1 The Science of Climate Change: Scale of the Environment Challenge

Key Messages

An overwhelming body of scientific evidence now clearly indicates that **climate change is a serious and urgent issue.** The Earth's climate is rapidly changing, mainly as a result of increases in greenhouse gases caused by human activities.

Most climate models show that **a doubling of pre-industrial levels of greenhouse gases is very likely to commit the Earth to a rise of between 2 – 5°C in global mean temperatures.** This level of greenhouse gases will probably be reached between 2030 and 2060. A warming of 5°C on a global scale would be far outside the experience of human civilisation and comparable to the difference between temperatures during the last ice age and today. Several new studies suggest up to a 20% chance that warming could be greater than 5°C.

If annual greenhouse gas emissions remained at the current level, concentrations would be more than treble pre-industrial levels by 2100, committing the world to 3 – 10°C warming, based on the latest climate projections.

Some impacts of climate change itself may amplify warming further by triggering the release of additional greenhouse gases. This creates a real risk of even higher temperature changes.

- Higher temperatures cause plants and soils to soak up less carbon from the atmosphere and cause permafrost to thaw, potentially releasing large quantities of methane.
- Analysis of warming events in the distant past indicates that such feedbacks could amplify warming by an additional 1 – 2°C by the end of the century.

Warming is very likely to intensify the water cycle, reinforcing existing patterns of water scarcity and abundance and increasing the risk of droughts and floods.

Rainfall is likely to increase at high latitudes, while regions with Mediterranean-like climates in both hemispheres will experience significant reductions in rainfall. Preliminary estimates suggest that the fraction of land area in extreme drought at any one time will increase from 1% to 30% by the end of this century. In other regions, warmer air and warmer oceans are likely to drive more intense storms, particularly hurricanes and typhoons.

As the world warms, the risk of abrupt and large-scale changes in the climate system will rise.

- Changes in the distribution of heat around the world are likely to disrupt ocean and atmospheric circulations, leading to large and possibly abrupt shifts in regional weather patterns.
- If the Greenland or West Antarctic Ice Sheets began to melt irreversibly, the rate of sea level rise could more than double, committing the world to an eventual sea level rise of 5 – 12 m over several centuries.

The body of evidence and the growing quantitative assessment of risks are now sufficient to give clear and strong guidance to economists and policy-makers in shaping a response.

1.1 Introduction

Understanding the scientific evidence for the human influence on climate is an essential starting point for the economics, both for establishing that there is indeed a problem to be tackled and for comprehending its risk and scale. It is the science that dictates the type of economics and where the analyses should focus, for example, on the economics of risk, the nature of public goods or how to deal with externalities, growth and development and intra- and inter-generational equity. The relevance of these concepts, and others, is discussed in Chapter 2.

This chapter begins by describing the changes observed in the Earth's system, examining briefly the debate over the attribution of these changes to human activities. It is a debate that, after more than a decade of research and discussion, has reached the conclusion there is no other plausible explanation for the observed warming for at least the past 50 years. The question of precisely how much the world will warm in the future is still an area of active research. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC)[1] in 2001 was the last comprehensive assessment of the state of the science. This chapter uses the 2001 report as a base and builds on it with more recent studies that embody a more explicit treatment of risk. These studies support the broad conclusions of that report, but demonstrate a sizeable probability that the sensitivity of the climate to greenhouse gases is greater than previously thought. Scientists have also begun to quantify the effects of feedbacks with the natural carbon cycle, for example, exploring how warming may affect the rate of absorption of carbon dioxide by forests and soils. These types of feedbacks are predicted to further amplify warming, but are not typically included in climate models to date. The final section of this chapter provides a starting point for Part II, by exploring what basic science reveals about how warming will affect people around the world.

1.2 The Earth's climate is changing

An overwhelming body of scientific evidence indicates that the Earth's climate is rapidly changing, predominantly as a result of increases in greenhouse gases caused by human activities.

Human activities are changing the composition of the atmosphere and its properties. Since pre-industrial times (around 1750), carbon dioxide concentrations have increased by just over one third from 280 parts per million (ppm) to 380 ppm today (Figure 1.1), predominantly as a result of burning fossil fuels, deforestation, and other changes in land-use.[2] This has been accompanied by rising concentrations of other greenhouse gases, particularly methane and nitrous oxide.

There is compelling evidence that the rising levels of greenhouse gases will have a warming effect on the climate through increasing the amount of infrared radiation (heat energy) trapped by the atmosphere: "the greenhouse effect" (Figure 1.2). In total, the warming effect due to all (Kyoto) greenhouse gases emitted by human activities is now equivalent to around 430 ppm of carbon dioxide (hereafter, CO_2 equivalent or CO_2e)[3] (Figure 1.1) and rising at around 2.3 ppm per year[4]. Current levels of greenhouse gases are higher now than at any time in at least the past 650,000 years.[5]

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[1] The fourth assessment is due in 2007. The scientific advances since the TAR are discussed in Schellnhuber *et al.* (2006)

[2] The human origin of the accumulation of carbon dioxide in the atmosphere is demonstrated through, for example, the isotope composition and hemispheric gradient of atmospheric carbon dioxide (IPCC 2001a).

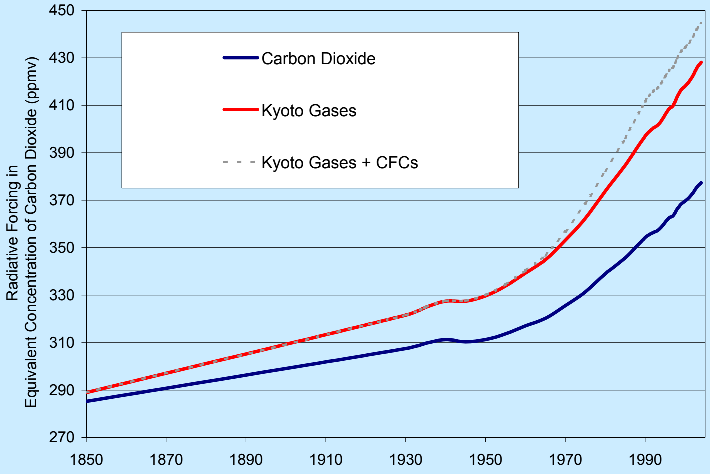
[3] In this Review, the total radiative effect of greenhouse gases is quoted in terms of the equivalent concentration (in ppm) of carbon dioxide and will include the six Kyoto greenhouse gases. It will not include other human influences on the radiation budget of the atmosphere, such as ozone, land properties (i.e. albedo), aerosols or the non-greenhouse gas effects of aircraft unless otherwise stated, because the radiative forcing of these substances is less certain, their effects have a shorter timescale and they are unlikely to form a substantial component of the radiative forcing at equilibrium (they will be substantially decreasing over the timescale of stabilisation). The definition excludes greenhouse gases controlled under the Montreal Protocol (e.g. CFCs). Note however, that such effects are included in future temperature projections. The CO_2 equivalence here measures only the instantaneous radiative effect of greenhouse gases in the atmosphere and ignores the lifetimes of the gases in the atmosphere (i.e. their future effect).

[4] The 1980-2004 average, based on data provided by Prof K Shine and Dr L Gohar, Dept. of Meteorology, University of Reading.

[5] Siegenthaler *et al.* (2005) using data from ice cores. The same research groups recently presented analyses at the 2006 conference of the European Geosciences Union, which suggest that carbon dioxide levels are unprecedented for 800,000 years.

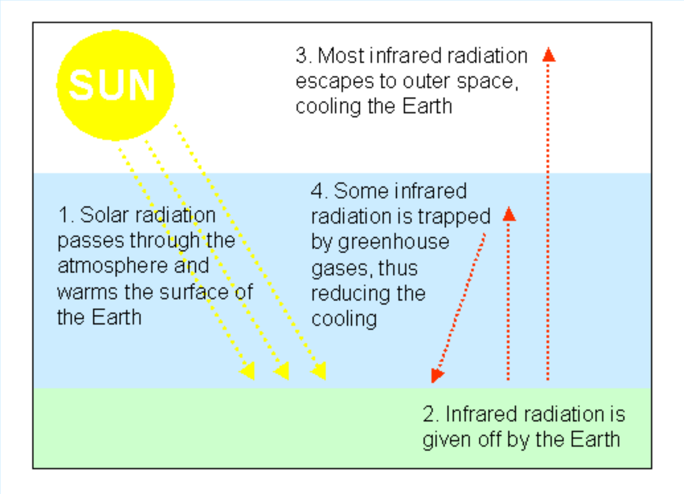
Figure 1.1 Rising levels of greenhouse gases

The figure shows the warming effect of greenhouse gases (the 'radiative forcing') in terms of the equivalent concentration of carbon dioxide (a quantity known as the CO_2 equivalent). The blue line shows the value for carbon dioxide only. The red line is the value for the six Kyoto greenhouse gases (carbon dioxide, methane, nitrous oxide, PFCs, HFCs and SF_6)[6] and the grey line includes CFCs (regulated under the Montreal Protocol). The uncertainty on each of these is up to 10%[7]. The rate of annual increase in greenhouse gas levels is variable year-on-year, but is increasing.



Source: Dr L Gohar and Prof K Shine, Dept. of Meteorology, University of Reading

Figure 1.2 The Greenhouse Effect



Source: Based on DEFRA (2005)

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[6] Kyoto greenhouse gases are the six main greenhouse gases covered by the targets set out in the Kyoto Protocol.

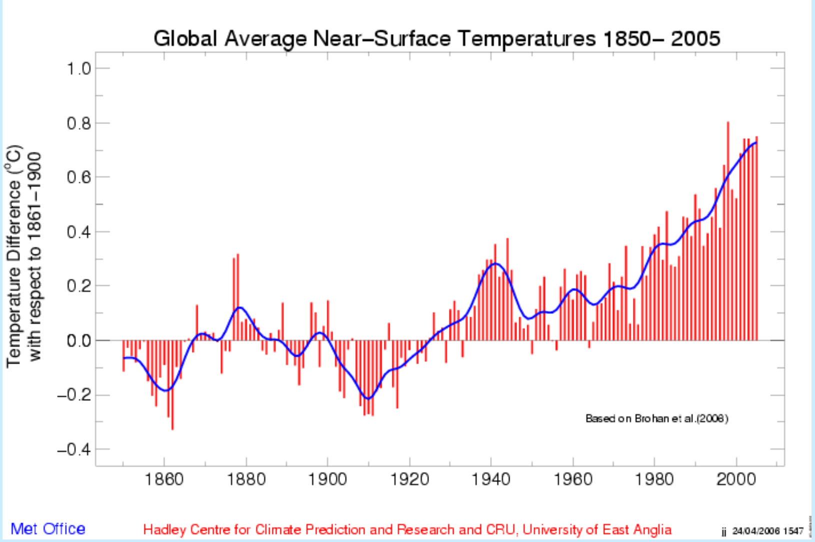
[7] Based on the error on the radiative forcing (in CO_2 equivalent) of all long-lived greenhouse gases from Figure 6.6, IPCC (2001b)

As anticipated by scientists, global mean surface temperatures have risen over the past century. The Earth has warmed by 0.7°C since around 1900 (Figure 1.3). Global mean temperature is referred to throughout the Review and is used as a rough index of the scale of climate change. This measure is an average over both space (globally across the land-surface air, up to about 1.5 m above the ground, and sea-surface temperature to around 1 m depth) and time (an annual mean over a defined time period). All temperatures are given relative to pre-industrial, unless otherwise stated. As discussed later in this chapter, this warming does not occur evenly across the planet.

Over the past 30 years, global temperatures have risen rapidly and continuously at around 0.2°C per decade, bringing the global mean temperature to what is probably at or near the warmest level reached in the current interglacial period, which began around 12,000 years ago[8]. All of the ten warmest years on record have occurred since 1990. The first signs of changes can be seen in many physical and biological systems, for example many species have been moving poleward by 6 km on average each decade for the past 30 – 40 years. Another sign is changing seasonal events, such as flowering and egg laying, which have been occurring 2 – 3 days earlier each decade in many Northern Hemisphere temperate regions.[9]

Figure 1.3 The Earth has warmed 0.7°C since around 1900.

The figure below shows the change in global average near-surface temperature from 1850 to 2005. The individual annual averages are shown as red bars and the blue line is the smoothed trend. The temperatures are shown relative to the average over 1861 – 1900.



Source: Brohan et al. (2006)

The IPCC concluded in 2001 that there is new and stronger evidence that most of the warming observed over at least the past 50 years is attributable to human activities.[10] Their confidence is based on several decades of active debate and effort to scrutinise the detail of the evidence and to investigate a broad range of hypotheses.

Over the past few decades, there has been considerable debate over whether the trend in global mean temperatures can be attributed to human activities. Attributing trends to a single influence is difficult to establish unequivocally because the climate system can often respond in unexpected ways to external

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[8] Hansen et al. (2006)

[9] Parmesan and Yohe (2003) and Root et al. (2005) have correlated a shift in timing and distribution of 130 different plant and animal species with observed climate change.

[10] IPCC (2001a) - this key conclusion has been supported in the Joint Statement of Science Academies in 2005 and a report from the US Climate Change Science Programme (2006).

influences and has a strong natural variability. For example, Box 1.1 briefly describes the debate over whether the observed increase in temperatures over the last century is beyond that expected from natural variability alone throughout the last Millennium.

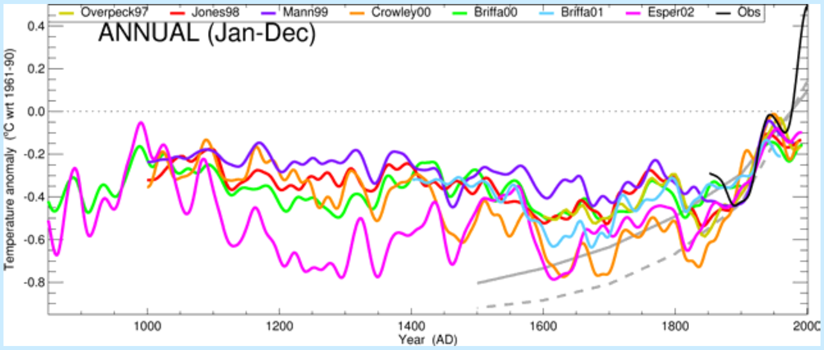
Box 1.1 The "Hockey Stick" Debate.

Much discussion has focused on whether the current trend in rising global temperatures is unprecedented or within the range expected from natural variations. This is commonly referred to as the "Hockey Stick" debate as it discusses the validity of figures that show sustained temperatures for around 1000 years and then a sharp increase since around 1800 (for example, Mann *et al.* 1999, shown as a purple line in the figure below).

Some have interpreted the "Hockey Stick" as definitive proof of the human influence on climate. However, others have suggested that the data and methodologies used to produce this type of figure are questionable (e.g. von Storch *et al.* 2004), because widespread, accurate temperature records are only available for the past 150 years. Much of the temperature record is recreated from a range of 'proxy' sources such as tree rings, historical records, ice cores, lake sediments and corals.

Climate change arguments do not rest on "proving" that the warming trend is unprecedented over the past Millennium. Whether or not this debate is now settled, this is only one in a number of lines of evidence for human induced climate change. The key conclusion, that the build-up of greenhouse gases in the atmosphere will lead to several degrees of warming, rests on the laws of physics and chemistry and a broad range of evidence beyond one particular graph.

Reconstruction of annual temperature changes in the Northern Hemisphere for the past millennium using a range of proxy indicators by several authors. The figure suggests that the sharp increase in global temperatures since around 1850 has been unprecedented over the past millennium. Source: IDAG (2005)



Recent research, for example from the Ad hoc detection and attribution group (IDAG), uses a wider range of proxy data to support the broad conclusion that the rate and scale of 20th century warming is greater than in the past 1000 years (at least for the Northern Hemisphere). Based on this kind of analysis, the US National Research Council (2006)[11] concluded that there is a high level of confidence that the global mean surface temperature during the past few decades is higher than at any time over the preceding four centuries. But there is less confidence beyond this. However, they state that in some regions the warming is unambiguously shown to be unprecedented over the past millennium.

Much of the debate over the attribution of climate change has now been settled as new evidence has emerged to reconcile outstanding issues. It is now clear that, while natural factors, such as changes in solar intensity and volcanic eruptions, can explain much of the trend in global temperatures in the early nineteenth century, the rising levels of greenhouse gases provide the only plausible explanation for the observed trend for at least the past 50 years. Over this period, the sustained globally averaged warming

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[11] National Research Council (2006) – a report requested by the US Congress

contrasts strongly with the slight cooling expected from natural factors alone. Recent modelling by the Hadley Centre and other research institutes supports this. These models show that the observed trends in temperatures at the surface and in the oceans[12], as well as the spatial distribution of warming[13], cannot be replicated without the inclusion of both human and natural effects.

Taking into account the rising levels of aerosols, which cool the atmosphere,[14] and the observed heat uptake by the oceans, the calculated warming effect of greenhouse gases is more than enough to explain the observed temperature rise.

1.3 Linking Greenhouse Gases and Temperature

The causal link between greenhouse gases concentrations and global temperatures is well established, founded on principles established by scientists in the nineteenth century.

The greenhouse effect is a natural process that keeps the Earth's surface around 30°C warmer than it would be otherwise. Without this effect, the Earth would be too cold to support life. Current understanding of the greenhouse effect has its roots in the simple calculations laid out in the nineteenth century by scientists such as Fourier, Tyndall and Arrhenius[15]. Fourier realised in the 1820s that the atmosphere was more permeable to incoming solar radiation than outgoing infrared radiation and therefore trapped heat. Thirty years later, Tyndall identified the types of molecules (known as greenhouse gases), chiefly carbon dioxide and water vapour, which create the heat-trapping effect. Arrhenius took this a step further showing that doubling the concentration of carbon dioxide in the atmosphere would lead to significant changes in surface temperatures.

Since Fourier, Tyndall and Arrhenius made their first estimates, scientists have improved their understanding of how greenhouse gases absorb radiation, allowing them to make more accurate calculations of the links between greenhouse gas concentrations and temperatures. For example, it is now well established that the warming effect of carbon dioxide rises approximately logarithmically with its concentration in the atmosphere[16]. From simple energy-balance calculations, the direct warming effect of a doubling of carbon dioxide concentrations would lead to an average surface warming of around 1°C.

But the atmosphere is much more complicated than these simple models suggest. The resulting warming will in fact be much greater than 1°C because of the interaction between feedbacks in the atmosphere that act to amplify or dampen the direct warming (Figure 1.4). The main positive feedback comes from water vapour, a very powerful greenhouse gas itself. Evidence shows that, as expected from basic physics, a warmer atmosphere holds more water vapour and traps more heat, amplifying the initial warming.[17]

Using climate models that follow basic physical laws, scientists can now assess the likely range of warming for a given level of greenhouse gases in the atmosphere.

It is currently impossible to pinpoint the exact change in temperature that will be associated with a level of greenhouse gases. Nevertheless, increasingly sophisticated climate models are able to capture some of the chaotic nature of the climate, allowing scientists to develop a greater understanding of the many

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[12] Barnett et al. (2005a)

[13] For example, Ad hoc detection and attribution group (2005)

[14] Aerosols are tiny particles in the atmosphere also created by human activities (e.g. sulphate aerosol emitted by many industrial processes). They have several effects on the atmosphere, one of which is to reflect solar radiation and therefore, cool the surface. This effect is thought to have offset some of the warming effect of greenhouse gases, but the exact amount is uncertain.

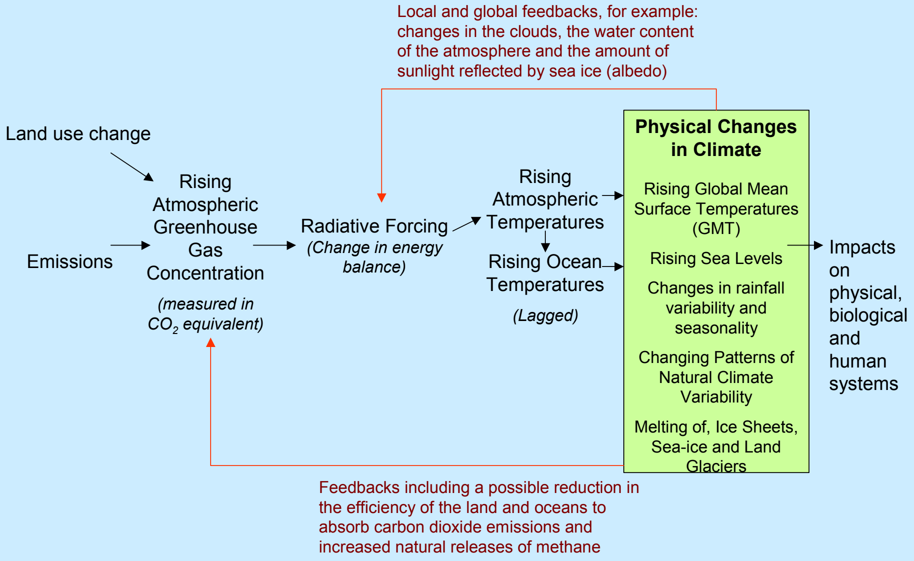
[15] For example, Pearce (2003), Pierrehumbert (2004)

[16] i.e. the incremental increase in radiative forcing due to an increase in concentration (from pre-industrial) will fall to around half of the initial increase when concentrations reach around 600ppm, a quarter at 1200ppm and an eighth at 2400ppm. Note that other greenhouse gases, such as methane and nitrous oxide, have a linear relationship.

[17] It has been suggested that water vapour could act as a negative feedback on warming, on the basis that the upper atmosphere would dry out as it warms (Lindzen 2005). Re-analysis of satellite measurements published last year indicated that in fact the opposite is happening (Soden *et al.* 2005). Over the past two decades, the air in the upper troposphere has become wetter, not drier, countering Lindzen's theory and confirming that water vapour is having a *positive* feedback effect on global warming. This positive feedback is a major driver of the indirect warming effects from greenhouse gases.

complex interactions within the system and estimate how changing greenhouse gas levels will affect the climate. Climate models use the laws of nature to simulate the radiative balance and flows of energy and materials. These models are vastly different from those generally used in economic analyses, which rely predominantly on curve fitting. Climate models cover multiple dimensions, from temperature at different heights in the atmosphere, to wind speeds and snow cover. Also, climate models are tested for their ability to reproduce past climate variations across several dimensions, and to simulate aspects of present climate that they have not been specifically tuned to fit.

Figure 1.4 The link between greenhouse gases and climate change.



The accuracy of climate predictions is limited by computing power. This, for example, restricts the scale of detail of models, meaning that small-scale processes must be included through highly simplified calculations. It is important to continue the active research and development of more powerful climate models to reduce the remaining uncertainties in climate projections.

The sensitivity of mean surface temperatures to greenhouse gas levels is benchmarked against the warming expected for a doubling of carbon dioxide levels from pre-industrial (roughly equivalent to 550 ppm CO_2e). This is called the “climate sensitivity” and is an important quantity in accessing the economics of climate change. By comparing predictions of different state-of-the-art climate models, the IPCC TAR concluded that the likely range of climate sensitivity is 1.5° – 4.5°C. This range is much larger than the 1°C direct warming effect expected from a doubling of carbon dioxide concentrations, thus emphasising the importance of feedbacks within the atmosphere. For illustration, using this range of sensitivities, if greenhouse gas levels could be stabilised at today’s levels (430 ppm CO_2e), global mean temperatures would eventually rise to around 1° - 3°C above pre-industrial (up to 2°C more than today)[18]. This is not the same as the “warming commitment” today from past emissions, which includes the current levels of aerosols in the atmosphere (discussed later in this chapter).

Results from new risk based assessments suggest there is a significant chance that the climate system is more sensitive than was originally thought.

Since 2001, a number of studies have used both observations and modelling to explore the full range of climate sensitivities that appear realistic given current knowledge (Box 1.2). This new evidence is important in two ways: firstly, the conclusions are broadly consistent with the IPCC TAR, but indicate that

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[18] Calculated using method shown in Meinshausen (2006).

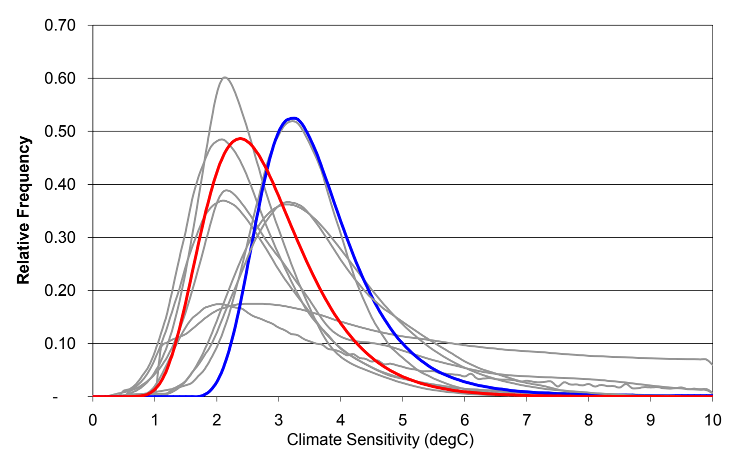
higher climate sensitivities cannot be excluded; and secondly, it allows a more explicit treatment of risk. For example, eleven recent studies suggest only between a 0% and 2% chance that the climate sensitivity is less than 1°C, but between a 2% and 20% chance that climate sensitivity is greater than 5°C[19]. These sensitivities imply that there is up to a one-in-five chance that the world would experience a warming in excess of 3°C above pre-industrial even if greenhouse gas concentrations were stabilised at today's level of 430 ppm CO_2e.

Box 1.2 Recent advances in estimating climate sensitivity

Climate sensitivity remains an area of active research. Recently, new approaches have used climate models and observations to develop a better understanding of climate sensitivity.

- Several studies have estimated climate sensitivity by benchmarking climate models against the observed warming trend of the 20th century, e.g. Forest et al. (2006) and Knutti et al. (2002).
- Building on this work, modellers have systematically varied a range of uncertain parameters in more complex climate models (such as those controlling cloud behaviour) and run ensembles of these models, e.g. Murphy *et al.* (2004) and Stainforth et al. (2005). The outputs are then checked against observational data, and the more plausible outcomes (judged by their representation of current climate) are weighted more highly in the probability distributions produced.
- Some studies, e.g. Annan & Hargreaves (2006), have used statistical techniques to estimate climate sensitivity through combining several observational datasets (such as the 20th century warming, cooling following volcanic eruptions, warming after last glacial maximum).

These studies provide an important first attempt to apply a probabilistic framework to climate projections. Their outcome is a series of probability distribution functions (PDFs) that aim to capture some of the uncertainty in current estimates. Meinhausen (2006) brings together the results of eleven recent studies (below). The red and blue lines are probability distributions based on the IPCC TAR (Wigley and Raper (2001)) and recent Hadley Centre ensemble work (Murphy *et al.* (2004)), respectively. These two distributions lie close to the centre of the results from the eleven studies.



Source: Reproduced from Meinhausen (2006)

The distributions share the characteristic of a long tail that stretches up to high temperatures. This is primarily because of uncertainty over clouds[20] and the cooling effect of aerosols. For example, if cloud properties are sensitive to climate change, they could create an important addition feedback. Similarly, if the cooling effect of aerosols is large it will have offset a substantial part of past warming due to greenhouse gases, making high climate sensitivity compatible with the observed warming.

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[19] Meinshausen (2006)

[20] An increase in low clouds would have a negative feedback effect, as they have little effect on infrared radiation but block sunlight, causing a local cooling. Conversely, an increase in high clouds would trap more infrared radiation, amplifying warming.

In the future, climate change itself could trigger additional increases in greenhouse gases in the atmosphere, further amplifying warming. These potentially powerful feedbacks are less well understood and only beginning to be quantified.

Climate change projections must also take into account the strong possibility that climate change itself may accelerate future warming by reducing natural absorption and releasing stores of carbon dioxide and methane. These feedbacks are not incorporated into most climate models to date because their effects are only just beginning to be understood and quantified.

Rising temperatures and changes in rainfall patterns are expected to weaken the ability of the Earth's natural sinks to absorb carbon dioxide (Box 1.3), causing a larger fraction of human emissions to accumulate in the atmosphere. While this finding is not new, until recently the effect was not quantified. New models, which explicitly include interactions between carbon sinks and climate, suggest that by 2100, greenhouse gas concentrations will be 20 – 200 ppm higher than they would have otherwise been, amplifying warming by 0.1 – 1.5°C.[21] Some models predict future reductions in tropical rainforests, particularly the Amazon, also releasing more carbon into the atmosphere[22]. Chapter 8 discusses the implications of weakened carbon sinks for stabilising greenhouse gas concentrations.

Widespread thawing of permafrost regions is likely to add to the extra warming caused by weakening of carbon sinks. Large quantities of methane (and carbon dioxide) could be released from the thawing of permafrost and frozen peat bogs. One estimate, for example, suggests that if all the carbon accumulated in peat alone since the last ice age were released into the atmosphere, this would raise greenhouse gas levels by 200 ppm CO_2e.[23] Additional emissions may be seen from warming tropical wetlands, but this is more uncertain. Together, wetlands and frozen lands store more carbon than has been released already by human activities since industrialisation began. Substantial thawing of permafrost has already begun in some areas; methane emissions have increased by 60% in northern Siberia since the mid-1970s[24]. Studies of the overall scale and timing of future releases are scarce, but initial estimates suggest that methane emissions (currently 15% of all emissions in terms of CO_2 equivalent[25]) may increase by around 50% by 2100 (Box 1.3).

Preliminary estimates suggest that these "positive feedbacks" could lead to an addition rise in temperatures of 1 - 2°C by 2100.

Recent studies have used information from past ice ages to estimate how much extra warming would be produced by such feedbacks. Warming following previous ice ages triggered the release of carbon dioxide and methane from the land and oceans, raising temperatures by more than that expected from solar effects alone. If present day climate change triggered feedbacks of a similar size, temperatures in 2100 would be 1 - 2°C higher than expected from the direct warming caused by greenhouse gases.[26]

There are still many unanswered questions about these positive feedbacks between the atmosphere, land and ocean. The combined effect of high climate sensitivity and carbon cycle feedbacks is only beginning to be explored, but first indications are that this could lead to far higher temperature increases than are currently anticipated (discussed in chapter 6). It remains unclear whether warming could initiate a self-perpetuating effect that would lead to a much larger temperature rise or even runaway warming, or if some unknown feedback could reduce the sensitivity substantially[27]. Further research is urgently required to quantify the combined effects of these types of feedbacks.

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[21] Friedlingstein *et al.* (2006)

[22] Cox *et al.* (2000) with the Hadley Centre model and Scholze *et al* (2006) with several models.

[23] Gorham et al. (1991)

[24] Walter et al. (2006)

[25] Emissions measured in CO_2 equivalent are weighted by their global warming potential (see chapter 8).

[26] These estimates come from recent papers by Torn and Harte (2006) and Scheffer *et al.* (2006), which estimate the scale of positive feedbacks from release of carbon dioxide and methane from past natural climate change episodes, e.g. Little Ice Age and previous inter-glacial period, into current climate models.

[27] One study to date has examined this question and suggested that a run away effect is unlikely, at least for the land-carbon sink (Cox et al. 2006). It remains unclear how the risk of run-away climate change would change with the inclusion of other feedbacks.

Box 1.3 Changes in the earth system that could amplify global warming

Weakening of Natural Land-Carbon Sinks: Initially, higher levels of carbon dioxide in the atmosphere will act as a fertiliser for plants, increasing forest growth and the amount of carbon absorbed by the land. A warmer climate will increasingly offset this effect through an increase in plant and soil respiration (increasing release of carbon from the land). Recent modelling suggests that net absorption may initially increase because of the carbon fertilisation effects (chapter 3). But, by the end of this century it will reduce significantly as a result of increased respiration and limits to plant growth (nutrient and water availability).[28]

Weakening of Natural Ocean-Carbon Sinks: The amount of carbon dioxide absorbed by the oceans is likely to weaken in the future through a number of chemical, biological and physical changes. For example, chemical uptake processes may be exhausted, warming surface waters will reduce the rate of absorption and CO_2 absorbing organisms are likely to be damaged by ocean acidification[29]. Most carbon cycle models agree that climate change will weaken the ocean sink, but suggest that this would be a smaller effect than the weakening of the land sink[30].

Release of Methane from Peat Deposits, Wetlands and Thawing Permafrost: Thawing permafrost and the warming and drying of wetland areas could release methane (and carbon dioxide) to the atmosphere in the future. Models suggest that up to 90% of the upper layer of permafrost will thaw by 2100.[31] These regions contain a substantial store of carbon. One set of estimates suggests that wetlands store equivalent to around 1600 $GtCO_2e$ (where Gt is one billion tonnes) and permafrost soils store a further 1500 $GtCO_2e$[32]. Together these stores comprise more than double the total cumulative emissions from fossil fuel burning so far. Recent measurements show a 10 – 15% increase in the area of thaw lakes in northern and western Siberia. In northern Siberia, methane emissions from thaw lakes are estimated to have increased by 60% since the mid 1970's[33]. It remains unclear at what rate methane would be released in the future. Preliminary estimates indicate that, in total, methane emissions each year from thawing permafrost and wetlands could increase by around 4 – 10 $GtCO_2e$, more than 50% of current methane emissions and equivalent to 10 – 25% of current man-made emissions.[34]

Release of Methane from Hydrate Stores: An immense quantity of methane (equivalent to tens of thousands of $GtCO_2$, twice as much as in coal, oil and gas reserves) may also be trapped under the oceans in the form of gas hydrates. These exist in regions sufficiently cold and under enough high pressures to keep them stable. There is considerable uncertainty whether these deposits will be affected by climate change at all. However, if ocean warming penetrated deeply enough to destabilise even a small amount of this methane and release it to the atmosphere, it would lead to a rapid increase in warming.[35] Estimates of the size of potential releases are scarce, but are of a similar scale to those from wetlands and permafrost.

1.4 Current Projections

Additional warming is already in the pipeline due to past and present emissions.

The full warming effect of past emissions is yet to be realised. Observations show that the oceans have taken up around 84% of the total heating of the Earth's system over the last 40 years[36]. If global emissions were stopped today, some of this heat would be exchanged with the atmosphere as the system came

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[28] Friedlingstein *et al.* (2006) found that all eleven climate models that explicitly include carbon cycle feedbacks showed a weakening of carbon sinks.

[29] Orr *et al.* (2005)

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

[31] Lawrence and Slater (2005), based on IPCC A2 Scenario

[32] Summarised in Davidson and Janssens (2006) (wetlands) and Archer (2005) (permafrost) - CO_2 equivalent emissions (chapter 7).

[33] Walter et al. (2006) and Smith et al. (2005)

[34] Estimates of potential methane emissions from thawing permafrost range around 2 - 4$GtCO_2$/yr. Wetlands emit equivalent to 2 – 6 $GtCO_2$/yr and studies project that this may rise by up to 80%. Davidson & Janssens (2006), Gedney et al. (2004) and Archer (2005).

[35] Hadley Centre (2005)

[36] Barnett et al. (2005a) and Levitus *et al.* (2005)

back into equilibrium, causing an additional warming. Climate models project that the world is committed to a further warming of 0.5° - 1°C over several decades due to past emissions[37]. This warming is smaller than the warming expected if concentrations were stabilised at 430 ppm CO_2e, because atmospheric aerosols mask a proportion of the current warming effect of greenhouse gases. Aerosols remain in the atmosphere for only a few weeks and are not expected to be present in significant levels at stabilisation[38].

If annual emissions continued at today's levels, greenhouse gas levels would be close to double pre-industrial levels by the middle of the century. If this concentration were sustained, temperatures are projected to eventually rise by 2 – 5ºC or even higher.

Projections of future warming depend on projections of global emissions (discussed in chapter 7). If annual emissions were to remain at today's levels, greenhouse gas levels would reach close to 550 ppm CO_2e by 2050[39]. Using the lower and upper 90% confidence bounds based on the IPCC TAR range and recent research from the Hadley Centre, this would commit the world to a warming of around 2 – 5°C (Table 1.1). As demonstrated in Box 1.2, these two climate sensitivity distributions lie close to the centre of recent projections and are used throughout this Review to give illustrative temperature projections. Positive feedbacks, such as methane emissions from permafrost, could drive temperatures even higher.

Near the middle of this range of warming (around 2 – 3°C above today), the Earth would reach a temperature not seen since the middle Pliocene around 3 million years ago[40]. This level of warming on a global scale is far outside the experience of human civilisation.

Table 1.1 Temperature projections at stabilisation

Meinshausen (2006) used climate sensitivity estimates from eleven recent studies to estimate the range of equilibrium temperature changes expected at stabilisation. The table below gives the equilibrium temperature projections using the 5 – 95% climate sensitivity ranges based on the IPCC TAR (Wigley and Raper (2001)), Hadley Centre (Murphy *et al.* 2004) and the range over all eleven studies. Note that the temperature changes expected prior to equilibrium, for example in 2100, would be lower.

Stabilisation level (ppm CO_2 equivalent)	Temperature increase at equilibrium relative to pre-industrial (°C)		
	IPCC TAR 2001 (Wigley and Raper)	Hadley Centre Ensemble	Eleven Studies
400	0.8 – 2.4	1.3 – 2.8	0.6 – 4.9
450	1.0 – 3.1	1.7 – 3.7	0.8 – 6.4
500	1.3 – 3.8	2.0 – 4.5	1.0 – 7.9
550	1.5 – 4.4	2.4 – 5.3	1.2 – 9.1
650	1.8 – 5.5	2.9 – 6.6	1.5 – 11.4
750	2.2 – 6.4	3.4 – 7.7	1.7 – 13.3
1000	2.8 – 8.3	4.4 – 9.9	2.2 – 17.1

However, these are conservative estimates of the expected warming, because in the absence of an effective climate policy, changes in land use and the growth in population and energy consumption around the world will drive greenhouse gas emissions far higher than today. This would lead greenhouse gas levels to attain higher levels than suggested above. The IPCC projects that without intervention

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[37] Wigley (2005) and Meehl *et al.* (2005) look at the amount of warming "in the pipeline" using different techniques.
[38] In many countries, aerosol levels have already been reduced by regulation because of their negative health effects.
[39] For example, 45 years at 2.5 ppm/yr gives 112.5ppm. Added to the current level, this gives 542.5ppm in 2050.
[40] Hansen *et al.* (2006)

greenhouse gas levels will rise to 550 – 700 ppm CO_2e by 2050 and 650 – 1200 ppm CO_2e by 2100[41]. These projections and others are discussed in Chapter 7, which concludes that, without mitigation, greenhouse gas levels are likely to be towards the upper end of these ranges. If greenhouse gas levels were to reach 1000 ppm, more than treble pre-industrial levels, the Earth would be committed to around a 3 – 10°C of warming or more, even without considering the risk of positive feedbacks (Table 1.1).

1.5 Large Scale Changes and Regional Impacts

This chapter has so far considered only the expected changes in global average surface temperatures. However, this can often mask both the variability in temperature changes across the earth's surface and changes in extremes. In addition, the impacts on people will be felt mainly through water, driven by shifts in regional weather patterns, particularly rainfall and extreme events (more detail in Part II).

In general, higher latitudes and continental regions will experience temperature increases significantly greater than the global average.

Future warming will occur unevenly and will be superimposed on existing temperature patterns. Today, the tropics are around 15°C warmer than the mid-latitudes and more than 25°C warmer than the high latitudes. In future, the smallest temperature increases will generally occur over the oceans and some tropical coastal regions. The largest temperature increases are expected in the high latitudes (particularly around the poles), where melting snow and sea ice will reduce the reflectivity of the surface, leading to a greater than average warming. 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.

The risk of heat waves is expected to increase (Figure 1.5). For example, new modelling work by the Hadley Centre shows that the summer of 2003 was Europe's hottest for 500 years and that human-induced climate change has already more than doubled the chance of a summer as hot as 2003 in Europe occurring.[42] By 2050, under a relatively high emissions scenario, the temperatures experienced during the heatwave of 2003 could be an average summer. The rise in heatwave frequency will be felt most severely in cities, where temperatures are further amplified by the urban heat island effect.

Changes in rainfall patterns and extreme weather events will lead to more severe impacts on people than that caused by warming alone.

Warming will change rainfall patterns, partly because warmer air holds more moisture, and also because the uneven distribution of warming around the world will lead to shifts in large-scale weather regimes. Most climate models predict increases in rainfall at high latitudes, while changes in circulation patterns are expected to cause a drying of the subtropics, with northern Africa and the Mediterranean experiencing significant reductions in rainfall. There is more uncertainty about changes in rainfall in the tropics (Figure 1.6), mainly because of complicated interactions between climate change and natural cycles like the El Niño, which dominate climate in the tropics.[43] For example, an El Niño event with strong warming in the central Pacific can cause the Indian monsoon to switch into a "dry mode", characterised by significant reductions in rainfall leading to severe droughts. These delicate interactions could cause abrupt shifts in rainfall patterns. This is an area that urgently needs more research because of the potential effect on billions of people, especially in South and East Asia (more detail in Part II).

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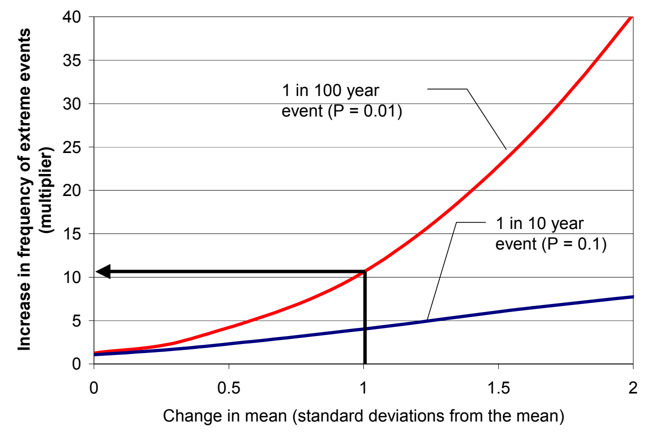
[41] Based on the IPCC TAR central radiative forcing projections for the six illustrative SRES scenarios (IPCC 2001b).

[42] According to Stott *et al.* (2004), climate change has increased the chance of the 2003 European heatwave occurring by between 2 and 8 times. In 2003, temperatures were 2.3°C warmer than the long-term average.

[43] In an El Niño year (around once every 3-7 years), the pattern of tropical sea surface temperatures changes, with the eastern Pacific warming significantly. This radically alters large-scale atmospheric circulations across the globe, and causes rainfall patterns to shift, with some regions experiencing flooding and others severe droughts. As the world warms, many models suggest that the East Pacific may warm more intensely than the West Pacific, mimicking the pattern of an El Niño, although significant uncertainties remain. Models do not yet agree on the nature of changes in the frequency or intensity of the El Niño (Collins and the CMIP Modelling Groups 2005).

Figure 1.5 Rising probability of heatwaves

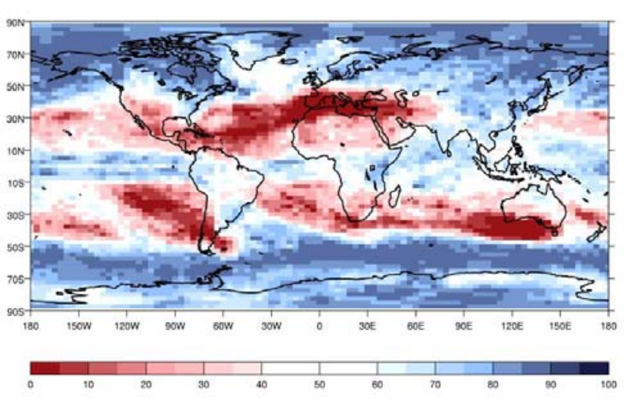
There will be more extreme heat days (relative to today) and fewer very cold days, as the distribution of temperatures shifts upwards. The figure below illustrates the change in frequency of a one-in-ten (blue) and one-in-one-hundred (red) year event. The black arrow shows that if the mean temperature increases by one standard deviation (equal to, for example, only 1°C for summer temperatures in parts of Europe), then the probability of today's one-in-one-hundred year event (such as a severe heatwave) will increase ten-fold. This result assumes that the shape of the temperature distribution will remain constant. However, in many areas, the drying of land is expected to skew the distribution towards higher temperatures, further increasing the frequency of temperature extremes[44].



Source: Based on Wigley (1985) assuming normally distributed events.

Figure 1.6 Consistency of future rainfall estimates

The figure below indicates the percentage of models (out of a total of 23) that predict that annual rainfall will increase by 2100 (for a warming of around 3.5°C above pre-industrial). Blue shading indicates that most models (>75%) show an increase in annual rainfall, while red shading indicates that most models show a decrease in rainfall. Lightly shaded areas are where models show inconsistent results. The figure shows only the direction of change and gives no information about its scale. In general, there is agreement between most of the models that high latitudes will see increases in rainfall, while much of the subtropics will see reductions in rainfall. Changes in rainfall in the tropics are still uncertain.



Source: *Climate Directorate of the National Centre for Atmospheric Science, University of Reading*

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[44] Schär C *et al.* (2004)

Greater evaporation and more intense rainfall will increase the risk of droughts and flooding in areas already at risk.[45] It could also increase the size of areas at risk; one recent study, the first of its kind, estimates that the fraction of land area in moderate drought at any one time will increase from 25% at present to 50% by the 2090s, and the fraction in extreme drought from 3% to 30%[46].

Hurricanes and other storms are likely to become more intense in a warmer, more energised world, as the water cycle intensifies, but changes to their location and overall numbers[47] remain less certain. There is growing evidence the expected increases in hurricane severity are already occurring, above and beyond any natural decadal cycles. Recent work suggests that the frequency of very intense hurricanes and typhoons (Category 4 and 5) in the Atlantic Basin has doubled since the 1970s as a result of rising sea-surface temperatures.[48] This remains an active area of scientific debate[49]. In higher latitudes, some models show a general shift in winter storm tracks towards the poles.[50] In Australia, this could lead to water scarcity as the country relies on winter storms to supply water[51].

Climate change could weaken the Atlantic Thermohaline Circulation, partially offsetting warming in both Europe and eastern North America, or in an extreme case causing a significant cooling.

The warming effect of greenhouse gases has the potential to trigger abrupt, large-scale and irreversible changes in the climate system. One example is a possible collapse of the North Atlantic Thermohaline Circulation (THC). In the North Atlantic, the Gulf Stream and North Atlantic drift (important currents of the North Atlantic THC) have a significant warming effect on the climates of Europe and parts of North America. The THC may be weakened, as the upper ocean warms and/or if more fresh water (from melting glaciers and increased rainfall) is laid over the salty seawater.[52] No complex climate models currently predict a complete collapse. Instead, these models point towards a weakening of up to half by the end of the century[53]. Any sustained weakening of the THC is likely to have a cooling effect on the climates of Europe and eastern North America, but this would only offset a portion of the regional warming due to greenhouse gases. A recent study using direct ocean measurements (the first of its kind) suggests that part of the THC may already have weakened by up to 30% in the past few decades, but the significance of this is not yet known.[54] The potential for abrupt, large-scale changes in climate requires further research.

Sea levels will continue to rise, with very large increases if the Greenland Ice Sheet starts to melt irreversibly or the West Antarctic Ice Sheet (WAIS) collapses.

Sea levels will respond more slowly than temperatures to changing greenhouse gas concentrations. Sea levels are currently rising globally at around 3 mm per year and the rise has been accelerating[55]. According to the IPCC TAR, sea levels are projected to rise by 9 - 88 cm by 2100, mainly due to expansion of the warmer oceans and melting glaciers on land.[56] However, because warming only penetrates the oceans very slowly, sea levels will continue to rise substantially more over several centuries. On past emissions alone, the world has built up a substantial commitment to sea level rise. One study estimates an existing commitment of between 0.1 and 1.1 metres over 400 years.[57]

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[45] Huntington (2006) reviewed more than 50 peer-reviewed studies and found that many aspects of the global water cycle have intensified in the past 50 years, including rainfall and evaporation. Modelling work by Wetherald & Manabe (2002) confirms that warming will increase rates of both precipitation and evaporation.

[46] Burke, Brown and Christidis (2006) using one model under a high emissions scenario. Other climate models are needed to verify these results. The study uses one commonly used drought index: The Palmer Drought Severity Index (PDSI). This uses temperature and rainfall data to formulate a measure of 'dryness'. Other drought indices do not show such large changes.

[47] For example, Lambert and Fyfe (2006) and Fyfe (2003)

[48] Emanuel (2005); Webster et al. (2005)

[49] Pielke (2005); Landsea (2005)

[50] For example, Geng and Sugi (2003); Bengtsson, Hodges and Roeckner (2006)

[51] Hope (2006)

[52] Summarised in Schlesinger *et al.* (2006)

[53] Wood *et al.* (2006). Complex climate models project a weakening of between 0% and 50% by the end of the century.

[54] Bryden *et al.* (2005). It is unclear whether the weakening is part of a natural cycle or the start of a downward trend.

[55] Church and White (2006)

[56] IPCC (2001b). This range covers several sources of uncertainty, including emissions, climate sensitivity and ocean responses

[57] Wigley (2005). The uncertainty reflects a range of climate sensitivities, aerosol forcings and melt-rates.

Box 1.4 Ice sheets and sea level rise

Melting ice sheets are already contributing a small amount to sea level rise. Most of recent and current global sea level rise results from the thermal expansion of the ocean with a contribution from glacier melt. As global temperatures rise, the likelihood of substantial contributions from melting ice sheets increases, but the scale and timing remain highly uncertain. While some models project that the net contribution from ice sheets will remain close to zero or negative over the coming century, recent observations suggest that the Greenland and West Antarctic ice sheets may be more vulnerable to rising temperatures than is projected by current climate models:

- **Greenland Ice Sheet.** Measurements of the Greenland ice sheet have shown a slight inland growth,[58] but significant melting and an acceleration of ice flows near the coast,[59] greater than predicted by models. Melt water is seeping down through the crevices of the melting ice, lubricating glaciers and accelerating their movement to the ocean. Some models suggest that as local temperatures exceed 3 - 4.5°C (equivalent to a global increase of around 2 - 3°C) above pre-industrial,[60] the surface temperature of the ice sheet will become too warm to allow recovery from summertime melting and the ice sheet will begin to melt irreversibly. During the last interglacial period, around 125,000 years ago when Greenland temperatures reached around 4 - 5°C above the present[61], melting of ice in the Arctic contributed several metres to sea level rise.
- **Collapse of the West Antarctic Ice Sheet**:[62] In 2002, instabilities in the Larsen Ice Shelf led to the collapse of a section of the shelf the size of Rhode Island (Larsen B – over 3200 km^2 – and 200 m thick) from the Antarctic Peninsula. The collapse has been associated with a sustained warming and resulting rapid thinning of Larsen B at a rate of just under 20 cm per year[63]. A similar rapid rate of thinning has now been observed on other parts of the WAIS around Amundsen Bay (this area alone contains enough water to raise sea levels by 1.5 m)[64]. Rivers of ice on the ice-sheet have been accelerating towards the ocean. It is possible that ocean warming and the acceleration of ice flows will destabilise the ice sheet and cause a runaway discharge into the oceans. Uncertainties over the dynamics of the ice sheet are so great that there are few estimates of critical thresholds for collapse. One study gives temperatures between 2°C and 5°C, but these remain disputed.

As global temperatures continue to rise, so do the risks of additional sea level contributions from large-scale melting or collapse of ice sheets. If the Greenland and West Antarctic ice sheets began to melt irreversibly, the world would be committed to substantial increases in sea level in the range 5 – 12 m over a timescale of centuries to millennia.[65] The immediate effect would be a potential doubling of the rate of sea level rise: 1 - 3 mm per year from Greenland and as high as 5 mm per year from the WAIS.[66] For illustration, if these higher rates were reached by the end of this century, the upper range of global sea level rise projections would exceed 1m by 2100. Both of these ice sheets are already showing signs of vulnerability, with ice discharge accelerating over large areas, but the thresholds at which large-scale changes are triggered remain uncertain (Box 1.4).

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[58] For example, Zwally et al. 2006 and Johannessen et al. 2005

[59] For example, Hanna et al. 2005 and Rignot and Kanagaratnam 2006

[60] Lower and higher estimates based on Huybrechts and de Wolde (1999) and Gregory and Huybrechts (2006), respectively.

[61] North Greenland Ice Core Project (2004). The warm temperatures in the Northern Hemisphere during the previous interglacial reflected a maximum in the cycle of warming from the Sun due to the orbital position of the Earth. In the future, Greenland is expected to experience some of the largest temperature changes. A 4-5°C greenhouse warming of Greenland would correspond to a global mean temperature rise of around 3°C (Gregory and Huybrechts (2006)).

[62] Rapley (2006)

[63] Shepherd et al. 2003. The collapse of Larsen B followed the collapse in 1995 of the smaller Larsen A ice shelf.

[64] Zwally et al. (2006)

[65] Based on 7m and 5m from the Greenland and West Antarctic ice sheets, respectively. Rapley (2006) and Wood *et al.* (2006)

[66] Huybrechts and DeWolde (1999) simulated the melting of the Greenland Ice Sheet for a local temperature rise of 3°C and 5.5°C. These scenarios led to a contribution to sea level rise of 1m and 3m over 1000 years (1mm/yr and 3mm/yr), respectively. Possible contributions from the West Antarctic Ice Sheet (WAIS) remain highly uncertain. In an expert survey reported by Vaughan and Spouge (2002), most glaciologists agree that collapse might be possible on a thousand-year timescale (5mm/yr), but that this contribution is unlikely to be seen in this century. Few scientists considered that collapse might occur on a century timescale.

1.6 Conclusions

Climate change is a serious and urgent issue. While climate change and climate modelling are subject to inherent uncertainties, it is clear that human activities have a powerful role in influencing the climate and the risks and scale of impacts in the future. All the science implies a strong likelihood that, if emissions continue unabated, the world will experience a radical transformation of its climate. Part II goes on to discuss the profound implications that this will have for our way of life.

The science provides clear guidance for the analysis of the economics and policy. The following chapter examines the implications of the science for the structuring of the economics.

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