PART I

Climate change mitigation: scientific, political and international and trade law perspectives

1

Earth in the greenhouse — a challenge for the twenty-first century

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Greenhouse gas concentrations in the long-term perspective

As part of the European Project for Ice Coring in Antarctica (EPICA), an ice core of 3,270 metres in length was drilled at Dome Concordia (75° 06′ S, 123° 21′ E, 3233 m.a.s.l., −54.5°C mean annual temperature, 2.5 cm H_2O precipitation per year). This ice contains information on climate evolution over the last 800,000 years.[1] Important results of the analysis of the ice and the enclosed gas are now available and provide a unique context within which the present changes in the climate system should be interpreted.

The top layers of a polar ice sheet consist of firn (compacted snow), which is in contact with the atmosphere above. Air is exchanged with the atmosphere and can circulate freely in channels of the porous firn. Beyond a depth of about 80 metres, the high pressure of the overlying ice constricts the channels progressively until air bubbles are formed. Analysis of the air enclosed in these bubbles permits the reconstruction of past concentrations of the most important greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Measurements demonstrate that the current concentration of CO_2 is higher by 27 per cent, and that of CH_4 by 130 per cent, than any concentration during the last 650,000 years before industrialisation. Many different and independent studies show that these increases are caused primarily by the burning of fossil fuels, the change of land use and the production of cement.[2]

[1] EPICA Community Members, 'Eight glacial cycles from an Antarctic ice core', *Nature* 429 (2004), 623–8.

[2] The major raw materials for cement ($3CaO{\cdot}SiO_2$ and $2CaO{\cdot}SiO_2$) are limestone ($CaCO_3$) and sand (SiO_2). The production process involves sintering at temperatures exceeding 1000°C during which the $CaCO_3$ dissociates into CaO and CO_2. The former builds a structure with sand, the latter is emitted to the environment. In 2004, CO_2 emissions

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Figure 1 shows the CO_2 concentration over the last 650,000 years from measurements of the air entrapped in several different Antarctic ice cores.[3,4] The increase in the concentration of CO_2 during the past fifty years has passed beyond the range of natural fluctuations. These analyses also demonstrate the tight relationship between the CO_2 concentrations and temperature estimates: during ice ages, concentrations are low and in the range of about 200 parts per million (ppm), whereas during interglacials they are about 280 to 300 ppm. The present concentration is higher than 380 ppm and continues to increase.[5]

The challenge of the twenty-first century

It is beyond doubt that the accelerated warming of the last fifty years has been caused primarily by the increase in the concentration of greenhouse gases and is hence man-made.[6] Numerous model simulations demonstrate that natural forcings, such as the change in solar radiation or volcanic events, as well as natural cycles, are of only secondary importance.[7] The evolution of the surface temperature over the last thirty years can only be explained in a quantitative way by the radiative forcing caused by an increase in greenhouse gases (figure 2). *Climate sensitivity*, i.e. the global mean warming due to a doubling of the atmospheric CO_2 concentration, and a fundamental measure of the effect of greenhouse gases, can now be better constrained owing to better paleoclimate reconstructions.[8] These two results reinforce and consolidate the basis on which calculations of future climate change rest.

associated with global cement production amounted to 3.8 per cent of the global CO_2 emissions of 7.9×10^9 tonnes of carbon per year (G. Marland, T. A. Boden and R. J. Andres, 'Global, regional, and national CO_2 emissions' in *Trends: A Compendium of Data on Global Change* (Oak Ridge, Tenn.: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, 2007). http://cdiac.esd.ornl.gov/trends/emis/tre_glob.htm.

3 U. Siegenthaler, T. F. Stocker, E. Monnin, *et al.*, 'Stable carbon cycle-climate relationship during the Late Pleistocene', *Science* 310 (2005), 1313–17.

4 R. Spahni, J. Chappellaz, T. F. Stocker, *et al.*, 'Atmospheric methane and nitrous oxide of the Late Pleistocene from Antarctic ice cores', *Science* 310 (2005), 1317–21.

5 Current data on CO_2 from Mauna Loa (Hawaii) are available at www.cmdl.noaa.gov/ccgg/trends

6 S. Solomon, *et al.* (eds.), *Climate Change 2007: The Physical Science Basis* (Cambridge University Press, 2007).

7 P. A. Stott, J. F. B. Mitchell, M. R. Allen, *et al.*, 'Observational constraints on past attributable warming and predictions of future global warming', *J. Climate* 19 (2006), 3055–69.

8 G. C. Hegerl, T. J. Crowley, W. T. Hyde, *et al.*, 'Climate sensitivity constrained by temperature reconstructions over the past seven centuries', *Nature* 440 (2006), 1029–32.

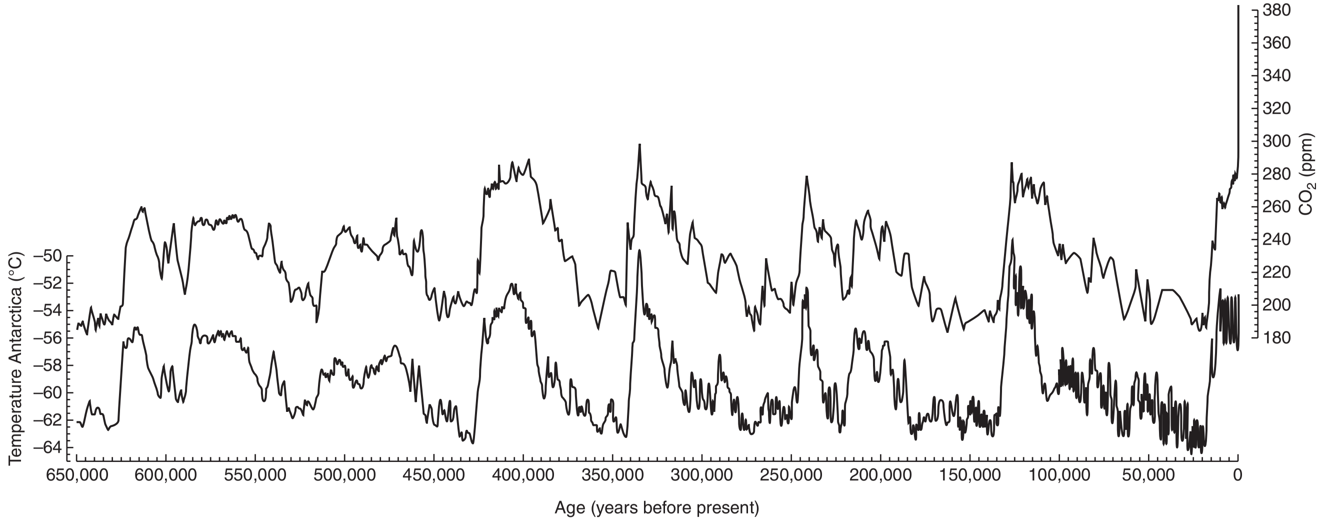

Figure 1 Reconstruction of the atmospheric CO_2 concentration over the last 650,000 years measured in different Antarctic ice cores, combined with the increase in CO_2 of the last fifty years directly measured in the atmosphere (upper curve). Temperature in Antarctica is estimated based on measurements of the stable isotopes of water (lower curve). Data sources: U. Siegenthaler, T. F. Stocker, E. Monnin, D. Lüthi, J. Schwander, B. Stauffer, D. Raynaud, J.-M. Barnola, H. Fischer, V. Masson-Delmotte, and J. Jouzel, Stable carbon cycle-climate relationship during the Late Pleistocene, *Science*, *310*, 1313–17, 2005. J. R. Petit, J. Jouzel, D. Raynaud, N. I. Barkov, J.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V. M. Kotlyakov, M. Legrand, V. Y. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, and M. Stievenard, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, *399*, 429–36, 1999. A. Indermühle, T. F. Stocker, F. Joos, H. Fischer, H. J. Smith, M. Wahlen, B. Deck, D. Mastroianni, J. Tschumi, T. Blunier, R. Meyer, and B. Stauffer, Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica, *Nature*, *398*, 121–6, 1999. EPICA Community Members, Eight glacial cycles from an Antarctic ice core, *Nature*, *429*, 623–8, 2004.

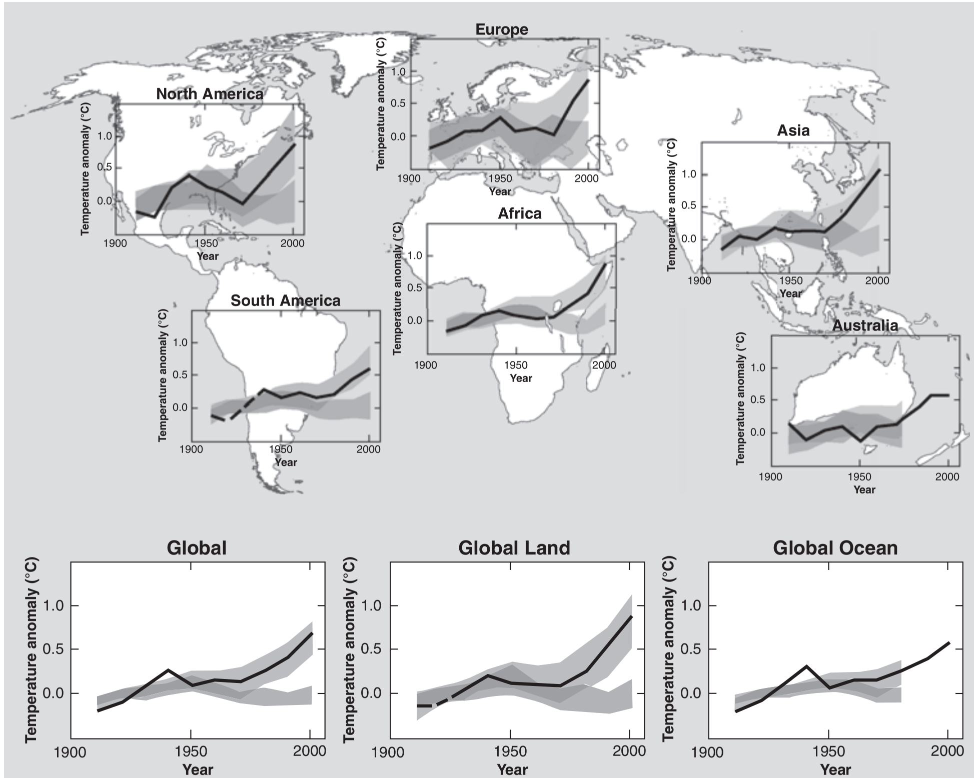

Figure 2 Temperature change in the twentieth century on the six continents. Measurements (black curves) are compared with simulations using different climate models, which consider only changes of solar radiation and volcanic events (darker grey bands), or which also take into account the increase of greenhouse gas and aerosol concentrations as observed (lighter grey bands, following the observations in the last decades of the twentieth century).[9]

A question of fundamental importance for policy-makers is how large the probability is of staying below an agreed global warming target. This can only be addressed using climate models which permit a large number of simulations. Knutti *et al.*[10] have used the climate model of reduced complexity of the University of Bern[11] and assumed an estimated probability density function for climate sensitivity.[12] The results are summarised in figure 3. They show that the agreed climate target of the European Union, i.e. to limit global warming at 2°C, can be achieved, but that this requires rapid implementation and efficient reduction of CO_2 emissions. A capping of atmospheric concentrations at twice the pre-industrial concentrations, i.e. at around 560 ppm, would permit a global

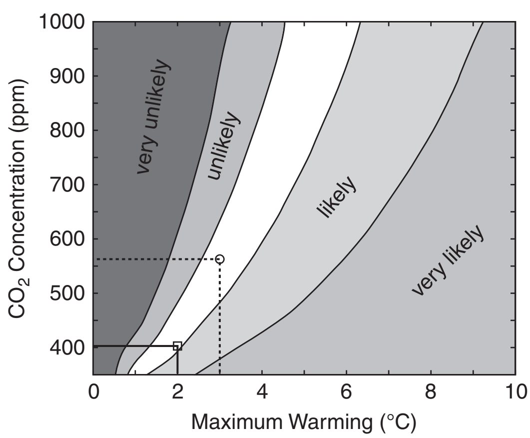

Figure 3 Estimate of likelihood that for a given CO_2 concentration, a maximum warming will not be exceeded. 'Very unlikely' denotes < 10%, 'unlikely' < 33%, 'likely' > 66%, and 'very likely' > 90%.
Source: Knutti *et al.*[13]

[9] IPCC, 'Summary for Policymakers' in S. Solomon, *et al.* (eds.), *Climate Change 2007: The Physical Science Basis* (Cambridge University Press, 2007), p. 18 *et seq.*
[10] R. Knutti, F. Joos, S. A. Müller, *et al.*, 'Probabilistic climate change projections for CO_2 stabilization profiles', *Geophys. Res. Lett.* 32 (2005), L20707.
[11] T. F. Stocker, D. G. Wright and L. A. Mysak, 'A zonally averaged, coupled ocean-atmosphere model for paleoclimate studies', *J. Climate* 5 (1992), 773–97.
[12] R. Knutti, T. F. Stocker, F. Joos, *et al.*, 'Constraints on radiative forcing and future climate change from observations and climate model ensembles', *Nature* 416 (2002), 719–23.
[13] R. Knutti, F. Joos, S. A. Müller, *et al.*, 'Probabilistic climate change projections for CO_2 stabilization profiles', *Geophys. Res. Lett.* 32 (2005), L20707.

warming target of about 3°C. It is evident from these calculations that the challenge increases rapidly with increasing CO_2 concentrations and more stringent temperature limits.

A global increase in temperature of 2°C is often assumed to be tolerable and has been declared as a climate target by the European Union. However, four points need to be considered.

First, while global temperature changes are an abstract metric, it is the regional changes that are relevant for the environment and society. Due to fundamental physical processes, the warming will be greater in areas of seasonal snow and ice cover. This is the snow/ice albedo feedback. In particular, at latitudes north of 60°N, the warming will be increased by at least a factor of two. Towards the end of the twenty-first century, large-scale melting of the Arctic sea ice cover[14] as well as accelerated loss of mass of the Greenland ice sheet are expected.[15] This feedback process is also responsible for a shortening of the winter season in Alpine areas. Even if the very ambitious climate target of 2°C can be achieved, tourism, water and hydropower economies will be seriously affected in these areas.

Second, changes in the occurrence of extreme events have captured the attention of the public because these are costly and immediate burdens to society. Simple statistical considerations show that the frequency of the occurrence of extreme events is particularly sensitive to small changes in the mean values (figure 4). Therefore, changes in the mean climate manifest themselves in changing statistics of extreme events. A small increase in the mean summer temperature, as illustrated in figure 4, will lead to a strongly increased probability of heat waves. Calculations suggest that the historic heat wave of 2003 can already be attributed to global warming.[16] Estimates of the future probability of the occurrence of such heat waves show that a situation such as the heat wave of 2003 or stronger could occur two to three times per decade towards the end of the twenty-first century.[17] Paleoclimate reconstructions corroborate these

[14] G. M. Flato and Participating CMIP Modeling Groups, 'Sea-ice and its response to CO_2 forcing as simulated by global climate change studies', *Clim. Dyn.* 23 (2004), 220–41.

[15] P. Huybrechts, J. Gregory, I. Janssens, *et al.*, 'Modelling Antarctic and Greenland volume changes during the 20th and 21st centuries forced by GCM time slice integrations', *Glob. Planet. Change* 42 (2004), 83–105.

[16] P. A. Stott, D. A. Stone and M. R. Allen, 'Human contribution to the European heatwave of 2003', *Nature* 432 (2004), 610–13.

[17] C. Schär, P. L. Vidale, D. Lüthi, *et al.*, 'The role of increasing temperature variability in European summer heat waves', *Nature* 427 (2004), 332–6.

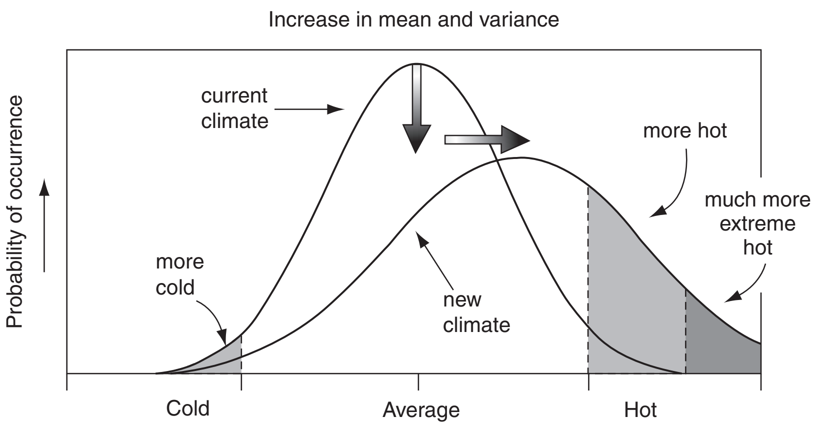

Figure 4 Schematic probability distribution of summer temperature. A small increase of the mean (shift of the curve towards the right) causes a decrease of the frequency of cold summers. The occurrence of hot summers and extreme hot summers will increase by many factors of ten (light and dark shaded areas on the right, respectively).

analyses and demonstrate that the heat wave of 2003 was unique in the last 500 years![18]

Third, long-term changes must be considered, too. The greenhouse gases already emitted have a long lifetime. In particular, about 15 per cent of the emitted CO_2 will remain in the atmosphere for centuries. Due to its large thermal inertia, the ocean is far from being in equilibrium. The increase in sea levels will persist well into the twenty-second century and would do so even if emissions were reduced today. This is due to the slow uptake of heat into the ocean. This so-called *climate commitment* implies that we have not yet experienced all the consequences of past greenhouse gas emissions.

Fourth, the latest climate research has shown that several components in the climate system exhibit non-linear behaviour and tipping points. Among the best known is the northward extension of the Gulf Stream. Strong and rapid warming has the potential to destabilise this circulation, causing a strong reduction in it, or even a cessation.[19] Model simulations point to the possibility of an ice-free Arctic if fossil fuel emissions continue at a high

[18] J. Luterbacher, D. Dietrich, E. Xoplaki, *et al.*, 'European seasonal and annual temperature variability, trends, and extremes since 1500', *Science* 303 (2004), 1499–503.

[19] T. F. Stocker and A. Schmittner, 'Influence of CO_2 emission rates on the stability of the thermohaline circulation', *Nature* 388 (1997), 862–5.

rate.[20] The latest simulations suggest that there is a threshold in the range of a warming between 1.9 and 4.6°C beyond which Greenland could melt completely.[21] Vegetation cover, in particular the tropical rainforest, could also reach tipping point if warming continues.[22]

Is there a magic fix?

Magic fixes for global warming are regularly proposed and make headlines in the media. But the large amounts of greenhouse gases which have been emitted during the past 250 years cannot be removed from the atmosphere within just a few years. Short-term measures such as piping greenhouse gas emissions into abandoned mines, or reforestation of some land areas, are futile efforts in comparison to the huge amounts of emissions. Only long-term strategies and global measures, such as the increase of fossil fuel efficiency and the gradual worldwide reduction in emissions will enable us to meet climate targets.

In addition to these indispensable mitigation measures which concern the origin of global warming, adaptation to the effects of past emissions and related climate change commitments will be necessary. Adaptation is highly region-specific. Not only *climate change mitigation* (as often claimed), but also *climate change adaptation* will be associated with high costs and the necessity for changes and investments in infrastructure. These costs are highly unlikely to scale linearly with the warming. Rather, greater warming and related changes will cause disproportionately large costs for adaptation. Whether we will be faced with a global warming of 2°C or 4°C is solely determined by the amount of greenhouse gases emitted from today onwards and hence is directly determined by our decisions at the local, regional and global levels.

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