Climate Change and the New World Economy: Implications for the Nature and Timing of Policy Responses

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Abstract

In recent years, the world has moved to a new economic growth path, driven by the rapid growth of developing country economies such as China and India. This paper provides an initial assessment of this new path for key vulnerabilities climate change and its implications for policy. We project greenhouse gas emissions based on current policies to 2030, with a minimum achievable emissions path assuming aggressive reductions after 2030; probabilities for global mean temperature to 2100 are estimated using a simple climate model for climate outcomes and applied to damage probabilities for four key vulnerabilities. Five conclusions are reached. First, CO_2 emissions from fuel combustion are projected to grow by 3.1% per annum over 2004–2030. This is well above any of the Intergovernmental on Panel Change's (IPCC) Special Report for Emission Scenarios (SRES) marker scenarios, which are no longer a reliable tool for medium term analysis in the new economy. Second, an atmospheric CO_2 concentration level of over 900 ppm CO_2-e and warming of 2.2°C to 4.7°C are projected by 2100, even if aggressive emission reductions after 2030 are achieved. Third, on this path there is a very high risk of adverse outcomes for the four key vulnerabilities. There is almost a 90% chance that irreversible melting of the Greenland ice-sheet would commence, and a >90% loss of coral reefs is highly likely. There is an even chance that more than 50% of species would be at risk of extinction and that the THC overturning rate would reduce by one third. Fourth, policies relying the diffusion of existing technologies to 2030 and on the development of major new technologies that mostly come into play after 2030 are insufficient to mange emerging climate risks. Fifth, early global action can reduce but not eliminate these risks. Effective global policy stabilising then reducing emissions in the near term would significantly reduce damage risks, though substantial risks would remain. If emissions are to be reduced in the near term, policy measures to reduce global energy consumption and to accelerate the diffusion of existing non-fossil fuel technologies are urgently needed. The development and diffusion of technologies that would otherwise have their main impact after 2030, also needs to be accelerated.

Keywords: climate change; greenhouse gas emissions; integrated assessment; climate risk; climate policy.

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1 The New World Economy

In recent decades, the continuing adoption of advanced information, communications technologies and of more open, market-based economic policies has led to further integration of the world economy, accelerating technological change and sustained rapid growth in countries such as China and India. This is a well-documented process, often referred to as rise of the new economy or of the global knowledge economy (OECD 1996; World Bank 1999; Grewal and Kumnick 2002). It has reached a new stage since IPCC's Third Assessment Report (IPCC 2001) was released, especially since China entered into the World Trade Organisation in 2001 and the United Progressive Alliance Government in India implemented its reform program in 2004. Sustained, higher than expected global economic growth has produced much greater energy demand than markets, providers and analysts have anticipated.

This new growth path is widely seen as not just another boom but as reflecting long-term factors: the emergence of China and India as economic powers, the revival of Japan, better economic prospects in Russia and other CIS states, and more generally an open world economy with low inflation. Reflecting current demand and revised future expectations, global market prices for oil, coal and resources have risen sharply. Large scale investments are being made in key markets such as China and India, and in supplier countries such as Australia, Brazil and Russia. This new economic path has led governments and businesses around the world to reassess their position in a world in which China and India are major economic powers.

As a result, global growth projections are being revised upwards. The IMF *World Economic Outlook 2006* projects global growth (in constant purchasing parity prices) of 4.9% per annum over 2001–2011, compared with 3.4% over the previous two decades (1981–2001; IMF 2006). This acceleration is a result of much faster growth in developing countries than in the OECD countries, with non-OECD GDP projected to grow by an unprecedented 7.1% per annum over 2001–2011 (Figure 1).

This accelerated growth path must have fundamental implications for the world's climate, although there is to our knowledge no detailed climate study accounting for this. Higher energy use in both developed and many developing countries, such as China and India, will rely heavily on coal to supply energy needs, thus increasing CO_2 emissions. Most climate analysis is still based on the SRES scenarios, which were prepared in 1998–9, well before the current pace of expansion became apparent (cf. Nakiçenovic and Swart 2000). None of the SRES marker scenarios envisaged the rapid growth in global GDP prior to 2020 that is now taking place. For example, on present trends, global GDP is likely to be some 20% higher in 2020 than in the A1 scenario family. More recently, the International Energy Agency's *World Energy Outlook*, published in November 2006, uses a growth rate of GDP in China over 2004–2030 (5.5%) little more than half that achieved over 1978–2004, and a growth rate for India (5.1%) marginally lower than in the earlier period. While these assumptions may prove to be accurate, they are not consistent with economic projections being used by governments, companies and financial agencies in their forward planning. Nor do they vary much from the November 2004 *World Energy Outlook* (IEA 2004a), in spite of the widespread change in expectations occurring since that time.[2]

[2] Perhaps in recognition of this fact, the IEA indicated when releasing the *World Energy Outlook 2006* in November 2006 that the 2007 edition will focus on the implications of developments in China and India for global energy

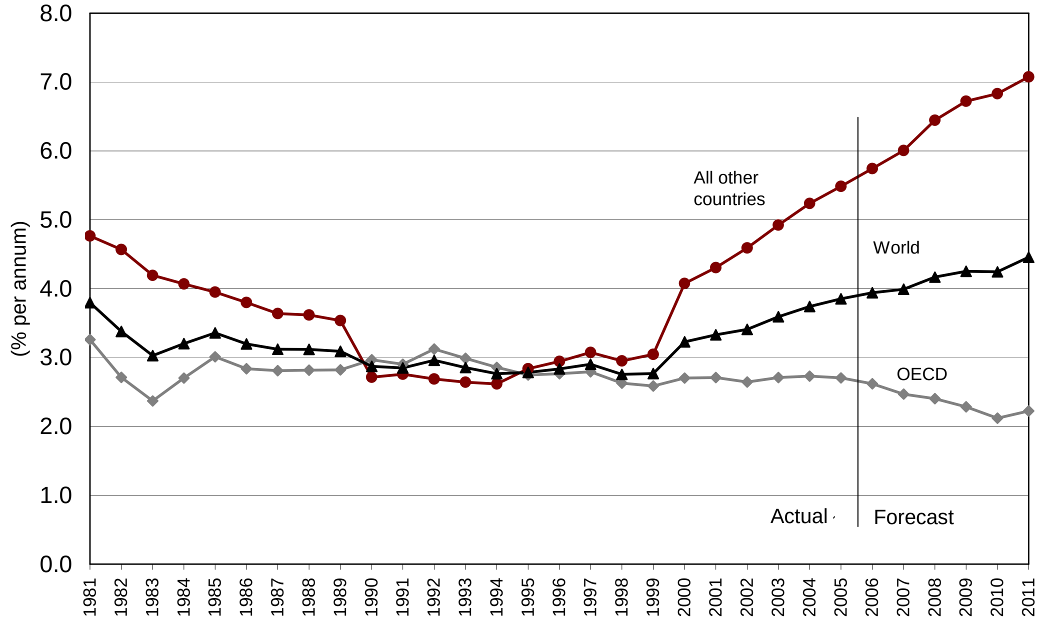

Figure 1: Long term growth in GDP in the OECD and non-OECD areas, 1981–2011 (ten-year moving average annual growth in GDP, at purchasing power parity prices).
Source: IMF (2006).

This paper explores the likely impact of this new growth path on CO_2 emissions, the resulting global warming and selected damage variables. A particular focus is on the nature and timing of the policy responses required to reduce the likelihood of damaging impacts produced in this new world economy. Rather than creating several alternate but plausible storylines, we prepare a single unchanged policy estimate for CO_2 emissions to 2030, building on the *World Energy Outlook 2006* (IEA 2006) projection adjusted for the new realities in China and India (Section 2). Section 3 reviews the now extensive evidence on the timing of the development and diffusion of new energy technologies. We use this analysis to specify a minimum achievable level of emissions over 2030–2100 (a 'minimum emissions path') consistent with the projection to 2030. This represents a 'wait and see' policy to 2030 followed by a globally co-ordinated technology-driven approach after then to minimise emissions. The major difference between this scenario and the SRES is the inclusion of higher economic growth rates to 2030 and a specific set of emission reduction policies beyond 2030. Reference emissions are then used in a simple climate model to estimate atmospheric CO_2 concentrations and global warming to 2100 (Section 4).

In Section 5, we describe the development of a meta-analytic modelling approach to study the probability of adverse outcomes on four key vulnerabilities (melting of the Greenland ice sheet, slowdown of the thermohaline circulation, species extinction and coral reef loss) for a given warming path. This model is then used in Section 6 to estimate the likelihood of damage for each of the four key vulnerabilities. Because, emissions follow a minimum emissions path

markets (http://www.worldenergyoutlook.org/weo2007.htm). The IEA's full global forecasts are, however, prepared every two years, with the next set due for release in November 2008.

after 2030, this is the implied damage committed to by allowing the unchanged policy path to continue to 2030. Section 7 investigates how those damage probabilities could be reduced if effective global policies to establish a minimum emissions path were implemented before 2030. Starting points are applied at five year intervals from 2010. Finally, in Section 8 we examine the nature and timing of the policy response necessary to substantially reduce damages from those implied by the reference path.

2 An Unchanged Policy Projection to 2030

Scenarios describe possible ways in which the world *might* develop, but sometimes pay limited attention to information about how the world *is* developing. This may be a decided advantage because it does not anchor thinking about the future to the past. Alternatively, if a specific pathway has a great deal of momentum supported by specific policies and actions, then the ramifications of that pathway need to be adequately represented. We contend that the second type is most useful for looking at the risks associated in following a well-established set of norms (the reference future), while the first is most useful for investigating a wide range of possible futures that look beyond the dictates of the reference (the 'what if' future). This typology does not discount the fact that complex system futures are highly uncertain and cannot be predicted via deterministic methods.[3]

The SRES scenarios encapsulate four 'storylines' that describe different social, economic and emissions outcomes over this century, with no likelihoods being assigned to these outcomes beyond their being plausible, qualify as 'what if' scenarios[4]. This approach, again using the SRES scenarios, is also adopted in the Fourth Assessment Report (IPCC, 2007), in spite of considerable debate concerning their use in calculating probabilities to assess risk (Schneider 2001; Pittock et al. 2001) and the suitability of the scenarios themselves to adequately describe the future (Schiermeier 2006). Here, we follow the practise of applying reference and policy scenarios as followed by a number of modelling groups (e.g., Weyant, 2004).

These projections use knowledge about future energy use embedded in the energy system. For example, asset lives of plant and equipment (such as power stations) are very long, established fuel types and technologies change relatively slowly, technology diffusion processes are well-documented and projections based on such information are widely used in government and business circles.

We start by building an unchanged policy projection out to 2030, using the International Energy Agency projections in the *World Energy Outlook 2006* (IEA 2006) as our baseline. A full assessment of the impact of the new economy on global energy use and emissions requires a complete re-analysis but in this first instance, we revise the projections only for China and India, retaining the IEA projections for other countries.

The two main limitations of this preliminary approach are likely to be offsetting rather than reinforcing. One is the growth effect of the new economy on other countries. Strong growth in China and India will promote more rapid growth in countries that can provide goods or services to those markets, even as exports from China and India accelerate structural change in many

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[3] However, the use of subjective probabilities can be instructive, because of the ability to represent objective and subjective elements separately. A future that everyone *thinks* is going to happen is no more likely than any other to occur if people do not act, but a future where more people *act* on a specific idea becomes more likely to occur (if those actions play out as intended).

[4] This requirement was placed on the SRES process to avoid having any 'IPCC sanctioned' future.

advanced countries. This stronger growth is evident in providers of capital goods and intermediate inputs such as Japan and Korea, in resource suppliers such as Australia, Russia and Brazil, and in some developing countries. The other effect is the impact on resource and energy prices. Continued strong global growth will promote a greater demand for energy and resources, increasing the relative prices for these commodities, placing downward pressure on global growth. The full analysis of these offsetting issues for the new economy is an urgent but very complex task. The present analysis is a first approximation.

The unchanged policy projection is based on policies enacted or adopted by mid 2006, and does not account for any future initiatives. It also allows for improvement in energy supply and end use technologies, but not any new initiatives to enhance those technologies. For further details of the unchanged policy specification, see IEA (2006, Chapter 1).

Projection Framework

The basic framework is as follows. For a given country *i* in year *t*, *n* years from some initial period, real GDP in international purchasing power parity prices (Y^t_i) is given by:

$$Y^t_i = Y_0 (1 + \alpha^t_i)^n,$$

where Y_0 is opening period real GDP and α^t_i is the average annual growth rate of real GDP for country *i* from the initial year to year *t*. The elasticity of energy use with respect to GDP in country *i* over the period to year *t* (ε^t_i) is defined as the ratio of the average annual rate of growth of total primary energy supply (e^t_i) to the average annual rate of growth of GDP (α^t_i). That is:

$$\varepsilon^t_i = e^t_i / \alpha^t_i .$$

Hence the rate of growth of total energy use (e^t_i) over the period is $\varepsilon^t_i.\alpha^t_i$, and total energy use by country *i* in year *t* is:

$$E^t_i = E^0_i (1 + \varepsilon^t_i.\alpha^t_i)^n.$$

Energy use involves different types of fuels (coal, oil, natural gas and various types of non-fossil and renewable fuel types), each with a different propensity to generate CO_2 emissions. The share of fuel type *j* in total energy use in country *i* (s^j_i) will vary over time, depending on availability, relative prices, investment patterns, policy initiatives and other factors. The energy use met by fuel *j* in country *i* in year *t* can then be denoted by:

$$E^{tj}_i = E^t_i . s^{tj}_i = E^0_i (1 + \varepsilon^t_i.\alpha^t_i)^n . s^{tj}_i .$$

Finally, CO_2 emissions per unit of fuel use (m^{tj}_i) will vary across countries, depending for example on the quality of fuel used and the technological processes involved, and over time within a given country. Total CO_2 emissions from the use of fuel *j* in country *i* in year *t* will then be given by:

$$M^{tj}_i = m^{tj}_i . E^{tj}_i = m^{tj}_i. s^{tj}_i . E^t_i .$$

Thus total CO_2 emissions in country *i* in year *t* (M^t_i) are given by:

$$M^t_i = \sum_j m^{tj}_i . s^{tj}_i . E^0_i(1 + \varepsilon^t_i.\alpha^t_i)^n .$$

Given this relationship, four key parameters are focussed on for a given country or region: α^t_i, the rate of growth of real GDP; ε^t_i, the elasticity of energy use (total primary energy supply) with respect to GDP; s^{tj}_i, the shares of various fuel types in total energy use and m^{tj}_i, the level of CO_2 emissions per unit of energy supply for different fuel types. In aggregating emissions, energy use from fossil fuels only (coal, oil and natural gas) is included; non-fossil fuel use emits no CO_2 and biomass and waste are excluded by convention. This relationship summarises only the reduced form specification, and in many applications, the parameters are modelled with considerable sectoral detail.

Growth and Energy Use in China

China's GDP grew by 10.1% per annum between 2001 and 2006, following growth of nearly 10% per annum between 1980 and 2001. The reported growth rate in 2006 was 10.7%, with exports, investment in fixed assets and increases in industrial production driving growth (NBSC 2006a&b, 2007). This growth rate shows few signs of falling much below 10% in 2007. In projecting China's growth we assume a gradual moderation from these high levels: to 8% by 2010, a further reduction to 7.5% per annum over 2010–15, to 7.0% per annum over 2015–20, and to 6.5% per annum over 2020–30. These assumptions involve a slowing of Chinese growth from its current hectic pace, but with continued strong growth over the longer term. Estimated average growth rate for China over 2004–30 is 7.3%, much higher than the IEA (2006) assumption of 5.5% (Table 1).

Table 1: GDP in constant US dollars (year 2000 purchasing power parity values), actual 1971–2004 and projected 2004–2030.

	GDP (US $trillion, in 2000 PPPs)			Annual rate of change (% per annum)		
	1971	2004	2030	Actual, 1971–2004	Projection, 2004–30	
					Current paper	IEA (2006)
OECD	11.5	29.5	51.9	2.9	2.2	2.2
Transition	1.8	2.4	6.0	0.8	3.6	3.6
China	0.5	7.3	45.5	8.7	7.3	5.5
India	0.6	3.1	17.8	5.0	6.9	5.1
Other	3.1	10.1	26.9	3.7	3.8	3.8
World	17.5	52.3	148.2	3.4	4.1	3.4

Source: Historical data to 2004 is from IEA website (http://data.iea.org/ieastore/statslisting.asp) with projections by the authors.

The energy elasticity of GDP is the key variable relating economic growth to energy use. Because trends in this elasticity may differ across the economy, it is best modelled in terms of significant sectoral disaggregation. The estimates reported here are consistent with the results produced from a 13-sector model of China's energy use, reported in Sheehan and Sun (2006).

During the development phase, energy elasticity is widely believed to be ≥1, but with higher living standards this elasticity reduces, in some cases to <0.5. This is consistent with the global data from the past thirty years, with the major exceptions being China over 1979–2001 and India after 1990. Thus, over 1971–2004 the energy elasticity with respect to GDP (in constant purchasing power parity terms) was 0.5 for OECD countries and 1.1 for the developing world.

The situation in China is more complex. From the ‘opening to the market’ in 1979 to 2001, energy use grew 4.1% per annum compared with GDP growth of 9.7%, implying an energy elasticity of <0.5. Since 2001, energy use has exploded catching the Chinese Government, energy analysts and energy providers unawares, leading to severe shortages in 2003 and subsequent years. Between 2001 and 2006, total energy use grew by 11.5% per annum,[5] for an elasticity of 1.1.

The following factors influenced the low energy intensity over 1979–2001: inefficient energy systems inherited from the previous planned economy allowed ‘easy pickings’ for energy efficiency; energy rationing through continued state control of energy production and use; strong investment in energy conservation; and broadly based development across all sectors, with no particular emphasis on energy intensive sectors (e.g. Sinton and Levine 1994; Andrews-Speed 2004; Zhang 2003). Many of these factors no longer apply. The Chinese economy has become more competitive and market based with strong growth in energy supplies, catalysing a structural shift to heavy, energy-intensive industry with sharply reduced investment in energy conservation (Lin 2007).

Table 2: Energy use (Total Primary Energy Supply – TPES), actual 1971–2004 and projected 2004–2030.

	Total primary energy supply (mtoe)			Annual change (% per annum)				
				Actual	Projected			
					Current paper			IEA (2006)
	1971	2004	2030 (projected)	1971-2004	2004-15	2015-30	2004-30	2004-30
OECD	3,309	5,320	6,481	1.4	1.1	0.5	0.8	0.8
Transition	852	1,066	1,404	0.7	1.4	0.8	1.1	1.1
China	241	1,406	7,186	5.5	8.1	5.3	6.5	3.2
India	61	358	1,597	5.5	6.0	5.9	5.9	3.4
Others	455	1,900	4,351	4.4	4.1	2.6	3.2	2.5
World	4,918	10,050	21,018	2.2	3.2	2.7	2.9	1.7

Source: Historical data to 2003 is from IEA website (http://data.iea.org/ieastore/statslisting.asp) with projections by the authors. Total primary energy supply exclude energy from biomass but includes bunkers, and is measured in million tonnes oil equivalent (mtoe).

China’s Eleventh Five Year Plan (2006–10) aims to reduce the energy intensity of GDP by 20% over that period, implying an elasticity of about 0.5. Our modelling noted above suggests that, on the policies in force in mid 2006, this is not likely to be achieved, and was not achieved in 2006. We project an average elasticity for China of 1.0 through to 2010, somewhat lower than over 2001–06. With existing government programs and higher prices expected to moderate demand and with a structural shift in the economy to the knowledge-intensive service sector, energy elasticity is projected to fall steadily after 2010, to an average of 0.85 and 0.75 during the next two decades, respectively (Sheehan and Sun 2006). Total primary energy use in China is projected to grow by 8.1% per annum between 2004 and 2015, with growth slowing appreciably

[5] This figure is based on NBSC (2006a) for 2001–05, NBSC (2006b) for the first half of 2006 and estimates of the authors based on a range of other data for the second half of 2006.

after 2010, to average 5.3% per annum between 2015 and 2030 (Table 2). For the period 2004–30, annual growth in energy use in China is projected to average 6.5%, compared with 5.5% over 1971–2004 and with the IEA projection of 3.2%. Given actual growth in energy use to 2006, the IEA projection implies growth of only 2.6% per annum over 2006–30.

Growth and Energy Use in India

India's growth has accelerated since the late 1970s, reaching 5.4% in the Ninth Plan period, 1997–2002. The Planning Commission estimates that growth for the Tenth Plan period (2002–07) will be 7% per annum, compared with a target of 8.1% (PC 2005) and is assuming a growth rate of 8.5% for the Eleventh Plan period, 2007–12 (PC 2006). The initial estimate of real growth for 2005–06 was 8.4% (http://www.mospi.nic.in). India's growth has traditionally been service rather than industry driven, but recently secondary industry growth rates have outstripped those for GDP. Thus for the Eleventh Plan period, the initial target for industry is 10% per annum and for manufacturing 12% per annum compared with the GDP rate of 8.5% (PC 2006). We use lower figures than those of the Planning Commission, which still imply strong growth out to 2030: 7% for the next two years and for the Eleventh Plan period, and 6.5% from 2012–30.

The energy elasticity of GDP (excluding energy from biomass) for India was 1.15 over 1971–2005, lower over 1990–2002 than in the earlier period. Energy use has been limited by a focus on service industries and by supply shortages – half the country's population remains without electricity (PC 2006). But industrial and household demand is increasing and sustained efforts are being made to increase electricity generation, primarily through coal-fired power stations. Demand for coal is projected to rise by 7.6% per annum between 2005–06 and 2011–12 (PC 2006). India also depends heavily on energy from biomass and waste, but with limited expansion possibilities, growing energy demand will mostly need to be met from commercial sources.

The Report of the Expert Committee on Integrated Energy Policy, tabled in December 2005 (Parikh 2006), outlines both India's growing energy needs and the programs intended to meet them. We project energy elasticity to gradually return to an average of 1.0 over the 2010–2020 period and decline after 2020. Average annual growth in total primary energy supply (TPES) in India of 5.9% is projected over 2002–2030, with some slowing in the final decade. This is broadly consistent with the Expert Committee, who use a lower elasticity but higher growth assumptions to projected growth of 5.1–6.2% over the period 2006–07 to 2031–32.

The Overall Emissions Projections

Fuel types vary between and within countries over time. Projected fuel shares for China and India are varied from the IEA (2006) estimates only where increased knowledge of the emerging energy use path is available. Given the current large-scale expansion of coal-fired electricity generation capacity in China, coal's share of TPES is projected to increase between 2004 and 2015, rather than to decline as in IEA (2006). This reflects a substantial move away from oil, which is already underway. After 2015, coal's share in TPES should decline significantly as the non-fossil fuel and renewable energy sector expands, as foreshadowed by Government policies, and as natural gas usage increases. Renewable sources are expected to provide 9% of TPES in China by 2030, compared with 3.1% in 2004. Similar trends are also projected for India: a continued high coal share, with oil being increasingly replaced by natural gas and renewable energy sources. For both China and India, the IEA (2006) projected emission intensities of different fuel types (CO_2 emissions per unit of fuel use) are retained.

The most important factor for global fuel use over 2004–30 is the shift in the pattern of energy to heavy coal users such as India and China. In 2004, coal provided 71.1% of TPES in China and 54.5% in India, compared with 21.2% for the OECD countries. As a result, coal is projected to comprise 36.8% of world TPES by 2030, compared with 27.6% in 2004 and 28.7% in 2030 in IEA (2006). The share of renewable resources in world TPES was 10.1% in 2004, a number projected to remain unchanged to 2030. This is the net effect of rapid growth in coal use, the long-term effects of nuclear power plant closures in developed countries, especially in Europe, and rapid growth in many forms of renewable energy from a very low base in 2004.

Global CO_2 emissions from fuel combustion and cement production are projected to rise from 7.5 billon tonnes of carbon in 2004 and to 16.6 billion tonnes by 2030, an increase of 121% or 3.1% per annum (Table 3). Growth over 2002–12 is particularly strong (3.7% per annum) and continues at a slowing rate over the next two decades. Emissions from the OECD and economies in transition[6] both grow at 1% per annum or more over 2004–15, reflecting increasing energy use with limited transition to renewable energy sources, but the growth rate slows appreciably over 2015–30. Emissions in developing countries are projected to grow at the same average rate over 2004–30 as over 1971–2004 (5.2%). China generates nearly 60% of the increase in global emissions from 2004 to 2030, but India will also be important as its power generation system develops. Together, the two countries account for 70% of the increase in emissions over 2004–30.

Table 3: CO_2 Emissions from fuel combustion and cement production, actual 1971–2004, projected to 2030.

	CO_2 emissions (GtC)			Annual change (% per annum)				
	1971	2004	2030 (projected)	Actual	Projected			
					Current paper			IEA (2006)
				1971-2004	2004-15	2015-30	2004-30	2004-30
OECD	2.6	3.6	4.3	1.0	1.0	0.5	0.7	0.7
Transition	0.6	0.7	0.9	0.4	1.4	0.5	0.9	0.9
China	0.2	1.4	6.8	5.8	7.9	4.9	6.2	3.3
India	0.1	0.3	1.4	5.4	5.8	5.7	5.7	3.3
Others	0.4	1.5	3.3	3.9	3.8	2.6	3.1	2.5
World	3.9	7.5	16.6	2.0	3.5	2.8	3.1	1.8

Source: Historical data to 2003 is from IEA website (http://data.iea.org/ieastore/statslisting.asp) with projections by the authors. The table covers CO_2 emissions from fuel combustion, including bunkers, and cement production, measured in gigatonnes of carbon (GtC).

Coal accounts for 62% of the global increase in CO_2 emissions to 2030 (Figure 2, upper panel); emissions from coal use rise at 4.8% per annum over 2004–15 and 3.6% per annum over 2015–30. Global consumption of coal rose by 5.3% per annum between 2000 and 2005 (British Petroleum 2006). The main factor generating much faster emissions growth in the projection period compared to 1971–2004 is not due to growth in either developing countries (5.2% growth in both periods) or in the OECD countries (0.7% over 2004–2030 compared with 1.0% for the

[6] Former Soviet Union and Eastern Bloc countries.

earlier period), but is due to the increased weight of the developing countries in world aggregates. The increasing importance of developing countries in the total is crucial – even if emissions growth in those countries over 2004–30 decreased to well below the 1971–2004 rate, global emissions growth to 2030 would still be much more rapid than over 1971–2004.

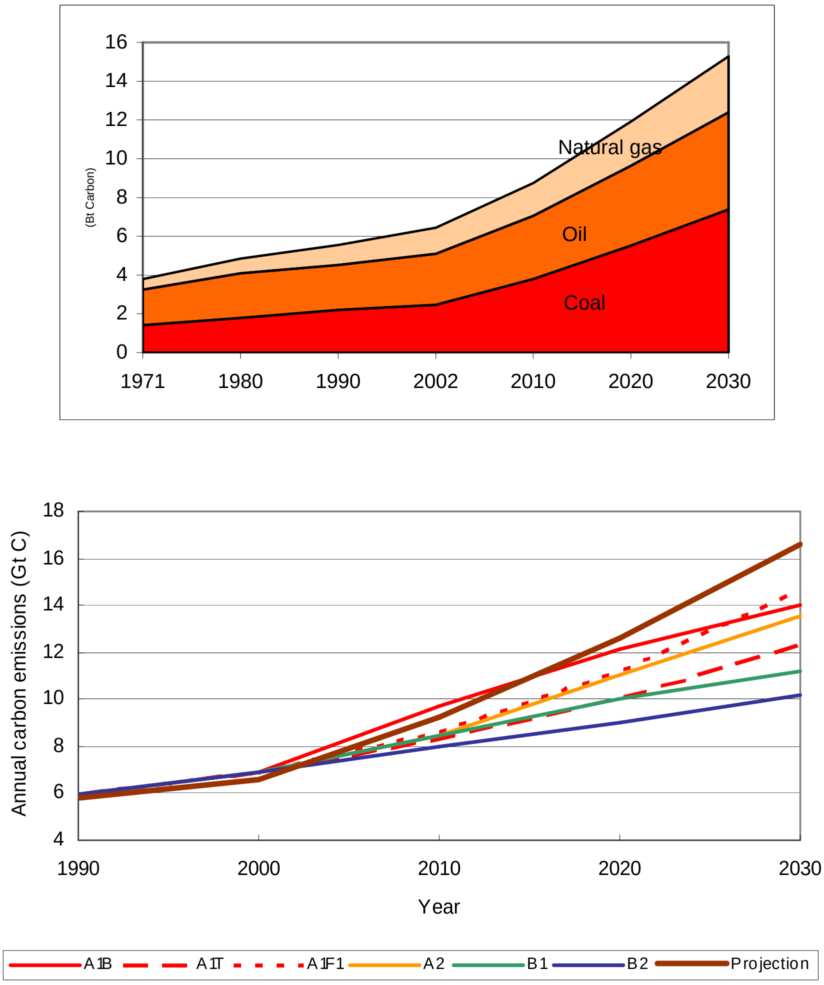

Figure 2: Global CO_2 emissions from fuel combustion, 1971–2030, by fuel type (upper panel) and comparison of projected CO_2 emissions with corresponding values for the six SRES marker scenarios, 1990s to 2030s (lower panel). Note: Data for the upper panel exclude emissions from cement production and are for the calendar years shown, while the lower panel data include cement and are scaled to the common 1990s value used for the SRES scenarios.
Source: IPCC (2001, Appendix II) and estimates of the authors.

Figure 2 (lower panel) shows that this unchanged policy projection is well above the envelope described by the six SRES marker scenarios over the next three decades. Average emissions for 2030 are 17%–52% higher than in the SRES marker scenarios. Therefore, the SRES scenarios, developed in the second half of the 1990s and representing the state of the art at that time, do not accurately describe emerging emissions trends over the next few decades. As such, they no longer provide a reliable tool for the medium term analysis of human impacts on the climate.

3 The Timing of Embodied Technological Change and the Minimum Emissions Path to 2100

Projecting on an unchanged policy basis beyond 2030 is not feasible. Fossil fuel use after 2030 is likely to be constrained by rising prices and supply limitations, even though advanced technologies could bring large additional supplies of oil and gas into play (IEA 2005i). Supplies of coal are plentiful. The dominant factor for CO_2 emissions is likely to be the development and diffusion of technologies related to energy production and use, spurred by higher fossil fuel prices, and by policies implemented to accelerate the development and diffusion of these technologies.

Many aspects of the economics of new technology R&D and diffusion are well understood (see, for example, the papers in Grubler et al. 2002). Key features include long lead times and considerable uncertainty in the R&D stage; competition between a wide range of technologies; the long life of existing plant and equipment constraining the rapid application of new technologies; and the major roles of economies of scale and learning by doing in reducing unit costs of a given technology as it diffuses and matures. Even in advanced economies, development and diffusion is a long term process that can be broadly defined for a specific technology, subject to R&D and commercial uncertainties. This section reviews the likely time path of the key energy production and use technologies, using this information to define an emissions path over 2030–2100.

Evidence on the Timing and Diffusion of New Technologies

The literature on the timing of energy technology development and diffusion is extensive and is summarised for transport and energy production technologies in Table 4. The sources used include fourteen IEA reports (IEA 2003, 2004b–d, 2005a–h; Riis and Hagen 2005; Riis and Sandrock 2005), two OECD studies (2004, 2005), one recent IPCC report (2005) and several other sources (*Economist* 2001; *Technology Quarterly* 2005). For detailed analysis of technology issues based on these reports see several studies by Jolley (2006a–d). The table does not cover some important areas, including the use of energy technologies in industrial processes or in buildings. Four conclusions are most relevant.

First, a wide range of technologies currently in extensive use or in the early stages of diffusion could substantially reduce energy use and/or emissions if they were extensively used. Examples shown include hybrid electric vehicles, combined heat and power systems, and wind, solar and geothermal energy technologies. Gradual diffusion of these more efficient technologies for producing and using energy, and of non-fossil fuel methods of energy production, is embodied in the reference projection to 2030. Under present policy settings, this process in OECD countries will be limited and its aggregate effects in developing countries are likely to be modest.

Second, few major new technologies are undergoing large-scale, focused development. New products and processes need critical mass to reduce costs to competitive levels, but achieving this is constrained by long asset lives for existing plant and by the number of competing technologies. Thus, on current policies, no major new technologies that could transform either energy use or emissions intensity of energy production are likely to be widely used before 2030.

Table 4: The status of selected new technologies for energy production and use: a summary of recent reviews

Transport	Non-renewable Energy	Renewable Energy
Currently in commercial use – diffusion underway		
Biofuels from sugar Hybrid electric vehicles Advanced two-stroke engines Other technologies for road vehicles and aircraft	Efficient power plants Combined Heat and Power (CHP) systems	Wind energy – onshore Solar photovoltaics Geothermal energy
Commercially available – diffusion beginning		
Light weight materials Electronic road pricing Advanced transit systems	Advanced sensors and controls Improved electricity transmission/distribution Advanced gas turbines	Advanced hydropower systems
Commercial prospects beyond 2030		
Biofuels from cellulosic fibres Fuel-cell road vehicles Intelligent vehicle highway systems Self-driving cars Ultra light weight vehicles	Advanced CHP systems Power electronics Integrated energy production and use systems (energyplexes) Superconducting cables Carbon capture /storage	New designs for nuclear power Advanced bioenergy and biomass systems Hydrogen from fossil fuels Advanced solar photovoltaics, energy storage Solar thermal energy Wave, offshore wind energy, marine currents Geothermal hot dry rock Integrated hydrogen systems and storage
Commercial prospects beyond 2050		
Hydrogen-fuelled aircraft Alternative fuel marine vessels New urban freight systems	Wide diffusion of energyplexes Diffusion of carbon capture and storage technologies	Nuclear fusion technologies Tapping the ocean salt-gradient New hydrogen production methods Solid hydrogen storage

Source: Seventeen international agency reviews plus other sources, as noted in the text. This table excludes technologies related to energy use in industrial processes or in buildings.

Thirdly, by 2030 many technologies – such as ultra light weight hybrid or fuel cell vehicles, improved buildings systems, advanced fossil fuel power generation, carbon capture and storage, energyplexes and a wide array of renewable energy technologies – are likely to be commercially viable. By about 2050 the most successful of these technologies should be mature, with growing market share in OECD countries and, in due course, in developing countries. The speed of diffusion will depend on the policy framework put in place and many other factors.

Fourthly, other technologies that are currently difficult to foresee, including advanced hydrogen technologies and nuclear fusion, may become commercially viable after 2050.

However, the limiting factors that constrain the technology diffusion process – cost competitiveness, critical mass, slow turnover of capital stock, parallel advances in fossil fuel and renewable technologies and delayed adoption in the developing countries – will also persist, even under rising fossil fuel prices.

These findings imply: (i) that the prospects for significantly reducing emissions relative to the unchanged policy projection over the next twenty years lie much more with the rapid diffusion of existing technologies rather than in the advent of major new technologies; and (ii) that after 2030 a range of important new technologies for reducing energy use and/or reducing emissions should become available for widespread commercial use. Both conclusions are used in the analysis below.

A Minimum Emissions Path from 2030 to 2100

The minimum emissions path is the lowest emissions path beyond 2030 that might be achieved if coordinated and effective global policies to eliminate emissions from fuel combustion were implemented from 2030, given the likely state of technology if current policies were followed to then. That is, the *minimum* climate implications to 2100 of the unchanged policy projection to 2030 are estimated by specifying the lowest emissions path possible after 2030.

In the minimum emissions path, emissions are stabilised shortly after 2030, and then effectively eliminated over the next century. We account for a number of factors: different countries will stabilise emissions over differing periods; some level of emissions may be irreducible; and the achievable rate of reduction is likely to increase over time, as zero emissions technologies become more mature.

We use the following specifications:

- if an MEP is established from year *n*, emissions are stabilised, via a progressive reduction in annual emission growth rates to zero, over a period ranging from *n*+5 years for OECD countries to *n*+20 years for India and other developing countries;
- when stabilised, emissions are reduced to 10% of that level over 100 years, in equal annual reductions, implying an accelerating rate of decline.

From 2030, global CO_2 emissions from fuel combustion peak at 20.8 GtC in 2045 but fall to nearly half that level (10.6 GtC) by 2100 (see Table 5). The greatest reduction takes place in the OECD countries, because of the more rapid stabilisation process.

This is not a projection or forecast beyond 2030, but a lower bound path given the projection to 2030, based on an assessment of the maximum realistic potential of new technologies and committed global policies. Even as a lower bound, the emissions path beyond 2030 is indicative only and other specifications could be provided. However, the major results of the paper are not sensitive to modest variations such specifications.

4 Climate Outcomes for the Minimum Emissions Path

Climate-related risks associated with the reference path are explored using the most recent version of the simple climate model, MAGICC (Wigley 2000; see also http://www.cgd.ucar.edu) and using a small set of impact response functions. MAGICC consists of a suite of coupled gas-cycle, climate and ice-melt models and has been used extensively to compare the global climate implications of different emissions scenarios and to explore the sensitivity of results to different model parameters.

The physical uncertainty with the greatest impact on global mean warming is climate sensitivity measured as: the equilibrium global mean temperature increase consequent to a doubling of atmospheric CO_2 relative to pre-industrial levels. Recent work describes the systematic accounting of uncertainties in model inputs to derive a probability density function for its value (e.g., Andronova and Schlesinger 2001; Wigley and Raper 2001; Forest et al. 2002; Murphy et al. 2004; Stainforth et al. 2005). We use the results of Annan and Hargreaves (2006), who explored three independent lines of evidence from palaeoclimate, volcanic cooling and the instrumental temperature record producing a 95% range for this parameter of 1.7–4.9°C, with a median of 3.0°C. This result is close to that recently concluded by the IPCC (2007). Non-CO_2 greenhouse gas emissions were scaled according to the proportional difference in CO_2 emissions between the SRES A1B marker scenario and the reference scenario. Sulphate aerosols from the A1T marker scenario were scaled in a similar manner, representing recent aggressive cuts in sulphate emissions in OECD countries (van Vuuren and O'Neill, 2006) and future aggressive cuts assumed for regions such as India and China. All parameters used in MAGICC, other than climate sensitivity, were set at the mid range.

Key results for the reference emission scenario are summarised in Table 5. Rapid near-term emissions growth produces and increase in atmospheric CO_2 concentrations similar to the highest of the SRES scenarios, A1FI, through to 2050, reaching 580 ppm (or 785 ppm CO_2-e). In spite of falling emissions levels after 2050, concentration levels approach 750 ppm (or 925 ppm CO_2-e) by 2100. Mean global warming by 2100, relative to 1990 levels, ranges from 2.2°C to 4.7°C, with an increase of 3.4°C for the median value. Therefore, even though the minimum emissions path is followed after 2030, substantial increases in global temperatures to 2100 are anticipated.

Table 5: Reference emissions and climate outcomes (atmospheric CO_2 concentration and global mean temperature) for reference path, MAGICC Model

Climate sensitivity	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
	CO_2 emissions from fuel combustion and cement (GtC)									
	9.2	12.6	16.6	20.3	20.2	18.3	16.4	14.4	12.5	10.6
	Atmospheric CO_2 concentration (ppm)									
3.0	391	423	466	522	580	630	671	704	730	748
	Atmospheric CO_2 equivalent (Kyoto GHG) Concentration (ppm)									
3.0	412	491	572	695	785	847	886	912	922	925
	Increase in global mean surface temperature, relative to 1990 levels (°C)									
1.7	0.3	0.5	0.8	1.2	1.5	1.7	1.9	2.0	2.1	2.2
3.0	0.4	0.8	1.1	1.7	2.2	2.6	2.9	3.1	3.3	3.4
4.9	0.5	1.0	1.5	2.2	2.9	3.4	3.9	4.3	4.5	4.7

5 Impact Assessment – A Meta-analytic Model of Four Key Vulnerabilities

By allowing the unchanged policy path to continue until 2030 the world is likely to experience rapid warming throughout this century. Warming rates approaching those derived from the highest of the SRES scenarios increases the risk of potentially severe and irreversible impacts on the world's climate, environment and peoples by 2100. Here we apply a simple probabilistic model to link warming exceedance curves with the probability of damage to key climate vulnerabilities expressed as functions of global warming (impact response functions). This adds a probabilistic element to the assessment of dangerous impacts as suggested by O'Neill and Oppenheimer (2002). The impact response functions for four key vulnerabilities are described below.

Impact Response Functions – Greenland Ice Sheet

The response function for the commencement of irreversible melting of the Greenland ice sheet, representing the point where melting and runoff exceed accumulation, is based on the following estimates from the literature. At temperatures slightly above this point the ice sheet may reach a new steady state equilibrium, but only after losing approximately 50% of its current mass (Huybrechts et al. 1991). Complete melting would take in the order of a millennium and would add about 7 m to world's oceans.

Based on the Earth's energy imbalance from historical greenhouse gas emissions and mean global warming during recent interglacial periods, Hansen (2004) proposed a threshold for melting of the Greenland ice sheet of 1°C increase in global mean temperature. Huybrechts et al. (1991) and Greve (2000), proposed thresholds of 2.7°C and 3.0°C increase, respectively, in Greenland surface air temperatures based upon the response of ice sheet models to climate forcing. Huybrechts and de Wolde (1999) presented a regional threshold of 2.2°C that would limit the loss of the Greenland ice sheet to 10% of its present volume over 1,000 years. This was assumed to be a tolerable loss rate, representing an upper temperature limit on long-term stability of the ice sheet. Gregory and Huybrechts (2006) combined ice-sheet average time-series from GCMs, with information from high-resolution climate model and 20km ice-sheet mass-balance model runs to estimate a local threshold of 4.5±0.9°C and global threshold of 3.1±0.8°C.

Except for the Hansen (2004) global threshold, all the Greenland temperatures were converted to global mean temperature changes by applying the ratio of Greenland temperature change to the global mean. Values ranging from 1.3–3.1°C were obtained from nine different climate models (Huybrechts et al. 2004). This resulted in a total of 28 estimates of the threshold for the commencement of irreversible melting of the Greenland ice sheet of approximately 0.75–2.5°C.

A polynomial regression ($r^2 = 0.99$) was used to construct a cumulative probability distribution for the sensitivity of the Greenland ice sheet to climate-induced irreversible loss (see Figure 3). Subject to the true uncertainty, responses indicate the likelihood of exceeding the threshold of irreversible melting for a given magnitude of climate change.

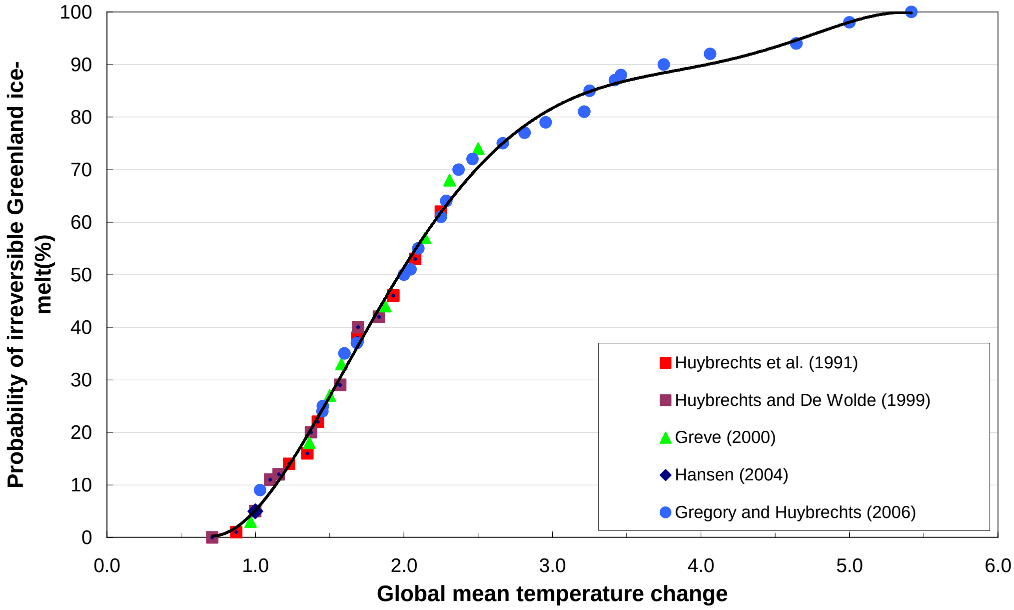

Figure 3: Estimated probabilistic sensitivity distribution for irreversible loss of the Greenland ice sheet. Notes: Values for Huybrechts et al. (1991), Huybrechts and de Wolde (1999), Greve (2000) and Gregory and Huybrechts (2006) have been converted from Greenland temperature changes using estimates of polar amplification over Greenland from nine climate models.

Impact Response Functions – Thermohaline Circulation

Estimates of the response of North Atlantic thermohaline circulation (THC) to increases in global mean temperature were derived from a number of sources. THC slowdown is thought to affect the climate of northern Europe, which may cool substantially if the Gulf Stream were to weaken significantly or was prevented from reaching high northern latitudes. The long-term ventilation of the ocean may also be at risk. If oxygen was no longer ventilated into the deep ocean the biology of deep ocean waters may be significantly altered.

For each study, the maximum THC reduction and associated global mean temperature change over the 21st century were recorded. Wood et al. (1999) reported reductions in THC using the HADCM3 coupled model and the IS92a emissions scenario. Washington et al. (1999) and Hu et al. (2004) reported responses of the PCM coupled model to CO2 increases of 1% per year. With the same model, Dai et al. (2005) applied a “business-as-usual” scenario for anthropogenic forcing analogous to the mean of the IPCC’s SRES scenarios. Boer et al. (2000) reported THC responses for the Canadian Climate Model given an increase in CO_2 emissions of 1% per year over the 21st century. Voss and Milkolajewicz (2001) reported reductions in THC using the ECHAM3 coupled model driven by CO_2 increases of 1% per year. Raper et al. (2001) reported the global mean temperature and THC responses of eight different coupled climate models from the CMIP2 experiments.

A similar set of results were reported in the IPCC’s Third Assessment Report (TAR) (IPCCa, 2001). Absolute reductions in 2100 from the IPCC TAR were compared with baseline overturning for the models reported in Raper et al. (2001) to estimate percent reductions. Kamenkovich et al. (2003) reported estimated THC responses from a model of intermediate complexity tuned to the NASA GISS coupled climate model, with CO_2 increasing at 1% per year. Zickfeld et al. (2004) developed a box model of the THC, based upon the CLIMBER-2 climate model, and reported THC responses for the box model and CLIMBER-2 for a forcing scenario resembling a 1% per year increase in CO_2. Schmittner et al. (2005) reported global mean temperature and THC responses for a suite of models used for the IPCC's Fourth Assessment Report in response to forcing from the SRES A1B scenario (see also Gregory et al., 2005). Several modelling studies have found no significant change in the THC response to warming (Sun and Bleck 2001; Bleck and Sun 2004; Gent 2001; Latif et al. 2000). A least-squares linear regression (r^2=0.61) was performed on the data from the above studies to develop a relationship between THC response and global warming (Figure 4).

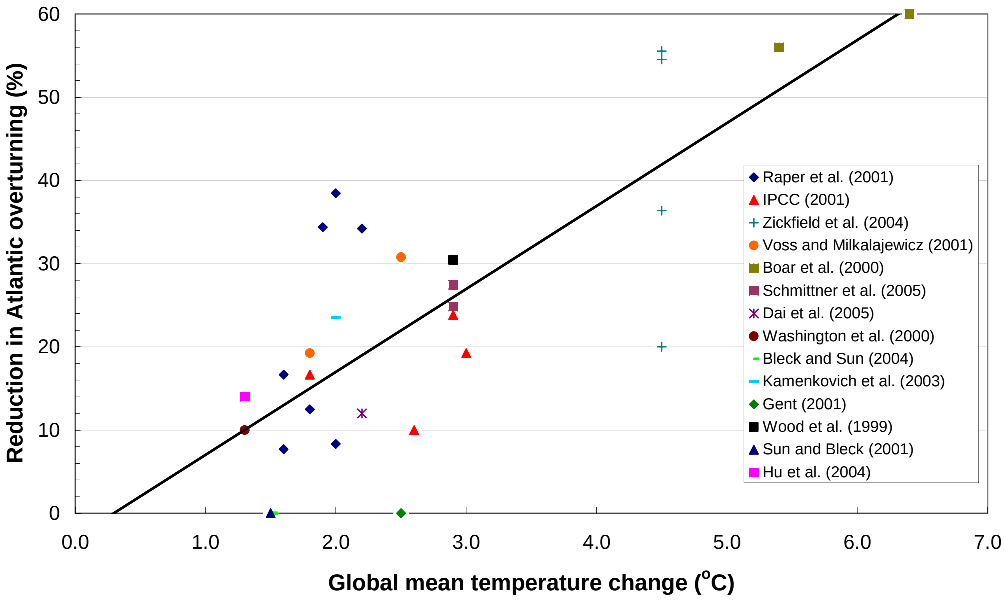

Figure 4: Estimated responses of thermohaline circulation to increasing global mean temperature over the 21st century from a range of studies.

Significant uncertainty about the general form of this relationship remains. Some model simulations indicate that slowing of the THC is reversible. Other recent studies have assessed the possibility that the North Atlantic THC may shut down due to the injection of freshwater from melting ice, possibly at warming levels that may be encountered by 2100 (Schlesinger et al., 2006; Zickfield et al., in press). Such assessments account for a wider range of physical phenomena than allowed for in coupled climate model simulations. However, IPCC (2007) conclude that an abrupt transition this century would be very unlikely.

Impact Response Functions – Coral Reef Systems

Two sets of information were used to project critical damage due to thermal bleaching and mortality to the coral reef communities of the Great Barrier Reef (GBR). Because this relationship is based on the world's largest single reef system and one of the healthiest, we assume that extensive damage affecting the GBR will similarly affect most other reef systems worldwide.

The two major aspects to the model involve:

1. ***Spatial bleaching risk*** across the GBR based on bleaching events in 1998 and 2002. Sea surface temperatures (SST) at Magnetic Island an inshore location reached about 1.2°C above the bleaching threshold during these events (Maximum 3-day SST; '*max3day*'). Averaged across the 1988 and 2002 events, bleaching affected approximately 50% of the GBR and moderate to severe bleaching affected 18% (Berkelmans et al. 2004) killing sensitive species at some sites (Wooldridge and Done 2004). Based on observations and experiment, moderate to severe bleaching is estimated to occur at ≥0.5°C above the bleaching threshold and widespread mortality to sensitive corals occurs at ≥1°C above the bleaching threshold. A simple regression model based on *max3day* and areal extent of bleaching suggests that 82% of the GBR will bleach at 2°C, 97% at 3°C and 100% at 4°C anomalies above the bleaching threshold, respectively (Berkelmans et al. 2004). This model allows for the range of bleaching thresholds on the reef that vary from highest to lowest in a north to south direction and inshore to offshore (Berkelmans 2002).

2. ***Temporal bleaching risk*** expressed as the frequency of events above a given threshold. These were estimated using the ReefClim model (Done et al. 2003; Jones 2004a) to calculate the frequency of bleaching and mortality risks for two sites, Magnetic Island (close to shore) and Davies Reef (outer reef), on the GBR under warming. This model reproduces bleaching events observed between 1990 and 2002 for three sites (Jones 2004a). Sensitivity analysis of bleaching using an artificially weather-generated record of SST shows that the probability of bleaching threshold exceedance under rising SST at a site is sigmoidal (Jones 2004a).

Bleaching frequency at a particular site and the spatial extent of bleaching can both be expressed as a function of increasing local SST. Three critical thresholds based on modelled bleaching and mortality frequency at specific sites were linked to the spatial bleaching extent and initialised using observations. The joint relationship was quantified using a Weibull function.

The critical thresholds are:

CT1. Non-lethal bleaching every second year (p_{ann}=0.5), affecting coral health by reducing spawning rates and resistance to other stresses (e.g. disease). Threshold exceedance is likely to result in low resilience to stress.

CT2. Widespread mortality of sensitive, fast growing corals (e.g., *Acropora*) on a frequency of ≥ 10 years (p_{ann}=0.1), preventing sufficient time for recovery to a state of ecological viability. The local temperature anomaly is exceeded at bleaching +1°C. Such a reef will have an altered mix of coral species, favouring slow growing species.

CT3. Widespread mortality of tolerant, slow growing species (e.g., *Porites*) on a frequency of ≥ 25 years (p_{ann}=0.04), allowing sufficient time for the community to recover to a state of ecological viability. The local temperature anomaly is set at bleaching +2°C. A reef in this state will have few, or no, live corals, depending on the viability of recruiting species and frequency of thermal extremes.

CT1 begins to be exceeded at +0.4°C above current warming, CT2 at +0.5°C and CT3 at +1.1°C. By linking each critical threshold to the spatial model at its zero point, the extent of the GBR that would be exceeded by each of the critical thresholds for any estimate of local warming can be estimated. Local temperature anomalies were converted into estimates of global mean temperature by assuming that GBR SSTs will rise at 0.8 of the rate of global mean temperature, the average of regional estimates from eight models run by four modelling groups (Done et al. 2003). The bleaching/area relationship is assumed to rise extremely rapidly from zero to 50% (the area affected in 1998 and 2002) because bleaching events were not commonly observed prior to 1980 (Lough 2001).

The relationship between the three critical thresholds spans ≤1°C, with CT1 and CT2 occurring very close together (Figure 5). More than 50% of the reef area is exceeded CT1 and CT2 under <1°C global warming and CT3 by about 1.5°C. Only an estimated 15% of the GBR region is free of critical damage at >2°C.

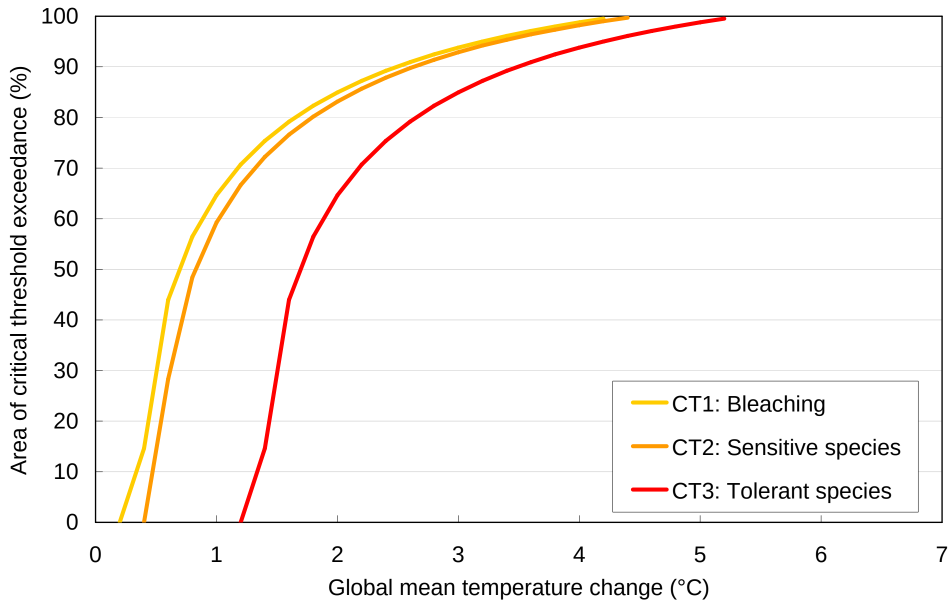

Figure 5: Global warming/areal relationships for the exceedance of three Critical Thresholds
Note: Thresholds: CT1: Bleaching in ≥ 50% of years; CT2: widespread mortality of sensitive coral species in ≥ 10% of years; CT3: widespread mortality of tolerant coral species in ≥ 4% of years.

Impact Response Functions – Species Extinction Risk

Species' extinction risk was based on data used in the global analysis by Thomas et al. (2004) with data points for global mean temperature change >3°C added from two Australian studies. Thomas et al. (2004) used climate scenarios to assess potential shifts in species' bioclimatic envelopes to assess extinction risks. When a bioclimatic envelope becomes totally removed from a specie's current range, that specie is deemed to be at risk of extinction. Thomas et al.'s (2004) analysis used sample regions covering some 20% of the Earth's land surface. Three approaches of estimating the probability of extinction showed a power-law relationship with geographical range size, suggesting that local, endemic species are those most at risk.

Estimates from Thomas et al.'s (2004) scenarios allowing for dispersal were used to create a relationship between global mean temperature change and extinction risk, measured by the total dislocation of current and future habitat, and exceeding reasonable estimates of dispersal. Because those estimates only assessed increases in global temperature up to 3.5°C, we used data from two further studies, where a relationship between extinction risk and local increase in temperature for over 40 vertebrate Australian endemic species each has been created; by Williams et al. (2003) and by us based on data from Brereton et al. (1995). The resulting distribution is sigmoidal, reflecting a normally distributed sample. The upper limit is highly uncertain because it is based on only two studies involving endemic vertebrates (Figure 6).

Establishing extinction risk using bioclimatic envelopes is subject to factors which are unknown for most species. For example: their physiological and ecological limits, how they respond to changing extremes and how fast they can acclimatise to changing conditions. Therefore, extinction risk assessed using bioclimatic modelling may turn out to be more or less positive than projected. Risk will also be affected by factors such as land use change and the impacts of pests, weeds and diseases, all of which will also be influenced by climate change.

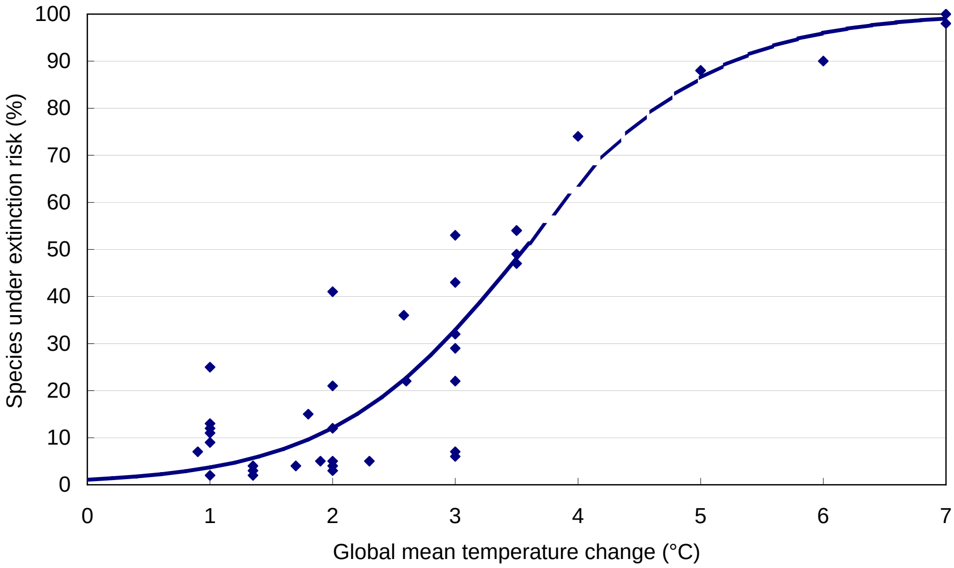

Figure 6: Relationship between global mean temperature change and extinction risk based on studies carried out for Latin/South America, Europe, South Africa and Australia.

6 Minimum Damage Estimates for the Unchanged Policy Projection to 2030

The impact response functions in Figures 3 to 6 are all non-market damages with major consequences for ecosystems and for economic and social life. We used biophysical impacts that will be largely unaffected by any socio-economic response. Because such impacts are largely independent of any development assumptions within a given emission path, they can be directly related to the magnitude of temperature increase. Where underlying socio-economic drivers are important, existing adaptive capacity may be exercised, making it difficult to establish such a direct relationship. Examples include agriculture, human health and damage to infrastructure. Thus, here we have not calculated damage functions for market damages or impacts will strong social drivers, although the sensitivity of such damages within a risk framework has been tested (Jones and Preston, 2006; Jones and Yohe, in press).

Impact response functions expressed as a function of global warming allow us to study the probability of serious impacts associated with different emission paths. A simple probabilistic model calculating the likelihood of exceeding a given level of warming in 2100 developed from the MAGICC simulations (Jones, 2004a&b) was used to compare warming exceedance curves with the damage response functions from the previous section. Uncertainties in greenhouse gas forcing and carbon cycle uncertainties are allowed for by allowing for ±0.5 Wm^{-2} in the estimation of radiative forcing from the scenarios, tested using the MAGICC model. Climate sensitivity follows the distribution of Annan and Hargreaves (2006). Figure 7 compares the warming exceedance curve for the reference case with the impact response functions for the four key vulnerabilities.

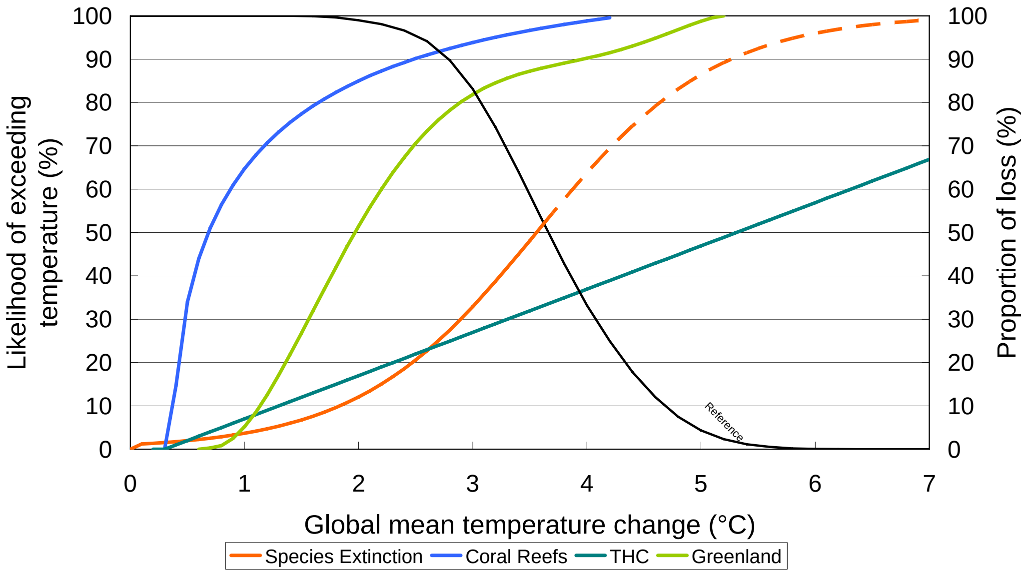

Figure 7: Likelihood of exceeding a specific level of mean global warming by 2100 for the reference path, superimposed on impact response functions for the four key vulnerabilities.

This information can be used to derive the likely degree of damage associated with any given probability of warming for the reference case. Because the minimum emissions path is followed after 2030, these results can be interpreted as the minimum damage risk ensuing from the unchanged policy projection to 2030. Table 6 extracts those minimum damage estimates for selected probabilities of exceeding the relevant warming level. The likelihoods are those used by the IPCC (2007) to frame the presentation of uncertainty surrounding their assessments. The risk-weighted outcome is calculated by multiplying the probability of reaching a given warming with each impact response function.

Irreversible melting of the Greenland ice-sheet is likely (almost highly likely) on a risk-weighted basis. Coral reefs are highly likely to suffer critical damaged over 90% of their range. More than 50% species of species would be at risk of extinction and the rate of the THC cycle decreases by one-third on a risk-weighted basis. In three cases, risk-weighting is similar to the median outcome, only species extinction risk indicating that the consequence outweighs the likelihood. Greenland ice melt and coral reefs are both high consequence risks that are highly likely to occur. The THC risk shows a high likelihood of moderate consequence. By any standards, the reference path carries very high risks of major economic, social and biophysical damage to the planet.

Table 6: Minimum damage estimates for the Reference Case, for selected probabilities of exceeding the relevant warming level. The risk-weighted outcome is calculated by multiplying the probability of reaching warming in 2100 with each impact response function. Likelihood values based on IPCC (2007).

	Highly likely (90%)	Likely (67%)	Even chance (50%)	Unlikely (33%)	Highly Unlikely (10%)	Risk weighted
	Probability of exceeding warming level					
Warming (°C)	2.8	3.3	3.7	4.0	4.7	
	Likelihood of crossing threshold/proportion of loss/extent of reduction in overturning (%)					
Greenland ice sheet	78	86	88	90	96	87
Coral reef damage	92	96	98	99	100	97
Species extinction risk	28	42	55	64	82	71
Reduced THC overturning	25	30	34	37	44	34

7 Assessing the Implications of Earlier Policy Responses

The most appropriate approach for setting climate change policy is to assess the risks associated with given policy options in tandem with the benefits achieved by taking this policy path – the benefits being assessed as the avoided damages of climate change (Corfee-Morlot and Agrawala 2004). Here, we examine the time scales required to minimize climate-related damages by establishing MEPs by 2010, 2015, 2020 and 2025 respectively. In each case the unchanged policy projection is followed until the MEP comes into force. MEP 2030 is the reference case.

Carbon dioxide equivalent concentrations and mean global warming of the resulting emissions paths to 2100 are displayed in Figure 8. For MEP 2010, the atmospheric CO_2 concentration level would rise rapidly to about 560 ppm CO_2-e by 2050 and peak at close to 570 ppm in 2060, before beginning to decline. For the median value of climate sensitivity (3°C), the global mean temperature increase relative to the 1990 level would be about 1.4°C by 2050 and would stabilise at about 1.7°C. For MEP 2020, the CO_2-e concentration level would rise to 680 ppm by 2050 and peak at about 680 ppm by 2080.

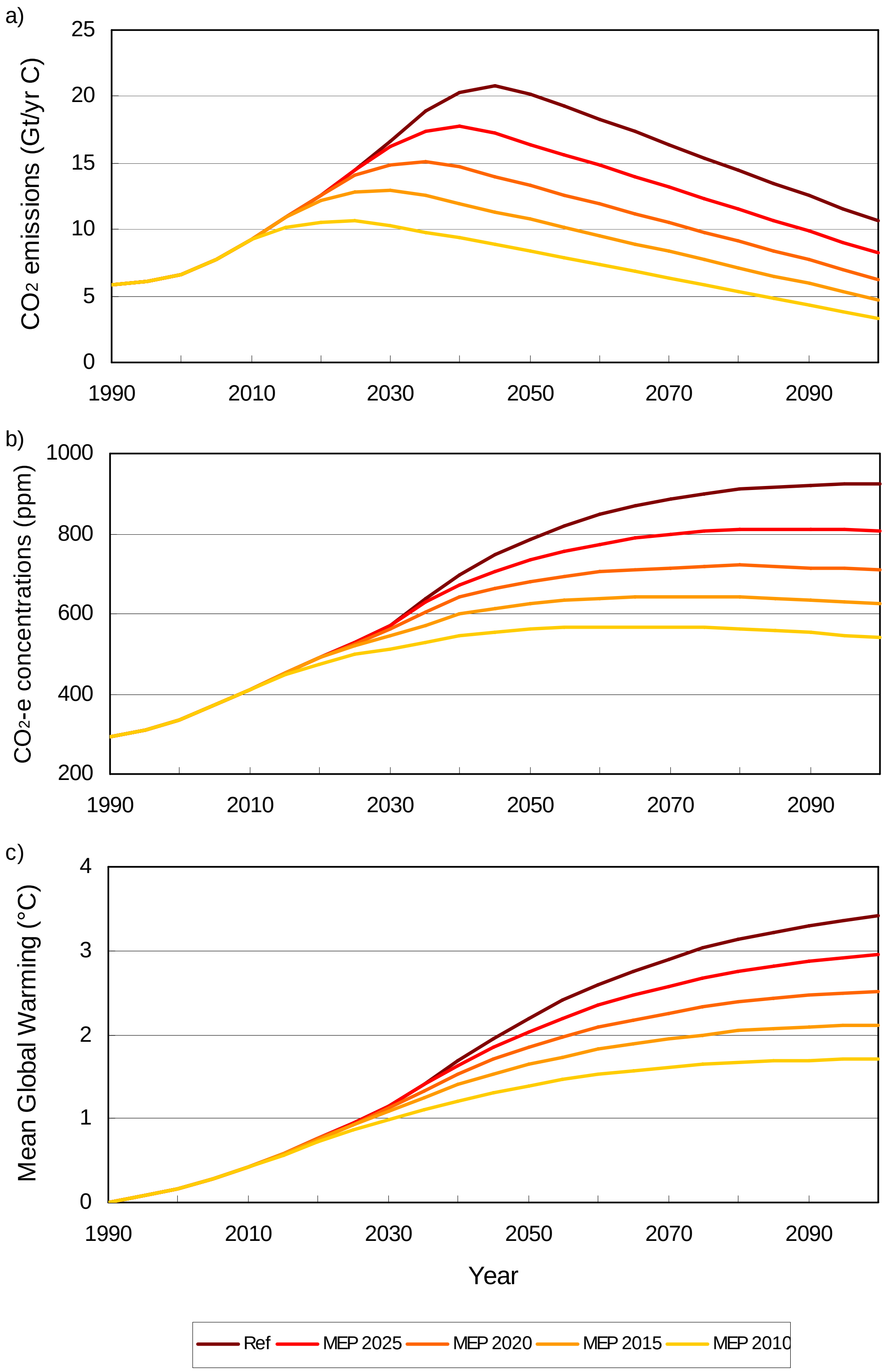

Figure 8: a) Annual CO_2 emissions (Gt C), b) CO_2 equivalent concentrations of the Kyoto Protocol greenhouse gases (ppm) and b) global mean warming relative to 1990 (°C); reference case and Minimum Emission Paths, 1990–2100. Warming is with a climate sensitivity of 3°C.

On this path the global temperature increase is 1.8°C by 2050 and 2.5°C by 2100, using the median sensitivity estimate. These results are to be compared with the reference path discussed earlier (MEP in force by 2030), for which the CO_2-e concentration level rises to 750 ppm by 2050 and 925 by 2100, with temperature increase (median climate sensitivity) of 2.2°C by 2050 and 3.4°C by 2100.

There has been considerable discussion about the desirability of limiting the level of atmospheric carbon concentration to 550 ppm CO_2-e (e.g. Stern et al. 2007). Note that Stern et al. (2007) used the SRES A2 scenario as their baseline, producing substantially lower emissions to 2050 than the reference scenario produced here. Of the paths we analyse only the MEP 2010 comes close to achieving 550 ppm CO_2-e (MEP 2015 implies a peak level of over 640 ppm CO_2-e).

Figure 9 compares the warming exceedance curve for the various MEP paths in 2100 with the impact response functions for the four key vulnerabilities, deriving the likely degree of damage associated with any given probability of warming for each of these paths. As before, these results can be interpreted as the minimum damage estimates implied by allowing the reference policy projection to continue unchanged until the MEP comes into force. Table 7 extracts those minimum damage estimates for selected probabilities of exceeding the relevant warming level, comparing the estimates for MEPs in force in 2010 and 2020 with the reference case.

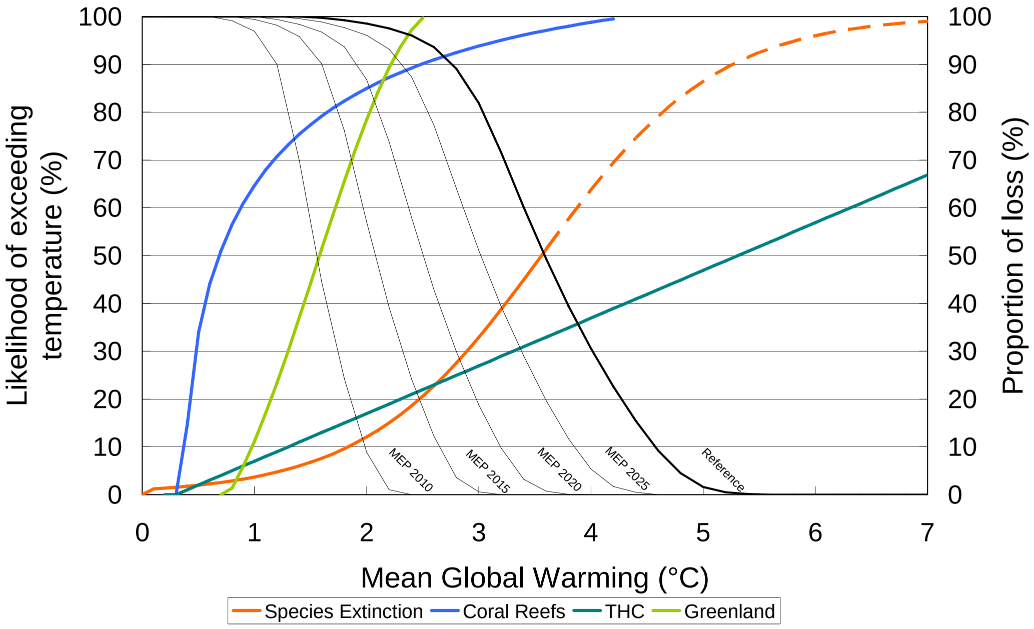

Figure 9: Likelihood of exceeding a specific level of mean global warming by 2100 for alternative emissions paths, superimposed on impact response functions for the four key vulnerabilities.

Establishing an MEP by 2010 significantly reduces the damage risks for all four vulnerabilities, even though substantial risks remain. For the irreversible melting of the

Greenland ice sheet, the likelihood of crossing the threshold falls from very likely on both the reference path to unlikely on MEP 2010 (one in three chance). The estimated coral reef loss falls somewhat to about 80%, while species extinction is sharply reduced to 9% and the reduction in THC overturning falls to 14%. If the establishment of an MEP is delayed until 2020 then, on these estimates, the initiation of melting of the Greenland ice sheet is likely and almost complete coral reef loss is highly likely, while there is an even chance of species extinction risk of about 20% and of a reduction in THC overturning of more than 20%. Species extinction risk shows the most dramatic decrease of all the vulnerabilities tested.

Table 7: Minimum damage estimates for alternative emissions paths, for selected probabilities of exceeding the relevant warming level. The risk-weighted outcome is calculated by multiplying the probability of warming in 2100 with each impact response function. Likelihood values based on IPCC (2007). All figures in percent unless otherwise indicated.

	Highly likely (90%)	Likely (67%)	Even chance (50%)	Unlikely (33%)	Highly Unlikely (10%)	Risk weighted
	Likelihood of crossing threshold/proportion of loss/extent of reduction in overturning (%)					
MEP at 2030 (Ref)						
Warming (°C)	2.8	3.3	3.7	4.0	4.7	
Greenland ice sheet	78	86	88	90	96	87
Coral reef damage	92	96	98	99	100	97
Species extinction risk	28	42	55	64	82	71
Reduced THC overturning	25	30	34	37	44	34
MEP at 2020						
Warming (°C)	1.9	2.3	2.5	2.8	3.3	
Greenland ice sheet	47	64	71	78	86	70
Coral reef damage	84	88	90	92	96	90
Extent of species extinction	11	17	21	28	42	27
Reduction in THC overturning	16	20	22	25	30	23
MEP at 2010						
Warming (°C)	1.1	1.4	1.6	1.8	2.2	
Greenland ice sheet	9	22	32	42	60	34
Coral reef damage	68	75	79	82	87	79
Extent of species extinction	4	6	8	10	15	9
Reduction in THC overturning	8	11	13	15	19	14

Therefore, while the risks of profound damage are very high on the reference path, these risks can be significantly reduced by earlier effective action, in particular by achieving a global minimum emissions path from 2010. However, such risk will not be eliminated, particular for the initiation of Greenland ice melt and for coral reefs. It is important to note the implications of following the MEP 2010 path. After 2010, emissions fall rapidly relative to the reference path, being 2 GtC or 16% less by 2020 and 6.3 GtC or 38% less by 2030. Achieving the MEP 2010 path requires an immediate and sustained reduction, with the required saving relative to that benchmark by 2030 of 6.3 GtC being about equal to the total level of emissions in 2030.

8 Conclusion – The Timing of Policy Responses

Five main empirical conclusions emerge from our analysis of the implications of the new world economy for climate change:

(i) *Rapid emissions growth is underway; the SRES scenarios are no longer a reliable tool for medium term analysis*. On unchanged policies, global CO_2 emissions from fuel combustion and cement production are projected to rise from 7.5 billon tonnes of carbon in 2004 and to 16.6 billion tonnes by 2030, an increase of 121% or 3.1% per annum. Growth in the decade after 2002 is particularly strong (3.7% per annum over 2002–12). This unchanged policy projection is well above the envelope described by the six SRES marker scenarios over the next three decades. Therefore, these scenarios no longer provide a reliable tool for medium term analysis of the risks of anthropogenic climate change.

(ii) *The unchanged policy path to 2030 and minimum emissions path beyond implies atmospheric concentration level of over 900 ppm CO_2-e and warming of 2.2°C to 4.7°C by 2100.* On the basis of the reference projection to 2030 and the minimum achievable path over 2030–2100, the CO_2 concentration level rises to 580 ppm (or 785 ppm CO_2-e) to 2050 and to 750 ppm (or 925 ppm CO_2-e) by 2100. The increase in global mean temperature by 2100, relative to 1990 levels, ranges from 2.2°C to 4.7°C, with an increase of 3.4°C for the median value of climate sensitivity.

(iii) *Adverse outcome for the four vulnerabilities range from moderate to highly likely*. For the reference path, there almost a 90% chance that the threshold for the irreversible melting of the Greenland ice-sheet will be passed, and over 90% loss of coral reefs is highly likely. There is an even chance that more than 50% of species will face extinction risk and that the THC overturning rate would reduce by one third. Thus, even on a minimum emissions path from 2030, the reference path carries very high risks of major economic, social and biophysical damage to the planet.

(iv) *Policies relying on the diffusion of existing technologies to about 2030 and on major new technologies beyond 2030 are insufficient to manage emerging climate change risks.* A range of policy positions are being advanced that rely on modest diffusion of existing technology to 2030 and substantial new technology development after 2030 to substantially reduce climate risks. This rationale is designed to protect existing economic growth, and to allow time for experience and new knowledge to reduce the uncertainties surrounding those risks. However, as we have shown here, higher than anticipated emissions growth to 2030 show that this strategy holds significant risk of climate damages occurring.

(v) *Much earlier global action will reduce but not eliminate these risks*. Getting effective global policy to stabilise and then reduce emissions in place by 2010 world significantly reduce the damage risks for all four vulnerabilities, even though very substantial risks would remain.

This assessment concentrates on selected climate risks ensuing from high emissions projected over the next few decades, and does not address the economic implications of establishing the minimum emission paths beyond 2030, or indeed earlier. One main purpose was to show that climate change is not a long run issue that requires assessments projecting forward several centuries. The major global development issues affecting the knowledge economy and its energy demands, and consequently climate change, need to be addressed over the coming decade, if not immediately.

The simple model applied here could be improved by the addition of multi-gas emission scenarios, and using methods to estimate the joint impacts of socio-economic change and climate change on human systems by using an expanded library of impact response functions. However, we believe its basic conceptual structure, a development of earlier probabilistic methods (Jones 2004a&b; Mastrandrea and Schneider 2004), is sound. Further applications of this approach investigating economic risks can be found in Jones and Preston (2006) and Jones and Yohe (submitted).

The policy storyline of the reference scenario is one where a conservative "wait and see approach" is taken to 2030, followed by the intensive development of new technologies designed to obtain the maximum reductions possible. Reference emission scenarios based on similar assumptions of high economic growth, especially for India and China, extending through to 2050 are described by Ahammad et al. (2006) and Matysek et al. (2006). Such high emissions combined with recent estimates of climate sensitivity placing median equilibrium sensitivity ($2\times CO_2$) at 3°C (IPCC, 2007), produces warming towards the higher limits of the IPCC (2001) range (Jones and Preston, 2006). In contrast, the bulk of earlier assessments have either utilised reference scenarios with lower emissions, or those that reflect a wide range of emission uncertainties (e.g., assessments using the IPCC SRES marker scenarios; Figure 2).

The underlying conditions resulting in higher emissions are a robust aspect of the knowledge economy. Such high growth poses substantial issues about the nature and timing of policy responses. Three main sources of uncertainty affect the costs of inaction: the range of reference emission pathways, the climate response (expressed mainly as climate sensitivity at the global scale) and the resulting damages costs. A "wait and see" approach can only be justified as a rational strategy if there is a significant likelihood that the costs of delaying action outweigh the costs of early action. By establishing that high emissions are likely over the short term we can significantly reduce some of the emissions uncertainty. While acknowledging that low emission pathways remain plausible as a reference case, they are much less likely than the high emission scenario presented here.

High emissions embedded in the knowledge economy strengthen the case for early action, an issue we address by constructing a range of minimum emissions paths beginning in 2010 to 2025 at five-year intervals. They show that delaying action by several decades (e.g., 2020 to 2025) still carries significant risks that may be adjudged as contributing to dangerous anthropogenic climate change.

If emissions are to be reduced relative to the unchanged policy path in the near term, policy measures to reduce global energy consumption and to accelerate the diffusion of existing non-fossil fuel technologies are urgently needed. The necessary reductions will not be achieved by the development and diffusion of technologies that will have their main impact after 2030, but requires measures that act directly on the level of energy use and on the nature of energy production in the immediate future.

References

Ahammad, H., Matysek, A., Fisher, B.S., Curtotti, R., Gurney, A., Jakeman, G., Heyhoe, E. and Gunasekera, D. (2006) *Economic Impact of Climate Change Policy: The Role of Technology and Economic Instruments*. ABARE Research Report 06.7, Australian Bureau for Agricultural and Resource Economics, Canberra, 65 pp.

Andrews-Speed, P. 2004, *Energy Policy and Regulation in the People's Republic of China*, Kluwer Law International, The Hague.

Annan, J.D. and Hargreaves, J.C. (2006) Using multiple observationally-based constraints to estimate climate sensitivity, *Geophysical Research Letters* **33**, L06704, doi:10.1029/2005GL025259.

Andronova, N. G. and Schlesinger, M. E. (2001) Objective estimation of the probability density function for climate sensitivity, *Journal of Geophysical Research* **106**, 22605–22612.

Berkelmans, R. and Willis, B.L. (1999) Seasonal and local spatial patterns in the upper thermal limits of corals on the inshore Central Great Barrier Reef, *Coral Reefs* **18**, 219–228.

Berkelmans, R. (2002) Time-integrated thermal bleaching thresholds of reefs and their variation on the Great Barrier Reef, *Marine Ecology Progress Series* **229**, 73–82.

Berkelmans, R., De'ath, G., Kininmonth, S. and Skirving, W. (2004) A comparison of the 1998 and 2002 bleaching events on the Great Barrier Reef: Correlation, patterns and prediction, *Coral Reefs* **23**, 74–83.

Bleck, R., and Sun, S. (2004) Diagnostics of the oceanic thermohaline circulation in a coupled climate model, *Global and Planetary Change* **40**, 233–248.

Boer, G.J., Flato, G. and Ramsden, D. (2000) A transient climate change simulation with greenhouse gas and aerosol forcing: Projected climate to the twenty-first century, *Climate Dynamics* **16**, 427–450.

Brereton, R., Bennett, S. and Mansergh, I. (1995) Enhanced greenhouse climate change and its potential effect on selected fauna of south-eastern Australia: A trend analysis, *Biological Conservation* **72**, 339–354.

British Petroleum (BP) (2006), *BP Statistical Review of World Energy June 2006,* London.

Corfee-Morlot, J. and Agrawala, S. (2004) The benefits of climate policy, *Global Environmental Change* **14**, 197–199.

Dai, A., Meehl, G. A., Washington, W. M. and Strand, W. G. (2005) Atlantic thermohaline circulation in a coupled general circulation model: Unforced variations vs. forced changes, *Journal of Climate* **18**, 3270–3293.

Done, T., Whetton, P., Jones, R., Berkelmans, R., Lough, J., Skirving, W. and Wooldridge, S. (2003) *Global Climate Change and Coral Bleaching on the Great Barrier Reef*, Final Report to the State of Queensland Greenhouse Taskforce through the Department of Natural Resources and Mines, QDNRM, Brisbane, available at: http://www.nrm.qld.gov.au/science/pdf/barrier_reef_report_1.pdf and http://www.nrm.qld.gov.au/science/pdf/barrier_reef_report_2.pdf.

Economist (2001) Special report: Nuclear power, a renaissance that may not come, May 19, 25–27.

Forest, C. E. Stone, P.H., Sokolov, A.P., 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.

Gent, P. R. (2001) Will the North Atlantic Ocean thermohaline circulation weaken during the 21st century?, *Geophysical Research Letters* **28**, 1023–1026.

Gregory, J. M., Huybrechts, P. and Raper, S. C. B. (2004) Threatened loss of the Greenland ice sheet, *Nature* **428**, 616.

Gregory, J.M. Dixon, K.W., Stouffer, R.J., Weaver, A.J., Driesschaert, E., Eby, E., Fichefet, T., Hasumi, H., Hu, A., Jungclause, J., Kamenkovich, IV., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Sokolov, A. and Trorpe, R.B. (2005) A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration, *Geophysical Research Letters* **32**, L12703, doi:10.1029/2005GL023209.

Greve, R. (2000) On the response of the Greenland ice sheet to greenhouse climate change, *Climatic Change* **46**, 289–303.

Grewal, B. and Kumnick, M. (eds) (2002) *China's Future in the Knowledge Economy: Engaging the New World*, Victoria University, Melbourne.

Grübler, A., Nakiçenovic, N. and Nordhaus, W. (2002) *Technological Change and the Environment*, Resources for the Future, Washington DC.

Hansen, J. E. (2004) Defusing the global warming time bomb, *Scientific American* **290**, 68–77.

Hu, A., Meehl, G. A., Washington, W. M. and Dai, A. (2004) Response of the Atlantic thermohaline circulation to increased atmospheric CO_2 in a coupled model, *Journal of Climate* **17**, 4267–4279.

Huybrechts, P. and de Wolde, J. (1999) The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climatic warming, *Journal of Climate* **12**, 2169–2188.

Huybrechts, P., Letreguilly, A. and Reeh, N. (1991) The Greenland ice sheet and greenhouse warming, *Global Planet Change* **89**, 399–412.

IEA (International Energy Agency) (2003) *Renewables for Power Generation: Status and Prospects*, OECD/IEA, Paris.

IEA (2004a) *World Energy Outlook 2004*, OECD/IEA, Paris.

IEA (2004b) *Advanced Fuel Cells Implementing Agreement Annual Report 2003*, OECD/IEA, Paris.

IEA (2004c) *Hydrogen and Fuel Cells, Review of National R&D Programs*, OECD/IEA, Paris.

IEA (2004d) *Prospects for CO_2 Capture and Storage*, OECD/IEA, Paris.

IEA (2005a) *Alternative Fuels: An Energy Perspective*, IEA/ETO Working Paper, Paris.

IEA (2005b) *Clean Coal Technologies, Collaboration and Climate Change*, Mitigation Case Study 4, Paris.

IEA (2005c) *CO_2 Capture and Storage*, OECD/IEA, Paris.

IEA (2005d) *International Energy Technology Collaboration and Climate Change Mitigation*, Case Study 1: Concentrating Solar Power Technologies, OECD/IEA, Paris.

IEA (2005e) *Energy Technologies at the Cutting Edge*, OECD/IEA, Paris.

IEA (2005f) *Prospects for Hydrogen and Fuel Cells*, OECD/IEA, Paris.

IEA (2005g) *Offshore Wind Experiences*, OECD/IEA, Paris.

IEA (2005h) *Variability of Wind Power and Other Renewables*, OECD/IEA, Paris.

IEA (2005i) *Alternative Fuels: An Energy Perspective*, IEA/ETO Working Paper, Paris.

IEA (2006) *World Energy Outlook 2006*, OECD/IEA, Paris.

IMF (International Monetary Fund) (2006), *World Economic Outlook: Globalisation and Inflation*, Washington DC.

IPCC (Intergovernmental Panel on Climate Change) (2000) *IPCC Special Report on Emission Scenarios*, Cambridge University Press, Cambridge.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A. (eds.), Cambridge University Press, Cambridge.

IPCC (2005) *Special Report on Carbon Dioxide Capture and Storage*, Metz, B., Davidson, O., de Coninck, H., Loos, M. and Meyer, L. (eds) Cambridge University Press, Cambridge.

IPCC (2007) Summary for policy makers, In *Climate Change 2007: The Scientific Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge (in press).

Jolley, A. (2006a) Transport technologies, *Climate Change Working Paper No. 5*, Centre for Strategic Economic Studies, Melbourne, available at: http://www.cfses.com/publish/papers_climate.htm.

Jolley, A. (2006b) Technologies for reducing stationary energy use, *Climate Change Working Paper No. 6*, Centre for Strategic Economic Studies, Melbourne, available at: http://www.cfses.com/publish/papers_climate.htm.

Jolley, A. (2006c) Technologies for alternative energy, *Climate Change Working Paper No. 7*, Centre for Strategic Economic Studies, Melbourne, available at: http://www.cfses.com/publish/papers_climate.htm.

Jolley, A. (2006d) Advanced technologies applicable to fossil fuels: Cross-cutting technologies and carbon capture/storage, *Climate Change Working Paper No. 8*, Centre for Strategic Economic Studies, Melbourne, available at: http://www.cfses.com/publish/papers_climate.htm.

Jones, R.N. (2004a) Managing climate change risks, in Agrawala, S. and Corfee-Morlot, J. (eds), *The Benefits of Climate Change Policies: Analytical and Framework Issues*, OECD, Paris, 249–298.

Jones, R.N. (2004b) Incorporating agency into climate change risk assessments, *Climatic Change* **67**, 13–36.

Jones, R.N. and Preston, B.L. (2006) *Climate Change Impacts, Risk and the Benefits of Mitigation*, CSIRO Melbourne, 97 pp.

Jones, R.N. and Yohe, G. (submitted) Applying risk analytic techniques to the integrated assessment of climate policy benefits, *Integrated Assessment*.

Kamenkovich, I.V., Sokolov, A.P. and Stone, P H. (2003) Feedbacks affecting the response of the thermohaline circulation to increasing CO_2: A study with a model of intermediate complexity, *Climate Dynamics* **21**, 119–130.

Latif, M., Roeckner, E., Mikolajewicz, U. and Voss, R. (2000) Tropical stabilization of the thermohaline circulation in a greenhouse warming simulation, *Journal of Climate* **13**, 1809–1813.

Lin, J. (2007) Energy conservation investments: A comparison between China and the US, *Energy Policy* **35**, 916-924.

Lough, J.M. (2001) Climate variability and change on the Great Barrier Reef, in Wolanski, E. (ed.) *Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef*, CRC Press, Boca Raton, Florida, 269–300.

Mastrandrea, M.D. and Schneider, S.H. (2004) Probabilistic integrated assessment of "dangerous" climate change, *Science* **304**, 571–575.

Matysek, A., Ford, M., Jakeman, G., Gurney, A. and Fisher, B.S. (2006) *Technology: Its Role in Economic Development and Climate Change*. ABARE Research Report 06.6, Australian Bureau for Agricultural and Resource Economics, Canberra, 109 pp.

Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M. and Stainforth, D.A. (2004) Quantifying uncertainties in climate change from a large ensemble of general circulation model predictions, *Nature* **430**, 768–772.

Nakiçenovic, N. and Swart, R. (eds) (2000), *Special Report on Emissions Scenarios*, Cambridge University Press, Cambridge.

NBSC (2006a) *China Statistical Yearbook 2006*, Beijing.

NBSC (2006b) Fast and Stable Economic Growth in the First Half of 2006, Beijing, 18 July, available at: http://www.stats.gov.cn/english/newsandcomingevents/t20060718_402337744.htm

NBSC (2007) The National Economy Maintained a Steady and Fast Growth in 2006, 25 January, Beijing, available at: http://www.stats.gov.cn/english/newsandcomingevents/t20070125_402382300.htm

OECD (Organisation for Economic Cooperation and Development) (1996) *The Knowledge-Based Economy*, OECD, Paris.

OECD (2004) *Biomass and Agriculture: Sustainability, Markets and Policies*, OECD, Paris.

OECD (2005) *Cool Appliances: Policy Strategies for Energy-Efficient Homes*, OECD, Paris.

O'Neill, B.C. and Oppenheimer, M. (2002) Dangerous Climate Impacts and the Kyoto Protocol, *Science* **296**, 1971-1972

Parikh, K.S. (2006) *Integrated Energy Policy*: *Report of the Expert Committee*, Planning Commission, Government of India, New Delhi, available at: http://planningcommission.nic.in/reports/genrep/rep_intengy.pdf

Pittock, A.B., Jones, R.N. and Mitchell, C.D. (2001) Probabilities will help us plan for climate change, *Nature* **413**, 249.

PC (Planning Commission) (2005) *Mid -Term Appraisal of the Tenth Five Year Plan (2002–2007)*, Government of India, New Delhi.

PC (2006) *Towards Faster and More Inclusive Growth: An Approach to the Eleventh Five Year Plan, 2007–2012*, Government of India, New Delhi.

Raper, S.C.B., Gregory, J.M. and Stouffer, R.J. (2001) The role of climate sensitivity and ocean heat uptake on AOGCM transient temperature response, *Journal of Climate* **15**, 124–130.

Riis, T. and Hagen, E. (2005) *Hydrogen Production – Gaps and Priorities*, IEA Hydrogen Implementing Agreement, IEA, Paris.

Riis, T. and Sandrock, G. (2005) *Hydrogen Storage – Gaps and Priorities*, IEA Hydrogen Implementing Agreement, IEA, Paris.

Schiermeier, Q. (2006) The costs of global warming, *Nature* **439**, 374–375.

Schmittner, A., Latif, M. and Schneider, B. (2005) Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations, *Geophysical Research Letters* **32**, doi: 10.1029/2005GL024368.

Schneider, S. (2001) What is “dangerous” climate change?, *Nature* **411**, 17–19.

Sheehan, P. and Sun, F. (2006) Energy Use and Emissions in China, submitted to and under revision for *Energy Journal*.

Sinton, J.E. and Fridley, D.G. (2003) Comments on recent energy statistics from China, *Sinosphere* **6**, 6-12.

Stainforth, D.A., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D.J., Kettleborough, J.A., Knight, S., Martin, A., Murphy, J.M., Piani, C., Sexton, D., Smith, L.A., Spicer, R.A., Thorpe, A.J. and Allen, M.R. (2005) Uncertainty in predictions of the climate response to rising levels of greenhouse gases, *Nature* **433**, 403–406.

Stern, N., Peters, S., Bakhshi, V., Bowen, A., Cameron, C., Catovsky, S. Crane, D., Cruickshank, S., Dietz, S., Edmondson, N., Garbett, S., Hamid, L., Hoffman, G., Ingram, D., Jones, B., Patmore, N., Radcliffe, H., Sathiyarajah, R., Stock, M., Taylor, C., Vernon, T., Wanjie, H. and Zenghelis, D. (2007) *Stern Review on the Economics of Climate Change*, HM Treasury and UK Cabinet Office, London, available at http://www.sternreview.org.uk

Sun, S. and Bleck, R. (2001) Atlantic thermohaline circulation and its response to increasing CO_2 in a coupled atmosphere-ocean model, *Geophysical Research Letters* **28**, 4223–4226.

Technology Quarterly (2005) Sunrise for renewable energy?, **December 10**, 16–18.

Thomas, C.D. Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega Huerta, M.A., Peterson, A.T., Phillips, O.L. and Williams, S.E. (2004) Extinction risk from climate change, *Nature* **427**, 145–148.

van Vuuren, D.P. and O'Neill, B.C. (2006) The consistency of IPCC's SRES scenarios to 1990–2000: Trends and recent projections, *Climatic Change* **75**, 9-46.

Voss, R. and Milkalajewicz, U. (2001) Long-term climate changes due to increased CO_2 concentration in the couple atmosphere-ocean general circulation model ECHAM3/LSG, *Climate Dynamics* **17**, 45–60.

Washington, W. M., et al. (2000) Parallel Climate Model (PCM) control and transient simulations, *Climate Dynamics* **16**, 755–774.

Weyant, J.P. (ed) (2004) EMF 19 Alternative Technology Strategies for Climate Change Policy, *Energy Economics*, **26**, 501–755.

Wigley, T.M.L. (1994) *MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change): User's Manual and Scientific Reference Manual*, National Center for Atmospheric Research, Boulder, CO.

Wigley, T.M.L. (2000) *Updated version of and results from the simple climate model MAGICC*, National Center for Atmospheric Pressure, Boulder, CO.

Wigley, T.M.L. and Raper, S.C.B. (2001) Interpretation of high projections for global-mean warming, *Science* **293**, 451–454.

Williams, S.E., Bolitho, E.E. and Fox, S. (2003) Climate change in Australian tropical rainforests: An impending environmental catastrophe, in *Proceedings of the Royal Society of London Series B – Biological Sciences* **270**, 1887–1892.

Wood, R.A., Keen, A.B., Mitchell, J.F.B. and Gregory, J.M. (1999) Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model, *Nature* **399**, 572–575.

Wooldridge, S. and Done, T. (2004) Learning to predict large-scale coral bleaching from past events: A Bayesian approach using remotely sensed data, in-situ data, and environmental proxies, *Coral Reefs* **23**, 96–108.

World Bank (1999) *World Bank World Development Report: Knowledge for Development 1998/99*, Washington DC.

Zhang, Z. (2003) Why did the energy intensity fall in China's industrial sector in the 1990s?, *Energy Economics* **25**, 625-638.

Zickfeld, K., Slawig, T. and Rahmstorf, S. (2004) A low-order model of the response of the Atlantic thermohaline circulation to climate change, *Ocean Dynamics* **54**, 8–26.