Climate Change and the Global Knowledge Economy: An Immediate Challenge

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CSES Climate Change Working Paper No. 11

2006

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Future climate impacts can be studied by scenario methods or by using information about likely outcomes embedded in the energy system and in technology assessment. Following the latter approach, we develop a reference projection to 2030 for global CO_2 emissions, with a lower bound extension to 2100, and study the climate implications. CO_2 emissions grow by 35% between 2002 and 2010, double before 2025 and decline after 2050, and are well above all six SRES marker scenarios to 2030. Mean global temperature rises 3.2−5.5°C by 2100, implying large-scale climate damage. Projected warming exceeds critical thresholds for catastrophic damage to coral reefs and for irreversible melting of the Greenland ice-sheet, and implies heavy species extinction and significant thermohaline circulation slowdown. Early intervention to stabilise, then reduce, emissions can reduce the likelihood of exceeding these thresholds. The decisive factor is the doubling of emissions over the next two decades, so immediate measures are necessary.

Since the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) in 2001[1], continuing adoption of advanced information and communications technologies and of more open, market-based economic policies has led to growing integration of the world economy, accelerating technological change and sustained rapid growth in countries such as China and India. This continuing process is often referred to as the rise of the global knowledge economy[2,3], and its implications for the world's climate have been debated[4,5]. If much higher living standards are achieved quickly by an additional 30–40% of the world's population, using existing development patterns and without major reductions in energy use by the advanced countries, the pressure on the climate will be intense. On the other hand, shifts in the structure of economic activity to more knowledge intensive activities (such as education and health) reduce the energy intensity of GDP, while rapid technological change offers the prospect of reduced emissions in the long term.

One standard view is that uncertainty in socio-economic variables needs to be to be represented by a range of internally consistent scenarios. In 1996 the IPCC decided to establish a new set of emissions scenarios to provide input to the TAR. The *Special Report on Emissions Scenarios*[6] (the SRES scenarios) encapsulates four 'storylines' that describe different social, economic and emissions outcomes over this century. The SRES authors did not assign likelihoods to these outcomes beyond their being plausible[6]. This approach, again using the SRES scenarios, will be repeated in the

Fourth Assessment Report to be published in 2007[7], in spite of considerable debate about this method, concerning the use of probabilities to assess risk[8,9] and the suitability of the scenarios themselves to adequately describe the future[10].

Scenarios describe possible ways in which the world *might* develop, but give limited attention to information about how the world *will* develop. An alternative approach is to project likely emissions on unchanged policies for some decades, making use of the information about the future that is embedded in global economic and energy systems, and to use studies of the development and diffusion of energy technologies to specify a minimum longer term emissions path consistent with that projection. Asset lives of plant and equipment (such as power stations) are very long, fuel types used and technologies in place change slowly, technology diffusion processes are well documented and projections based on such information are widely used in government and business circles. We show that robust conclusions can be obtained by drawing on existing knowledge – of the likely energy path over the next 25–30 years, of the minimum time-scales for new technology diffusion and of the probability of irreversible impacts for given levels of global warming.

To achieve these ends, we build a simple unchanged policy projection out to 2030 for global energy use and CO_2 emissions from fuel combustion and cement production, with a lower bound extension to 2100 based on the projection dynamics and on evidence about the development and diffusion of many technologies. The resulting emissions path – the reference path – represents projected emissions to 2030 and the minimum achievable level of emissions to 2100 consistent with the projection to 2030, and is used to study the risk of not implementing new climate policies over different time frames. The climate outcomes of the reference path to 2100 are derived using a simple climate model, and the risks associated with those outcomes are examined by a probabilistic analysis of warming and of critical thresholds for four key vulnerabilities.

The Unchanged Policy Projection to 2030

The starting point is the authoritative global energy projections of the International Energy Agency (IEA), last published in November 2004[11]. Substantial revision is necessary for key developing countries, in part accounting for later information about growth in GDP and energy use, especially in China[12,13] and India[14]. Four key parameters are central to projections for a given country or region: the rate of growth of real GDP; the elasticity of energy use with respect to GDP; the shares of various fuel types in total energy use and the level of CO_2 emissions per unit of energy supply for different fuel types. The projections provided here adopt the IEA assumptions and results in full for the OECD countries except those in Asia and the Pacific that are particularly affected by rapid growth in China and India, and use many other parameter estimates from the IEA study for other countries. More detail on the projections, including some discussion of energy supply issues and a comparison with those of the IEA, is provided in the Technical Appendix. A single historical data set from the IEA is used as the projection base. These unchanged policy projections account for the impact of all current policies, including those to increase energy efficiency and reduce emissions, and allow for the evolution of technologies under current policies.

Table 1. CO_2 emissions from fuel combustion and cement production, actual 1971–2002, projected to 2030 (Mt C)

	1971	2002	2010	2020	2030	1971-2002	2002-10	2010-20	2020-30	2002-30
	(Gigatonnes of carbon)					(Per cent per annum)				
OECD	2.6	3.5	3.9	4.3	4.6	0.9	1.4	1.0	0.6	1.0
North America	1.3	1.8	2.0	2.2	2.4	1.0	1.5	1.0	0.7	1.0
Europe	1.0	1.1	1.2	1.3	1.3	0.2	1.1	0.8	0.2	0.7
Asia	0.2	0.5	0.5	0.6	0.7	2.3	1.7	1.6	1.1	1.4
Oceania	0.0	0.1	0.1	0.1	0.1	2.8	1.7	1.4	0.6	1.2
Transition economies	0.6	0.7	0.8	0.9	1.0	0.2	1.7	1.3	0.9	1.3
Developing countries	0.5	2.3	4.1	6.9	10.2	4.8	7.5	5.3	3.9	5.4
China	0.2	1.0	2.3	4.1	6.0	4.9	11.0	6.0	3.9	6.6
India	0.1	0.3	0.5	0.9	1.4	5.4	5.9	6.4	5.1	5.8
SE Asia	0.0	0.2	0.3	0.5	0.7	6.9	4.8	4.1	3.3	4.0
Other developing	0.2	0.8	1.1	1.5	2.1	4.0	3.4	3.6	3.2	3.4
Other countries	0.0	0.1	0.1	0.1	0.2	6.3	3.0	2.7	2.2	2.6
Bunkers	0.1	0.1	0.1	0.2	0.2	1.0	1.0	1.0	1.0	1.0
World	3.9	6.7	9.0	12.4	16.0	1.8	3.8	3.7	2.6	3.2

Source: Historical data to 2002 is from IEA website (http://data.iea.org/ieastore/statslisting.asp) with projections by the authors.

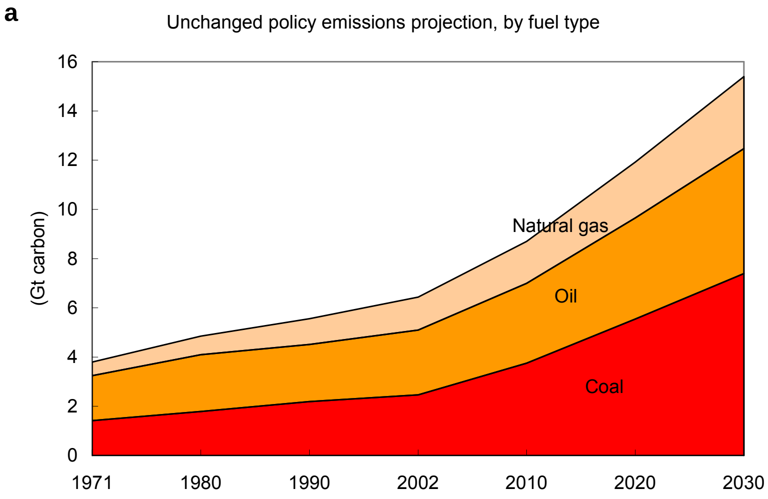
China has entered a new stage of its development since it was admitted into the WTO in 2001. Official data (from www.stats.gov.cn) show sustained rapid growth in real terms in key aggregates in China over 2001–2005, with annual rates in excess of 9.5% for GDP, 25% for exports and 20% for investment in fixed assets. This drive to become the ‘factory to the world’, together with a high level of construction activity, has meant that growth has been highly energy intensive, with total energy use excluding biomass rising by 13.6% per annum over 2001–2005, implying an energy elasticity in GDP of 1.4. This rapid pace slows over time in the projections; annual GDP grows by 6.5% per annum from 2010–30 with an energy elasticity of only 0.78, as rising energy prices and energy efficiency measures take effect. With these assumptions China’s energy use excluding biomass is projected to increase annually by 6.9%, and its CO_2 emissions by 6.6%, between 2002 and 2030.

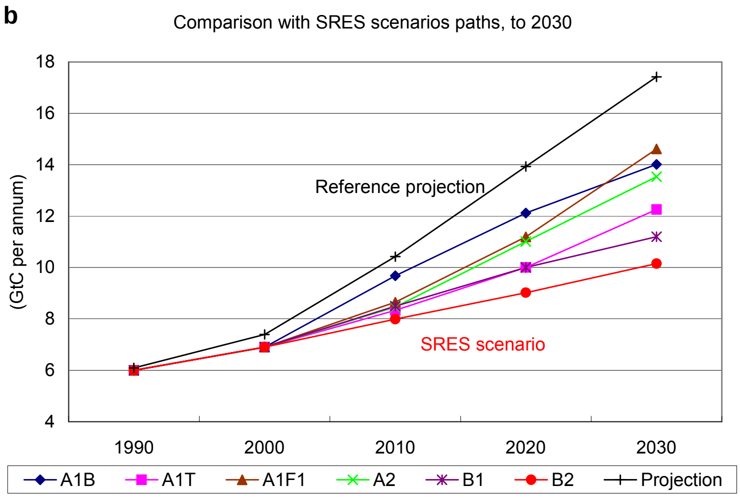
India’s GDP growth outcome for the Tenth Plan period, 2002–07, is now expected to be 7% per annum, and the Indian Planning Commission is using a growth rate of 8% as the working basis for the Eleventh Plan period, 2007–12[15]. Energy use in India has been limited to date by a focus on service industries and by supply shortages, but industrial and household demand is increasing and sustained efforts are being made to increase electricity generation, primarily through coal-fired power stations. Projected growth rates for energy use excluding biomass and CO_2 emissions for India over the period 2002–2030 are 6.0% and 5.8% respectively.

Global CO_2 emissions are projected to rise from 6.7 billon tonnes of carbon in 2002 to 16.0 billion tonnes by 2030, an increase of 139% or 3.2 % per annum (Table 1). Growth in the current decade is particularly strong (3.8% per annum over 2002–10) and continues at a slowing rate over the next two decades. Emissions from the OECD and the transition economy regions both grow at 1% per annum or more over 2002–30, reflecting increasing energy use with limited transition to renewable energy sources. Nevertheless, the major increase in emissions comes from the developing countries, whose emissions are projected to grow at a somewhat faster rate (5.4% per annum) over 2002–30 than over 1971–2002 (4.9%). China generates over the half of the increase in global emissions to 2030, but India will also be important as its power generation system develops. Rising emissions from developing countries reflect the combination of strong growth in energy demand and heavy reliance on coal for fuel supply, especially in China and India. Increased use of coal accounts for 55% of the global increase in CO_2 emissions to 2030 (Figure 1a); emissions from coal use rise at 5.6% per annum over 2002–10 and 4.0% per annum over 2002–30. This is a continuation of recent trends: global consumption of coal rose by 6.6% per annum between 2000 and 2004[16].

As shown in Figure 1b, this unchanged policy projection is well above the envelope described by the six SRES illustrative marker scenarios[6] over the period to 2030, with average emissions for the decade beginning in 2030, for example, being 19%–72% higher than in the SRES scenarios. Therefore, the SRES marker 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. Thus, if the scenario method is to be retained, the IPCC scenarios need to be reconstructed to account for emerging trends.

Figure 1. Global CO_2 emissions from fuel combustion, 1971–2030, (a) by fuel type and (b) comparison of projected CO_2 emissions with corresponding values for the six SRES marker scenarios, 1990s to 2030s





Notes: Data for panel (a) exclude emissions from cement production and are for the calendar year shown, while data for panel (b) include cement, are averages for the decades starting with the years shown and are scaled to the common 1990s value used for the SRES scenarios.

Technology and Emissions to 2100

Projecting on an unchanged policy basis beyond 2030 is not feasible, but we construct a reasonable lower bound to emissions beyond 2030. Use of fossil fuels after 2030 will be further constrained by rising prices and supply limitations, even though under these conditions advanced technologies could bring large additional supplies of oil and gas into play[17], and 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, which will also be spurred by higher fossil fuel prices.

An extensive literature on the timing of energy technology diffusion is summarised in Table 2. While much R&D is being undertaken, few new technologies are the subject of truly large-scale, focused development. New products and processes need critical mass to reduce costs to competitive levels, but achieving critical mass is constrained by long asset lives for existing plant and by the wealth of competing technologies. Under unchanged policies, gradual diffusion of more efficient technologies for producing and using energy, and of non-fossil fuel methods of energy production, will continue through to about 2030. This process will be limited in OECD countries and its aggregate effects in developing countries are likely to be modest through to 2030. This gradual diffusion of more efficient technologies for producing and using energy is embodied in the reference projection to 2030.

Table 2. 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 2020/2030		
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 (see Technical Appendix).
Note: Excludes technologies related to energy use in industrial processes or in buildings.

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 proven and will be increasingly used, especially in OECD countries. 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. Other technologies, such as advanced hydrogen technologies and possibly even nuclear fusion, are likely to become commercially viable in the second half of the century. 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.

A matrix of emission growth rates between 2030 and 2100 has been developed to create a path through to 2100 that provides a reasonable lower bound to CO_2 emissions after 2030 (Table 3). Emissions are assumed to stabilise in the OECD countries in the 2030s, and then to fall at an accelerating rate. The transition economies follow a similar path with a lag of a decade or more. Given the underlying momentum of their development processes, together with a higher emissions elasticity of GDP, a slower path of adoption of advanced technologies and their heavy reliance on coal, emissions from China, India and other developing countries continue to increase over 2030–2060, but at a slowing rate. As new technologies become increasingly adopted emissions fall at an increasingly rapid rate after 2070. On this path global CO_2 emissions from fuel combustion peak at 22.6 Gt C in 2060 but fall to about one quarter of that level by 2110.

It should be stressed that this is not a projection beyond 2030, but a lower bound path given the projection to 2030, based on an assessment of the maximum realistic potential of new technologies. Even as a lower bound, the emissions path beyond 2030 is indicative only, and other specifications for such a path could be provided, but the major results of the paper are not sensitive to variations in this lower bound trajectory. On this reference path, by 2110 emissions from the OECD and transition economies are virtually eliminated, developed country emissions are 31% of their peak level in 2060 and global emissions are 37% of their level in 2030. Given the projection to 2030 and the ongoing dynamics of the knowledge economy, this would be a substantial achievement. The lower bound characteristic of the overall path after 2030 in the long term can be seen by comparing it to the scenario recently provided, but not published in any detail, by the Australian Bureau of Agricultural and Resource Economics (ABARE)[18]. The ABARE path is somewhat lower than that of Table 3 in the earlier decades, with emissions of about 17 billion tonnes by 2050, but in it emissions continue to increase after 2050, and exceed 30 billion tonnes by 2100.

Table 3. Growth rate matrix for CO_2 emissions from fuel combustion beyond 2030, and resulting emissions reference path, to 2110

Growth in emissions		(Average annual rate of growth, %)								
		Decade to:								
	1971-2002	2030	2040	2050	2060	2070	2080	2090	2100	2110
OECD	0.9	0.6	0.0	-1.0	-2.0	-3.5	-5.0	-7.5	-7.5	-7.5
Transition economies	0.2	0.9	0.7	0.3	0.0	-1.0	-2.0	-3.5	-5.0	-7.5
China	4.9	3.9	3.0	2.0	1.0	0.0	-1.0	-2.0	-3.5	-5.0
India	5.4	5.1	3.0	2.0	1.0	0.0	-1.0	-2.0	-3.5	-5.0
Other	4.5	3.2	2.0	2.0	1.0	0.0	-1.0	-2.0	-3.5	-5.0
CO_2					(Gigatonnes of carbon)					
emissions	2002	2030	2040	2050	2060	2070	2080	2090	2100	2110
OECD	3.5	4.6	4.6	4.2	3.4	2.4	1.4	0.6	0.3	0.1
Transition economies	0.7	1.0	1.0	1.1	1.1	1.0	0.8	0.5	0.3	0.1
China	1.0	6.0	8.0	9.6	10.8	10.8	9.8	8.0	5.6	3.4
India	0.3	1.4	1.9	2.3	2.6	2.6	2.4	1.9	1.4	0.8
Other	1.0	3.0	3.6	4.2	4.7	4.7	4.3	3.5	2.4	1.4
World	6.7	16.0	19.1	21.4	22.6	21.5	18.6	14.6	10.0	5.9

Source: As for Table 1.

Climate Risks

Climate-related risks associated with the reference path are explored using the most recent version of the simple climate model, MAGICC[19] (see also www.cgd.ucar.edu) and a small set of damage 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.

One crucial input is the climate sensitivity parameter: the equilibrium global mean temperature rise consequent to a doubling of the atmospheric CO_2 concentration 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[20,21,22,23,24]. We use the results of Murphy et al.[23], who found that the 5–95% range for this parameter was 2.4–5.4°C, with a median of 3.5°C. Non-CO_2 greenhouse gas emissions were scaled from the P50 scenario in MAGICC 4.1 (an average of the six SRES marker scenarios) according to the CO_2 emissions in Table 3. Sulphate aerosols from the A1B marker scenario were scaled in a similar manner. All parameters in the model, other than climate sensitivity, are at the mid range.

The key results are summarised in Table 4. Given rapid growth in emissions in the near-term, the atmospheric CO_2 concentration level rises at similar rates to the highest of the SRES scenarios, A1FI, through to 2050 when 550 ppm is exceeded. Decelerating emissions growth after 2050 produce levels approaching 800 ppm by 2100. The increase in global mean temperature by 2100, relative to 1990 levels, ranges from 3.2°C to 5.5°C, with an increase of 4.2°C for the median value of climate sensitivity. If CO_2 emissions follow the unchanged policy projection to 2030 and over 2030–2100 are assumed to be at the lower bound estimates, then rapid increases in global temperatures to 2100 are anticipated.

Table 4. Climate outcomes (atmospheric CO_2 concentration and global mean temperature) for reference path, MAGICC Model

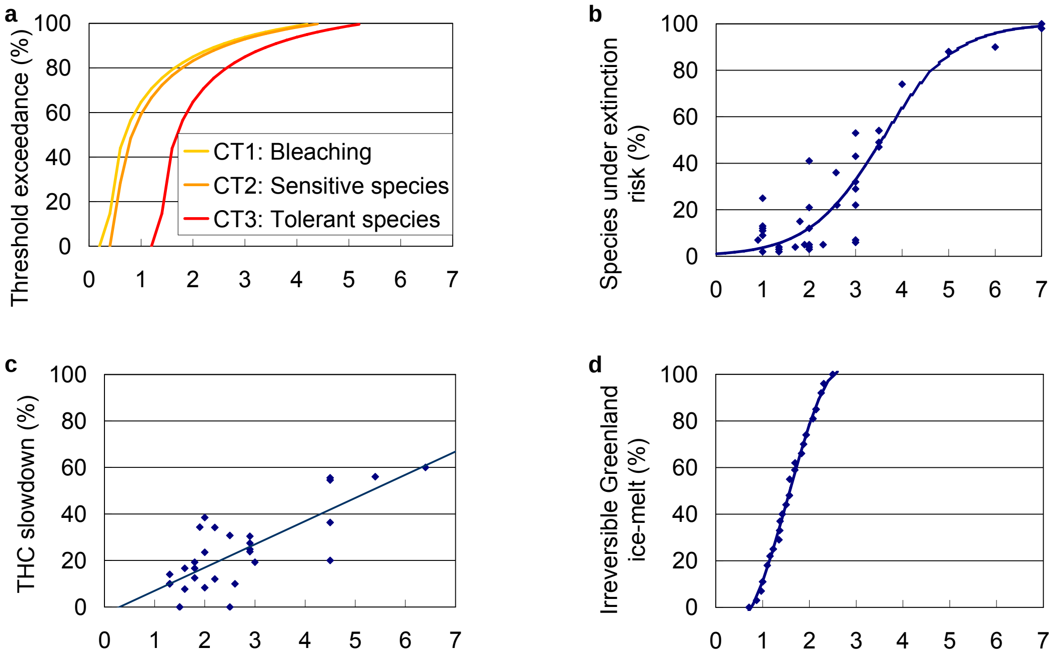
Climate sensitivity	2010	2030	2050	2070	2100
	Atmospheric CO_2 concentration (ppm)				
3.5	390	461	568	688	784
	Atmospheric CO_2 equivalent (All GHG) concentration (ppm)				
3.5	357	507	737	966	1024
	Increase in global mean surface temperature, relative to 1990 levels (°C)				
2.4	0.3	0.8	1.7	2.7	3.2
3.5	0.3	1.0	2.1	3.4	4.2
5.4	0.4	1.2	2.7	4.3	5.5

Source: Estimates of the authors.

Such changes, if unchecked, may have serious consequences, in terms of both market and non-market damages. Here we concentrate on non-market damages, including the risk of setting in train large-scale physical processes, such as the slowdown of the thermohaline circulation or disintegration of the Greenland ice sheets, which would have major consequences for ecosystems and for economic and social life[25,26]. These are all biophysical impacts, so are largely independent of any socio-economic assumptions contained within a given emission scenario. Where the rate and magnitude of impacts are subject to underlying socio-economic drivers, then it is difficult to assume levels of impact solely as a function of climate change, so we have not calculated damage functions for activities such as agriculture or human settlements.

Figure 2 summarises recent findings about critical thresholds for major impacts in four key areas of vulnerability, where a critical threshold is defined as the point at which the relationship between a change variable and an outcome becomes highly negative or non-linear[27]. Critical thresholds for most activities remain highly uncertain. The reference path, using the median climate sensitivity parameter, shows a rise in the global mean temperature by 4.2°C in 2100, exceeding most of the published estimates of the four critical thresholds listed, except for the shutdown of the thermohaline circulation.

Figure 2. Damage functions for four key vulnerabilities



Note: a) Percentage of the Great Barrier Reef affected by critical thresholds for bleaching, sensitive species mortality and tolerant species mortality; b) Extinction risk for species based on exceedance of ranges in bioclimatic envelopes and allowing for dispersal; c) Percentage of slowdown in Atlantic Ocean thermohaline circulation; d) Likelihood of exceeding published temperature thresholds at which the Greenland Ice-sheet may tip into irreversible melting. Details and assumptions in Technical AppendixI.

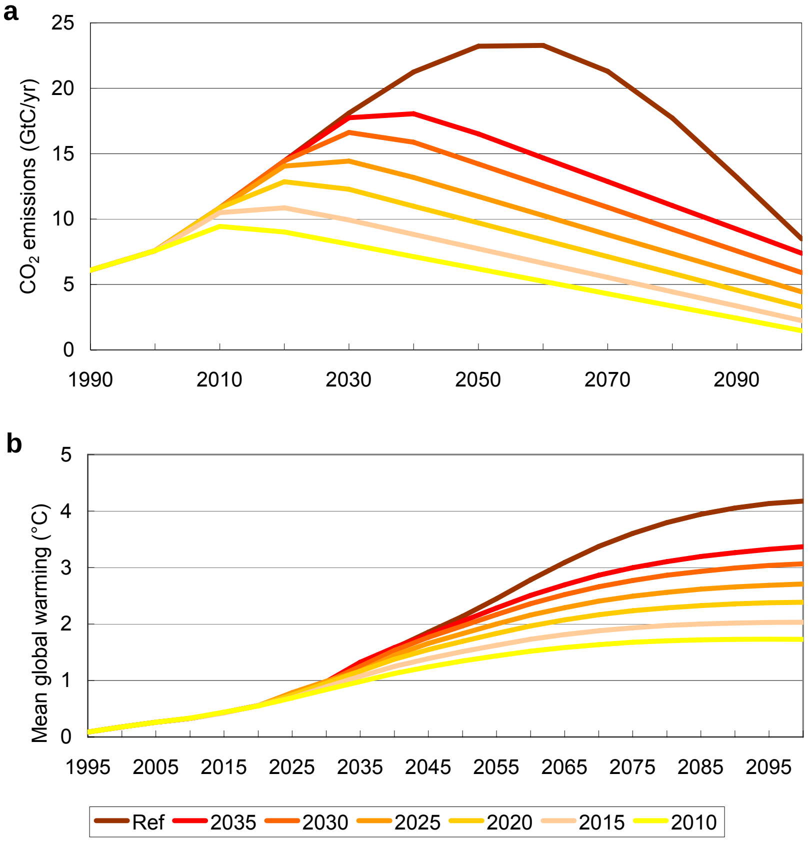
We have taken this analysis further for the four vulnerabilities. Using the results from the published scientific literature, we have mapped damage functions for coral reefs, species extinction and thermohaline circulation and the commencement of irreversible melting of the Greenland ice-sheet as a function of global warming (Figure 2). It is clear from the damage functions that the projected 4.2°C increase in warming by 2100 exceeds thresholds for catastrophic damage to coral reefs and irreversible melting of the Greenland ice-sheet, and implies heavy species extinction and significant levels of thermohaline circulation slowdown.

Timing and the Policy Window

The most appropriate approach for setting climate change policy is to assess both the risks associated with given policy options in tandem with the benefits achieved by taking this policy path[28]. Here, we look at the time scale of opportunities to minimize climate-related damages. To do so we again follow a lower bound approach, defining a series of minimum emissions paths (MEPs) that represent the lowest level of emissions that effective global policy might achieve from different points on the reference path over the next three decades. These paths stabilise average global emissions over a decade and then eliminate them over the long term. Specifically, an MEP from year *n* is defined as a path in which the level of emissions over the period from years *n+1* to *n+10* is equal to that in year *n* and in which after year *n+10* emissions are reduced to zero over the next 100 years, in equal absolute annual reductions, implying an accelerating percentage rate of decline. We specify the first path from 2010, and also explore paths from 2015, 2020, 2025, 2030 and 2035. These MEPs for CO_2 emissions are shown, relative to the reference path, in Figure 3a. Many alternative paths are possible but, given the long-term nature of adjustment processes in political, economic and energy systems, achieving this stringent specification of emissions reduction from a given starting year would require a major effort.

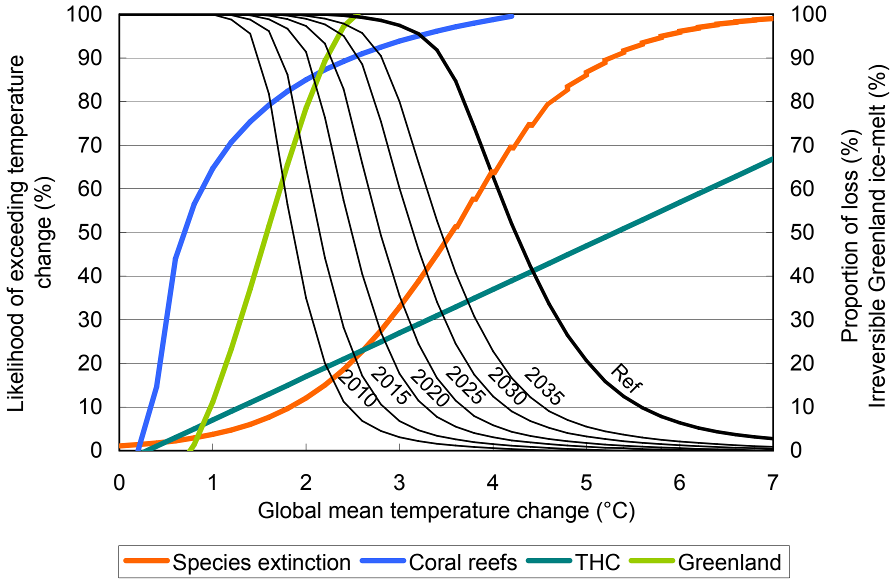
In using the MAGICC model, for each MEP non-CO_2 greenhouse gases and sulphate emissions are reduced relative to the reference path by the same percentage as for CO_2. All other specifications and assumptions are as for the modelling of the reference path. The results are reported in Figure 3 only for the case of the median value of the climate sensitivity parameter (3.5°C). Using a simple probability model, based on Jones[29] and Schneider[8], we have calculated the probabilities of exceeding a given temperature in 2100, for each MEP, using the Murphy et al.[23] probability density function for climate sensitivity. These are plotted and shown with the damage functions from Figure 2 in Figure 4.

Figure 3. a) CO_2 emissions, and b) change in global mean temperature relative to 1990, reference case and Minimum Emission Paths, 1995–2100



If an MEP were established by 2010, the atmospheric CO_2 concentration level would rise rapidly to about 460 ppm (540 ppm CO_2-e) by 2050 and stabilise slightly above that level. For the median value for climate sensitivity, the global mean temperature increase would be about 1.3°C by 2050 and would stabilise at about 1.7°C. On this path most of the major impacts from the key vulnerabilities in Figure 2 might be avoided, although warming might be much greater than this if a higher than median value of the climate sensitivity parameter applies. On the other hand, if achieving an MEP were delayed to 2035, the CO_2 concentration level rises to 575 ppm by 2050 and to close to 700 ppm by 2100, while the global temperature is 2.3°C by 2050 and 3.4°C by 2100, using the median sensitivity estimate. On the MEP 2035 path, irreversible melting of the Greenland Ice-sheet is highly likely, ~90% of coral reefs would be severely damaged, nearly 50% of species would be at risk of extinction and the thermohaline circulation would undergo a substantial slowdown.

Figure 4. Likelihood of exceeding a specific level of mean global warming by 2100 at a given emission path, superimposed on four key vulnerabilities, where proportion of loss for species extinction, coral reefs and thermoshaline slowdown is expressed as a function of global warming



Note: Irreversible Greenland ice-melt is labelled separately. The intersection of warming probability curves with a damage curve high on the graph denotes a high likelihood of critical thresholds being exceeded, and low on the graph means a low likelihood of exceedance.

Conclusion

By following the reference path of greenhouse gas emissions – an unchanged policy projection to 2030 and a lower bound estimate of emissions to 2100 – the world is likely to experience rapid warming throughout this century. Warming rates similar to those produced by the highest of the SRES scenarios would result in a high risk of potentially severe and irreversible impacts on the world's climate, environment and peoples by 2100. Using a simple probabilistic model to compare warming exceedance curves with damage to key climate vulnerabilities expressed as functions of global warming, we show that immediate intervention can still significantly reduce the risk of exceeding critical thresholds. However, if such efforts are delayed for several decades, high risks remain. The rapid increase of emissions to 2030 means that the window for avoiding the critical thresholds described above is closing rapidly.

The simple probabilistic model applied here would be improved by the addition of multi-gas emission scenarios, of methods to estimate the joint impacts of socio-economic change and climate change on human systems and of a greater library of damage functions. However, we believe its basic conceptual structure, a development of earlier probabilistic methods[27,30] is sound.

In the unchanged policy projection to 2030, CO_2 emissions to this date exceed those in all of the SRES marker scenarios for the projection period and are a key determinant of climate outcomes in 2100. Thus, the SRES scenarios no longer provide a reliable basis for studying future trends. There is a need to make greater use of existing knowledge of likely future trends, and to link detailed projections of energy futures on current policies with models of climate change in order to explore policy alternatives that minimise climate risks. A more detailed set of projections than those provided here should be prepared as a matter of urgency, by an international group coordinated by the IEA, and a detailed assessment of the potential impacts prepared. This projection, with either lower bound estimates or scenarios beyond the projection period, is urgently needed to assess the joint impact of development and climate change across regions and sectors.

Finally, if much more rapid global warming is to be avoided, CO_2 emissions need to be reduced substantially relative to the unchanged policy projection in the near future. This 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. The current rapid pace of growth in global emissions means that such action is urgent if the risks discussed here are to be avoided.

Methods

For more detailed information on methods, assumptions and detailed results for the creation of the reference path, on the MAGICC simulations and on the damage probability analysis see the Technical Appendix.

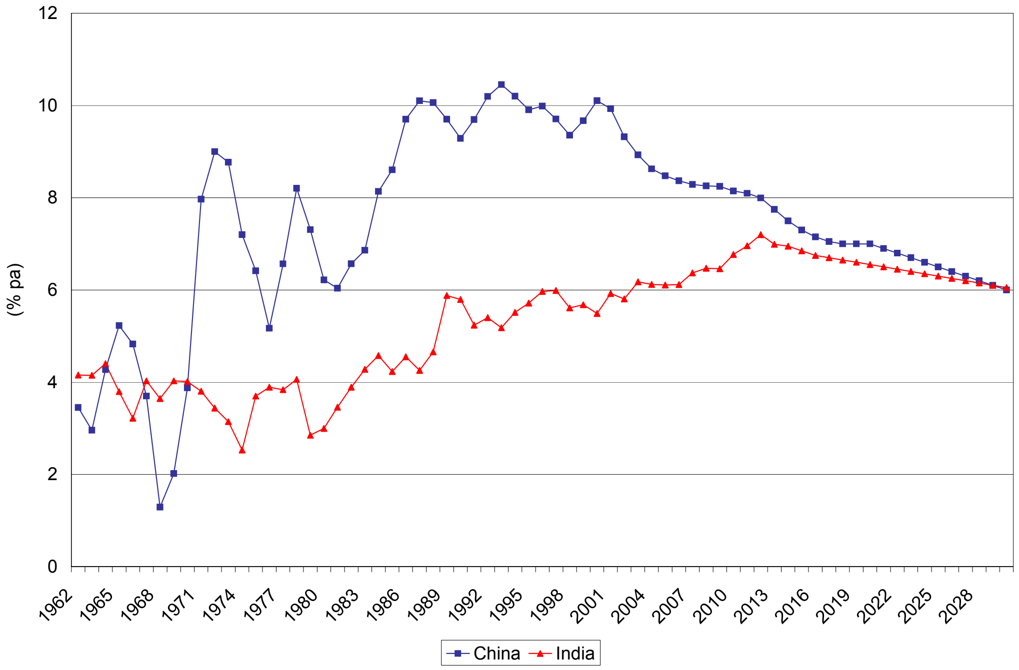
Acknowledgements

The authors gratefully acknowledge the exceptional research support provided by Alison Welsh and Margarita Kumnick, valuable advice and support from John Phillimore and Barrie Pittock, funding from the Australian Research Council under a Linkage Grant and the support of the Industry Partners to that Grant (the Department of Industry, Tourism and Resources, the Australian Greenhouse Office and the Australian Business Council). Valuable information on key vulnerabilities was supplied by the Australian Institute of Marine Science, especially Ray Berkelmans. Kevin Hennessy is thanked for review comments. None of these partners are in any way committed to the views expressed here.

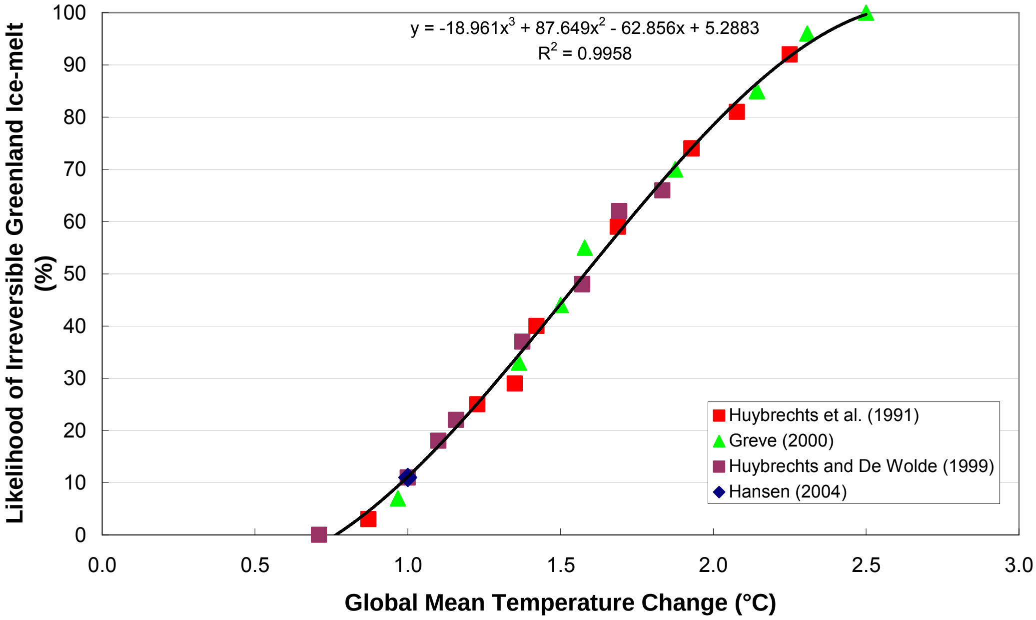
Technical Appendix

1. Technical Appendix (TA) Figures

TA Figure 1. Ten-year span growth rates for real GDP (in US$ PPPs), China and India, 1962–2030 (average annual GDP growth rate in decade to year shown)

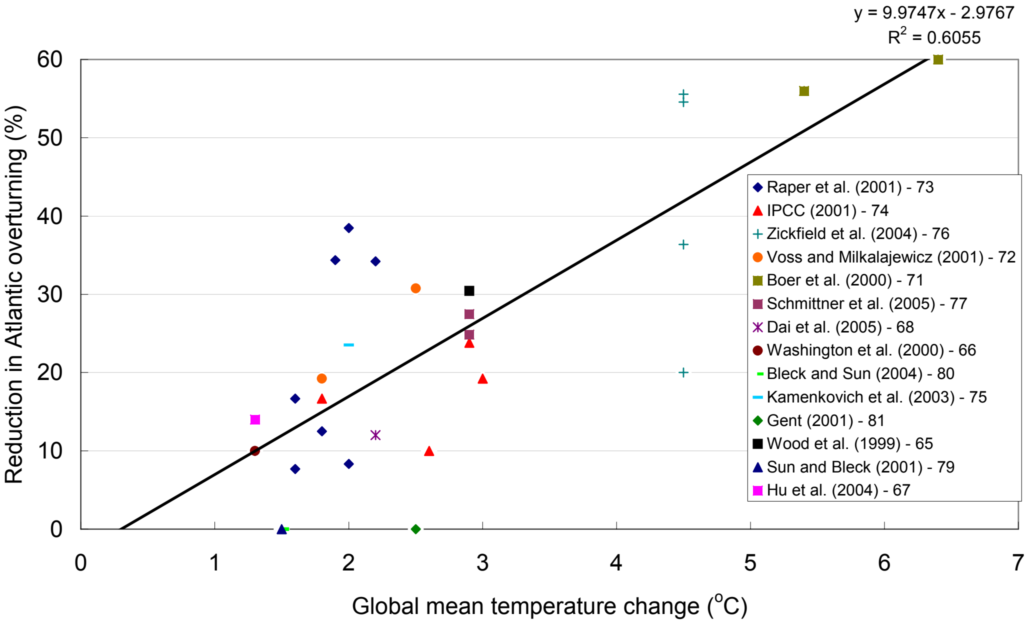


TA Figure 2. Estimated probabilistic sensitivity distribution for irreversible loss of the Greenland ice sheet.

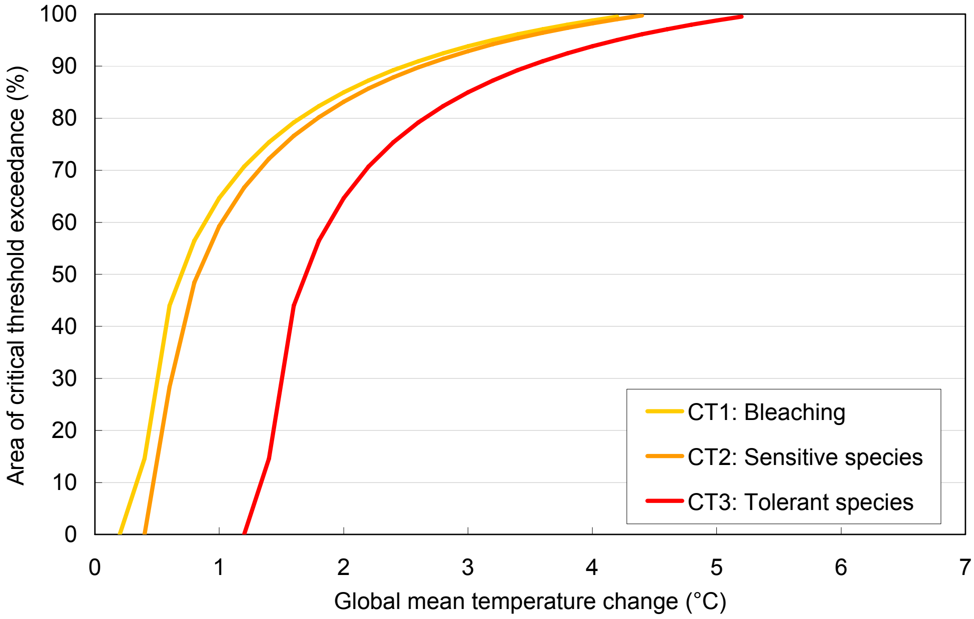


Notes: Values for Huybrechts et al.[60], Huybrechts and de Wolde[63], and Greve[61] have been converted from Greenland temperature changes using estimates of polar amplification over Greenland from nine climate models.

TA Figure 3. Estimated responses of thermohaline circulation to increasing global mean temperature over the 21st century from a range of studies

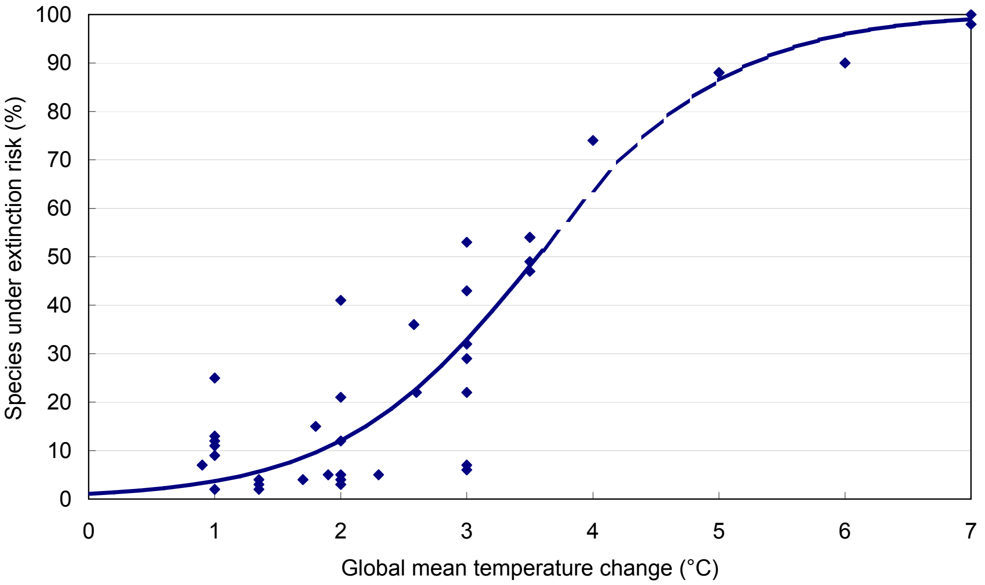


TA Figure 4. Global warming/areal relationships for the exceedance of three critical thresholds



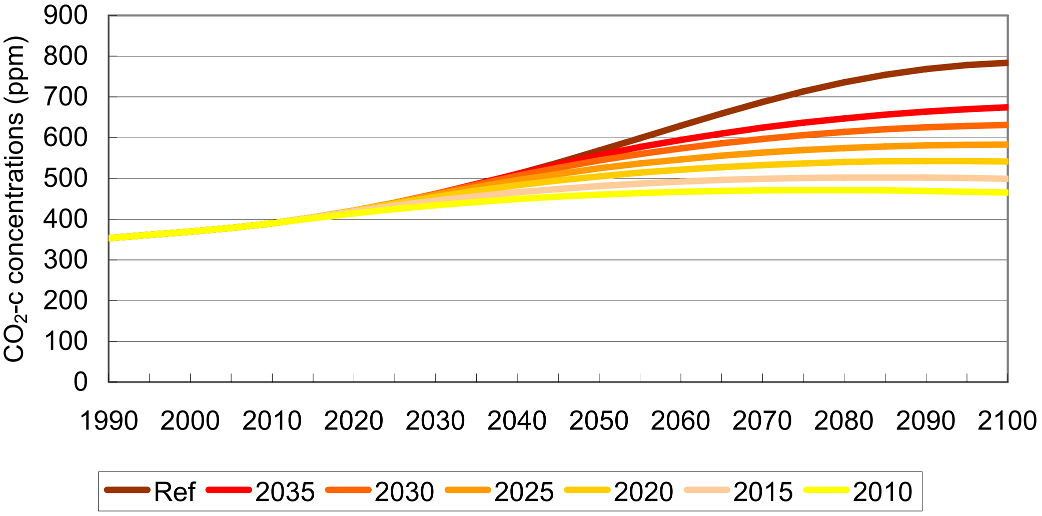
Note: CT1: Bleaching in ≥ 50% of years; CT2: widespread mortality of sensitive coral species in ≥ 10% of years; CT3: widespread mortality of tolerant coral species in ≥ 4% of years.

TA Figure 5. Relationship between global mean temperature change and extinction risk



Note: Based on studies carried out for Latin/South America, Europe, South Africa and Australia.

TA Figure 6. Atmospheric CO_2-equivalent concentration level



2. Technical Appendix: Methods

Reference Projection to 2030

Projection Framework

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 to 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 with 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, the projection methodology focuses on four key parameters 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, as non-fossil fuel use generates no CO_2 emissions and biomass and waste are excluded by convention.

Implementing the Framework

In implementing this framework to create the projection, values of the four parameters from IEA (2004) are used except where new data or other information make this no longer appropriate. For the OECD countries except Japan, Korea, Australia and New Zealand, and for the transition economies, the IEA forecasts are retained in full. The four OECD countries in the Asia Pacific region are particularly affected by rapid growth in China and India (for example as markets for their exports). For this and other reasons long term growth prospects for these countries are widely regarded as somewhat stronger than the relatively low estimates used in IEA (2004) - 1.9% pa growth in real GDP in Japan and Korea combined over 2002-30, and 2.3% growth for Australia and New Zealand combined. Key areas where variations from the IEA (2004) forecasts occur are noted in subsequent sections below.

Historical data for GDP, energy use and CO_2 emissions up to 2003 is available from the IEA website (http://data.iea.org/ieastore/statslisting.asp). To ensure consistency, these data have been used throughout this paper, although national sources have been examined to guide the projection process. The data available from this source now contains some revisions to the historical data to 2002 for GDP, energy use and CO_2 emissions outcomes relative to the data that were used in preparing the IEA (2004) forecasts. These revised data have been used both to replicate the IEA projections and as a basis for the revised projections. For each of these three variables the published projected growth rates for periods between 2002 and 2030 have been applied to the revised figures for 2002. This means that some small discrepancies can arise in replicating those projections, between the published projections and their replication on the new data.

One limitation of this approach is that, for those countries and regions for which the IEA (2004) projections are adopted in full, it is not possible to take account of developments since 2004. This relates in particular to the widespread expectation of higher fossil fuel prices in the long run and to higher growth rates, both relative to those assumed in IEA (2004). The net effect of these offsetting variations is not likely to be large. One indication of this is that the long-term growth rates for total energy use for both the OECD and for the transition economies are lower in the projection of this paper than in those of the US Energy Information Administration released in July 2005 (http://www.eia.doe.gov/oiaf/ieo/ieorefcase.html).

GDP Growth Projections (α^t_i)

The main area of variance from IEA (2004) is in the GDP growth and energy elasticity assumptions, particularly for the major developing countries. The GDP assumptions are provided in TA Table 1, which also shows a comparison of the current projected growth rates with those of IEA (2004) for the period 2002–30. China has been growing by more than 9.5% per annum between 2001 and 2005, following growth of nearly 10% per annum between 1980 and 2001, and the initial estimate of growth for 2005 was 9.9% (www.stats.gov.cn). In projecting that growth forward we assume a gradual moderation of growth to 7% by 2009, a persistence of that rate on average through to 2020, and an annual rate of 6% per annum over 2020–30. This assumption involves a considerable slowing of Chinese growth from its current hectic pace, but continued fairly strong growth over the longer term. On 20 December 2005 the Chinese Government announced that, as a result of the National Economic Census undertaken in 2004, the estimate of China's GDP for 2004 had been increased by 16.8%, and that both historical data and data for 2005 will be revised in due course[31]. As the new revisions are not yet available, these projections are based on the existing data. Given that 93% of the higher GDP value is located in the tertiary sector, the implications of this change for the analysis of energy use and emissions should be limited.

India's growth has been accelerating since the late 1970s, and reached 5.4% in the Ninth Plan period, 1997–2002. The Planning Commission estimates that the outcome for the Tenth Plan period, 2002–07, will be 7% per annum, by comparison with a target of 8.1%, and is using a growth rate of 8% as the working basis for the Eleventh Plan period, 2007–12[32]. India's growth has traditionally been driven by services rather than industry, and a notable feature of recent trends has been an increase in the growth of secondary industry relative to the overall growth of GDP. Thus for the Eleventh Plan period the working basis for industry is 9.1% per annum, by comparison with the GDP rate of 8.0%. For the projections we use lower figures than those foreshadowed by the Planning Commission, but ones that still imply strong growth out to 2030: 7% for the next two years, 7% for the Eleventh Plan period, 6.5% from 2012-20 and 6% per annum from 2020–30. TA Chart 1 shows past and projected GDP growth rates (in $US PPPs) for China and India over the period 1962–2030, in terms of moving average annual growth rates over a ten-year period. The chart brings out the projected convergence of growth rates in the two countries, with China's long run growth rate slowing from that of recent decades, with the underlying rate of growth in India continuing to increase for some time.

For other OECD regions (Asia and Oceania) and other developing countries projected growth rates are about 0.5 percentage points higher than in IEA (2004), reflecting factors such as the emergence of Japan from its long period of stagnation, the impact of resources and other demand from China on Australia's growth prospects and improved prospects for the developing countries generally. For details see TA Table 1.

Elasticity of Energy Use (ε^t_i) and Total Primary Energy Supply

It is widely held that, during the development phase, the elasticity of total primary energy use with respect to GDP is equal to or greater than one, but that once societies achieve higher living standards this elasticity becomes significantly less that one, and indeed less than 0.5. The assumptions made in relation to this variable are critical to long run projections of energy use. During the nineteenth century the elasticity of energy use was substantially greater than one for what are now the developed countries but, as TA Table 2 shows, the elasticity was 0.5 for the OECD countries as a whole over 1971–2002, with higher values only for OECD–Asia (Japan and Korea, 0.84) and for OECD–Oceania (Australia and New Zealand, 0.85). The IEA projections use a set of country specific figures that imply an overall OECD elasticity of 0.39 for 2002–2030, and our projections imply a similar figure (0.43), even after allowing for somewhat higher elasticities in the OECD–Asia and Oceania regions.

A critical issue, however, is the value of the elasticity parameter for developing countries. As is evident from TA Table 3, the energy elasticity of GDP for the developing countries as a whole was 1.04 over 1971–2002, in spite of an elasticity for China of only 0.57. For all developing countries other than China the elasticity over this period was 1.34. Prior to the opening up of the Chinese economy after 1979, it was both highly energy intensive and highly inefficient in its use of energy. As a result, energy use rose more slowly than GDP for the first fifteen years of the new expansion, implying a fall in the energy intensity of GDP and an elasticity well below one. Interpretation of trends became more complex in the second half of the 1990s, as the official Chinese energy data became unrealistic[33]. Between 1996 and 2001 real Chinese GDP was reported to have increased by 46%, but total energy consumption was reported to be 3% lower in 2001 than in 1996, implying a negative value for energy elasticity[31]. Since 2001 energy use in China has surged, with reported energy use growing by 13.6% between 2001 and 2005, implying an elasticity of 1.4 over this period. With continued energy shortages and massive construction programs in place to build more electricity generating capacity and to utilise foreign sources of energy, we assume an average elasticity for China of 1.4 through to 2010. Given that shortages will have been met, that government programs and higher prices will moderate demand and that the structure of the economy will increasingly shift to the knowledge intensive service sector, we assume that the elasticity will fall steadily after 2010, to 0.7 during the 2020s. For a full discussion of these and related issues, including a discussion of other projections of China's energy use, see Sheehan and Sun[34]. On the basis of these assumptions, total primary energy use in China is projected to grow by 11.5% per annum between 2002 and 2010, but with growth slowing appreciably after 2010, to 6.0% per annum and 4.2% per annum in the next two decades respectively (TA Table 4). For the period 2002–2030 annual growth in energy use is projected to average 6.9%, by comparison with 4.8% over 1971–2002.

Another important case is that of India. The energy elasticity of GDP (excluding biomass) for India was 1.15 over the period 1971–2005, although lower over 1990–2002 than in the earlier period. Energy use in India has been limited to date by a focus on service industries and by supply shortages, but industrial and household demand is increasing and sustained efforts are being made to increase electricity generation, primarily through coal-fired power stations. India has also been highly dependent on energy from biomass and waste. But with expansion possibilities limited in these traditional areas, growing demand for energy will need to be increasingly met from commercial sources. The Draft Report of the Expert Committee on Integrated Energy Policy, presented to the Indian Planning Commission in December 2005[35], outlines both India's growing energy needs and the programs that are being put in place to ensure that they are met. We assume (TA Table 2) that the energy elasticity of GDP in India will gradually return to an average of 1 over the 2010–2020 period, but decline after 2020. The net result is projected average annual growth in TPES in India of 6.0% over 2002–2030, with some slowing in the final decade of the projection period (TA Table 4). This is broadly consistent with the projections of the Expert Group, who use a lower elasticity but higher growth assumptions to generate a range of projected growth rates in TPES for India of 5.1%–6.0% over the period 2006–07 to 2031–32. The elasticity assumptions for other developing country regions can also be found in TA Table 2.

The revised treatment of China and India accounts for over 90% of the variation between the projected value of emissions in 2030 in TA Table 1 and in the IEA projections of 2004.

Fuel Use Type (s^{tj}_i) and Emissions Intensity of Fuel Type (m^{tj}_i)

The values of s^{tj}_i, the shares of various fuel types in total energy use, are varied from the IEA (2004) estimates only for two countries, India and China, where later information and increased knowledge of the emerging energy use path are available. Thus in TA Table 5, which shows the actual and projected share of different fuel types in TPES for given years and for selected countries/regions, all but the projected figures for India and China are consistent with IEA (2004). For China, one key change is that, given the large-scale expansion of coal-fired electricity generation capacity that is currently underway, the decline in coal's share of TPES is less rapid than in IEA (2004) – to 64% in 2030 rather than 59.2%. But a more rapid expansion of non-fossil fuel and renewable energy sector is also envisaged, given official commitments in this regard, with renewable sources providing 8% of TPES by 2030, by comparison with 5.8% in IEA (2004). With the share of natural gas also marginally higher, the share of oil falls significantly in our projections (from 24.5% in 2002 to 21% in 2030), rather than rising to 28.5% in IEA (2004). Similar, though more limited, adjustments are made for India, with the coal share somewhat higher by 2030 (49.0% as compared with 47.1%), the share of renewables higher also (8.0% as compared to 6.8%) and a sharper decline in the oil share.

In terms of aggregate fuel use, the most important factor is not these adjustments to fuel type shares for China and India, but the shift in the global pattern of energy use over the period 2002–30 to countries such as India and China that are heavy users of coal. In 2002 coal provided 69.2% of TPES in China and 49.0% in India, by comparison with 21.3% for the OECD countries. The result is a sharp shift in global energy supplies to coal over the period to 2030, with 33.8% of world TPES being provided by coal in 2030, by comparison with 25.9% in 2002 and 24.5% in 2030 on the IEA (2004) projection. On our projection, as with IEA (2004), the share of world TPES met from renewable sources falls, from 10.5% in 2002 to 9.1% in 2030. This is the net effect of rapid growth in coal use, the long-term effects of the closure of nuclear power plants in the developed countries and rapid growth in many forms of renewable energy from a very low base in 2002.

For all countries/regions, the values of m^{tj}_i, the level of CO_2 emissions per unit of energy supply for different fuel types, from IEA (2004) are used.

Comparison with IEA (2004) Projections

The CO_2 emissions projections to 2030 presented in Table 1 of the paper cover emissions from fuel combustion, including bunkers and cement production, to be consistent with the data used by the IPCC. The IEA (2004) projections do not include cement, and our projections are provided on this basis in TA Table 6. As previously discussed, the current projections are close to IEA (2004) for the OECD countries, the only variance being in somewhat stronger emissions from Japan and South Korea and from Oceania. The key differences are for India and China, where projected growth rates for CO_2 emissions are double (for India) and more than double (for China) those of IEA (2004). Projected growth rates are also somewhat higher for other developing countries.

The upshot is projected growth in global CO_2 emissions of 3.1% per annum to 2030, by comparison with the IEA (2004) figure of 1.7%, and with growth over 1971–2002 of 1.8%. The main factor generating much faster growth in the projection than over 1971–2002 is not increased growth in emissions in either developing countries (5.4% over 2002–30 compared with 4.8% over 1971–2002) or in the OECD countries (1.0% compared with 0.9%), but the much increased weight of the developing countries in world aggregates. IEA (2004) project the same growth rate over 2002–30 as over 1971–2002 only as a result of a projected sharp slowing of the growth of CO_2 emissions from developing countries, from 4.6% over 1971–2002 to 2.9% over 2002–30. This is not likely to occur, on present trends.

Extension to 2100

The sources used to assemble Table 2, and to develop the lower bound path for CO_2 emissions in Table 3, include fourteen IEA reports[36,37,38,39,40,41,42,43,44,45,46,47,48,49], two OECD studies[50,51], one recent IPCC report[52] and several other sources[53,54]. For detailed analysis of technology issues based on these reports see four studies by Jolley[55,56,57,58].

MAGICC Results

Figure 3 in the paper summarises the results for MAGICC runs for mean global warming for the CO_2 emissions paths for the reference case and for the six Minimum Emissions Paths. For completeness information on the level of atmospheric CO_2 concentration implied by those paths is provided in TA Figure 6.

Impact Response Functions

Greenland Ice Sheet

The function describing the threshold for the collapse of the Greenland ice sheet was based upon four estimates appearing in the literature. Hansen[59] proposed a threshold for the collapse of the Greenland ice sheet of 1°C increase in global mean temperature, based upon an analysis of Earth's energy imbalance from anthropogenic greenhouse gas emissions and global mean temperature change during recent interglacial periods. Huybrechts et al.[60] and Greve[61], proposed thresholds of 2.7 and 3.0°C increase in Greenland surface air temperatures based upon the response of ice sheet models to climate forcing. (The former of these thresholds was also cited in a risk analysis by Gregory et al.[62]) The final estimate of 2.2°C comes from Huybrechts and de Wolde[63], and represents the threshold global mean temperature change that would limit the loss of the Greenland ice sheet to 10% of its present volume over 1,000 years. This was assumed to represent a tolerable loss rate, and thus an upper temperature limit on the long-term stability of the ice sheet.

As the threshold temperatures for Huybrechts et al.[60], Huybrechts and de Wolde[63], and Greve[61] represent warming over Greenland, they were subsequently converted to global mean temperature changes, based upon estimated polar amplification (e.g., the ratio of Greenland temperature change to the global mean). Values for Greenland polar amplification were obtained from estimates reported in Huybrechts et al.[64] for nine different climate models (ranging from 1.3–3.1°C). To account for model uncertainty in polar amplification, the three thresholds for Huybrechts et al.[60], Huybrechts and de Wolde[63], and Greve[61] were divided by the polar amplification values from each of the nine climate models. With the addition of the Hansen[59] threshold, this resulted in a total of 28 estimates of the threshold for Greenland ice sheet collapse, indicating a range of uncertainty in global mean temperature change causing the loss of the Greenland ice sheet of approximately 0.75–2.5°C.

These thresholds were converted to a percentile scale, and a third-order 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 TA Figure 2). Assuming this distribution is representative of the true uncertainty in the global temperature threshold for collapse of the ice sheet, responses indicate the likelihood of exceeding said threshold for a given magnitude of climate change.

It should be noted that this threshold is assumed to represent the point where melting and runoff of the Greenland ice sheet exceeds accumulation. Here it is assumed that one this threshold is exceeded, the ice sheet is effectively lost, although the rate of loss and what constitutes a "collapse" are undefined. Simulations by Huybrechts et al.[60] indicate that it is possible that the ice sheet may reach a new steady state equilibrium, but only after losing approximately 50% of its current mass. Though this avoids a total loss of the ice sheet, losses of this magnitude are still consistent with substantial magnitudes of future sea-level rise and downstream consequences for natural and human systems.

Thermohaline Circulation

Estimates of the response of the thermohaline circulation (THC) to increases in global mean temperature were derived from a number of sources, which are summarised below. For each study, the maximum THC reduction (i.e., reduction in meridional overturning [Sv]) and associated global mean temperature change were recorded. A number of studies reported transient runs over multiple centuries. However, the current analysis was confined to 21st century responses (e.g., transient model runs <100 years).

Wood et al.[65] reported reductions in THC using the HADCM3 coupled model and the IS92a emissions scenario. Washington et al.[66] and Hu et al.[67] reported responses of the PCM coupled model to CO_2 increases of 1% per year until a doubling and quadrupling of the pre-industrial concentration. Dai et al.[68] also conducted experiments with the PCM, but using a 'business-as-usual' scenario for anthropogenic forcing analogous to the mean of the Intergovernmental Panel on Climate Change's SRES scenarios[69] (interpreted here as a 2.2°C increase in global mean temperature in 2100 based upon simulations with the MAGICC simple climate model[70]. Boer et al.[71] 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[72] reported reductions in THC using the ECHAM3 coupled model driven by CO_2 increases of 1% per year until a doubling and quadrupling of the pre-industrial concentration. Raper et al.[73] 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)[74] for a series of coupled models in response to the IS92a scenario. Absolute reductions in 2100 from the IPCC TAR were compared with baseline overturning for the models reported in Raper et al.[73] to estimate percent reductions. Kamenkovich et al.[75] 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 until it reached double the pre-industrial concentration. Zickfeld et al.[76] 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 up to a quadrupling of the pre-industrial concentration. Most recently, Schmittner et al.[77] 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.[78]).

It should be noted that a number of modelling studies have found no significant change in THC in response to anthropogenic climate change. Sun and Bleck[79] and Bleck and Sun[80] reported no significant change in the THC using the GISS atmospheric model coupled to the HYCOM ocean model, with CO_2 increasing at 1% per year until it reached double the pre-industrial concentration. Gent[81] also reported no significant change in the THC using the CSM model with forcing specified by the IPCC SRES A1 scenario over the 21st century. These results have been mirrored by Latif et al.[82] using the MPI coupled model with greenhouse gases increasing according to the IS92a scenario, although this study was not included in the current analysis.

A least-squares linear regression ($r^2=0.61$) was performed on the data from the aforementioned studies to develop a generalisable model of THC response to increases in global mean temperature (see TA Figure 3). It is clear from looking across the various studies that there is significant uncertainty in projections of future THC response to anthropogenic forcing. For example, Gregory et al.[78] recently reported transient THC responses from a range of AR4 coupled models, with THC reductions from 10–50% for a quadrupling of atmospheric CO_2. Nevertheless, assuming a mid-range estimate of global mean temperature change in 2100 of 2.9°C (median warming for SRES A1B scenario[74]), the response function calculated for the current study suggests a slowing in the THC of approximately 26%, consistent with the recent ensemble study of Schmittner et al.[77] In addition, this response function suggests warming on the order of 10°C would be required to induce a complete shutdown of the THC. This falls well within the range of global mean temperature change (5.0–25.0°C) required by various models to force a collapse of the THC[74]. Therefore, this meta-analysis represents a plausible aggregate estimate of the evolution of the THC in response to increasing global temperatures.

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 the model is based on temperature anomalies acting on the world's largest single reef system and one of the healthiest, we assume that extensive damage affecting the GBR will affect most other reef systems worldwide in a similar manner.

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%[83]. 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[98]. This model, because it uses anomalies, 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[84].

2. ***Temporal bleaching risk*** expressed as the frequency of events above a given threshold. These were estimated using the ReefClim model[85,86] 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[85]. 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[86].

Both bleaching frequency at a particular site and the spatial extent of bleaching can be expressed as a function of increasing local SST. We combine these two relationships by constructing three critical thresholds based on bleaching and mortality frequency then link them to the spatial extent model data above. The damage function is initialised using bleaching observations (e.g. Berkelmans and Willis[87]) and models developed for both onshore and offshore sites[85] and extends to yet to be affected sites. 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 (note that full cover will not be achieved in this time because critical threshold 2 is being exceeded on a frequency of >10 years making fast growing species unviable). The local temperature 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.

Each critical threshold was linked to bleaching and mortality model results for Magnetic Island (close to shore) and Davies Reef (outer reef), averaged between the two. CT1 reaches its 50% threshold at +0.4°C above current warming, CT2 reaches its 10% frequency at +0.5°C and CT3 reaches its 4% frequency at +1.1°C. Note that the 1998 and 2002 events killed sensitive species at some sites[88]. By linking each anomaly to the spatial model at its zero point, it was then possible to estimate the extent of the GBR that would be exceeded by each of the critical thresholds for any estimate of local warming. This was converted into estimates of global mean temperature by assuming that SST in the GBR region will rise at 0.8 of the rate of global mean temperature, which approximates the mid-range of the estimates per degree of global mean temperature of 8 models from four modelling groups for the GBR[85]. 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[89].

The relationship between the three critical thresholds spans ≤ 1°C, with CT1 and CT2 occurring very close together (TA Figure 4). 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.

Species Extinction

The risk of species extinction was based on data used in the global analysis by Thomas et al.[90] with data points for global mean temperature change >3°C added from two Australian studies[91,92]. Thomas et al.[90] used climate scenarios to assess potential shifts in species' bioclimatic envelopes to assess extinction risks. They used sample regions that cover some 20% of the Earth's land surface. Three approaches of estimating the probability of extinction showed a powerlaw relationship with geographical range size.

We used estimates from Thomas et al.'s[90] dispersal scenarios, as opposed to non-dispersal scenarios 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 extended to an increase of +3.5°C, we used data from two studies, where a relationship between closure of the climatic envelope and local increase in temperature for over 40 vertebrate Australian endemic species each has been created; by Williams et al.[92] and by us based on data from Brereton et al.[91]

The resulting distribution is sigmoidal, reflective of a normally distributed sample, and chosen because individual studies for a range of species types show this pattern, both across an individual specie's range and between species. The upper limit is highly uncertain because it is based on only two studies both involving endemic vertebrates (TA Figure 5).

3. Technical Appendix Tables

TA Table 1. GDP in constant US dollars (year 2000 purchasing power parity values), actual 1971–2002 and projected 2002–2030

	GDP in PPP US $2000					Annual change (% per annum)					
	1971	2002	2010	2020	2030	1971-2002	2002-10	2010-20	2020-30	2002-30	IEA (2004) 2002-30
	(US$ trillon)					(% per annum)					
OECD	11.5	27.9	34.8	43.8	53.1	2.9	2.8	2.3	1.9	2.3	2.2
North America	4.5	11.8	15.2	19.3	23.3	3.2	3.2	2.4	1.9	2.4	2.4
Europe	5.3	11.2	13.6	16.9	20.0	2.4	2.4	2.2	1.7	2.1	2.1
Asia	1.4	4.2	5.2	6.6	8.4	3.5	2.7	2.4	2.5	2.5	1.9
Oceania	0.2	0.6	0.8	1.1	1.4	3.0	3.4	2.9	2.4	2.9	2.3
Transition economies	1.8	2.1	3.0	4.3	5.7	0.4	4.6	3.7	2.9	3.7	3.7
Developing countries	4.1	17.0	27.5	48.1	80.5	4.7	6.2	5.7	5.3	5.7	4.3
China	0.5	5.8	10.9	21.4	38.3	8.5	8.2	7.0	6.0	7.0	5.0
India	0.6	2.7	4.7	8.9	15.9	4.9	7.3	6.5	6.0	6.5	4.7
SE Asia	0.4	1.9	2.8	4.3	6.4	5.4	5.0	4.5	4.0	4.5	3.8
Other	2.6	6.7	9.1	13.5	20.0	3.1	4.0	4.0	4.0	4.0	3.4
Other countries	0.1	0.6	0.8	1.0	1.4	6.4	3.7	3.2	2.7	3.2	3.2
World	17.4	47.5	66.0	97.2	140.7	3.3	4.2	3.9	3.8	4.0	3.2

TA Table 2. Elasticity of energy use (TPES) with respect to GDP, actual 1971–2002 and projected 2002–2030

	Actual					IEA (2004)
	1971-2002	2002-10	2010-20	2020-30	2002-30	2002-30
OECD	0.50	0.51	0.43	0.35	0.43	0.39
North America	0.45	0.45	0.42	0.36	0.42	0.42
Europe	0.45	0.43	0.27	0.14	0.28	0.28
Asia	0.84	0.80	0.70	0.60	0.70	0.50
Oceania	0.85	0.60	0.50	0.40	0.50	0.44
Transition economies	1.37	0.43	0.39	0.26	0.36	0.36
Developing countries	1.04	1.19	0.90	0.76	0.94	0.70
China	0.57	1.40	0.85	0.70	0.98	0.58
India	1.15	0.85	1.00	0.90	0.92	0.65
SE Asia	1.28	1.00	0.90	0.80	0.90	0.85
Other developing	1.46	0.90	0.90	0.80	0.86	0.87
Other countries	0.99	0.53	0.47	0.47	0.49	0.49
World	0.63	0.84	0.73	0.67	0.75	0.54

TA Table 3. Elasticity of energy use (TPES) with respect to GDP, developing countries, actual 1971–2002

	Annual GDP growth rate (% pa)			Annual TPES growth rate (% pa)			Elasticity of TPES with respect to GDP		
	1971-2002	1971-1990	1990-2002	1971-2002	1971-1990	1990-2002	1971-2002	1971-1990	1990-2002
China	8.5	7.8	9.6	4.8	5.7	3.4	0.57	0.73	0.35
India	4.9	4.6	5.3	5.6	6.1	4.7	1.15	1.34	0.89
SE Asia	5.4	6.0	4.4	6.9	7.2	6.5	1.28	1.19	1.47
Other	3.1	3.1	3.0	4.5	5.8	2.4	1.46	1.86	0.81
All Developing Countries	4.7	4.4	5.3	4.8	5.8	3.1	1.04	1.35	0.64

TA Table 4. Energy use (Total Primary Energy Supply – TPES), actual 1971–2002 and projected 2002–2030

	Total primary energy supply					Annual change (% per annum)					
						1971-					IEA (2004)
	1971	2002	2010	2020	2030	2002	2002-10	2010-20	2020-30	2002-30	2002-30
			(mtoe)					(% per annum)			
OECD	3,309	5,177	5,801	6,405	6,857	1.5	1.4	1.0	0.7	1.0	0.9
North America	1,730	2,608	2,927	3,239	3,465	1.3	1.5	1.0	0.7	1.0	1.0
Europe	1,237	1,730	1,880	1,993	2,041	1.1	1.0	0.6	0.2	0.6	0.6
Asia	287	714	849	1,005	1,166	3.0	2.2	1.7	1.5	1.8	1.0
Oceania	56	124	145	168	185	2.6	2.1	1.5	1.0	1.5	1.0
Transition economies	851	1,012	1,169	1,309	1,467	0.6	1.8	1.1	1.1	1.3	1.3
Developing countries	633	2,816	4,971	8,231	12,208	4.9	7.4	5.2	4.0	5.4	3.0
China	241	1,030	2,457	4,380	6,609	4.8	11.5	6.0	4.2	6.9	2.9
India	61	330	534	1,003	1,697	5.6	6.2	6.5	5.4	6.0	3.1
SE Asia	39	311	459	683	935	6.9	5.0	4.1	3.2	4.0	3.2
Other	292	1,145	1,520	2,165	2,966	4.5	3.6	3.6	3.2	3.5	3.0
Other countries	17	114	133	155	175	6.4	2.0	1.5	1.3	1.6	1.6
Bunkers	106	146	158	175	193	1.0	1.0	1.0	1.0	1.0	
World	4,916	9,264	12,232	16,274	20,901	2.1	3.5	2.9	2.5	2.9	1.7

TA Table 5. Distribution of Total Primary Energy Supply by fuel type, actual 1971 and 2002 and projected 2030

	Coal			Oil			Natural gas			Non-fossil fuels (ex biomass)		
	1971	2002	2030	1971	2002	2030	1971	2002	2030	1971	2002	2030
	Share of annual total, by fuel type (%)											
OECD	24.7	21.3	18.2	52.3	41.9	41.3	19.8	22.6	27.3	3.2	14.2	13.1
North America	17.2	22.2	19.4	47.8	41.4	42.7	32.2	24.8	27.2	2.9	11.6	10.8
Europe	35.3	18.5	14.6	53.7	40.1	39.2	7.5	23.6	32.8	3.6	17.8	13.4
Asia	21.7	21.0	18.4	73.8	50.0	42.2	1.2	12.3	18.5	3.3	16.7	20.8
Oceania	39.8	40.7	32.4	51.1	33.2	34.7	3.4	21.4	26.0	5.7	4.7	6.9
Transition economies	38.7	19.8	15.3	36.2	21.1	23.8	23.5	49.8	53.3	1.6	9.3	7.7
Developing countries	45.9	37.7	45.3	45.4	40.4	31.0	6.1	17.3	16.5	2.5	4.6	7.1
China	79.7	69.2	64.0	17.9	24.5	21.0	1.3	3.3	7.0	1.1	3.0	8.0
India	58.1	54.0	49.0	36.6	35.9	33.0	0.9	6.8	10.0	4.4	3.3	8.0
SE Asia	4.4	12.9	17.0	93.2	54.4	48.6	0.8	26.7	28.5	1.5	5.9	5.9
Other	20.9	11.4	10.4	63.6	52.1	46.8	12.0	30.4	37.7	3.5	6.1	5.1
Other countries	15.1	36.2	35.6	77.3	47.5	48.1	6.0	6.1	7.5	1.6	10.1	8.9
World	29.3	25.9	33.8	49.7	40.2	34.7	18.2	23.4	22.4	2.8	10.5	9.1

TA Table 6. Average annual rates of growth of CO_2 emissions from fuel combustion and cement, actual 1971–2002 and projected 2002–2030, IEA (2004) and current paper

	Actual	Projection	
		Current paper	IEA (2004)
	1971-2002	2002-30	2002-30
	(average annual percentage change, % pa)		
OECD	0.9	1.0	0.9
North America	1.0	1.0	1.0
Europe	0.2	0.7	0.7
Asia	2.4	1.4	0.7
Oceania	2.8	1.2	0.8
Transition economies	0.2	1.3	1.3
China	4.9	6.6	2.8
India	5.4	5.8	2.9
SE Asia	6.9	4.0	3.3
Other	4.0	3.4	3.0
Other countries	6.3	2.6	2.6
Bunkers	1.0	1.0	0.4
World	1.8	3.2	1.7

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