Part II
Impacts of Climate Change on Growth and Development

Part II considers how climate change will affect people's lives, the environment and the prospects for growth and development in different parts of the world. All three dimensions are fundamental to understanding how climate change will affect our future.

These effects will not be felt evenly across the globe. Although some parts of the world would benefit from modest rises in temperature, at higher temperature increases, most countries will suffer heavily and global growth will be affected adversely. For some of the poorest countries there is a real risk of being pushed into a downwards spiral of increasing vulnerability and poverty.

Average global temperature increases of only 1-2°C (above pre-industrial levels) could commit 15-40 percent of species to extinction. As temperatures rise above 2-3°C, as will very probably happen in the latter part of this century, so the risk of abrupt and large-scale damage increases, and the costs associated with climate change – across the three dimensions of mortality, ecosystems and income – are likely to rise more steeply. In mathematical terms, the global damage function is convex.

No region would be left untouched by changes of this magnitude, though developing countries would be affected especially adversely. This applies particularly to the poorest people within the large populations of both sub-Saharan Africa, and South Asia. By 2100, in South Asia and Sub Saharan Africa, up to 145 - 220 million additional people could fall below the $2-a-day poverty line, and every year an additional 165,000 - 250,000 children could die compared with a world without climate change.

Modelling work undertaken by the Review suggests that the risks and costs of climate change over the next two centuries could be equivalent to an average reduction in global per capita consumption of at least 5%, now and forever. The estimated damages would be much higher if non-market impacts, the possibility of greater climate sensitivity, and distributional issues were taken into account.

Part II is structured as follows:

- **Chapter 3** begins by exploring how climate change will affect people around the world, including the potential implications for access to food, water stress, health and well being, and the environment.

- **Chapter 4** focuses on the implications for developed countries. Some regions will benefit from temperature rises of up to 1 to 2°C, but the balance of impacts will become increasingly negative as temperature rises.

- **Chapter 5** considers the implications of climate change for developing countries. It explains why developing countries are so vulnerable to climate change – a volatile mix of geographic location, existing vulnerability and, linked to this, limited ability to deal with the pressures that climate change will create.

- **Chapter 6** aims to pull together the existing modelling work that has been done to estimate the monetary costs of climate change, and also sets out the detail of modelling work undertaken by the Review.

3 How Climate Change Will Affect People Around The World

Key Messages

Climate change threatens the basic elements of life for people around the world – access to water, food, health, and use of land and the environment. On current trends, average global temperatures could rise by 2 - 3°C within the next fifty years or so,[1] leading to many severe impacts, often mediated by water, including more frequent droughts and floods (Table 3.1).

- **Melting glaciers** will increase flood risk during the wet season and strongly reduce dry-season water supplies to one-sixth of the world's population, predominantly in the Indian sub-continent, parts of China, and the Andes in South America.
- **Declining crop yields**, especially in Africa, are likely to leave hundreds of millions without the ability to produce or purchase sufficient food - particularly if the carbon fertilisation effect is weaker than previously thought, as some recent studies suggest. At mid to high latitudes, crop yields may increase for moderate temperature rises (2 – 3°C), but then decline with greater amounts of warming.
- **Ocean acidification**, a direct result of rising carbon dioxide levels, will have major effects on marine ecosystems, with possible adverse consequences on fish stocks.
- **Rising sea levels** will result in tens to hundreds of millions more people flooded each year with a warming of 3 or 4°C. There will be serious risks and increasing pressures for coastal protection in South East Asia (Bangladesh and Vietnam), small islands in the Caribbean and the Pacific, and large coastal cities, such as Tokyo, Shanghai, Hong Kong, Mumbai, Calcutta, Karachi, Buenos Aires, St Petersburg, New York, Miami and London.
- Climate change will increase worldwide deaths from **malnutrition and heat stress**. Vector-borne diseases such as malaria and dengue fever could become more widespread if effective control measures are not in place. In higher latitudes, cold-related deaths will decrease.
- By the middle of the century, 200 million more people may become **permanently displaced** due to rising sea levels, heavier floods, and more intense droughts, according to one estimate.
- **Ecosystems** will be particularly vulnerable to climate change, with one study estimating that around 15 – 40% of species face extinction with 2°C of warming. Strong drying over the Amazon, as predicted by some climate models, would result in dieback of the forest with the highest biodiversity on the planet.

The consequences of climate change will become disproportionately more damaging with increased warming. Higher temperatures will increase the chance of triggering abrupt and large-scale changes that lead to regional disruption, migration and conflict.

- Warming may induce **sudden shifts in regional weather patterns** like the monsoons or the El Niño. Such changes would have severe consequences for water availability and flooding in tropical regions and threaten the livelihoods of billions.
- **Melting or collapse of ice sheets** would raise sea levels and eventually threaten at least 4 million Km^2 of land, which today is home to 5% of the world's population.

[1] All changes in global mean temperature are expressed relative to pre-industrial levels (1750 - 1850). A temperature rise of 1°C represents the range 0.5 – 1.5°C, a temperature rise of 2°C represents the range 1.5 – 2.5°C etc.

Table 3.1 Highlights of possible climate impacts discussed in this chapter

Temp rise (°C)	Water	Food	Health	Land	Environment	Abrupt and Large-Scale Impacts
1°C	Small glaciers in the Andes disappear completely, threatening water supplies for 50 million people	Modest increases in cereal yields in temperate regions	At least 300,000 people each year die from climate-related diseases (predominantly diarrhoea, malaria, and malnutrition) Reduction in winter mortality in higher latitudes (Northern Europe, USA)	Permafrost thawing damages buildings and roads in parts of Canada and Russia	At least 10% of land species facing extinction (according to one estimate) 80% bleaching of coral reefs, including Great Barrier Reef	Atlantic Thermohaline Circulation starts to weaken
2°C	Potentially 20 - 30% decrease in water availability in some vulnerable regions, e.g. Southern Africa and Mediterranean	Sharp declines in crop yield in tropical regions (5 - 10% in Africa)	40 – 60 million more people exposed to malaria in Africa	Up to 10 million more people affected by coastal flooding each year	15 – 40% of species facing extinction (according to one estimate) High risk of extinction of Arctic species, including polar bear and caribou	Potential for Greenland ice sheet to begin melting irreversibly, accelerating sea level rise and committing world to an eventual 7 m sea level rise Rising risk of abrupt changes to atmospheric circulations, e.g. the monsoon Rising risk of collapse of West Antarctic Ice Sheet Rising risk of collapse of Atlantic Thermohaline Circulation
3°C	In Southern Europe, serious droughts occur once every 10 years 1 - 4 billion more people suffer water shortages, while 1 – 5 billion gain water, which may increase flood risk	150 - 550 additional millions at risk of hunger (if carbon fertilisation weak) Agricultural yields in higher latitudes likely to peak	1 – 3 million more people die from malnutrition (if carbon fertilisation weak)	1 – 170 million more people affected by coastal flooding each year	20 – 50% of species facing extinction (according to one estimate), including 25 – 60% mammals, 30 – 40% birds and 15 – 70% butterflies in South Africa Onset of Amazon forest collapse (some models only)	
4°C	Potentially 30 – 50% decrease in water availability in Southern Africa and Mediterranean	Agricultural yields decline by 15 – 35% in Africa, and entire regions out of production (e.g. parts of Australia)	Up to 80 million more people exposed to malaria in Africa	7 – 300 million more people affected by coastal flooding each year	Loss of around half Arctic tundra Around half of all the world's nature reserves cannot fulfill objectives	
5°C	Possible disappearance of large glaciers in Himalayas, affecting one-quarter of China's population and hundreds of millions in India	Continued increase in ocean acidity seriously disrupting marine ecosystems and possibly fish stocks		Sea level rise threatens small islands, low-lying coastal areas (Florida) and major world cities such as New York, London, and Tokyo		
More than 5°C	The latest science suggests that the Earth's average temperature will rise by even more than 5 or 6°C if emissions continue to grow and positive feedbacks amplify the warming effect of greenhouse gases (e.g. release of carbon dioxide from soils or methane from permafrost). This level of global temperature rise would be equivalent to the amount of warming that occurred between the last age and today – and is likely to lead to major disruption and large-scale movement of population. Such "socially contingent" effects could be catastrophic, but are currently very hard to capture with current models as temperatures would be so far outside human experience.					

Note: This table shows illustrative impacts at different degrees of warming. Some of the uncertainty is captured in the ranges shown, but there will be additional uncertainties about the exact size of impacts (more detail in Box 3.2). Temperatures represent increases relative to pre-industrial levels. At each temperature, the impacts are expressed for a 1°C band around the central temperature, e.g. 1°C represents the range 0.5 – 1.5°C etc. Numbers of people affected at different temperatures assume population and GDP scenarios for the 2080s from the Intergovernmental Panel on Climate Change (IPCC). Figures generally assume adaptation at the level of an individual or firm, but not economy-wide adaptations due to policy intervention (covered in Part V).

Part II: The Impacts of Climate Change on Growth and Development

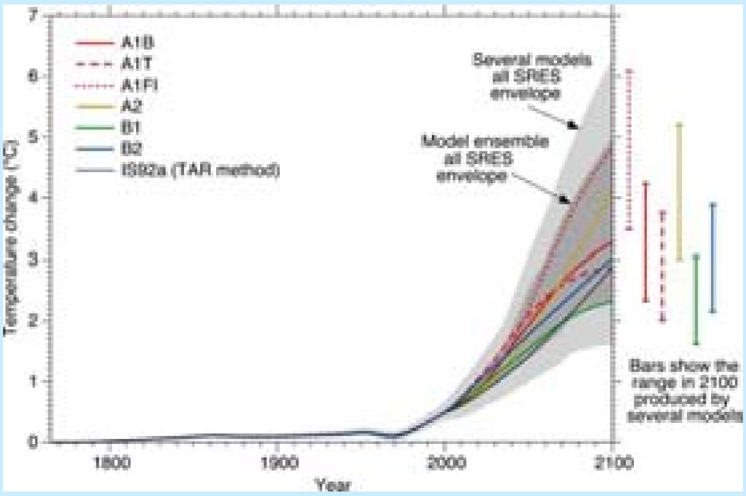
3.1 Introduction

This chapter examines the increasingly serious impacts on people as the world warms.

Climate change is a serious and urgent issue. The Earth has already warmed by 0.7°C since around 1900 and is committed to further warming over coming decades simply due to past emissions (Chapter 1). On current trends, average global temperatures could rise by 2 - 3°C within the next fifty years or so, with several degrees more in the pipeline by the end of the century if emissions continue to grow (Figure 3.1; Chapters 7 and 8).

This chapter examines how the physical changes in climate outlined in Chapter 1 affect the essential components of lives and livelihoods of people around the world - water supply, food production, human health, availability of land, and ecosystems. It looks in particular at how these impacts intensify with increasing amounts of warming. The latest science suggests that the Earth's average temperature will rise by even more than 5 or 6°C if feedbacks amplify the warming effect of greenhouse gases through the release of carbon dioxide from soils or methane from permafrost (Chapter 1). Throughout the chapter, changes in global mean temperature are expressed relative to pre-industrial levels (1750 - 1850).

Figure 3.1 Temperature projections for the 21st century



Notes: The graph shows predicted temperature changes through to 2100 relative to pre-industrial levels. Nine illustrative emissions scenarios are shown with the different coloured lines. Blue shading represents uncertainty between the seven different climate models used. Coloured bars show the full range of climate uncertainty in 2100 for each emissions scenario based on the models with highest and lowest climate sensitivity. Updated projections will be available in the Fourth Assessment Report of the Intergovernmental Panel of Climate Change (IPCC) in 2007. These are likely to incorporate some of the newer results that have emerged from probabilistic climate simulations and climate models including carbon cycle feedbacks, such as the Hadley Centre's (more details in Chapter 1).

Source: IPCC (2001)

The chapter builds up a comprehensive picture of impacts by incorporating two effects that are not usually included in existing studies (extreme events and threshold effects at higher temperatures). In general, impact studies have focused predominantly on changes in average conditions and rarely examine the consequences of increased variability and more extreme weather. In addition, almost all impact studies have only considered global temperature rises up to 4 or 5°C and therefore do not take account of threshold effects that could be triggered by temperatures higher than 5 or 6°C (Chapter 1).

- **Extreme weather events.** Climate change is likely to increase the costs imposed by extreme weather, both by shifting the probability distribution upwards (more heatwaves, but fewer cold-snaps) and by intensifying the water cycle, so that severe floods, droughts and storms occur more often (Chapter 1).[2] Even if the shape of the distribution of temperatures does not change, an upward shift in the distribution as a whole will disproportionately increase the probability of exceeding damaging temperature thresholds.[3] Changes in the variability of climate in the future are more uncertain, but could have very significant impacts on lives and livelihoods. For example, India's economy and social infrastructure are finely tuned to the remarkable stability of the monsoon, with the result that fluctuations in the strength of the monsoon both year-to-year and within a single season can lead to significant flooding or drought, with significant repercussions for the economy (see Box 3.5 later).[4]
- **Non-linear changes and threshold effects at higher temperatures (convexity).** The impacts of climate change will become increasingly severe at higher temperatures, particularly because of rising risks of triggering abrupt and large-scale changes, such as melting of the Greenland ice sheet or loss of the Amazon forest. Few studies have examined the shape of the damage function at higher temperatures, even though the latest science suggests that temperatures are 5 or 6°C or higher are plausible because of feedbacks that amplify warming (Chapter 1). For some sectors, damages may increase much faster than temperatures rise, so that the damage curve becomes convex - the consequences of moving from 4 to 5°C are much greater than the consequences of moving from 2 to 3°C. For example, hurricane damages increase as a cube (or more) of wind-speed, which itself scales closely with sea temperatures (Chapter 1 and Section 3.6). Theory suggests impacts in several key sectors will increase strongly at higher temperatures, although there is not enough direct quantitative evidence on the impacts at higher temperatures (Box 3.1).

The combined effect of impacts across several sectors could be very damaging and further amplify the consequences of climate change. Little work has been done to quantify these interactions, but the potential consequences could be substantial. For example, in some tropical regions, the combined effect of loss of native pollinators, greater risks of pest outbreaks, reduced water supply, and greater incidence of heatwaves could lead to much greater declines in food production than through the individual effects themselves (see Table 3.2 later in chapter).

The consequences of climate change will depend on how the physical impacts interact with socio-economic factors. Population movement and growth will often exacerbate the impacts by increasing society's exposure to environmental stresses (for example, more people living by the coast) and reducing the amount of resource available per person (for example, less food per person and causing greater food shortages).[5] In contrast, economic growth often reduces vulnerability to climate change (for example, better nutrition or health care; Chapter 4) and increases society's ability to adapt to the impacts (for example, availability of technology to make crops more drought-tolerant; Chapter 20). This chapter focuses on studies that in general calculate impacts by superimposing climate change onto a future world that has developed economically and socially and comparing it to the same future world without climate change (Box 3.2 for further details). Most of the studies generally assume adaptation at the level of an individual or firm, but not economy-wide adaptations due to policy intervention (covered in Part V).

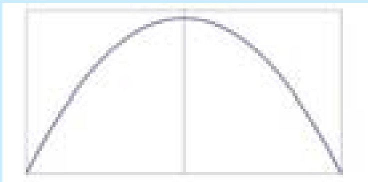
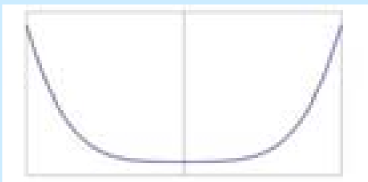
Building on the analyses presented in this chapter, Chapters 4 and 5 trace the physical impacts through to examine the consequences for economic growth and social progress in developing and developed countries. Chapter 6 brings together evidence on the aggregate impacts of climate change, including updated projections from the PAGE2002 model that incorporate the risk of abrupt climate change.

---

[2] "Extreme events" occur when a climate variable (e.g. temperature or rainfall) exceeds a particular threshold, e.g. two standard deviations from the mean.
[3] In looking at the effects on crop yields of severe weather during the Little Ice Age, Prof Martin Parry (1978) argued that the frequency of extreme events would change dramatically as a result of even a small change in the mean climate and that the probability of two successive extremes is even more sensitive to small changes in the mean. Often a single extreme event is easy to withstand, but a second in succession could be far more devastating. In a follow-up paper, Tom Wigley (1985) demonstrated these effects on extremes mathematically.
[4] Based on a technical paper prepared for the Stern Review by Challinor *et al.* (2006b)
[5] This will also depend on efficiency of use as well.

Box 3.1 The types of relationship between rising damages and sectoral impacts

Basic physical and biological principles indicate that impacts in many sectors will become disproportionately more severe with rising temperatures. Some of these effects are summarised below, but are covered in detail in the relevant section of the chapter. Empirical support for these relationships is lacking. Hitz and Smith (2004) reviewed studies that examined the nature of the relationship between the impacts of climate change and increasing global temperatures. They found increasingly adverse impacts for several climate-sensitive sectors but were not able to determine if the increase was linear or exponential (more details in Box 3.1). For other sectors like water and energy where there was a mix of costs and benefits they found no consistent relationship with temperature.

Type of effect	**Sector [location of source]**	**Proposed Functional Form**		**Basis**
Climate system	Water [Chapter 1]	Exponential $y = e^x$		The Clausius-Clapeyron equation shows that the water holding capacity of air increases exponentially with temperature. This means that the water cycle will intensify, leading to more severe floods and droughts. There will also be more energy to drive storms and hurricanes.
	Extreme temperatures (threshold effects) [Chapter 1]	Convex curve (i.e. gradient increases with temperature)		Because of the shape of the normal distribution, a small increase in the mean dramatically increases the frequency of an extreme event.
Physical impacts	Agricultural production [Section 3.3]	Inverse parabolic ("hill function") $y = -x^2$		In cooler regions, low levels of warming may improve conditions for crop growth (extended growing season and new areas opened up for production), but further warming will have increasingly negative impacts as critical temperature thresholds are crossed more often. Tropical regions may already be past the peak. The shape and location of the curve depend on crop.
	Heat-related human mortality [Section 3.4]	U-shaped		Sharp increase in mortality once human temperature tolerances are exceeded (heatwaves and cold-snaps). Initially mortality will be reduced by warming in cold regions.
	Storm damage [Section 3.6]	Cubic $y = x^3$		Infrastructure damage increases as a cube of wind-speed
Human response	Costs of coastal protection [Section 3.5]	Parabolic $y = x^2$		Costs of sea-wall construction increase as a square of defence height

Box 3.2 Assumptions and scenarios used in impact studies

This chapter bases much of its detailed analysis on a series of papers prepared by Prof. Martin Parry and colleagues ("FastTrack"), one of the few that clearly sets out the assumptions used and explores different sources of uncertainty.[6]

Climate change scenarios. Climate models produce different regional patterns of temperature and rainfall (especially). The original "FastTrack" studies were based on outputs of the Hadley Centre climate model. However, in some cases the analyses have been updated to examine sensitivity to a range of different climate models.[7] Other science uncertainties, such as the link between greenhouse gas concentrations and global temperatures, were not directly examined by the work (more detail in Chapter 1).

Socio-economic scenarios. The studies carefully separated out the effects of climate change from socio-economic effects, such as growing wealth or population size. In these studies, population and GDP per capita grew on the basis of four socio-economic pathways, as described by the IPCC (see table below).[8] The effects of climate change were calculated by comparing a future world with and without climate change (but with socio-economic development in every case). Changing socio-economic factors alongside climate may be crucial because: (1) a growing population will increase society's exposure to stress from malnutrition, water shortages and coastal flooding, while (2) growing wealth will reduce vulnerability to climate change, for example by developing crops that are more drought-tolerant. Other impact studies superimpose climate change in a future world where population and GDP remain constant at today's levels. These studies are perhaps less realistic, but still provide a useful indication of the scale of the impacts and may be easier to interpret.

Summary characteristics of IPCC socio-economic scenarios (numbers in brackets for 2100)

IPCC Scenarios	**A1 FI**	**A2**	**B1**	**B2**
Name	World Markets	National Enterprise	Global Sustainability	Local Stewardship
Population growth	Low (7 billion)	High (15 billion)	Low (7 billion)	Medium (10 billion)
World GDP growth[9]	Very high, 3.5% p.a. ($550 trillion)	Medium, 2% p.a. ($243 trillion)	High, 2.75% p.a. ($328 trillion)	Medium 2% p.a. ($235 trillion)
Degree of convergence: ratio of GDP per capita in rich vs. poor countries[10]	High (1.6)	Low (4.2)	High (1.8)	Medium (3.0)
Emissions	High	Medium High	Low	Medium Low

Adaptation assumptions. Clarity over adaptation is critical for work on the impacts of climate change, because large amounts of adaptation would reduce the overall damages caused by climate change (net of costs of adaptation). Within the literature, the picture remains mixed: some studies assume no adaptation, many studies assume individual (or "autonomous") adaptation, while other studies assume an "efficient" adaptation response where the costs of adaptation plus the costs of residual damages are minimised over time.[11] Unless otherwise stated, the results presented assume adaptation at the level of an individual or firm ("autonomous"), but not economy-wide. Such adaptations are likely to occur gradually as the impacts are felt but that require little policy intervention (more details in Part V). This provides the "policy neutral" baseline for analysing the relative costs and benefits of adaptation and mitigation.

[6] Special Issue of Global Environmental Change, Volume 14, April 2004 - further details on the new analysis are available from Warren *et al.* (2006). Risk and uncertainty are often used interchangeably, but in a formal sense, risk covers situations when the probabilities are known and uncertainty when the probabilities are not known.
[7] See, for example, Arnell (2006a)
[8] IPCC (2000)
[9] In 1990 US $
[10] Problematic as based on Market Exchange Rates
[11] For example, many integrated assessment models – details in Chapter 7

3.2 Water

People will feel the impact of climate change most strongly through changes in the distribution of water around the world and its seasonal and annual variability.

Water is an essential resource for all life and a requirement for good health and sanitation. It is a critical input for almost all production and essential for sustainable growth and poverty reduction.[12] The location of water around the world is a critical determinant of livelihoods. Globally, around 70% of all freshwater supply is used for irrigating crops and providing food. 22% is used for manufacturing and energy (cooling power stations and producing hydro-electric power), while only 8% is used directly by households and businesses for drinking, sanitation, and recreation.[13]

Climate change will alter patterns of water availability by intensifying the water cycle.[14] Droughts and floods will become more severe in many areas. There will be more rain at high latitudes, less rain in the dry subtropics, and uncertain but probably substantial changes in tropical areas.[15] Hotter land surface temperatures induce more powerful evaporation and hence more intense rainfall, with increased risk of flash flooding.

Differences in water availability between regions will become increasingly pronounced. Areas that are already relatively dry, such as the Mediterranean basin and parts of Southern Africa and South America, are likely to experience further decreases in water availability, for example several (but not all) climate models predict up to 30% decrease in annual runoff in these regions for a 2°C global temperature rise (Figure 3.2) and 40 – 50% for 4°C.[16] In contrast, South Asia and parts of Northern Europe and Russia are likely to experience increases in water availability (runoff), for example a 10 – 20% increase for a 2°C temperature rise and slightly greater increases for 4°C, according to several climate models.

These changes in the annual volume of water each region receives mask another critical element of climate change – its impact on year-to-year and seasonal variability. An increase in annual river flows is not necessarily beneficial, particularly in highly seasonal climates, because: (1) there may not be sufficient storage to hold the extra water for use during the dry season,[17] and (2) rivers may flood more frequently.[18] In dry regions, where runoff one-year-in-ten can be less than 20% of the average annual amount, understanding the impacts of climate change on variability of water supplies is perhaps even more crucial. One recent study from the Hadley Centre predicts that the proportion of land area experiencing severe droughts at any one time will increase from around 10% today to 40% for a warming of 3 to 4°C, and the proportion of land area experiencing extreme droughts will increase from 3% to 30%.[19] In Southern Europe, serious droughts may occur every 10 years with a 3°C rise in global temperatures instead of every 100 years if today's climate persisted.[20]

---

[12] Grey and Sadoff (2006) make a strong case for water resources being at the heart of economic growth and development. They show how in the late 19th and early 20th centuries, industrialised countries invested heavily in water infrastructure and institutions to facilitate strong economic growth. In least developed economies, climate variability and extremes are often quite marked, while the capacity to manage water is generally more limited.
[13] World Water Development Report (2006)
[14] Further detail in Chapter 1 - rising temperatures increase the water holding capacity of the air, so that more water will evaporate from the land in dry areas of the world. But where it rains, the water will fall in more intense bursts.
[15] At the same time, rising carbon dioxide levels will cause plants to use less water (a consequence of the carbon fertilisation effect – see Box 3.4 later) and this could increase water availability in some areas. Gedney *et al.* (2006) found that suppression of plant transpiration due to the direct effects of carbon dioxide on the closure of plant stomata (the pores on the leaves of plants) could explain a significant amount of the increase in global continental runoff over the 20th century.
[16] From Arnell (2006a); runoff, the amount of water that flows over the land surface, not only represents potential changes in water availability to people, but also provides a useful indication of whether communities will need to invest in infrastructure to help manage patterns of water supply (more details in Box 3.3).
[17] Arnell (2006a)
[18] Milly *et al.* (2002)
[19] Burke *et al.* (2006) using the Hadley Centre climate model (HadCM3). Drought was assessed with the Palmer Drought Severity Index (PDSI), with severe and extreme droughts classed as PDSI of less than 3.3 and 4.0, respectively.
[20] Lehner *et al.* (2001)

As the water cycle intensifies, billions of people will lose or gain water. Some risk becoming newly or further water stressed, while others see increases in water availability. Seasonal and annual variability in water supply will determine the consequences for people through floods or droughts.

Around one-third of today's global population live in countries experiencing moderate to high water stress, and 1.1 billion people lack access to safe water (Box 3.3 for an explanation of water stress). Water stress is a useful indicator of water availability but does not necessarily reflect access to safe water. Even without climate change, population growth by itself may result in several billion more people living in areas of more limited water availability.

The effects of rising temperatures against a background of a growing population are likely to cause changes in the water status of billions of people. According to one study, temperature rises of 2°C will result in 1 – 4 billion people experiencing growing water shortages, predominantly in Africa, the Middle East, Southern Europe, and parts of South and Central America (Figure 3.3).[21] In these regions, water management is already crucial for their growth and development. Considerably more effort and expense will be required on top of existing practices to meet people's demand for water. At the same time, 1 – 5 billion people, mostly in South and East Asia, may receive more water.[22] However, much of the extra water will come during the wet season and will only be useful for alleviating shortages in the dry season if storage could be created (at a cost). The additional water could also give rise to more serious flooding during the wet season.

Melting glaciers and loss of mountain snow will increase flood risk during the wet season and threaten dry-season water supplies to one-sixth of the world's population (over one billion people today).

Climate change will have serious consequences for people who depend heavily on glacier meltwater to maintain supplies during the dry season, including large parts of the Indian sub-continent, over quarter of a billion people in China, and tens of millions in the Andes.[23] Initially, water flows may increase in the spring as the glacier melts more rapidly. This may increase the risk of damaging glacial lake outburst floods, especially in the Himalayas,[24] and also lead to shortages later in the year. In the long run dry-season water will disappear permanently once the glacier has completely melted. Parts of the developed world that rely on mountain snowmelt (Western USA, Canadian prairies, Western Europe) will also have their summer water supply affected, unless storage capacity is increased to capture the "early water".

In the Himalaya-Hindu Kush region, meltwater from glaciers feeds seven of Asia's largest rivers, including 70% of the summer flow in the Ganges, which provides water to around 500 million people. In China, 23% of the population (250 million people) lives in the western region that depends principally on glacier meltwater. Virtually all glaciers are showing substantial melting in China, where spring stream-flows have advanced by nearly one month since records began. In the tropical Andes in South America, the area covered by glaciers has been reduced by nearly one-quarter in the past 30 years. Some small glaciers are likely to disappear completely in the next decade given current trends.[25] Many large cities such as La Paz,

---

[21] Warren *et al.* (2006) have prepared these results, based on the original analysis of Arnell (2004) for the 2080s. The results are based on hydrology models driven by monthly data from five different climate models. The results do not include adaptation and thus only represent "potential water stress".

[22] The large ranges come about from differences in the predictions of the five different climate models – particularly for tropical areas where the impacts are uncertain due to the dominant influence of the El Niño and the monsoon and the difficulty of predicting interactions with climate change.

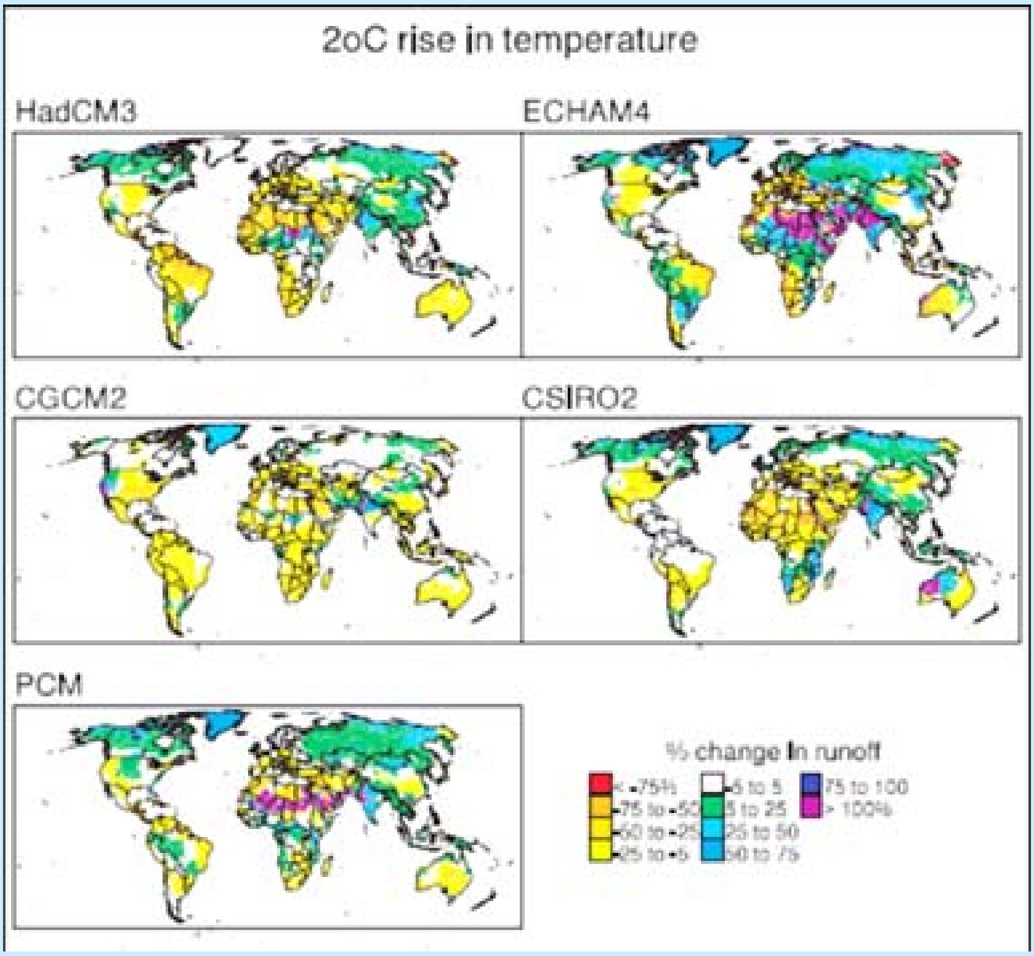
[23] Barnett *et al.* (2005) have comprehensively reviewed the glacier/water supply impacts. There are 1 billion people in snowmelt regions today, and potentially 1.5 billion by 2050. In a warmer world, runoff from snowmelt will occur earlier in the spring or winter, leading to reduced flows in the summer and autumn when additional supplies will be most needed.

[24] Nepal is particularly vulnerable to glacial lake outburst floods - – catastrophic discharges of large volumes of water following the breach of the natural dams that contain glacial lakes (described in Agrawala *et al.* 2005). The most significant flood occurred in 1985. A surge of water and debris up to 15 m high flooded down the Bhote Koshi and Dudh Koshi rivers. At its peak the discharge was 2000 m^3/s, up to four times greater than the maximum monsoon flood level. The flood destroyed the almost-completed Namche Small Hydro Project (cost $1 billion), 14 bridges, many major roads and vast tracts of arable land.

[25] Reported in Coudrain *et al.* (2005)

Lima and Quito and up to 40% of agriculture in Andean valleys rely on glacier meltwater supplies. Up to 50 million people in this region will be affected by loss of dry-season water.[26]

Figure 3.2 Changes in runoff with five different climate models



Source: Warren *et al.* (2006) analysing data from Arnell (2004) and Arnell (2006a)

Note: Runoff refers to the amount of water that flows over the land surface. Typically this water flows in channels such as streams and rivers, but may also flow over the land surface directly. It provides a measure of potential water availability (see Box 3.3).

[26] Nagy *et al.* (2006)

Box 3.3 Meaning of water stress metrics

Water is essential for human existence and all other forms of life. Over half of the world's drinking water is taken directly from rivers or reservoirs (natural or man-made), and the rest from groundwater. Water supply is determined by runoff – the amount of water that flows over the land surface. Typically this water flows in channels such as streams and rivers, but may also flow over the land surface directly.

Water stress is a useful indicator of water availability but does not necessarily reflect access to safe water. The availability of water resources in a watershed can be calculated by dividing long-term average annual runoff (or "renewable resource") by the number of people living in the watershed.[27] A country experiences *water scarcity (or "severe water stress")* when supply is below 1000 m^3 per person per year and *absolute scarcity (or "extreme water stress")* when supply is below 500m^3 per person per year. The thresholds are based loosely on average annual estimates of water requirements in the household, agricultural, industrial and energy sectors, and the needs of the environment.

For comparative purposes, the basic water requirement for personal human needs, excluding that used directly for growing food, is around 50 Litres (L) per person per day or 18.25 m^3 per person per year which includes allowances for drinking (2 - 5 L per person per day), sanitation (20 L per person per day), bathing (15 L per person per day), and food preparation (10 L per person per day). This does *not* include any allowance for growing food, industrial uses or the environment, which constitute the bulk of the use (see next point).[28]

The threshold for water scarcity is considerably higher than the basic water requirement for three reasons:

- Much of the water available to communities is used for purposes other than direct human consumption. Globally, the largest user of water is irrigated agriculture, representing 70% of present freshwater withdrawals. Industry accounts for 22% through manufacturing and cooling of thermoelectric power generation, although much of this is returned to the water system but at higher temperature. Domestic, municipal and service industry use accounts for just 8% of global water use. The proportions of water used in each sector can vary considerably by country. For example in Europe, water used for domestic, municipal and service industries is a very high proportion of total demand. Agriculture in large parts of Asia and Africa is rain-fed and does not rely on irrigation and storage infrastructure.
- Not all river flows are available for use (some flows occur during floods, and some is used by ecosystems). On average, approximately 30% of river flows occur as non-captured flood flows, and freshwater ecosystem use ranges between 20 and 50% of average flows. Taken together, 50 - 80% of average flow is unavailable to humans, meaning that a threshold of 1000 m^3 per person per year of average flows translates into 200 to 500 m^3/person/year *available* flows.
- The 1000 m^3 per person per year is an annual average and does not reflect year-to-year variability. In dry regions, runoff one-year-in-ten can be less than one-fifth the average, so that less than 200 m^3 would be available per person even before other uses are taken into account.

Water availability per person is only one indicator of potential exposure to stress. Some "stressed" watersheds will have effective management systems and water pricing in place to provide adequate supplies (e.g. through storage), while other watersheds with more than 1000 m^3 per person per year may experience severe water shortages because of lack of access to water.

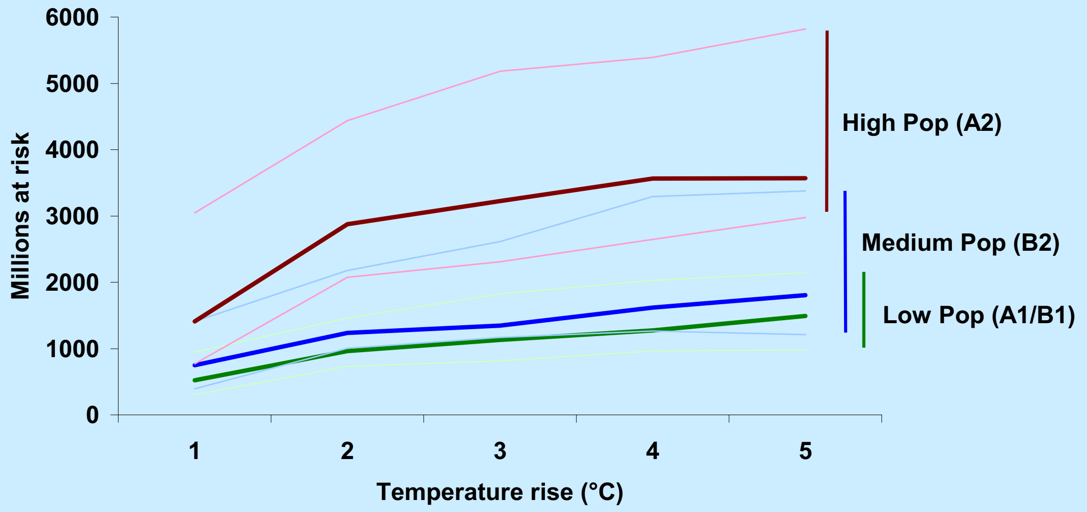
Source: Prepared with assistance from Prof Nigel Arnell, Tyndall Centre and University of Southampton

---

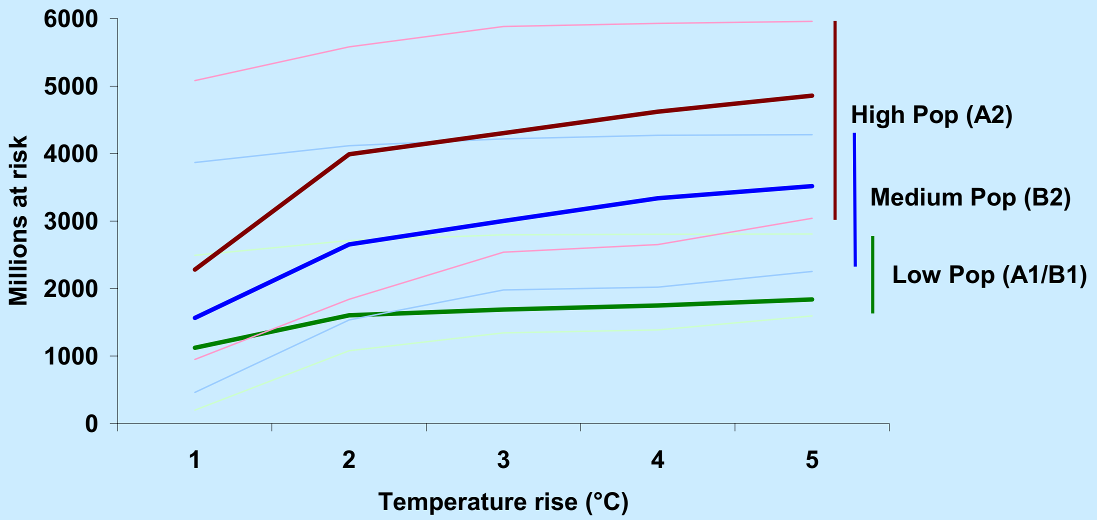
[27] Based on the work of Falkenmark *et al.* 1989, water availability per person per year is the most frequently used measure of water resource availability. The UN has widely adopted this measure, for which data are readily available. The next most frequently used measure is the ratio of withdrawals to availability, but this requires reliable estimates of actual and, most crucially, future withdrawals.
[28] Based on work of Gleick (1996). Actual usage varies considerably, depending on water availability, price, and cultural preferences (domestic consumption in UK is around 170 L per person per day; in large parts of Africa it is less than 20 L per person per day).

Figure 3.3 Changes in millions at risk of water stress with increasing global temperature

a) Increased water stress



b) Decreased water stress



Source: Warren *et al.* (2006) analysing data from Arnell (2004)

Note: Lines represent different population futures for the <u>*2080s*</u>*: green – low population (7 billion), blue – medium population (10 billion), red – high population (15 billion). The thick lines show the average based on six climate models, and the thin lines the upper and lower bounds. "Millions at risk of water stress" is defined as a threshold when a population has less than 1000 m^3 per person per day (more details in Box 3.3). "Increased stress" includes people becoming water stressed who would not have been and those whose water stress worsens because of climate change. "Decreased stress" includes people who cease to become water stressed because of climate change and those whose water stress situation improves (if not to take them out of water stress completely). These aggregate figures mask the importance of annual and seasonal variability in water supply and the potential role of water management to reduce stress, but often at considerable cost.*

3.3 Food

In tropical regions, even small amounts of warming will lead to declines in yield. In higher latitudes, crop yields may increase initially for moderate increases in temperature but then fall. Higher temperatures will lead to substantial declines in cereal production around the world, particularly if the carbon fertilisation effect is smaller than previously thought, as some recent studies suggest.

Food production will be particularly sensitive to climate change, because crop yields depend in large part on prevailing climate conditions (temperature and rainfall patterns). Agriculture currently accounts for 24% of world output, employs 22% of the global population, and occupies 40% of the land area. 75% of the poorest people in the world (the one billion people who live on less than $1 a day) live in rural areas and rely on agriculture for their livelihood.[29]

Low levels of warming in mid to high latitudes (US, Europe, Australia, Siberia and some parts of China) may improve the conditions for crop growth by extending the growing season[30] and/or opening up new areas for agriculture. Further warming will have increasingly negative impacts – the classic "hill function" (refer back to Box 3.1) - as damaging temperature thresholds are reached more often and water shortages limit growth in regions such as Southern Europe and Western USA.[31] High temperature episodes can reduce yields by up to half if they coincide with a critical phase in the crop cycle like flowering (Figure 3.4).[32]

The impacts of climate change on agriculture depend crucially on the size of the "carbon fertilisation" effect (Box 3.4). Carbon dioxide is a basic building block for plant growth. Rising concentrations in the atmosphere may enhance the initial benefits of warming and even offset reductions in yield due to heat and water stress. Work based on the original predictions for the carbon fertilisation effect suggests that yields of several cereals (wheat and rice in particular) will increase for 2 or 3°C of warming globally, according to some models, but then start to fall once temperatures reach 3 or 4°C.[33] Maize shows greater declines in yield with rising temperatures because its different physiology makes it less responsive to the direct effects of rising carbon dioxide. Correspondingly, world cereal production only falls marginally (1 – 2%) for warming up to 4°C (Box 3.4).[34] But the latest analysis from crops grown in more realistic field conditions suggests that the effect is likely to be no more than half that typically included in crop models.[35] When a weak carbon fertilisation effect is used, worldwide cereal production declines by 5% for a 2°C rise in temperature and 10% for a 4°C rise. By 4°C, entire regions may be too hot and dry to grow crops, including parts of Australia. Agricultural collapse across large areas of the world is possible at even higher temperatures (5 or 6°C) but clear empirical evidence is still limited.

---

[29] FAO World Agriculture report (Bruinsma 2003 ed.)
[30] Plants also develop faster at warmer temperatures such that the duration from seedling emergence to crop harvest becomes shorter as temperatures warm, allowing less time for plant growth. This effect varies with both species and cultivar. With appropriate selection of cultivar, effective use of the extended growing season can be made.
[31] Previous crop studies use a quadratic functional form, where yields are increasing in temperature up to an "optimal" level when further temperature increases become harmful (for example Mendelsohn *et al.* 1994). A crucial implicit assumption behind the quadratic functional form is symmetry around the optimum: temperature deviations above and below the "optimal" level give equivalent yield reductions. However, recent studies (e.g. Schlenker and Roberts 2006) have shown that the relationship is highly asymmetric, where temperature increases above the "optimal" level are much more harmful than comparable deviations below it. This has strong implications for climate change, as continued temperature increases can result in accelerating yield reductions.
[32] Evidence reviewed in Slingo *et al.* (2005); Ciais *et al.* (2005)
[33] The impacts depend crucially on the distribution of warming over land (Chapter 1). In general, higher latitudes and continental regions will experience temperature increases significantly greater than the global average. For a global average warming of around 4°C, the oceans and coasts generally warm by around 3°C, the mid-latitudes warm by more than 5°C and the poles by around 8°C.
[34] Warren *et al.* (2006) have prepared this analysis, based on the original work of Parry *et al.* (2004). More detail on method and assumptions are set out in Box 3.4. Production declines less than yields with increasing temperature because more land area at higher latitudes becomes more suitable for agriculture.
[35] New analysis by Long *et al.* (2006) showed that the high-end estimates (25 – 30%) were largely based on studies of crops grown in greenhouses or field chambers, while analysis of studies of crops grown in near-field conditions suggest that the benefits of carbon dioxide may be significantly less, e.g. no more than half.

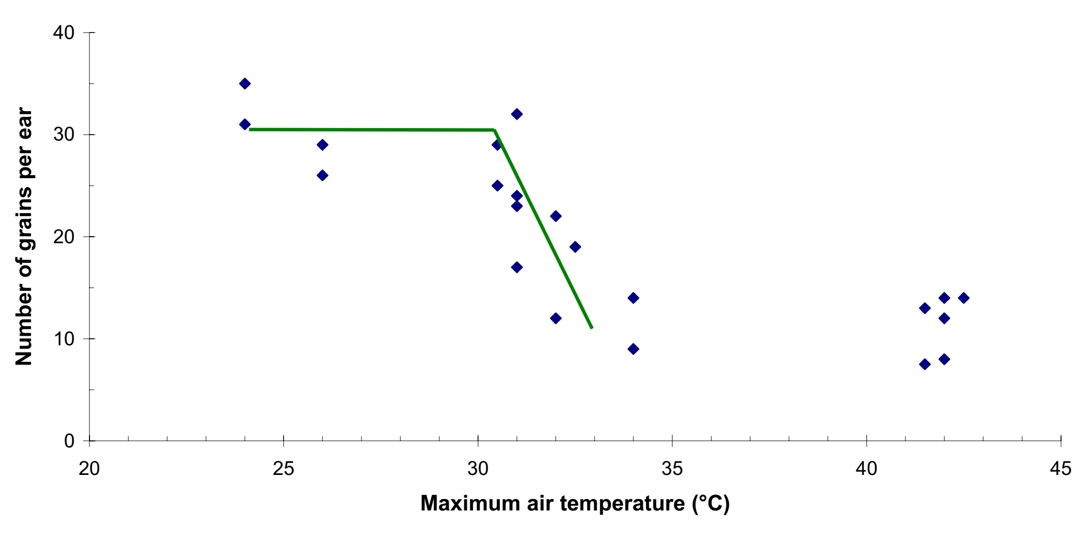
While agriculture in higher-latitude developed countries is likely to benefit from moderate warming (2 – 3°C), even small amounts of climate change in tropical regions will lead to declines in yield. Here crops are already close to critical temperature thresholds[36] and many countries have limited capacity to make economy-wide adjustments to farming patterns (Figure 3.5). The impacts will be strongest across Africa and Western Asia (including the Middle East), where yields of the predominant regional crops may fall by 25 – 35% (weak carbon fertilisation) or 15 – 20% (strong carbon fertilisation) once temperatures reach 3 or 4°C. Maize-based agriculture in tropical regions, such as parts of Africa and Central America, is likely to suffer substantial declines, because maize has a different physiology to most crops and is less responsive to the direct effects of rising carbon dioxide.[37]

Many of the effects of climate change on agriculture will depend on the degree of adaptation (see Part V), which itself will be determined by income levels, market structure, and farming type, such as rain-fed or irrigated.[38] Studies that take a more optimistic view of adaptation and assume that a substantial amount of land at higher latitudes becomes suitable for production find more positive effects of climate change on yield.[39] But the transition costs are often ignored and the movement of population required to make this form of adaptation a reality could be very disruptive. At the same time, many existing estimates do not include the impacts of short-term weather events, such as floods, droughts and heatwaves. These have only recently been incorporated into crop models, but are likely to have additional negative impacts on crop production (Table 3.2). Expansion of agricultural land at the expense of natural vegetation may itself exert additional effects on local climates with tropical deforestation leading to rainfall reductions because of less moisture being returned to the atmosphere once trees are removed.[40]

[36] The optimum temperature for crop growth is typically around 25 - 30°C, while the lethal temperature is usually around 40°C.
[37] Other staple crops in Africa (millet and sorghum) are also relatively unresponsive to the carbon fertilisation effect. They all show a small positive response because they require less water to grow.
[38] Types of adaptation discussed by Parry *et al.* (2005)
[39] For example Fischer *et al.* (2005)
[40] These effects are not yet routinely considered in climate models or impacts studies (Betts 2005).

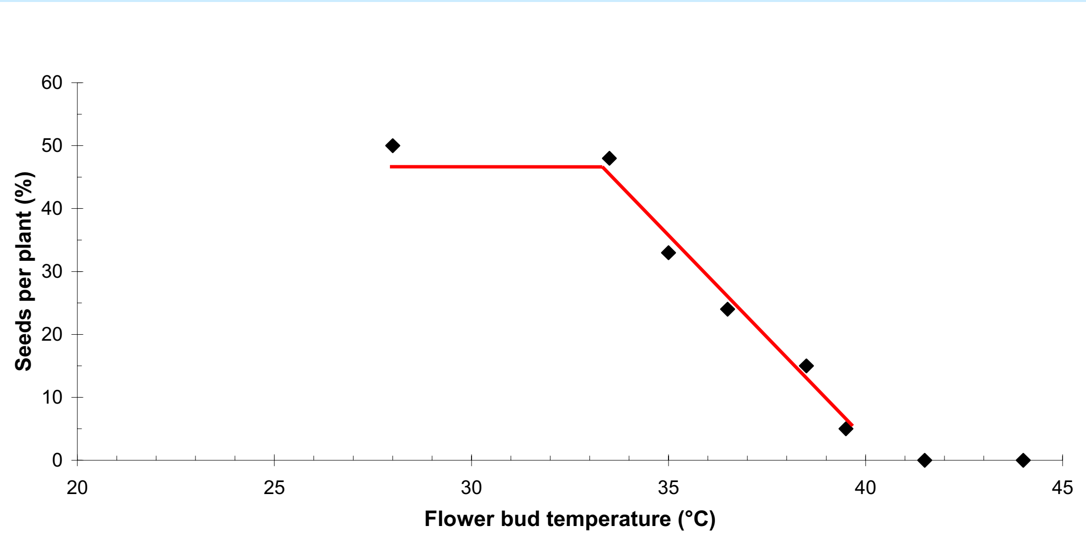
Figure 3.4 Yield loss caused by high temperature in a cool-season crop (wheat) and a tropical crop (groundnut)

a) Wheat in the UK



Source: Wheeler *et al.* (1996)

b) Groundnut in India



Source: Vara Prasad *et al.* (2001)

Notes: Figures show how indicators of crop yield (y-axis) change with increases in daily maximum temperature during flowering (x-axis). In both cases, crops show sharp declines in yield at a threshold maximum temperature.

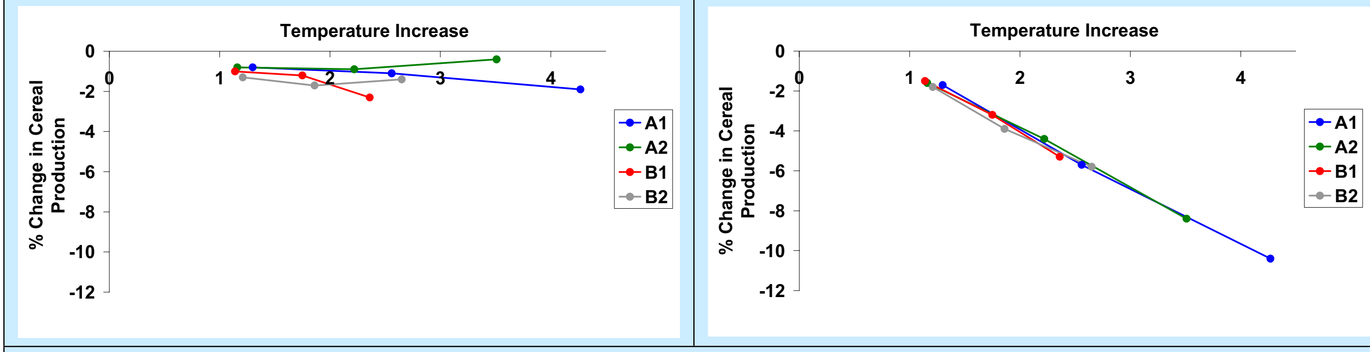
Box 3.4 Agriculture and the carbon fertilisation effect

Carbon dioxide is a basic building block for crop growth. Rising concentrations in the atmosphere will have benefits on agriculture – both by stimulating photosynthesis and decreasing water requirements (by adjusting the size of the pores in the leaves). But the extent to which crops respond depends on their physiology and other prevailing conditions (water availability, nutrient availability, pests and diseases).

Until recently, research suggested that the positive benefits of increasing carbon dioxide concentrations might compensate for the negative effects of rising mean temperatures (namely shorter growing season and reduced yields). Most crop models have been based on hundreds of experiments in greenhouses and field-chambers dating back decades, which suggest that crop yields will increase by 20 – 30% at 550 ppm carbon dioxide. Even maize, which uses a different system for photosynthesis and does not respond to the direct effects of carbon dioxide, shows increases of 18 – 25% in greenhouse conditions due to improved efficiency of water use. But new analysis by Long *et al.* (2006) showed that the high-end estimates were largely based on studies of crops grown in greenhouses or field chambers, whereas analysis of studies of crops grown in near-field conditions suggest that the benefits of carbon dioxide may be significantly less – an 8 – 15% increase in yield for a doubling of carbon dioxide for responsive species (wheat, rice, soybean) and no significant increase for non-responsive species (maize, sorghum).

These new findings may have very significant consequences for current predictions about impacts of climate change on agriculture. Parry *et al.* (2004) examined the impacts of increasing global temperatures on cereal production and found that significant global declines in productivity could occur if the carbon fertilisation is small (figures below). Regardless of the strength of the carbon fertilisation effect, higher temperatures are likely to become increasingly damaging to crops, as droughts intensify and critical temperature thresholds for crop production are reached more often.

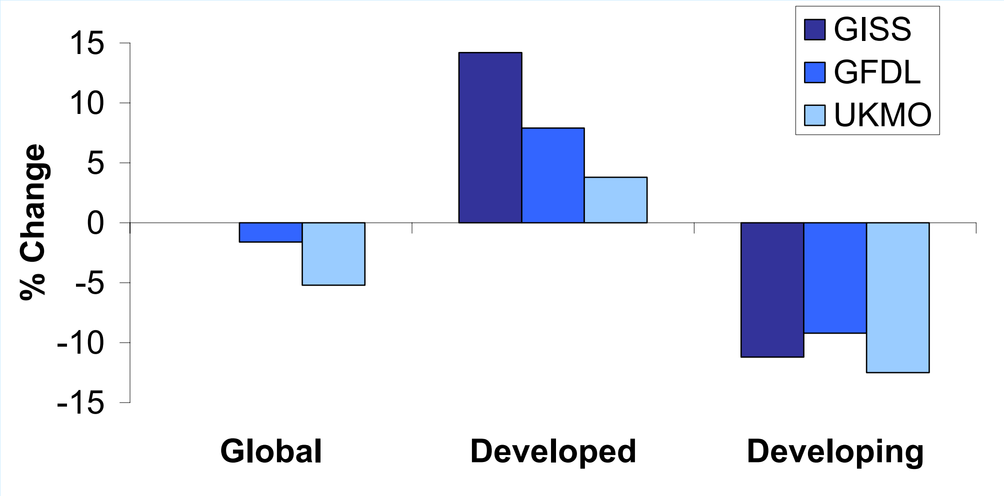
a) Strong carbon fertilisation | **b) Weak carbon fertilisation**



Source: Warren *et al.* (2006) analysing data from Parry *et al.* (2004)

Note: Percent changes in production are relative to what they would be in a future with no climate change but with socio-economic development. Lines represent different socio-economic scenarios developed by the IPCC. The results are based on crop models driven by monthly data from the Hadley Centre climate model, which shows greater declines in yield than two other climate models (GISS, GFDL) - see comparison in Figure 3.5. The research did not take account of the impacts of extremes, which could be significant (Box 3.5). The work assumed mostly farm-level adaptation in developing countries, but some economy-wide adaptation in developed countries (details in Figure 3.5).

Figure 3.5 Change in cereal production in developed and developing countries for a doubling of carbon dioxide levels (equivalent to around 3°C of warming in models used) simulated with three climate models (GISS, GFDL and UKMO Hadley Centre)



Source: Parry *et al.* (2005) analysing data from Rosenzweig and Parry (1994)

Note: Percent changes in production are relative to what they would be in a future with no climate change. Overall changes are relatively robust to different model outputs, but regional patterns differ depending on the model's rainfall patterns – more details in Fischer et al. (2005). The work assumed mostly farm-level adaptation in developing countries but some economy-wide adaptation in developed countries. The work also assumed a strong carbon fertilisation effect - 15 – 25% increase in yield for a doubling of carbon dioxide levels for responsive crops (wheat, rice, soybean) and a 5 – 10% increase for non-responsive crops (maize). These are about twice as high as the latest field-based studies suggest – see Box 3.4 for more detail.

Table 3.2 Climate change will have a wide range of effects on the environment, which could have knock-on consequences for food production. The combined effect of several factors could be very damaging.

Loss of essential species	Climate change will affect species' distributions and abundance (see Section 3.7), which in turn will threaten the viability of species that are essential for sustained agricultural outputs, including native pollinators for crops and soil organisms that maintain the productivity and fertility of land. Pollination is essential for the reproduction of many wild flowers and crops and its economic value worldwide has been estimated at $30 - 60 billion.
Increased incidence of flooding	Flood losses to US corn production from waterlogging could double in the next thirty years, causing additional damages totalling an estimated $3 billion per year (Rosenzweig *et al.* 2002).
Forest and crop fires	The 2003 European heatwave and drought led to severe wildfires across Portugal, Spain and France, resulting in total losses in forestry and agriculture of $15 billion (Munich Re 2004).
Climate-induced outbreaks of pests and diseases	The northward spread of Bluetongue virus in Europe, a devastating disease of sheep, has been linked to increased persistence of the virus in warmer winters and the northward expansion of the midge vector (Purse *et al.* 2005).
Rising surface ozone	Fossil fuel burning increases concentrations of nitrogen oxide in the atmosphere, which increase levels of ozone at the surface in the presence of sunlight and rising temperatures. Ozone is toxic to plants at concentrations as low as 30 ppb (parts per billion), but these effects are rarely included in future predictions. Many rural areas in continental Europe and Midwestern USA are forecast to see increases in average ozone concentrations of around 20% by the middle of the century, even though peak episodes may decline (Long *et al.* 2006).

Declining crop yields are likely to leave hundreds of millions without the ability to produce or purchase sufficient food, particularly in the poorest parts of the world.

Around 800 million people are currently at risk of hunger (~ 12% of world's population),[41] and malnutrition causes around 4 million deaths annually, almost half in Africa.[42] According to one study, temperature rises of 2 to 3°C will increase the people at risk of hunger, potentially by 30 - 200 million (if the carbon fertilisation effect is small) (Figure 3.6).[43] Once temperatures increase by 3°C, 250 - 550 million additional people may be at risk – over half in Africa and Western Asia, where (1) the declines in yield are greatest, (2) dependence on agriculture highest, and (3) purchasing power most limited. If crop responses to carbon dioxide are stronger, the effects of warming on risk of hunger will be considerably smaller. But at even higher temperatures, the impacts are likely to be damaging regardless of the carbon fertilisation effect, as large parts of the world become too hot or too dry for agricultural production, such as parts of Africa and even Western Australia.

Ocean acidification, a direct result of rising carbon dioxide levels, will have major effects on marine ecosystems, with possible adverse consequences on fish stocks.

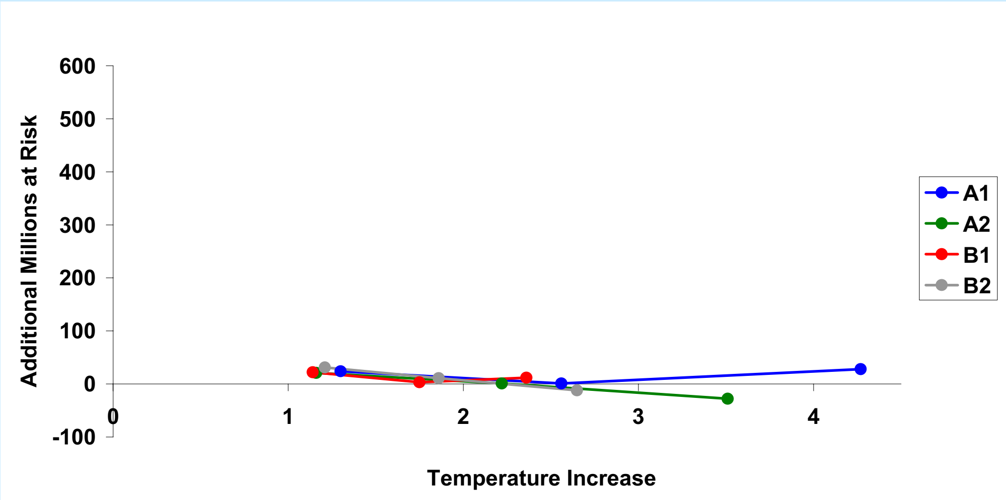
For fisheries, information on the likely impacts of climate change is very limited – a major gap in knowledge considering that about one billion people worldwide (one-sixth of the world's population) rely on fish as their primary source of animal protein. While higher ocean temperatures may increase growth rates of some fish, reduced nutrient supplies due to warming may limit growth.

Ocean acidification is likely to be particularly damaging. The oceans have become more acidic in the past 200 years, because of chemical changes caused by increasing amounts of carbon dioxide dissolving in seawater.[44] If global emissions continue to rise on current trends, ocean acidity is likely to increase further, with pH declining by an additional 0.15 units if carbon dioxide levels double (to 560 ppm) relative to pre-industrial and an additional 0.3 units if carbon dioxide levels treble (to 840 ppm).[45] Changes on this scale have not been experienced for hundreds of thousands of years and are occurring at an extremely rapid rate. Increasing ocean acidity makes it harder for many ocean creatures to form shells and skeletons from calcium carbonate. These chemical changes have the potential to disrupt marine ecosystems irreversibly - at the very least halting the growth of corals, which provide important nursery grounds for commercial fish, and damaging molluscs and certain types of plankton at the base of the food chain. Plankton and marine snails are critical to sustaining species such as salmon, mackerel and baleen whales, and such changes are expected to have serious but as-yet-unquantified wider impacts.

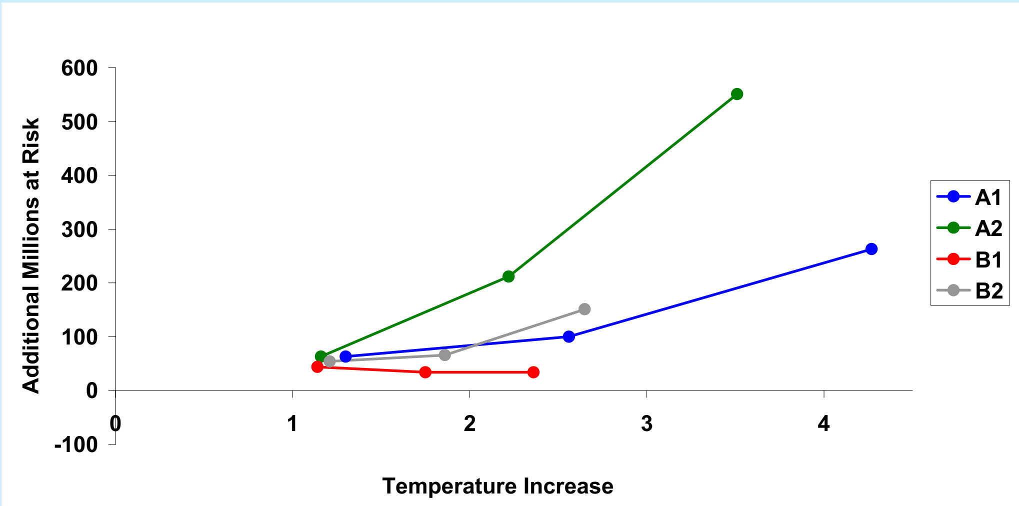
[41] According to Parry *et al.* (2004) people at risk of hunger are defined as the population with an income insufficient either to produce or procure their food requirements, estimated by FAO based on energy requirements deduced from an understanding of human physiology (1.2 – 1.4 times basal metabolic rate as minimum maintenance requirement to avoid undernourishment).
[42] Links between changes in income and mortality are explored in Chapter 5.
[43] Warren *et al.* (2006) have prepared these results, based on the original analysis of Parry *et al.* (2004) (more details in Box 3.6). These figures assume future socio-economic development, but no carbon fertilisation effect. There is likely to be some positive effect of rising levels of carbon dioxide (if not as much as assumed by most studies).
[44] Turley *et al.* (2006) - Ocean pH has changed by 0.1 pH unit over the last 200yrs. As pH is on a log scale, this corresponds to a 30% increase in the hydrogen ion concentration, the main component of acidity.
[45] Royal Society (2005) – a drop of 0.15 pH units corresponds to a 40% increase in the hydrogen ion concentration, the main component of acidity. A drop of 0.3 pH units corresponds to a doubling of hydrogen ion concentration.

Figure 3.6 Changes in millions at risk of hunger with increasing global temperature

a) Strong carbon fertilisation



b) Weak carbon fertilisation



Source: Warren *et al.* (2006) analysing data from Parry *et al.* (2004)

Note: Lines represent different socio-economic growth paths and emissions scenarios for the <u>*2080s*</u> *developed by the IPCC (details in Box 3.2). People at risk of hunger are defined as the population with an income insufficient either to produce or procure their food requirements, estimated by the Food and Agriculture Organisation (FAO) based on energy requirements deduced from an understanding of human physiology (1.2 – 1.4 times basal metabolic rate as minimum maintenance requirement to avoid undernourishment). There are currently around 800 million people malnourished based on this definition. The IIASA Basic Linked System (BLS) world food trade model was used to examine impacts of changes in crop yields on food distribution and hunger around the world, determined both by regional agricultural production and GDP per capita (a measure of purchasing power for any additional food required). The model assumes economic growth in different regions following the IPCC scenarios. "Strong carbon fertilisation" refers to runs where the fertilisation effect was about twice as high as the latest field-based studies suggest (see Box 3.4 and Long et al. 2006), while "weak carbon fertilisation" includes a minimal amount.*

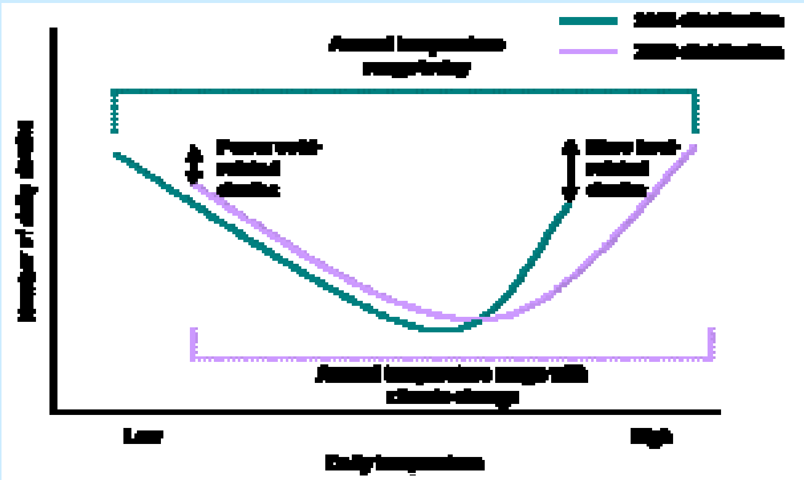
3.4 Health

Climate change will increase worldwide deaths from malnutrition and heat stress. Vector-borne diseases such as malaria and dengue fever could become more widespread if effective control measures are not in place. In higher latitudes, cold-related deaths will decrease.

Climate-sensitive aspects of human health make up a significant proportion of the global disease burden and may grow in importance.[46] The health of the world's population has improved remarkably over the past 50 years, although striking disparities remain.[47] Slum populations in urban areas are particularly exposed to disease, suffering from poor air quality and heat stress, and with limited access to clean water.

In some tropical areas, temperatures may already be at the limit of human tolerance. Peak temperatures in the Indo-Gangetic Plain often already exceed 45°C before the arrival of the monsoon.[48] In contrast, in northern latitudes (Europe, Russia, Canada, United States), global warming may imply fewer deaths overall, because more people are saved from cold-related death in the winter than succumb to heat-related death in the summer (Figure 3.7; more detail in Chapter 5).[49] In cities heatwaves will become increasingly dangerous, as regional warming together with the urban heat island effect (where cities concentrate and retain heat) leads to extreme temperatures and more dangerous air pollution incidents (see Box 6.4 in Chapter 5).

Figure 3.7 Stylised U-shaped human mortality curves as a function of temperature.



Source: Redrawn from McMichael et al. (2006).

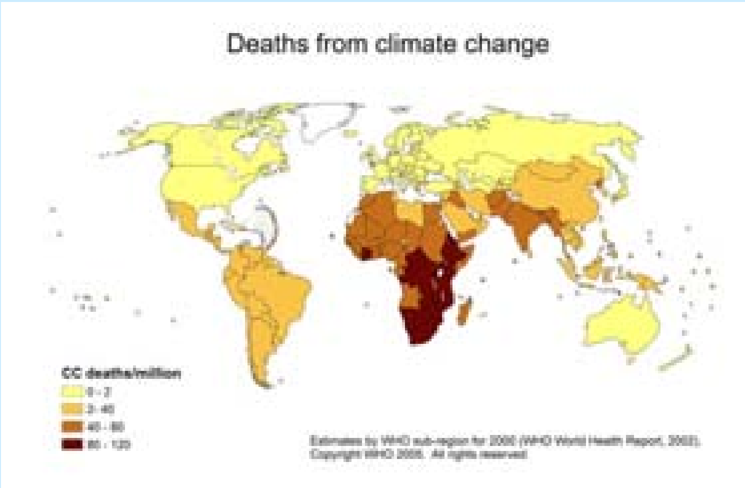
Note: The blue line shows a stylised version of today's distribution of daily temperatures through the year, and the purple line shows a future distribution shifted to the right because of climate change. Deaths increase sharply at both ends of the distribution, because Heatwaves and cold snaps that exceed thresholds for human temperature tolerance become more frequent. With climate change, there will be more heatwaves (in tropical areas or continental cities) but fewer cold snaps (in higher latitudes). The overall shape of the curve is not yet clearly characterised but is crucial because it determines the net effects of decreased deaths from the cold and increased deaths from heatwaves. These costs and benefits will not be evenly distributed around the world.

---

[46] Comprehensively reviewed by Patz *et al.* (2005)
[47] Average life expectancy at birth has increased by 20 years since the 1960s. But in parts of Africa life expectancy has fallen in the past 20 years because of the HIV/AIDS pandemic (McMichael *et al.* 2004).
[48] De *et al.* (2005)
[49] See Tol (2002) for indicative figures for different OECD regions

Climate change will amplify health disparities between rich and poor parts of the world. The World Health Organisation (WHO) estimates that climate change since the 1970s is already responsible for over 150,000 deaths each year through increasing incidence of diarrhoea, malaria and malnutrition, predominantly in Africa and other developing regions (Figure 3.8).[50] Just a 1°C increase in global temperature above pre-industrial could double annual deaths from climate change to at least 300,000 according to the WHO.[51] These figures do not account for any reductions in cold-related deaths, which could be substantial.[52] At higher temperatures, death rates will increase sharply, for example millions more people dying from malnutrition each year.[53] Climate change will also affect health via other diseases not included in the WHO modelling.[54]

Figure 3.8 WHO estimates of extra deaths (per million people) from climate change in 2000



Disease/Illness	Annual Deaths	Climate change component (death / % total)
Diarrhoeal diseases	2.0 million	47,000 / 2%
Malaria	1.1 million	27,000 / 2%
Malnutrition	3.7 million	77,000 / 2%
Cardiovascular disease	17.5 million	Total heat/cold data not provided
HIV/AIDS	2.8 million	No climate change element
Cancer	7.6 million	No climate change element

Source: WHO (2006) based on data from McMichael et al. (2004). The numbers are expected to at least double to 300,000 deaths each year by 2030.

The distribution and abundance of disease vectors are closely linked to temperature and rainfall patterns, and will therefore be very sensitive to changes in regional climate in a warmer world. Changes to mosquito distributions and abundance will have profound impacts on malaria prevalence in affected areas.

[50] Based on detailed analysis by McMichael *et al.* (2004), using existing quantitative studies of climate-health relationships and the UK Hadley Centre GCM (business as usual emissions) to estimate relative changes in a range of climate-sensitive outcomes, including diarrhoea, malaria, dengue fever and malnutrition. Changes in heat- and cold-related deaths were not included in the aggregate estimates of mortality. Climate change contributes 2% to today's climate disease burden (6.8 million deaths annually) and 0.3% to today's total global disease burden.

[51] Projections from Patz *et al.* (2005)

[52] See, for example, Tol (2002) and Bosello *et al.* (2006)

[53] As described earlier, today 800 million people are at risk of hunger and around 4 million of those die from malnutrition each year. Once temperatures increase by 3°C, 200 - 600 million additional people could be at risk (with little carbon fertilisation effect), suggesting 1 – 3 million more dying each year from malnutrition, assuming that the ratio of risk of hunger to mortality from malnutrition remains the same. This ratio will of course change with income status – see Chapter 4 for more detail.

[54] The impacts on human development mediated through changes in income are explored in Chapter 4.

This will be particularly significant in Africa, where 450 million people are exposed to malaria today, of whom around 1 million die each year. According to one study, a 2°C rise in temperature may lead to 40 – 60 million more people exposed to malaria in Africa (9 – 14% increase on present-day), increasing to 70 – 80 million (16 – 19%) at higher temperatures, assuming no change to malaria control efforts.[55] Much of the increase will occur in Sub-Saharan Africa, including East Africa. Some studies suggest that malaria will decrease in parts of West Africa, e.g. taking 25 – 50 million people out of an exposed region, because of reductions in rainfall.[56] Changes in future exposure depend on the success of national and international malaria programmes. Such adaptations are not taken into account in the estimates presented, but the effectiveness of such programmes remains variable.[57] Climate change will also increase the global population exposed to dengue fever, predominantly in the developing world, e.g. 5 – 6 billion people exposed with a 4°C temperature rise compared with 3.5 billion people exposed with no climate change.[58]

Health will be further affected by changes in the water cycle. Droughts and floods are harbingers of disease, as well as causing death from dehydration or drowning.[59] Prolonged droughts will fuel forest fires that release respiratory pollutants, while floods foster growth of infectious fungal spores, create new breeding sites for disease vectors such as mosquitoes, and trigger outbreaks of water-borne diseases like cholera. In the aftermath of Hurricane Mitch in 1998, Honduras recorded an additional 30,000 cases of malaria and 1,000 cases of dengue fever. The toxic moulds left in New Orleans in the wake of Hurricane Katrina continue to create health problems for its population, for example the so-called “Katrina cough”.

3.5 Land

Sea level rise will increase coastal flooding, raise costs of coastal protection, lead to loss of wetlands and coastal erosion, and increase saltwater intrusion into surface and groundwater.

Warming from the last century has already committed the world to rising seas for many centuries to come. Further warming this century will increase this commitment.[60] Rising sea levels will increase the amount of land lost and people displaced due to permanent inundation, while the costs of sea walls will rise approximately as a square of the required height. Coastal areas are amongst the most densely populated areas in the world and support several important ecosystems on which local communities depend. Critical infrastructure is often concentrated around coastlines, including oil refineries, nuclear power stations, port and industrial facilities.[61]

Currently, more than 200 million people live in coastal floodplains around the world, with 2 million Km^2 of land and \$1 trillion worth of assets less than 1-m elevation above current sea level. One-quarter of Bangladesh’s population (~35 million people) lives within the coastal floodplain.[62] Many of the world’s major cities (22 of the top 50) are at risk of flooding from coastal surges, including Tokyo, Shanghai, Hong Kong, Mumbai, Calcutta, Karachi, Buenos Aires, St Petersburg, New York, Miami and London.[63] In almost

[55] Calculations from Warren *et al.* (2006) based on research from Tanser *et al.* (2003), using one of only two models which has been validated directly to account for the observed effect of climate variables on vector and parasite population biology. They assume no increase in population size in the future or change in vulnerability (through effective treatment/prophylaxis). While this assumption of no change in control efforts is not realistic, the results illustrate the potential scale of the problem. The study used the Hadley Centre climate model to estimate regional temperature and rainfall patterns; other models produce different rainfall patterns and therefore may result in different regional patterns for malaria.
[56] Calculations from Warren *et al.* (2006) based on research from Van Lieshout *et al.* (2004), who take into account future population projections and used the Hadley Centre climate model. Similar to Tanser *et al.* (2003), they use the Hadley Centre model and find an increase in malaria exposure in Sub-Saharan Africa, but with slightly fewer people affected (50 million rather than 80 million for a 4°C temperature rise) because of different assumptions about rainfall thresholds.
[57] Malaria in Africa is particularly difficult to control because of the large numbers of mosquitoes spreading the disease, their effectiveness as transmitting the disease, and increasing drug resistance problems. Alternatives can be very effective, but are often much more expensive (WHO 2005).
[58] Hales *et al.* (2002) used a vector-specific model coupled to outputs of two climate models. Their estimates take account of projected population growth to the 2080s, but not any control measures.
[59] Reviewed in Epstein and Mills (2005)
[60] More detail in Chapter 1
[61] See Chapter 6 for discussion of implications for global trade
[62] Ali (2000)
[63] Munich Re (2005)

every case, the city relies on costly flood defences for protection. Even if protected, these cities would lie below sea level with a residual risk of flooding like New Orleans today.

The homes of tens of millions more people are likely to be affected by flooding from coastal storm surges with rising sea levels. People in South and East Asia will be most vulnerable, along with those living on the coast of Africa and on small islands.

Sea level rises will lead to large increases in the number of people whose homes are flooded (Figure 3.9).[64] According to one study that assumes protection levels rise in line with GDP per capita, between 7 – 70 million and 20 – 300 million additional people will be flooded each year by 3 to 4°C of warming causing 20 – 80 cm of sea level rise (low and high population growth assumptions respectively).[65] Upgrading coastal defences further could partially offset these impacts, but would require substantial capital investment and ongoing maintenance. At higher levels of warming and increased rates of sea level rise, the risks will become increasingly serious (more on melting polar ice sheets in Section 3.8).

South and East Asia will be most vulnerable because of their large coastal populations in low-lying areas, such as Vietnam, Bangladesh and parts of China (Shanghai) and India. Millions will also be at risk around the coastline of Africa, particularly in the Nile Delta and along the west coast. Small island states in the Caribbean, and in the Indian and Pacific Oceans (e.g. Micronesia and French Polynesia, the Maldives, Tuvalu) are acutely threatened, because of their high concentrations of development along the coast. In the Caribbean, more than half the population lives within 1.5 Km of the shoreline.

Some estimates suggest that 150 - 200 million people may become permanently displaced by the middle of the century due to rising sea levels, more frequent floods, and more intense droughts.

Today, almost as many people are forced to leave their homes because of environmental disasters and natural resource scarcity as flee political oppression, religious persecution and ethnic troubles (25 million compared with 27 million).[66] Estimates in this area, however, are still problematic. Norman Myers uses conservative assumptions and calculates that climate change could lead to as many as 150 - 200 million environmental refugees by the middle of the century (2% of projected population).[67] This estimate has not been rigorously tested, but it remains in line with the evidence presented throughout this chapter that climate change will lead to hundreds of millions more people without sufficient water or food to survive or threatened by dangerous floods and increased disease. People may also be driven to migrate within a region - Chapter 5 looks in detail at a possible climate-induced shift in population and economic activity from southern regions to northern regions of Europe and the USA.

---

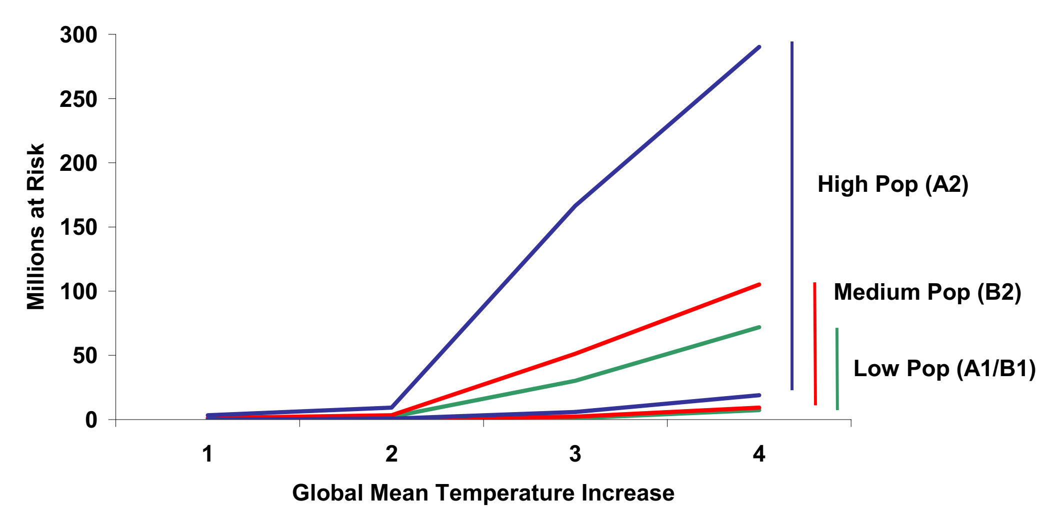
[64] Increased storm intensity could cause similar impacts and will exacerbate the effects of sea level rise – these effects are not included in the impact estimates provided here (see Chapter 6).

[65] Warren *et al.* (2006) have prepared these results, based on the original analysis of Nicholls (2004), Nicholls and Tol (2006) and Nicholls and Lowe (2006) for impacts of sea level rise on populations in 2080s with and without climate change. More details on method are set out in Figure 3.8. "Average annual people flooded" refers to the average annual number of people who experience episodic flooding by storm surge, including the influence of any coastal protection. In some low-lying areas without protection,

[66] International Federation of Red Cross and Red Crescent Societies (2001)

[67] Myers and Kent (1995)

Figure 3.9 Additional millions at risk from coastal flooding



Source: Warren *et al.* (2006) analysing data from Nicholls (2004), Nicholls and Tol (2006) and Nicholls and Lowe (2006)

Notes: Figure shows increase in number of people flooded by storm surge on average each year in the 2080s for different levels of global temperature rise (relative to pre-industrial levels). Results assume that flood defences are upgraded in phase with GDP per capita, but ignoring sea level rise itself. Lines represent different socio-economic futures for the 2080s based on a range of population and growth paths taken from the IPCC: green – A1/B1 low population (7 billion), red – B2 medium population (10 billion), blue – A2 high population (15 billion) (details of population and GDP per capita for each scenario set out in Box 3.2). A richer more populous country will be able to spend more on flood defences, but will have a greater number of people at risk. The impacts are shown for the "transient sea level rise" associated with reaching a particular level of warming, but do not include the consequences of the additional sea level rise that the world would be committed to for a given level of warming (0 – 15 cm for 1°C, 10 – 30 cm for 2°C, 20 – 50 cm for 3°C, 35 – 80 cm for 4°C; more details in Chapter 1). The ranges cover the uncertainties in climate modelling and how much sea level rises for a given change in temperature (based on IPCC Third Assessment Report data from 2001, which may be revised in the Fourth Assessment due in 2007).

3.6 Infrastructure

Damage to infrastructure from storms will increase substantially from only small increases in event intensity. Changes in soil conditions (from droughts or permafrost melting) will influence the stability of buildings.

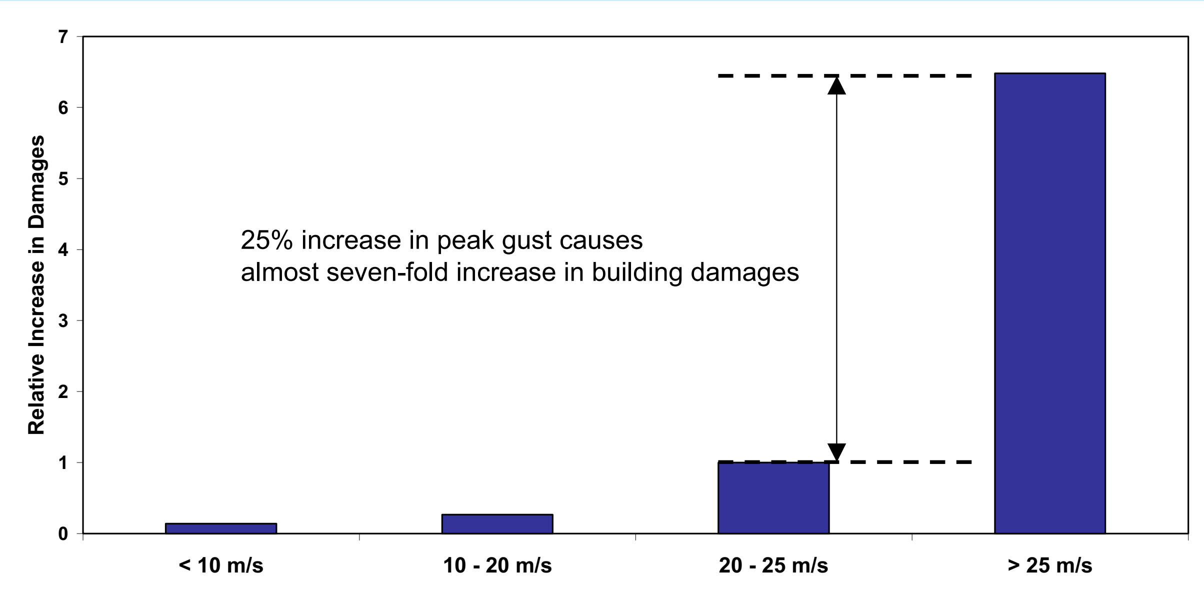
By increasing the amount of energy available to fuel storms (Chapter 1), climate change is likely to increase the intensity of storms. Infrastructure damage costs will increase substantially from even small increases in sea temperatures because: (1) peak wind speeds of tropical storms are a strongly exponential function of temperature, increasing by about 15 - 20% for a 3°C increase in tropical sea surface temperatures;[68] and (2) damage costs typically scale as the cube of wind-speed or more (Figure 3.10).[69] Storms and associated flooding are already the most costly natural disaster today, making up almost 90% of the total losses from natural catastrophes in 2005 ($184 billion from windstorms alone,

[68] Emanuel (1987)
[69] In fact Nordhaus (2006) found that economic damages from hurricanes rise as the ninth power of maximum wind-speed, perhaps as a result of threshold effects, such as water overtopping storm levees.

particularly hurricanes and typhoons).[70] A large proportion of the financial losses fall in the developed world, because of the high value and large amount of infrastructure at risk (more details in Chapter 5).

High latitude regions are already experiencing the effects of warming on previously frozen soil. Thawing weakens soil conditions and causes subsidence of buildings and infrastructure. Climate change is likely to lead to significant damage to buildings and roads in settlements in Canada and parts of Russia currently built on permafrost.[71] The Quinghai-Tibet Railway, planned to run over 500 Km of permafrost, is designed with a complex and costly insulation and cooling system to prevent thawing of the permafrost layer (more details in Chapter 20). However, most of the existing infrastructure is not so well designed to cope with permafrost thawing and land instability.

Figure 3.10 Damage costs increase disproportionately for small increases in peak wind speed



Source: IAG (2005)

3.7 Environment

Climate change is likely to occur too rapidly for many species to adapt. One study estimates that around 15 – 40% of species face extinction with 2°C of warming. Strong drying over the Amazon, as predicted by some climate models, would result in dieback of forest with the highest biodiversity on the planet.

The warming of the 20th century has already directly affected ecosystems. Over the past 40 years, species have been moving polewards by 6 Km on average per decade, and seasonal events, such as flowering or egg-laying, have been occurring several days earlier each decade.[72] Coral bleaching has become increasingly prevalent since the 1980s. Arctic and mountain ecosystems are acutely vulnerable – polar bears, caribou and white spruce have all experienced recent declines.[73] Climate change has already contributed to the extinction of over 1% of the world's amphibian species from tropical mountains.[74]

[70] Munich Re (2006)
[71] Nelson (2003)
[72] Root *et al.* (2005); Parmesan and Yohe (2003)
[73] Arctic Climate Impacts Assessment (2004)
[74] Pounds *et al.* (2006)

Ecosystems will be highly sensitive to climate change (Table 3.4). For many species, the rate of warming will be too rapid to withstand. Many species will have to migrate across fragmented landscapes to stay within their "climate envelope" (at rates that many will not be able to achieve). Migration becomes more difficult with faster rates of warming. In some cases, the "climate envelope" of a species may move beyond reach, for example moving above the tops of mountains or beyond coastlines. Conservation reserves may find their local climates becoming less amenable to the native species. Other pressures from human activities, including land-use change, harvesting/hunting, pollution and transport of alien species around the world, have already had a dramatic effect on species and will make it even harder for species to cope with further warming. Since 1500, 245 extinctions have been recorded across most major species groups, including mammals, birds, reptiles, amphibians, and trees. A further 800 known species in these groups are threatened with extinction.[75]

A warming world will accelerate species extinctions and has the potential to lead to the irreversible loss of many species around the world, with most kinds of animals and plants affected (see below). Rising levels of carbon dioxide have some direct impacts on ecosystems and biodiversity,[76] but increases in temperature and changes in rainfall will have even more profound effects. Vulnerable ecosystems are likely to disappear almost completely at even quite moderate levels of warming.[77] The Arctic will be particularly hard hit, since many of its species, including polar bears and seals, will be very sensitive to the rapid warming predicted and substantial loss of sea ice (more detail in Chapter 5).[78]

- **1°C warming.** At least 10% of land species could be facing extinction, according to one study.[79] Coral reef bleaching will become much more frequent, with slow recovery, particularly in the southern Indian Ocean, Great Barrier Reef and the Caribbean.[80] Tropical mountain habitats are very species rich and are likely to lose many species as suitable habitat disappears.

- **2°C warming.** Around 15 – 40% of land species could be facing extinction, with most major species groups affected, including 25 – 60% of mammals in South Africa and 15 – 25% of butterflies in Australia. Coral reefs are expected to bleach annually in many areas, with most never recovering, affecting tens of millions of people that rely on coral reefs for their livelihood or food supply.[81] This level of warming is expected to lead to the loss of vast areas of tundra and forest – almost half the low tundra and about one-quarter of the cool conifer forest according to one study.[82]

- **3°C warming.** Around 20 – 50% of land species could be facing extinction. Thousands of species may be lost in biodiversity hotspots around the world, e.g. over 40% of endemic species in some

[75] Ricketts *et al.* (2005)

[76] For example, fast-growing tropical tree species show greater growth enhancements with increased carbon dioxide concentrations than slower-growing species and could gain a dominant competitive advantage in tropical forests in the future (Körner 2004).

[77] Reviewed in detail in Hare (2006). These figures are likely to underestimate the impacts of climate change, because many of the most severe effects are likely to come from interactions with factors not taken into account in these calculations, including land use change and habitat fragmentation/loss, spread of invasive species, new pests and diseases, and loss of pollinators. In addition, ecosystem assessments rarely consider the rate of temperature change. It is likely that rates of change exceeding 0.05 – 0.1°C per decade (regional temperature) are more than most ecosystems can withstand, because species cannot migrate polewards fast enough (further details in Warren 2006).

[78] According to the Arctic Climate Impacts Assessment (2004), Arctic ecosystems will be strongly affected by climate change as temperatures here are rising at close to double the global average.

[79] Thomas *et al.* (2004a) – these (and subsequent) estimates of extinction risk are based on calculations of decreases in the availability of areas with suitable climate conditions for species into the future. As suitable areas to support a certain level of biodiversity disappear, species become "committed to extinction" when the average rate of recruitment of adults into the population is less than the average rate of adult mortality. There is likely to be a lag in response depending on the life span of the species in question - short-lived species rapidly disappear from an area while long-lived species can survive as adults for several years. There is a great deal of uncertainty inherent in such estimates of extinction risk (Pearson and Dawson 2003) and alternative modelling approaches have been shown to yield different estimates (Thuiller *et al.* 2004, Pearson *et al.* 2006). However, other studies looking at climate suitability also predict high levels of extinction, for example McClean *et al.* (2005) predict that 25 – 40% of African plan species will lose all suitable climate area with 3°C of warming globally.

[80] Coral bleaching describes the process that occurs when the tiny brightly coloured organisms that feed the main coral (through photosynthesis) leave the skeleton because they become heat-stressed. Bleached corals have significantly higher rates of mortality.

[81] Donner *et al.* (2005)

[82] Leemans and Eichkout (2004)

biodiversity hotspots such as African national parks and Queensland rain forest.[83] Large areas of coastal wetlands will be permanently lost because of sea level rise (up to one-quarter according to some estimates), with acute risks in the Mediterranean, the USA and South East Asia. Mangroves and coral reefs are at particular risk from rapid sea level rise (more than 5 mm per year) and their loss would remove natural coastal defences in many regions. Strong drying over the Amazon, according to some climate models, would result in dieback of forest with the highest biodiversity on the planet.[84]

Temperatures could rise by more than 4 or 5°C if emissions continue unabated, but the full range of consequences at this level of warming have not been clearly articulated to date. Nevertheless, a basic understanding of ecological processes leads quickly to the conclusion that many of the ecosystem effects will become compounded with increased levels of warming, particularly since small shifts in the composition of ecosystems or the timing of biological events will have knock-on effects through the food-chain (e.g. loss of pollinators or food supply).[85]

3.8 Non-linear changes and threshold effects

Warming will increase the chance of triggering abrupt and large-scale changes.

Human civilisation has lived through a relatively stable climate. But the climate system has behaved erratically in the past.[86] The chaotic nature of the climate system means that even relatively small amounts of warming can become amplified, leading to major shifts as the system adjusts to balance the new conditions. Abrupt and large-scale changes could potentially destabilise regions and increase regional conflict – for example shutdown of Atlantic Thermohaline Circulation (more details in Chapter 5).[87] While there is still uncertainty over the possible triggers for such changes, the latest science indicates that the risk is more serious than once thought (Table 3.3).[88] Some temperature triggers, like 3 or 4°C of warming, could be reached this century if warming occurs quite rapidly.

Melting/collapse of polar ice sheets would accelerate sea level rise and eventually lead to substantial loss of land, affecting around 5% of the global population.

The impacts of sea level rise in the long term depend critically on changes in both the Greenland and West Antarctic ice sheets. As temperatures rise, the world risks crossing a threshold level of warming beyond which melting or collapse of these polar ice sheets would be irreversible. This would commit the world to increases in sea level of around 5 to 12-m over coming centuries to millennia, much greater than from thermal expansion alone, and significantly accelerate the rate of increase (Chapter 1). A substantial area of land and a large number of people would be put at risk from permanent inundation and coastal surges. Currently, around 5% of the world's population (around 270 million people) and $2 trillion worth of GDP would be threatened by a 5-m rise (Figure 3.11). The most vulnerable regions are South and East Asia, which could lose 15% of their land area (an area over three times the size of the UK). Many major world cities would likely have to be abandoned unless costly flood defences were constructed.[89]

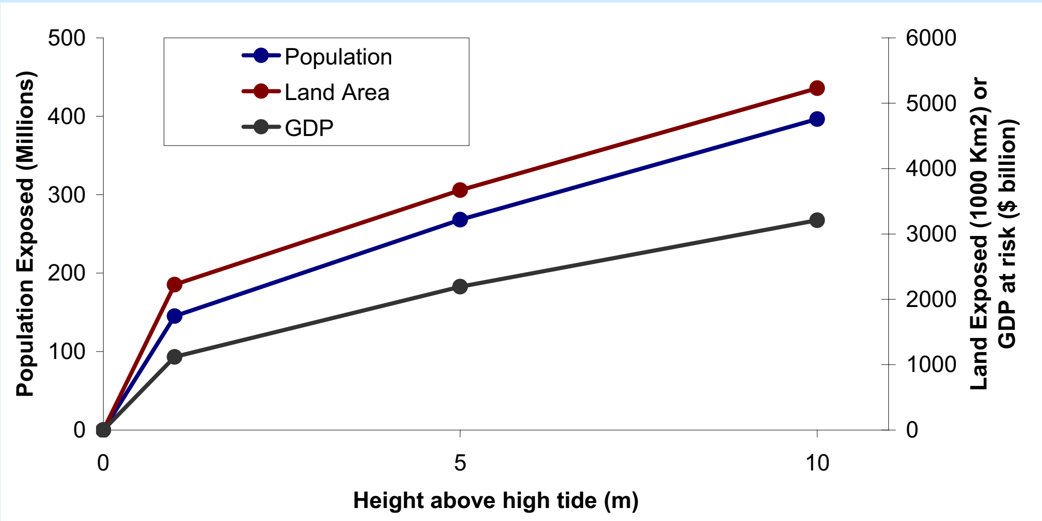
83 Malcolm *et al.* (2006)
84 This effect has been found with the Hadley Centre model (Cox *et al.* 2000) and several other climate models (Scholze *et al.* 2006).
85 Visser and Both (2005); Both *et al.* (2006) report declines of 90% in pied flycatcher populations in the Netherlands in areas where caterpillar numbers have been peaking two weeks earlier due to warming, which means there is little food when the flycatcher eggs hatch.
86 For example, Rial *et al*. (2004)
87 As set out in a Pentagon commissioned report by Schwartz and Randall (2004)
88 Schellnhuber (2006)
89 Nicholls *et al.* (2004)

Table 3.3 Potential temperature triggers for large-scale and abrupt changes in climate system

Phenomenon	Global Temperature Rise (above pre-industrial)	Relative Confidence*	References
Shifts in regional weather regimes (e.g. changes in monsoons or the El Niño)	Uncertain (although some changes are expected)	Medium	Hoskins (2003)
Onset of irreversible melting of Greenland	2 - 3°C	Medium	Lowe *et al.* (2006)
Substantial melting threatening the stability of the West Antarctic Ice Sheet	> 2 - 5°C	Low	Oppenheimer (2005)
Weakening of North Atlantic Thermohaline Circulation	Gradual weakening from present	High	Wood *et al.* (2006)
Complete collapse of North Atlantic Thermohaline Circulation	> 3 - 5°C	Low	O'Neill and Oppenheimer (2002)

Source: Adapted from Schneider and Lane (2006)

Figure 3.11 Global flood exposure from major sea level rise (based on present conditions)



Source: Anthoff *et al.* (2006)

Warming may induce sudden shifts in regional weather patterns that have severe consequences for water availability in tropical regions.

The strongly non-linear nature of weather systems, like the Asian and African monsoons, and patterns of variability, such as the El Niño (chapter 1), suggests that they may be particularly vulnerable to abrupt shifts. For example, recent evidence shows that an El Niño with strong warming in the central Pacific can cause the Indian monsoon to switch into a dry state, leading to severe droughts[90]. Currently, this type of

[90] Kumar *et al.* (2006)

shift is a temporary occurrence, but in the past, there is evidence that climate changes have caused such shifts to persist for many decades. For example, cold periods in the North Atlantic since the last ice age, such as a 2.5°C regional cooling during the Little Ice Age, led to an abrupt weakening of the Asian summer monsoon.[91] If such abrupt shifts were replicated in the future, they could have a very severe effect on the livelihoods of hundreds of millions of people (Box 3.5). The impacts would be strongest in the tropics, where such weather systems are a key driver of rainfall patterns. However, the confidence in projections of future changes is relatively low. Currently, several climate models predict that in the future average rainfall patterns will look more like an El Niño.[92] This could mean a significant shift in weather in many parts of the world, with areas that are normally wet perhaps rapidly becoming dryer. In the long term, it may be possible to adapt to such changes, but the short-term impacts would be highly disruptive. For example, the strong El Niño in 1997/98 had severe impacts around the Indian and Pacific oceans, causing flooding and droughts that led to thousands of deaths and several billion dollars of damage.

Extreme high temperatures will occur more often, increasing human mortality during the dry pre-monsoon months and damaging crops.[93] Critical temperatures, above which damage to crops increases rapidly, are likely to be exceeded more frequently. A recent study predicts up to a 70% reduction in crop yields by the end of this century under these conditions, assuming no adaptation.[94]

Box 3.5 Possible impacts of an abrupt change in Asian monsoon reliability

Any changes in rainfall patterns of the Asian monsoon would severely affects the lives of millions of people across southern Asia. Summer monsoon rains play a crucial role for agricultural and industrial production throughout South and East Asia. In India, for example, summer monsoon rains provide 75 – 90% of the annual rainfall.

Models suggest that climate change will bring a warmer, wetter monsoon by the end of the century.[95] This could increase water availability for around two billion people in South and East Asia.[96] However, the increased runoff would probably increase flood risk, particularly because models predict that rain will fall in more intense bursts. Without adaptation this could have devastating impacts. For example, over 1000 people died when Mumbai was devastated by flash floods from extremely heavy rainfall in August 2005.[97] A record-breaking one-metre of rain fell in just 24 hours and parts of Mumbai were flooded to a depth of 3 metres. Schools, banks, the stock exchange, and the airport all had to be closed. Hundreds of cases of dysentery and cholera were recorded as a result of contaminated water, and medical supplies were limited because of damages to storage warehouses.

But it is changes in the timing and variability of rainfall, both within the wet season and between years that are likely to have the most significant impacts on lives and livelihoods. A year-to-year fluctuation of just 10% in average rainfall can lead to food and water shortages. Confidence in projections of future rainfall variability is relatively low; however, this represents the difference between steady, predictable rainfall and a destructive cycle of flooding and drought. Most models predict a modest increase in year-to-year variability but to differing degrees. At the heart of this are the projections of what will happen to El Niño. Changes in variability within the wet season are more uncertain, but also vital to livelihoods. For example, in 2002, the monsoon rains failed during July, resulting in a seasonal rainfall deficit of 20%. This caused a massive loss of agricultural production, leading to severe hardship for hundreds of millions of people.

[91] Gupta *et al.* (2003)
[92] Collins and the CMIP Modelling Groups (2005)
[93] Defra (2005)
[94] Challinor *et al.* (2006a)
[95] Reviewed in detail in a report prepared for the Stern Review by Challinor *et al.* (2006b)
[96] This is a result from Arnell (2006b), who superimposed rainfall and temperature changes from past extreme monsoon years (average over five driest and five wettest years) on today's mean summer climate to understand consequences for water availability.
[97] Described in detail in Munich Re (2006)

3.9 Conclusion

Climate change will have increasingly severe impacts on people around the world, with a growing risk of abrupt and large-scale changes at higher temperatures.

This chapter has outlined the main mechanisms through which physical changes in climate will affect the lives and livelihoods of people around the world. A warmer world with a more intense water cycle and rising sea levels will influence many key determinants of wealth and wellbeing, including water supply, food production, human health, availability of land, and the environment. While there may be some initial benefits in higher latitudes for moderate levels of warming (1 – 2°C), the impacts will become increasingly severe at higher temperatures (3, 4 or 5°C). While there is some evidence in individual sectors for disproportionate increases in damages with increasing temperatures, such as heat stress (Box 3.1), the most powerful consequences will arise when interactions between sectors magnify the effects of rising temperatures. For example, infrastructure damage will rise sharply in a warmer world, because of the combined effects of increasing potency of storms from warmer ocean waters and the increasing vulnerability of infrastructure to rising windspeeds. At the same time, the science is becoming stronger, suggesting that higher temperatures will bring a growing risk of abrupt and large-scale changes in the climate system, such as melting of the Greenland Ice Sheet or sudden shift in the pattern of monsoon rains. Such changes are still hard to predict, but their consequences could be potentially catastrophic, with the risk of large-scale movement of populations and global insecurity. Chapter 6 brings this disparate material together to examine the full costs in aggregate.

While modelling efforts are still limited, they provide a powerful tool for taking a comprehensive look at the impacts of climate change. At the same time, it is the underlying detail, as described in this and the next two chapters, rather than the aggregate models that should be the primary focus. It is not possible in aggregate models to bring out the key elements of the effects, much is lost in aggregation, and the particular model structure can have their own characteristics. What matters is the magnitude of the risks of different kind for different people and the fact that they rise so sharply as temperatures move upwards.

Chapters 4 and 5 pick up this story. The poorest will be hit earliest and most severely. In many developing countries, even small amounts of warming will lead to declines in agricultural production because crops are already close to critical temperature thresholds. The human consequences will be most serious and widespread in Sub-Saharan Africa, where millions more will die from malnutrition, diarrhoea, malaria and dengue fever, unless effective control measures are in place. There will be acute risks all over the world – from the Inuits in the Arctic to the inhabitants of small islands in the Caribbean and Pacific. Developed countries may experience some initial benefits from warming, such as longer growing seasons for crops, less winter mortality, and reduced heating demands. These are likely to be short-lived and counteracted at higher temperatures by sharp increases in damaging extreme events such as hurricanes, floods, and heatwaves.

References

Dr Rachel Warren and colleagues from the Tyndall Centre (Warren *et al.* 2006) have prepared a detailed technical report for the Stern Review that looks at how the impacts of climate change vary with rising temperatures (working paper available from http://www.tyndall.ac.uk). The analysis drew heavily on a series of papers, known as "FastTrack", prepared by Prof. Martin Parry and colleagues in a Special Issue of Global Environmental Change (introduced in Parry 2004). These studies are among the few that use a consistent set of climate and socio-economic scenarios and explore different sources of risks and uncertainty (more details in Box 3.2). The work built on previous analyses by Grassl *et al.* (2003), Hare (2006) and Warren (2006). Sam Hitz and Joel Smith also analysed the "FastTrack" work, amongst others, in a special report for the OECD, focusing in particular on the functional form of the impacts with rising temperatures (Hitz and Smith 2004). They found increasingly adverse impacts for several climate-sensitive sectors but were not able to determine if the increase was linear or exponential (more details in Box 3.1). Prof. Richard Tol (2002) carried out a detailed study to examine both the costs and the benefits of climate change at different levels of global temperature rise in key economic sectors – agriculture, forestry, natural ecosystems, sea level rise, human mortality, energy consumption, and water resources. He found that some developed countries show net economic benefits for low levels of warming (1 – 2°C) because of reduced winter heating and cold-related deaths, and increased agricultural productivity due to carbon fertilisation. The book "Avoiding dangerous climate change" (edited by Schellnhuber 2006) currently provides the most up-to-date assessment of the full range of impacts of climate change, particularly the risk of abrupt and large-scale changes. The Fourth Assessment Report of the IPCC is expected to be published in 2007 and will provide the most comprehensive picture of the latest science.

Agrawala, S., S. Gigli, V. Raksakulthai et al. (2005): 'Climate change and natural resource management: key themes from case studies', in Bridge over troubled water: linking climate change and development, S. Agrawala (ed.), Paris: OECD, pp. 85 – 131

Ali, A. (2000): 'Vulnerability of Bangladesh coastal region to climate change with adaptation options', Dhaka: Bangladesh Space Research and Remote Sensing Organisation (SPARRSO), available from http://www.survas.mdx.ac.uk/pdfs/3anwaral.pdf

Anthoff, D., R. Nicholls, R.S.J. Tol, and A.T. Vafeidis (2006): 'Global and regional exposure to large rises in sea-level', Research report prepared for the Stern Review, Tyndall Centre Working Paper 96, Norwich: Tyndall Centre, available from http://www.tyndall.ac.uk/publications/working_papers/twp96.pdf

Arctic Climate Impacts Assessment (2004): 'Impacts of a warming Arctic', Cambridge: Cambridge University Press.

Arnell, N.W. (2004): 'Climate change and global water resources: SRES emissions and socio-economic scenarios', Global Environmental Change **14**: 31 – 52

Arnell, N.W. (2006a): 'Climate change and water resources', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 167 - 176

Arnell, N.W. (2006b): 'Global impacts of abrupt climate change: an initial assessment', Report commissioned by the Stern Review, available from http://www.sternreview.org.uk

Barnett, T.P., J.C, Adam, and D.P. Lettenmaier (2005): 'Potential impacts of a warming climate on water availability in snow-dominated regions', Nature **438**: 303-309

Betts, R.A. (2005): 'Integrated approaches to climate-crop modelling: needs and challenges'. Philosophical Transactions of the Royal Society B **360**: 2049-2065

Bosello, F., R. Roson, R.S.J. Tol et al. (2006): 'Economy-wide estimates of the implications of climate change: human health', Ecological Economics **58**: 579-591

Both, C., S.Bouwhius, C.M. Lessells, and M.E. Visser (2006): 'Climate change and population declines in a long-distance migratory bird', Nature **441**: 81 – 83

Bruinsma, J. (ed.) (2003): 'World agriculture: towards 2015/2030', FAO, London: Earthscan

Burke, E.J., S.J. Brown, and N. Christidis (2006): 'Modelling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model', Journal of Hydrometeorology, **7**: 1113 – 1125

Challinor, A.J., T.R. Wheeler, et al. (2006a): 'Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures, Agriculture, Ecosystems and Environment', (in press)

Challinor, A.J., J. Slingo, A. Turner, and T. Wheeler (2006b): 'Indian Monsoon, Contribution to Stern Review', available from http://www.sternreview.org.uk

Ciais, P., M. Reichstein, N. Viovy, F et al. (2005): 'Europe-wide reduction in primary productivity caused by the heat and drought in 2003', Nature **437**: 529 – 533

Collins, M. and the CMIP Modelling Groups (2005): 'El Niño – or La Niño-like climate change? Climate Dynamics' **24**: 89-104

Coudrain, A., B. Francou et al. (2005): 'Glacier shrinkage in the Andes and consequences for water resources', Hydrological Sciences Journal **50**: 925 – 932

Cox P.M., R.A. Betts, C.D. Jones, et al. (2000): 'Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model', Nature **408**: 184-187

Defra (Department for Environment, Food and Rural Affairs) (2005): 'Investigating the impacts of climate change in India', available from http://www.defra.gov.uk/environment/climatechange.htm

De, U.S., R.K. Dube and G.S. Prakasa Rao (2005): 'Extreme weather events over India in the last 100 years', Journal of the Indian Geophysical Union **9**: 173 – 187

Donner, S.D, W.J. Skirving, C.M. Little et al. (2005): 'Global assessment of coral bleaching and required rates of adaptation under climate change', Global Change Biology **11**: 2251 – 2265

Emanuel, K.A. (1987): 'The dependence of hurricane intensity on climate', Nature **326**: 483 – 485

Epstein, P.R. and E. Mills (2005): 'Climate change futures: health, ecological and economic dimensions', Center for Health and the Global Environment, Harvard Medical School, Cambridge, MA: Harvard University, available from http://www.climatechangefutures.org

Falkenmark, M., J. Lunquist, and C. Widstrand (1989): 'Macro-scale water scarcity requires micro-scale approaches', Natural Resources Forum **13**: 258 – 267

Fischer, G., M. Shah, F.N. Tubiello, and H. van Velhuizen (2005): 'Socio-economic and climate change impacts on agriculture', Philosophical Transactions of the Royal Society B **360**: 2067 – 2083

Gedney, N., P.M. Cox, R.A. Betts, et al. (2006) 'Detection of a direct carbon dioxide effect in continental river runoff records', Nature **439**: 835 – 838

Gleick, P.H. (1996): 'Basic water requirements for human activities: meeting basic needs', Water International **21**: 83 – 92

Grassl, H., J. Kokott, M. Kulessa, et al. (2003): 'Climate protection strategies for the 21st century: Kyoto and beyond', Special Report for German Advisory Council on Global Change (WBGU), Berlin: WBGU, available from http://www.wbgu.de/wbgu_sn2003_voll_engl.html

Grey, D., and C. Sadoff (2006): 'Water for growth and development, in Thematic documents of the IV World Water Forum', Mexico City: Comisíon Nacional del Agua

Gupta, A., D.M. Anderson, and J.T. Overpeck (2003): 'Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean', Nature **421**: 354 – 356

Hales, S., N. de Wet, J. Macdonald, and A. Woodward (2002): 'Potential effect of population and climate changes on global distribution of dengue fever: an empirical model', The Lancet **360**: 830 – 834

Hare, B. (2006): 'Relationship between increases in global mean temperature and impacts on ecosystems, food production, water and socio-economic systems', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 177 - 185

Hitz S. and J. Smith (2004): 'Estimating Global Impacts from Climate Change', pp. 31 – 82 in Morlot JC, Agrawala S (eds.), The benefits of climate change policies, Paris: OECD

Hoskins, B.J. (2003): 'Atmospheric processes and observations', Philosophical Transactions of the Royal Society B **361**:1945-1960

Insurance Australia Group (2005): 'Evidence to the Stern Review', Insurance Australia Group, Australia, available from http://www.sternreview.org.uk

International Federation of Red Cross and Red Crescent Societies (2001): 'World disasters report 2001', Geneva: International Federation of Red Cross and Red Crescent Societies, available from http://www.ifrc.org/publicat/wdr2001

Intergovernmental Panel on Climate Change (2000:) 'Emissions Scenarios. Special Report of the Intergovernmental Panel on Climate Change', [Nakicenovic N and Swart R (eds.)], Cambridge: Cambridge University Press

Intergovernmental Panel on Climate Change (2001): 'Climate Change 2001: Synthesis Report', Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change' [Watson R.T. and Core Team (Eds.)], Cambridge: Cambridge University Press

Körner, Ch. (2004): 'Through enhanced tree dynamics carbon dioxide enrichment may cause tropical forests to lose carbon', Philosophical Transactions of the Royal Society London B **359**: 493 – 498

Kumar, K.K., B. Rajagopalan, M. Hoerling et al. (2006): 'Unravelling the mystery of indian monsoon failure during the El Niño', Science **314**: 115-119, doi: 10.1126/science.1131152

Leemans, R. and B. Eickhout (2004): 'Another reason for concern: regional and global impacts on ecosystems for different levels of climate change', Global and Environmental Change **14**: 219 – 228

Lehner B, Henrichs T, Döll P, Alcamo J (2001): 'EuroWasser: Model-Based Assessment of European Water Resources and Hydrology in the Face of Global Change'. World Water Series 5. Centre for Environmental Systems Research, Kassel: University of Kassel, available from http://www.usf.uni-kassel.de/usf/archiv/dokumente/kwws/kwws.5.en.htm

Long, S.P., E.A. Ainsworth, A.D.B. Leakey et al. (2006): 'Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations', Science **312**: 1918 – 1921

Malcolm, J.R., C.R. Liu, R.P, Neilson, et al. (2006): Global warming and extinctions of endemic species from biodiversity hotspots, Conservation Biology **20**: 538 – 548

McClean, C.J., J.C. Lovett, W. Kuper, et al. (2005): 'African plant diversity and climate change', Annals of the Missouri Botanical Garden **92**: 139 – 152

McMichael, A., D. Campbell-Lendrum, S. Kovats, et al. (2004): 'Global climate change', in M.J. Ezzati, et al. (eds.), Comparative quantification of health risks: global and regional burden of disease due to selected major risk factors, Geneva: World Health Organisation, pp. 1543 - 1649

McMichael, A.J., R.E. Woodruff, and S. Hales (2006): 'Climate change and human health: present and future risks', The Lancet **367**: 859-869

Mendelsohn, R., W.D. Nordhaus, and D. Shaw (1994): 'The impact of global warming on agriculture: a Ricardian analysis', American Economic Review **84**: 753 – 771

Milly P.C.D., R.T. Wetherald, K.A. Dunne, and T.L. Delworth (2002): 'Increasing risk of great floods in a changing climate', Nature **415**: 514-517

Munich Re (2004): 'Annual review: natural catastrophes 2003', Munich Re Group: Munich

Munich Re (2005): 'Megacities – megarisks.' Munich Re Group: Munich

Munich Re (2006): 'Annual review: natural catastrophes 2005', Munich Re Group: Munich

Myers, N., and Kent, J. (1995): 'Environmental exodus: an emergent crisis in the global arena, Washington, DC: The Climate Institute

Nagy, G. et al. (2006): 'Understanding the potential impact of climate change in Latin America and the Caribbean', Report prepared for the Stern Review, available from http://www.sternreview.org.uk

Nelson, F.E. (2003): '(Un)frozen in Time', Science **299**: 1673 – 1675

Nicholls R.J. (2004): 'Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios', Global Environmental Change **14**: 69 – 86

Nicholls R.J., J.A. Lowe (2006): 'Climate stabilisation and impacts of sea-level rise', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 195 – 201

Nicholls, R.J., R.S.J. Tol, and N. Vafeidis (2004): 'Global estimates of the impact of a collapse of the West Antarctic Ice Sheet', Report for the Atlantis project, available from http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/atlantis.htm

Nicholls, R.J. and R.S.J. Tol, (2006): 'Impacts and responses to sea level rise: global analysis of the SRES scenarios over 21st century', Philosophical Transactions of the Royal Society B **364**: 1073 – 1095

Nordhaus, W.D. (2006): 'The economics of hurricanes in the United States, Prepared for Snowmass Workshop on Abrupt Climate Change', Snowmass: Annual Meetings of the American Economic Association, available from http://nordhaus.econ.yale.edu/hurricanes.pdf

O'Neill, B.C., and M. Oppenheimer (2002): 'Climate change – dangerous climate impacts and the Kyoto protocol', Science **296**: 1971-1972

Oppenheimer, M. (2005): 'Defining dangerous anthropogenic interference: the role of science, the limits of science', Risk Analysis **25**: 1399-1408

Parmesan, C. and G. Yohe (2003): 'A globally coherent fingerprint of climate change impacts across natural systems', Nature **421**: 37 – 42

Parry, M.L. (1978): 'Climatic change, agriculture and settlement', Folkestone, UK: Dawson and Sons

Parry, M.L (2004): 'Global impacts of climate change under the SRES scenarios', Global Environmental Change **14**: 1

Parry, M.L, C. Rosenzweig, A. Iglesias et al. (2004): 'Effects of climate change on global food production under SRES emissions and socio-economic scenarios', Global Environmental Change **14**: 53 – 67

Parry, M.L, C. Rosenzweig, and M. Livermore (2005): 'Climate change, global food supply and risk of hunger', Philosophical Transactions of the Royal Society B **360**: 2125 – 2136

Patz, J.A., D. Campbell-Lendrum, T. Holloway, and J.A. Foley (2005): 'Impact of regional climate change on human health', Nature **438**: 310 – 317

Pearson, R.G, W. Thuiller, M.B. Araújo, et al. (2006): 'Model-based uncertainty in species' range prediction'. Journal of Biogeography, **33**: 1704-1711, doi: 10.1111/j.1365-2699.2006.01460.x

Pearson, R.G., and T.P. Dawson (2003): 'Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful?' Global Ecology and Biogeography **12**: 361 – 371

Pounds, J.A., M.R. Bustamante, and L.A. Coloma (2006): 'Widespread amphibian extinctions from epidemic disease driven by global warming', Nature **439**: 161 – 167

Purse, B.V., P.S. Mellor, D.J. Rogers, et al. (2005): 'Climate change and the recent emergence of bluetongue in Europe', Nature Reviews Microbiology **3**: 171-181

Rial, J.A., R.A. Pielke, M. Beniston et al. (2004): 'Non-linearities, feedbacks and critical thresholds within the earth's climate system', Climatic Change **65**: 11-38

Ricketts, T.H., E. Dinerstein, T. Boucher, et al. (2005): 'Pinpointing and preventing imminent extinctions', Proceedings of the National Academy of Sciences **102**: 18497 – 18501

Root, T.L., D.P. MacMynowski, M.D. Mastrandrea, and S.H. Schneider (2005): 'Human-modified temperatures induce species changes', Proceedings of the National Academy of Sciences **102**: 7465 – 7469

Rosenzweig, C. and M.L. Parry (1994): 'Potential impacts of climate change on world food supply', Nature **367**: 133 – 138

Rosenzweig, C, F.N. Tubiello, R. Goldberg, et al. (2002): 'Increased crop damage in the US from excess precipitation under climate change', Global Environmental Change **12**: 197 – 202

Royal Society (2005): 'Ocean acidification due to increasing atmospheric carbon dioxide', London: Royal Society, available from http://www.royalsoc.ac.uk

Schellnhuber, H.J. (ed.) (2006): 'Avoiding dangerous climate change, Cambridge: Cambridge University Press

Schlenker, W. and M.J. Roberts (2006): 'Nonlinear effects of weather on corn yields', Review of Agricultural Economics **28**: in press

Schneider, S.H. and J. Lane (2006): 'An overview of 'dangerous' climate change', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 7 – 24

Scholze, M., W. Knorr, N.W. Arnell, and I.C. Prentice (2006): 'A climate-change risk analysis for world ecosystems', Proceedings of the National Academy of Sciences, DOI: 10.1073/pnas.0601816103

Schwartz, P. and D. Randall (2004): 'An abrupt climate change scenario and its implications for United States national security', Report prepared by the Global Business Network (GBN) for the Department of Defense, San Francisco: GBN, available from http://www.gbn.com/ArticleDisplayServlet.srv?aid=26231

Slingo, J.M., A.J. Challinor, B.J. Hoskins, and T.R. Wheeler (2005): 'Introduction: food crops in a changing climate', Philosophical Transactions of the Royal Society B **360**: 1983 – 1989

Tanser, F.C., B. Sharp, and D. le Seur (2003): 'Potential effect of climate change on malaria transmission in Africa', The Lancet **362**: 1792 - 1798

Thomas, C.D., A. Cameron, R.E. Green et al. (2004a): 'Extinction risk from climate change', Nature **427**: 145 – 148

Thomas C.D., S.E. Williams, A. Cameron, et al. (2004b): 'Reply (brief communication)', Nature **430**: doi:10.1038/nature02719

Thuiller, W., M.B. Araújo, R.G. Pearson, et al. (2004): 'Uncertainty in predictions of extinction risk', Nature **430**: doi:10.1038/nature02716

Tol, R.S.J. (2002): 'Estimates of the damage costs of climate change'. Part I: Benchmark estimates, Environmental and Resource Economics **21**: 47 - 73

Turley, C., J.C. Blackford, S. Widdicombe, et al. (2006): 'Reviewing the impact of increased atmospheric CO_2 on oceanic pH and the marine ecosystem', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 65 - 70

Van Lieshout, M., R.S. Kovats, M.T. Livermore, and P. Martens (2004): 'Climate change and malaria: analysis of the SRES climate and socio-economic scenarios', Global Environmental Change **14**: 87 – 99

Vara Prasad, P.V., P.Q. Craufurd, V.G. Kakani, et al. (2001): 'Influence of high temperature on fruit-set and pollen germination in peanuts', Australian Journal of Plant Physiology **28**: 233

Visser, M.E. and C. Both (2005): 'Shifts in phenology due to global climate change: the need for a yardstick', Proceedings of the Royal Society B **272**: 2561 - 2569

Warren, R. (2006): 'Impacts of global climate change at different annual mean global temperature increases', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 93 – 131

Warren, R., N. Arnell, R. Nicholls, P. Levy, and J. Price (2006): 'Understanding the regional impacts of climate change', Research report prepared for the Stern Review, Tyndall Centre Working Paper 90, Norwich: Tyndall Centre, available from http://www.tyndall.ac.uk/publications/working_papers/twp90.pdf

Wheeler, T.R., G.R. Batts, R.H. Ellis, et al. (1996): 'Growth and yield of winter wheat (Triticum aestivum) crops in response to CO_2 and temperature', Journal of Agricultural Science **127**: 37 – 48

World Health Organisation (2005): 'Susceptibility of Plasmodium falciparum to antimalarial drugs – report on global monitoring 1996 – 2004', Geneva: World Health Organisation.

World Health Organisation (2006): WHO/UNEP Health and Environment Linkages Initiative (website), WHO, Geneva, available from http://www.who.int/heli/risks/climate/climatechange

Wigley, T.M.L. (1985): 'Impact of extreme events', Nature **316**: 106 - 107

World Bank (2004): 'Towards a water-secure Kenya', Water Resources Sector Memorandum, Washington, DC: World Bank

World Water Development Report (2006): 'Water: a shared responsibility, World Water Assessment Programme', New York: United Nations, available from http://www.unesco.org/water/wwap

4 Implications of Climate Change for Development

Key Messages

Climate change poses a real threat to the developing world. Unchecked it will become a major obstacle to continued poverty reduction.

Developing countries are especially vulnerable to climate change because of their geographic exposure, low incomes, and greater reliance on climate sensitive sectors such as agriculture. Ethiopia, for example, already has far greater hydrological variability than North America but less than 1% of the artificial water storage capacity per capita. **Together these mean that impacts are proportionally greater and the ability to adapt smaller.**

Many developing countries are already struggling to cope with their current climate. For low-income countries, major natural disasters today can cost an average of 5% of GDP.

Health and agricultural incomes will be under particular threat from climate change. For example:

- Falling farm incomes will increase poverty and reduce the ability of households to invest in a better future and force them to use up meagre savings just to survive.
- Millions of people will potentially be at risk of climate-driven heat stress, flooding, malnutrition, water related disease and vector borne diseases. For example, dengue transmission in South America may increase by 2 to 5 fold by the 2050s.
- The cost of climate change in India and South East Asia could be as high as a 9-13% loss in GDP by 2100 compared with what could have been achieved in a world without climate change. Up to an additional 145-220 million people could be living on less than $2 a day and there could be an additional 165,000 to 250,000 child deaths per year in South Asia and sub-Saharan Africa by 2100 (due to income losses alone).

Severe deterioration in the local climate could lead, in some parts of the developing world, to mass migration and conflict, especially as another 2-3 billion people are added to the developing world's population in the next few decades:

- Rising sea levels, advancing desertification and other climate-driven changes could drive millions of people to migrate: more than a fifth of Bangladesh could be under water with a 1m rise in sea levels – a possibility by the end of the century.
- Drought and other climate-related shocks risk sparking conflict and violence, with West Africa and the Nile Basin particularly vulnerable given their high water interdependence.

These risks place an even greater premium on fostering growth and development to reduce the vulnerability of developing countries to climate change.

However, little can now be done to change the likely adverse effects that some developing countries will face in the next few decades, and so some adaptation will be essential. Strong and early mitigation is the only way to avoid some of the more severe impacts that could occur in the second half of this century.

4.1 Introduction

While all regions will eventually feel the effects of climate change, it will have a disproportionately harmful effect on developing countries – and in particular poor communities who are already living at or close to the margins of survival. Changes in the climate will amplify the existing challenges posed by tropical geography, a heavy dependence on agriculture, rapid population growth, poverty, and a limited capacity to cope with an uncertain climate. The world is already likely to fall short of the Millennium Development Goals for 2015 in many regions of the world (see Box 4.1 for the Goals). Climate change threatens the long-term sustainability of development progress.[1]

Box 4.1 Millennium Development Goals

In September 2000, 189 countries signed the United Nations Millennium Declaration. In so doing, they agreed on the fundamental dimensions of development, translated into an international blueprint for poverty reduction. This is encapsulated by the Millennium Development Goals that are focused on a target date of 2015:

- Halve extreme poverty and hunger
- Achieve universal primary education
- Empower women and promote equality between women and men
- Reduce under five mortality by two thirds
- Reduce maternal mortality by three-quarters
- Reverse the spread of diseases, especially HIV/AIDS and malaria
- Ensure environmental sustainability
- Create a global partnership for development, with targets for aid, trade and debt relief

But it is important to recognise that the scale of future climate impacts will vary between regions, countries and people. The last 30 years or so has already seen strong advances in many developing countries on income, health and education. Those developing countries that continue to experience rapid growth will be much better placed to deal with the consequences of climate change. Other areas, predominantly low-income countries, where growth is stagnating may find their vulnerability increases.

The challenge now is to limit the damage, both by mitigation and adaptation. It is vital therefore to understand just how, and how much, climate change is likely to slow development progress. The chapter begins by examining the processes by which climate change impacts will be felt in developing counties. Section 4.2 considers what it is about the starting position of these countries that makes them vulnerable to the physical changes set out in Chapter 3. Understanding why developing countries are especially vulnerable is critical to understanding how best to improve their ability to deal with climate change (discussed in Chapter 20). Sections 4.3 and 4.4 move on to consider the consequences of a changing climate on health, income and growth. The first part of the analysis draws on evidence from past and current exposure to climate variability to show how vulnerable groups are affected by a hostile climate. The second summarises key regional impacts. Section 4.5 explores the potential effects on future growth and income levels, which in turn affect the numbers of people living below poverty thresholds as well as the child mortality rate. The chapter concludes with Section 4.6 reviewing the possible consequences for migration, displacement and risk of conflict resulting from the socio-economic and environmental pressures of climate change.

4.2 The vulnerability of developing countries to a changing climate

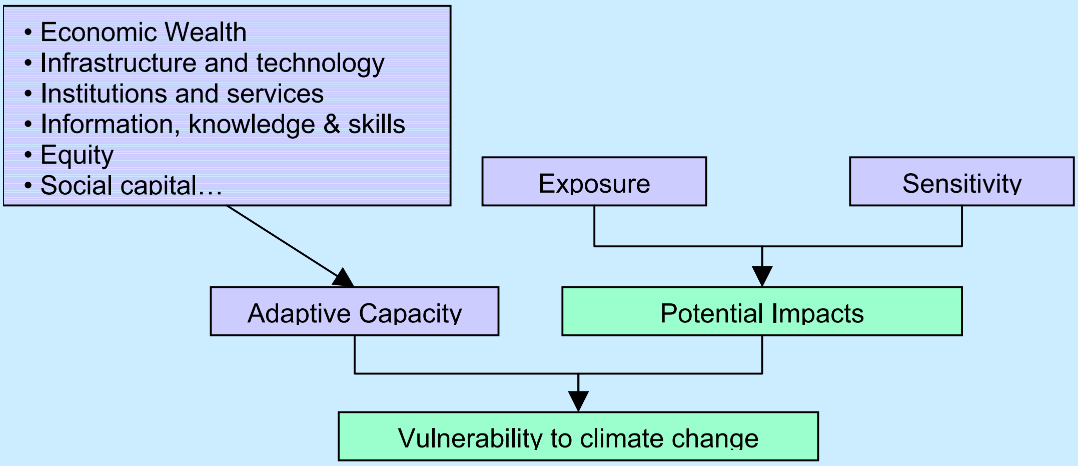
Developing countries are especially vulnerable to the physical impacts of climate change because of their exposure to an already fragile environment, an economic structure that is highly sensitive to an adverse and changing climate, and low incomes that constrain their ability to adapt.

The effects of climate change on economies and societies will vary greatly over the world. The circumstances of each country - its initial climate, socio-economic conditions, and growth prospects – will shape the scale of the social, economic and environmental effects of climate change. Vulnerability to climate change can be classified as: *exposure* to changes in the climate, *sensitivity* – the degree to which a system is affected by or responsive to climate

[1] The physical effects of climate change are predicted to become progressively more significant by the 2050s with a 2 to 3°C warming, as explained in Chapter 3.

stimuli,[2] and *adaptive capacity* - the ability to prepare for, respond to and tackle the effects of climate change. This is illustrated in Figure 4.1. Developing countries score poorly on all three criteria. This section provides a brief overview of some of the key vulnerabilities facing many developing countries. Unless these vulnerabilities are overcome they are likely to increase the risk and scale of damaging impacts posed by climate change.

Figure 4.1 Vulnerability to climate change: the IPCC Third Assessment Report



Source: redrawn from Ionescu et al (2005)

Exposure: The geography of many developing countries leaves them especially vulnerable to climate change.

Geographical exposure plays an important role in determining a country's growth and development prospects. Many developing countries are located in tropical areas. As a result, they already endure climate extremes (such as those that accompany the monsoon and El Niño and La Niña cycles), intra and interannual variability in rainfall,[3] and very high temperatures. India, for example, experienced peak temperatures of between 45°C and 49°C during the pre-monsoon months of 2003.[4] Geographical conditions have been identified as important contributors to lower levels of growth in developing countries. If rainfall - that arrives only in a single season in many tropical areas - fails for example, a country will be left dry for over a year with powerful implications for their agricultural sector. This occurred in India in 2002 when the monsoon rains failed, resulting in a seasonal rainfall deficit of 19% and causing large losses of agricultural production and a drop of over 3% in India's GDP.[5] Recent analysis has led Nordhaus to conclude that "tropical geography has a substantial negative impact on output density and output per capita compared to temperate regions".[6] Sachs, similarly, argues that poor soils, the presence of pests and parasites, higher crop respiration rates due to warmer temperatures, and difficulty in water availability and control explain much of the tropical disadvantage in agriculture.[7] Climate change is predicted to make these conditions even more challenging, with the range of possible physical impacts set out in Chapter 3. Even slight variations in the climate can have very large costs in developing countries as many places are close to the upper temperature tolerance of activities such as crop production. Put anther way, climate change will have a disproportionately damaging

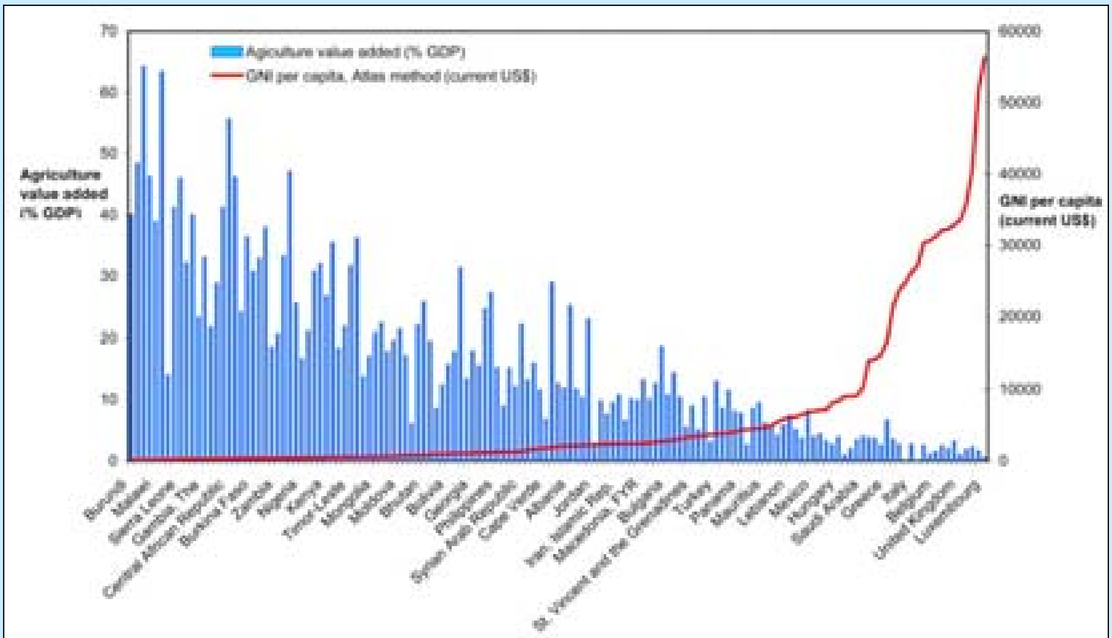
[2] IPCC (2001). The classification of *sensitivity* is similar to *susceptibility* to climate change, the degree to which a system is open, liable, or sensitive to climate stimuli.
[3] Intra-annual variability refers to rainfall concentrated in a single season, whilst interannual variability refers to large differences in the annual total of rainfall. The latter may be driven by phenomena such as the El Nino/Southern Oscillation (ENSO) or longer-term climate shifts such as those that caused the ongoing drought in the African Sahel. Brown and Lall (2006)
[4] De et al (2005)
[5] Challinor et al (2006). The scale of losses in the agricultural sector is indicated by the fact that this sector contributed just over one fifth of GDP at the time.
[6] Nordhaus (2006). Approximately 20% of the difference in per capita output between tropical Africa and two industrial regions is attributed to geography according to Nordhaus' model and analysis.
[7] Sachs (2001a)

impact on developing countries due, in part at least, to their location in low latitudes, the amount and variability of rainfall they receive, and the fact that they are "already too hot".[8]

Sensitivity: Developing economies are very sensitive to the direct impacts of climate change given their heavy dependence on agriculture and ecosystems, rapid population growth and concentration of millions of people in slum and squatter settlements, and low health levels.

Dependence on agriculture: Agriculture and related activities are crucial to many developing countries, in particular for low income or semi-subsistence economies. The rural sector contributes 21% of GDP in India, for example, rising to 39% in a country like Malawi,[9] whilst 61% and 64% of people in South Asia and sub-Saharan Africa are employed in the rural sector.[10] This concentration of economic activities in the rural sector – and in some cases around just a few commodities - is associated with low levels of income, as illustrated in Figure 4.2.[11] The concentration of activities in one sector also limits flexibility to switch to less climate-sensitive activities such as manufacturing and services. The agricultural sector is one of the most at risk to the damaging impacts of climate change – and indeed current extreme climate variability - in developing countries, as discussed in Chapter 3.

Figure 4.2 The share of agriculture in GDP and per capita income in 2004



Source: Updated from an earlier version by Tol et al (2004) using data from World Bank (World Development Indicators for 2004) for all countries for which such data are available. Countries are ranked by per capita income.

Dependence on vulnerable ecosystems: All humans depend on the services provided by natural systems. However, environmental assets and the services they provide are especially important for poor people, ranging from the provision of subsistence products and market income, to food security and health services.[12] Poor people are consequently highly sensitive to the degradation and destruction of these natural assets and systems by climate change. For example, dieback of large areas of forest – some climate models show strong drying over the Amazon if global temperature increases by more than 2°C, for example – would affect

[8] Mendelsohn et al (2006)
[9] World Bank (2006a) using 2004 data
[10] ILO (2005). The employment figures are given as a share of total employment, 2005.
[11] For example, the Central African Republic derives more than 50% of its export earnings from cotton alone (1997/99). Commission for Africa (2005)
[12] Natural medicines, for example, are often the only source of medicine for poor people and can help reduce national costs of supplying medical provisions in developing countries. The ratio of traditional healers to western-trained doctors is approximately 150:1 in some African countries for example. UNEP-WCMC (2006)

many of the one billion or more people who depend to varying degrees on forests for their livelihoods (Table 4.1).[13]

Table 4.1 Direct roles of forests in household livelihood strategies

Poverty aspects	Function	Description
Safety net	Insurance	Food and cash income in periods of unexpected food and income shortfall
Support current consumption	Gap-filling	Regular (seasonal, for example) shortfall of food and income
	Regular subsistence uses	Fuelwood, wild meat, medicinal plants, and so on
	Low-return cash activities	A wide range of extractive or "soft management" activities, normally in economies with low market integration
Poverty reduction	Diversified forest strategies	Forest activities that are maintained in economies with high market integration
	Specialised forest strategies	Forest activities that form the majority of the cash income in local economies with high market integration
	Payment for environmental services	Direct transfers to local communities from off-site beneficiaries

Source: Classification based on Arnold (2001), Kaimowitz (2002), Angelsen and Wunder (2003), and Belcher, Ruiz-perez, and Achdiawan (2003)

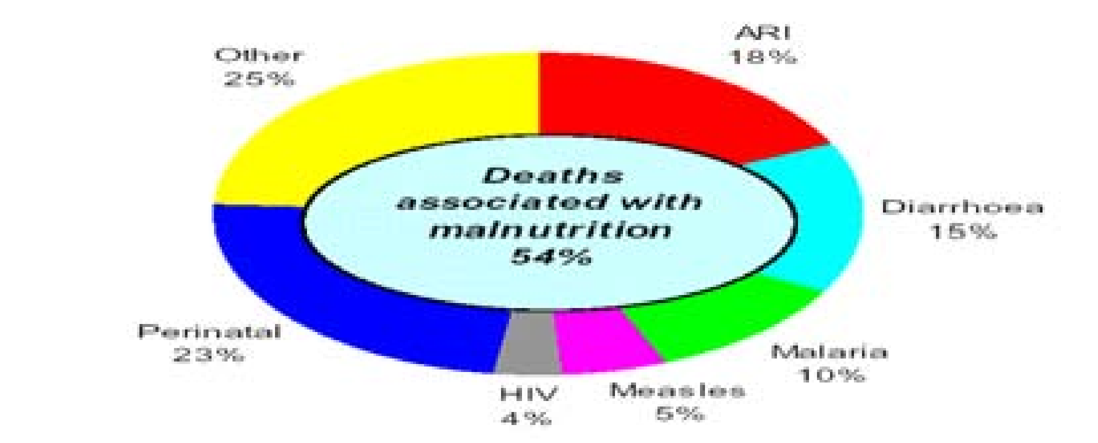
Population growth and rapid urbanisation: Over the next few decades, another 2-3 billion people will be added to the world's population, virtually all of them in developing countries.[14] This will add to the existing strain on natural resources - and the social fabric - in many poor countries, and expose a greater number of people to the effects of climate change. Greater effort is required to encourage lower rates of population growth. Development on the MDG dimensions (in particular income, the education of women, and reproductive health) is the most powerful and sustainable way to approach population growth.[15]

Developing countries are also undergoing rapid urbanisation, and the trend is set to continue as populations grow. The number of people living in cities in developing countries is predicted to rise from 43% in 2005 to 56% by 2030.[16] In Africa, for example, the 500km coast between Accra and the Niger delta will likely become a continuous urban megalopolis with more than 50 million people by 2020.[17] It does not follow from this that policies to slow urbanisation are desirable. Urbanisation is closely linked to economic growth and it can provide opportunities for reducing poverty and decreasing vulnerability to climate change.[18] Nonetheless, many of those migrating to cities live in poor conditions – often on marginal land – and are particularly vulnerable because of their limited access clean water, sanitation, and location in flood-prone areas.[19] In Latin America, for example, where urbanisation has gone far further than in Africa or Asia, more and more people are likely be forced to locate in cheaper, hazard prone areas such as floodplains or steep slopes.

[13] Vedeld et al (2004). This effect on the Amazon has been found with the Hadley Centre model, as reported in Cox *et al.* (2000), and several other climate models (Scholze *et al.* 2006) as discussed in Chapter 3.
[14] World Bank (2003b)
[15] Stern et al (2005)
[16] World Population Prospects (2004); and World Urbanization Prospects (2005).
[17] Hewawasam (2002)
[18] For example, proximity and economies of scale enable cost-effective and efficient targeting and provision of basic infrastructure and services.
[19] Approximately 72% of Africa's urban inhabitants now live in slums and squatter settlements for example (Commission for Africa, 2005)

Food insecurity, malnutrition and health: Approximately 40% of the population of sub-Saharan Africa is undernourished, largely because of the poor diet and severe and repeated infections that afflict poor people.[20] Even if the Millennium Development Goals are met, more than 400 million people could be suffering from chronic hunger in 2015.[21] Malnutrition is a health outcome in itself, but it also lowers natural resistance to infectious diseases by weakening the immune system. This is a challenge today - malnutrition was associated with 54% of child deaths in developing countries in 2001 (10.8 million children), as illustrated in Figure 4.3. Climate change will potentially exacerbate this vulnerability as a greater number of malaria carrying mosquitoes move into previously uninfected areas. This is likely to generate higher morbidity and mortality rates among people suffering from malnutrition than among food-secure people.

Figure 4.3 Proportional mortality in children younger than five years old in developing countries



Source: WHO (2005) Note: Acute Respiratory Infection (ARI)

Adaptive capacity: People will adapt to changes in the climate as far as their resources and knowledge allow. But developing countries lack the infrastructure (most notably in the area of water supply and management), financial means, and access to public services that would otherwise help them adapt.

Poor water-related infrastructure and management: Developing countries are highly dependent on water – the most climate-sensitive economic resource - for their growth and development. Water is a key input to agriculture, industry, energy and transport and is essential for domestic purposes. Irrigation and effective water management will be very important in helping to reduce and manage the effects of climate change on agriculture.[22] But many developing countries have low investment in irrigation systems, dams, and ground water. For example, Ethiopia has less than 1% of the artificial water storage capacity per capita of North America, despite having to manage far greater hydrological variability.[23] Many developing countries do not have enough water storage to manage annual water demand based on the current average seasonal rainfall cycle, as illustrated in Table 4.2. This will become an even greater bind with a future, less predictable cycle.

---

[20] WHO (2005). Poverty impacts a person's standard of living, the environmental conditions in which they live, and their ability to meet basic needs such as food, housing and health care that in turn affects their level of nutrition.
[21] One of the MDGs is to halve, between 1990 and 2015, the proportion of people who suffer from hunger. In 2002 there were 815 million hungry people in the developing world, 9 million less than in 1990. (UN, 2005)
[22] Irrigation plays an important role in improving returns from land, with studies identifying an increase in cropping intensity of 30% with the use of irrigation (Commission for Africa, 2005). Similarly, effective water management enables water to be stored for multiple uses, increases the reliability of water services, reduces peak flows and increases off-peak flows, and reduces the risk of water-related shocks and damage (World Bank, 2006b).
[23] World Bank (2006c)

Table 4.2 Investment in water storage in developing countries

The seasonal storage index (SSI) indicates the volume of storage needed to satisfy annual water demand based on the average seasonal rainfall cycle (calculated as the volume needed to transfer water from wet months to dry months). The countries listed below need water during dry seasons and have water available to be captured during wet seasons. The 'Hard Water' column represents water storage requirements. Surface water reservoir development or groundwater development could provide additional storage. Some developing countries will also require 'soft water' (with water needs in excess of the volume that can be captured from internal renewable water resources) through increasing the efficiency of water use. However, the average GDP of countries with soft water needs is $8,477 compared to an average GDP of $601 of countries with hard water requirements. South Asia faces problems of seasonal and inter-annual deficits, requiring both seasonal and inter-annual storage, and 'soft' water.[24]

	Seasonal Storage Index (km3)	SSI as % of Annual Volume	% Hard Water (of total)	Current Storage (% of SSI)	GDP ($, 2003)
India	356.6	21%	17%	76%	555
Bangladesh	62.28	41%	40%	33%	385
Ethiopia	40.99	10%	100%	8%	91
Nepal	29.86	47%	100%	0%	233
Vietnam	27.64	10%	100%	3%	471
North Korea	23.32	45%	100%	0%	494
Senegal	22.3	40%	100%	7%	641
Malawi	18.98	34%	100%	0%	158
Algeria	6.6	6%	100%	91%	2,049
Tanzania	5.5	1%	33%	76%	271
El Salvador	5.45	37%	100%	59%	2,302
Haiti	3.73	25%	79%	0%	300
Guinea	3.71	2%	100%	51%	424
Eritrea	2.75	11%	15%	3%	305
Burundi	2.64	19%	27%	0%	86
Albania	2.64	23%	100%	21%	1,915
Guinea-Bissau	2.48	11%	100%	0%	208
Sierra Leone	2.21	3%	100%	0%	197
The Gambia	2.14	56%	100%	0%	224
Rwanda	1.38	9%	3%	0%	185
Mauritania	1.34	2%	100%	66%	381
Swaziland	0.98	15%	100%	59%	1,653
Bhutan	0.4	1%	13%	0%	303

Source: Brown and Lall (2006)

In addition, inappropriate water pricing and subsidised electricity tariffs that encourage the excessive use of groundwater pumping (for agricultural use, for example) also increase vulnerability to changing climatic conditions. For example, 104 of Mexico's 653 aquifers (that provide half the water consumed in the country) drain faster than they can replenish themselves, with 60% of the withdrawals being for irrigation.[25] Similarly, water tables are falling in some drought-affected districts of Pakistan by up to 3 meters per year, with water

[24] Brown and Lall (2006)
[25] International Commission on Irrigation and Drainage (2005)

now available only at depths of 200-300 meters.[26] The consequences of inadequate investment in water-related infrastructure and poor management are important given that most climate change impacts are mediated through water (as discussed in Chapter 3).

Low incomes and underdeveloped financial markets: In many developing countries the capacity of poor people to withstand extreme weather events such as a drought is constrained both by low income levels and by limited access to credit, loans or insurance (in terms of access and affordability).[27] These constraints are likely to become worse as wet and dry seasons become increasingly difficult to predict with climate change.[28] This is often exacerbated by weak social safety nets that leave the poorest people very vulnerable to climate shocks. At the national level, many low-income countries have limited financial reserves to cushion the economy against natural disasters,[29] coupled with underdeveloped financial markets and weak links to world financial markets that limit the ability to diversify risk or obtain or reallocate financial resources. Less than 1% of the total losses from natural disasters, for example, were insured in low-income countries during the period 1985 to 1999.[30]

Poor public services: Inadequate resources and poor governance (including corruption) often result in poor provision of public services. Early warning systems for extreme weather conditions, education programmes raising awareness of climate change, and preventive measures and control programmes for diseases spread by vectors or caused by poor nutrition are examples of public services that would help to manage and cope with the effects of climate change but receive weak support and attention in developing countries.

Implications for future vulnerability of different growth pathways.

The following sections assume current levels of vulnerabilities in the developing world. However, some parts of the developing world may look very different by the end of the century. If development progress is strong, then much of Asia and Latin America may be middle income or above, with substantial progress also being made in Africa. Growth and development should equip these countries to better manage climate change, and possibly avoid some of the most adverse impacts. For example, if there are more resources to build protection against rising sea levels, and economies become more diversified. But the extent to which these countries will be able to cope with climate change will depend on the scale of future impacts, and hence the action today to curb greenhouse gas emissions.

Further, the speed of climate change over the next few decades will - in part - determine the ability of developing countries to develop and grow. Climate change is likely to lead to an increase in extreme weather events.[31] Evidence (discussed below) shows that extreme climate variability can set back growth and development prospects in the poorest countries. If climatic shocks do become more intense and frequent before these countries have been able to reduce their vulnerability, long-term growth potential could be called into question. And some developing countries are already exposed to the damaging impacts of climate change that, in extreme cases such as Tuvalu, have already constrained their long-term development prospects.

[26] Roy (2006)

[27] An estimated 2.5 billion low income people globally do not have access to bank accounts, with less than 20% of people in many African countries having access (compared to 90-95% of people in the developed world) (CGAP, 2004). Poor people are typically constrained by their lack of collateral to offer lenders, unclear property rights, insufficient information to enable lenders to judge credit risk, volatile incomes, and lack of financial literacy, among other things.

[28] The incomes of poor people will become less predictable, making them less able to guarantee the returns that are needed to pay back loans, while insurers will face higher risks and losses making them even less willing to cover those most in need.

[29] IMF (2003)

[30] Freeman et al (2002)

[31] For example, a recent study from the Hadley Centre shows that the proportion of land experiencing extreme droughts is predicted to increase from 3% today to 30% for a warming of around 4°C, and severe droughts at any one time will increase from 10% today to 40% (discussed in Chapters 1 and 3).

4.3 Direct implications of climate change for health, livelihoods and growth: what can be learnt from natural disasters?

The impact of climate change on poor countries is likely to be severe through both the effects of extreme weather events and a longer-term decline in the environment. The impact of previous extreme weather events provides an insight into the potential consequences of climate change.

Many developing countries are already struggling to cope with their current climate. Both the economic costs of natural disasters and their frequency have increased dramatically in the recent past. Global losses from weather related disasters amounted to a total of around $83 billion during the 1970s, increasing to a total of around $440 billion in the 1990s with the number of 'great natural catastrophe' events increasing from 29 to 74 between those decades.[32] The financial costs of extreme weather events represent a greater proportion of GDP loss in developing countries, even if the absolute costs are more in developed countries given the higher monetary value of infrastructure.[33] And over 96% of all disaster related deaths worldwide in recent years have occurred in developing countries. Climatic shocks can - and do - cause setbacks to economic and social development in developing countries. The IMF, for example, estimates costs of over 5% of GDP per large disaster on average in low-income countries between 1997 and 2001.[34]

Climate change will exacerbate the existing vulnerability of developing countries to an often difficult and changing climate. This section focuses on those aspects that will likely feel the largest impacts: health, livelihoods and growth. The analysis draws on evidence from past and current exposure to climate variability to demonstrate the mechanisms at work.

Despite some beneficial effects in colder regions, climate change is expected to worsen health outcomes substantially.

Climate change will alter the distribution and incidence of climate-related health impacts, ranging from a reduction in cold-related deaths to greater mortality and illness associated with heat stress, droughts and floods. Equally the geographic incidence of illnesses such as malaria will change.

As noted in Chapter 3, if there is no change in malaria control efforts, an additional 40 to 60 million people in Africa could be exposed to malaria with a 2°C rise in temperature, increasing to 70 to 80 million at 3 - 4°C.[35] Though some regions such as parts of West Africa may experience a reduction in exposure to vector borne diseases (see Chapter 3), previously unaffected regions may not have appropriate health systems to cope with and control malaria outbreaks. For poor people in slums, a greater prevalence of malaria – or cholera – may lead to higher mortality rates given poor sanitation and water quality, as well as malnutrition. In Delhi, for example, gastroenteritis cases increased by 25% during a recent heat wave as slum dwellers had to drink contaminated water.[36]

The additional heath risks will not only cost lives, but also increase poverty. Malnutrition, for example, reduces peoples' capacity to work and affects a child's mental development and educational achievements with life-long effects. The drought in Zimbabwe in 2000, for

[32] Data extracted from Munich Re (2004). These figures are calculated on the basis of the occurrence and consequences of 'great natural disasters'. This definition is in line with that used by the United Nations and includes those events that over-stretch the ability of the affected regions to help themselves. As a rule, this is the case when there are thousands of fatalities, when hundreds of thousands of people are made homeless or when the overall losses and/or insured losses reach exceptional orders of magnitude. While increases in wealth and population growth account for a proportion of this increase, it cannot explain it all (see Chapter 5 for more details). The losses are given in constant 2003 values.

[33] The true cost of disasters for developing countries is often undervalued. Much of the data on the costs of natural disasters is compiled by reinsurance companies and focused on economic losses rather than livelihood losses, and is unlikely to capture the effect of slow-onset and small-scale disasters and the impact these have on households. Furthermore, the assessments typically do not capture the cumulative economic losses as they are based on snapshots in time. Benson and Clay (2004)

[34] IMF (2003)

[35] Warren et al (2006)

[36] Huq and Reid (2005)

example, is estimated to have contributed to a loss of 7-12% of lifetime earnings for the children who suffered from malnutrition.[37] Managing the consequences of these health impacts can in itself lead to further impoverishment. Households face higher personal health expenditures through clinic fees, anti-malarial drugs and burials, for example. This was seen in the case of Vietnam where rising health expenditures were found to have pushed about 3.5% of the population into absolute poverty in both 1993 and 1998.[38] The effects can be macroeconomic in scale: malaria is estimated to have reduced growth in the most-affected countries by 1.3% per year.[39]

Falling agricultural output and deteriorating conditions in rural areas caused by climate change will directly increase poverty of households in poor countries.

Current experience of extreme weather events underlines how devastating droughts and floods can be for household incomes. For example:

- In North-Eastern Ethiopia, drought induced losses in crop and livestock between 1998 – 2000 were estimated at $266 per household – greater than the annual average cash income for more than 75% of households in the study region;[40]
- In Ecuador the 1997-98 El Niño contributed to a loss of harvest and rise in unemployment that together increased poverty incidence by 10 percentage points in the affected municipalities.[41]

These immediate impacts are often compounded by the rising cost of food - following the drought in Zimbabwe in 1991-92, for example, food prices increased by 72%[42] - and loss of environmental assets and ecosystems that would otherwise provide a safety net for poor people.

These risks and the scale of impacts may increase with climate change if people remain highly exposed to the agricultural sector and have limited resources to invest in water management or crop development. As discussed in Chapter 1, climate change is likely to result in more heatwaves, droughts, and severe floods. In addition to these short-term shocks in output, climate change also risks a long-term decline in agricultural productivity in tropical regions. As Chapter 3 notes, yields of the key crops across Africa and Western Asia may fall by between 15% to 35% or 5% to 20% (assuming a weak or high carbon fertilisation respectively) once temperatures reach 3 or 4°C. Such a decline in productivity would pose a real challenge for the poorest countries, especially those already facing water scarcity. In sub-Saharan Africa, for example, only 4% of arable land is currently irrigated and the effects of climate change may constrain the long-term feasibility of this investment.[43] Some extreme scenarios suggest that by 2100 the Nile could face a decrease in flow of up to 75%,[44] with normal irrigation practices having been found to cease when annual flow is reduced by more than 20%.[45]

Strategies to manage the risks and impacts of an adverse climate can lock people into long-term poverty traps.

The survival strategies adopted by poor people to cope with a changing climate may damage their long-term prospects. Equally, if there is a risk of more frequent extreme weather events, then households may also have shorter periods in which to recover, thus increasing the

---

[37] Alderman et al (2003)
[38] Wagstaff and van Doorslaer (2003)
[39] These results were estimated after controlling for initial poverty, economic policy, tropical location and life expectancy (using different time frames). Sachs and Gallup (2001)
[40] Carter et al (2004)
[41] Vos et al (1999)
[42] IMF (2003). This was largely due to the higher price of food that had to be imported following a drought induced reduction in agricultural output, as described in Box 4.2, coupled with an increase in inflation to 46%.
[43] Commission for Africa (2005)
[44] Strzepek et al (2001)
[45] Cited in Nkomo et al (2006)

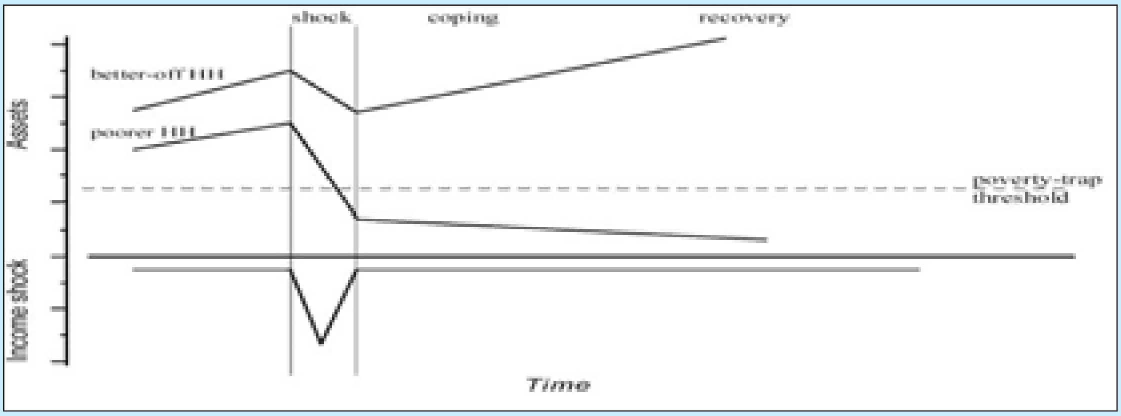
possibility of being pushed into a poverty-trap (as illustrated in Figure 4.4).[46] There are two aspects to this:

- *Risk-managing:* Poor households may switch to low risk crops. In India, for example, poor households have been found to allocate a larger share of land to safer traditional varieties of rice and castor than to riskier but high-return varieties. This response in itself can reduce the average income of these people. Households in Tanzania that allocated more of their land to sweet potatoes (a low return, low risk crop), for example, were found to have a lower return per adult.[47]

- *Risk-coping:* Poor households may also be forced to sell their only assets (such as cattle and land). This can then compromise their long-term prospects as they are unable to educate their children, or raise levels of income over time. Following the 1991-92 droughts in Zimbabwe, many households had to sell their goats that were intended as a form of savings to pay, for example, for secondary education.[48],[49] Alternatively, to try and avoid permanent destitution households may decide to reduce their current consumption levels. This strategy can have long-term effects on health and human capital.[50] Reductions in consumption levels during a drought in Zimbabwe, for example, led to permanent and irreversible growth losses among children - losses that would reduce their future educational and economic achievement.[51]

Figure 4.4 Impact of a climate shock on asset trajectory and income levels

This diagram illustrates: a) the period of shock itself (e.g. hurricanes or drought), b) the coping period in which households deal with the immediate losses created by the shock, and c) the recovery period where a household will try to rebuild the assets they have lost as a result of the climate shock or through the coping strategy they adopted.



Source: Carter et al (2005)

Climate change and variability cuts the revenues and increases the spending of nations, worsening their budget situation.

Dealing with climate change and extreme variability will also place a strain on government budgets, as illustrated in the case of Zimbabwe following the drought of 1991-92 (Box 4.2). The severity of the effect on government revenues will in part depend on the structure of the

---

[46] This refers to a minimum asset threshold beyond which people are unable to build up their productive assets, educate their children and improve their economic position over time. Carter et al (2005)
[47] Dercon (2003). Households with an average livestock holding in Tanzania were found to allocate 20% less of their land to sweet potatoes than a household with no liquid assets, with the return per adult of the wealthiest group being 25% higher for the crop portfolio compared to the poorest quintile.
[48] Hicks (1993)
[49] A household survey in eight peasant associations in Ethiopia found that distressed sales of livestock following the drought in 1999 sold for less than 50% of the normal price. Carter et al (2004)
[50] People can be pushed below a critical nutritional level whereby no productive activity is possible, with little scope for recovery given dependence on their own labour following the loss or depletion of their physical assets. Dasgupta and Ray (1986)
[51] Hoddinott (2004)

economy. For example, the drought in southern Africa in 1991-92 resulted in a fall in income of over 8% in Malawi where agriculture contributed 45% of GDP at the time, but only 2% of GDP in South Africa where just 5% of GDP was obtained from agriculture.[52] Climate change will also necessitate an increase in spending at the national level to deal with the aftermath of extreme weather events and the consequences of a gradual reduction in food and water supplies. For example, the logistical costs of importing cereal into drought affected southern African countries in 1991-92 alone were $500million.[53] In some cases, the expenditure requirements may be beyond the government's capacity. This was the case following Hurricane Mitch in 1998 where the Honduras government (with a GNP of $850 per capita) faced reconstruction costs equivalent to $1250 per capita.[54]

Box 4.2 Economic Impacts of Drought in Zimbabwe, 1991-92

In late 1991 to early 1992, Zimbabwe was hit by a severe drought. This resulted in a fall in production of maize, cotton and sugarcane by 83%, 72% and 61% respectively; the death/slaughter of more than 23% of the national herd; water shortages that led to the deterioration in quality and price of Zimbabwean tobacco; and reduction in hydro-electricity generation that affected industry and the mineral export sector. The direct impacts of the drought contributed to a doubling of the current account deficit from 6% to 12% of GDP between 1991 and 1992 and an increase in external debt from 36% of GDP in 1991 to 60% in 1992 and 75% by 1995. Government revenues fell in 1992-93 due to drought-induced loss of incomes, slowdown in non-food imports and slow-down in the private sector. Current expenditures increased by 2 percentage points of GDP in 1992-93 due predominantly to drought-related emergency outlays. Government expenditures on health and education were reduced as a share of the budget, in particular for primary education. By the end of 1992, real GDP had fallen by 9% and inflation increased to 46% with food prices having increased by 72%.

At the time of the drought the country was one of the better educated and more functional of states in sub-Saharan Africa. The more recent difficulties with governance, mismanagement and inflation, for example, were not anywhere near as problematic at the time of the drought.

Source: IMF (2003)

When governments face financial constraints, their response to the impacts of climate change and extreme variability – ranging from expenditure switching to additional financing through increasing debt levels - can itself amplify the negative effect on the growth and development of the economy. For example, if key investments to raise economic performance are deferred indefinitely.[55] In reality Official Development Assistance (ODA) will often step in to help fill this financing gap, as was the case in Honduras following Hurricane Mitch for example. However these emergency funds are rarely additional and often reallocated funds or existing commitments within multi-year country programmes brought forward.

The experience of past extreme weather events and episodes testifies to the damaging effect that an adverse climate can have on social and economic prospects in developing countries. If climate change increases the frequency and severity of these events, as the science suggests, the costs on developing countries will grow significantly unless considerable effort is made today to reduce their vulnerability and exposure. And coupled with this will be a longer-term decline in the environment that will have to be managed. This will exert greater pressure still on resources and declines in the productivity and output of climate sensitive sectors.

[52] IMF (2003); World Bank (2006a)
[53] Benson and Clay (2004). Similarly the climatically less severe 1994/95 drought involved costs of US$1 billion in cereal losses (due to higher prices in a tighter international cereal market).
[54] ODI (2005)
[55] IMF (2003)

4.4 What do global climate change models predict for developing countries?

Climate models predict a range of impacts on developing countries from a decrease in agricultural output and food security to a loss of vital river flows. The impacts are predominantly negative.

Evidence from the past and current extreme climate variability demonstrates the effect that a hostile climate can have on development. This section summarises some of the key findings from climate change impact studies undertaken by academics from particular developing regions to contribute to the Stern Review. These reports can be found on the Stern Review website (www.sternreview.org.uk). These summaries are not intended to be comprehensive but are rather more to highlight the key areas where climate change will be seen.

South Asia[56]

- India's economy and societal infrastructures are vulnerable to even small changes in monsoon rainfall. Climate change may increase the intensity of heavy rainfall events (the Mumbai floods of 2005 may be an example)[57] whilst the number of rainy days may decrease. Floods could become more extreme as a result with droughts remaining just as likely. Temperatures will increase for all months. Consequently, during the dry pre-monsoon months of April and May, the incidence of extreme heat is likely to increase, leading to greater mortality.
- Changes in the intensity of rainfall events, and the active / break cycles of the monsoon – combined with an increased risk of critical temperatures being exceeded more frequently – could significantly change crop yields. For example, mean yields for some crops in northern India could be reduced by up to 70% by 2100.[58] This is set against a background of a rapidly rising population that will need an additional 5 million tons of food production per year just to keep pace with the predicted increase in population to about 1.5 billion by 2030.
- Meltwater from Himalayan glaciers and snowfields currently supplies up to 85% of the dry season flow of the great rivers of the Northern Indian Plain. This could be reduced to about 30% of its current contribution over the next 50 years, if forecasts of climate change and glacial retreat are realised. This will have major implications for water management and irrigated crop production, as well as introducing additional hazards to highland communities through increasingly unstable terrain.[59]

Sub-Saharan Africa[60]

- Africa will be under severe pressure from climate change. Many vulnerable regions, embracing millions of people, are likely to be adversely affected by climate change, including the mixed arid-semiarid systems in the Sahel, arid-semiarid rangeland systems in parts of eastern Africa, the systems in the Great Lakes region of eastern Africa, the coastal regions of eastern Africa, and many of the drier zones of southern Africa (see Thornton et al).[61]
- Between 250–550 million additional people may be at risk of hunger with a temperature increase of 3°C, with more than half of these people concentrated in Africa and

[56] Information based largely on Challinor et al (2006). See also Roy (2006)
[57] As ever it is difficult to attribute an outside event to climate change but the evidence is strong that the severity of such events is likely to increase.
[58] Challinor et al (2006). 70% was the maximum reduction in yield that came from the study, in northern regions. Reductions in the 30-60% range were found over much of India. Strictly speaking these results are for groundnut only, although many annual crops are expected to behave similarly. The study was based on an SRES A2 scenario. The values assume no adaptation.
[59] Challinor et al (2006)
[60] Information based largely on Nkomo et al (2006)
[61] The regions at risk of climate change were identified by looking at the possibility of losses in length of growing period that was used as an integrator of changing temperatures and rainfall to 2050. This was projected by downscaling the outputs from several coupled Atmosphere-Ocean General Circulation Models for four different scenarios of the future using the SRES scenarios of the IPCC. Several different combinations of GCM and scenario were used. The vulnerability indicator was derived from the weighted sum of the following four components: 1) public health expenditure and food security issues; 2) human diseases and governance; 3) Human Poverty Index and internal renewable water resources; and 4) market access and soil degradation. (Thornton et al, 2006)

Western Asia.[62] And there are risks of higher temperatures still. Climate change is also predicted to decrease - and/or shift - the areas of suitable climate for 81% to 97% of Africa's plant species. By 2085, 25% - 42% of plant species could find they no longer have any suitable habitat.[63]

- Tens of millions of additional people could be at risk of malaria by the 2080s.[64] Previously unsuitable areas for malaria in Zimbabwe could become suitable for transmission with slight temperature and precipitations variations, whist in South Africa the area suitable for malaria may double with 7.8 million people at risk by 2100.[65]
- Water pressures may be intensified as rainfall becomes more erratic, glaciers retreat and rivers dry up. While there is much uncertainty about flow of the Nile, several models suggest a decrease in river flow, with nine recent climate scenario impacts ranging from no change to more than 75% reduction in flows by 2100.[66] This will have a significant impact on the millions of people that have competing claims on its supplies.
- Many large cities in Africa that lie on or very close to the coast could suffer severe damages from sea level rise. According to national communications to the UNFCCC, a 1 meter sea-level rise (a possibility by the end of the century) could result in the complete submergence of the capital city of Gambia, and losses of more than $470 million in Kenya for damage to three crops (mangoes, cashew nuts and coconuts).[67]

Latin America[68]

- Countries in Latin American and the Caribbean are significantly affected by climate variability and extremes, particularly the ENSO events.[69] The region's economy is strongly dependent on natural resources linked to climate, and patterns of income distribution and poverty exacerbate the impacts of climate change for specific sub-regions, countries and populations.
- Living conditions and livelihood opportunities for millions of people may be affected. By 2055 subsistence farmers' maize production (the main source of food security) in the Andean countries and Central America could fall by around 15% on average, for example, based on projections of HadCM2.[70] The potential die-back, or even collapse, of the Amazon rainforest (discussed in Chapter 3) presents a great threat to the region. The Amazonian forests are home to around 1 million people of 400 different indigenous groups, and provide a source of income and medical and pharmaceutical supplies to millions more.
- Climate change could contribute to a 70% rise in the projected number of people with severe difficulties in accessing safe water by 2025. About 40 million people may be at risk of water supply for human consumption, hydro-power and agriculture in 2020, rising to 50 million in 2050 through the predicted melting of tropical Andean glaciers between 2010 and 2050. The cities of Quito, Lima and La Paz are likely to be most affected. Dengue transmission is likely to increase by 2 to 5 fold by the 2050s in most areas of South America and likely that new transmission areas will appear in the southern half of the continent and at higher elevations.

[62] Cited in Warren *et al* (2006) based on the original analysis of Parry et al. (2004). These figures assume future socio-economic development, but no carbon fertilisation effect, as discussed in Chapter 3.
[63] McClean et al (2005). This is estimated using the Hadley Centre third generation coupled ocean-atmosphere General Circulation Model.
[64] van Lieshout et al (2004)
[65] Republic of South Africa (2000) cited in Nkomo et al (2006)
[66] Strzepek et al (2001)
[67] Gambia (2003) and Republic of Kenya (2002) cited in Nkomo et al (2006)
[68] Information based on Nagy et al (2006)
[69] El Nino-Southern Oscillation events (as discussed in Chapter 1).
[70] Jones and Thornton (2003), cited in Nagy et al (2006)

China[71]

- There is significant variation in climatic patterns across China's regions including arid, temperate and mountainous regions. The average surface air temperature in China has increased by between 0.5 and 0.8°C over the 20th century with increases more marked in North China and Tibetan Plateau compared to southern regions. Temperature rise will lead to temperate zones in China moving north as well as an extension of arid regions. Cities such as Shangai are expected to experience an increase in the frequency and severity of heat waves causing significant discomfort to fast growing urban populations.
- Overall water scarcity is a critical problem in China with existing water shortages, particularly in the north (exacerbated by economic and population growth). Climate change is expected to increase water scarcity in northern provinces such as Ningxia, Gansu, Shanxi and Jilin province. An increase in average rainfall in southern provinces such as Fujian, Zhejiang and Jiangxi is anticipated over the next 50 to 100 years leading to more instances of flooding. From 1988 to 2004, China experienced economic losses from drought and flood equating to 1.2% and 0.8% of GDP respectively.
- Climate change is expected to have mixed effects on agricultural output and productivity across different regions with impacts closely related to changes in water availability. On average, irrigated land productivity is expected to decrease between 1.5% to 7% and rain fed land by between 1.1% to 12.6% under rain- fed conditions from 2020s to 2080s under HadCM2, CGCM1 and ECHAM4 scenarios in China.[72] Overall a net decrease in agriculture production is anticipated with seven provinces in the north and northwest of China particularly vulnerable (accounting for ¼ of total arable land and 14% of China's total agricultural output by value).[73]

Middle East and North Africa

- The region is already very short of fresh water and faces difficulty meeting the needs of fast-growing populations. Most if not all the region may be adversely affected by changing rainfall patterns as a result of climate change. An additional 155 to 600 million people may be suffering an increase in water stress in North Africa with a 3°C rise in temperature according to one study.[74] Yemen is particularly at risk given its low income levels, rapidly growing populations and acute water shortages today. Competition for water within the region and across its borders may grow, carrying the risk of conflict.
- Reduced water availability combined with even modestly higher temperatures will reduce agricultural productivity and in some areas may make crops unsustainable. Maize yields in North Africa, for example, could fall by between 15-25% with a 3°C rise in temperature according to one recent report.[75]
- Some parts of the region – notably the Nile Delta and the Gulf coast of the Arabian peninsula - are in addition vulnerable to flooding from rising sea levels which could lead to loss of agricultural land and/or threats to coastal cities. Others are vulnerable to increased desertification.

Climate change poses a wide range of potentially very severe threats to developing countries. Understanding the impact of climate change on developing countries – at both a regional and national level - is essential to get a better understanding of the scale of threat and urgency of mitigation action, but also to help prepare for some of the now inevitable impacts of climate change. To date, however, analysis undertaken in developing countries of potential threats and impacts has been very limited. Many climate changes are on the way and foresight and action will be crucial if damages to development progress are to be managed both by the private and by public sectors. Further work is required on studying the impacts of climate change on developing countries at a national, regional and global level.

[71] Information based on Erda and Ji (2006)
[72] Tang Guoping et al (2000)
[73] NBSC (2005)
[74] Warren et al (2006)
[75] Warren et al (2006)

4.5 Impact of climate change on economic growth prospects and implications for incomes and health

Over time, there is a real risk that climate change will have adverse implications for growth. This section looks at how income levels and growth have been affected by extreme climate variability and then moves on to summarise illustrative modelling work undertaken as part of the review. If climate change results in lower output and growth levels than would otherwise be the case, there will be implications for poverty levels. But income levels also affect health, and mortality rates will rise above what they would otherwise have been, in addition to any immediate health impacts through illnesses such as malaria. The previous section reviewed a range of projected direct climate impacts on factors affecting lives and livelihoods that recent research has highlighted. This section provides an analysis of their possible impacts on income and health.

Extreme weather events can – and do – affect growth rates in developing countries. Climate change presents a greater threat still.

The output of an economy in a given year depends on labour, environmental quality and capital available in that year (illustrated, for example, in Box 5.1 of Chapter 5). All three will be affected by climate change – be it through the damaging effects on the health and productivity of the labour force, the loss and damage to agriculture and infrastructure, or lower quality investment and capital. As the output and factors of production of an economy are repeatedly affected, so growth prospects will change. This will be particularly true for poorer economies with a stronger focus on agriculture and with less ability to diversify their economies.[76]

The effects of current extreme climate variability demonstrate the potential impact a changing climate can have on output and growth. Changes in the hydrological cycle can be especially damaging. Too much rainfall can inundate transport, for example, limiting trade potential and communication. It has been estimated that the 2000 floods in West Bengal destroyed 450km of rail track and 30 bridges and culverts, and adversely affected 1739km of district roads, 1173km of state highways and 328km of national highways.[77] Too little rainfall will affect crop production but also reduce the flow of surface water that could provide irrigation and hydroelectricity production. The La Niña drought in Kenya**,** for example, caused damage to the country amounting to 16% of GDP in each of 1998–99 and 1999–2000 financial years, with 26% of these damages due to hydropower losses and 58% due to shortfalls in industrial production.[78]

Economy-wide, multi-market models that incorporate historical hydrological variability project that hydrological variability may cut average annual GDP growth rates in Ethiopia by up to 38% and increase poverty rates by 25%.[79] These models capture the impacts of both deficit and excess rainfall on agricultural and non-agricultural sectors. As climate change increases the variability of rainfall, the scale of these growth impacts could rise significantly.

[76] Increased agricultural productivity has been identified as a key factor in reducing poverty and inequality. This is based on work undertaken by Bourguignon and Morrisson (1998) using data from a broad sample of developing countries in the early 1970s and mid 1980s. Evidence from Zambia, for example, suggests that an extra US$1.5 of income is generated in other businesses for every $1 of farm income. Hazel and Hojjati (1995). Similarly, Block and Timer (1994) estimated an agricultural multiplier in Kenya of 1.64 versus a non-agricultural multiplier of 1.23 in Kenya.
[77] Cited in Roy (2006)
[78] World Bank (2006c)
[79] World Bank (2006c). The model shows growth projections dropping 38% when historical levels of hydrological variability are assumed, relative to the same model's results when average annual rainfall is assumed in all years. Hydrological variability included drought, floods and normal variability of 20% around the mean.

Slower growth could cause an increase in poverty and child mortality relative to a world without climate change, as found by illustrative modelling work undertaken by and for the Stern Review.

The Stern Review has used the PAGE2002 model (an integrated assessment model that takes account of a wide range of risks and uncertainties) to assess how climate change may affect output and growth in the future.[80] Integrated assessment models can be useful vehicles for exploring the kinds of costs that might follow from climate change. However, these are highly aggregative and simplified models and, as such, the results should be seen as illustrative only.

By 2100, under a baseline-climate-change scenario,[81] the mean cost of climate change in India and South East Asia, and in Africa and the Middle East is predicted by PAGE2002[82] to be equivalent to around a 2.5% and 1.9% loss in GDP respectively, compared with what could have been achieved in a world without climate change. Under a high-climate-change scenario,[83] the mean cost of climate change is predicted by PAGE2002 to be 3.5% in India and South East Asia, and 2.7% in Africa and the Middle East.

There are good reasons, however, for giving more emphasis to the higher (95th percentile) impacts predicted in these scenarios, as the model is unlikely to capture the full range of costs to developing countries. In particular:

- The poorest people will be hit the hardest by climate change, an effect for which the highly aggregated models do not allow;
- There are specific effects, such as possible loss of Nile waters and the cumulative effects of extreme weather events (as discussed above), that aggregated global and regional models do not capture;
- This is a long-term story. If emissions continue unabated, temperatures will rise to much higher levels in the next century, committing these regions to far greater impacts (as discussed in Chapters 3 and 6), including the risks associated with mass migration and conflict discussed in the next section;

At the 95th percentile, and under the baseline-climate-change scenario, the projections rise to a 9% loss in GDP in India and South East Asia, and a 7% loss in Africa and the Middle East by 2100. And, under the high-climate-change scenario, the costs of climate change rise significantly to losses of 13% and 10% in GDP respectively (again at 95th percentile).

Given the strong correlation between growth and poverty reduction (see Box 4.3), a climate-driven reduction in GDP would increase the number of people below the $2 a day poverty line by 2100, and raise the child mortality rate compared with a world without climate change. This is illustrated below by modelling work undertaken for the Stern Review. This analysis assumes reductions in poverty and child mortality are driven primarily by GDP growth.[84] As with the PAGE2002 model itself, projections that extend so far into the future should be treated with caution, but are useful for illustrative purposes. The projections summarised below focus only on income effects.

---

[80] This model picks up the aggregate impacts of climate change on a range of market sectors such as agriculture. The estimates used in this analysis are based on the impact of climate change on market sectors. PAGE2002 allows examination of either market impacts only (as used here to ensure no double counting of poverty impacts) or market plus non-market impacts. These estimates and further details on the PAGE2002 model are given in Chapter 6.

[81] The baseline-climate-change scenario is based largely on scientific evidence in the Third Assessment Report of the IPCC, in which global mean temperature increases to 3.9°C in 2100 (see Chapter 6 for more detail).

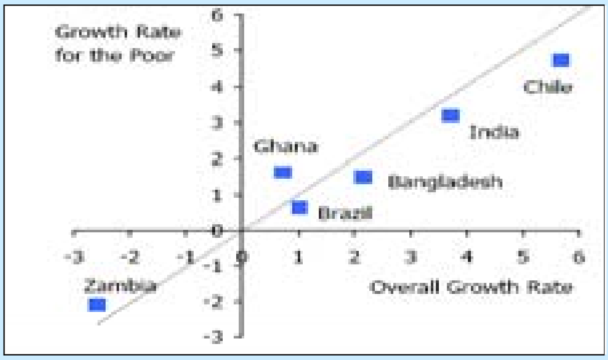
[82] Using the IPCC A2 SRES baseline

[83] In the high-climate-change scenario, global mean temperature increases to 4.3°C in 2100. The high-climate-scenario is designed to explore the impacts that may be seen if the level of temperature change is pushed to higher levels through positive feedbacks in the climate system, as suggested by recent studies (see Chapter 1 and Chapter 6 for more detail).

[84] Other factors – such as changes in income distribution – that may also affect poverty levels or child mortality are assumed to be constant.

Box 4.3 Relationship between growth and development

Countries with higher overall growth rates tend to have higher growth in incomes of poor people. Poverty is estimated to decline on average by 2% for a 1 percentage point rise in economic growth across countries.[85] Kraay estimates that, over the short run, growth accounts for about 70% of the variation in poverty (as measured by a $1 a day poverty line). As the time horizon lengthens, that proportion increases to above 95%.[86] There is a close relationship between growth and many non-income indicators of development, ranging from under-five mortality to educational attainment and peace and security. Income-earning opportunities provide citizens with a vested interest in avoiding conflict, and security allows governments to invest in productive assets and social expenditures, rather than defence. East Asia has grown rapidly (5.8% in the 80s and 6.3% in the 90s) and has seen the fastest fall in poverty in human history. An annual growth of more than 7% will be needed to halve severe poverty in Africa by 2015 (and a 5% annual growth is required just to keep the number of poor people from rising).[87]



zSource: World Bank (2003c)

While growth is clearly an important contributor to poverty reduction, much depends on how the benefits of this growth are distributed and the extent to which the additional resources generated are used to fund public services such as healthcare and education. Poor people benefit the most from economic growth when it occurs in those parts of the economy that offer higher returns for poor people's assets.

Poverty projections

By 2100, climate change could cause an additional 145 million people to be living on less than $2 a day in South Asia and sub-Saharan Africa (100 million people and 45 million people respectively) because of GDP losses alone at the 95th percentile of the baseline-climate-change scenario and runs, or 35 million people at the mean of these runs.

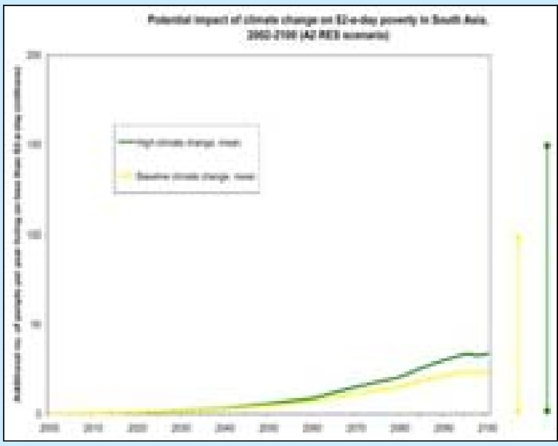
Under the high-climate-change scenario at the 95th percentile, up to an additional 220 million people could be living on less than $2 a day in South Asia and sub-Saharan Africa (150 million people and 70 million people respectively), because of GDP losses alone. The effects at the mean of the distribution are smaller but still significant: up to an additional 50 million people living on less than $2 a day per year.

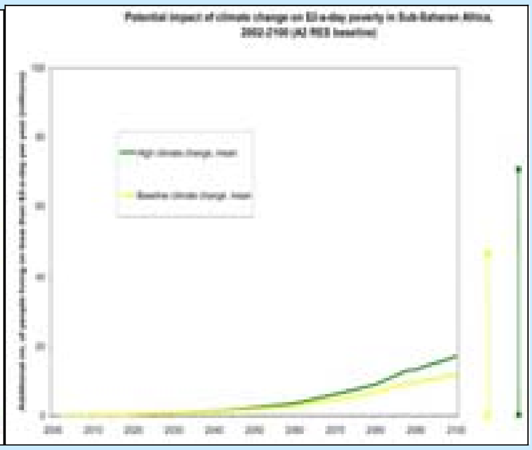
These projections are illustrated in Box 4.4 below. If growth proceeds faster than predicted, then the overall numbers of people living on below $2 per day will be less, while if it is slower, there will be more people pushed into poverty. These calculations should be viewed as indicative of the risks.

[85] Ravallion (2001)
[86] Kraay (2005)
[87] World Bank (2000)

Box 4.4 Potential impact of climate change on additional people living on less than $2 a day in South Asia and sub-Saharan Africa

These projections are calculated using the formulae for the poverty headcount used in World Bank calculations,[88] population forecasts, and the assumptions that average household income grows at 0.8 times the rate of GDP per capita[89] and distribution of income remains constant.





Source: Anderson (2006)

Child mortality projections

There is also a well-studied relationship between reduced income and child mortality. Falling income and GDP levels from what could have been achieved in a world without climate change will slow the improvement of child (and adult) health in developing countries.[90] Lower per capita expenditures are likely on goods that improve health, such as safe water, food and basic sanitation at both a public and private level. Previous econometric studies have reported a range of values for the income elasticity of infant and child mortality, the vast majority falling between –0.3 and –0.7. Taking an elasticity of 0.4, for example, implies that a 5% fall in GDP from what could have been achieved in a world without climate change will lead to a 2% increase in infant mortality.[91] This analysis uses a value of -0.5 for the elasticity of the child mortality rate (deaths per 1,000 births) with respect to per capita income, the mid-point of this range.[92]

Using the illustrative output and growth scenarios generated by PAGE2002, climate change could cause an additional 40,000 (mean) to 165,000 (95th percentile) child deaths per year in South Asia and sub-Saharan Africa through GDP losses alone under the baseline-climate-change scenario.

Under the high-climate-change scenario, climate change could cause an additional 60,000 (mean) to 250,000 (95th percentile) child deaths per year by 2100 in South Asia and sub-

[88] The formulae express the level of poverty as a function of the poverty line, average household income and the distribution of income. The $2 poverty line is used throughout.

[89] This figure is obtained from a cross-country regression of rates of growth in mean household expenditure per capita on GDP per capita. Ravaillion (2003)

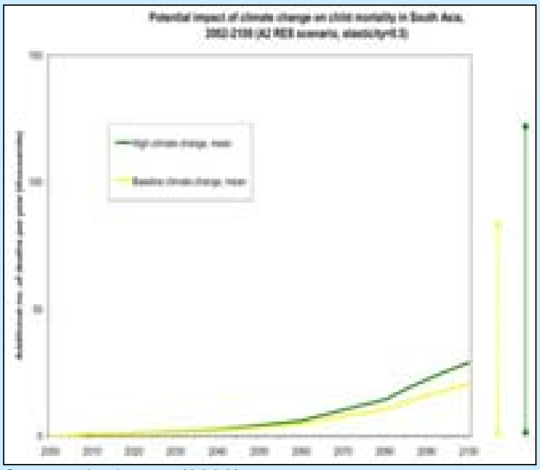
[90] It is important to note that income alone does not determine health outcomes, efficient public programmes and access to education for women are also important factors, for example. Furthermore, the way in which GDP per capita changes (for example if there is a change in the distribution of income that coincides with the change in national income) can affect the impact it has on health.

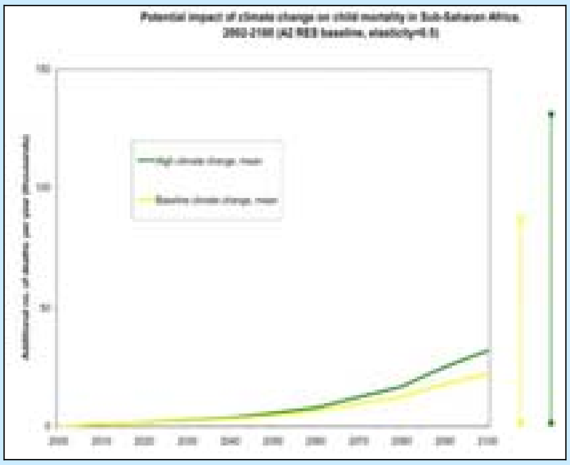
[91] Analysis demonstrates the health effects today of slowing or negative per capita growth. For example, in 1990, over 900,000 infant deaths would have been prevented had developing countries been able to maintain the same rate of growth in the 1980s as in the period 1960-80 (assuming an elasticity of -0.4), rather than the slow or negative growth they in fact experienced. The effects were particularly significant in African and Latin America, where growth was lower by 2.5% on average (Pritchett and Summers, 1993).

[92] The elasticity is assumed to be a constant across countries and over time, consistent with econometric evidence (such as Kakwani (1993)). However, the average elasticity of child mortality with respect to GDP over a period of time will typically not be the same as the actual elasticity that applies on a year-to-year basis, even if the latter is assumed constant, because of compounding.

Saharan Africa through GDP losses alone 2100, and compared with a world without climate change. These projections are illustrated in Box 4.5 below.

Box 4.5 Potential impact of climate change on additional child deaths per year in South Asia and sub-Saharan Africa





Source: Anderson (2006)

The above projections pick up the pure income effect of climate change on poverty and child mortality through its dampening effect on GDP, and do *not* include the millions of people that will be exposed to heat stress or malaria, or risk losing their jobs, assets and livelihoods through extreme weather events, for example, as discussed in Section 4.3. This analysis and projections are simply illustrative of possible risks associated with a loss in income through climate change.

4.6 Population movement and risk of conflict

Greater resource scarcity, desertification, risks of droughts and floods, and rising sea levels could drive many millions of people to migrate – a last-resort adaptation for individuals, but one that could be very costly to them and the world.

The impacts of climate change, coupled with population growth in developing countries, will exert significant pressure for cross-border and internal population movement. There is already evidence of the pressure that an adverse climate can impose for migration. Approximately 7 million people migrated in order to obtain relief food out of the 80 million considered to be semi-starving in sub-Saharan Africa primarily due to environmental factors.[93]

Millions of people could be compelled to move between countries and regions, to seek new sources of water and food if these fall below critical thresholds. Rising sea levels may force others to move out of low-lying coastal zones. For example, if sea levels rise by 1 metre (a possible scenario by the end of the century, Chapter 3) and no dyke enforcement measures are taken, more than one-fifth of Bangladesh may be under water for example.[94] And atolls and small islands are at particular risk of displacement with the added danger of complete abandonment. As one indication of this, the government of Tuvalu have already begun negotiating migration rights to New Zealand in the event of serious climate change impacts.[95]

The total number of people at risk of displacement or migration in developing countries is very large. This ranges from the millions of people at risk of malnutrition and lack of clean water to those currently living in flood plains. Worldwide, nearly 200 million people today live in coastal flood zones that are at risk; in South Asia alone, the number exceeds 60 million people.[96] In

[93] Myers (2005)
[94] Nicholls (1995) and Anwar (2000/2001)
[95] Barnett and Adger (2003)
[96] Warren *et al.* (2006) analysing data from Nicholls (2004), Nicholls and Tol (2006) and Nicholls and Lowe (2006). This is calculated on the basis of the number of people that are exposed each year to storm surge elevation that has

addition, there are potentially between 30 to 200 million people at risk of hunger with temperature rises of 2 to 3°C – rising to 250 to 550 million people with a 3°C warming;[97] and between 0.7 to 4.4 billion people who will experience growing water shortages with a temperature rise of 2°C,[98] as discussed in Chapter 3.

The exact number of people who will actually be displaced or forced to migrate will depend on the level of investment, planning and resources at a government's disposal to defend these areas or provide access to public services and food aid. The Thames Barrier, for example, protects large parts of London. In Shanghai and Tokyo, flood defences and pumped drainage prevent flooding of areas lying below normal tides.

Protection is expensive, however, particularly relative to income levels in developing countries. A project to construct 8,000 kilometres of river dykes in Bangladesh – a country with a GNI of $61 billion - is costing $10 billion. These high costs will discourage governments from investing. Defensive investments must be made early to be effective, but they may be politically unpopular if they would divert large amounts of money from programmes with more immediate impact such as infrastructure, health and education.

Drought and other climate-related shocks may spark conflict and violence, as they have done already in many parts of Africa.

The effects of climate change - particularly when coupled with rapid population growth, and existing economic, political, ethnic or religious tensions - could be a contributory factor in both national and cross-border conflicts in some developing countries.

- Long-term climate deterioration (such as rising temperatures and sea levels) will exacerbate the competition for resources and may contribute to forced dislocation and migration that can generate destabilising pressures and tensions in neighbouring areas.

- Increased climate variability (such as periods of intense rain to prolonged dry periods) can result in adverse growth shocks and cause higher risks of conflict as work opportunities are reduced, making recruitment into rebel groups much easier. Support for this relationship has been provided by empirical work in Africa, using rainfall shocks as an instrument for growth shocks.[99]

Adverse climatic conditions already make societies more prone to violence and conflict across the developing world, both internally and cross-border. Long periods of drought in the 1970s and 1980s in Sudan's Northern Darfur State, for example, resulted in deep, widespread poverty and, along with many other factors such as a breakdown in methods of coping with drought, has been identified by some studies as a contributor to the current crisis there.[100] Whilst climate change can contribute to the risk of conflict, however, it is very unlikely to be the single driving factor. Empirical evidence shows that a changing and hostile climate has resulted in tension and conflict in some countries but not others. The risk of climate change sparking conflict is far greater if other factors such as poor governance and political instability, ethnic tensions and, in the case of declining water availability, high water interdependence are already present. In light of this, West Africa, the Nile Basin and Central Asia have been identified as regions potentially at risk of future tension and conflict. Box 4.6 indicates areas vulnerable to future tension and past conflicts where an adverse climate has played an important role.

a one in a thousand year chance of occurring. These odds and the numbers explored could be rising rapidly. This has already been demonstrated in the case of heat waves in Southern Europe where the chance of having a summer as hot as in 2003 that in the past would be expected to occur once every 1000 years, will be commonplace by the middle of the century due to climate change, as discussed in Chapter 5.

[97] Warren et al. (2006) based on the original analysis of Parry *et al.* (2004).

[98] Warren et al. (2006) based on the original analysis of Arnell (2004) for the 2080s.

[99] Miguel et al (2004), Collier and Hoeffler (2002), Hendrix and Glaser (2005) and Levy et al (2005)

[100] University for Peace Africa Programme (2005)

Box 4.6 Future risks and past conflicts

Future risks

- *West Africa:* Whilst there is still much uncertainty surrounding the future changes in rainfall in this part of the world, the region is already exposed to declining average annual rainfall (ranging from 10% in the wet tropical zone to more than 30% in the Sahelian zone since the early 1970s) and falling discharge in major river systems of between 40 to 60% on average. Changes of this magnitude already give some indication of the magnitude of risks in the future given that we have only seen 0.7°C increase and 3°C or 4°C more could be on the way in the next 100 to 150 years. The implications of this are amplified by both the high water interdependence in the region - 17 countries share 25 transboundary watercourses – and plans by many of the countries to invest in large dams that will both increase water withdrawals and change natural water allocation patterns between riparian countries.[101] The region faces a serious risk of water-related conflict in the future if cooperative mechanisms are not agreed.[102]

- *The Nile:* Ten countries share the Nile.[103] While Egypt is water scarce and almost entirely dependent on water originating from the upstream Nile basin countries, approximately 70% of the Nile's waters flow from the Ethiopian highlands. Climate change threatens an increase in competition for water in the region, compounded by rapid population growth that will increase demand for water. The population of the ten Nile countries is projected to increase from 280 million in 2000 to 860 million by 2050. A recent study by Strzepek et al (2001) found a propensity for lower Nile flows in 8 out of 8 climate scenarios, with impacts ranging from no change to a roughly 40% reduction in flows by 2025 to over 60% by 2050 in 3 of the flow scenarios.[104] Regional cooperation will be critical to avoid future climate-driven conflict and tension in the region.

Past conflicts

- *National conflict*: Drought in Mali in the 1970s and 1980s damaged the pastoral livelihoods of the semi-nomadic Tuareg. This resulted in many people having to seek refuge in camps or urban areas where they experienced social and economic marginalisation or migrated to other countries. On their return to Mali, these people faced unemployment and marginalisation which, coupled with the lack of social support networks for returning migrants, continuing drought and competition for resources between nomadic and settles peoples (among many other things), helped create the conditions for the 'Second Tuareg Rebellion' in 1990. A similar scenario has played out in the Horn of Africa,[105] and may now be replicating itself in northern Nigeria, where low rainfall combined with land-use pressures have reduced the productivity of grazing lands, and herders are responding by migrating southward into farm areas.[106]

- *Cross-border conflict:* Following repeated droughts in the Senegal River Basin in the 1970s - 80s, the Senegal River Basin Development Authority was created by Mali, Mauritania and Senegal with the mandate of developing and implementing a major water infrastructure programme. Following the commissioning and completion of agreed dams, conflict erupted between Senegal and Mauritania when the river started to recede from adjacent floodplains. The dispute and tension escalated with hundreds of Senegalese residents being killed in Mauritania and a curfew imposed by both Governments such that 75,000 Senegalese and 150,000 Mauritanians were repatriated by June 1989. Diplomatic relationships between the two countries were restored in 1992, but a virtual wall has effectively been erected along the river.[107] Drought has also caused conflict between

[101] For example, there are 20 plans in place to build large dams along the Niger River alone.
[102] Niasse (2005)
[103] Ethiopia, the Sudan, Egypt, Kenya, Uganda, Burundi, Tanzania, Rwanda, the Democratic Republic of Congo and Eritrea.
[104] Strzepek et al (2001). Whilst there is general agreement regarding an increase in temperature with climate change that will lead to greater losses to evaporation, there is more uncertainty regarding the direction and magnitude of future changes in rainfall. This is due to large differences in climate model rainfall predictions.
[105] Meier and Bond (2005)
[106] AIACC (2005)
[107] Niasse (2005)

Ugandan and Kenyan pastoralists, and has led Ethiopian troops to move up north to stop the Somalis crossing the border in search of pasture and water for their livestock.[108] Similarly, extreme weather events in 2000 that affected approximately 3 million people in Bangladesh resulted in migration and violence as tribal people in North India clashed with emigrating Bangladeshis.[109]

4.7 Implications of Climate Change on other Aspects of Development

All development aspirations could be affected by climate change. Education and gender goals, for example, will be at risk to the effects of climate change, in turn further amplifying vulnerability to the impacts of climate change (as discussed in Box 4.7). Limited research has been undertaken on the impact of climate change to date on these important aspects of development. This merits much greater attention going forward.

Box 4.7 Impact of Climate change on Education and Gender Equality

Education

Climatic disasters can threaten educational infrastructure making it physically impossible for children to attend school. For example in 1998 Hurricane Mitch destroyed 25% of Honduras' schools.[110] Education levels may also decline through climate-induced changes in income and health conditions. Schooling will become less affordable and accessible, especially for girls, as income, assets and employment opportunities are affected by climate change. Children will need to help more with household tasks or prematurely engage in paid employment leaving less time for schooling. Deteriorating health conditions will also affect both a child's learning abilities and school attendance, and the supply of teachers. Children will be deprived of the long-term benefits of education and be more vulnerable to the effects of climate change. Better-educated farmers, for example, absorb new information quickly, use unfamiliar inputs, and are more willing to innovate. An additional year of education has been associated with an annual increase in farm output of between 2 to 5%.[111]

Gender equality

Gender inequalities will likely worsen with climate change. Workloads and responsibilities such as collecting water, fuel and food will grow and become more time consuming in light of greater resource scarcity. This will allow less time for education or participation in market-based work. A particular burden will be imposed on those households that are short of labour, further exacerbated if the men migrate in times of extreme stress leaving women vulnerable to impoverishment, forced marriage, labour exploitation and trafficking.[112] Women are 'over-represented' in agriculture and the informal economy, sectors that will be hardest hit by climate change. This exposure is coupled with a low capacity to adapt given their unequal access to resources such as credit and transport. Women are also particularly vulnerable to the effects of natural disasters with women and children accounting for more than 75% of displaced persons following natural disasters.[113]

4.8 Conclusion

The impacts of climate change will exacerbate poverty – in particular through its effects on health, income and future growth prospects. Equally, poverty makes developing countries more vulnerable to the impacts of climate change. This chapter has discussed some of the specific risks faced by developing countries. However it is the sum of the parts that creates perhaps the greatest concern. Poor households and governments may, for example, face falling food and water supplies that will increase poverty directly, while also facing greater health risks - for example, through malaria or as a result of extreme weather events. These impacts may be compounded if governments' have limited – or reduced - financial resources

[108] Christian Aid (2006)
[109] Tanzler et al (2002)
[110] ODI (2005)
[111] This takes into account farm size, inputs, hours worked etc. This is drawing on evidence from Malaysia, Ghana and Peru Information drawn from Birdsall (1992)
[112] Chew and Ramdas (2005)
[113] Chew and Ramdas (2005)

to manage these impacts, and to invest in building resilience against the future impacts of climate change. An important priority for future research will be to identify the type and scale of climate change impacts on developing countries and to understand more deeply the nature of these compounding, aggregated effects.

The threats posed by climate change increase the urgency of promoting growth and development today. This is key to reducing the vulnerability of developing countries to some of the now inevitable impacts of climate change, and enabling them to better manage these impacts. But adaptation can only mute the effects and there are limits to what it can achieve.

Unchecked, climate change could radically alter the prospects for growth and development in some of the poorest countries. This underlines the urgency of strong and early action to reduce greenhouse gas emissions. This is discussed further in part III of the report.

References

Abramovitz, J. N. (2001): 'Averting unnatural disasters' in State of the World 2001: A Worldwatch Institute Report on Progress Toward a Sustainable Society, Brown L. R., C. Flavin, and H. French, New York: W. W. Norton & Company.

AIACC (2005): 'For Whom the Bell Tolls: Vulnerabilities in a changing climate' Washington, DC: AICC Working Papers.

Alderman, H., J. Hoddinott, and B. Kinsey (2003): 'Long term consequences of early childhood malnutrition' FCND Discussion Paper 168, Washington, DC: International Food Policy Research Institute (IFPRI).

Anderson, E. (2006): Potential impacts of climate change on $2-a-day poverty and child mortality in Sub-Saharan Africa and South Asia. Mimeo, Overseas Development Institute, London.

Angelsen, A. and S. Wunder (2003): Exploring the forest–poverty link: key concepts, issues and research implications. Occasional Paper No. 40. Bogor, Indonesia: Center for International Forestry Research.

Anwar, A. (2000/2001): 'Vulnerability of Bangladesh coastal region to climate change with adaptation options', Bangladesh: SPARRSO.

Arnell, N.W. (2004): 'Climate change and global water resources: SRES emissions and socio-economic scenarios', Global Environmental Change **14**: 31 – 52

Arnold, J. E. M. (2001): Forestry, poverty and aid. Occasional Paper No 33. Bogor, Indonesia: Center for International Forestry Research.

Auffret, P. (2003), "High consumption volatility: the impact of natural disasters," World Bank Working Paper 2962, Washington, DC: World Bank.

Barnett, J. and W.N. Adger (2003): 'Climate dangers and atoll countries', Climatic Change **61**: 321-337

Belcher, B., M. Ruiz-Perez, and R. Achdiawan (2003): "Global Patterns and Trends in Non-Timber Forest Product Use." International Conference on Rural Livelihoods, Forest and Biodiversity. Bonn, Germany, 20–23 May 2003.

Benson, C. and E. Clay (2004): 'understanding the economic and financial impacts of natural disasters', Washington, DC: World Bank.

Birdsall, N. (1992): 'Social development is economic development' Presentation to delegates of Social Committee, United Nations General Assembly, October 19, D3934.

Block, S. and C.P. Timmer (1994): 'Agriculture and economic growth: conceptual issues and the Kenyan experience', Cambridge, MA: Harvard Institute for International Development.

Bourguignon, F. and C. Morrisson (1998): 'Inequality and development: the role of dualism', Journal of Development Economics **57**: 233-58

Brown, C. and U. Lall, (2006): 'Water and economic development: the role of interannual variability and a framework for resilience', Working Paper, Columbia University, NY: International Research Institute for Climate Prediction.

Carter, M.R., P.D. Little, T. Mogues and W. Negatu (2005): 'The long-term impacts of short-term shocks: poverty traps and environmental disasters in Ethiopia and Honduras', Wisconsin: BASIS.

Carter, M.R., P.D. Little, T. Mogues and W. Negatu (2004): 'Shock, sensitivity and resilience: tracking the economic impacts of environmental disaster on assets in Ethiopia and Honduras'. Wisconsin: BASIS.

CGAP (2004): 'Financial Institutions with a 'double bottom line': implications for the future of microfinance' Occasional Paper No 8.

Challinor, A., J. Slingo, A. Turner, and T. Wheeler (2006): 'Indian monsoon: contribution to chapter 4 of Stern Review', University of Reading.

Chew, L. and K.N. Ramdas (2005): 'Caught in the storm: impact of natural disasters on women'. San Fransisco, CA: Global Fund for Women.

Christian Aid Report (2006): 'The climate of poverty: facts, fears and hope'. May 2006, London: Christian Aid.

Collier, P. and Hoeffler, A. (2001): 'Greed and grievance in civil war'. Washington, DC: World Bank

Collier, P. and A. Hoeffler (2002): 'On the incidence of civil war in Africa'. Journal of Conflict Resolution **46** (1): 13-28

Commission for Africa (2005): 'Our common interest – report of the Commission for Africa', London: Penguin.

Conway, D. (2005): 'From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile Basin', Global Environmental Change, 2005, 99-114.

UN (2005): 'The Millennium Development Goals Report'. New York: United Nations Department of Public Information.

Cox, P.M., R.A. Betts, C.D. Jones, et al. (2000): 'Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model', Nature **408**: 184-187

Dasgupta, P. and D. Ray (1986): Inequality as a determinant of malnutrition and unemployment: theory', Economic Journal, **90**, December: 1011-34

De, U.S., R.K. Dube and G.S. Prakasa Rao, (2005): 'Extreme weather events over India in the last 100 years' J. Ind Geophys. Union (July 2005) **9** (3): 173-187

Dercon, S. (2003): 'Poverty traps and development: the equity-efficiency trade-off revisited'. Paper prepared for the Conference on Growth, Inequality and Poverty, organised by the Agence francaise de development and the European Development Research Network (EUDN).

Erda, L. and Ji, Z. et al (2006): 'Climate Change Impacts and its Economics in China', Report prepared for the Stern Review, available from http://www.sternreview.org.uk.

Freeman, P. K., L.A. Martin, R. Mechler, et al. (2002): 'Catastrophes and development: integrating natural catastrophes into development planning,' World Bank DMF Paper 1, Washington, DC: World Bank.

Gambia (2003): 'First national communication of the republic of the Gambia to the United Nations Framework Convention on Climate Change'.

Guoping, T., L. Xiubin, G. Fischer, and S. Prieler (2000): Climate change and its impacts on China's agriculture. Acta Geographic Sinica, vol.55 (2), p129-138.

Hazell, P. and B. Hojjati (1995): 'Farm–nonfarm linkages in Zambia'. Journal of African Economies **4** (3): 406-435

Hendrix, C. S., and S.M. Glaser (2005): 'Trends and triggers: climate change and civil conflict in sub-Saharan Africa, human security and climate change: an international workshop', 21-23 June 2005.

Hewawasam, I. (2002): 'Managing the marine and coastal environment of sub-Saharan Africa. Strategic directions for sustainable development'. Washington, DC: World Bank.

Hicks, D. (1993): 'an evaluation of the Zimbabwe drought relief programme 1992/93: the roles of household level response and decentralised decision-making', Harare: World Food Programme.

Hoddinott, J. (2004): 'Shocks and their consequences across and within households in rural Zimbabwe', Wisconsin: BASIS CRSP.

Huq, S. and H. Reid (2005): 'Millennium Development Goals' in Tiempo: A bulletin on climate and development, Issue 54, January 2005.

International Labour Office (2005): 'Global Employment Trends Model', Geneva: ILO.

International Monetary Fund (2003): 'Fund assistance for countries facing exogenous shocks'. Prepared by the Policy Development and Review Department (In consultation with the Area, Finance, and Fiscal Affairs Departments), Washington, DC: IMF.

International Commission on Irrigation and Drainage (2005): 'Water policy issues of Mexico', Delhi: ICID.

Ionescu, C., R.J.T. Klein, J. Hinkel, et al. (2005): 'Towards a formal framework of vulnerability to climate change', NeWater Working Paper 2, Osnabrueck: NeWater.

Intergovernmental Panel on Climate Change (2001): 'Climate Change 2001: Synthesis Report', Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change' [Watson R.T. and Core Team (Eds.)], Cambridge: Cambridge University Press.

Jones P G., and Thornton, P. K. (2003): 'The potential impacts of climate change on maize production in Africa and Latin America in 2055'. Global Environmental Change 13: 51-59.

Kaimowitz, D. (2002): Forest and rural livelihoods in developing countries. Bogor, Indonesia: Center for International Forestry Research.

Kakwani, N. (1993): ' Performance in living standards: an international comparison'. Journal of Development Economics 41(2): 307-336

Kraay, A. (2005): 'When is growth pro-poor? Evidence from a Panel of Countries.' Journal of Development Economics, **80**, June: 198-227

Levy, M.L., C. Thorkelson, C. Vörösmarty, et al. (2005): 'Freshwater availability anomalies and outbreak of internal war: results from a global spatial time series analysis'. Oslo: Human Security and Climate Change International Workshop.

McClean, C. J., J. C. Lovett, W. Kuper, et al. (2005): 'African plant diversity and climate change', Annals of the Missouri Botanical Garden **92** (2): 139 – 152

Meier, P. and D. Bond (2005): 'The influence of environmental factors on conflict in the horn'. Journal of Political Geography (in review).

Mendelsohn, R., A. Dinar, and L. Williams. (2006): 'The distributional impact of climate change on rich and poor countries', Environment and Development Economics 2006 **11**: 1-20

Miguel, E., S. Satyanath, and E. Sergenti (2004): 'Economic shocks and civil conflict: an instrumental variables approach', Journal of Political Economy **112**

Munich Re (2004): 'Topics Geo Annual review: Natural catastrophes' Munich: Munich Re Group.

Myers, N. (2005) Environmental Refugees: An Emergent Security Issue, 13th Economic forum Prague, 23-27 May

Nagy, G. et al. (2006): 'Understanding the potential impact of climate change in Latin America and the Caribbean', Report prepared for the Stern Review, available from http://www.sternreview.org.uk

NBSC (National Bureau of Statistics of China) (2005): 'China Agricultural Yearbook', 2005, Beijing: Statistic Press of China, (in Chinese).

Niasse, M. (2005): 'Climate-induced water conflict risks in West Africa: recognising and coping with increasing climate impacts on shares watercourses' available at http://www.gechs.org/activities/holmen/Niasse.pdf

Nicholls, R.J., (1995): 'Synthesis of vulnerability analysis studies', in Proceedings of the World Coast Conference 1993, P. Beukenkamp et al. (eds.), Noordwijk, The Netherlands,1-5 November 1993, Coastal Zone Management Centre Publication 4, National Institute for Coastal and Marine Management: The Hague: 181-216

Nicholls R.J. (2004): 'Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios', Global Environmental Change **14**: 69 – 86

Nicholls R.J., J.A. Lowe (2006): 'Climate stabilisation and impacts of sea-level rise', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 195 – 201.

Nicholls, R.J. and R.S.J. Tol, (2006): 'Impacts and responses to sea level rise: global analysis of the SRES scenarios over 21st century', Philosophical Transactions of the Royal Society B **364**: 1073 – 1095

Nkomo, J.C., A. Nyong and K. Kulindwa (2006): 'The Impacts of Climate Change in Africa', Report prepared for the Stern Review, available from http://www.sternreview.org.uk

Nordhaus, W. (2006): 'Geography and macroeconomics: New data and new findings', PNAS, **103**(10): 3510-3517

NBSC (National Bureau of Statistics of China) (2005): China agricultural Yearbook in Chinese). Beijing: Statistic Press of China.

Overseas Development Institute (2005): 'Aftershocks: Natural Disaster Risk and Economic Development Policy', London: ODI.

Parry, M.L, C. Rosenzweig, A. Iglesias et al. (2004): 'Effects of climate change on global food production under SRES emissions and socio-economic scenarios', Global Environmental Change **14**: 53 – 67

Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2004): 'World Population Prospects: The 2004 Revision'. Washington, DC: World Bank.

Pritchett, L. and L.H. Summers, (1993): 'Wealthier is healthier'. World Bank, WPS 1150, Washington, DC: World Bank.

.
Ravallion, M. (2001): 'Growth, inequality and poverty: looking beyond averages' Working Paper no 2558, Washington, DC: World Bank.

Ravallion, M. (2003): 'Measuring aggregate welfare in developing countries: how well do national accounts and surveys agree?' Review of Economics and Statistics, **85** (3): 645-652

Republic of Kenya (2002): First national communication of the Republic of Kenya to the United Nations Framework Convention on Climate Change, Ministry of Finance and Natural Resources.

Republic of South Africa (2000): South Africa initial national communication to the United Nations Framework Convention on Climate Change. Pretoria.

Roy, J. (2006): 'The economics of climate change: a review of studies in the context of South Asia with a special focus on India', Report prepared for the Stern Review, available from http://www.sternreview.org.uk

Sachs, J. D., and J. L. Gallup, (2001): 'The economic burden of malaria', CMH Working Paper Series paper No WG1: 10: Commission on Macroeconomics and Health, Washington, DC: World Health Organisation.

Sachs, J.D., (2001): 'Tropical Underdevelopment'. Working Paper w8119, Cambridge, MA: National Bureau of Economic Research.

Scholze, M., W. Knorr, N.W. Arnell, I.C. Prentice (2006): 'A climate-change risk analysis for world ecosystems', Proceedings of the National Academy of Sciences, DOI: 10.1073/pnas.0601816103

Stern, N, J-J-. Dethier, and F.H. Rogers (2005): 'Growth and Empowerment – making development happen', Cambridge, MA: MIT Press.

Strzepek, K., D.N. Yates, G. Yohe, et al. (2001): 'Constructing not 'implausible' climate and economic scenarios for Egypt'. Integrated Assessment **2**, 139-157

Tanzler, D., A. Carius, and S. Oberthus (2002): 'Climate change and conflict prevention' report on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Thornton, P.K., P.G. Jones, T. Owiyo et al. (2006): 'Mapping climate vulnerability and poverty in Africa.' Report to the Department for International Development, ILRI, PO Box 30709, Nairobi 00100, Kenya. pp 171.

Tol, R.S.J., T.E. Downing, O.J. Kuik and J.B. Smith (2004): 'Distributional Aspects of Climate Change Impacts', Global Environmental Change, **14** (3), 259-272

United Nations (2005): 'The Millennium Development Goals Report 2005' available from http://millenniumindicators.un.org/unsd/mi/pdf/MDG%20Book.pdf

UNEP-WCMC (2006): 'Biodiversity and poverty reduction: the importance of biodiversity for ecosystem services', Cambridge: UNEP.

University for Peace Africa Programme (2005): 'Environmental degradation as a cause of conflict in Darfur', Switzerland: University for Peace.

Vedeld, P., A. Angelsen, E. Sjaasrad and G. Berg (2004):' Counting on the environment: Forest income and the rural poor', Environmental Economics Series No. 98, Washington DC: World Bank.

Vincent, K. (2004): 'Creating an index of social vulnerability to climate change for Africa'. Tyndall Centre for Climate Change Research, Working Paper 54, Norwich: Tyndall Centre.

van Lieshout, M., R.S. Kovats, M.T.J. Livermore and P. Martens, (2004): 'Climate change and malaria: analysis of the SRES climate and socio-economic scenarios', Global Environmental Change **14**: 87–99.

Vos R., M. Velasco, and E. De Labatisda. (1999): 'Economic and social effects of El Niño in Ecuador'. Washington, D.C: Inter-American Development Bank.

Wagstaff, A., and E. van Doorslaer. (2003): 'paying for health care: quantifying fairness, catastrophe, and impoverishment with applications to Vietnam, 1993–98.' Health Economics **12** (11): 921–33

Warren, R., N. Arnell, R. Nicholls, et al. (2006): 'Understanding the regional impacts of climate change', Research report prepared for the Stern Review, Tyndall Centre Working Paper 90, Norwich, UK, available from http://www.tyndall.ac.uk/publications/working_papers/working_papers.shtml

World Health Organisation (2005): 'Malnutrition: Quantifying the health impact at national and local levels'. Environmental burden of diseases series, No. 12, Washington DC: WHO.

World Bank (2000): Can Africa Claim the 21st Century, Washington DC: World Bank

World Bank (2003a): World Development Indicators Washington, DC: World Bank.

World Bank (2003b): World Development Report, Washington, DC: World Bank.

World Bank (2003c): Global Poverty Monitoring Database, Washington, DC: World Bank.

World Bank (2004): World Development Indicators Washington, DC: World Bank.

World Bank (2006a): The Little Data Book, Washington, DC: World Bank.

World Bank (2006b) 'Water for Growth and Development.' D. Grey and C. W. Sadoff in Thematic Documents of the IV World Water Forum. Comision Nacional del Agua: Mexico City. 2006, Washington, DC: World Bank.

World Bank (2006c) 'Managing Water Resources to Maximize Sustainable Growth: A Country Water Resources Assistance Strategy for Ethiopia', Washington, DC: World Bank.

World Bank (2006d) *Financing Health in Low-Income Countries*

World Urbanization Prospects: 'The 2005 Revision', available from http://esa.un.org/unup.

5 Costs Of Climate Change In Developed Countries

Key Messages

Climate change will have some positive effects for a few developed countries for moderate amounts of warming, but will become very damaging at the higher temperatures that threaten the world in the second half of this century.

- In higher latitude regions, such as Canada, Russia and Scandinavia, climate change could bring net benefits up to 2 or 3°C through higher agricultural yields, lower winter mortality, lower heating requirements, and a potential boost to tourism. But these regions will also experience the most rapid rates of warming with serious consequences for biodiversity and local livelihoods.
- Developed countries in lower latitudes will be more vulnerable. Regions where water is already scarce will face serious difficulties and rising costs. Recent studies suggest a 2°C rise in global temperatures may lead to a 20% reduction in water availability and crop yields in southern Europe and a more erratic water supply in California, as the mountain snowpack melts by 25 – 40%.
- In the USA, one study predicts a mix of costs and benefits initially (± 1% GDP), but then declines in GDP even in the most optimistic scenarios once global temperatures exceed 3°C.
- The poorest will be the most vulnerable. People on lower incomes are more likely to live in poor-quality housing in higher-risk areas and have fewer financial resources to cope with climate change, including lack of comprehensive insurance cover.

The costs of extreme weather events, such as storms, floods, droughts, and heatwaves, will increase rapidly at higher temperatures, potentially counteracting some of the early benefits of climate change. Costs of extreme weather alone could reach 0.5 - 1% of world GDP by the middle of the century, and will keep rising as the world warms.

- Damage from hurricanes and typhoons will increase substantially from even small increases in storm severity, because they scale as the cube of windspeed or more. A 5 – 10% increase in hurricane windspeed is predicted to approximately double annual damages, resulting in total losses of 0.13% of GDP each year on average in the USA alone.
- The costs of flooding in Europe are likely to increase, unless flood management is strengthened in line with the rising risk. In the UK, annual flood losses could increase from around 0.1% of GDP today to 0.2 – 0.4% of GDP once global temperature increases reach 3 to 4°C.
- Heatwaves like 2003 in Europe, when 35,000 people died and agricultural losses reached $15 billion, will be commonplace by the middle of the century.

At higher temperatures, developed economies face a growing risk of large-scale shocks.

- Extreme weather events could affect trade and global financial markets through disruptions to communications and more volatile costs of insurance and capital.
- Major areas of the world could be devastated by the social and economic consequences of very high temperatures. As history shows, this could lead to large-scale and disruptive population movement and trigger regional conflict.

5.1 Introduction

While the most serious impacts of climate change will fall on the poorest countries, the developed world will be far from immune.

On the whole, developed countries will be less vulnerable to climate change because:[1]

- A smaller proportion of their economy is in sectors such as agriculture that are most sensitive to climate.

[1] Tol *et al.* (2004) set out these arguments in some detail and with great clarity.

- They are located in cooler higher latitudes and therefore further from critical temperature thresholds for humans and crops. Higher latitudes are expected to warm faster than lower latitudes, but this effect is small compared with the initial difference in temperatures between regions.
- Adaptive capacity is higher. Richer countries have more resources to invest in adaptation, more flexible economies, and more liquid financial markets to increase resilience to climate change.

Nevertheless, the advances in the science over the last few years have shown that there are now significant risks of temperatures much higher than the 2 or 3°C that were the focus of analytical discourse up to a few years ago. The potential damages with temperature increases of 4 to 5°C and higher are likely to be very severe for all countries, rich and poor.

This chapter examines the potential costs and opportunities of climate change in developed countries, with a particular focus on the consequences for wealth and output. The analysis suggests that, while there may be benefits in some sectors for 1 or 2°C of warming, climate change will have increasingly negative effects on developed countries as the world warms, even under the most optimistic assumptions. In particular, at higher temperatures (4 or 5°C), the impacts will become disproportionately more damaging (Chapter 3). Extreme weather events (storms, floods, droughts and heatwaves) are likely to intensify in many cases. The risks of large-scale and abrupt impacts will increase significantly, such as melting/collapse of ice-sheets or shutdown of the thermohaline circulation (Gulf Stream). Large-scale shocks and financial contagion originating from poorer countries who are more vulnerable to climate change (Chapter 4) will also pose growing risks for rich countries, with increasing pressures for large-scale migration and political instability.

5.2 Impacts on wealth and output

Climate change will have some positive effects for a few developed countries for moderate amounts of warming, but is likely to be very damaging for the much higher temperature increases that threaten the world in the second half of this century and beyond if emissions continue to grow.

Climate change will influence economic output in the developed world via several different paths (Box 5.1), including the availability of commodities essential for economic growth, such as water, food and energy. While it will be possible to moderate increased costs through adaptation, this in itself will involve additional expenditure (Part V).

Water: Warming will have strong impacts on water availability in the developed world. Altered patterns of rainfall and snowmelt will affect supply through changes in runoff.[2] Water availability will generally rise in higher latitude regions where rainfall becomes more intense. But regions with Mediterranean-like climates will have existing pressures on limited water resources exacerbated because of reduced rainfall and loss of snow/glacial meltwater. Population pressures and water-intensive activities, such as irrigation, already strain the water supplies in many of the regions expected to see falling supplies. Based on recent studies:

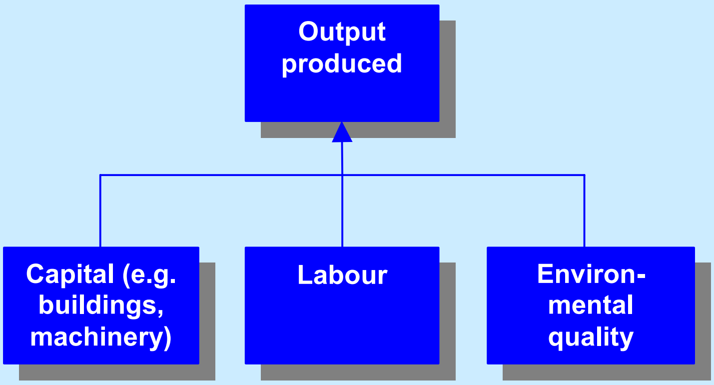
- In Southern Europe, summer water availability may fall by 20 - 30% due to warming of 2°C globally and 40 - 50% for 4°C.[3]
- The West Coast of the USA is likely to experience more erratic water supply as mountain snowpack decreases by 25 – 40% for a 2°C increase in global temperatures and 70 – 90% for 4°C.[4] The snow will melt several weeks earlier in the spring, but the supply will eventually diminish as glaciers disappear later in the century.
- In Australia (the world's driest continent) winter rainfall in the southwest and southeast is likely to decrease significantly, as storm tracks shift polewards and away from the continent itself. River

[2] Projections for changes in rainfall patterns in developed countries are generally more reliable than those in developing countries (due to their higher latitude location).
[3] Schröter *et al.* (2006) and Arnell (2004)
[4] Hayhoe *et al.* (2006)

flows in New South Wales, including those supplying Sydney, have been predicted to drop by 15% for a 1 – 2°C rise in temperature.[5]

Box 5.1 A simple production function with environmental quality

The market impacts of climate change on economic growth can be framed using a simple theoretical structure, beginning with a general production function in which the output of an economy in a given year depends on the stocks (and, implicitly, the marginal productivities) of capital, labour and environmental quality available in that year.



or $$Y(t) = F(K,L,E)$$

Where Y is the output of the economy in year t and is a function of capital, K, labour, L, and environmental quality, E, which together are the factors of production. In this way, environmental quality is a (natural) capital asset that provides a flow of services on which output depends.

If the net impacts of climate change are negative, then environmental quality E is reduced. This will reduce the output obtainable with a given supply of capital and labour, because output is jointly dependent on all three factors of production. In practice, either the productivity of capital and labour is directly reduced, or a portion of the output produced in a given year is destroyed that same year by climate change, for example by an extreme weather event. The opposite of this story is true if climate change brings with it net benefits, thereby increasing environmental quality.

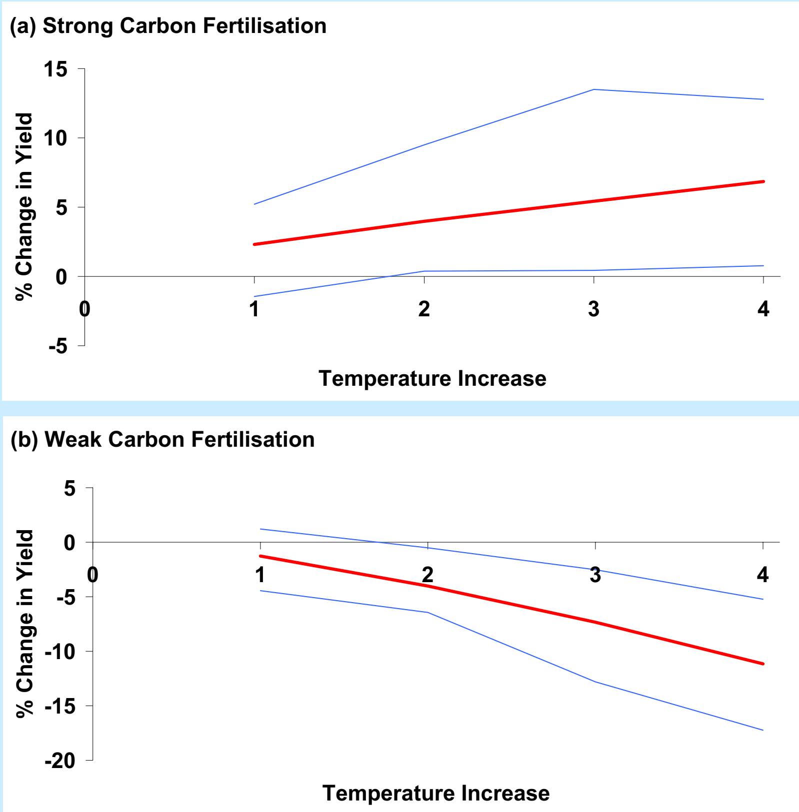
Adaptation to climate change will be an important economic option (Part V). Adaptation will reduce losses in E and/or enhance gains in E, but it too comes at a cost relative to a world without climate change. In this case, the opportunity cost of adaptation is lost consumption or investment diverted away from adding to K.

Food: While agriculture is only a small component of GDP in developed countries (1 – 2% in the USA, for example), it is highly sensitive to climate change and could contribute substantially to economy-wide changes in growth.[6] In higher latitudes, such as Canada, Russia and Northern Europe, rising temperatures may initially increase production of some crops – but only if the carbon fertilisation effect is strong (still a key area of uncertainty; further details in Chapter 3) (Figure 5.1).[7] In these regions, any benefits are likely to be short-lived, as conditions begin to exceed the tolerance threshold for crops at higher temperatures. In many lower latitude regions, such as Southern Europe, Western USA, and Western Australia, increasing water shortages in regions where water is already scarce are likely to limit the carbon fertilisation effect and lead to substantial declines in crop yields. This north-south disparity in

[5] Preston and Jones (2006)
[6] Using a general equilibrium model for the USA, Jorgenson *et al.* (2005) found that agriculture contributed 70 – 80% of the changes in GDP driven by climate change (more details later in chapter). This work did not include the costs of extreme weather, particularly infrastructure damage from hurricanes and storms.
[7] Mendelsohn *et al.* (1994); see also Schlenker *et al.* (2005) for a recent critique of this work

impacts was observed during the 2003 heatwave when crop yields in southern Europe dropped by 25% while they increased in northern Europe (25% in Ireland and 5% in Scandinavia).[8]

Figure 5.1 Changes in wheat yield with increasing global temperatures across North America, Europe and Australasia



Source: Warren *et al.* (2006) analysing data from Parry *et al.* (2004). More details on method in Chapter 3.

Notes: The strong carbon fertilisation runs assumed a 15 – 25% increase in yield for a doubling of carbon dioxide levels. These are about twice as high as the latest field-based studies suggest. The red line represents the average across different scenario runs developed by the IPCC, while the blue lines show the full range. Yield changes were based on monthly temperature and rainfall data from the Hadley Centre climate model. Using other climate models produces a greater increase in yield at low levels of warming. The work assumed farm-level adaptation with some economy-wide adaptation. Much larger declines in yield are expected at higher temperatures (more than 4°C), as critical thresholds for crop growth are reached. Few studies have examined the consequences of higher temperatures.

Energy: In higher latitude regions, climate change will reduce heating demands, while increasing summer cooling demands; the latter effect seems smaller in most cases (Table 5.1).[9] In lower latitude regions, overall energy use is expected to increase, as incremental air-conditioning demands in the summer outstrip the reduction in heating demands in the winter. In Italy, winter energy use is predicted to fall by 20% for a warming of 3°C globally, while summer energy use rises by 30%.[10] Climate change could also

[8] COPA COGECA (2003)
[9] Warren *et al.* (2006) have prepared these results, based on the original analysis of Prof Nigel Arnell (University of Southampton). Energy requirements are expressed as Heating Degree Days and Cooling Degree Days (more detail in Table 5.1).
[10] MICE (2005)

disrupt energy production. During the 2003 heat wave in Europe, for example, energy production in France's nuclear power stations fell because the river water was too hot to cool the power stations adequately. Similarly, at the height of the 2002 drought, Queensland's power stations had to reduce output considerably. In California, hydropower generation is predicted to fall by 30% for a warming of 4°C globally as storage lakes deplete.[11]

Table 5.1 Temperature-driven changes in energy requirements in the developed world

World Region	Change in Heating Degree Days	Change in Cooling Degree Days
Russia	- 935	+ 358
Europe	- 667	+ 310
North America	- 614	+ 530
Australia	- 277	+ 427

Source: Warren *et al.* (2006) analysing data from Prof Nigel Arnell, University of Southampton

Note: Regions ranked by largest net change in energy demand. Both Heating Degree Days (HDD) and Cooling Degree Days (CDD) are calculated with reference to a base temperature (B), defined as the target "comfort" temperature, and are calculated from daily temperatures T_i, summed over all days (i) in the year. In most global-scale studies, the base temperature is taken as 18°C.

$HDD = \Sigma (B - T_i)$ *where* T_i *is less than B*

$CDD = \Sigma (T_i - B)$ *where* T_i *is greater than B*

These changes assume: (1) no change to the target "comfort" base temperature; (2) no effects mediated through humidity; and (3) implicitly no acclimatisation or adaptation, in the sense of accepting warmer temperatures. Comfort temperatures will differ across the world, but using a fixed "base" temperature provides an index of potential changes in heating and cooling requirements in the future.

The distribution of impacts is likely to follow a strong north-south gradient – with regions such as Canada, Russia and Scandinavia experiencing some net benefits from moderate levels of warming, while low latitude regions will be more vulnerable. At higher temperatures, the risks become severe for all regions of the developed world.

Climate change will have widespread consequences across the developed world (major impacts set out in Box 5.2). The impacts will become more damaging from north to south. For example, in higher latitudes, where winter death rates are relatively high, more people are likely to be saved from cold-related death than will die from the heat in the summer.[12] In lower latitude regions, summer deaths could outstrip declines in winter deaths, leading to an overall increase in mortality.[13] Similarly, tourism may shift northwards, as cooler regions enjoy warmer summers, while warmer regions like southern Europe suffer increased heat wave frequency and reduce water availability. One study projected that Canada and Russia would both see a 30% increase in tourists with only 1°C of warming.[14] On the other hand, mountain regions such as the Alps or the Rockies that rely on snow for winter recreation (skiing) may experience significant declines in income. Australia's $32 billion tourism industry will suffer from almost complete bleaching of the Great Barrier Reef.[15]

This broad distribution of impacts across many sectors might stimulate a broad northward shift in economic activity and population in regions such as the North America or Europe, as southern regions begin to suffer disproportionate increases in risks to human health and extreme events, coupled with loss

[11] Cayan *et al.* (2006)
[12] Department of Health (2003) study for the UK found an increase in heat-related mortality by 2,000 and decrease in cold-related mortality by 20,000 by the 2050s using the Hadley Centre climate model.
[13] Benson *et al.* (2000) report on studies in five US cities in the Mid-Atlantic region (Baltimore, Greensboro, Philadelphia, Pittsburgh and Washington DC) and find a net increase in temperature-related mortality of up to two- to three-fold by 2050 (using outputs from three global climate models). These cities see larger increases in summer heat-related mortality than some other cities in the USA.
[14] Hamilton *et al.* (2005)
[15] Preston and Jones (2006)

of competitiveness in agriculture and forestry, reduced water availability and rising energy costs.[16] There could be additional knock-on consequences for long-run growth, as changes in economic output have knock-on effects on growth and investment, capital stock, and labour (more detail in Box 5.2 for the USA and in Chapter 6 more generally).

Arctic regions will not follow this general north-south trend. Warming will occur most rapidly here - averages temperatures have already risen twice as fast as in other parts of the world in recent decades.[17] For example, in Alaska and western Canada, winter temperatures have already increased by as much as 3 – 4°C in the past 50 years. Over the past 30 years, average sea ice extent has declined by 8% or nearly 1 million Km^2, an area larger than all of Norway, Sweden and Denmark combined, and the melting trend is accelerating. Over half of all the ice could have disappeared by 2100. Loss of even a small fraction of sea ice will have devastating consequences for polar bears, seals and walrus, as well as for the livelihoods of Inuits and others who rely on these animals for food. Shrinking arctic tundra will also threaten grazing animals, such as Caribou and Reindeer, and breeding habitats for millions of migratory bird species.

[16] Suggested by Pew Center study by Jorgenson *et al.* (2005)
[17] All impacts in the Arctic are clearly and comprehensively set out in the Arctic Climate Impacts Assessment (2004)

Box 5.2 Summary of regional impacts of climate change

USA

- Climate change impacts in the USA will be unevenly distributed, with potential short-term benefits in the North and extensive damage possible in the South. In the short to medium term, the most costly impacts are expected from coastal flooding and extreme events. More powerful hurricanes raise risks along the eastern seaboard and Gulf of Mexico. Defensive investment could be substantial.
- Reduced snowfall and shorter winters will change snowmelt patterns – affecting water supply both along the Pacific coast and California and the farmlands of the Mississippi basin whose western tributaries are fed by snow melt.
- Impacts on overall agricultural yields should be moderate (or even positive with a strong carbon fertilisation effect) up to around 2 - 3ºC given adaptation to shifting crop varieties and planting times. But this depends on sufficient irrigation water particularly in the southeast and Southern Great Plains. Farm production in general is expected to shift northwards. Above 3ºC, total output could fall by 5 – 20% even with effective adaptation because of summer drought and high temperatures.
- The north could benefit from lower energy bills and fewer cold-related deaths as winter temperatures rise. The south will see rising summer energy use for air-conditioning and refrigeration and more heat-related deaths. This rebalance of economic activity could also induce a northward population shift.

Canada

- Canada has large areas of permafrost, forest and tundra. Melting permafrost raises the cost of protecting infrastructure and oil and gas installations from summer subsidence.
- Reduced sea-ice cover and shorter winters should increase the summer Arctic navigation period offering improved access to oil, gas and mineral resources and to isolated communities.
- But warmer summers and smaller ice packs will make life difficult for the polar bear, seal and other Arctic mammals and fish on which indigenous people depend.
- A warmer climate and carbon fertilisation could lengthen summer growing seasons and increase agricultural productivity. But thinner winter snow cover risks making winter wheat crops vulnerable.

UK

- Infrastructure damage from flooding and storms is expected to increase substantially, especially in coastal regions, although effective flood management policies are likely to keep damage in check.
- Water availability will be increasingly constrained, as runoff in summer declines, particularly in the South East where population density is increasing. Serious droughts will occur more regularly.
- Milder winters will reduce cold-related mortality rates and energy demand for heating, while heatwaves will increase heat-related mortality. Cities will become more uncomfortable in summer.
- Agricultural productivity may initially increase because of longer growing seasons and the carbon fertilisation effect but this depends on adequate water and requires changing crops and sowing times.

Mainland Europe

- Europe has large climatic variations from the Baltic to the Mediterranean and the Atlantic to the Black Sea and will be affected in a diverse fashion by climate change. The Mediterranean will see rising water stress, heat waves and forest fires. Spain, Portugal and Italy are likely to be worst affected. This could lead to a general northward shift in summer tourism, agriculture and ecosystems.
- Northern Europe could experience rising crop yields (with adaptation) and falling energy use for winter heating. But warmer summers will raise demand for air conditioning. Melting Alpine snow waters and more extreme rainfall patterns could lead to more frequent flooding in major river basins such as the Danube, Rhine and Rhone. Winter tourism will be severely affected.
- Many coastal countries across Europe are also vulnerable to rising sea levels: the Netherlands, where 70% of the population would be threatened by a 1-m sea level rise, is most at risk.

Russia

- A vast swathe of northern Russia is permafrost, apart from a short, hot summer when the surface melts to form marshy lakes. Rising temperatures will push the permafrost boundary further north and deepen the surface melt. This has big implications for future oil, gas and other investment projects. De-stabilised, shifting permafrost conditions release greenhouse gases and could lead to flooding, but also require more expensive underpinning of buildings, refineries and other infrastructure such as the Baikal Amur railway and the planned East Siberia-Pacific export oil pipeline.
- Melting of the Arctic ice cap will prolong both the northern sea and Siberian river navigation seasons but could lead to more extreme weather patterns. At higher global temperatures there is a possibility that Arctic warming could be reversed if the Gulf Stream weakens before it reaches the Barents Sea.
- Agriculture, and tree growth in the vast Siberian pine forests, should benefit from a longer, warmer growing season and the carbon fertilisation effect. But the most fertile black earth regions of Southern Russia and Ukraine could suffer from increased drought.
- Warmer winters should reduce domestic heating costs and free energy for export. But higher summer temperatures will raise air conditioning energy use.

Japan

- Japan consists of a long chain of narrow, mountainous islands on a seismic fault line, naturally subject to large climatic variations from north to south. Densely urbanised and heavily industrialised, Japan's topography, lack of raw materials, and heavy dependence on international trade, ensure that most people are concentrated in highly industrialised port cities.
- Climate change will exacerbate Japan's existing vulnerability to typhoons and coastal storms. Tokyo extends over a flat coastal plain, vulnerable both to typhoons and rising sea levels. Most other major cities are also heavily industrialised ports, with many factories, refineries, gas liquefaction and chemical plants, steel mills, shipyards, oil storage tanks and other vulnerable infrastructure.
- Agriculture, especially rice cultivation, is not significant economically but has strong cultural importance. Higher temperatures will make rice more difficult to grow in the south. Fish are another key part of a national cuisine. Fish are vulnerable to rising ocean temperatures and increased acidity.
- Major cities will be increasingly affected by the urban heat island effect. Over 40% of summer power generation is consumed by air conditioning. Rising temperatures will make a fast ageing population more vulnerable both to heat and the spread of infectious diseases such as malaria and dengue fever.

Australia[18]

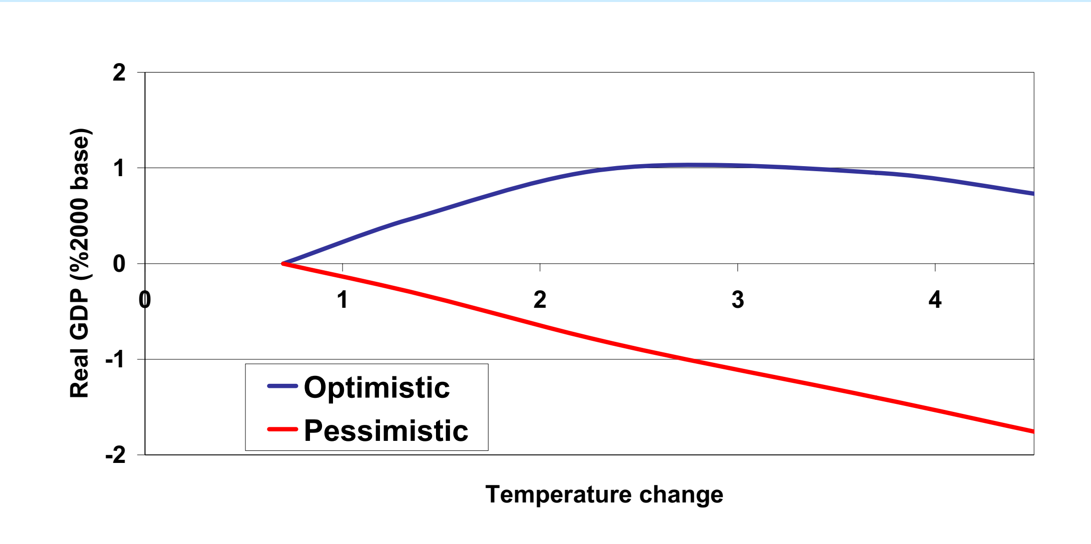
- Australia, as the world's driest continent, is particularly vulnerable to the impact of rising sea temperatures on the major Pacific and Indian Ocean currents. These determine both overall rainfall patterns and unpredictable year-to-year variations. Over the last 30 years stronger tropical typhoons have brought higher storm damage, but increased rainfall, to a wide swathe of North West Australia.
- At the same time the east coast – home to over 70% of the population and location for most major cities and crop farming – has suffered longer droughts and declining rainfall. Southerly regions have lost most rainfall as the warmer ocean and related air currents have pushed rain further south. The 2002 drought cut farm output by 30% and shaved 1.6% off GDP. Water supply to big cities will become more difficult – Melbourne's could fall by 7 – 35% with only 2°C of warming.
- Drier and hotter summers threaten the survival of the Queensland rain forest. Warmer winters, reduced snowfall, endanger the habitat of mountain top fauna and flora. Rising ocean temperatures threaten the future of Australia's coral reefs and the $2 billion fishing and tourist industries. Over 60% of the Great Barrier Reef suffered coral bleaching in 2002, 10% of it permanent. Studies show ocean warming could be fatal to large tracts of reef within 40 years. The carbon fertilisation effect may lead to a thickening of native eucalyptus and savannah habitats. But higher inland temperatures are likely to cause more bush fires.
- Tropical diseases are spreading southward as the north becomes wetter. The dengue fever transmission zone could reach Brisbane and possibly Sydney with 3°C of warming.

[18] Prepared with assistance from Nick Rowley and Josh Dowse of KINESIS Consulting, Sydney, Australia http://www.kinesis.net.au

Box 5.3 Costs of climate change: USA case study on long-run growth impacts

Jorgenson *et al.* (2005) used a general equilibrium model to estimate the impacts of climate change on investment, the capital stock, labour and consumption in the USA for two scenarios: one "optimistic" (assuming "optimal" adaptation, a strong carbon fertilisation effect and low potential damages) and one "pessimistic" (assuming little adaptation, a weak carbon fertilisation effect and high potential damages). Recent field-based studies suggest that the carbon fertilisation effect may be about half as large as the values used in the "optimistic" case (more details in Chapter 1).

For a warming of 3°C, the study projects a net damage of 1.2% of GDP in the pessimistic case and a benefit of 1% of GDP in the optimistic case. In the optimistic case, the benefits peak at just over 2°C warming and then decline from around 3.5°C. In the pessimistic case, warming causes increasingly negative impacts on GDP. The range of outcomes encompasses other earlier estimates of the costs of climate change for the US economy, such as Mendelsohn (2001).



In both optimistic and pessimistic cases, the change was driven largely by changes in agricultural prices (70 – 80%), with a lesser contribution from changes in energy prices and mortality. In the pessimistic case, productive resources were diverted from more efficient uses to the affected sectors, leading to overall productivity losses. The end effect was a significant reduction in consumption. In the optimistic case, the reverse process occurred.

The study did not take full account of the impacts of extreme weather events, which could be very significant (Section 6.4). Nordhaus (2006) shows that just a small increase in hurricane intensity (5 – 10%), which several models predict will occur 2 – 3°C of warming globally, could alone double costs of storm damage to around 0.13% GDP. The risks of higher temperatures, as the latest science suggests, could bring even greater damage costs, particularly given the very non-linear relationship between temperature and hurricane destructiveness (Chapter 3).

Source: Jorgenson *et al.* 2005

5.3 Key vulnerabilities

The poorest in developed countries will be the most vulnerable to climate change.

Low-income households will be disproportionately affected by increases in extreme weather events.[19]

- Those on lower incomes often live in higher-risk areas, marginal lands,[20] and poor quality housing. In the UK, the Environment Agency found that the most deprived 10% of the population were eight times more likely to be living in the coastal floodplain than those from the least deprived 10%.[21]

- Lower-income groups will typically have fewer financial resources to cope with climate change, including lack of comprehensive insurance cover. In New Orleans, disproportionately more people (22%) were below the poverty line in areas flooded by Hurricane Katrina than in non-flooded areas (15%) (Box 5.4a). More than half the people in flooded areas did not own a car compared with one-third in non-flooded areas.[22]

- Residents in deprived areas are likely to be less aware and worse prepared for an extreme weather event like a flood. The health impacts will be more severe for those already characterised by poor health. Across Europe, a large majority of the 35,000 people who died during the 2003 heatwave were the elderly and the sick (Box 5.4b). The most deprived proportion of the population are more likely to be employed in outdoor labour and therefore have little relief from the heat at work.

5.4 Impacts of extreme events

The costs of extreme weather events, such as storms, floods, droughts, and heatwaves, will increase rapidly at higher temperatures, potentially countering some of the early benefits of climate change. Costs of extreme weather alone could reach 0.5 - 1% of world GDP by the middle of the century, and will keep rising as the world continues to warm.

The consequences of climate change in the developed world are likely to be felt earliest and most strongly through changes in extreme events - storms, floods, droughts, and heatwaves.[23] This could lead to significant infrastructure damage and faster capital depreciation, as capital-intensive infrastructure has to be replaced, or strengthened, before the end of its expected life. Increases in extreme events will be particularly costly for developed economies, which invest a considerable amount in fixed capital each year (20% of GDP or $5.5 trillion invested in gross fixed capital today). Just over one-quarter of this investment typically goes into construction ($1.5 trillion - mostly for infrastructure and buildings; more detail in Chapter 19). The long-run production losses from extreme weather could significantly amplify the immediate damage costs, particularly when there are constraints to financing reconstruction.[24]

The costs of extreme weather events are already high and rising, with annual losses of around $60 billion since the 1990s (0.2% of World GDP), and record costs of $200 billion in 2005 (more than 0.5% of World GDP).[25] New analysis based on insurance industry data has shown that weather-related catastrophe losses have increased by 2% each year since the 1970s over and above changes in wealth, inflation and population growth/movement.[26] If this trend continued or intensified with rising global temperatures, losses

[19] Environment Agency (2006), McGregor *et al.* (2006)
[20] O'Brien *et al.* (2006)
[21] Environment Agency (2003)
[22] Brookings Institution (2005)
[23] Described by low frequency but high impact events (e.g. more than two standard deviations from the mean)
[24] Hallegatte *et al.* (2006) define the "economic amplification ratio" as the ratio of the overall production losses from the disaster to its direct losses.
[25] 2005 prices for total losses (insured and uninsured) - analysis of data from Swiss Re and Munich Re in Mills (2005) and Epstein and Mills (2005); Munich Re (2006)
[26] Muir-Wood *et al.* (2006)

from extreme weather could reach 0.5 - 1% of world GDP by the middle of the century.[27] If temperatures continued to rise over the second half of the century, costs could reach several percent of GDP each year, particularly because the damages increase disproportionately at higher temperatures (convexity in damage function; Chapter 3).

Box 5.4 Impacts of recent extreme weather events

Extreme weather events are likely to occur with greater frequency and intensity in the future, particularly at higher temperatures.

(a) Hurricane Katrina (2005) was the costliest weather catastrophe on record, totalling $125 billion in economic losses (~1.2% of US GDP), of which around $45 billion was insured through the private market and $15 billion through the National Flood Insurance Program. More than 1,300 people died as a result of the hurricane and over one million people were displaced from their homes. By the end of August, Katrina had reached a Category 5 status (the most severe) with peak gusts of 340 km per hour, in large part driven by the exceptionally warm waters of the Gulf (1 – 3°C above the long-term average). Katrina maintained its force as it passed over the oilfields off the Louisiana coast, but dropped to a Category 3 hurricane when it hit land. New Orleans was severely damaged when the hurricane-induced 10-metre storm-surge broke through the levees and flooded several quarters (up to 1 Km inland). The Earth Policy Institute estimates that 250,000 former residents have established homes elsewhere and will not return.

Source: Munich Re (2006)

(b) European Heatwave (2003). Over a three-month period in the summer, Europe experienced exceptionally high temperatures, on average 2.3°C hotter than the long-term average. In the past, a summer as hot as 2003 would be expected to occur once every 1000 years, but climate change has already doubled the chance of such a hot summer occurring (now once every 500 years).[28] By the middle of the century, summers as hot as 2003 will be commonplace. The deaths of around 35,000 people across Europe were brought forward because of the effects of the heat (often through interactions with air pollution). Around 15,000 people died in Paris, where the urban heat island effect sustained nighttime temperatures and reduced people's tolerance for the heat the following day. In France, electricity became scarce because of a lack of water needed to cool nuclear power plants. Farming, livestock and forestry suffered damages of $15 billion from the combined effects of drought, heat stress and fire.

Source: Munich Re (2004)

Even a small increase in the intensity of hurricanes or coastal surges is likely to increase infrastructure damage substantially.

Storms are currently the costliest weather catastrophes in the developed world and they are likely to become more powerful in the future as the oceans warm and provide more energy to fuel storms. Many of the world's largest cities are at risk from severe windstorms - Miami alone has $900 billion worth of total capital stock at risk. Two recent studies have found that just a 5 - 10% rise in the intensity of major storms with a 3°C increase in global temperatures could approximately double the damage costs, resulting in total losses of 0.13% of GDP in the USA each year on average or insured losses of $100 – 150 billion in an

[27] Based on simple extrapolation through to the 2050s. The lower bound assumes a constant 2% increase in costs of extreme weather over and above changes in wealth and inflation. The upper band assumes that the rate of increase will increase by 1% each decade, starting at 2% today, 3% in 2015, 4% in 2025, 5% in 2035, and 6% in 2045. These values are likely underestimates: (1) they exclude "small-scale" events which have large aggregate costs, (2) they exclude data for some regions (Africa and South America), (3) they fail to capture many of the indirect economic costs, such as the impacts on oil prices arising from damages to energy infrastructure, and (4) they do not adjust for the reductions in losses that would have otherwise occurred without disaster mitigation efforts that have reduced vulnerability.
[28] Stott *et al.* (2004)

extreme year (2004 prices).[29] If temperatures increase by 4 or 5°C, the losses are likely to be substantially greater, because any further increase in storm intensity has an even larger impact on damage costs (convexity highlighted in Chapter 3). This effect will be magnified for the costs of extreme storms, which are expected to increase disproportionately more than the costs of an average storm. For example, Swiss Re recently estimated that in Europe the costs of a 100-year storm event could double by the 2080s with climate change ($50/€40 billion in the future compared with $25/€20 billion today), while average storm losses were estimated to increase by only 16 – 68% over the same period.[30]

Rising sea levels will increase the risk of damages to coastal infrastructure and accelerate capital depreciation (Box 5.5). Costs of flood defences on the coast will rise, along with insurance premiums. A Government study calculated that in the UK the average annual costs of flood damage to homes, businesses and infrastructure could increase from around 0.1% of GDP currently to 0.2 – 0.4% of GDP if global temperatures rise by 3 to 4°C.[31] Greater investment in flood protection is likely to keep damages in check. Similarly, preliminary estimates suggest that annual flood losses in Europe could rise from $10 billion today to $120 – 150 billion (€100 – 120 billion) by the end of the century.[32] If flood management is strengthened in line with the rising risk, the costs may only increase two-fold. According to one recent report, storm surge heights all along Australia's East Coast from Victoria to Cairns could rise by 25 – 30% with only a 2°C increase in global temperatures.[33]

Heatwaves like 2003 in Europe, when 35,000 people died and agricultural losses reached $15 billion, will be commonplace by the middle of the century.

People living and working in urban areas will be particularly susceptible to increases in heat-related mortality because of the interaction between regional warming, the urban heat island and air pollution (Chapter 3). In California, a warming of around 2°C relative to pre-industrial is expected to extend the heat wave season by 17 – 27 days and cause a 25 - 35% rise in high pollution days, leading to a 2 to 3-fold increase in the number of heat related deaths in urban areas.[34] In the UK, for a global temperature rise of 3°C, temperatures in London could be up to 7°C warmer than today because of the combined effect of climate change and the urban heat island effect, meaning that comfort levels will be exceeded for people at work for one-quarter of the time on average in the summer.[35] In years that are warmer than average or at higher temperatures, office buildings could become difficult to work in for large spells during the summer without additional air-conditioning. In already-dry regions, such as parts of the Mediterranean and South East England, hot summers will further increase soil drying and subsidence damage to properties that are not properly underpinned.[36]

---

[29] Recent papers from Nordhaus (2006) and the Association of British Insurers (2005a) examined consequences of increased hurricane wind-speeds of 6% on loss damages, keeping socio-economic conditions and prices constant. Several climate models predict a 6% increase in storm intensity for a doubling of CO_2 concentrations (close to a 3°C temperature rise). The insurance study used existing industry catastrophe loss models validated with historic events to predict future losses. The extreme event costs are defined from an event with a 0.4% chance of occurring (1 in 250 year loss).
[30] Heck *et al.* (2006)
[31] UK Government Foresight Programme (2004) calculations for flooding from rivers, the sea and flash-flooding in urban areas. Prof Jim Hall at the University of Newcastle has provided some additional analysis.
[32] Research from the Association of British Insurers (2005a) extrapolated from a UK-based study of flood losses that assumed no change in flood management policies beyond existing programme. Some of the increased cost is driven by economic growth of the century and greater absolute wealth in physical assets.
[33] Preston and Jones (2006)
[34] Hayhoe *et al.* (2006)
[35] London Climate Change Partnership (2004)
[36] Association of British Insurers (2004) estimates that subsidence costs to buildings could double by the middle of the century to £600 million (2004 prices).

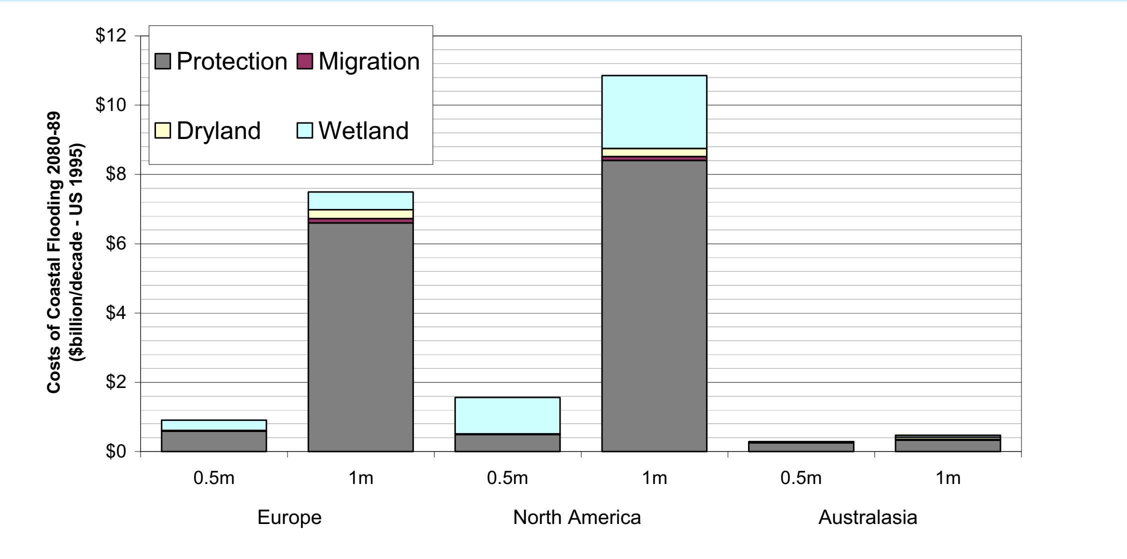
Box 5.5 Costs of coastal flooding in developed country regions

1-m of sea level rise is plausible by the end of the century under rapid rates of warming (Chapter 1), particularly if one of the polar ice sheets begins to melt significantly (Greenland) or collapses (West Antarctic). This could impose significant costs on developed countries with long, exposed coastlines.

For North America, an area just under half the size of Alaska (640,000 km^2) would be lost with 1-m of sea level rise, unless defences are in place to protect the land. Much of this land will in sparsely populated areas, but a significant proportion covers the Gulf Coast and large parts of Florida. These areas will be particularly vulnerable as rising risks of tropical storms combine with rising sea levels to create sharp increases in damages from coastal surges.

In Europe, sea level rise will affect many densely populated areas. An area of 140,000 km^2 is currently within 1-m of sea level. Based on today's population and GDP, this would affect over 20 million people and put an estimated $300 billion worth of GDP at risk. The Netherlands is by far the most vulnerable European country to sea level rise, with around 25% of the population potentially flooded each year for a 1-m sea level rise.[37]

Projected costs of coastal flooding over the period 2080-2089 under two different sea level rise scenarios



Source: Anthoff *et al.* (2006) analysing data from Nicholls and Tol (2006)

Note: Costs were calculated as net present value in US $ billion (1995 prices). Damage costs include value of dryland and wetland lost and costs of displaced people (assumed in this study to be three times average per capita income). The protection costs only include costs to protect against permanent inundation. Infrastructure damage from storm surges is not included (see additional costs in text). Discounting with a constant growth rate (2%) and a pure time preference rate of 0.1% per year increases values by around 2.5 fold (more details in Chapter 2 and technical appendix).

[37] Nicholls and Klein (2003)

5.5 Large-scale impacts and systemic shocks

Abrupt shifts in climate and rising costs of extreme weather events will affect global financial markets.

Well-developed financial markets will help richer countries moderate the impacts of climate change – for example hedging with derivatives to smooth commodity prices. Such markets help to spread the risk across different regional markets and over time, but cannot reduce the risks by themselves. In addition, they are at risk of severe disruption from climate change:

- **Physical risks**. The world's major financial centres (London, New York and Tokyo) are all located in coastal areas. The insurance industry estimates that in London alone at least $220 billion (£125 billion) of assets lie in the floodplain.[38]

- **Correlated risks**. At higher temperatures, climate change is likely to have severe impacts on many parts of the economy simultaneously. The shock may well exceed the capacity of markets and could potentially destabilise regions.[39] For example, a collapse of the Atlantic Thermohaline Circulation would have a massive effect on many parts of the economy of the countries around the Northern Atlantic Ocean and polar seas.[40] A collapse in the next few decades would lead to a decrease in temperatures across much of the northern hemisphere, with a peak cooling of around 2°C in the UK and Scandinavia. Preliminary estimates suggest that this would be accompanied by a reduction in rainfall over much of the northern hemisphere,[41] reducing agriculture productivity, water supplies and threatening ecosystems.

- **Capital constraints on insurance**. Increasing costs of extreme weather will not only raise insurance premiums - they will also increase the amount of capital that insurance companies have to hold to cover extreme losses, such as a hurricane that occurs once every 100 years (Box 5.6). The insurance industry will have to develop new financial products to gain more widespread access to international capital markets.[42] New opportunities for diversifying risk are already emerging, for example weather derivatives and catastrophe bonds, but in future these will require new risk valuation techniques to deal with the changing profile of extreme weather events. If the insurance industry looks to access additional capital from the securities and bond markets, investors are likely to demand higher rates of return for placing more capital at risk, causing a rise in the cost of capital.

- **Spillover risks to other financial sectors.**[43] Failure to raise sufficient capital could mean restrictions in insurance coverage. After seven costly hurricanes in the past two years, higher reinsurance prices have pushed up the cost of insurance coverage in the USA and contributed to decisions by some insurers to transfer more risk back to the homeowner or business, for example by raising deductibles or cutting back on coverage in riskier areas.[44] In future, if rising weather risks cause insurance to become even less available in high-risk areas like the coast, this could be severely disruptive for other parts of the economy. Banks, for example, would be unable to offer finance where insurance is required as part of the collateral package for mortgages or loans.

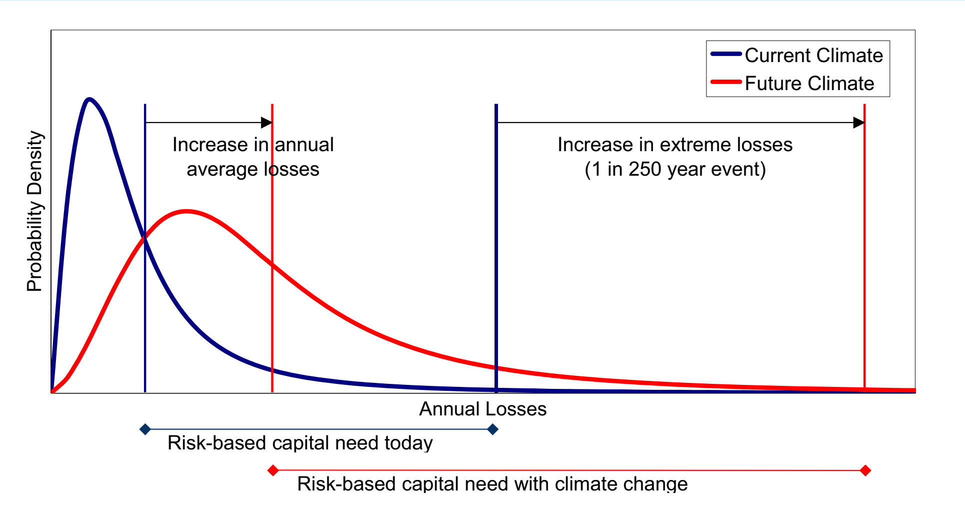
[38] Association of British Insurers (2005b)
[39] As set out in a Pentagon commissioned report by Schwartz and Randall (2004)
[40] A complete collapse of the Thermohaline Circulation is considered to be unlikely (but still plausible) this century (Chapter 1).
[41] Vellinga and Wood (2002)
[42] Salmon and Weston (2006)
[43] Mills (2005)
[44] Mills and Lecomte (2006) provide many examples of increasing prices or withdrawing cover in the US. For example, reinsurance prices have increased by 200% in some parts of the US. Commercial customers are also being affected by the availability and affordability of insurance. Allstate insurance dropped 16,000 commercial customers in Florida in 2005, and some commercial businesses in the Gulf of Mexico are unable to find insurance at any price.

Lack of insurance could be particularly damaging for small and medium enterprises that will find it harder to access capital to protect against extreme events.[45]

Box 5.6 Climate change and constraints on insurance capital

The insurance industry requires sufficient capital to bridge the gap between losses in an average year, which are covered by premium income, and those in an "extreme" year.[46] Today, the insurance industry holds around $120 billion to cover extreme losses from natural weather catastrophes (principally hurricanes, typhoons and winter storms).

Climate change is likely to lead to a shift in the distribution of losses towards higher values, with a greater effect at the tail.[47] Average annual losses (or expected losses) will increase by a smaller amount than the extreme losses (here shown as a 1 in 250 year event), with the result that the amount of capital that insurers are required to hold to deal with extremes increases.



If storm intensity increases by 6%, as predicted by several climate models for a doubling of carbon dioxide or a 3°C rise in temperature, this could increase insurers' capital requirements by over 90% for US hurricanes and 80% for Japanese typhoons – an additional $76 billion in today's prices.

Source: Association of British Insurers (2005a)

Major areas of the world could be devastated by the social and economic consequences of very high temperatures. As history shows, this could lead to large-scale and disruptive population movement and trigger regional conflict.

The impacts of climate change will be more serious for developing countries than developed countries, in part because poorer countries have more existing economic and social vulnerabilities to climate and less access to capital to invest in adaptation (Chapter 4). As the impacts become increasingly damaging at higher temperatures, the effects on the developing world may have knock-on consequences for developed economies, through disruption to global trade and security (Box 5.7), population movement and financial contagion. Climate change will affect the prices and volumes of goods traded between developed and developing countries, particularly raw materials for manufacturing and food products, with wider macroeconomic consequences.

[45] Crichton (2006) found that today in the UK one-third of small and medium-sized businesses had any form of business interruption cover against extreme weather.
[46] "Extreme" is defined by an insurers risk appetite and regulatory requirements.
[47] Heck *et al.* (2006)

Climate change is likely to increase migratory pressures on developed countries significantly, although the potential scale and effect are still very uncertain and require considerably more research.

- **Income gap.** Pressures for long-distance and large-scale migration is likely to grow as climate change raises existing inequalities and the relative income differential between developed and developing countries (Chapter 4). Wage differentials were a strong driver of the mass migration of 50 million people from Europe to the New World in the second half of the 19th century, alongside over-population and the resulting land hunger.[48]

- **Environmental disasters.** As temperatures rise and conditions deteriorate significantly, climate change will test the resilience of many societies around the world. Large numbers of people will be compelled to leave their home when resources drop below a critical threshold. Bangladesh, for example, faces the permanent loss of large areas of coastal land affecting 35 million people, about one-quarter of its population, while one-quarter of China's population (300 million people) could suffer from the wholesale reduction in glacial meltwater. The Irish Potato Famine is an important example from history of how a dramatic loss in basic subsistence triggered large-scale population movement.[49] The famine took hold in 1845 with the appearance of "the Blight" - a potato fungus that almost instantly destroyed the primary food source for the majority of the population. It led to the death of 1 million people and the emigration of a further 1 million, many of them to the USA.

Developed countries may become drawn into climate-induced conflicts in regions that are hardest hit by the impacts (Chapter 4), particularly as the world becomes increasingly interconnected politically and socially. In the past, climate variability and resource management have both been important contributory factors in conflict.[50] So-called "water wars" have started because competition over water resources and the displacement of populations as a result of dam building have led to unrest.[51] Direct conflict between nation states because of water scarcity has been rare in the past, but dam building and water extraction from shared rivers has served to heighten political tensions in several regions, including the Middle East (discussed in detail in Chapter 4).

[48] The fundamental drivers of past, current and future world migration are clearly set out by Hatton and Williamson (2002).
[49] See, for example, Woodham-Smith (1991)
[50] Brooks *et al.* (2005)
[51] Shiva (2002) describes several examples of conflict within a nation or between nations that has been exacerbated by tensions over construction of dams to manage water availability. Every river in India has become a site of major, irreconcilable water conflicts, including the Sutlej, Yamuna, Ganges, Krishna and Kaveri Rivers. The Tigris and Euphrates Rivers, the major water bodies sustaining agriculture for thousands of years in Turkey, Syria and Iraq have led to several major clashes among the three countries. The Nile, the longest river in the world, is shared by ten African countries and is another complicated site of water conflict, particularly following construction of the Aswan Dam.

Box 5.7 Potential impacts of climate change on trade routes and patterns

Few studies have examined the effects of climate change on global trade patterns, but the consequences could be substantial, particularly for sea-borne trade and linked coastal manufacturing and refining activities.

Rising sea levels will demand heavy investment in flood protection around ports and the export and import related activities concentrated in and around them. Stronger storm surges, winds and heavier rainfall already point to the requirement for stronger ships and sturdier offshore oil, gas and other installations. Multi-billion dollar processing installations such as oil refineries, liquefied natural gas plants and re-gasification facilities may have to be re-located to more protected areas inland.

This would reverse decades of building steel mills, petrochemical plants and other energy-related facilities close to the deepwater ports accommodating bulk cargo vessels, super-tankers and ever larger container ships which have become the key vectors of rising global trade and just-on-time production schedules. Both increased protection and relocation inland would have significant capital and transport costs, and make imports in particular more expensive.

Rapidly rising temperatures in the polar regions will affect trade, transport and energy/resource exploitation patterns. Both Canada's putative North West passage and the Arctic sea-lanes that Russia keeps open with icebreakers could become safer and more reliable alternative transport routes. But melting permafrost risks damaging high latitude oil and gas installations, pipelines and other infrastructure, including railways, such as Russia's Baikal-Amur railway, and will also require expensive remedial investment. Stormier seas could raise the attraction of land routes from Asia to Europe, including the planned new Eurasian railway across Kazakhstan.

Any weakening of the Gulf Stream however would have a dramatic cooling impact on water temperatures in the Arctic region. At present the lingering impact of the Gulf Stream keeps Murmansk open all year as an ice-free port. Russian plans to develop the offshore Shtokman gas field and associated export facilities depend on the waterway remaining navigable. In the Middle East higher temperatures and more severe droughts will cause serious problems to both water supply and agriculture.

5.6 Conclusion

The costs of climate change for developed countries could reach several percent of GDP as higher temperatures lead to a sharp increase in extreme weather events and large-scale changes.

The cooler climates of many developed countries mean that small increases in temperature (2 or 3°C) may increase economic output through greater agricultural productivity, reduced winter heating bills and fewer winter deaths. But at the same time, many developed regions have existing water shortages that will be exacerbated by rising temperatures that increase evaporation and dry out land that is already dry (Southern Europe, California, South West Australia). Water shortages will increase the investment required in infrastructure, reduce agricultural output and increase infrastructure damage from subsidence.

As temperatures continue to rise, the costs of damaging storms and floods are likely to increase rapidly. Losses could potentially reach several percent of world GDP if damages increase, as expected, in a highly non-linear manner.[52] Higher temperatures will increase the risk of triggering abrupt and large-scale changes in the climate system. These could have a direct impact on the economies of developed countries, ranging from several metres of sea level rise following melting of Greenland ice sheet to several degrees of cooling in Northern Europe following collapse of the thermohaline circulation (considered plausible but unlikely this century). Other impacts, such as monsoon failure or loss of glacial meltwater,

[52] For example, hurricane damages scale as the cube of windspeed (or more), which itself increases exponentially with ocean temperatures.

could have devastating effects in developing countries, particularly on food and water availability, and trigger large-scale population movement and regional conflict. These effects may exacerbate existing political tensions and could drive greater global instability.

Table 5.2 Summary costs of extreme weather events in developed countries with moderate climate change. Costs at higher temperatures could be substantially higher.

Region	Event Type	Temperature	Costs as % GDP	Notes
Global	All extreme weather events	2°C	0.5 - 1.0% (0.1%)	Based on extrapolating and increasing current 2% rise in costs each year over and above changes in wealth
USA	Hurricane	3°C	1.3% (0.6%)	Assumes a doubling of carbon dioxide leads to a 6% increase in hurricane windspeed
	Coastal Flood	1-m sea level rise	0.01 – 0.03%	Only costs of wetland loss and protection against permanent inundation
UK	Floods	3 – 4°C	0.2 – 0.4% (0.13%)	Infrastructure damage costs assuming no change in flood management to cope with rising risk
Europe	Coastal Flood	1-m sea level rise	0.01 - 0.02%	Only costs of wetland loss and protection against permanent inundation

Notes: Numbers in brackets show the costs in 2005. Temperatures are global relative to pre-industrial levels. The costs are likely to rise sharply as higher temperatures lead to even more intense extreme weather events and the risk of triggering abrupt and large-scale changes. Currently, there is little robust quantitative information for the costs at even higher temperatures (4 or 5°C), which are plausible if emissions continue to grow and feedbacks amplify the original warming effect (such as release of carbon dioxide from warming soils or release of methane from thawing permafrost).

References

The study by Jorgenson *et al.* (2004) for the Pew Center on Global Climate Change is one of the most comprehensive top-down assessments of the market impacts of climate change in a developed country (the USA). In contrast, the recent Metroeconomica (2006) study takes a bottom-up approach to calculating the costs and benefits of climate change for key sectors in the UK. Neither of these studies takes a detailed look at the costs of increased frequency or severity of extreme weather events. A new conference paper by Prof Bill Nordhaus (2006) examines the economics of hurricanes, showing that the costs may well double of the course of the century. This supports earlier work by the Association of British Insurers (2005) looking at the financial risks of climate change from hurricanes, typhoons and winter-storms. Hallegatte *et al.* (2006) develop these arguments further by setting out the potential long-run effects of changes in extreme weather on economic growth. Recent papers by Dr Evan Mills have examined the financial consequences of such changes in extreme weather for the insurance industry and wider capital markets (Mills 2005, Mills and Lecomte 2006).

Anthoff, D., R. Nicholls, R.S.J. Tol, and A.T. Vafeidis (2006): 'Global and regional exposure to large rises in sea-level: a sensitivity analysis', Research report prepared for the Stern Review, available from http://www.sternreview.org.uk

Arctic Climate Impacts Assessment (2004): 'Impacts of a warming Arctic', Cambridge: Cambridge University Press, available from http://www.acia.uaf.edu

Arnell, W.N. (2004): 'Climate change and global water resources: SRES scenarios and socio-economic scenarios'. Global Environmental Change **14**: 31-52

Association of British Insurers (2005a): 'Financial risks of climate change', London: Association of British Insurers, available from http://www.abi.org.uk/flooding

Association of British Insurers (2005b): 'Making communities sustainable: managing flood risks in the growth areas', London: Association of British Insurers, available from http://www.abi.org.uk/housing

Benson, K., P. Kocagil and J. Shortle (2000): 'Climate change and health in the Mid-Atlantic Region', Climate Research **14**: 245 – 253

Brookings Institution (2005): 'New Orleans after the storm: lessons from the past', Washington, DC: The Brookings Institution, available from http://www.brookings.edu/metro/pubs/20051012_NewOrleans.htm

Brooks, N., J. Gash, M. Hulme, et al. (2005): 'Climate stabilisation and "dangerous" climate change: a review of relevant issues', Scoping Study, London: Defra

Cayan, D., A.L. Luers, M. Hanemann, et al. (2006): 'Scenarios of climate change in California: an overview', California Climate Change Center, available from http://www.climatechange.ca.gov

COPA-COGECA (2003): 'Assessment of the impacts of the heatwave and drought of summer 2003 on agriculture and forestry', available from http://www.copa-cogeca.be

Crichton, D. (2006): 'Climate change and its effects on small businesses in the UK', London, UK: AXA Insurance, available from http://www.axa.co.uk/aboutus/corporate_publications/climate_change.html

Department of Health (2003): 'Health effects of climate change in the UK', The Stationary Office, UK

Dlugolecki, A. (2004): 'A changing climate for insurance', London: Association of British Insurers, available from http://www.abi.org.uk/climatechange

Environment Agency (2003): 'Deprived communities experience disproportionate levels of environmental threat', Bristol: Environment Agency

Environment Agency (2006): 'Addressing environmental inequalities: flood risk', Bristol: Environment Agency

Epstein, P.R. and E. Mills (2005): 'Climate change futures: health, ecological and economic dimensions', Center for Health and the Global Environment, Harvard Medical School, Cambridge, MA: Harvard University, available from http://www.climatechangefutures.org

Hallegatte, S., J-C- Hourcade and P. Dumas (2006): 'Why economic dynamics matter in assessing climate change damages: illustration on extreme events', Ecological Economics, in press

Hamilton, J.M., D.J. Maddison and R.S.J. Tol (2005): 'Climate change and international tourism: a simulation study', Global Environmental Change **15**: 253 – 266

Hatton, T.J.and J.G. Williamson (2002): 'What fundamentals drive world migration?', Working Paper 9159, Cambridge, MA: National Bureau of Economic Research, available from http://ww.nber.org/papers/w9159

Hayhoe, K., P. Frunhoff, S. Schneider, et al. (2006): 'Regional assessment of climate impacts on California under alternative emission scenarios', in Avoiding dangerous climate change, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press, pp. 227 – 234

Heck, P., D. Bresch and S. Tröber (2006): 'The effects of climate change: storm damage in Europe on the rise', Zurich: Swiss Re

Jorgenson, D.W., R.J. Goettle, B.H. Hurd et al. (2004): 'US market consequences of global climate change', Washington, DC: Pew Center on Global Climate Change, available from http://www.pewclimate.org/global-warming-in-depth/all_reports/marketconsequences

London Climate Change Partnership (2002): 'London's warming', London Climate Change Partnership, available from http://www.london.gov.uk/gla/publications/environment/londons_warming02.pdf

McGregor, G.R., M. Pelling and T. Wolf (2006): 'The social impacts of heat waves', Forthcoming Report to the Environment Agency

Mendelsohn, R., W.D. Nordhaus and D. Shaw (1994): 'The impact of global warming on agriculture: a Ricardian analysis', American Economic Review **84**: 753 – 771

Mendelsohn, R.O. (ed.) (2001): 'Global warming and the American economy: a regional assessment of climate change impacts', Cheltenham: Edward Elgar Publishing

Metroeconomica (2006): 'Cross-regional research programme - Quantify the costs of impacts and adaptation' (GA01075), Research report for Defra, London: Defra

MICE [Modelling the Impacts of Climate Extremes] (2005): MICE Summary of Final Report, available from http://www.cru.uea.ac.uk/cru/projects/mice/html/reports.html

Mills, E., (2005): 'Insurance in a climate of change', Science **309**: 1040 – 1044

Mills, E. and Lecomte E (2006): 'From risk to opportunity: how insurers can proactively and profitably manage climate change', Boston, MA: Ceres, available from http://www.ceres.org/pub/docs/Ceres_Insurance_Climate_%20Report_082206.pdf

Muir-Wood, R., S. Miller and A. Boissonade (2006): 'The search for trends in a global catalogue of normalized weather-related catastrophe losses', Climate change and disaster losses workshop, Hohenkammer: Munich Re, available from http://w3g.gkss.de/staff/storch/material/060525.hohenkammer.pdf

Munich Re (2004): 'Annual review: natural catastrophes 2003', Munich: Munich Re Group

Munich Re (2006): 'Annual review: natural catastrophes 2005', Munich: Munich Re Group

Nicholls, R.J., and R.J. Klein (2003): 'Climate change and coastal management on Europe's coast', EVA Working Paper 3, Potsdam: Potsdam Institute for Climate Impact Research

Nicholls, R.J., and R.S.J. Tol (2006): 'Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over 21st century', Philosophical Transactions of the Royal Society A **364**: 1073 – 1095

Nordhaus, W.D. (2006): 'The economics of hurricanes in the United States', prepared for the Snowmass Workshop on Abrupt and Catastrophic Climate Change, Snowmass, CO: Annual Meetings of the American Economic Association, available from http://nordhaus.econ.yale.edu/hurricanes.pdf

O'Brien, K., S. Eriksen, L. Sygna and L.O. Naess (2006): 'Questioning complacency: climate change impacts, vulnerability, and adaptation in Norway', Ambio **35**: 50 –56

Parry, M.L., C. Rosenzweig, A. Iglesias, et al. (2004): 'Effects of climate change on global food production under SRES emissions and socio-economic scenarios', Global Environmental Change **14**: 53 – 67

Preston, B.L. and R.N. Jones (2006): 'Climate change impacts on Australia and the benefits of early action to reduce global greenhouse gas emissions: a report prepared for the Australian Business Roundtable on Climate Change', Victoria: CSIRO

Salmon, M., and S. Weston (2006): 'Evidence to Stern Review', available from http://www.sternreview.org.uk

Schröter et al. (2005): Ecosystem service supply and vulnerability to global change in Europe, Science **310**: 1333:1337

Schlenker, W., W.M. Hanemann and A. Fisher (2005): 'Will US agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach', American Economic Review **95**: 395 – 406

Schwartz, P. and D. Randall (2004): 'An abrupt climate change scenario and its implications for United States security', Report prepared by the Global Business Network (GBN) for the Department of Defense, San Francisco, CA: GBN, available from, http://www.gbn.com/ArticleDisplayServlet.srv?aid=26231

Shiva, V. (2002) 'Water wars', Cambridge, MA: South End Press.

Stott, P.A, D.A Stone and M.R. Allen (2004): 'Human contribution to the European heatwave of 2003', Nature **432**: 610 - 614

Tol, R.S.J., T.E.Downing, O.J. Kuik and J.B. Smith (2004): 'Distributional aspects of climate change impacts', Global Environmental Change **14**: 259 – 272

UK Government Foresight Programme (2004):' Future flooding', London: Office of Science and Technology, available from http://www.foresight.gov.uk/Previous_Projects/Flood_and_Coastal_Defence

Vellinga, M. and R.A. Wood (2002): 'Global climatic impacts of a collapse of the Atlantic thermohaline circulation', Climatic Change **54**: 251-267

Warren, R., N. Arnell, R. Nicholls, et al. (2006): 'Understanding the regional impacts of climate change', Research report prepared for the Stern Review, Tyndall Centre Working Paper 90, Norwich: Tyndall Centre, available from http://www.tyndall.ac.uk/publications/working_papers/twp90.pdf

Woodham-Smith, C. (1991): 'The Great Hunger, 1845 – 1849', London: Penguin Books

6 Economic modelling of climate-change impacts

Key Messages

The monetary cost of climate change is now expected to be higher than many earlier studies suggested, because these studies tended not to include some of the most uncertain but potentially most damaging impacts.

Modelling the overall impact of climate change is a formidable challenge, involving forecasting over a century or more as the effects appear with long lags and are very long-lived. The limitations to our ability to model over such a time scale demand caution in interpreting results, but projections can illustrate the risks involved – and policy here is about the economics of risk and uncertainty.

Most formal modelling has used as a starting point 2 - 3°C warming. In this temperature range, the cost of climate change could be equivalent to around a 0 - 3% loss in global GDP from what could have been achieved in a world without climate change. Poor countries will suffer higher costs.

However, 'business as usual' (BAU) temperature increases may exceed 2 - 3°C by the end of this century. This increases the likelihood of a wider range of impacts than previously considered, more difficult to quantify, such as abrupt and large-scale climate change. With 5 - 6°C warming, models that include the risk of abrupt and large-scale climate change estimate a 5 - 10% loss in global GDP, with poor countries suffering costs in excess of 10%. The risks, however, cover a very broad range and involve the possibility of much higher losses. This underlines the importance of revisiting past estimates.

Modelling over many decades, regions and possible outcomes demands that we make distributional and ethical judgements systematically and explicitly. Attaching little weight to the future, simply because it is in the future ('pure time discounting'), would produce low estimates of cost – but if you care little for the future you will not wish to take action on climate change.

Using an Integrated Assessment Model, and with due caution about the ability to model, we estimate the total cost of BAU climate change over the next two centuries to equate to an average reduction in global per-capita consumption of 5%, at a minimum, now and forever.

The cost of BAU would increase still further, were the model to take account of three important factors:

- First, including direct impacts on the environment and human health ('non-market' impacts) increases the total cost of BAU climate change from 5% to 11%, although valuations here raise difficult ethical and measurement issues. But this does not fully include 'socially contingent' impacts such as social and political instability, which are very difficult to measure in monetary terms;
- Second, some recent scientific evidence indicates that the climate system may be more responsive to greenhouse-gas emissions than previously thought, because of the existence of amplifying feedbacks in the climate system. Our estimates indicate that the potential scale of the climate response could increase the cost of BAU climate change from 5% to 7%, or from 11% to 14% if non-market impacts are included. In fact, these may be only modest estimates of the bigger risks – the science here is still developing and broader risks are plausible;
- Third, a disproportionate burden of climate change impacts fall on poor regions of the world. Based on existing studies, giving this burden stronger relative weight could increase the cost of BAU by more than one quarter.

Putting these three additional factors together would increase the total cost of BAU climate change to the equivalent of around a 20% reduction in current per-capita consumption, now and forever. Distributional judgements, a concern with living standards beyond those elements reflected in GDP, and modern approaches to uncertainty all suggest that the appropriate estimate of damages may well lie in the upper part of the range 5 – 20%. Much, but not all, of that loss could be avoided through a strong mitigation policy. We argue in Part III that this can be achieved at a far lower cost.

6.1 Introduction

The cost of climate change is now expected to be larger than many earlier studies suggested.

This brings together estimates from formal models of the monetary cost of climate change, including evidence on how these costs rise with increasing temperatures. It builds on and complements the evidence presented in Chapters 3, 4 and 5, which set out the effects of climate change in detail and separately considered its consequences for key indicators of development: income, health and the environment.

In estimating the costs of climate change, we build on the very valuable first round of integrated climate-change models that have come out over the past fifteen years or so. We use a model that is able to summarise cost simulations across a wide range of possible impacts – taking account of new scientific evidence – based on a theoretical framework that can deal effectively with large and uncertain climate risks many years in the future (see Section 6.4). Thus our focus is firmly on the economics of risk and uncertainty.

Our estimate of the total cost of 'business as usual' (BAU) climate change over the next two centuries equates to an average welfare loss equivalent to at least 5% of the value of global per-capita consumption, now and forever. That is a minimum in the context of this model, and there are a number of omitted features that would add substantially to this estimate. Thus the cost is shown to be higher if recent scientific findings about the responsiveness of the climate system to greenhouse gas (GHG) emissions turn out to be correct and if direct impacts on the environment and human health are taken into account. Were the model also to reflect the importance of the disproportionate burden of climate-change impacts on poor regions of the world, the cost would be higher still. Putting all these together, the cost could be equivalent to up to around 20%, now and forever.

The large uncertainties in this type of modelling and calculation should not be ignored. The model we use, although it is able to build on and go beyond previous models, nonetheless shares most of their limitations. In particular, it must rely on sparse or non-existent observational data at high temperatures and from developing regions. The possibilities of very high temperatures and abrupt and large-scale changes in the climate system are the greatest risks we face in terms of their potential impact, yet these are precisely the areas we know least about, both scientifically and economically – hence the uncertainty about the shape of the probability distributions for temperature and impacts, in particular at their upper end. Also, if the model is to quantify the full range of effects, it must place monetary values on health and the environment, which is conceptually, ethically and empirically very difficult. But, given these caveats, even at the optimistic end of the 5 – 20% range, 'business as usual' climate change implies the equivalent of a permanent reduction in consumption that is strikingly large.

In interpreting these results, economic models that look out over just a few years are insufficient. The impacts of GHGs emitted today will still be felt well over a century from now. Uncertainty about both scientific and economic possibilities is very large and any model must be seen as illustrative. Nevertheless, getting to grips with the analysis in a serious way does require us to look forward explicitly. These models should be seen as one contribution to that discussion. They should be treated with great circumspection. There is a danger that, because they are quantitative, they will be taken too literally. They should not be. They are only one part of an argument. But they can, and do, help us to gain some understanding of the size of the risks involved, an issue that is at the heart of the economics of climate change.

Although this Review is based on a multi-dimensional view of economic and social goals, rather than a narrowly monetary one, models that can measure climate-change damage in monetary terms have an important role.

A multi-dimensional approach to development is crucial, as our discussions in Part II make clear and as is embodied, for example, in the Millennium Development Goals (MDGs). In this Chapter, we focus on three dimensions most affected by climate change: income/consumption, health, and the environment. Chapters 3 to 5 have laid out how these dimensions are affected individually. Here we consider how they might be combined in a single metric of damage[1].

Our preference is to consider the multiple dimensions of the cost of climate change separately, examining each on its own terms. A toll in terms of lives lost gains little in eloquence when it is converted into dollars; but it loses something, from an ethical perspective, by distancing us from the human cost of climate change.

Nevertheless, in this chapter the Review does engage with formal models of the monetary cost of climate change. Such models produce useful insights into the global cost of climate change. In making an analytical assessment in terms of the formal economics of risk and uncertainty, our models incorporate, systematically and transparently, the high risks that climate change is now thought to pose. Estimating those costs is essential for taking action (although we have emphasised strongly the dangers of taking them too literally). Once the aggregate cost of climate change is expressed in monetary terms, it is possible to compare this cost with the anticipated cost of mitigating and adapting to climate change. This is covered in Chapter 13, where the Review also considers other ways, beyond this modelling, of examining the case for action.

6.2 What existing models calculate and include

Modelling the monetary impacts of climate change globally is very challenging: it requires quantitative analysis of a very broad range of environmental, economic and social issues. Integrated Assessment Models (IAMs), though limited, provide a useful tool.

IAMs simulate the process of human-induced climate change, from emissions of GHGs to the socio-economic impacts of climate change (Figure 6.1). We focus on the handful of models specially designed to provide monetary estimates of climate impacts. Although the monetary cost of climate change can be presented in a number of ways, the basis is the difference between income growth with and without climate change impacts. To do this, the part of the model that simulates the impacts of climate change is in effect 'switched off' in the 'no climate change' scenario.

Income in the 'no climate change' scenario is conventionally measured in terms of GDP – the value of economic output. The difficulty is that some of the negative effects of climate change will actually lead to increases in expenditure, which increase economic output. Examples are increasing expenditure on air conditioning and flood defences. But it is correct to subtract these from GDP in the 'no climate change' scenario, because such expenditures are a cost of climate change. As a result, the measure of the monetary cost of climate change that we derive is really a measure of income loss, rather than output loss as conventionally measured by GDP.

Making such estimates is a formidable task in many ways (discussed below). It is also a computationally demanding exercise, with the result that such models must make drastic, often heroic, simplifications along all stages of the climate-change chain. What is more, large uncertainties are associated with each element in the cycle. Nevertheless, the IAMs remain the best tool available for estimating aggregate quantitative global costs and risks of climate change.

The initial focus of IAMs is on economic sectors for which prices exist or can be imputed relatively straightforwardly. These 'market' sectors include agriculture, energy use and forestry. But this market-sector approach fails to capture most direct impacts on the environment and human health, because they are not priced in markets. These important impacts – together with some other effects in agriculture and forestry that are not covered by market prices – are often described as 'non-market'.

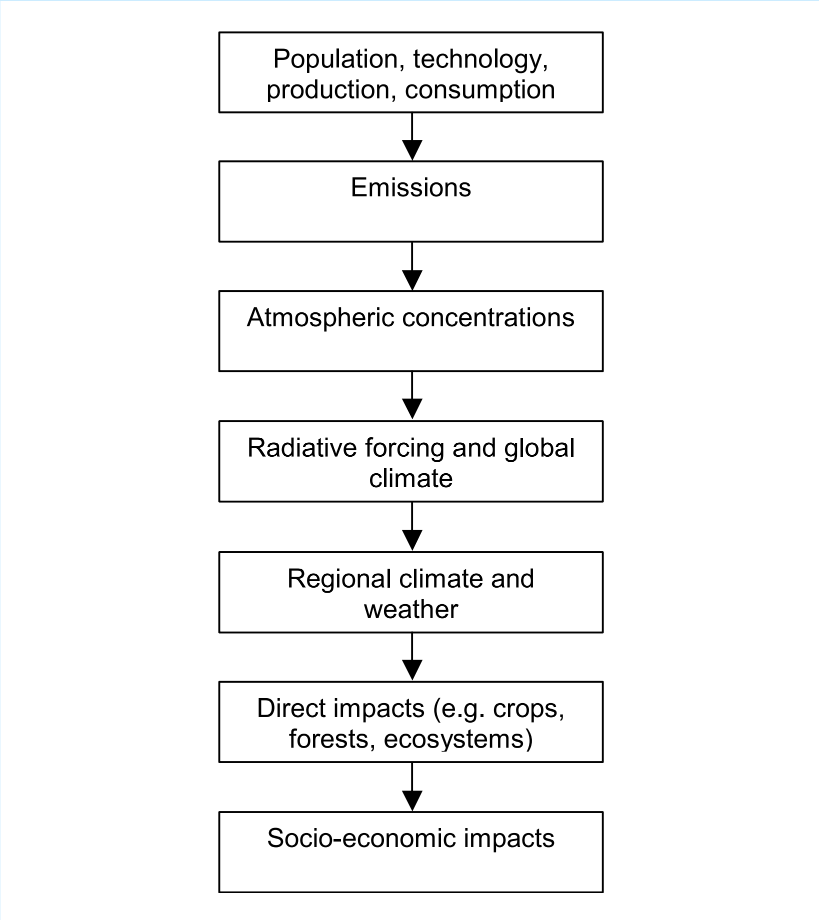
Economists have developed a range of techniques for calculating prices and costing non-market impacts, but the resulting estimates are problematic in terms of concept, ethical framework, and practicalities. Many would argue that it is better to present costs in human lives and environmental quality side-by-side with income and consumption, rather than trying to summarise them in monetary terms. That is indeed the approach taken across most of the Review. Nevertheless, modellers have

[1] Ethical perspectives other than those embodied in the models below – such as the approaches based on rights and liberties, intergenerational responsibilities, and environmental stewardship discussed in Chapter 2 – also point towards focusing on the costs of climate change in terms of income/consumption, health, and environment.

tried to do their best to assess the full costs of climate change and the costs of avoiding it on a comparable basis, and thus make their best efforts to include 'non-market' impacts.

Figure 6.1 Modelling climate change from emissions to impacts.

This figure describes a simple unidirectional chain. This is a simplification as, in the real climate-human system, there will be feedbacks between many links in the chain.



Source: Hope (2005).

Estimates from the first round of IAMs laid an important foundation for later work, and their results are still valuable for informing policy. However, they were limited to snapshots of climate change at temperatures now likely to be exceeded by the end of this century.

The first round of estimates from a wide range of IAMs, presented in the IPCC's 1996 *Second Assessment Report*,[2] were based on a snapshot increase in global mean temperature. The models estimated the effects of a doubling of atmospheric CO_2 concentrations from pre-industrial levels, which was believed likely to lead to a 2.5°C mean temperature increase from pre-industrial levels. The costs of such an increase were estimated at 1.5 - 2.0% of world GDP, 1.0 - 1.5% of GDP in developed countries, and 2 - 9% in developing countries.

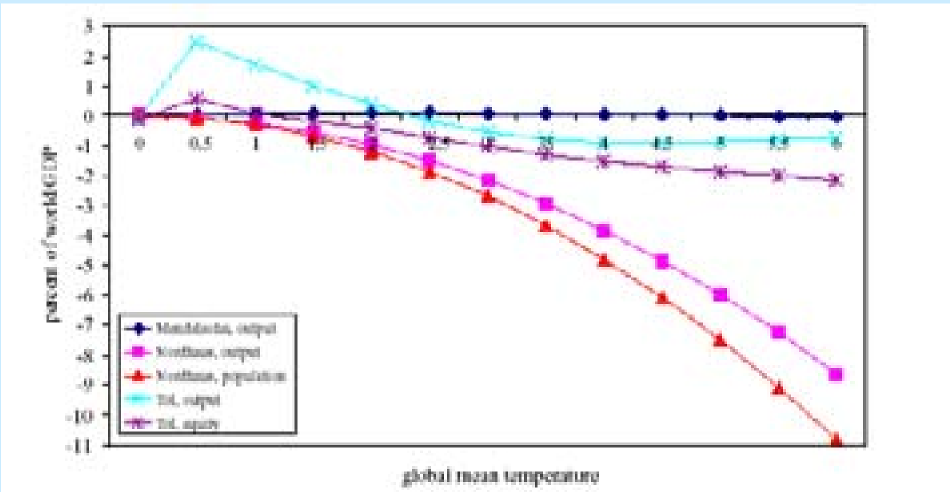
Because they took a snapshot of climate change at 2.5°C warming, these early IAM-based studies did not consider the risks associated with higher temperatures. Since then, a smaller number of models have traced the costs of climate change as temperatures increase, although their parameters are still largely calibrated on estimates of impacts with a doubling of atmospheric CO_2. These models have also covered new sectors and have looked more carefully at adaptation to climate change.

[2] Pearce *et al*. (1996)

Figure 6.2 Estimates of the global impacts of climate change, as a function of global mean temperature, considered by the 2001 IPCC *Third Assessment Report*.

The figure below traces the global monetary cost of climate change with increases in global mean temperature above pre-industrial levels (shown on the x-axis), according to three models:

- 'Mendelsohn, output' traces the estimates of Mendelsohn *et al*. (1998), with regional monetary impact estimates aggregated to world impacts without weighting;
- 'Nordhaus, output' traces the estimates of Nordhaus and Boyer (2000), with regional monetary impact estimates aggregated to world impacts without weighting;
- 'Nordhaus, population' also traces the estimates of Nordhaus and Boyer (2000), with regional monetary impact estimates aggregated to world impacts based on regional population;
- 'Tol, output' traces the estimates of Tol (2002), with regional monetary impact estimates aggregated without weighting;
- 'Tol, equity' also traces the estimates of Tol (2002), with regional monetary impacts estimated at world average values and then aggregated, weighting by the ratio of global average per-capita income to regional average per-capita income.



Source: Smith et al. (2001).

Figure 6.2 illustrates the results of three important models (whose assumptions are reported in detail in Warren *et al*. (2006)) at different global mean temperature rises:

- **The 'Mendelsohn' model**[3] estimates impacts only for five 'market' sectors: agriculture, forestry, energy, water and coastal zones. The global impact of climate change is calculated to be very small (virtually indistinguishable from the horizontal axis) and is positive for increases in global mean temperature up to about 4°C above pre-industrial levels.

- **The 'Tol' model**[4] estimates impacts for a wider range of market and non-market sectors: agriculture, forestry, water, energy, coastal zones and ecosystems, as well as mortality from vector-borne diseases, heat stress and cold stress. Costs are weighted either by output or by equity-weighted output (see below). The model estimates that initial increases in global mean temperature would actually yield net global benefits. Since these benefits accrue primarily to rich countries, the method of aggregation across countries matters for the size of the global benefits. According to the output-weighted results, global benefits peak at around 2.5% of global GDP at a warming of 0.5°C above pre-industrial. But, according to the equity-weighted results, global benefits peak at only 0.5% of global GDP (also for a 0.5°C temperature increase). Global impacts become negative beyond 1°C (equity-weighted) or 2 - 2.5°C

[3] Mendelsohn *et al*. (1998)
[4] Tol (2002)

(output-weighted), and they reach 0.5 - 2% of global GDP for higher increases in global mean temperature.

- **The 'Nordhaus' model**[5] includes a range of market and non-market impact sectors: agriculture, forestry, energy, water, construction, fisheries, outdoor recreation, coastal zones, mortality from climate-related diseases and pollution, and ecosystems. It also includes what were at the time pioneering estimates of the economic cost of catastrophic climate impacts (the small probability of losses in GDP running into tens of percentage points – see below). These catastrophic impacts drive much of the larger costs of climate change at high levels of warming. At 6°C warming, the 'Nordhaus' model estimates a global cost of between around 9 - 11% of global GDP, depending on whether regional impacts are aggregated by output (lower) or population (higher). The Nordhaus model also predicts that the cost of climate change will increase faster than global mean temperature, so that the aggregate loss in global GDP almost doubles as global mean temperature increases from 4°C to 6°C above pre-industrial levels. As Section 6.3 explains, this reflects the fact that higher temperatures will increase the chance of triggering abrupt and large-scale changes, such as sudden shifts in regional weather patterns like the monsoons or the El Niño phenomenon (and see Chapter 3 for a discussion of increasing marginal damages).

Models differ on whether low levels of global warming would have positive or negative global effects. But all agreed that the effects of warming above 2 - 3°C would reduce global welfare, and that even mild warming would harm poor countries.

These results are quite difficult to compare, because of the many differences between the models and the inputs they use, but some key points can be made:

- ***Up to around 2 - 3°C warming,*** there is disagreement about whether the global impact of climate change will be positive or negative. But, even at these levels of warming, it is clear that any benefits are temporary and confined to rich countries, with poor countries suffering significant costs. For example, Tol estimates a cost to Africa of 4.1% of GDP for 2.5°C warming, very close to Nordhaus and Boyer's estimate of 3.9%.

- ***For warming beyond 2 - 3°C***, the models agree that climate change will reduce global consumption. However, they disagree on the size of this cost, ranging from a very small fraction of global GDP to 10% or more. In this range too, the models agree that poor countries will suffer the highest costs, although in the Nordhaus model the estimated cost to Western Europe of 6°C warming is second only to the cost to Africa.[6]

These results depend on key modelling decisions, including how each model values the costs to poor regions and what it assumed about societies' ability to reduce costs by adapting to climate change.

Each model's results depend heavily on how it aggregates the impacts across regions, and in particular how it values costs in poor regions relative to those in rich ones. The prices of marketed goods and services, as well as the hypothetical values assigned to health and the environment, are typically higher in rich countries than in poor countries. Thus, in these models, a 10% loss in the volume of production of an economic sector is worth more in a rich country than in a poor country. Similarly, a 5% increase in mortality, if 'values of life' are based on willingness to pay, is worth more in purely monetary terms in a rich country than a poor country, because incomes are higher in the former. Many ethical observers would reject both of these statements. Thus some of the authors have used welfare or 'equity' weighting. Explicit functions to capture distributional judgements are also used in this Review – see Chapter 2 and Appendix. In summary, if aggregation is done purely on the basis of adding incomes or GDP, then very large physical impacts in poor countries will tend to be overshadowed by even small impacts in rich countries.

---

[5] Nordhaus and Boyer (2000)

[6] The European result is driven in large part by Europe's expected willingness to pay to reduce the risk of a catastrophic event such as a significant weakening of the Atlantic thermohaline circulation – part of which keeps Western Europe warmer than its latitude would otherwise imply.

Nordhaus and Boyer and Tol both adopt equity-weighting approaches, a step which in our view is supported by the type of ethical considerations discussed in Chapter 2 and its Appendix, as well as empirical observations of the attitudes that people actually hold towards inequality in wealth.[78] Mendelsohn does not use equity weights.

Adaptation to climate change is another important factor in these models, because it has the capacity to reduce the cost of BAU climate change. The key questions are how much adaptation can be assumed without extra stimulus from policy (financial, legal and otherwise), how much will it cost, because the costs of adaptation themselves are part of the cost of climate change, and what would it achieve? Again, it is difficult to compare the models, because each treats adaptation in a different manner. In general, the models do assume that households and businesses do what they can to adapt, without extra stimulus from policy.

The 'Mendelsohn' model is most optimistic about adaptation, and – not coincidentally – it estimates the lowest cost of climate change.[9] In their method, future responses to climate change are calibrated against the relationship between output and climate that can be seen from region to region today, or that can be determined from laboratory experiments.[10] The former method models adaptation most completely. In effect, as temperatures increase, and controlling for other climate and non-climate variables, environmental and economic conditions migrate from the equator towards the poles. High-latitude regions climb a hill of rising productivity for a time as temperatures make conditions easier (e.g. for agriculture), while low-latitude regions fall further into more difficult conditions. This method encompasses a variety of ways a region can adapt, because regions can be assumed to be well adapted to their current climates. Its major drawback, however, is that it makes no provision for the costs and difficulties of transition from one climate to another or the potential movement of people. Whether these are small or large, it is, on balance, an underestimate of the cost of climate change.

A final point to keep in mind is that all three models are based on scientific evidence up to the mid- to late 1990s. Since then, new evidence has come to light, most importantly on the possibilities of higher and more rapidly increasing temperatures than envisaged then, as well as possibilities of abrupt and large-scale changes to the climate system. Section 6.3 explores the consequences of these risks at greater length.

6.3 Do the existing models fully capture the likely cost of climate change?

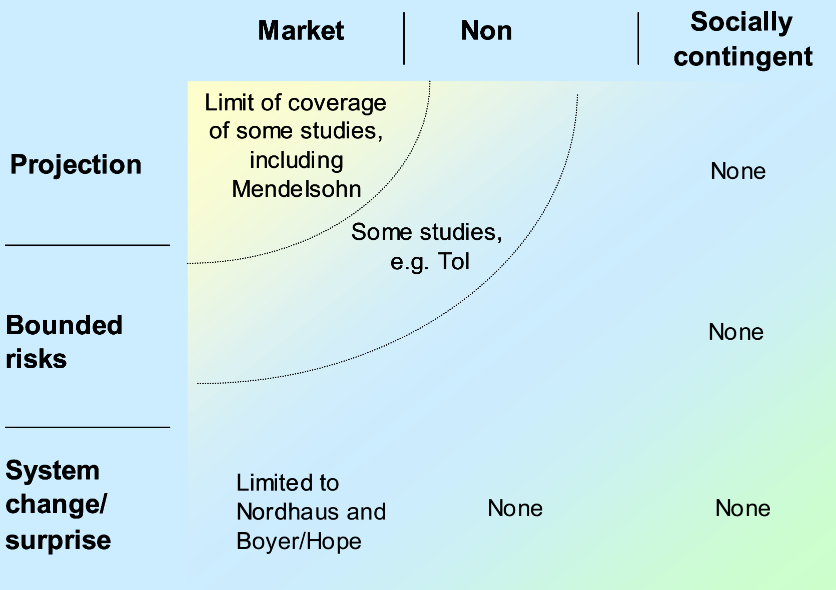
Existing estimates of the monetary cost of climate change, although very useful, leave many questions unanswered and omit potentially very important impacts. Taking omitted impacts into account will increase cost estimates, and probably strongly.

Understanding of the science and economics of climate change is constantly improving to overcome substantial gaps, but many remain. This is particularly true of the existing crop of IAMs, due in part to the demands of modelling and in part to their reliance on knowledge from other active areas of research. Indeed, the knowledge base on which the cost of climate change is calibrated – specialised studies of impacts on agriculture, ecosystems and so on – is particularly patchy at high temperatures.[11] In principle, the gaps that remain may lead to underestimates or overestimates of global impacts. In practice, however, most of the unresolved issues will increase damage estimates.

[7] Stern (1977), Pearce and Ulph (1999)
[8] Equity weights should reflect the choice of social welfare function – sometimes called the 'objective' function. This aggregates the consumption of individuals over space and time, reflecting judgements about the value of consumption enjoyed by individuals in different regions at different times (see the Appendix to Chapter 2). Here we focus on how this weighting should be carried out across regions within the present generation when considering the aggregation of small changes. The first step in calculating a weighted average change is to calculate the proportional impact of climate change on the representative individual in each region. If the utility function for an individual has constant marginal utility, the proportional impacts on per capita consumption can then be aggregated to give the proportional impact on overall social welfare by weighting them by the share of each individual's consumption in total consumption. At the regional level, this means weighting the impact on the representative individual by the region's share in global consumption (i.e. regional per-capita consumption multiplied by regional population, as a share of total global consumption). With a utility function given by the log of individual consumption, the proportional impacts on individuals should simply be added up; thus, at the regional level, the proportional impact on the representative consumer is weighted by the region's population.
[9] There are several reasons why the 'Mendelsohn' model estimates the lowest cost of climate change. Adaptation is likely to be one, its omission of non-market impacts and the risk of catastrophe another.
[10] That is, they estimate the relationship between production in their five market sectors and climate based on how production varies across current world climates, and control for other important determining factors.
[11] See Hitz and Smith (2004)

Existing models omit many possible impacts. Watkiss *et al.*[12] have developed a 'risk matrix' of uncertainty in projecting climate change and its impacts to illustrate the limitations of existing studies in capturing potentially important effects. Figure 6.3 presents this matrix and locates the existing models on it.

Figure 6.3 Coverage of existing integrated assessment studies.



Source: Watkiss, Downing *et al*. (2005).

Figure 6.3 summarises which impacts existing estimates of the monetary cost of climate change cover (by reference to the authors of the various studies) and which impacts are omitted.

The vertical axis captures uncertainty in predicting climate change, with uncertainty increasing as we go down. There are three categories:

- Projection – high confidence on the direction of these changes and bounds can be placed around their magnitude (i.e. temperature change and sea-level rise);
- Bounded risks – more uncertainty about the direction and magnitude of these changes, though reasonable bounds can be placed around them (i.e. precipitation, extreme events);
- System change and surprises – large uncertainty about the potential trigger and timing of these changes (e.g. weakening of the thermohaline circulation, collapse of the West Antarctic Ice Sheet). However, evidence on the risk of such changes is building (see Chapters 1 and 3).

The horizontal axis captures uncertainty in the economic measurement of impacts, with uncertainty increasing as we go from left to right. There are again three categories:

- 'Market' impacts – where prices exist and a valuation can be made relatively easily, such as in agriculture, energy use and forestry;
- 'Non-market' impacts – directly on human health and the environment, where market prices tend not to exist and methods are required to create them;
- 'Socially contingent' responses – large-scale, 'second-round' socio-economic responses to the impacts of climate change, such as conflict, migration and the flight of capital investment.

As the figure shows, most existing studies are confined to the top left part of the matrix and are thus limited to a small subset of the most well understood, but least damaging, impacts (for example, the 'Mendelsohn' model, which is also most optimistic about adaptation: see previous section). By contrast, because the impacts in the bottom right corner of the matrix are surrounded by the greatest

[12] Watkiss *et al*. (2005)

scientific uncertainty, they have not been incorporated into IAMs. Yet it is also these paths that have the potential to inflict the greatest damage.

Extreme weather events are not fully captured in most existing IAMs;[13] the latest science suggests that extreme events will increase in frequency and severity with climate change.

Chapters 1 and 3 laid out the newer evidence that climate change will spur an increase in extreme weather events – notably floods, droughts, and storms. Experience of weather disasters in many parts of the world demonstrates that the more extreme events can have lasting economic effects, especially when they fall on an economy weakened by previous weather disasters or other shocks, or if they fall on an economy that finds it difficult to adjust quickly.[14] Thus it is very important to consider the economic impacts of variations in weather around mean trends in climate change.

However, it is at least as important to consider the climatic changes and impacts that will occur if GHG emissions lead to very substantial warming, with global mean temperatures 5 - 6°C above pre-industrial levels or more. High temperatures are likely to generate a hostile and extreme environment for human activity in many parts of the world. Some models capture aspects of this, because costs both in market and non-market sectors accelerate as temperatures increase.[15] At 5 - 6°C above pre-industrial levels, the cost of climate change on, for example, agriculture can be very high.

Further, Chapter 1 detailed emerging evidence of risks that higher temperatures will trigger massive system 'surprises', such as the melting and collapse of ice sheets and sudden shifts in regional weather patterns like the monsoons. Thus there is a danger that feedbacks could generate abrupt and large-scale changes in the climate and still further losses.

Existing IAMs largely omit these system-change effects; including them is likely to increase cost estimates significantly. Although many factors can produce differences in results from model to model, it is nevertheless intuitive that the Nordhaus estimates[16], produced by the only model to include catastrophic 'system change/surprise', were the highest among the existing IAMs. For increases in global mean temperature of 5 - 6°C above pre-industrial levels or more, costs were estimated to approach and even exceed 10% of global GDP.

The Nordhaus method is based on polling a number of experts on the probability that a very large loss of 25% of global GDP, roughly equivalent to the effect of the Great Depression, will result from increases in global mean temperature of 3°C by 2090, 6°C by 2175 and 6°C by 2090. Taking account of estimated differences in regional vulnerability to catastrophic climate change, the model uses survey data to estimate people's willingness to pay to avoid the resulting risk. This approach is simple, but it takes us some way towards capturing the economic importance of complex, severe responses of the climate system.

Most existing IAMs also omit other potentially important factors – such as social and political instability and cross-sectoral impacts. And they have not yet incorporated the newest evidence on damaging warming effects.

One factor omitted at least in part from most models is 'socially contingent' responses – the possibility that climate change will not only increase the immediate costs of climate change, but also affect investment decisions, labour supply and productivity, and even social and political stability.

On the one hand, these knock-on effects could dampen the negative effect of climate change, if the economic response is to adapt, for example, by shifting production from the most climate-sensitive sectors into less climate-sensitive sectors. As mentioned, recent models have taken adaptation more fully into account.

On the other hand, knock-on effects could amplify the future consequences of today's climate change, for example if they reduce investment. This possibility has yet to be taken fully into account. In some models, baseline income is taken from outside the model, so that the impacts in any one time period do not affect growth in future periods. In other models, such as that employed by Nordhaus and

[13] Warren *et al*. (2006)
[14] Hallegatte and Hourcade (2005) and Chapter 4.
[15] Although this depends on how rapidly costs increase in proportion to temperature.
[16] Nordhaus and Boyer (2000)

Boyer,[17] the economy makes investment and saving decisions based on the level of income it starts off with and on expectations of how that income will grow in the future. Climate change reduces investment and saving, as the income available to invest and the returns to saving fall.[18]

How important might these effects be? Fankhauser and Tol[19] unpack the 'Nordhaus' estimates to show that the knock-on cost of depressed investment on the total, long-run cost of 3°C warming is at least an additional 90% over and above the immediate cost. Furthermore, substituting for a more powerful model of economic growth that is better able to explain past and present growth trends, world GDP losses are almost twice as high as they are for immediate impacts alone. These dynamic effects may be especially strong in some developing regions, where the further effect of climate change may be to precipitate instability, conflict and migration (see Chapters 4 and 5).

A second omitted factor is possible interactions between impacts in one sector and impacts in another, which past IAMs have not generally taken into account. Climate damage in one sector could multiply damage in another – for example, if water-sector impacts amplify the impacts of climate change on agriculture. The reasons for excluding these effects have to do with the modelling approach: in the basic IAM method, impacts are characteristically enumerated on a sector-by-sector basis, and then added up to arrive at the overall economy-wide impact.

Finally, even in market sectors that the IAMs do cover well, the latest specialised impact studies suggest that IAM-based estimates may be too optimistic.[20] The underlying impacts literature on which the IAMs are based dates primarily from 2000 or earlier. Since then, many of the predictions of this literature have become more pessimistic, for example, on the possible boost from CO_2 fertilisation to agriculture (Chapter 3).

The building of the IAMs has been a valuable contribution to our understanding of possible effects. Any model must necessarily leave out much that is important and can use only the information available at the time of construction. The science has moved quickly and the economic analysis and modelling can move with it.

6.4 Calculating the global cost of climate change: an 'expected-utility' analysis

Modelling the global cost of climate change presents many challenges, including how to take account of risks of very damaging impacts, as well as uncertain changes that occur over very long periods.

A model of the monetary cost of climate change ideally should provide:

- Cost simulations across the widest range of possible impacts, taking into account the risks of the more damaging impacts that new scientific evidence suggests are possible.
- A theoretical framework that is fit for the purpose of analysing changes to economies and societies that are large, uncertain, unevenly distributed and that occur over a very long period of time.

This section begins with the first challenge, illustrating the consequences of BAU climate change in a framework that explicitly brings out risk. The second challenge is addressed later in the chapter, allowing consideration of how to value the risks with different consequences, particularly the risks, however small, of very severe climate impacts.

[17] Nordhaus and Boyer (2000)
[18] Because the Nordhaus and Boyer model simplifies the economy to one sector, it ignores the possibility that productivity will increase if production is shifted from low productivity/highly climate-sensitive sectors to high productivity/low sensitivity sectors. But a multi-sector study for the USA (Jorgensen *et al*., 2005) indicates that such processes are negligible, at least in that region.
[19] Fankhauser and Tol (2003)
[20] Warren *et al.* (2006)

The model we use – the PAGE2002 IAM[21] – can take account of the range of risks by allowing outcomes to vary probabilistically across many model runs, with the probabilities calibrated to the latest scientific quantitative evidence on particular risks.

The first challenge points strongly to the need for a modelling approach based on probabilities (that is, a 'stochastic' approach). The PAGE2002 (Policy Analysis of the Greenhouse Effect 2002) IAM meets this requirement by producing estimates based on 'Monte Carlo' simulation. This means that it runs each scenario many times (e.g. 1000 times), each time choosing a set of uncertain parameters randomly from pre-determined ranges of possible values. In this way, the model generates a probability distribution of results rather than just a single point estimate. Specifically, it yields a probability distribution of future income under climate change, where climate-driven damage and the cost of adapting to climate change are subtracted from a baseline GDP growth projection[22].

The parameter ranges used as model inputs are calibrated to the scientific and economic literatures on climate change, so that PAGE2002 in effect summarises the range of underlying research studies. So, for example, the probability distribution for the climate sensitivity parameter – which represents how temperatures will respond in equilibrium to a doubling of atmospheric carbon dioxide concentrations – captures the range of estimates across a number of peer-reviewed scientific studies. Thus, the model has in the past produced mean estimates of the global cost of climate change that are close to the centre of a range of peer-reviewed studies, including other IAMs, while also being capable of incorporating results from a wider range of studies.[23] This is a very valuable feature of the model and a key reason for its use in this study.

PAGE2002 has a number of further desirable features. It is flexible enough to include market impacts (for example, on agriculture, energy and coastal zones) and non-market impacts (direct impacts on the environment and human mortality), as well as the possibility of catastrophic climate impacts. Catastrophic impacts are modelled in a manner similar to the approach used by Nordhaus and Boyer.[24] When global mean temperature rises to high levels (an average of 5°C above pre-industrial levels), the chance of large losses in regional GDP in the range of 5 - 20% begins to appear. This chance increases by an average of 10% per ºC rise in global mean temperature beyond 5°C.

At the same time, PAGE2002 shares many of the limitations of other formal models. It must rely on sparse or non-existent data and understanding at high temperatures and in developing regions, and it faces difficulties in valuing direct impacts on health and the environment. Moreover, like the models depicted in Figure 6.3, the PAGE2002 model does not fully cover the 'socially contingent' impacts. As a result, the estimates of catastrophic impacts may be conservative, given the damage likely at temperatures as high as 6 - 8°C above pre-industrial levels. Thus the results presented below should be viewed as indicative only and interpreted with great caution. Given what is excluded, they should be regarded as rather conservative estimates of costs, relative to the ability of these models to produce reliable guidance.

We present results based on different assumptions along two dimensions: first, of how fast global temperatures increase in response to GHG emissions and, second, different categories of economic impact.

To reflect the considerable uncertainty about likely probability distributions and difficulties in measuring different effects, we examine models that differ along two dimensions:

- **Response of the climate to GHG emissions.** We run the model under two different assumed levels of climatic response. The 'baseline climate' scenario is designed to give outputs consistent with the IPCC *Third Assessment Report* (TAR)[25]. The 'high climate' scenario adds to this a risk of there being amplifying natural feedbacks in the climate system. This is based on recent studies showing that there is a real risk of additional feedbacks, such as weakening carbon sinks and natural methane releases from wetlands and thawing

[21] Hope (2003)
[22] We follow PAGE in referring to 'GDP' but, as remarked above, it is preferable to think of a broader income concept in interpreting some of the results.
[23] Tol (2005)
[24] Nordhaus and Boyer (2000)
[25] IPCC (2001)

permafrost. This scenario gives a higher probability of larger temperature changes. These scenarios are discussed in more detail in Box 6.1. Both climate scenarios give temperature outputs that are roughly consistent with other studies.

Box 6.1 The PAGE2002 climate scenarios.

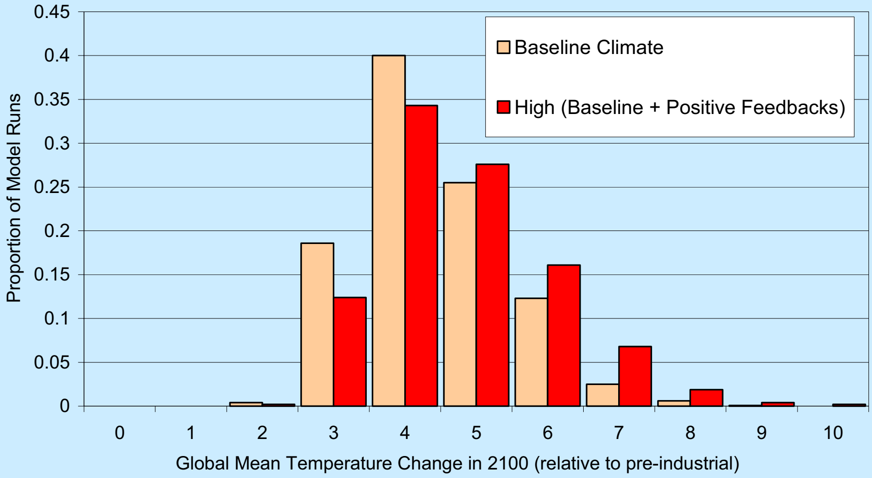
Baseline Climate: This is designed to give outputs consistent with the range of assumptions presented in the IPCC *Third Assessment Report* (TAR). The scenario produces a mean warming of 3.9°C relative to pre-industrial in 2100 and a 90% confidence interval of 2.4 – 5.8°C (see figure below) for the A2 emissions scenario used in this exercise. This is in line with the mean projection of 4.1°C given by the IPCC TAR. The IPCC does not give a probability range of temperatures. It does quote a range across several models of 3.0 – 5.3°C. The wider range of temperatures produced by PAGE2002 mainly reflects the wider combinations of parameters explored by the model.

High Climate: This is designed to explore the impacts that may be seen if the level of temperature change is pushed to higher levels through the action of amplifying feedbacks in the climate system. Scientists are only just beginning to quantify these effects, but these preliminary studies suggest that they will form an important part of the climate system's response to GHG emissions. No studies have yet combined ranges of climate sensitivity and feedbacks in this way, so these results should be treated as only indicative of the possible potential scale of response. The scenario includes recent estimates of two types of amplifying feedback: a weakening of natural carbon absorption and increased natural methane releases from, for example, thawing permafrost.

- **Weakened carbon sinks:** As temperatures increase, plant and soil respiration increases. Recent evidence suggests that these extra natural emissions will offset any increase in natural sink capacity due to carbon fertilisation, so that carbon sinks will be weakened overall (discussed in chapter 1). Weakening of carbon sinks are modelled as a function of temperature, based on Friedlingstein et al. (2006).

- **Increased natural methane releases:** Natural methane currently locked in wetlands and permafrost is released as temperatures rise. This is simulated using a probability distribution based on recent studies (Box 1.3)[26].

In this exercise, these feedbacks push the mean temperature change up by around 0.4°C and give a higher probability of larger temperature increases. Accordingly, the 90% confidence interval increases to 2.6 - 6.5°C. There is little effect on the lower bound of temperature changes, as, at this level, temperatures are not large enough to initiate a significant feedback effect from the carbon cycle. The increase in the mean and upper bound are consistent with recent studies (chapter 1).

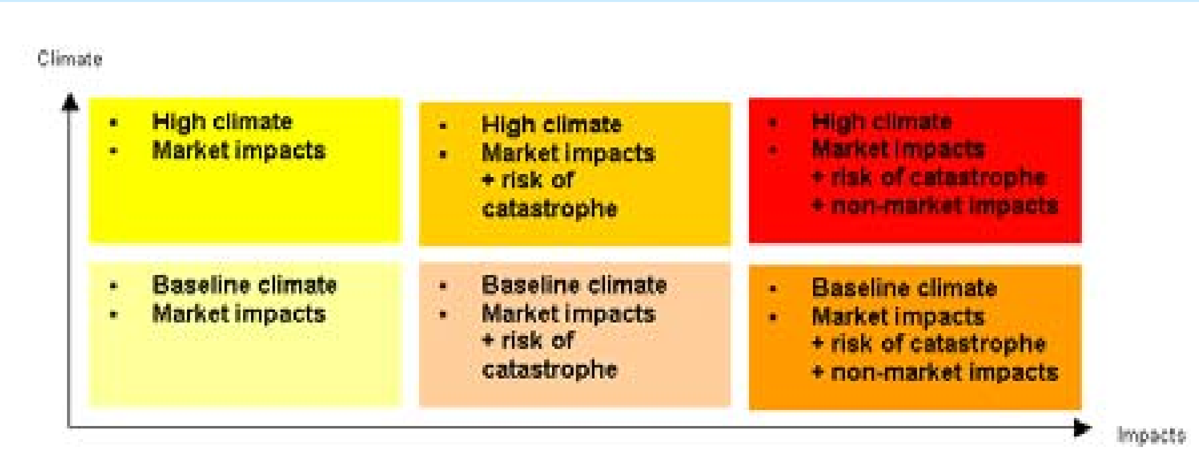


[26] For example, the central value is based on Gedney *et al*. (2004) assuming 4.5°C temperature rise in 2100

- **Categories of economic impact.** Our analyses also vary in the comprehensiveness with which they measure the impacts of climate change on the economy and on welfare. The first set of estimates includes only the impacts of 'gradual climate change' on market sectors of the economy. In other words, it takes no account of the possibility of catastrophic events that we now know may occur. The second set also includes the risk of catastrophic climate impacts at higher temperatures. Figure 6.3 illustrated that these also fall on market sectors of the economy, but are much more uncertain. Finally, the third set includes market impacts, the risk of catastrophe *and* direct, non-market impacts on human health and the environment. This chapter shall argue that attention should be focused on the second and third cases here, since there is very good reason to believe that both are relevant.

These dimensions combine to produce a 2x3 matrix of scenarios (Figure 6.4). For example, the lowest cost estimates would be expected to come from the scenario that (i) uses the baseline-climate scenario and (ii) considers only those impacts from gradual climate change on market sectors.

Figure 6.4 A 2x3 matrix of scenarios.



Preliminary estimates of average losses in global per-capita GDP in 2200 range from 5.3 to 13.8%, depending on the size of climate-system feedbacks and what estimates of 'non-market impacts' are included.

Estimates of losses in per-capita income over time are benchmarked against projected GDP growth in a world without climate change. The baseline-climate/market-impacts scenario generates the smallest losses, where climate change reduces global per-capita GDP by, on average, 2.2% in 2200. However, as discussed in the previous section, the omission of the very real risk of abrupt and large-scale changes at high temperatures creates an unrealistic negative bias in estimates.

Figure 6.5 shows the results of scenarios including a risk of 'catastrophe'. The lower-bound estimate of the global cost of climate change in Figure 6.5 uses the baseline climate and includes both market impacts and the risk of catastrophic changes to the climate system (Figure 6.5a). In this scenario, the mean loss in global per-capita GDP is 0.2% in 2060. By 2100, it rises to 0.9%, but by 2200 it rises steeply to 5.3%.

There is a substantial dispersion of possible outcomes around the mean and, in particular, a serious risk of very high damage. The grey-shaded areas in Figure 6.5 give the range of estimates in each year taken from the 5th and 95th percentile damage estimates over the 1000 runs of the model. For the lower-bound estimate in 2100, the range is 0.1 - 3 % loss in global GDP per capita. By 2200, this rises to 0.6 – 13.4%.

Figures 6.5b to d demonstrate the loss in global GDP per capita when first, the risk of more feedbacks in the climate system is included (the high-climate scenario), and second, estimates of non-market impacts of climate change are included.
In the high-climate scenario, the losses in 2100 and 2200 are increased by around 35%. In 2200, the range of losses is increased to between 0.9% and 17.9%.

The inclusion of non-market impacts increases these estimates further still. In this Review, non-market impacts, on health and the environment, are generally considered separately to market impacts. However, if the goal is to compare the cost of climate change in monetary terms with the equivalent cost of mitigation, then excluding non-market costs is misleading. For the high-climate scenario with non-market impacts (Figure 6.5c), the mean total losses are 2.9% in 2100 and 13.8% in 2200. In 2200, the 5th and 95th percentiles increase significantly, to 2.9% to 35.2%.

These estimates still do not capture the full range of impacts. The costs of climate change could be greater still. For example, recent studies demonstrate that the climate sensitivity could be greater than the range used in the PAGE2002 climate scenarios (Chapter 1). Were this to be the case, costs would rise again. The potential impacts of higher climate sensitivity are explored speculatively in Box 6.2.

Box 6.2 Exploring the consequences of high climate sensitivity.

The climate scenarios described in Box 6.1 are based on a climate sensitivity (the equilibrium temperature increase following a doubling in atmospheric carbon dioxide concentrations) range of 1.5 - 4.5°C, as outlined in the IPCC TAR[27]. However, studies since the TAR have shown up to a 20% chance that the climate sensitivity could be greater than 5°C.

In order to explore the possible consequences of recent scientific evidence on a higher climate sensitivity, we develop a ‘high+’ climate scenario that combines the amplifying natural feedbacks explained in Box 6.1 with a higher probability distribution for the climate sensitivity parameter. We use the climate sensitivity distribution estimated by Murphy *et al*. (2004). This is has a 5 - 95% range of 2.4 - 5.4°C, and a mode of 3.5, with a loglogistic distribution (Box 1.2).

This scenario is particularly speculative, but we cannot rule out that this is the direction that further evidence might take us. Combining the high+ scenario with market impacts and the risk of catastrophe, the mean loss in global per-capita GDP is 0.4% in 2060. In 2100, it rises to 2.7%, but by 2200 it rises to 12.9%. Adding non-market impacts, the mean loss is 1.3% in 2060, 5.9% in 2100 and 24.4% in 2200.

In addition, these results reflect the aggregation of costs across the world, but aggregating simply by adding GDP across countries or regions masks the value of impacts in poor regions. A given absolute loss is more damaging for a person on lower incomes. Nordhaus and Boyer[28] and Tol[29] demonstrate that giving more weight to impacts in poor regions increases the global cost of climate change. Nordhaus and Boyer estimate that the global cost increases from 6% to 8% of GDP for 5°C warming, one quarter higher. Tol estimates that the global cost is almost twice as high for 5°C warming, if he uses welfare weights (see Section 6.2).

Only a small portion of the cost of climate change between now and 2050 can be realistically avoided, because of inertia in the climate system.

Past emissions of GHGs have already committed the world to much of the loss in global GDP per capita over the next few decades. Over this period, market impacts are likely to be relatively small. This is, in large part, because the risk of catastrophic, large-scale changes to the climate system, as well as amplifying natural feedbacks (which boost the temperature response to GHG emissions), become a bigger factor later. Non-market impacts are significant in the period to 2050, reaching around 0.5% of per-capita global GDP in 2050 in both the baseline and high-climate scenarios.

27 IPCC (2001)
28 Nordhaus and Boyer (2000)
29 Tol (2002)

Figure 6.5 a. Baseline-climate scenario, with market impacts and the risk of catastrophe.

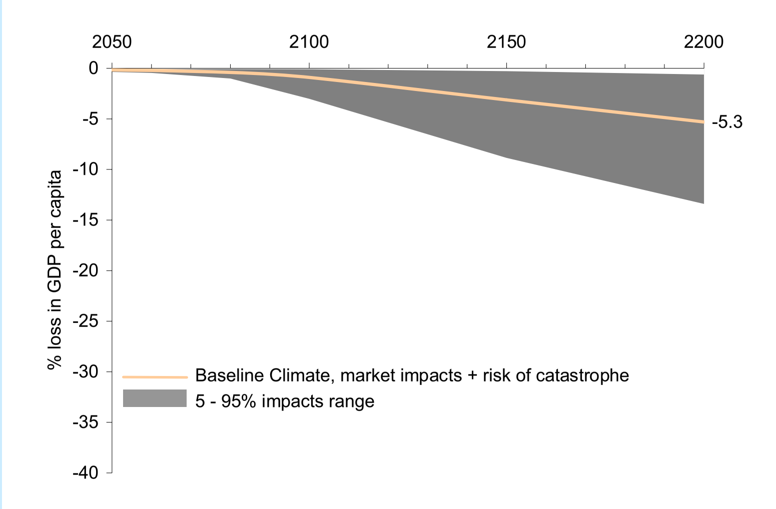


Figure 6.5b. High-climate scenario, with market impacts and the risk of catastrophe.

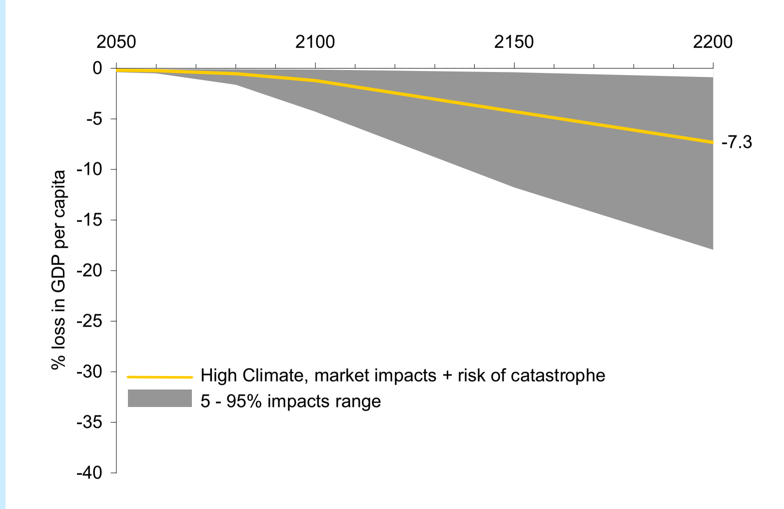


Figure 6.5c. High-climate scenario, with market impacts, the risk of catastrophe and non-market impacts.

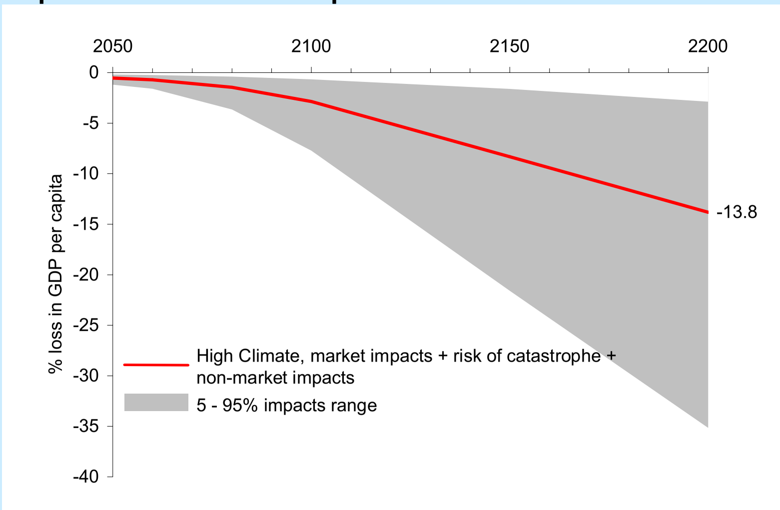


Figure 6.5d. Combined scenarios.

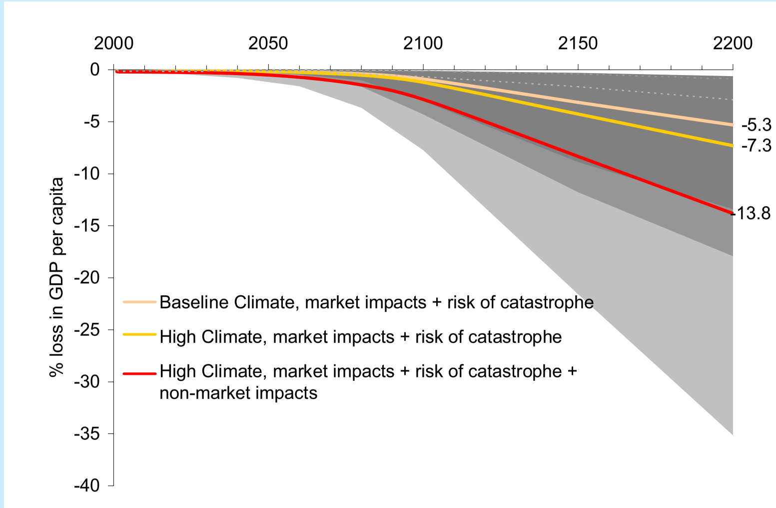


Figure 6.5a-d traces losses in income per capita due to climate change over the next 200 years, according to three of our main scenarios of climate change and economic impacts. The mean loss is shown in a colour matching the scenarios of Figure 6.4. The range of estimates from the 5th to the 95th percentile is shaded grey.

In all scenarios, the highest impacts are in Africa and the Middle East, and India and South-East Asia.

For example, in the baseline-climate scenario with all three categories of economic impact, the mean cost to India and South-East Asia is around 6% of regional GDP by 2100, compared with a global average of 2.6%.

In all scenarios, the consequences of climate change will become disproportionately more severe with increased warming.

Figure 6.6 examines the relationship between mean losses in per-capita GDP and average increases in global mean temperature produced by the baseline and high-climate scenarios. The figure makes two important points graphically:

- The first is that the climatic effects suggested by the newer scientific evidence have the potential to nudge global temperatures, and therefore impacts, to higher levels than those suggested by the IPCC TAR report. In the high scenario, global mean temperature rises to an average of nearly 4.3°C above pre-industrial levels by 2100, compared with an average of 3.9°C above pre-industrial levels in the baseline scenario. The difference between the two scenarios increases beyond 2100, because the effect of the amplifying natural feedbacks becomes more marked at higher temperatures. By 2200, the rise in global mean temperature increases to 8.6°C in the high climate scenario, while the baseline reaches only 7.4°C. These numbers should be treated as indicative, as climate models have not yet been used to explore the high temperatures that are likely to be realised beyond 2100. They do demonstrate that, if emissions continue unabated, the climate is very likely to enter unknown territory with the potential to cause severe impacts.

- Second, scenarios that include the risk of catastrophe and non-market impacts project higher costs of climate change at any given temperature. The figure makes an additional point that the incremental cost associated with including these non-market and catastrophic impacts increases as temperatures rise, so that the wedge between the economic scenarios becomes more and more substantial.

Estimates of income effects and distribution of risks can also be used to calculate the overall welfare cost of climate change.

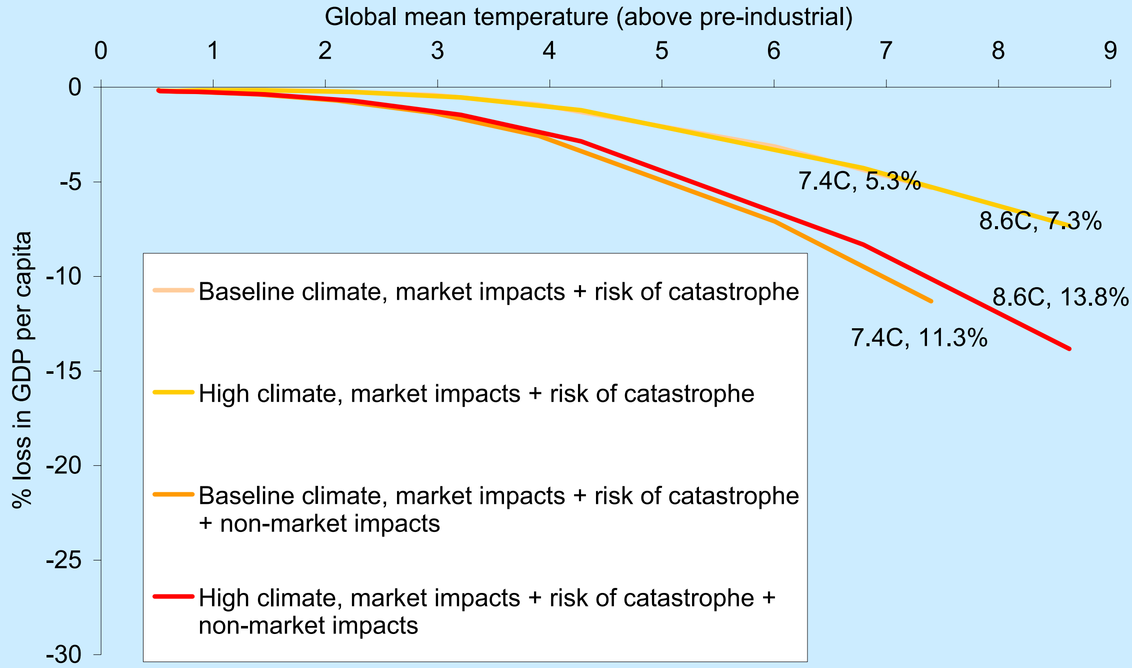
Whereas the first part of Section 6.4 estimated how BAU climate change would affect income, the remainder of the section tackles a still more important challenge: estimating the global welfare costs of climate change, taking explicitly into account the risks involved. Because the forecast changes are large, uncertain, and unevenly distributed, and because they occur over a very long period of time, this exercise must take on the problem of aggregating across different possible outcomes (risk), over different points of time (inter-temporal distribution), and over groups with different incomes (intra-temporal distribution). It should carry out these three types of aggregation consistently. At this stage of the analysis, we have not incorporated intra-temporal distribution.

First, the analysis requires evaluation of the significance of severe climate risks that would result in very low levels of global GDP relative to the world without climate change. In the high-climate scenario with market impacts, the risk of catastrophe and non-market impacts, for example, the 95th percentile estimate is a 35.2% loss in global per-capita GDP by 2200. This is not the statistical mean, but it is nevertheless a risk that few would want to ignore. As discussed below, such risks have a disproportionate effect on welfare calculations, because they reduce income to levels where every marginal dollar or pound has greater value. That is indeed how risk is generally treated in economics.

Second, it requires deciding how to express the future costs of BAU climate change in terms that can be compared with current levels of well-being: we have to evaluate costs occurring at different times on a common basis. The process of warming builds over many decades. In the baseline-climate scenario, 5°C warming is not predicted to occur until some time between 2100 and 2150. By then, growth in GDP will have made the world considerably richer than it is now.

Figure 6.6 Mean losses in income per capita from four scenarios of climate change and economic impacts, plotted against average increases in global mean temperature (above pre-industrial levels).

This figure traces mean losses in per-capita GDP due to climate change as a function of increasing global mean temperature, according to four of the scenarios of climate change and economic impacts. Losses are compared to baseline growth in per-capita GDP without climate change. Because temperature is one of the probabilistic outputs of the PAGE2002 model, increases in temperature in each scenario are averaged across all 1000 runs.



To make these calculations, the model uses the standard tools of applied welfare economics, as described in Chapter 2 and its Appendix.

In these highly aggregated models, the basic approach has to be simple, but it does depend on key assumptions. It is important to lay them out transparently. First, in applying this basic welfare-economics theory to the PAGE2002 model, we follow many other studies in calculating overall social welfare (or global 'utility', to use the standard economic term) as the sum of social utilities of consumption of all individuals in the world. In practice, for this exercise, this means that we convert per-capita global GDP at each point in time into consumption[30], and then calculate the social utility of per-capita consumption. This is then multiplied by global population (Box 6.3).

An approach that would better reflect the consequences of climate change on different world regions would take regional per-capita utility (e.g. for India and South-East Asia) and multiply by regional population to get 'regional utility'. Global utility would then be the sum of regional utilities[31]. Doing so was beyond the scope of this exercise, given the limited time available for analysis, but it is possible to provide some assessment of the bias from this omission. Taking this regional approach would increase the climate-change cost estimates, as illustrated in Section 6.2, so our decision to use a simpler global aggregation approach will bias our model toward lower cost estimates.

[30] In these calculations, we assume that some fixed proportion of income is saved for future consumption. A more sophisticated model would vary the rate of saving as a result of prospects for future consumption, as determined by the model itself.
[31] As in Nordhaus and Boyer (2000)

Second, we use the assumption of diminishing marginal utility as we evaluate risks and future welfare. This standard assumption in economics, generally supported by empirical evidence on behaviour and preferences, holds that the extra utility produced by additional consumption falls as the level of consumption rises. That is, an extra dollar or pound is worth more to a poor person than it is to a rich person. This assumption plays an important role in the welfare calculations, in that it places greater weight on:

- Near-term consumption than on consumption in the distant future, because even with climate change, the world will be richer in the future as a result of economic growth; and
- The most severe climate impacts, because they reduce consumption to such low levels (see Chapter 2 and its Appendix for the underlying welfare economics).

Third, consumption growth is allowed to vary in the future in systematic ways. Traditionally, economic appraisal of projects and policies has taken a simplified approach to this basic welfare-economics framework. Consumption is simply assumed to grow at a certain rate in the future, with uncertainty entering the projection only to the extent that there will be perturbations around this assumed path. In our case, however, climate change could substantially reduce consumption growth in the future, and so two probabilistic model runs with different climate impacts produce different growth rates. So the simplified approach will not work here. Instead, we have to go back to the underlying theory, which implies that consumption paths must be valued separately along each of the model's many (1000, say) runs.

Fourth, in carrying out the expected-utility valuation process, we use a pure rate of time preference (or 'utility discount rate') to weight (or value) the utility of consumption at each point in the future. Thus utility in the future has a different weight simply because it is in the future.[32] This assumption is difficult to justify on ethical grounds, as discussed in Chapter 2 and its Appendix, except where we take into account the probability that individuals will be alive in the future to enjoy the projected consumption stream. In other words, if we know a future generation will be present (that is, apart from discounting for the small chance of global annihilation), we suppose that it has the same claim on our ethical attention as the current one.

Putting all this together, we can:

- Calculate the aggregate utility of the different paths over the future by adding utilities over time, as described, and then;
- Average utility across all 1000 runs to calculate the expected utility under each scenario.

Finally, we need to decide in what terms to express the loss in expected future welfare due to climate change. If the result is to guide policy, it must be easily understandable. When we calculate social utility and aggregate over time for risk, the resulting measure might most immediately be expressed in expected 'utils', but this would not be easily understood. Instead, we introduce the idea of a 'Balanced Growth Equivalent' (hereafter BGE)[33] to calibrate welfare along a path. The BGE essentially measures the utility generated by a consumption path in terms of the consumption now that, if it grew at a constant rate, would generate the same utility.[34]

Taking the difference between the BGE of a single consumption path with climate damage and a consumption path without it gives the costs of climate change, measured in terms of a permanent loss of consumption, now and forever. One can think of the costs measured in this way as like a tax levied on consumption now and forever, the proceeds of which are simply poured away.

[32] We are not considering here the discounting of extra units of consumption in the future because consumption itself may be higher then.
[33] Proposed by Mirrlees and Stern (1972)
[34] Formally, the change in the BGE is a natural commodity measure of welfare that expresses changes in future consumption due to policy in terms of the percentage increase in consumption (along a steady-state growth path), now and forever, that is equal to the changes that are forecast to follow from the policy change being examined. In a one-sector growth model with natural growth α and consumption C at time t, we want to calibrate welfare from the path [C(t)]. If this is equivalent, in welfare terms, to the balanced growth path yielding consumption $\gamma e^{\alpha t}$, then γ is the BGE of [C(t)].

Box 6.3 'Expected-utility' analysis of the global cost of climate change.

PAGE2002 takes baseline GDP growth from an exogenous scenario[35] and produces 1000 runs of global GDP, less the cost of climate change damage and adaptation to climate change, from 2001 to 2200. Thus we obtain a probability distribution of global income pathways net of climate change damage and adaptation costs.

We first transform this probability distribution into GDP per capita, dividing through each run by a population scenario determined exogenously.[36] Then we transform each run into global consumption per capita, taking an arbitrary, exogenous rate of saving of 20%.

We transform consumption per capita into utility:

$$U(t) = \frac{C^{1-\eta}}{1-\eta} \quad (1)$$

where *U* is utility, *C* is consumption per capita, *t* is the year[37] and η is the elasticity of the marginal utility of consumption (see appendix to Chapter 2). In our main case, we take η to be 1, in line with recent empirical estimates.[38] Further work would investigate a broader range of η, including higher values.[39] Where η is 1, the utility function is a special case:

$$U(t) = \ln C(t) \quad (2)$$

Then discounted utility (with constant population) is given by:

$$W = \int_{t=1}^{\infty} U(t)e^{-\delta t}dt \quad (3)$$

where *W* is social welfare and δ is the utility discount rate. The value of δ is taken to be 0.1% per annum, so that the probability of surviving beyond time *T* is described by a Poisson process $e^{-\delta T}$, where δ is the annual risk of catastrophe eliminating society, here 0.1%. So the probability of surviving beyond, say, 2106 is $e^{-0.001*100}$, which is 90.5%. The Appendix to Chapter 2 discusses the implications of this choice in more detail.

Where population varies exogenously over time, we would automatically weight by population. In the case of just one region (i.e. the world), this means that we integrate global utility weighted by global population over time:

$$W = \int_{t=1}^{\infty} N(t)U(t)e^{-\delta t}dt \quad (4)$$

where *N* is global population. Where global income data can be disaggregated, regional utility should be evaluated for consistency using similar utility functions to that used in (4).[40] For endogenous population growth, some difficult ethical issues are involved and we cannot automatically apply this criterion (see Chapter 2 and appendix).

In the PAGE2002 modelling horizon – 2001 to 2200 – we can calculate total discounted utility as the sum of discounted utility in each individual year:

$$W = \sum_{t=1}^{2200} U(t)e^{-\delta t} \quad (5)$$

We approximate utility from 2200 to infinity based on an assumed, arbitrary rate of per-capita consumption growth *g*, which is achieved by all paths, as well as assessing constant population. We use 1.3% per annum, which is the annual average projection from 2001 to 2200 in PAGE2002's baseline world without climate change. In other words, as a simplification, in each run the world

[35] An extrapolated version of the IPCC's A2 scenario (IPCC, 2000), characterised by annual average GDP growth of about 1.9%.
[36] Also extrapolated from the IPCC's A2 scenario. Annual average population growth is about 0.6%.
[37] In fact, the model is restricted to a subset of uneven time steps. Thus we interpolate linearly between time steps to produce an annual time series.
[38] See Pearce and Ulph (1999).
[39] Pearce and Ulph (1999) and Stern (1977).
[40] Nordhaus and Boyer (2000).

instantaneously overcomes the problems of climate change in the year 2200 (zero damages and zero adaptation) and all runs grow at an arbitrary 1.3% into the far-off future. In this sense there is an underestimate of the costs of climate change.

where T is 2200. The second term is the simplified utility integral from T to infinity. Again, a special case arises where the elasticity of the marginal utility of consumption is 1:

$$W = \sum_{t=1}^{2200} N(t) \ln C(t) e^{-\delta t} + \left(\frac{N_T \ln C_T}{\delta} + \frac{N_T g}{\delta^2}\right) e^{-\delta T} \quad (6)$$

Expected utility is given by the mean of total discounted utility from 2001 to infinity along all 1000 runs.

Finally, we can find the balanced growth equivalent (BGE) of the discounted consumption path described in 6. This is the current level of consumption per capita (i.e. in 2001), which, growing at a constant rate g set again to 1.3% per annum, delivers the same amount of utility as in (6) for the case of η = 1.

$$W = \sum_{t=1}^{2200} N(t) \left(\frac{C_{BGE}^{1-\eta}}{1-\eta} + gt\right) e^{-\delta t} + \left(\frac{N(t)\left(\frac{(C_{BGE} + 200g)^{1-\eta}}{1-\eta}\right)}{\delta - g(1-\eta)}\right) e^{-\delta T} \quad (7)$$

We have to go beyond the simple BGE generated in this way to take account of uncertainty. Thus the BGEs calculated here calibrate the expected utility in a particular scenario (with many possible paths) in terms of the definite or certain consumption that, if it grew at a constant rate, would generate the same expected utility. One can, therefore, think of the BGE measure of climate-change costs not as a tax but as the maximum insurance premium society would be prepared to pay, on a permanent basis, to avoid the risk of climate change (if society shared the policy-maker's ethical judgements). In practice, as we shall see, society will not in fact have to pay as much as this. Thus the BGE here combines the growth idea of Mirrlees and Stern[41] with the certainty equivalence ideas in, say, Rothschild and Stiglitz[42]. The next step, if intra-temporal income distribution is taken into account explicitly, would be to combine it with the 'equally distributed equivalent' income of Atkinson[43]. Box 6.3 outlines our calculations in more detail.

The welfare costs of BAU climate change are very high. Climate change is projected to reduce average global welfare by an amount equivalent to a permanent cut in per-capita consumption of a minimum of 5%.

Table 6.1 presents results in terms of Balanced Growth Equivalents (BGEs), based on defensible values for the utility discount rate (0.1% per annum) and for the elasticity of the marginal utility of consumption (1.0) (see Chapter 2 and its appendix for an explanation and justification). For each of our six scenarios of climate change and economic impacts, we calculate three BGEs:

- For mean total discounted utility;
- For total discounted utility along the 5th percentile run;
- For total discounted utility along the 95th percentile run.

Table 6.1 shows the results. In each case, we quote the difference between the BGEs with and without climate change – the cost of climate change – in percentage terms. These are our headline results from the modelling. The numbers express the cost of 'business as usual' (BAU) climate change over the next two centuries in terms of present per-capita consumption for each scenario as a whole and for specific paths with impacts at the low and high end of the underlying probability distributions.

[41] Mirrlees Stern (1972)
[42] Rothschild and Stiglitz (1970)
[43] Atkinson (1970)

Table 6.1 Losses in current per-capita consumption from six scenarios of climate change and economic impacts*.

Scenario		**Balanced growth equivalents: % loss in current consumption due to climate change**		
Climate	**Economic**	**Mean**	**5th percentile**	**95th percentile**
Baseline climate	**Market impacts**	2.1	0.3	5.9
	Market impacts + risk of catastrophe	5.0	0.6	12.3
	Market impacts + risk of catastrophe + non-market impacts	10.9	2.2	27.4
High climate	**Market impacts**	2.5	0.3	7.5
	Market impacts + risk of catastrophe	6.9	0.9	16.5
	Market impacts + risk of catastrophe + non-market impacts	14.4	2.7	32.6

*Utility discount rate = 0.1% per annum; elasticity of marginal utility of consumption = 1.0.

The cases that we would argue are central for the market imports are highlighted. The non-market effects are of great importance but involve difficulties in evaluation.

The results under the different scenarios range greatly, but virtually all project that BAU climate change will have very significant costs. In our lower-bound scenario, comprising the baseline climate scenario and including both market impacts and the risk of catastrophe, the BGE of the mean outcome is 5% below the equivalent BGE without climate change, meaning that the expected welfare cost of BAU climate change between 2001 and 2200 is equivalent to a 5% loss in per-capita consumption, now and forever. The BGE of the 95th percentile run amounts to a 12.3% loss in consumption now and forever, while the BGE of the 5th percentile run amounts to a 0.6% loss.

Climate change will reduce welfare even more if non-market impacts are included, if the climatic response to rising GHG emissions takes account of feedbacks, and if regional costs are weighted using value judgements consistent with those for risk and time. Putting these three factors together would probably increase the cost of climate change to the equivalent of a 20% cut in per-capita consumption, now and forever.

- Adding the possibility of the feedback involved in the high-climate scenario reduces the BGE of mean total discounted utility to 6.9% below the equivalent BGE without climate change. The BGE of the 95th percentile run is 16.5% below, while the BGE of the 5th percentile run is just 0.9% below.

- In the high-climate scenario and with all three categories of economic impact (that is, adding the non-market impact), the BGE of the mean outcome is reduced to 14.4% below the equivalent BGE without climate change. The BGE of the 95th percentile run is 32.6% below, while the BGE of the 5th percentile run is 2.7% below. If the possibility of still higher climate sensitivities is taken into account, the incremental cost might be higher still.

- Calculating the BGE cost of climate change after including value judgements for regional distribution is beyond the scope of this Review, given our limited time. But if we take as an indication of how much estimates might increase the results of Nordhaus and Boyer[44], then estimates might be one quarter higher. In addition, because their deterministic approach could not take into account the valuation of risk, there is good reason to believe that the weighting would in our model increase estimates still further (see the appendix to Chapter 2). In total, the global cost of climate change would probably be equivalent to around a 20% reduction in the BGE compared with a world without climate change.

[44] Nordhaus and Boyer (2000)

Finally, we should discuss where one might place the evaluation of the losses from climate change between the 5 and 20% figures. There are two types of issue. The first is the inclusion of relevant effects and the second is the presence of different possible probability distributions.

On the first, it is reasonable to include what we consider to be relevant effects. This means catastrophic events, non-market effects and distribution of impacts within a generation. We have calculated the first two of these. However, we have conceptual, ethical and practical reservations about how non-market impacts should be included, although there is no doubt they are important. We have yet to calculate the distributional effects – that is for further work – but, based on previous studies, we can hazard a guess.

The second type of issue concerns the fact that we are unsure of which probability distribution to use. This takes us back to the distinction between risk and uncertainty discussed in Chapter 2 and the Appendix. We argued there that we now have some theory to guide us. Essentially, it points to taking a weighted average of the best and worst expected utility.

The first type of issue would take the evaluation towards an overall loss in the region of 13-15% (using the 10.9% figure of Table 6.1 and scaling up by one-quarter or more for distribution). The second type of issue would lead to taking a weighted average somewhere between this figure (13 or 14%) and 20%. The weights would depend on crude judgements about likelihoods of different kinds of probability distributions, on judgements about the severity of losses in this context, and on the basic degree of cautiousness on the part of the policy-maker. Together, they would make up the 'aversion to ambiguity' discussed in Chapter 2 and the Appendix.

This discussion points to areas for further work in the context of this particular model: distribution within a generation and explaining different distributional judgements. Of course, there is much more to do in terms of considering different economic models – we have investigated just one – and exploring different probability distributions.

6.5 Conclusion

This Chapter has presented global cost estimates of the losses from 'business as usual' climate change. They have been expressed in terms of their equivalent permanent percentage loss in consumption. They are averages over time and risk and can be compared with percentage costs, similarly averaged over time, of mitigation – that is the subject of Part III of this Review. In the final chapter of that part, we include a discussion of how much of the losses estimated in this Chapter could be saved by mitigation. The loss estimates of this Chapter should be viewed as complementary to the discussions of the scale of the separate impacts on consumption, health, and environment that were presented in Chapters 3 to 5.

What have we learned from this exercise? Notwithstanding the limitations inherent in formal integrated models, there can be no doubt that the economic risks of a 'business as usual' approach are very severe – and probably more severe than suggested by past models. Relying on the scientific knowledge that informed the IPCC's TAR, the cost of BAU climate change over the next two centuries is equivalent to a loss of at least 5% of global per-capita consumption, now and forever. More worrying still, when the model incorporates non-market impacts and more recent scientific findings on natural feedbacks, this total average cost is pushed to 14.4%.

Cost estimates would increase still further if the model incorporated other important omitted effects. First, the welfare calculations fail to take into account distributional impacts, even though these impacts are potentially very important: poorer countries are likely to suffer the largest impacts. Second, there may be greater risks to the climate from dynamic feedbacks and from heightened climate sensitivity beyond those included here. If these are included, the total cost would be likely to be around 20% of current per-capita consumption, now and forever.

Further, there are potentially worrying 'social contingent' impacts such as migration and conflict, which have not been quantified explicitly here. If the world's physical geography is changed, so too will be its human geography.

Finally, we must close with the warning about over-literal interpretation of these results with which we began this chapter. The estimates have arisen from an attempt to add two things to the previous literature on IAM models. The first is use of recent scientific estimates of probabilities and the second is putting these probabilities to work using the economics of risk and uncertainty. The most worrying possible impacts are also among the most uncertain, given that so little is known about the risks of very high temperatures and potential dynamic instability. The exercise allows us to see what the implications of the risks, as we currently understand them, might be. The answer is that they would imply very large estimates of potential losses from climate change. They give an indication of the stakes involved in making policy on climate change. The analysis of this chapter shows the inevitable difficulties of all these models in extrapolating over very long periods of time. We therefore urge the reader to avoid an over-literal interpretation of these results. Nevertheless, we think that they illustrate a very important point: the risks involved in a 'business as usual' approach to climate change are very large.

References

Successive IPCC assessments of the IAM literature can be found in Pearce *et al.* (1996) and Smith *et al*. (2001). Hitz and Smith (2004) provide a more recent summary, focussing on the nature of the relationship between rising temperatures and the cost of climate change. William Nordhaus and Joseph Boyer's 2000 book *Warming the World* provides an important and well-structured discussion of the issues, while Hope (2005) explains Integrated Assessment Modelling in detail. Watkiss *et al*. (2005) is a valuable discussion of the uncertainties around estimating the monetary cost of climate change, while Warren et al. (2006) subject the damage functions in IAMs to critical scrutiny.

Atkinson, A. B. (1970): 'On the measurement of inequality', Journal of Economic Theory, **2**(3): 244-263

Fankhauser, S. and R.S.J. Tol (2003): 'On climate change and economic growth', Resource and Energy Economics **27**: 1-17

Friedlingstein, P., P. Cox, R. Betts et al. (2006): 'Climate-carbon cycle feedback analysis: results from C4MIP model intercomparison', Journal of Climate, **19**: 3337-3353

Gedney, N., P.M. Cox and C. Huntingford (2004): 'Climate feedback from wetland methane emissions', Geophysical Research Letters **31**(20): L20503.

Hallegatte, S. and J.-C. Hourcade (2006): 'Why economic dynamics matters in the assessment of climate change damages: illustration on extreme events', Ecological Economics (forthcoming).

Hitz, S. and J.B. Smith (2004): 'Estimating global impacts from climate change', The Benefits of Climate Change Policies, J. -C. Morlot and S. Agrawala. Paris: OECD, pp 31-82.

Hope, C. (2003): 'The marginal impacts of CO2, CH4 and SF6 emissions,' Judge Institute of Management Research Paper No.2003/10, Cambridge, UK, University of Cambridge, Judge Institute of Management.

Hope, C. (2005): 'Integrated assessment models' in Helm, D. (ed.), Climate-change policy, Oxford: Oxford University Press, pp 77-98.

Intergovernmental Panel on Climate Change (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 JT, Ding Y, Griggs DJ, *et al.* (Eds.)], Cambridge: Cambridge University Press.

Jorgenson, D.W., R.J. Goettle, B.H. Hurd et al. (2004): 'US market consequences of global climate change', Washington, DC: Pew Center on Global Climate Change.

Mendelsohn, R.O., W.N. Morrison, M.E. Schlesinger and N.G. Andronova (1998): 'Country-specific market impacts of climate change', Climatic Change **45**(3-4): 553-569

Mirrlees, J.A. and N.H. Stern (1972): 'Fairly good plans', Journal of Economic Theory **4**(2): 268-288

Murphy J.M. et al. (2004): 'Quantification of modelling uncertainties in a large ensemble of climate change simulations ', Nature **430**: 768 – 772

Nordhaus, W.D. and J.G. Boyer (2000): 'Warming the World: the Economics of the Greenhouse Effect', Cambridge, MA: MIT Press.

Pearce, D.W. et al. (1996): 'The social costs of climate change: greenhouse damage and the benefits of control' Climate Change 1995: Economic and Social Dimensions of Climate Change, Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press pp 183-224

Pearce, D.W. and A. Ulph (1999): ’A social discount rate for the United Kingdom‘ Economics and the Environment: Essays in Ecological Economics and Sustainable Development, D.W. Pearce, Cheltenham: Edward Elgar.

Rothschild, M.D. and J.E. Stiglitz (1970): ‘Increasing Risk: I. A Definition’, Journal of Economic Theory, September 2, pp255-243.

Smith, J.B. et al. (2001): ‘Vulnerability to climate change and reasons for concern: a synthesis’ Climate Change 2001: Impacts, Adaptation and Vulnerability, Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press pp 913-967.

Stern, N. (1977): ‘The marginal valuation of income’, in Artis, M. and R. Nobay (eds.), Studies in Modern Economic Analysis, Oxford: Blackwell.

Tol, R.S.J. (2002): ’Estimates of the damage costs of climate change – part II: dynamic estimates‘, Environmental and Resource Economics **21**: 135-160

Tol, R.S.J. (2005): 'The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties', Energy Policy **33**(16): 2064-2074

Warren, R. et al. (2006): 'Spotlighting Impacts Functions in Integrated Assessment Models', Norwich, Tyndall Centre for Climate Change Research Working Paper 91.

Watkiss, P. et al. (2005): 'Methodological Approaches for Using Social Cost of Carbon Estimates in Policy Assessment, Final Report', Culham: AEA Technology Environment.