5 Costs Of Climate Change In Developed Countries

Key Messages

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

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

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

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

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

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

5.1 Introduction

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

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

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

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

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

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

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

5.2 Impacts on wealth and output

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

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

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

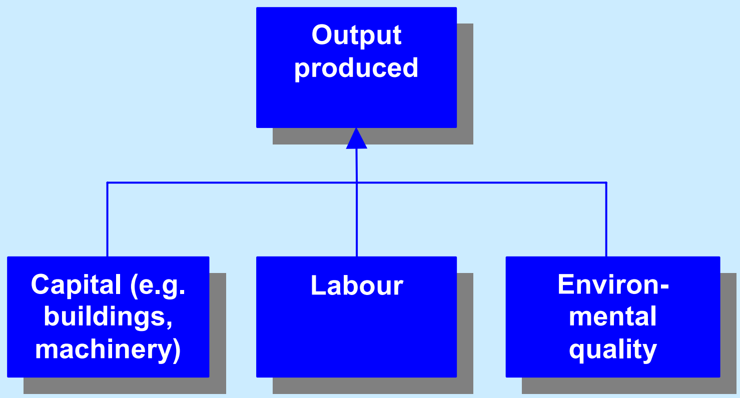
- In Southern Europe, summer water availability may fall by 20 - 30% due to warming of 2°C globally and 40 - 50% for 4°C.[3]
- The West Coast of the USA is likely to experience more erratic water supply as mountain snowpack decreases by 25 – 40% for a 2°C increase in global temperatures and 70 – 90%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

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

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

Box 5.1 A simple production function with environmental quality

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



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

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

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

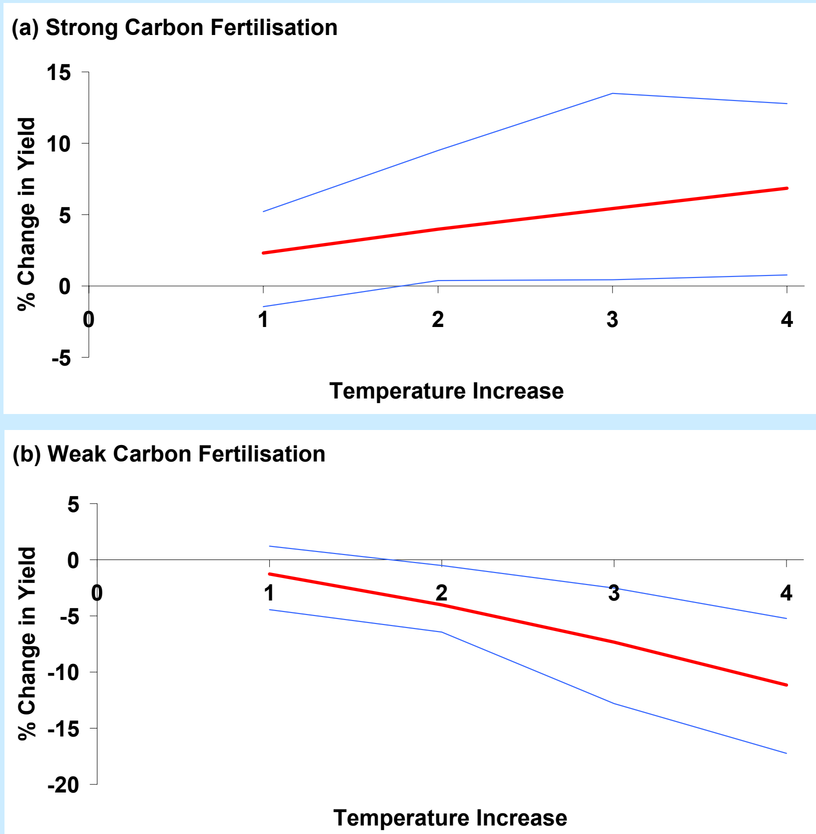
Adaptation to climate change will be an important economic option (Part V). Adaptation will reduce losses in E and/or enhance gains in E, but it too comes at a cost relative to a world without climate change. In this case, the opportunity cost of adaptation is lost consumption or investment diverted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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Box 5.2 Summary of regional impacts of climate change

USA

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

Canada

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

UK

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

Mainland Europe

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

Russia

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

Japan

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

Australia[18]

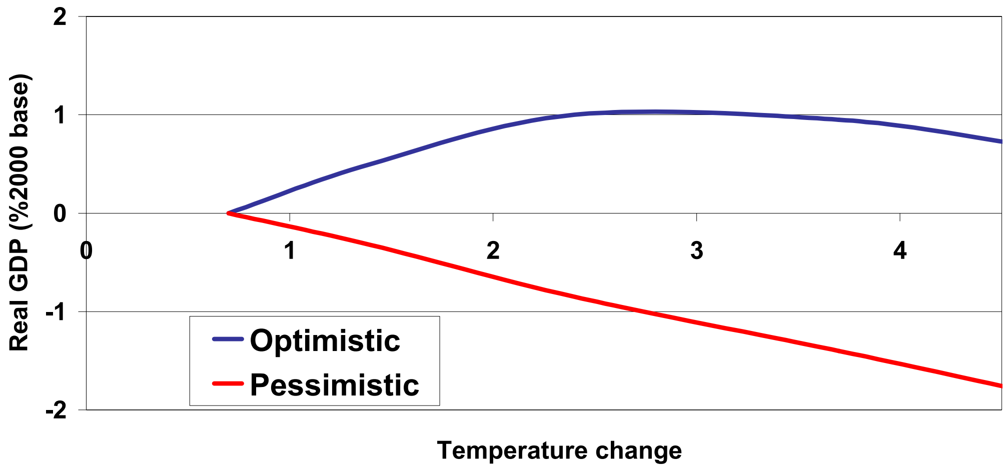
- Australia, as the world's driest continent, is particularly vulnerable to the impact of rising sea temperatures on the major Pacific and Indian Ocean currents. These determine both overall rainfall patterns and unpredictable year-to-year variations. Over the last 30 years stronger tropical typhoons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

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

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

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

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



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

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

Source: Jorgenson *et al.* 2005

5.3 Key vulnerabilities

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

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

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

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

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

5.4 Impacts of extreme events

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

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

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

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

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

Box 5.4 Impacts of recent extreme weather events

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

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

Source: Munich Re (2006)

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

Source: Munich Re (2004)

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

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

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

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

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

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

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

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[29] Recent papers from Nordhaus (2006) and the Association of British Insurers (2005a) examined consequences of increased hurricane wind-speeds of 6% on loss damages, keeping socio-economic conditions and prices constant. Several climate models predict a 6% increase in storm intensity for a doubling of CO_2 concentrations (close to a 3°C temperature rise). The insurance study used existing industry catastrophe loss models validated with historic events to predict future losses. The extreme event costs are defined from an event with a 0.4% chance of occurring (1 in 250 year loss).

[30] Heck *et al.* (2006)

[31] UK Government Foresight Programme (2004) calculations for flooding from rivers, the sea and flash-flooding in urban areas. Prof Jim Hall at the University of Newcastle has provided some additional analysis.

[32] Research from the Association of British Insurers (2005a) extrapolated from a UK-based study of flood losses that assumed no change in flood management policies beyond existing programme. Some of the increased cost is driven by economic growth of the century and greater absolute wealth in physical assets.

[33] Preston and Jones (2006)

[34] Hayhoe *et al.* (2006)

[35] London Climate Change Partnership (2004)

[36] Association of British Insurers (2004) estimates that subsidence costs to buildings could double by the middle of the century to £600 million (2004 prices).

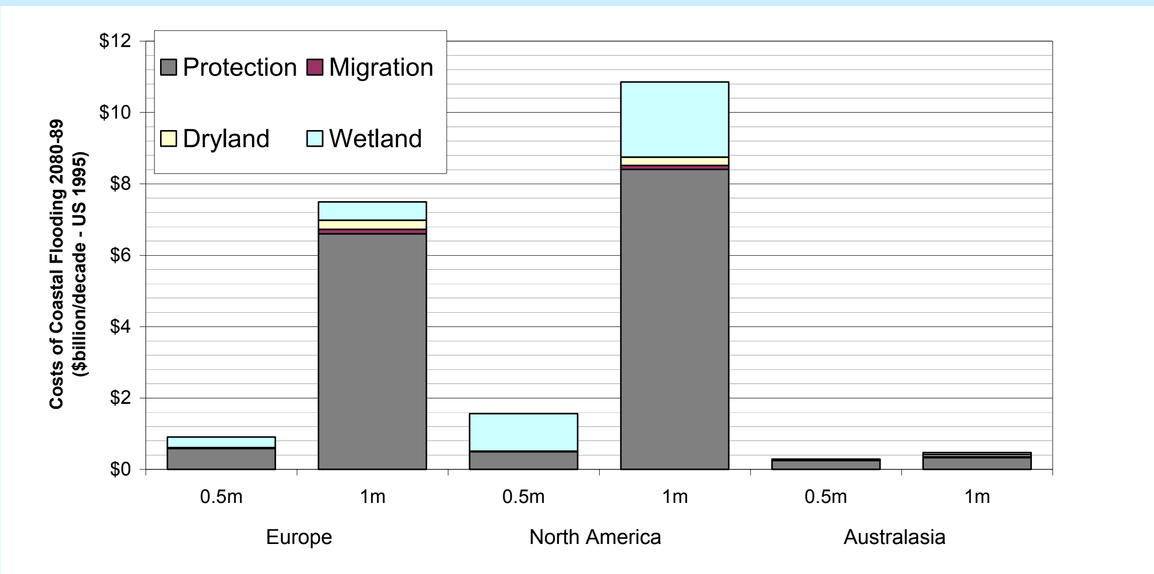
Box 5.5 Costs of coastal flooding in developed country regions

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

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

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

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



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

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

[37] Nicholls and Klein (2003)

5.5 Large-scale impacts and systemic shocks

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

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

- **Physical risks**. The world's major financial centres (London, New York and Tokyo) are all located in coastal areas. The insurance industry estimates that in London alone at least $220 billion (£125 billion) of assets lie in the floodplain.[38]
- **Correlated risks**. At higher temperatures, climate change is likely to have severe impacts on many parts of the economy simultaneously. The shock may well exceed the capacity of markets and could potentially destabilise regions.[39] For example, a collapse of the Atlantic Thermohaline Circulation would have a massive effect on many parts of the economy of the countries around the Northern Atlantic Ocean and polar seas.[40] A collapse in the next few decades would lead to a decrease in temperatures across much of the northern hemisphere, with a peak cooling of around 2°C in the UK and Scandinavia. Preliminary estimates suggest that this would be accompanied by a reduction in rainfall over much of the northern hemisphere,[41] reducing agriculture productivity, water supplies and threatening ecosystems.
- **Capital constraints on insurance**. Increasing costs of extreme weather will not only raise insurance premiums - they will also increase the amount of capital that insurance companies have to hold to cover extreme losses, such as a hurricane that occurs once every 100 years (Box 5.6). The insurance industry will have to develop new financial products to gain more widespread access to international capital markets.[42] New opportunities for diversifying risk are already emerging, for example weather derivatives and catastrophe bonds, but in future these will require new risk valuation techniques to deal with the changing profile of extreme weather events. If the insurance industry looks to access additional capital from the securities and bond markets, investors are likely to demand higher rates of return for placing more capital at risk, causing a rise in the cost of capital.
- **Spillover risks to other financial sectors.**[43] Failure to raise sufficient capital could mean restrictions in insurance coverage. After seven costly hurricanes in the past two years, higher reinsurance prices have pushed up the cost of insurance coverage in the USA and contributed to decisions by some insurers to transfer more risk back to the homeowner or business, for example by raising deductibles or cutting back on coverage in riskier areas.[44] In future, if rising weather risks cause insurance to become even less available in high-risk areas like the coast, this could be severely disruptive for other parts of the economy. Banks, for example, would be unable to offer finance where insurance is required as part of the collateral package for mortgages or loans.

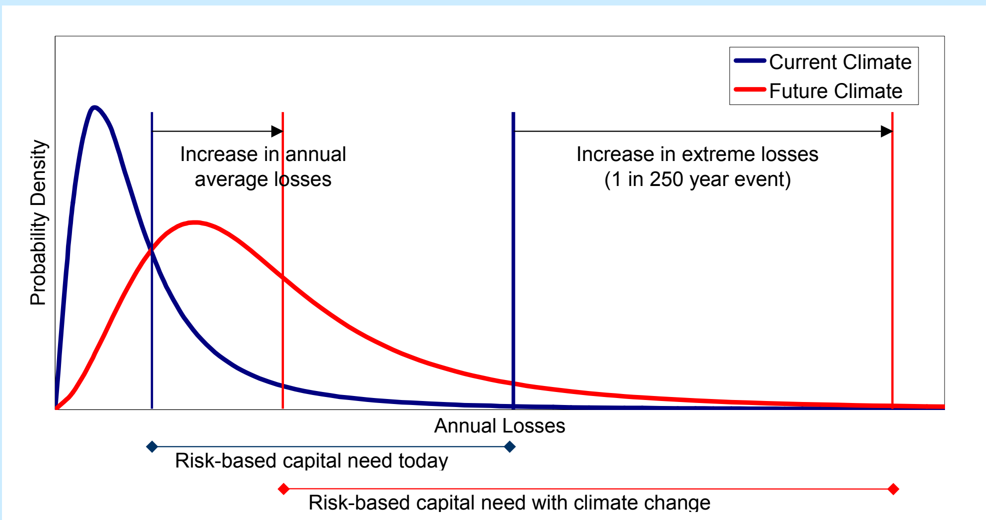
[38] Association of British Insurers (2005b)
[39] As set out in a Pentagon commissioned report by Schwartz and Randall (2004)
[40] A complete collapse of the Thermohaline Circulation is considered to be unlikely (but still plausible) this century (Chapter 1).
[41] Vellinga and Wood (2002)
[42] Salmon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

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

Box 5.6 Climate change and constraints on insurance capital

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

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



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

Source: Association of British Insurers (2005a)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.6 Conclusion

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

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

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

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

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

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

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

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

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