What is the Economics of Climate Change?

Discussion Paper

31 January 2006

Technical Annex The science of climate change

Our changing climate

1 We are seeing evidence of the greenhouse effect in practice. Measurements are compiled from thousands of weather stations all over the world – on land, from ships and buoys at sea, from balloon-borne sensors, and most recently from satellites. Together all these sources – now including satellite-derived data for the upper atmosphere[1] – support the picture of a warming world.

2 The Earth has warmed by 0.7°C since 1900.[2] All ten warmest years on record have occurred since 1994. The rate and scale of 20th century warming has been unprecedented for at least the past 1,000 years.[3] The rate of sea level rise has doubled to 2 mm each year over the past 150 years.[4] We can see the effects of this warming all around us - widespread retreat of mountain glaciers (very rapid retreats observed recently, e.g. Alaska – 14Km since 1980, Greenland – 5Km per year), decreased snow cover, and the lengthening of growing seasons in northern latitudes.[5]

The nature of the evidence for climate change

3 The evidence for human-induced climate change is growing ever stronger. Climate models now show with a very high degree of confidence that human-induced increases in carbon dioxide and other greenhouse gases are responsible for much of the warming we have observed.[6] Climate models that take account only of natural factors, such as levels of solar activity and volcanic eruptions, predict a slight cooling in recent years. It is only when both natural factors and man-made influences such as air pollution and rising greenhouse gas concentrations are included that the models accurately predict the changes we have seen (Figure A1). More recently, temperature measurements in thousands of locations in the ocean (down to several hundred metres) taken by satellite

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[1] Mears CA, Wentz FJ (2005) The effect of diurnal correction on satellite-derived lower tropospheric temperature, *Science* **309**:1548 - 1551

[2] Hadley Centre (2005) Climate change, rivers and rainfall, http://www.metoffice.com/research/hadleycentre/pubs/brochures/B2005/COP11.pdf

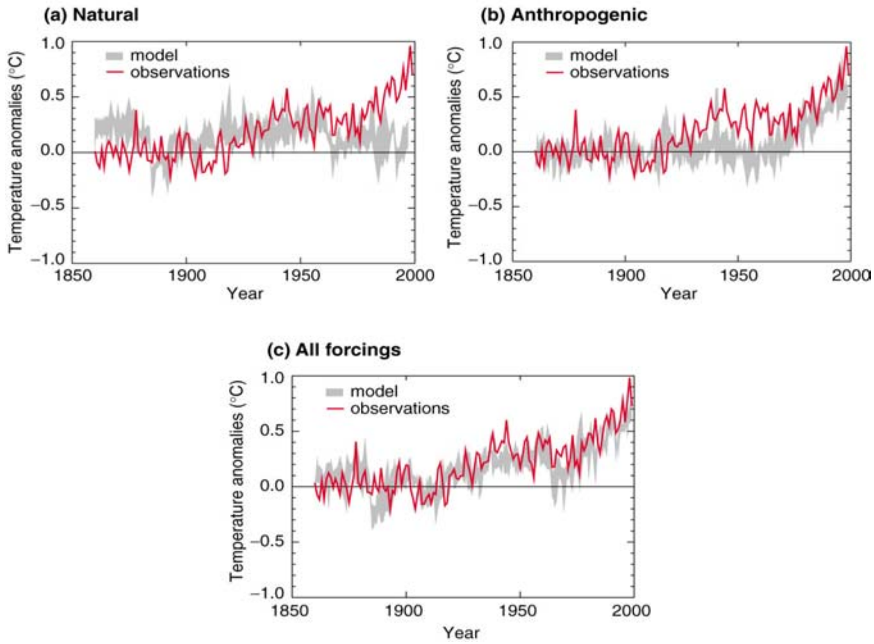
[3] International ad hoc detection group (2005) Detecting and attributing external influences on the climate system: a review of recent advances, *Journal of Climate* **18**:1291-1314

[4] Miller KG, Kominz MA, Browning JV *et al.* (2005) The Phanerozoic Record of Global Sea-Level Change, *Science* **310**: 1293 - 1298

[5] Intergovernmental Panel on Climate Change (2001) Climate change 2001: summary for policymakers, Cambridge University Press, Cambridge, http://www.ipcc.ch

[6] Intergovernmental Panel on Climate Change (2001) Climate change 2001: summary for policymakers, Cambridge University Press, Cambridge, http://www.ipcc.ch

Figure A1. *Comparison of outputs from climate model compared with observations of global temperature change under different forcing scenarios.*



Source: Hadley Centre (as reported in IPCC 2001)

showed a pattern of warming that was entirely consistent with model predictions of climate change.[7]

4 The basic physics of climate change is well established. The French mathematician Fourier coined the term "greenhouse effect" and established the principles in 1827. Solar energy penetrates the atmosphere and directly warms the Earth's surface, which radiates heat back into the atmosphere. Certain gases in the atmosphere (most importantly carbon dioxide and water vapour) trap some of the infrared radiation emitted by the Earth's surface, thus warming the surface of the Earth and lower atmosphere. The natural greenhouse effect has operated for billions of years, making our planet habitable by keeping the Earth's temperature around 30°C warmer than it would be without this "greenhouse effect". The Swedish scientist Arrhenius identified the physical link between carbon dioxide levels and global temperatures in 1896, predicting that global temperatures could rise by 5 – 6°C if carbon dioxide levels doubled (which, as we will see, is not far from some of today's predictions).

Future projections of climate change

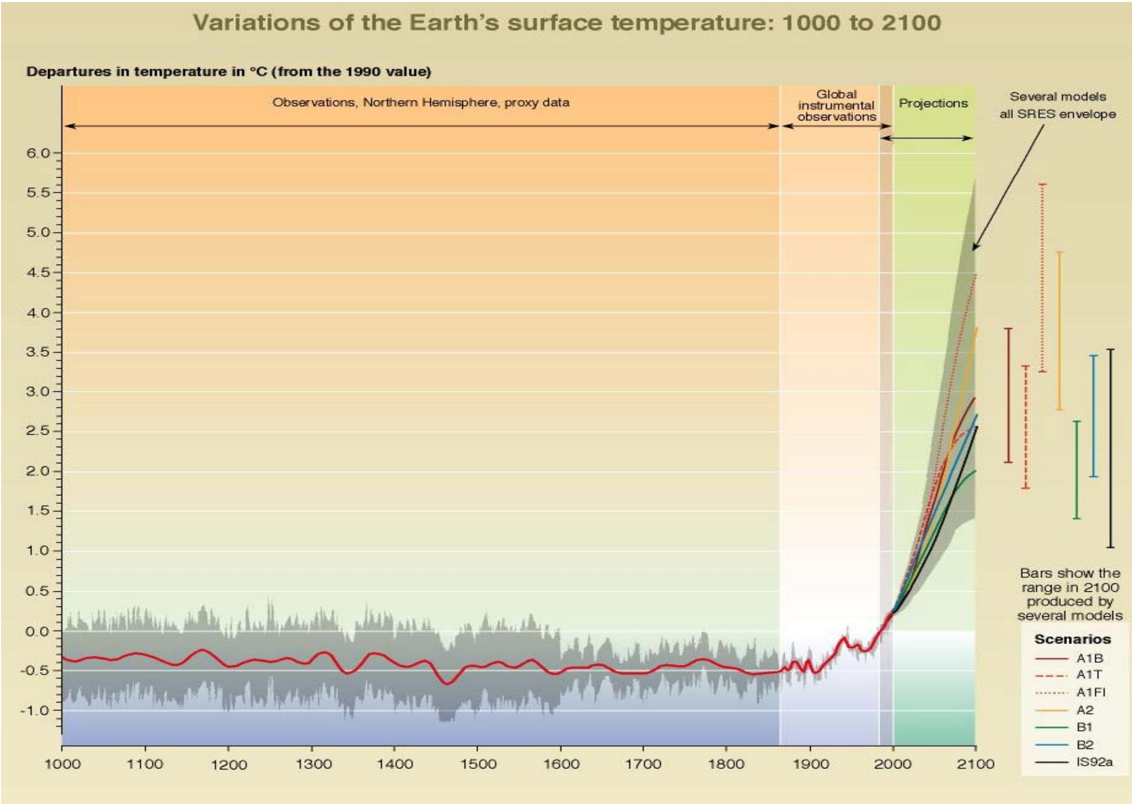
5 The Intergovernmental Panel on Climate Change (IPCC) uses scenario-based analysis to calculate that carbon dioxide concentrations could increase from around 380 ppm today to 540 - 970 ppm by 2100 (depending on various assumptions made about population growth, economic growth, energy prices and patterns of energy use). These concentrations translate into an increase in global average temperature of 1.4 - 5.8°C and sea level rise of 9 - 88cm over the period 1990 – 2100 (Figure A2). These average figures mask changes in the distribution of climate in space and time. Continental areas are expected to warm by more than the average (2.2 – 6.2°C by 2100) and some of the largest changes will be seen in the Arctic (3.6 – 11.4°C by 2100). These changes will

[7] Barnett TP, Pierce DW, AchutaRao KM, *et al.* (2005) Penetration of human-induced warming into the world's oceans, Science 309: 284 - 287

also be accompanied by changing patterns of rainfall and more extreme weather events (heatwaves, droughts, floods).

6 We have an increasingly good understanding of future trends. Even if all emissions stopped tomorrow, we are already locked into some climate change due to inertia in the climate system. Over the next 30 - 50 years we expect to see a continuing rise in global average temperatures, purely as a result of past emissions. Scientists are now able to assess the range of warming for a given level of carbon dioxide in the atmosphere (Figure A3) and the scale of the effort required to achieve particular stabilisation targets (Figure A4).[8]

Figure A2. *Projected changes in global average temperature to 2100 under different emissions scenarios (highest – A1FI, lowest – B1).*



Source: IPCC (2001)

7 This global average warming will have knock-on effects for regional climate. There are some strong global and regional effects of climate change that are predicted consistently across most climate models and that will have major impacts on lives and livelihoods (Figure A5).

[8] Hare B, Meinhausen M (2004) How much warming are we committed to and how much can be avoided? Potsdam Institute for Climatic Impact Research, http://www.pik-potsdam.de/publications/pik_reports/reports/pr.93/pr93.pdf

Figure A3. *Global mean temperature change associated with different greenhouse gas stabilisation levels.*

Greenhouse Gas Stabilisation Level		**Global-mean temperature change relative to pre-industrial based on IPCC 2001 results (90% confidence interval)[9]**		**Global-mean temperature change relative to pre-industrial based on Hadley centre ensemble results (90% confidence band)[10]**	
CO_2 Equivalent[11]	**CO_2 only level[12]**	**Temperature change in 2100**	**Temperature change at equilibrium[13]**	**Temperature change in 2100**	**Temperature change at equilibrium**
400 ppm	350 – 375 ppm	1.2 - 2.5°C	0.8 - 2.4°C	1.6 - 2.8°C	1.3 - 2.8°C
450 ppm	400 – 420 ppm	1.3 - 2.7°C	1.0 - 3.1°C	1.8 - 3.0°C	1.7 - 3.7°C
550 ppm	475 – 500 ppm	1.5 - 3.2°C [14]	1.5 - 4.4°C	2.2 - 3.6°C	2.4 – 5.3°C

Source: Based on den Elzen and Meinhausen (2005)[15].

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9 Temperature change derived from the projections of the IPCC Third Assessment Report (2001), based on seven climate models with climate sensitivities between about 1.5°C and 4.5°C (Wigley and Raper (2001), "Interpretation of high projections for global mean warming", Science 293, pp. 451-454).

10 Temperature change derived from recent estimates by the Hadley Centre using a large ensemble of model runs with perturbed physics. The ensemble gives a range of climate sensitivities between about 2.5° to 5.5°C (Murphy et al. (2004), "Quantification of modelling uncertainties in a large ensemble of climate change simulations", Nature 430, pp. 768-772).

11 Final stabilisation level for all greenhouse gases expressed as the equivalent level in CO_2

12 The final stabilisation level of CO_2 only. For example, for a stabilisation of 400ppm CO_2 equivalent, 350 - 375ppm will be from CO_2 and the remaining 25 –50 ppm from other greenhouse gases, such as methane.

13 The 'equilibrium' temperature change is the final stable temperature change obtained due to the build-up of greenhouse gases. The equilibrium point is generally reached sometime after 2300.

14 The full range based on results from the IPCC 2001 WRE stabilisation scenarios is approximately 2.0 - 3.2°C.

15 Elzen and Meinhausen (2005) "Meeting the EU 2°C climate target: global and regional emission implications"

Figure A4. *Two example sets of global emissions pathways to achieve different target stabilisation levels*

Scenario Name	Final Stabilised Concentration of CO_2 only	Global Emissions Pathway		
		Year When Global Emissions Fall below 1990 levels	Change in Global Emissions in 2050 relative to 1990 levels	Change in Global Emissions in 2050 relative to IPCC A2 Scenario[16]
IPCC 2001 Stabilisation Scenarios: CO_2 only[17]				
450ppm CO_2	450	2000 – 2040	-5% to –60%	-60% to –85%
550ppm CO_2	550	2030 – 2100	-10% to +70%	-30% to –65%
650ppm CO_2	650	2055 – 2145	+10% to +110%	-15% to –55%
2005 Stabilisation Scenarios: major greenhouse gases expressed as CO_2 equivalent (CO_2e)[18]				
400ppm CO_2e	350 - 375	2020 - 2030	-40% to -55%	-75% to -85%
450ppm CO_2e	400 - 420	2030 - 2040	-15% to -40%	-65% to -75%
500ppm CO_2e	440 - 460	2035 - 2055	Up to -25%	-60% to -70%
550ppm CO_2e	475 - 500	2045 - 2065	-10% to +10%	-50% to -60%

Sources: den Elzen and Meinhausen (2005) and the IPCC Third Assessment Report (2001)

[16] The A2 scenario outlines a future of increasing emissions of CO_2 at an average rate of about 1.3% increase per year. In 2050, the CO_2 emissions are 17.5MtC/yr and all emissions are around 20MtC/yr CO_2 equivalent. The scenario is described in the IPCC Special Report on Emissions Scenarios (SRES).

[17] CO_2-only stabilisation scenarios from the IPCC Third Assessment Report (2001). The values express only emissions of CO_2 required to meet the final CO_2 concentration. The uncertainties reflect uncertainties in the modelling of the global carbon cycle.

[18] Multi-gas stabilisation scenarios from den Elzen and Meinshausen (2005) "Meeting the EU 2°C climate target: global and regional emission implications". For each scenario, the emissions peak at around 2015 and then reduce at different rates to achieve the final stabilisation. The uncertainties reflect different emissions pathways with varied assumptions about technology, land-use changes and non-CO_2 greenhouse gases. The ranges do not reflect any uncertainty about the global carbon cycle and therefore are smaller than the IPCC 2001 ranges.

Figure A5. *Some key effects of climate change that are more certain*

Change	Region	Example consequences
More heatwaves	Continental areas	Temperatures experienced during the European heatwave of 2003 could be commonplace by the middle of the century and unusually cool by the end of the century (Hadley Centre 2004)
Less snow and reduced glacier extent	Many northern latitudes and areas that rely on snowmelt for summer water supply (e.g. China, India, Peru)	Millions more people suffering water shortage in Peru, China and India (Barnett *et al.* 2005) Unreliable snowfall could make ski resorts less attractive tourist destinations (Bürki *et al.* 2003)
Sea level rise and increased risk of coastal flooding	Many low-lying areas, including small island states, Western Africa, parts of South East Asia (e.g. Bangladesh)	1-m sea level could potentially affect 6 million people in Egypt, 13 million in Bangladesh, and 72 million in China
More intense precipitation events	Northern latitudes	Greater incidence of flooding with increasing weather damages to people, property and their possessions
Drier summers and increasing risk of severe droughts	Many mid-latitude continental areas, e.g. Mediterranean, Central America, Australia, Southern Africa	Proportion of years where run-off drops to drought levels could increase by 30% by 2050 in Southern Africa
Increasing ocean acidity	Our oceans could become considerably more acidic by the year 2100, probably be lower than has been experienced for hundreds of millennia and, critically, at a rate of change probably 100 times greater than at any time over this period.	Widespread impacts of marine ecosystems and biodiversity, with knock-on effects for local communities dependent on fishing

Source: Updated from IPCC (2001)

8 Recent work suggests that the climate could be even more sensitive to increases in greenhouse gases than we had previously thought, with some model runs suggesting that doubling CO_2 could produce 11°C of warming (compared with the 4.5°C reported in the IPCC).[19] Air pollutants may have masked the strength of the climate's response to greenhouse gases to date, meaning that a decline in air pollution in future could lead to a faster rate of warming.[20]

9 In addition, climate change will bring surprises – the risks of which are become clearer all the time. As global temperatures rise, there is an increased likelihood of reaching 'tipping points' - exceeding particular triggers in the climate system, leading to major irreversible disruptions (Figure A6).[21] Melting of permafrost in the Arctic could lead to the release of huge quantities of methane. Dieback of the Amazon forest could turn the region from a sink for carbon to a source. These feedbacks could lead to warming that is at least twice as fast as current high-emissions projections, with temperatures higher than seen in the past 50 million years (Figure A7).[22]

10 The book "Avoiding Dangerous Climate Change" launched yesterday by the UK Government highlights how our understanding of some of the most significant

Figure A6. *Potential impacts of rapid climate change, with some estimates of likely global trigger temperatures.*

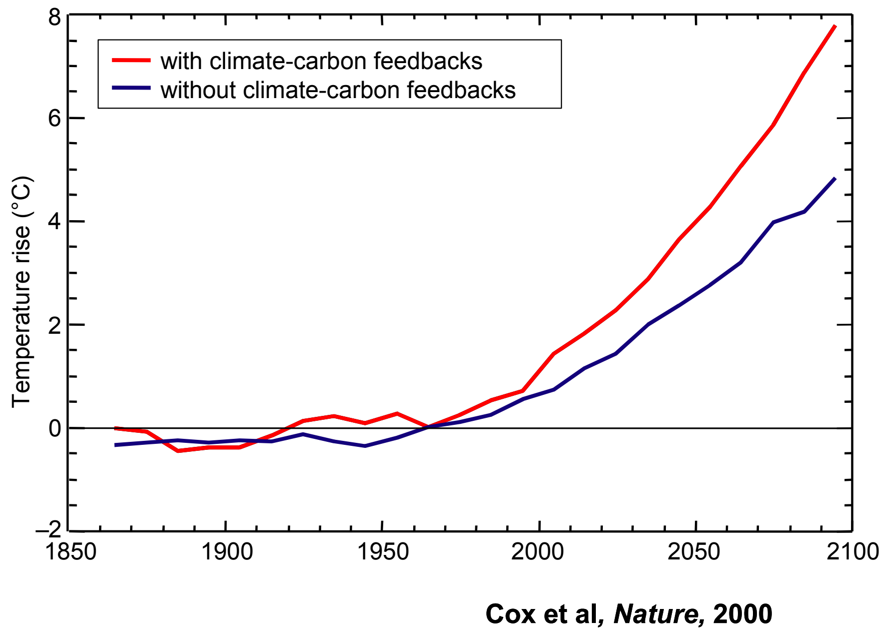
Global Temperature Increase (relative to 2000)	Potential Impact
2 – 3°C	Onset of melt of Greenland Ice Sheet, increasing sea levels by 75cm by 2100 and causing eventual additional sea level rise of 7m over millennia
	Collapse of Amazon rainforest, with forest replaced by savannah, leading to significant consequences for biodiversity and human livelihoods
	Desertification of many world regions with widespread loss of forest and grassland
2 – 5°C	Potential to trigger melting of West Antarctic Ice Sheet, raising sea levels by a further 5 – 6 m for centuries or up to 75cm by 2100
	Chance of complete collapse of Thermohaline circulation, cooling Northern Hemisphere by several degrees and changing rainfall patterns
	Potential release of methane from melting tundra and shallow seas, further accelerating warming

Source: Adapted from Schneider and Lane (2006)

[19] Stainforth DA, T. Aina T, C. Christensen C, *et al.* (2005) Uncertainty in predictions of the climate response to rising levels of greenhouse gases, *Nature* **433**: 403 - 406
[20] Bellouin N, Boucher O, Haywood J, *et al.* (2005) Global estimate of aerosol direct radiative forcing from satellite measurements, *Nature* **438**: 1138-1141
[21] Schneider SH, Lane J (2006) An overview of "dangerous" climate change, in *Avoiding dangerous climate change*, Schellnhuber HJ (ed), Cambridge University Press, Cambridge
[22] Hadley Centre (2005) Stabilising climate to avoid dangerous climate change, http://www.metoffice.com/research/hadleycentre/pubs/brochures/2005/CLIMATE_CHANGE_JOURNAL_150.pdf

(but uncertain) impacts of climate change is constantly improving.[23] We now realise that we could see some of these more extreme impacts within our lifetime, e.g. the start of an irreversible collapse of the Greenland ice sheet, which would

Figure A7. *Increase in global temperature with and without carbon cycle feedbacks. The red line include dieback of the Amazon forest and other vegetation sources – which release carbon into the atmosphere and change from becoming a sink to a source of carbon.*



Source: Hadley Centre (2000)

lead to an eventual rise in sea level of 7m.[24]

11 While uncertainty remains a central issue in climate change projections, scientists continue to make significant advances in understanding the climate system. The use of supercomputers means that climate models are able to use increasingly detailed representations of these processes.[25] Recent approaches have investigated physical uncertainties in the climate system by varying parameters within climate models and running ensembles of these models.[26] Each resulting model is weighted according to its ability to simulate current climate, and weighted models are combined to produce frequency distributions of temperature (and other variables) for a given increase in concentrations.

[23] Schellnhuber HJ (ed.) (2006) *Avoiding dangerous climate change*, Cambridge University Press, Cambridge
[24] Lowe JA, Gregory JM, Ridley J, *et al.* (Jan 2006) The role of sea-level rise and the Greenland ice sheet in dangerous climate change: implications for the stabilisation of climate, in *Avoiding dangerous climate change*, Schellnhuber HJ (ed), Cambridge University Press, Cambridge
[25] Johns TC (submitted) The new Hadley Centre climate model, HadGEM1: evaluation of coupled simulations in comparison to previous models, *Journal of Climate (submitted)*
[26] Murphy JM, Sexton DMH, Barnett DN, *et al.* (2004) Quantification of modelling uncertainties in a large ensemble of climate change simulations, *Nature* **430**: 768 – 772; L Smith notes that "a single best guess from a complicated model run without good uncertainty estimates is impotent, while a beautiful set of ensemble statistics on too simple a model is irrelevant." Smith, L (2005): 'What might we learn from climate forecasts?'