On the Risk of Overshooting 2°C

Malte Meinshausen

Swiss Federal Institute of Technology (ETH Zurich), Environmental Physics, Department of Environmental Sciences, Rämistrasse 101, CH-8092 Zurich, Switzerland, Email: malte.meinshausen@env.ethz.ch

Abstract

This article explores different greenhouse gas stabilization levels and their implied risks of overshooting certain temperature targets, such as limiting global mean temperature rise to 2°C above pre-industrial levels. The probabilistic assessment is derived from a compilation of recent estimates of the uncertainties in climate sensitivity, which summarizes the key uncertainties in climate science for long-term temperature projections. The risk of overshooting 2°C equilibrium warming is found to lie between 68% and 99% for stabilization at 550ppm CO_2 equivalence. Only at levels around 400ppm CO_2 equivalence are the risks of overshooting low enough so that the achievement of a 2°C target can be termed "likely". Based on characteristics of 54 IPCC SRES and post-SRES scenarios, multi-gas emission pathways are presented that lead to stabilization at 550, 450 and 400ppm CO_2eq in order to assess the implications for global emission reductions. Sensitivity studies on delayed global action show that the next 5 to 15 years might determine whether the risk of overshooting 2°C can be limited to a reasonable range.

1. Introduction

In 1996, the European Council adopted a climate target that reads "[…] the Council believes that global average temperatures should not exceed 2 degrees above pre-industrial level". This target has since been reaffirmed by the EU on a number of occasions, including as recently as December 2004[1].

However, reviews of the scientific literature on climate impacts largely conclude that a temperature increase of 2°C above pre-industrial levels can not be regarded as 'safe'. For example, the loss of the Greenland ice-sheet may be triggered by a local temperature increase of approximately 2.7°C [*1, 2*], which could correspond to a global mean temperature increase of less than 2°C. This loss is likely to cause a sea level rise of 7 meters over the next 1000 years or more [*2*]. Similarly, unique ecosystems, such as coral reefs, the Arctic, and alpine regions, are increasingly under pressure and may be severely damaged by global mean temperature increases of 2°C or below [*3-5*]. Beyond 2°C, climate impacts are likely to increase substantially. A sea level rise of up to 3-5 meters by 2300 is possible for a 3°C global mean warming [*6*] due to, among other factors, the disintegration of the West Antarctic Ice-Sheet [*7*]. Other large scale discontinuities are increasingly likely for higher temperatures, such as strong carbon cycle feedbacks, [*8-10*] or potentially large, but still very uncertain, methane releases from thawing permafrost or ocean methane hydrates [*11, 12*].

For these reasons, this study focuses on an analysis of the risk of overshooting[2] global mean temperature levels of 2°C above pre-industrial levels. In order to allow for a more comprehensive climate impact risk assessment for different greenhouse gas stabilization levels, temperature levels between 1.5°C and 4°C are also analyzed.

2. Method

Climate sensitivity is the expected equilibrium warming for doubled pre-industrial CO_2 concentrations (2x278=~556ppm) (see Figure 1)[3]. Since the IPCC TAR, some key studies [*13-18*] have published ranges and probability density functions (PDFs) for climate sensitivity. Using a standard formula for the radiative forcing ΔQ caused by increased CO_2 concentrations C above pre-industrial levels C_o ($\Delta Q = 5.35 \ln(C/C_o)$)[*20*], one can derive equilibrium temperatures ΔT_{eq} for any CO_2 (equivalent) concentration and climate sensitivity ΔT_{2xCO2} as $\Delta T_{eq}=\Delta T_{2xCO2}(\Delta Q/5.35\ln(2))$. Thus, the risk $R(\Delta T_{crit},PDF_i,C)$ of overshooting a certain warming threshold ΔT_{crit} when stabilizing

---

[1] 2632nd Council Meeting Environment, Luxembourg, see http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/envir/83237.pdf

[2] Note that throughout this paper, the term 'risk of overshooting' is used for the 'probability of exceeding a threshold'. Technically speaking, 'risk' is thereby used as describing the product of likelihood and consequence with the consequence being sketched as a step function around the threshold.

[3] In this study, when necessary, climate sensitivity PDFs have been truncated at 10°C. Furthermore, the 90% uncertainty range given by Schneider von Deimling [*17*] for tropical sea surface temperatures between 2.5°C and 3°C during the last glacial maximum has been translated into a lognormal PDF in the same way as the conventional IPCC 1.5°C to 4.5°C range has been translated into a PDF by Wigley and Raper [*19*]. Note as well that the climate sensitivity PDF by Andronova and Schlesinger is the one that includes solar and aerosol forcing.

CO_2 (equivalent) concentrations at level C can be calculated as the integral $R(\Delta T_{crit}, PDF_i, C) = \int_{\Delta T_{crit}}^{\infty} PDF_i\left(x\left(\ln(2)/\ln(C/C_o)\right)\right)dx$ where $PDF_i(\Delta T_{2xCO2})$ is the assumed probability density for climate sensitivity ΔT_{2xCO2}.

In contrast to the parameterized calculations, transient probabilistic temperature evolutions were computed for this study with a simple climate model, namely the upwelling diffusion energy balance model MAGICC 4.1 by Wigley, Raper et al. [*21*]. As this study focuses on long-term temperature projections, the probabilistic treatment of uncertainties has been confined to the climate sensitivity on the basis of the above cited probability density estimates. For other uncertainties, this study assumes IPCC TAR 'best estimate' parameters, such as those related to climate system inertia and carbon cycle feedbacks. Assumptions in regard to solar and volcanic forcing are described elsewhere [*22*].

In order to assess the emission implications of different stabilization levels, this study presents new multi-gas emission pathways that were derived by the 'Equal Quantile Walk' method [*23*] on the basis of 54 existing IPCC SRES and Post-SRES scenarios. The emissions that have been adapted to meet the pre-defined stabilization targets include those of all major greenhouse gases (fossil CO_2, land use CO_2, CH_4, N_2O, HFCs, PFCs, SF_6), ozone precursors (VOC, CO, NO_x) and sulphur aerosols (SO_2). The basic idea behind the 'Equal Quantile Walk' method is that emissions for all gases of the new emission pathway are in the same quantile of the existing distribution of IPCC SRES and post-SRES scenarios. In other words, if fossil CO_2 emissions are assumed in the lower 10% region of the existing SRES and Post-SRES scenario pool, then methane, N_2O and all other emissions are designed to also be in the pool's respective lower 10% region [*23*].

The CO_2 equivalent (CO_2eq) stabilization targets are here defined as the CO_2 concentrations that would correspond to the same radiative forcing as caused by all human-induced increases in concentrations of greenhouse gases, tropospheric ozone and sulphur aerosols.

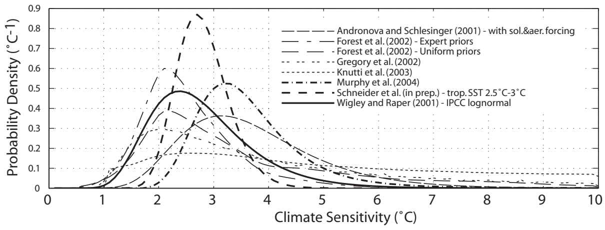

Figure 1 - Probability density functions of the climate sensitivity [*13-18*] used in this study.

3. The risk of overshooting 2°C in equilibrium

At 550ppm CO_2 equivalence (corresponding approximately to a stabilization at 475ppm CO_2 only), the risk of overshooting 2°C is very high, ranging between 68% and 99% for the different climate sensitivity PDFs with a mean of 85%. In other words, the probability that warming will stay below 2°C could be categorized as 'unlikely' using the IPCC WGI terminology[4]. If greenhouse gas concentrations were to be stabilized at 450ppm CO_2eq then the risk of exceeding 2°C would be lower, in the range of 26% to 78% (mean 47%), but still significant. In other words, 7 out of the 8 studies analyzed suggest that there is either a "medium likelihood" or "unlikely" chance to stay below 2°C. Only for a stabilization level of 400ppm CO_2eq and below can warming below 2°C be roughly classified as 'likely' (risk of overshooting between 2% and 57% with mean 27%). The risk of exceeding 2°C at equilibrium is further reduced, 0% to 31% (mean 8%), if greenhouse gases are stabilized at 350ppm CO_2eq (see Figure 2).

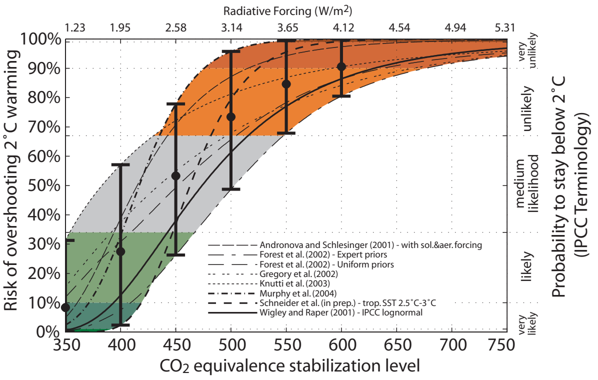

Figure 2 – The risk of overshooting 2°C global mean equilibrium warming for different CO_2 equivalent stabilization levels.

4. The risk of overshooting different warming levels

For a more comprehensive climate impact assessment across different stabilization levels, it is warranted to also include the lower risk / higher magnitude adverse climate impacts that can be expected at higher temperature levels. Given that climate sensitivity PDFs largely differ on the likelihood of very high climate sensitivities (>4.5°C), it is not surprising that a rising spread of risk is obtained for higher warming thresholds. For stabilization at 550ppm CO_2eq the risk of overshooting a rise in global mean temperature by

---

[4] See IPCC TAR Working Group I Summary for Policymakers: Virtually certain (>99%), very likely (90%-99%), likely (66%-90%), medium likelihood (33%-66%), unlikely (10%-33%), very unlikely (1%-10%), exceptionally unlikely (<1%).

3°C is still substantial, ranging from 21% to 69%. Furthermore, four out of the eight analyzed climate sensitivity PDFs suggest that the risk of overshooting 4°C is between 25% and 33%. Three studies suggest a risk between 1% and 9% (Figure 3).

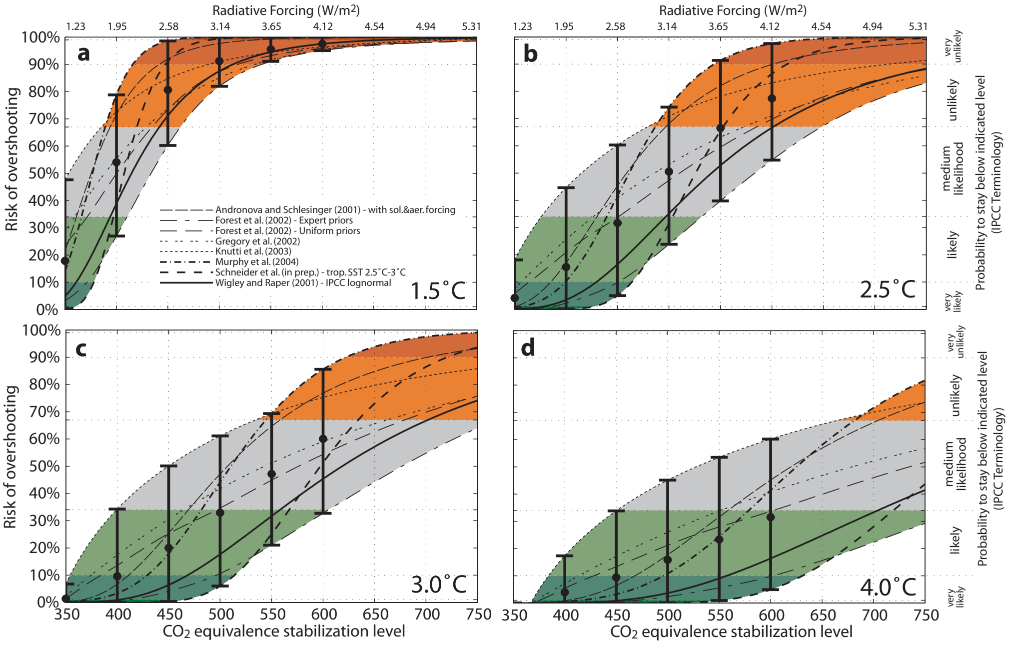

Figure 3 - The risk of overshooting (a) 1.5°C, (b) 2.5°C, (c) 3°C and (d) 4°C global mean equilibrium warming for different CO_2 equivalent stabilization levels.

5. Default stabilization scenarios and their transient temperature implications

In order to assess probabilistic temperature evolutions over time and the associated emission implications, three multi-gas emission pathways have been designed which stabilize at CO_2 equivalence levels of 550ppm (3.65W/m^2), 450ppm (2.58W/m^2) and 400ppm (1.95W/m^2) (see Methods). The latter two pathways are assumed to peak at 500ppm (3.14W/m^2) and 475ppm (2.86W/m^2) before they return to their ultimate stabilization levels around 2150 (see Figure 4). This peaking is partially justified by the already substantial present net forcing levels [*22*] and the attempt to avoid sudden drastic reductions in the presented emission pathways. The lower two stabilization pathways are within the range of the lower mitigation scenarios in the literature [*22*].

Due to the inertia of the climate system, (which is generally thought to be greater, the higher the real climate sensitivity is [*24, 25*]) the peak of 3.14W/m^2 in radiative forcing before the stabilization at 450ppm CO_2eq (2.58W/m^2) does not translate into a comparable peak in global mean temperatures. However, for the presented 400ppm CO_2eq stabilization scenario, the initial peak at 475ppm CO_2eq seems to be decisive when addressing the question of whether a 2°C, or any other temperature threshold, will be crossed (see Figure 5).

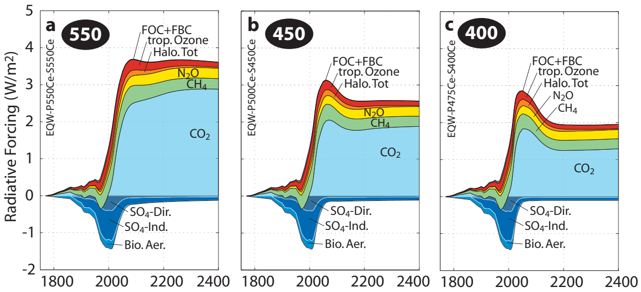

Figure 4 – The contribution to net radiative forcing by the different forcing agents under the three default emissions pathways for stabilization at (a) 550, (b) 450 and (c) 400ppm CO_2 equivalent concentration after peaking at (b) 500 and (c) 475ppm, respectively. The upper line of the stacked area graph represents net human-induced radiative forcing. The net cooling due to the direct and indirect effect of SO_x aerosols and aerosols from biomass burning is depicted by the lower negative boundary, on top of which the positive forcing contributions are stacked (from bottom to top) by CO_2, CH_4, N_2O, fluorinated gases, tropospheric ozone and the combined effect of fossil organic & black carbon. Note that a significant reduction of SO_2 aerosol emissions (and consequently radiative forcing) for the near future is implied by the pathways.

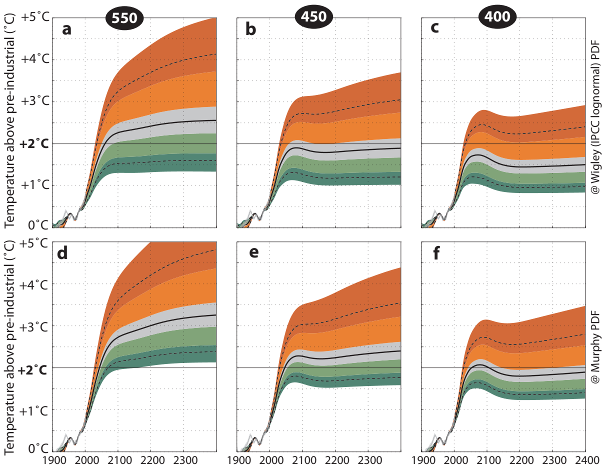

Figure 5 – The probabilistic temperature implications for stabilization scenarios at (a,d) 550ppm, (b,e) 450ppm, (c,f) and 400ppm CO_2 equivalent concentrations based on the climate sensitivity PDFs by (a-c) Wigley and Raper (IPCC lognormal) [*19*] and (d-f) Murphy et al. [*18*][5]. Shown are the median (solid lines), and 90% confidence interval boundaries (dashed lines), as well as the 1%, 10%, 33%, 66%, 90%, and 99% percentiles (borders of shaded areas). The historic temperature record and its uncertainty is shown from 1900 to 2001 (grey shaded band)[*26*].

6. (Non-)Flexibility to delay mitigation action

The global greenhouse gas emissions of the presented emission pathways can be summarized by their GWP-weighted sum for illustrative purposes[6] (see Figure 6). Under the default scenario for stabilization at 550ppm CO_2eq, Kyoto-gas emissions would have to return to approximately their 1990 levels by 2050. For stabilization at 450ppm CO_2eq, global Kyoto-gas emissions would need to be about 20% lower by 2050 compared to 1990 levels. If land use CO_2 emissions did not decrease as rapidly as assumed here (cf. Figure 8), but continued at presently high levels, Kyoto-gas emissions by 2050 would need to be approximately 30% below 1990 levels. Under the default emission pathway for stabilization at 400ppm with an initial peaking at 475ppm CO_2, global emissions would need to be 40% to 50% lower by the year 2050.

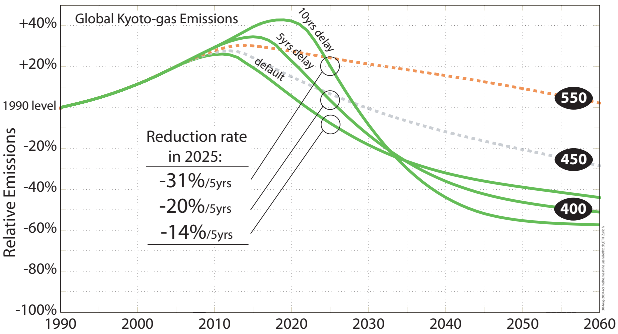

Figure 6 - Global Kyoto-gas emissions for stabilization at 550 and 450ppm CO_2eq (dotted lines) as well as 400ppm CO_2eq, including 2 delayed sensitivity variants (solid lines). Kyoto-gases include fossil CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6 emissions (GWP-weighted). If land use CO_2 emissions continued at their present high levels (cf. Figure 8), or carbon cycle feedbacks were significantly underestimated by the 'best estimate' climate model parameters, Kyoto-gas emissions would need to be 10% lower than shown here from around 2025 onwards.

Clearly, many different pathways can lead to the ultimate stabilization level. Thus, two delayed emission pathways for stabilization at 400ppm CO_2eq are presented here. The default and the two sensitivity pathways all imply the same risk of overshooting 2°C[7]. Specifically, emissions peak between 2010 and 2013 under the default emission pathway, around 2015 for the first delayed pathway and around 2020 for the second delayed pathway[8]. Around 2035, absolute levels must become lower for the delayed pathways than the default scenario in order to compensate for the initially higher emissions. Not only will absolute emission levels beyond 2035 have to be lower under the delayed emission pathways, but also the required emission reduction rates around 2025 will reach very high levels. Under the default pathway, emission reductions per five years are approximately 14% (relative to current 2025 levels). If the onset of emission reductions were delayed by 5 or 10 years, global emission reduction rates would increase to -20% per five years and -31% per five years, respectively (cf. Figure 6).

---

[5] These two climate sensitivity studies were selected for illustrative purposes in order to reflect one [19], which is consistent with the conventional 1.5°C to 4.5°C uncertainty range and one of the most recently published ones[18].

[6] Note that the Global Warming Potentials (GWPs) were not applied in any of the underlying calculations for deriving CO_2 equivalence concentrations (which is a different concept than CO_2 equivalent emissions). The GWPs, specifically the 100 year GWPs (IPCC 1996), were simply used here to present the different greenhouse gas emissions in a manner consistent with the current practice in policy documents, such as the Kyoto Protocol.

[7] Practically, the condition has been imposed on the delayed emission pathways that they have to peak at 2°C for the same climate sensitivity (~3.25°C) as the default pathway peaks at 2°C. Therefore, due to the dependency between climate sensitivity and climate inertia, the risk of overshooting temperature levels below 2°C will be (marginally) higher, while the risk of overshooting temperature levels above 2°C will be (marginally) lower for the delayed pathways.

[8] Specifically, it is assumed under the default scenario that OECD and Economies in Transition enter stringent emission reductions around 2010, while the Asia, Africa and Latin America regions follow five years later. Under the delayed profiles, the departure from the median emissions of the 54 SRES and post-SRES scenarios is assumed to happen 5 and 10 years later for all regions.

7. Discussion and Conclusion

The results of this study should not be interpreted as a prediction of what will be the ultimately tolerable stabilization or peaking level of greenhouse gases. Rather, the results presented attempt to sketch what the risks are that one must be willing to accept when embarking on one emission pathway or another.

Given the potential scale of climate impacts, climate policy decisions could benefit from an analysis of risk levels that seem acceptable in other policy areas, such as air traffic regulations, nuclear power plant building standards or national security. By taking a decision with respect to acceptable levels of risk, acceptable peaking and stabilization levels of greenhouse gases in the atmosphere could be inferred. In the future, we are unlikely to be able to lower the risks much by our action, as increasingly drastic and economically destructive emissions reduction rates would be required to correct the peaking/stabilization target downwards.

Without having undertaken an analysis of accepted risk levels in other policy areas, the following conclusions can be drawn:

First, the results indicate that a 550ppm CO_2 equivalent stabilization scenario is clearly not in line with a climate target of limiting global mean temperature rise to 2°C above pre-industrial levels. Even for the most 'optimistic' estimate of a climate sensitivity PDF, the risk of overshooting 2°C is 68% in equilibrium (cf. Figure 2).

Second, there is also a substantial risk of overshooting extremely high temperature levels for stabilization at 550ppm CO_2eq. Assuming the climate sensitivity PDF, which is consistent with the conventional IPCC 1.5°C to 4.5°C range[*19*], the risk of overshooting 4°C as a global mean temperature rise is still 9%. Assuming the recently published climate sensitivity PDF by Murphy et al. [*18*], the risk of overshooting 4°C is as high as 25% (cf. Figure 3).

Third, risks of overshooting 2°C can be substantially reduced for lower stabilization levels. In this paper, two emission pathways that lead to stabilization at 450ppm and 400ppm CO_2eq are presented and analyzed. In the latter case, seven out of eight climate sensitivity PDFs suggest that the chance of staying below 2°C warming in equilibrium is "likely" based on the IPCC Terminology for probabilities. For stabilization at 450ppm CO_2 equivalence, the chance to stay below 2°C is still rather limited according to the majority of studies, namely "medium likelihood" or "unlikely" (cf. Figure 2).

Fourth, delaying global mitigation action by just 5 years matters, if one does not wish to increase the risk of overshooting warming levels like 2°C. The rate of annual global emission reductions by 2025 might double, if the onset of stringent global mitigations is delayed by 10 years until 2020 in Annex-I and 2025 in non-Annex I countries.

8. Acknowledgements

The author is most grateful to Bill Hare, who inspired large parts of this work, and Stefan Rahmstorf, who provided inspiring comments on an earlier presentation on which this paper is based. In particular, I would like to thank Claire Stockwell and Fiona Koza for their goddess-like editing support and helpful comments, as well as Paul Bear and Michèle Bättig. Dieter Imboden is warmly thanked for his support. Finally, the author would like to thank Tom Wigley for providing me with vital assistance and the MAGICC 4.1 climate model.

9. Appendix: regional and global emissions of the presented pathways

This appendix details the emissions that underly the presented default pathways for stabilization at 550, 450 and 400ppm CO_2eq concentrations. The method to derive these emission pathways, namely the 'Equal Quantile Walk' method, makes only minimal assumptions with regards to the different gases' emission shares. The gas-to-gas emission characteristics are based on the pool of 54 IPCC SRES and post-SRES emission scenarios. Similarly, the stabilization pathways are not based on one specific socio-economic development path, as all of the underlying 54 scenarios are. The complete dataset for gas-to-gas emissions and the 4 SRES World regions OECD, Economies in Transition, Asia, and Latin America & Africa is available at www.simcap.org.

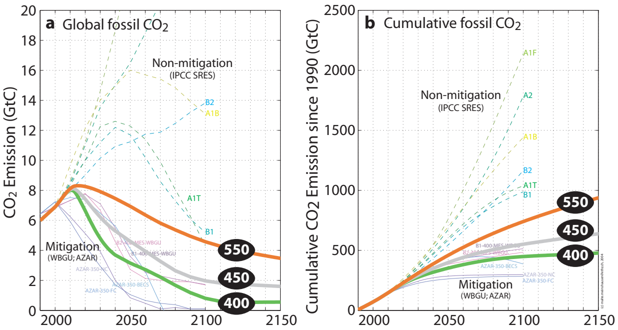

Figure 7 - Global fossil CO_2 emissions (a) and cumulative fossil CO_2 emissions (b). Note that the indicated cumulative emissions may be up to 100GtC lower, if landuse CO_2 emissions do not decline as steeply as depicted in Figure 8 a. Emissions of the illustrative IPCC SRES non-mitigation scenarios [*27*] are depicted for comparative purposes (thin dashed lines) together with some of the lower mitigation scenarios available in the literature [*28, 29*] (thin solid lines).

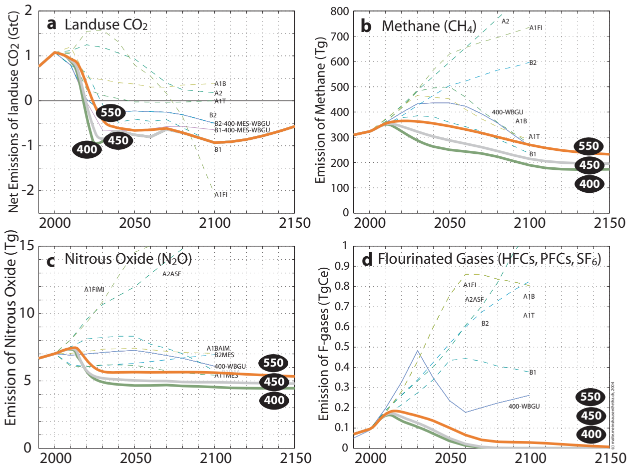

Figure 8 -Global emissions of the presented stabilization pathways: (a) Landuse CO_2, (b) Methane, (c) Nitrous Oxide, (d) the GWP weighted sum of CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca, and SF6, which are treated as separate gases in the climate model and emission pathways. Emissions of the illustrative IPCC SRES non-mitigation scenarios are depicted in thin dashed lines.

10. References

[1] Huybrechts, P., Letreguilly, A. and Reeh, N.: 1991, 'The Greenland Ice-Sheet and Greenhouse Warming', Global and Planetary Change 89, 399-412.

[2] Gregory, J.M., Huybrechts, P. and Raper, S.C.B.: 2004, 'Climatology - Threatened loss of the Greenland ice-sheet', Nature 428, 616-616.

[3] Smith, J.B., Schellnhuber, H.-J. and Mirza, M.Q.M.: 2001, 'Vulnearability to Climate Change and Reasons for Concern: A Synthesis', in McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. and White, K.S. (eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability, Cambridge University Press, Cambridge, UK, pp. 1042.

[4] Hare, W.: 2003, 'Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Art. 2 of the UNFCCC'. Potsdam, Berlin, WBGU - German Advisory Council on Global Change. http://www.wbgu.de/wbgu_sn2003_ex01.pdf

[5] ACIA: 2004, Impacts of a Warming Arctic - Arctic Climate Impact Assessment, Cambridge University Press, Cambridge, UK.

[6] Rahmstorf, S. and Jaeger, C.: 2004, 'Sea level rise as a defining feature of dangerous interference with the climate system'. Potsdam, Germany, Potsdam Institute for Climate Impact Research: 3. available at http://forum.europa.eu.int/Public/irc/env/action_climat/library

[7] Oppenheimer, M. and Alley, R.B.: 2004, 'The West Antarctic Ice Sheet and Long Term Climate Policy', Climatic Change 64, 1-10.

[8] Friedlingstein, P., Dufresne, J.L., Cox, P.M. and Rayner, P.: 2003, 'How positive is the feedback between climate change and the carbon cycle?' Tellus Series B-Chemical and Physical Meteorology 55, 692-700.

[9] Jones, C., Cox, P.M., Essery, R.L.H., Roberts, D.L. and Woodage, M.J.: 2003, 'Strong carbon cycle feedbacks in a climate model with interactive CO2 and sulphate aerosols', Geophysical Research Letters 30, 1479-1483.

[10] Jones, C.D., Cox, P. and Huntingford, C.: 2003, 'Uncertainty in climate-carbon-cycle projections associated with the sensitivity of soil respiration to temperature', Tellus Series B-Chemical and Physical Meteorology 55, 642-648.

[11] Archer, D., Martin, P., Buffett, B., Brovkin, V., Rahmstorf, S. and Ganopolski, A.: 2004, 'The importance of ocean temperature to global biogeochemistry', Earth and Planetary Science Letters 222, 333-348.

[12] Buffet, B. and Archer, D.: in press, 'Global Inventory of Methane Clathrate: Sensitivity to Changes in the Deep Ocean', Earth and Planetary Science Letters.

[13] Andronova, N.G. and Schlesinger, M.E.: 2001, 'Objective estimation of the probability density function for climate sensitivity', Journal of Geophysical Research-Atmospheres 106, 22605-22611.

[14] Forest, C.E., Stone, P.H., Sokolov, A., Allen, M.R. and Webster, M.D.: 2002, 'Quantifying Uncertainties in Climate System Properties with the Use of Recent Climate Observations', Science 295, 113-117.

[15] Gregory, J.M., Stouffer, R.J., Raper, S.C.B., Stott, P.A. and Rayner, N.A.: 2002, 'An observationally based estimate of the climate sensitivity', Journal of Climate 15, 3117-3121.

[16] Knutti, R., Stocker, T.F., Joos, F. and Plattner, G.-K.: 2003, 'Probabilistic climate change projections using neural networks', Climate Dynamics 21, 257-272.

[17] Kerr, R.A.: 2004, 'Climate change - Three degrees of consensus', Science 305, 932-934.

[18] Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M. and Stainforth, D.A.: 2004, 'Quantification of modelling uncertainties in a large ensemble of climate change simulations', Nature 430, 768-772.

[19] Wigley, T.M.L. and Raper, S.C.B.: 2001, 'Interpretation of high projections for global-mean warming', Science 293, 451-454.

[20] Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajiama, T., Shi, G.Y. and Solomon, S.: 2001, 'Radiative Forcing of Climate Change', in Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (eds.), Climate Change 2001: The Scientific Basis, Cambridge University Press, Cambridge, UK, pp. 892.

[21] Wigley, T.M.L.: 2003, 'MAGICC/SCENGEN 4.1: Technical Manual'. Boulder, Colorado, UCAR - Climate and Global Dynamics Division. available at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html

[22] Hare, B. and Meinshausen, M.: 2004, 'How much warming are we committed to and how much can be avoided?' PIK Report. Potsdam, Potsdam Institute for Climate Impact Research: 49. No. 93 http://www.pik-potsdam.de/publications/pik_reports

[23] Meinshausen, M., Hare, B., Wigley, T.M.L., van Vuuren, D., den Elzen, M.G.J. and Swart, R.: submitted, 'Multi-gas emission pathways to meet arbitrary climate targets', Climatic Change, 50.

[24] Hansen, J., Russell, G., Lacis, A., Fung, I., Rind, D. and Stone, P.: 1985, 'Climate Response-Times - Dependence on Climate Sensitivity and Ocean Mixing', Science 229, 857-859.

[25] Raper, S.C.B., Gregory, J.M. and Stouffer, R.J.: 2002, 'The Role of Climate Senstivity and Ocean Heat Uptake on AOGCM Transient Temperature Response', Journal of Climate 15, 124-130.

[26] Folland, C.K., Rayner, N.A., Brown, S.J., Smith, T.M., Shen, S.S.P., Parker, D.E., Macadam, I., Jones, P.D., Jones, R.N., Nicholls, N. and Sexton, D.M.H.: 2001, 'Global temperature change and its uncertainties since 1861', Geophysical Research Letters 28, 2621-2624.

[27] Nakicenovic, N. and Swart, R., eds: 2000, IPCC Special Report on Emissions Scenarios, Cambridge University Press, Cambridge, United Kingdom, 612.

[28] Nakicenovic, N. and Riahi, K.: 2003, 'Model runs with MESSAGE in the Context of the Further Development of the Kyoto-Protocol'. Berlin, WBGU - German Advisory Council on Global Change: 54. Report-No.: WBGU II/2003 available at http://www.wbgu.de/wbgu_sn2003_ex03.pdf

[29] Azar, C., Lindgrena, K., Larsonb, E., Möllersten, K. and Yand, J.: submitted, 'Carbon capture and storage from fossil fuels and biomass - Costs and potential role in stabilizing the atmosphere', Climatic Change.