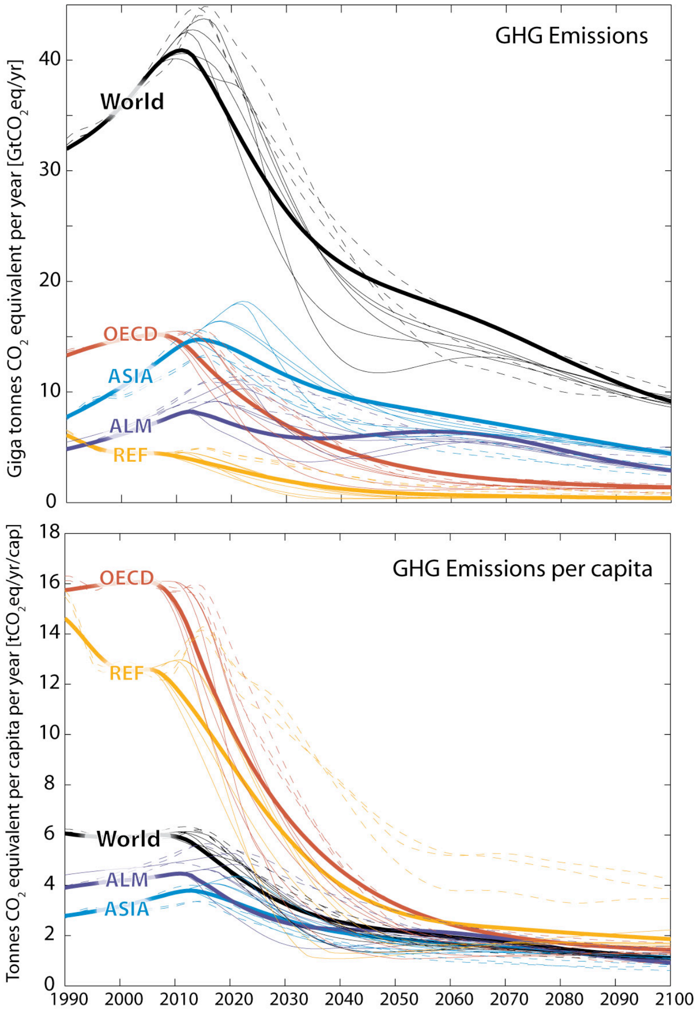

Figure 2 - Absolute greenhouse gas emissions (a) and per capita emissions (b) under different emission paths leading to a peaking at 475-500 CO_2 equivalence and subsequent decline of atmospheric GHG & aerosol concentrations down to around 400ppm CO_2 equivalence. Emissions are shown for different world regions (OECD, ASIA, REF - Economies in Transition, and ALM - Africa and Latin America). The fossil & industrial carbon dioxide (CO_2), methan (CH4), nitrious oxide (N_2O), and flourinated gas emissions (HFCs, PFCs, SF6) emissions are aggregated by using Global Warming Potentials (GWPs) as under the Kyoto Protocol, not including land-use CO_2 emissions. Note that the inclusion of landuse CO2 emissions would lower the pathways by approximately 10% for 2050 and beyond. The default emission pathway with a low emission reduction rate (bold lines) is compared to other EQW pathways with later peaking of global emissions (thin solid), as well as three pathways of the FAIR-SiMCaP model (thin dashed), all leading to 400ppm CO_2eq stabilization (assuming a 3°C climate sensitivity and standard carbon cycle feedbacks) after peaking at around 475ppm or slightly above.

6. Uncertainties cut both ways

Many uncertainties remain in regard to this translation of temperatures into emissions. This uncertainty can cut both ways. If carbon cycle feedbacks will turn out to be less than previously thought, or if aerosol cooling will be stronger than previously predicted, then emission allowances for a 475ppm peaking scenario could be higher than estimated here. On the other hand, many uncertainties rather point in the opposite direction. For example, stronger carbon cycle feedbacks (Cox et al., 2006), a higher climate sensitivity or methane releases from thawing Siberian permafrost lakes (see e.g. Walter et al., 2006) could shrink the available budget for emissions from human activities under a 2°C target.

7. Conclusions

To avoid a likely global warming of more than 2°C and all its consequences, global emissions would need to be reduced significantly, i.e. around -50% by 2050. Per-capita greenhouse gas emissions would need to be reduced by around 70%, so that global emissions could be halved despite the globally increasing population.

There are more than four decades until 2050, but only a few years until 2015-2020 when global emissions will have to peak in order to avoid a likely exceeding of 2°C warming. If global emissions level off much later, then subsequently necessary emission reductions of -4% or -5% each year could render the achievement of low stabilization levels practically infeasible.

Acknowledgements
Thanks to Bill Hare and Antonella Battaglini for support and stimulating discussions, and to my colleagues for earlier collaborative work on the matters of this briefing note, namely Michel den Elzen, Reto Knutti, and Dave Frame and to a superb anonymous editorial assistance.

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