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.

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[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 Collapse of Amazon rainforest (according to some models)	
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).

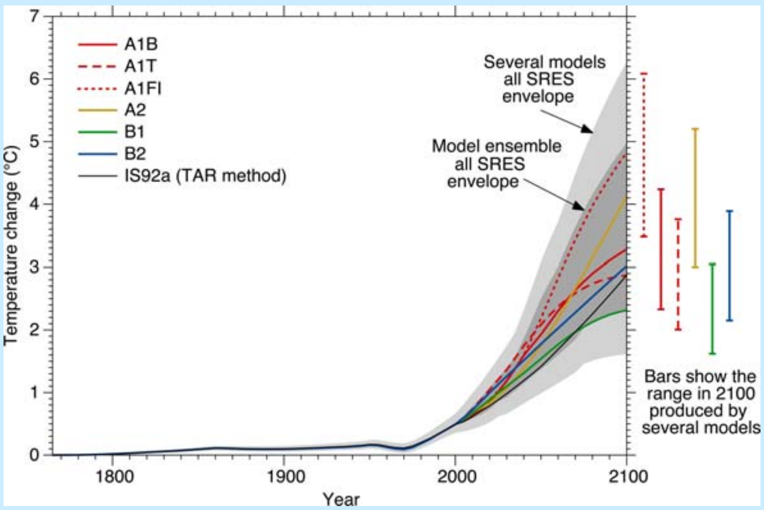
3.1 Introduction

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.

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[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.

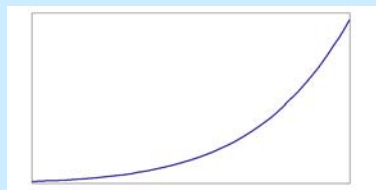
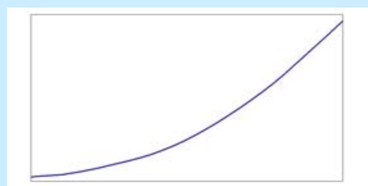
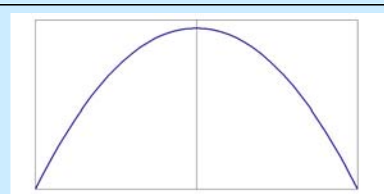
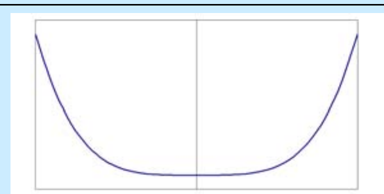
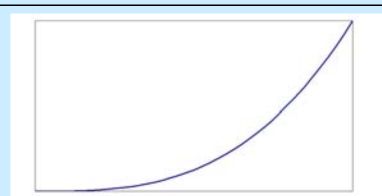
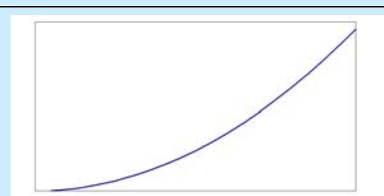
[3] In looking at the effects on crop yields of severe weather during the Little Ice Age, Prof Martin Parry (1978) argued that the frequency of extreme events would change dramatically as a result of even a small change in the mean climate and that the probability of two successive extremes is even more 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]

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[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.

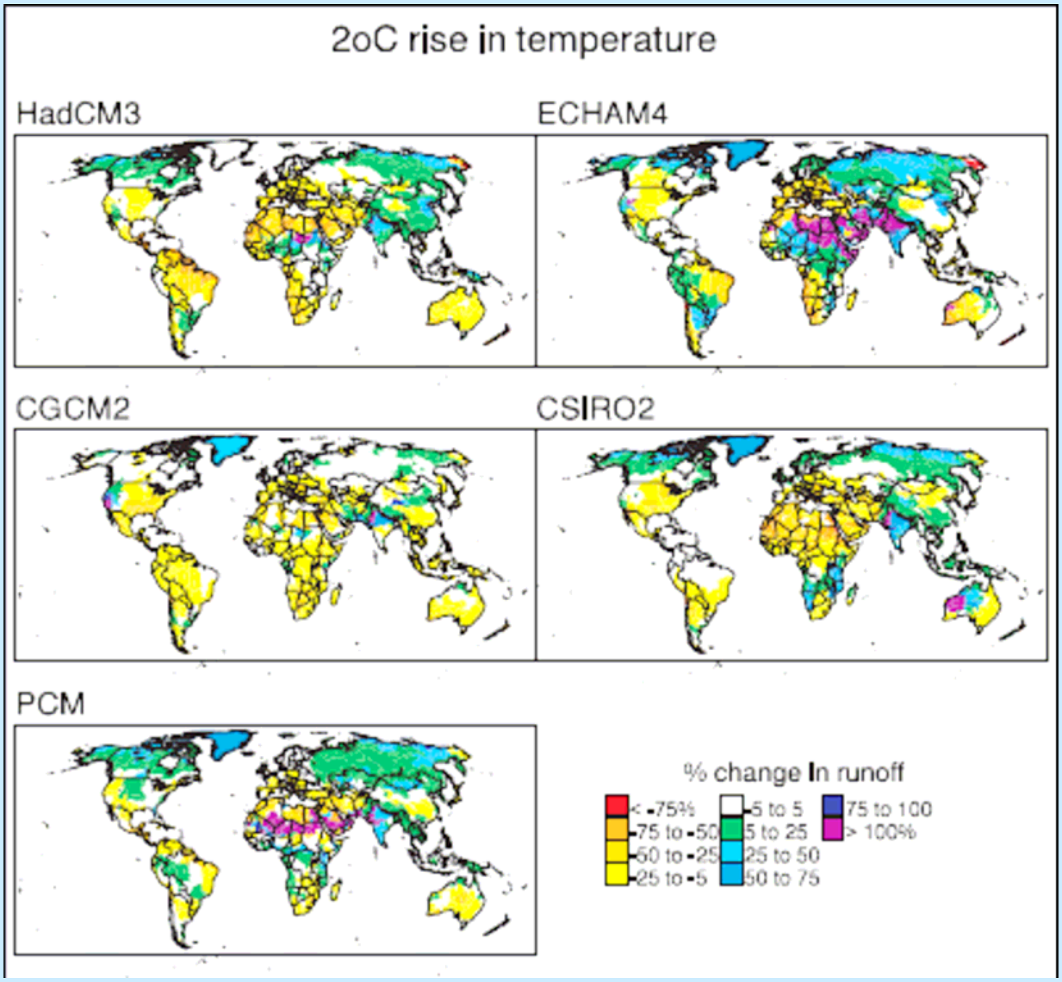
[23] Barnett *et al.* (2005) have comprehensively reviewed the glacier/water supply impacts. There are 1 billion people in snowmelt regions today, and potentially 1.5 billion by 2050. In a warmer world, runoff from snowmelt will occur earlier in the spring or winter, leading to reduced flows in the summer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

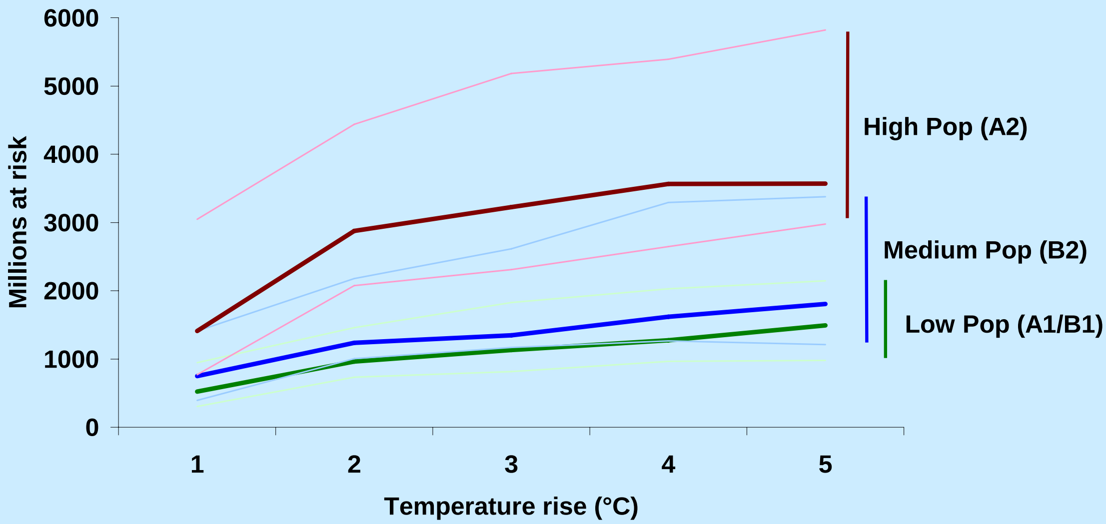
Water availability per person is only one indicator of potential exposure to stress. Some "stressed" watersheds will have effective management systems and water pricing in place to provide adequate supplies (e.g. through storage), while other watersheds with more than 1000 m^3 per person per year may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

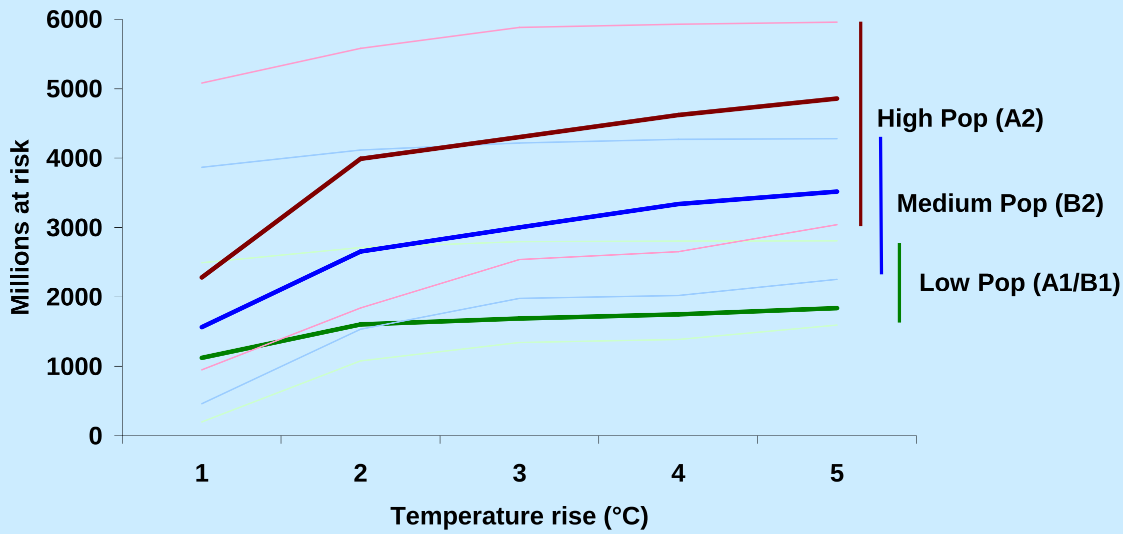
[27] Based on the work of Falkenmark *et al.* 1989, water availability per person per year is the most frequently used measure of water resource availability. The UN has widely adopted this measure, for which data are readily available. The next most frequently used measure is the ratio of withdrawals 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 2080s: 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.

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[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.

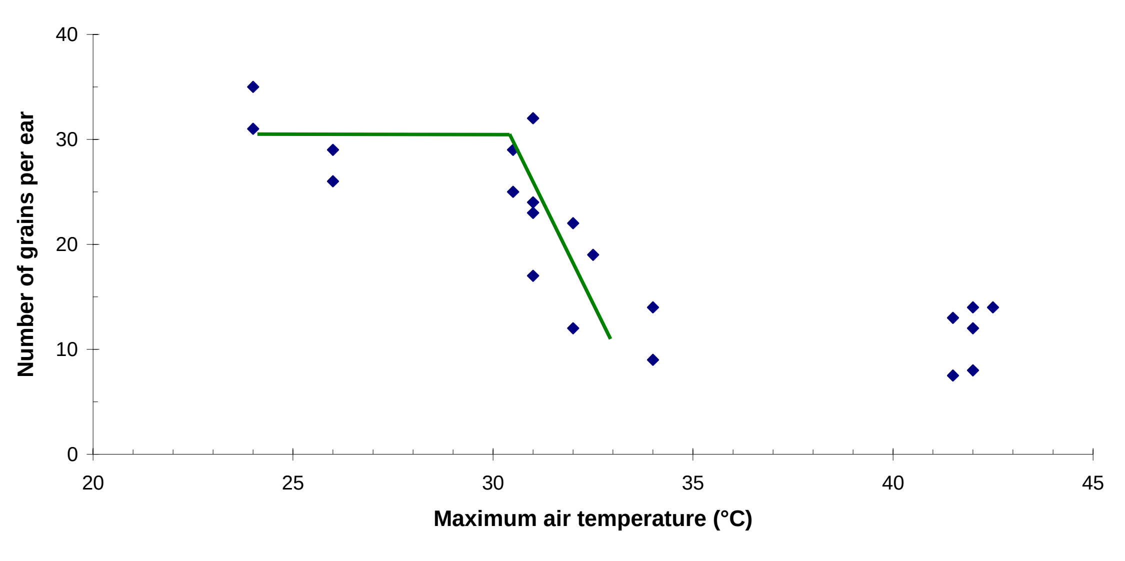
While agriculture in higher-latitude developed countries is likely to benefit from moderate warming (2 – 3°C), even small amounts of climate change in tropical regions will lead to declines in yield. Here crops are already close to critical temperature thresholds[36] and many countries have limited capacity 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).

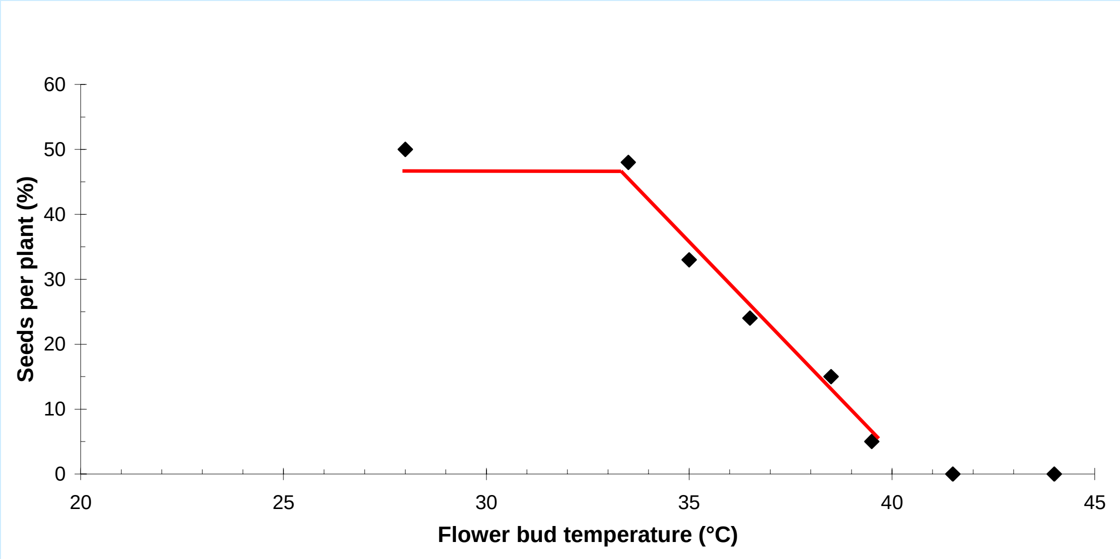
Figure 3.4 Yield loss caused by high temperature in a cool-season crop (wheat) and a tropical crop (groundnut)

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.

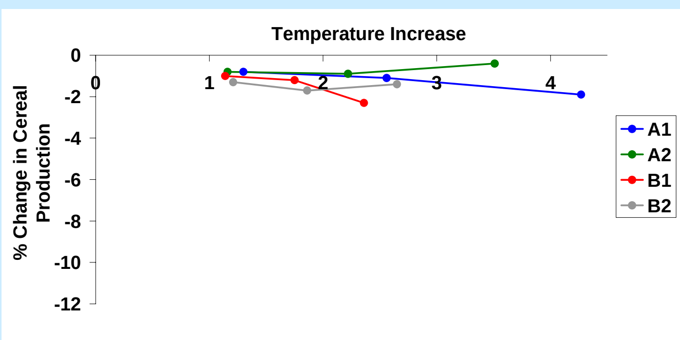
Box 3.4 Agriculture and the carbon fertilisation effect

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).

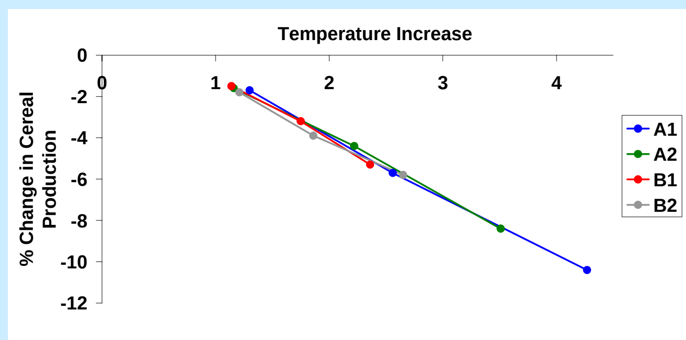
Until recently, research suggested that the positive benefits of increasing carbon dioxide concentrations might compensate for the negative effects of rising mean temperatures (namely shorter growing season and reduced yields). Most crop models have been based on hundreds of experiments in greenhouses 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



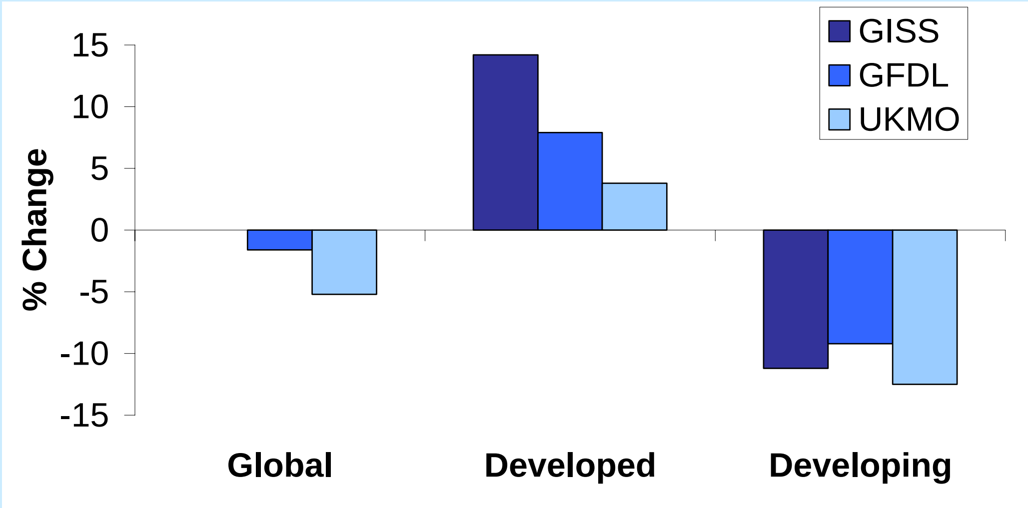
b) Weak carbon fertilisation



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 <u>combined</u> 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.

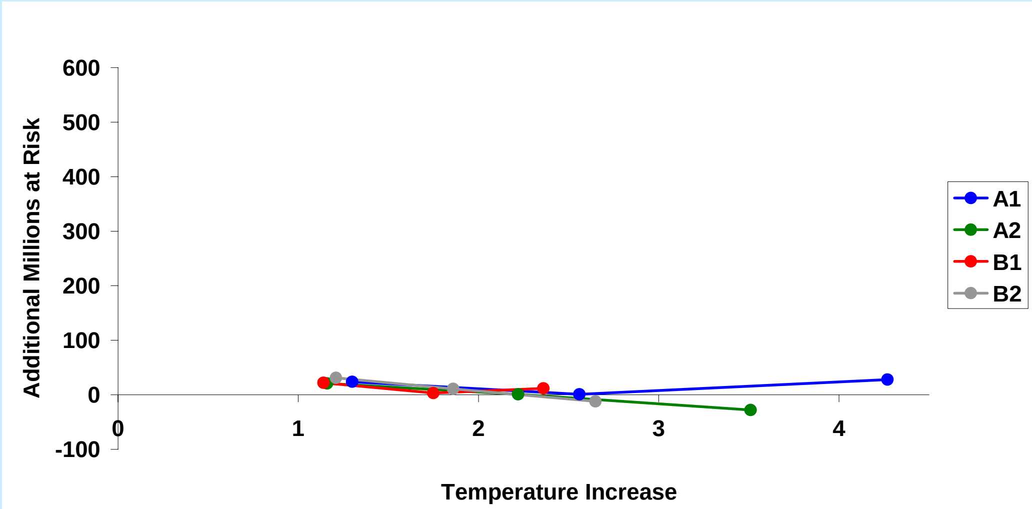
For fisheries, information on the likely impacts of climate change is very limited – a major gap in knowledge considering that about one billion people worldwide (one-sixth of the world's population) rely on fish as their primary source of animal protein. While higher ocean temperatures may increase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

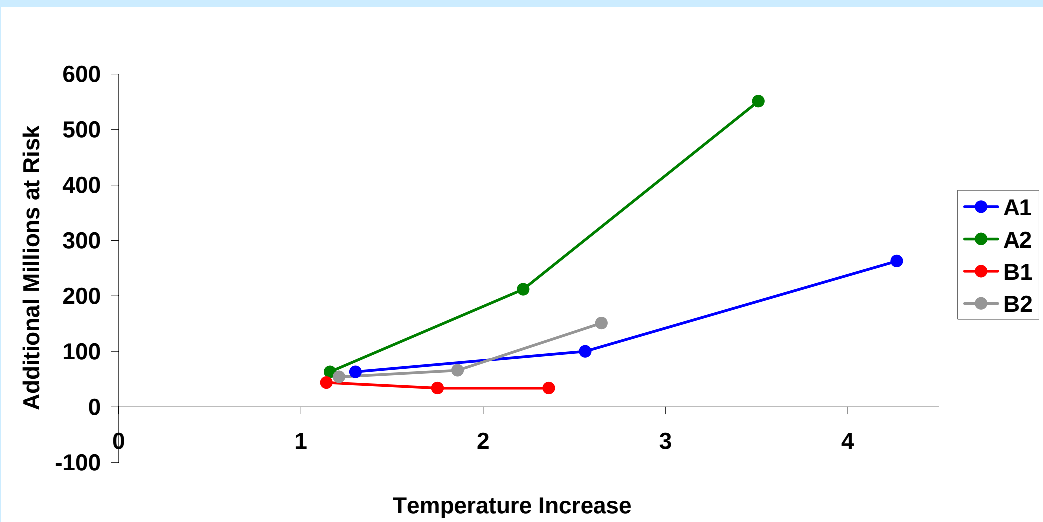
[41] According to Parry *et al.* (2004) people at risk of hunger are defined as the population with an income insufficient either to produce or procure their food requirements, estimated by FAO based on energy requirements deduced from an understanding of human physiology (1.2 – 1.4 times basal metabolic 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 2080s 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.

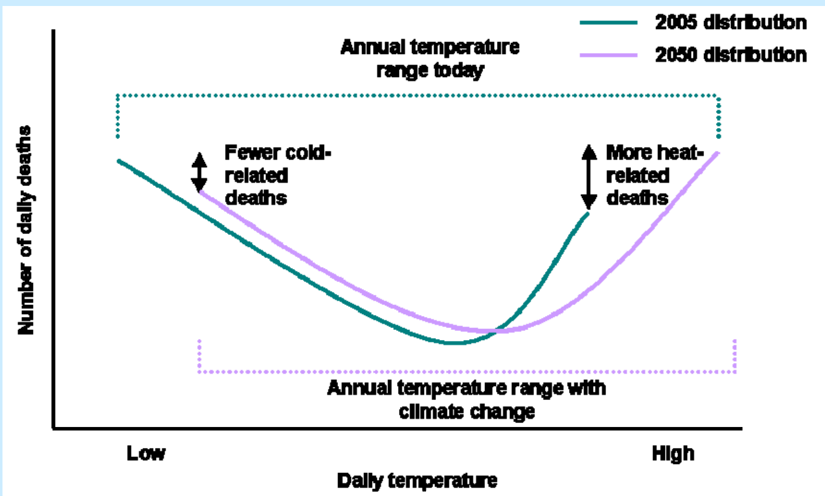
3.4 Health

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.



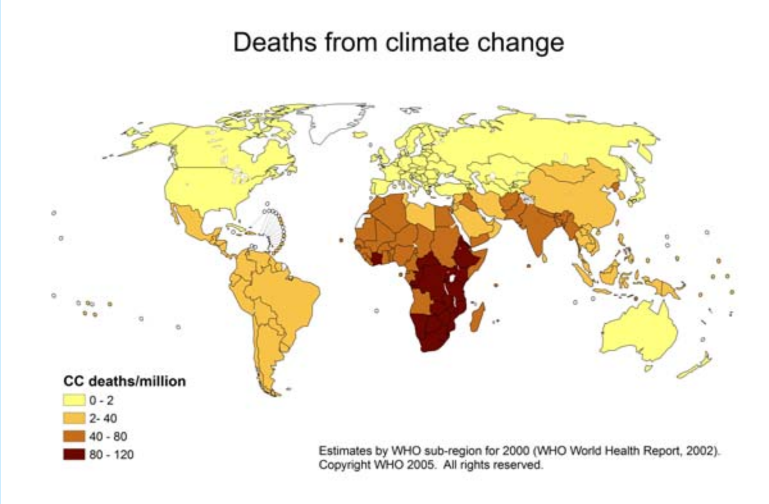
Source: Redrawn from McMichael et al. (2006).

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).

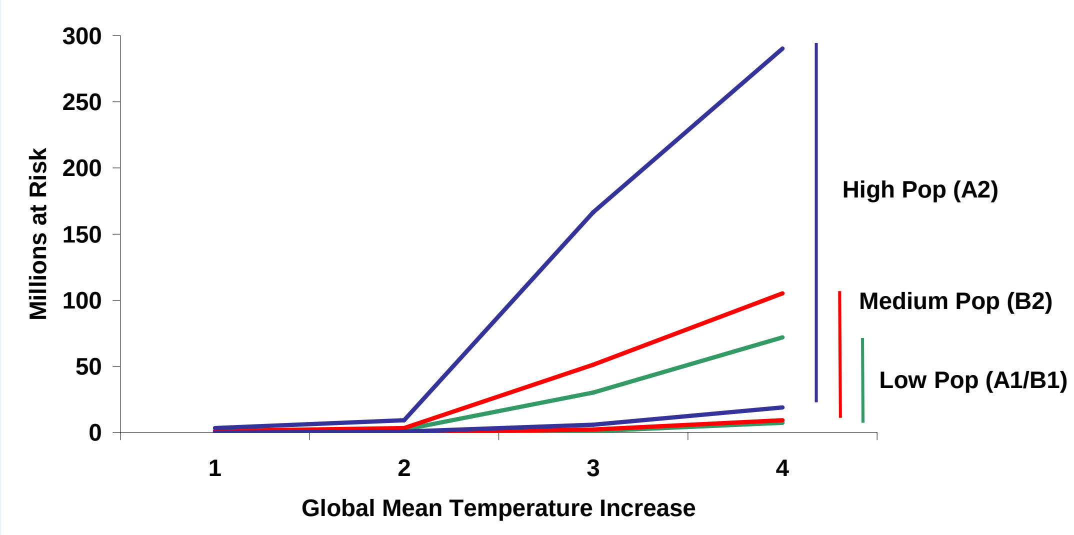
South and East Asia will be most vulnerable because of their large coastal populations in low-lying areas, such as Vietnam, Bangladesh and parts of China (Shanghai) and India. Millions will also be at risk around the coastline of Africa, particularly in the Nile Delta and along the west coast. Small 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.

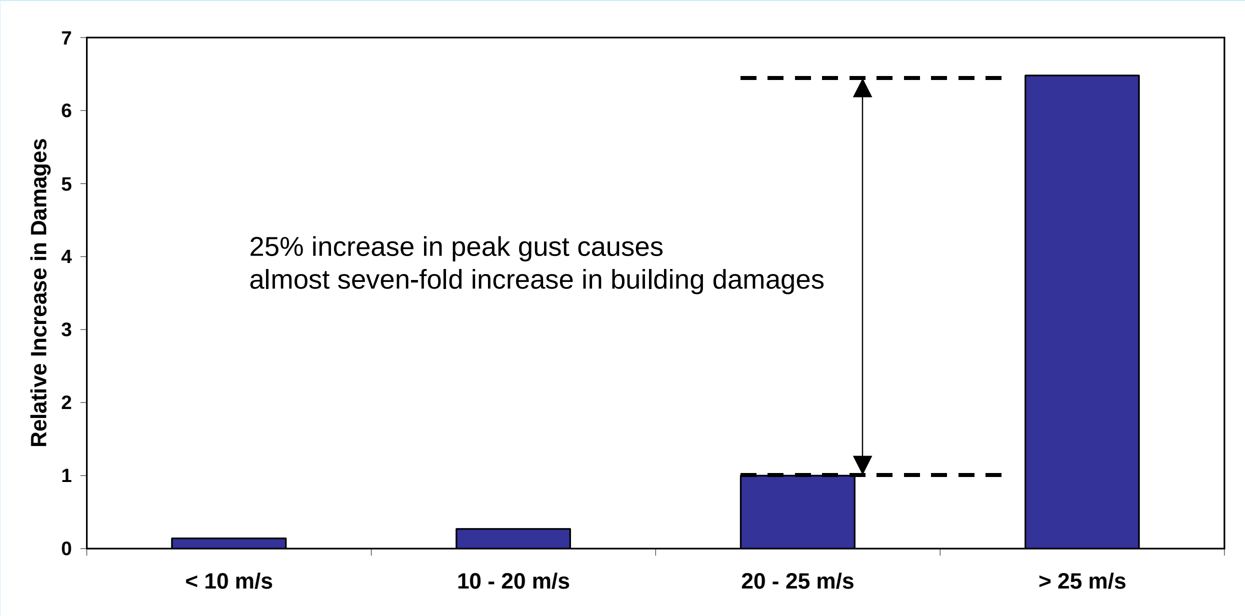
By increasing the amount of energy available to fuel storms (Chapter 1), climate change is likely to increase the intensity of storms. Infrastructure damage costs will increase substantially from even small increases in sea temperatures because: (1) peak wind speeds of tropical storms are a strongly 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]

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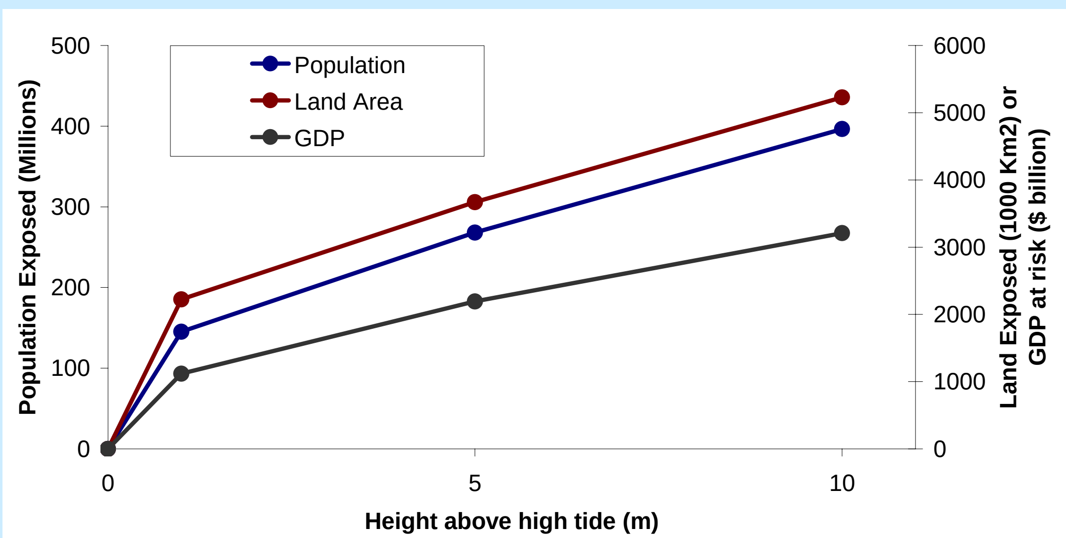
[83] Malcolm *et al.* (2006)
[84] This effect has been found with the Hadley Centre model (Cox *et al.* 2000) and several other climate models (Scholze *et al.* 2006).
[85] Visser and Both (2005); Both *et al.* (2006) report declines of 90% in pied flycatcher populations in the Netherlands in areas where 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.

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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.

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