Part I
Climate Change – our approach

Part I of the Review considers the nature of the scientific evidence for climate change, and the nature of the economic analysis required by the structure of the problem which follows from the science.

The first half of the Review examines the evidence on the economic impacts of climate change itself, and explores the economics of stabilising greenhouse gas concentrations in the atmosphere. The second half of the Review considers the complex policy challenges involved in managing the transition to a low-carbon economy and in ensuring that societies can adapt to the consequences of climate change that can no longer be avoided.

The Review takes an international perspective. Climate change is global in its causes and consequences, and the response requires international collective action. Working together is essential to respond to the scale of the challenge. An effective, efficient and equitable collective response to climate change will require deeper international co-operation in areas including the creation of price signals and markets for carbon, scientific research, infrastructure investment, and economic development.

Climate change presents a unique challenge for economics: it is the greatest example of market failure we have ever seen. The economic analysis must be global, deal with long time horizons, have the economics of risk and uncertainty at its core, and examine the possibility of major, non-marginal change. Analysing climate change requires ideas and techniques from most of the important areas of economics, including many recent advances.

Part I is structured as follows:

- **Chapter 1** examines the latest scientific evidence on climate change. The basic physics and chemistry of the scientific understanding begins in the 19th century when Fourier, Tyndall and Arrhenius laid the foundations. But we must also draw on the very latest science which allows a much more explicit analysis of risk than was possible five years ago.

- **Chapter 2** considers how economic theory can help us analyse the relationship between climate change and the divergent paths for growth and development that will result from 'business as usual' approaches and from strong action to reduce emissions. We look at the range of theories required and explain some of the technical foundations necessary for the economics that the scientific analysis dictates.

- **The technical annex to Chapter 2** addresses the complex issues involved in the comparison of alternative paths and their implications for individuals in different places and generations. Building on Chapter 2, we explore the ethical issues concerning the aggregation of the welfare of individuals across time, place and uncertain outcomes. This annex also provides a technical explanation of the approach to discounting used throughout the Review, and in particular in our own analysis of the costs of climate-change impacts.

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.

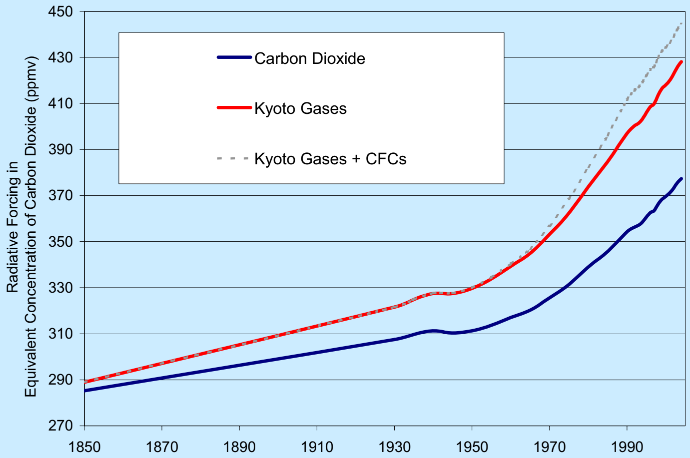
Human activities are changing the composition of the atmosphere and its properties. Since pre-industrial times (around 1750), carbon dioxide concentrations have increased by just over one third from 280 parts per million (ppm) to 380 ppm today (Figure 1.1), predominantly as a result of burning fossil 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]

[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.

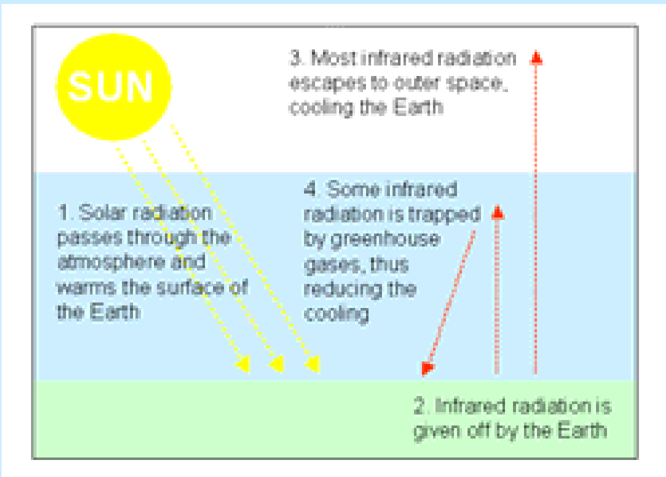
Figure 1.1 Rising levels of greenhouse gases

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)

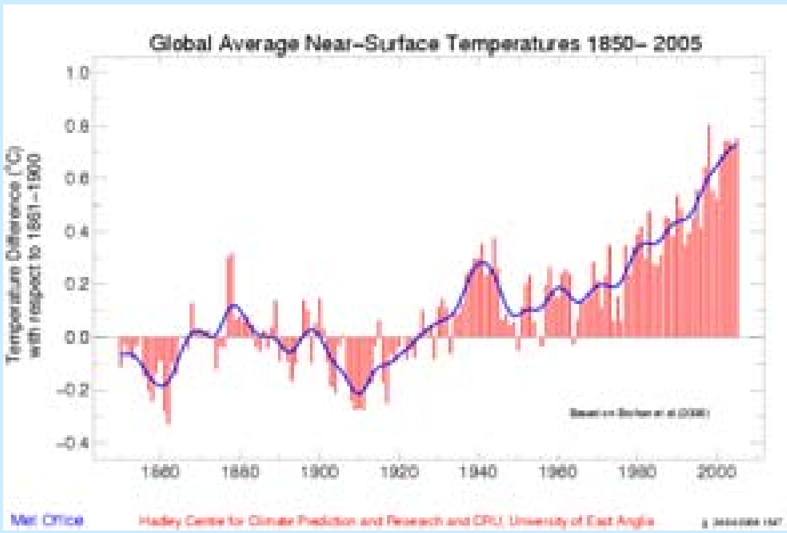
[6] Kyoto greenhouse gases are the six main greenhouse gases covered by the targets set out in the Kyoto Protocol.
[7] Based on the error on the radiative forcing (in CO_2 equivalent) of all long-lived greenhouse gases from Figure 6.6, IPCC (2001b)

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

[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.

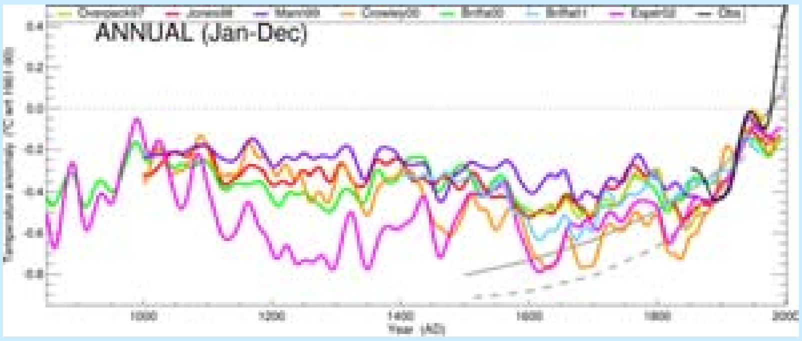
Box 1.1 The "Hockey Stick" Debate.

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

[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]

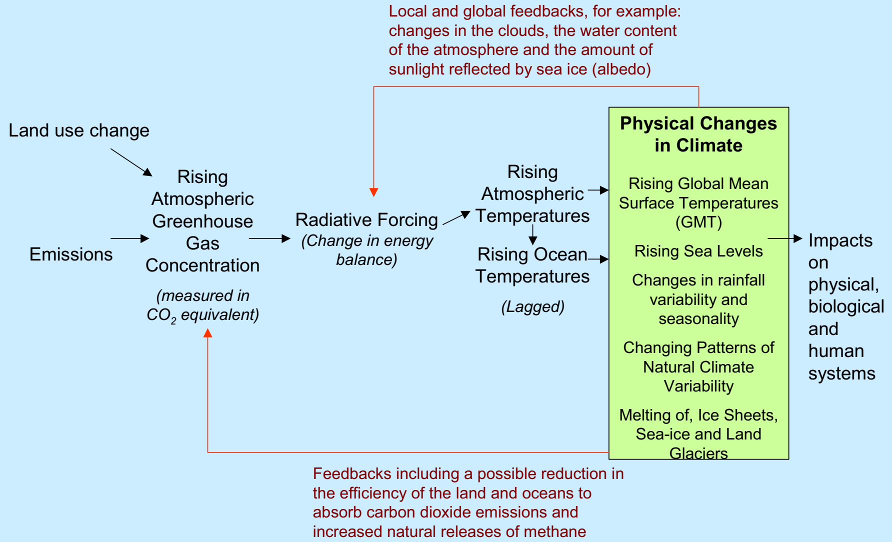
Using climate models that follow basic physical laws, scientists can now assess the likely range of warming for a given level of greenhouse gases in the atmosphere.

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

[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

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

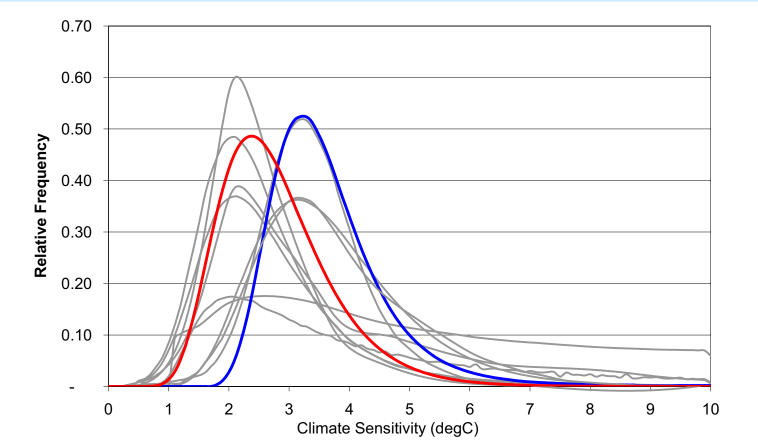
higher climate sensitivities cannot be excluded; and secondly, it allows a more explicit treatment of risk. For example, eleven recent studies suggest only between a 0% and 2% chance that the climate sensitivity is less than 1°C, but between a 2% and 20% chance that climate sensitivity is greater than 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.

[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

[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

[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.

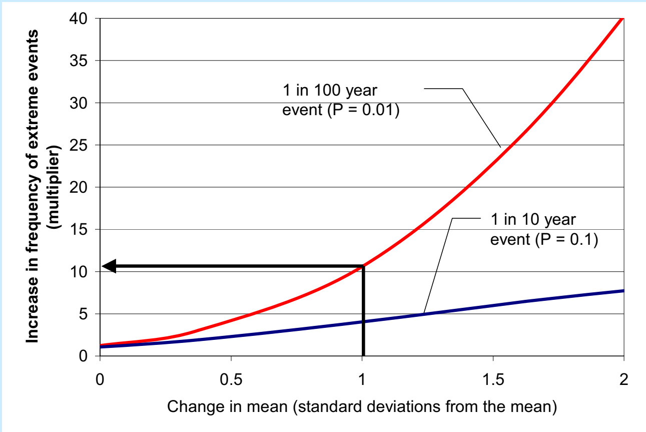
Changes in rainfall patterns and extreme weather events will lead to more severe impacts on people than that caused by warming alone.

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).

[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

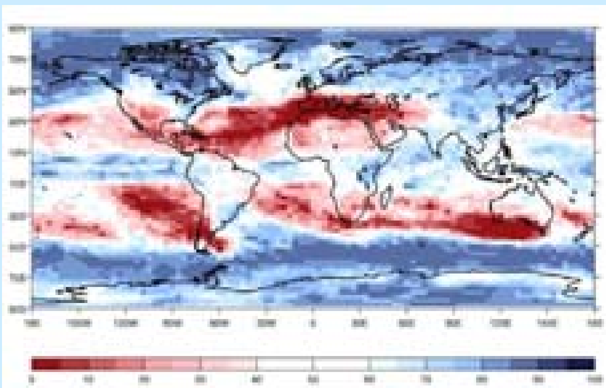
There will be more extreme heat days (relative to today) and fewer very cold days, as the distribution of temperatures shifts upwards. The figure below illustrates the change in frequency of a one-in-ten (blue) and one-in-one-hundred (red) year event. The black arrow shows that if the mean temperature 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*

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]

[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.

References

The Third Assessment Report of the IPCC gives the most comprehensive assessment of the science of climate change up to 2001 (IPCC 2001a,b). The summary for policymakers gives a good introduction to the more in-depth analyses of the three working groups. Maslin (2004) provides a more narrative description of climate change, including an overview of the history. Schellnhuber (2006) gives a good summary of the evolution of the science from early 2001 to 2005, including articles describing temperature projections based on new estimates of climate sensitivity (e.g. Meinshausen (2006)), positive feedbacks in the carbon cycle (e.g. Cox *et al.* (2006)) and several articles on the impacts of climate change.

Annan, J.D. and J.C. Hargreaves (2006): 'Using multiple observationally-based constraints to estimate climate sensitivity', Geophysical Research Letters **33**: L06704

Archer, D. (2005): 'Methane hydrates and anthropogenic climate change', Reviews of Geophysics, submitted, available from http://geosci.uchicago.edu/~archer/reprints/archer.ms.clathrates.pdf

Barnett T.P., D.W. Pierce, K.M. AchutaRao et al. (2005): 'Penetration of human-induced warming into the world's oceans', Science **309:** 284 – 287

Bengtsson, L., K. Hodges and E. Roeckner (2006): 'Storm tracks and climate change', Journal of Climate, in press.

Brohan. P., J.J. Kennedy, I. Harris, et al. (2006): 'Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850'. Journal of Geophysical Research, **111**, D12106, doi: 10.1029/2005JD006548

Burke, E.J., S.J. Brown and N. Christidis (2006): 'Modelling the Recent Evolution of Global Drought and Projections for the Twenty-First Century with the Hadley Centre Climate Model', Journal of Hydrometeorology, **7**(5):1113–1125

Bryden, H.L., H.R. Longworth and S.A. Cunningham (2005): 'Slowing of the Atlantic meridional overturning circulation at 25°N', Nature **438**: 655-657

Church, J.A., and N.J. White (2006): 'A 20th century acceleration in global sea-level rise', Geophysical Research Letters, **33**, L01602, doi: 10.1029/2005GL024826.

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

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

Cox P.M., C. Huntingford and C.D. Jones (2006): 'Conditions for Sink-to-Source Transitions and Runaway Feedbacks from the Land Carbon Cycle', in Avoiding dangerous climate change, H.J. Schellnhuber et al. (eds.), Cambridge: Cambridge University Press, pp.155 – 163.

Davidson and Janssens (2006): 'Temperature sensitivity of soil carbon decomposition and feedbacks to climate change', Nature **440**: 165-173

DEFRA (2005): 'Climate change and the greenhouse effect: a briefing from the Hadley Centre', available from http://www.metoffice.com/research/hadleycentre/pubs/brochures/2005/climate_greenhouse.pdf

Emanuel, K. (2005): 'Increased destructiveness of tropical cyclones over the past 30 years', Nature **436**: 686-688

Forest, C.E., P.H. Stone and A.P. Sokolov (2006): 'Estimates PDFs of climate system properties including natural and anthropogenic forcings', Geophysical Research Letters **33**: L01705, doi: 10.1029/2005GL023977

Friedlingstein, P., P. Cox, R. Betts et al. (2006): 'Climate-carbon cycle feedback analysis: results from C4MIP model intercomparison', Journal of Climate, **19**: 3337-3353

Fyfe, J.C. (2003): 'Extratropical southern hemisphere cyclones: Harbingers of climate change?' Journal of Climate **16**, 2802-2805

Gedney, N., P.M. Cox and C. Huntingford (2004): 'Climate feedback from wetland methane emissions', Geophysical Research Letters **31** (20): L20503

Geng, Q.Z. and M. Sugi (2003): 'Possible changes in extratropical cyclone activity due to enhanced greenhouse gases and aerosols – Study with a high resolution AGCM'. Journal of Climate **16**: 2262-2274.

Gorham, E. (1991): 'Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming', Ecological Applications **1**: 182-195, doi: 10.2307/1941811

Gregory, J. and P. Huybrechts (2006): 'Ice sheet contributions to future sea level change', Phil Trans Royal Soc A **364**: 1709 – 1731, doi: 10.1098/rsta.2006.1796

Hadley Centre (2005): 'Stabilising climate to avoid dangerous climate change – a summary of relevant research at the Hadley Centre', available from
http://www.metoffice.com/research/hadleycentre/pubs/brochures

Hanna, E., P. Huybrechts, and I. Janssens, et al. (2005): 'Runoff and mass balance of the Greenland ice sheet: 1958-2003'. Journal of Geophysical Research **110,** D13108, doi: 10.1029/2004JD005641

Hansen, J., M. Sato, R. Ruedy, et al. (2006): 'Global temperature change, Proceedings of the National Academy', **103**: 14288-14293

Hope, P.K. (2006): 'Projected future changes in synoptic systems influencing southwest Western Australia. Climate Dynamics' **26**: 765-780, doi: 10.1007/s00382-006-0116-x

Huntington, T.G. (2006): 'Evidence for intensification of the global water cycle: review and synthesis', Journal of Hydrology **319**: 1 – 13

Huybrechts, P. and J. de Wolde (1999): 'The dynamic response of the Greenland Ice Sheet and Antarctic ice sheets to a multiple century climatic-warming', Journal of Climate **12**: 2169-2188

International ad hoc detection group (2005): 'Detecting and attributing external influences on the climate system: a review of recent advances', Journal of Climate **18**: 1291-1314

Intergovernmental Panel on Climate Change (2001a): 'Climate change 2001: summary for policymakers, A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change' [Watson RT, and the Core Writing Team (eds.)], Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (2001b): 'Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change' [Houghton JT, Ding Y, Griggs DJ, et al. (eds.)], Cambridge: Cambridge University Press.

Johannessen, O.M., K. Khvorostovsky, M.W. Miles et al. (2005): 'Recent ice-sheet growth in the interior of Greenland'. Science **310**: 1013-1016

Knutti, R., T.F. Stocker, F. Joos and G-K Plattner (2002): 'Constraints on radiative forcing and future climate change from observations and climate model ensembles', Nature **416**: 719 – 723

Lawrence D.M. and A.G. Slater (2005): 'A projection of severe near-surface permafrost degradation during the 21st century', Geophysical Research Letters **32**: L24401

Lambert S.J. and J.C. Fyfe (2006): 'Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: results from models participating in the IPCC diagnostic exercise', Climate Dynamics **1432**, 0894

Landsea, C. (2005): 'Atlantic hurricanes and global warming', Nature **438**, E11-E12

Levitus, S.J., J. Antonov and T. Boyer (2005): 'Warming of the world ocean 1955 – 2003', Geophysical Research Letters **32**: L02604, doi:10.1029/2004GL021592

Lindzen, R.S., M-D Chou and A.Y. Hou (2001): 'Does the earth have an adaptive infrared iris?' Bulletin of the American Meteorological Society **82**: 417-432

Mann, M.E., R.S. Bradley and M.K. Hughes (1999): 'Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations', Geophysical Research Letters, 26, 759-762.

Maslin, M. (2004): 'Global warming: a very short introduction', New York: Oxford University Press,
Meehl, G.A., W.M. Washington, W.D. Collins et al. (2005): 'How much more global warming and sea level rise?' Science **307**:1769 – 1772

Meinshausen, M. (2006): 'What does a 2°C target mean for greenhouse gas concentrations? A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates', Avoiding dangerous climate change, in H.J. Schellnhuber et al. (eds.), Cambridge: Cambridge University Press, pp.265 – 280.

Murphy, J.M., D.M.H. Sexton D.N. Barnett et al. (2004): 'Quantification of modelling uncertainties in a large ensemble of climate change simulations', Nature **430**: 768 – 772

National Research Council (2006): 'Surface temperature reconstructions for the past 2,000 years', available from http://www.nap.edu/catalog/11676.html

North Greenland Ice Core Project (2004): 'High-resolution record of Northern Hemisphere climate extending into the last interglacial maximum', Nature **431**: 147-151

Orr, J.C., V.J. Fabry, O. Aumont et al. (2005): 'Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms', Nature **437**: 681-686

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

Pearce, F. (2003): 'Land of the midnight sums', New Scientist **177**: 2379

Pierrehumbert, R.T. (2004): 'Warming the world', Nature **432**: 677, doi: 10.1038/432677a

Pielke, R. (2005): 'Meteorology: Are there trends in hurricane destruction?' Nature **438**: E11

Rapley, C. (2006): 'The Antarctic ice sheet and sea level rise', in Avoiding dangerous climate change, Schellnhuber HJ (ed.), Cambridge: Cambridge University Press, pp. 25 – 28.

Rignot, E. and P. Kanagaratnam (2006): 'Changes in the velocity structure of the Greenland ice sheet. Science' **311**: 986-990

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

Schär, C., P.L. Vidale, D. Lüthi, et al. (2004): 'The role of increasing temperature variability in European summer heatwaves', Nature **427**: 332-336, doi: 10.1038/nature02300

Scheffer, M., V. Brovkin and P. Cox (2006): 'Positive feedback between global warming and the atmospheric CO2 concentration inferred from past climate change'. Geophysical Research Letters 33, L10702

Schellnhuber, H.J., W. Cramer, N. Nakicenovic et al. (eds.) (2006): 'Avoiding dangerous climate change', Cambridge: Cambridge University Press.

Schlesinger, M.E., J. Yin, G. Yohe, et al. (2006): 'Assessing the risk of a collapse of the Atlantic Thermohaline Circulation', in Avoiding dangerous climate change, H.J. Schellnhuber et al. (eds.) Cambridge: Cambridge University Press, pp. 37 – 47.

Scholze, M., K. Wolfgang, N. Arnell and C. Prentice (2006): 'A climate-change risk analysis for world ecosystems', Proceedings of the National Academy of Sciences **103**: 13116 – 13120

Siegenthaler U, Stocker TF, Monnin E, et al. (2005) Stable carbon cycle-climate relationship during the late Pleistocene, Science **310**: 1313 – 1317

Shepherd, A., D. Wingham, T. Payne and P. Skvarca (2003): 'Larsen Ice Shelf has progressively thinned', Science **302**: pp 856-859, doi: 10.1126/science.1089768

Smith, L.C., Y. Sheng, G.M. MacDonald, et al. (2005): 'Disappearing artic lakes'. Science, **308**: 1429

Soden, B.J., D.L. Jackson, V. Ramaswamy, et al. (2005): 'The radiative signature of upper tropospheric moistening', Science, **310**: 841-844

Stainforth, D., T. Aina, C. Christensen, et al. (2005): 'Uncertainty in predictions of the climate response to rising levels of greenhouse gases', Nature **433**: 403-406

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

Torn, M.SS and J. Harte (2006): 'Missing feedbacks, asymmetric uncertainties, and underestimation of future warming', Geophysical Research Letters **33**: L10703

US Climate Change Programme (2006): 'Temperature trends in the lower atmosphere: steps for understanding and reconciling differences', available from http://www.climatescience.gov/Library/sap/sap1-1/finalreport

Vaughan, D.G. and J.R. Spouge (2002): 'Risk estimation of collapse of the West Antarctic ice sheet', Climatic Change **52**: 65-91

von Storch, H., E. Zorita, J.M. Jones, et al. (2004): Reconstructing past climate from noisy data, Science **306**: 679-682

Walter, K.M., S.A. Zimov, J.P. Chanton, et al. (2006): 'Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming', Nature **443**: 71-75

Webster, P.J., G.J. Holland, J.A. Curry and H-R Chang (2005): 'Changes in tropical cyclone number, duration, and intensity in a warming environment', Science **309**,1844-1846

Wetherald, R.T. and S. Manabe (2002): 'Simulation of hydrologic changes associated with global warming', Journal of Geophysical Research **107**: 4379

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

Wigley, T.M.L. and S.C.B. Raper (2001): 'Interpretation of high projections for global-mean warming', Science **293**: 451-454

Wigley, T.M.L. (2005): 'The climate change commitment', Science **307**: 1766 – 1769

Wood, R., M. Collins, J. Gregory, et al. (2006): 'Towards a risk assessment for shutdown of the Atlantic Thermohaline Circulation', in Avoiding dangerous climate change, H.J Schellnhuber et al. (eds.), Cambridge: Cambridge University Press, pp. 49 – 54.

Zwally, H.J., M.B. Giovinetto, J. Li, et al. (2006): 'Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002', Journal of Glaciology **51**: 509–527

2 Economics, Ethics and Climate Change

Key Messages

Climate change is a result of the externality associated with greenhouse-gas emissions – it entails costs that are not paid for by those who create the emissions.

It has a number of features that together distinguish it from other externalities:

- It is **global** in its causes and consequences;
- The impacts of climate change are **long-term and persistent;**
- **Uncertainties and risks** in the economic impacts are pervasive.
- There is a serious risk of major, irreversible change with **non-marginal economic effects**.

These features shape the economic analysis: it must be **global**, deal with **long** time horizons, have the economics of **risk and uncertainty** at its core, and examine the possibility of major, **non-marginal** changes.

The **impacts of climate change are very broad ranging and interact with other market failures and economic dynamics, giving rise to many complex policy problems**. Ideas and techniques from most of the important areas of economics have to be deployed to analyse them, including many recent advances.

The breadth, magnitude and nature of impacts imply that several ethical perspectives, such as those focusing on welfare, equity and justice, freedoms and rights, are relevant. Most of these perspectives imply that the outcomes of climate-change policy are to be understood in terms of impacts on consumption, health, education and the environment over time but different ethical perspectives may point to different policy recommendations.

Questions of intra- and inter-generational equity are central. Climate change will have serious impacts within the lifetime of most of those alive today. Future generations will be even more strongly affected, yet they lack representation in present-day decisions.

Standard externality and cost-benefit approaches have their usefulness for analysing climate change, but, as they are methods focused on evaluating marginal changes, and generally abstract from dynamics and risk, they can only be starting points for further work.

Standard treatments of discounting are valuable for analysing marginal projects but are inappropriate for non-marginal comparisons of paths; the approach to discounting must meet the challenge of assessing and comparing paths that have very different trajectories and involve very long-term and large inter-generational impacts. We must go back to the first principles from which the standard marginal results are derived.

The severity of the likely consequences and the application of the above analytical approaches form the basis of powerful arguments, developed in the Review, in favour of strong and urgent global action to reduce greenhouse-gas emissions, and of major action to adapt to the consequences that now cannot be avoided.

2.1 Introduction

The science described in the previous chapter drives the economics that is required for the analysis of policy. This chapter introduces the conceptual frameworks that we will use to examine the economics of climate change. It explores, in Section 2.2, the distinctive features of the externalities associated with greenhouse-gas emissions and draws attention to some of the difficulties associated with a simplistic application of the standard theory of externalities to this problem. Section 2.3 introduces a variety of ethical approaches and relates them to the global and long-term nature of the impacts (the discussion is extended in the appendix to the chapter). Section 2.4 examines some specifics of intertemporal allocation, including discounting (some further technical details are provided in the appendix to the chapter). Sections 2.5 and 2.6 consider how economic analysis can get to grips with a problem that is uncertain and involves a serious risk of large losses of wellbeing, due to deaths, extinctions of species and heavy economic costs, rather than the marginal changes more commonly considered in economics. For most of economic policy, the underlying ethical assumptions are of great importance, and this applies particularly for climate change: that is why they are given special attention in this chapter.

The economics introduced in this chapter applies, in principle, to the whole Review but the analysis of Sections 2.2 to 2.6 is of special relevance to Parts II and III, which look at impacts and at the economics of mitigation – assessing how much action is necessary to reduce greenhouse-gas emissions. Parts IV, V, VI of this report are devoted to the analysis of policy to promote mitigation and adaptation. The detailed, and often difficult, economics of public policy and collective action that are involved in these analyses are introduced in the sections themselves and we provided only brief coverage in Sections 2.7 and 2.8. In the former section, we refer briefly to the modern public economics of carbon taxation, trading and regulation and of the promotion of research, development and deployment, including the problems of various forms of market imperfection affecting innovation. It also covers an analysis of the role of 'responsible behaviour' and how public understanding of this notion might be influenced by public policy. Section 2.8 explores some of the difficulties of building and sustaining global collective action in response to the global challenge of climate change.

In these ways, this chapter lays the analytical foundations for much of the economics required by the challenge of climate change and which is put to work in the course of the analysis presented in this Review.

The subject demands analysis across an enormous range of issues and requires all the tools of economics we can muster – and indeed some we wish we had. In setting out some of these tools, some of the economic analysis of this chapter is inevitably technical, even though the more mathematical material has been banished to an appendix. Some readers less interested in the technical underpinnings of the analysis may wish to skim the more formal analytical material. Nevertheless, it is important to set out some of the analytical instruments at the beginning of the Review, since they underpin the analysis of risk, equity and allocation over time that must lie at the heart of a serious analysis of the economics of climate change.

2.2 Understanding the market failures that lead to climate change

Climate change results from greenhouse-gas emissions associated with economic activities including energy, industry, transport and land use.

In common with many other environmental problems, human-induced climate change is at its most basic level an externality. Those who produce greenhouse-gas emissions are bringing about climate change, thereby imposing costs on the world and on future generations, but they do not face directly, neither via markets nor in other ways, the full consequences of the costs of their actions.

Much economic activity involves the emission of greenhouse gases (GHGs). As GHGs accumulate in the atmosphere, temperatures increase, and the climatic changes that result impose costs (and some benefits) on society. However, the full costs of GHG emissions, in terms of climate change, are not immediately – indeed they are unlikely ever to be – borne by the emitter, so they face little or no economic incentive to reduce emissions. Similarly, emitters do not have to compensate those who lose out because of climate change.[1] In this sense, human-induced climate change is an externality, one that is not 'corrected' through any institution or market,[2] unless policy intervenes.

[1] Symmetrically, those who benefit from climate change do not have to *reward* emitters.
[2] Pigou (1912).

The climate is a public good: those who fail to pay for it cannot be excluded from enjoying its benefits and one person's enjoyment of the climate does not diminish the capacity of others to enjoy it too.[3] Markets do not automatically provide the right type and quantity of public goods, because in the absence of public policy there are limited or no returns to private investors for doing so: in this case, markets for relevant goods and services (energy, land use, innovation, etc) do not reflect the consequences of different consumption and investment choices for the climate. Thus, climate change is an example of market failure involving externalities and public goods.[4] Given the magnitude and nature of the effects initially described in the previous chapter and taken forward in Parts II and III, it has profound implications for economic growth and development. All in all, it must be regarded as market failure on the greatest scale the world has seen.

The basic theory of externalities and public goods is the starting point for most economic analyses of climate change and this Review is no exception. The starting point embodies the basic insights of Pigou, Meade, Samuelson and Coase (see Part IV). But the special features of this particular externality demand, as we shall see, that the economic analysis go much further.

The science of climate change means that this is a very different form of externality from the types commonly analysed.

Climate change has special features that, together, pose particular challenges for the standard economic theory of externalities. There are four distinct issues that will be considered in turn in the sections below.

- Climate change is an externality that is global in both its causes and consequences. The incremental impact of a tonne of GHG on climate change is independent of where in the world it is emitted (unlike other negative impacts such as air pollution and its cost to public health), because GHGs diffuse in the atmosphere and because local climatic changes depend on the global climate system. While different countries produce different volumes the marginal damage of an extra unit is independent of whether it comes from the UK or Australia.
- The impacts of climate change are persistent and develop over time. Once in the atmosphere, some GHGs stay there for hundreds of years. Furthermore, the climate system is slow to respond to increases in atmospheric GHG concentrations and there are yet more lags in the environmental, economic and social response to climate change. The effects of GHGs are being experienced now and will continue to work their way through in the very long term.
- The uncertainties are considerable, both about the potential size, type and timing of impacts and about the costs of combating climate change; hence the framework used must be able to handle risk and uncertainty.
- The impacts are likely to have a significant effect on the global economy if action is not taken to prevent climate change, so the analysis has to consider potentially non-marginal changes to societies, not merely small changes amenable to ordinary project appraisal.

These features shape much of the detailed economic analysis throughout this Review. We illustrate with just one example, an important one, which shows how the dynamic nature of the accumulation of GHGs over time affects one of the standard analytical workhorses of the economics of externalities and the environment. It is common to present policy towards climate change in terms of the social cost of carbon on the margin (SCC) and the marginal abatement (MAC). The former is the total damage from now into the indefinite future of emitting an extra unit of GHGs now – the science says that GHGs (particularly CO_2) stay in the atmosphere for a very long time. Thus, in its simplest form, the nature of the problem is that the stock of gases in the atmosphere increases with the net flow of GHGs emissions in this period, and thus decreases with abatement. Therefore, on the one hand, the SCC curve

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[3] Samuelson (1954).

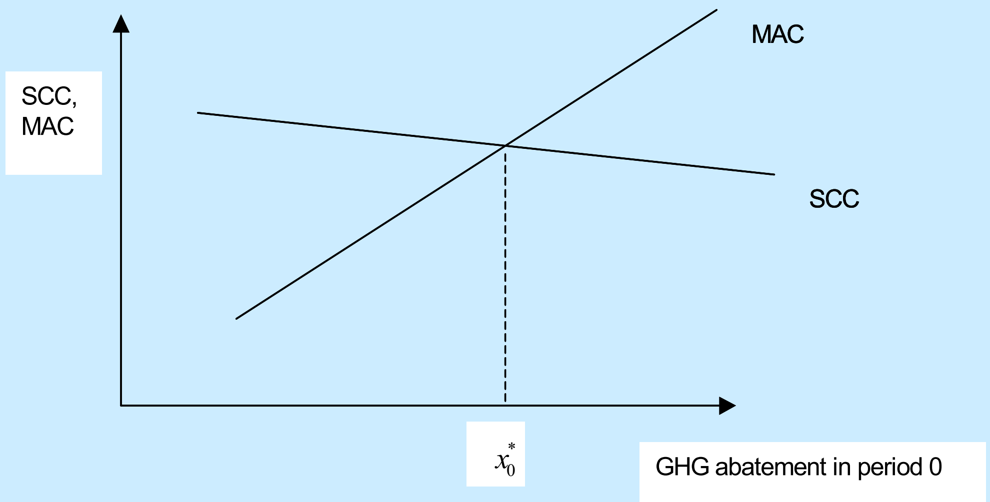
[4] Formally, in economic theory, public goods are a special case of externalities where the effects of the latter are independent of the identity of the emitters or origin of the externalities.

slopes downwards with increasing abatement in any given period, assuming that the lower the stock at any point in the future, the less the marginal damage. On the other hand, the MAC curve slopes upwards with increasing abatement, if it is more costly on the margin to do more abatement as abatement increases in the given period. The optimum level of abatement must satisfy the condition that MAC equals SCC. If, for example, SCC were bigger than MAC, the social gain from one extra unit of abatement would be less than the cost and it would be better to do a little more. We call the optimum level this period x_0^*.

It should be clear that the SCC curve this period depends on future emissions: if we revised upwards our specified assumptions on future emissions, the whole SCC curve would shift upwards, and so would the optimum abatement level in this period, x_0^*. Thus, if we are thinking about an optimum path over time, rather than simply an optimum emission for this period, we must recognise that the SCC curve for any given period depends on the future stock and thus on the future path of emissions. **We cannot sensibly calculate an SCC without assuming that future emissions and stocks follow some specified path. For different specified paths, the SCC will be different.** For example, it will be much higher on a 'business as usual' path (BAU) than it will be on a path that cuts emissions strongly and eventually stabilises concentrations. It is remarkable how often SCC calculations are vague on this crucial point (see Chapter 13 for a further discussion).

Thus we must be very careful how we use a diagram that is pervasive in the economics of climate change – see Figure 2.1.

Figure 2.1 The optimum degree of abatement in a given period

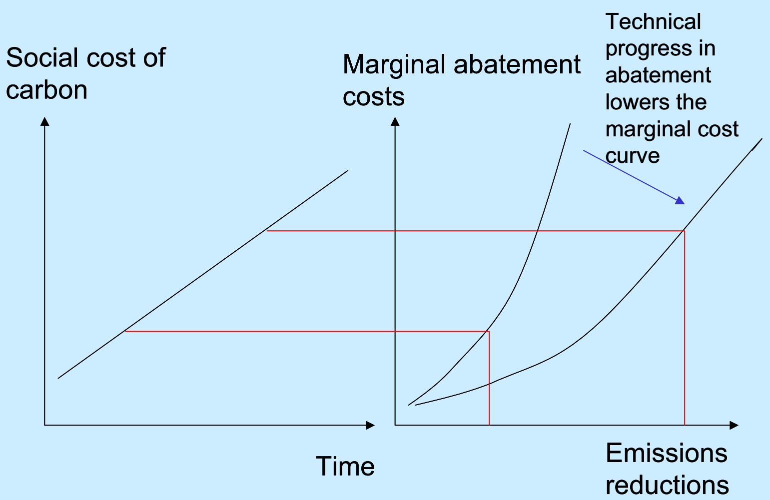


In the figure, the SCC and the MAC are drawn as functions of emissions in this period, call it period 0. As drawn, the SCC curve is fairly flat and downward sloping, since extra emissions this period do not affect the total stock very much, but nevertheless extra abatement now implies a slightly lower stock in the future. The MAC curve rises, since we assume that, as abatement increases in this period, the marginal cost goes up. The optimum path for abatement is where x_0^*, x_1^*, x_2^*, … x_t^* ,…. are all set optimally for each period 0,1,2, t,…. into the indefinite future, and the SCC curve is drawn for each period on the assumption that all future periods are set optimally.

A number of important points follow from this, in addition to the basic one that an SCC curve cannot be drawn, nor an SCC calculated, without specific assumptions on future paths. First, if the SCC rises over time along the specified path then, for optimality, so too must the MAC. It is very likely that the SCC *will* rise over time, since stocks of GHGs will rise as further emissions take place, up to the point where stabilisation is reached. Thus the MAC at the optimum rises and the intersection of the MAC and SCC curves will imply successively greater abatement. This is true even though the whole MAC curve is likely to be lower for any particular degree of abatement in the future because learning will have taken place.

Figure 2.2 is thus perhaps more helpful than Figure 2.1 in sketching the nature of the solution to the problem. The position of the schedule in the left-hand side panel depends on the stabilisation target chosen for the atmospheric concentration of greenhouse gases, which in turn depends upon how the expected present values (in terms of discounted utility) of costs and benefits of mitigation through time change as the stabilisation level changes. Hence the choice of stabilisation target implies a view about what is likely to happen to abatement costs over time. The right-hand panel shows the shifts in the MAC curve expected at the time the stabilisation target is chosen.

Figure 2.2 How the path for the social cost of carbon drives the extent of abatement



This illustrates how important it is that the dynamics of the problem are considered. The conclusion that the MAC rises along an optimum path does not automatically follow from an analysis that simply shifts the SCC curve upwards over time (with higher stocks) and shifts the MAC down over time (with learning), without linking to the full dynamic optimisation. That optimisation takes account of the known future fall in costs in determining the whole path for the SCC. We are simply assuming that this fall in costs could not be of a magnitude to make it optimum for stocks to fall, that is, for emissions to be less than the Earth system's equilibrium capacity to absorb greenhouse gases from the atmosphere.

This analysis raises the second point, about the role of uncertainty. In the above argument, there is no consideration of uncertainty. If that vital element is now introduced, the argument becomes more complex. It has to be asked whether the resolution of uncertainty in any period would lead to a revision of views about the future probability distributions for abatement costs and climate-change damages. If, for example, there is unexpected good news that abatement is likely to be much cheaper than previously thought, then a lower stabilisation target and more abatement over time than originally planned would become appropriate. This would reduce the SCC from where it would otherwise have been. However, one surprisingly good period for costs does not necessarily imply that future periods will be just as good. In Figure 2.2, persistently faster technical progress than expected (as opposed to random fluctuations of the MAC around its expected value) would lead to a downward revision of the stabilisation target and hence a downward shift in the schedule in the left-hand panel.

Dynamics and uncertainty are explored further in Chapters 13 and 14, while analyses involving risk are taken further in Sections 2.5 and 2.6 and in Chapter 6.

This important example shows how important it is to integrate the scientific features of the externality into the economics and shows further that there are difficult conceptual and technical questions to be tackled. The analysis must cover a very broad range, including the economics of: growth and development; industry; innovation and technological change; institutions; the international economy; demography and migration; public finance; information and uncertainty; and the economics of risk and equity; and environmental and public economics throughout.

2.3 Ethics, welfare and economic policy

The special features of the climate-change externality pose difficult questions for the standard welfare-economic approach to policy.

Chapter 1 shows that the effects of climate change are global, intertemporal and highly inequitable. The inequity of climate change is examined further in Part II.. Generally, poor countries, and poor people in any given country, suffer the most, notwithstanding that the rich countries are responsible for the bulk of past emissions. These features of climate change, together with the fact that they have an impact on many dimensions of human well-being, force us to look carefully at the underlying ethical judgements and presumptions which underpin, often implicitly, the standard framework of policy analysis. Indeed, it is important to consider a broader range of ethical arguments and frameworks than is standard in economics, both because there are many ways of looking at the ethics of policy towards climate change, and, also, because in so doing we can learn something about how to apply the more standard economic approach. There is a growing literature on the ethics of climate change: analysis of policy cannot avoid grappling directly with the difficult issues that arise. These ethical frameworks are discussed more formally in the technical appendix to this chapter; the discussion here is only summary [5].

The underlying ethics of basic welfare economics, which underpins much of the standard analysis of public policy, focuses on the consequences of policy for the consumption of goods and services by individuals in a community. These goods and services are generated by labour, past saving, knowledge and natural resources. The perspective sees individuals as having utility, or welfare, arising from this consumption.

In this approach, the objective is to work out the policies that would be set by a decision-maker acting on behalf of the community and whose role it is to improve, or maximise, overall social welfare. This social welfare depends on the welfare of each individual in the community. When goods and services are defined in a broad way, they can include, for example, education, health and goods appearing at different dates and in different circumstances. Thus the theory covers time and uncertainty. And, to the extent that individuals value the environment, that too is part of the analysis. Many goods or services, including education, health and the environment, perform a dual role: individuals directly value them and they are inputs into the use or acquisition of other consumption goods. In the jargon, they are both goals and instruments.

The standard economic theory then focuses on flows of goods or services over time and their distribution across individuals. The list of goods or services should include consumption (usually monetary or the equivalent), education, health and the environment. These are usually the areas focused upon in cross-country comparisons of living standards, such as, for example, in the *World Development Indicators* of the World Bank, the *Human Development Report* of the UNDP, and the *Millennium Development Goals* (MDGs) agreed at the UN at the turn of the millennium. 'Stocks' of wealth, infrastructure, the natural environment and so on enter into the analysis in terms of their influence on flows. Through these choices of data for central attention and through the choice of goals, the international community has identified a strong and shared view on the key dimensions of human well-being.

Those choices of data and goals can be derived from a number of different ethical perspectives (see, for example, Sen (1999)). Most ethical frameworks generally used in the analyses of economic policy have some relevance for the economics of climate change and

[5] Particularly important contributions on ethics are those of Beckerman and Pasek (2001), Broome (1992, 1994, 2004, 2005), Gardiner (2004) and Müller (2006). We are very grateful to John Broome for his advice and guidance, but he is not responsible for the views expressed here.

there are some – for example, those involving stewardship and sustainability – that are particularly focused on environmental issues.

The ethical framework of standard welfare economics looks first only at the consequences of actions (an approach often described as 'consequentialism') and then assesses consequences in terms of impacts on 'utility' (an approach often described as 'welfarism', as in Sen (1999), Chapter 3 and the appendix to this chapter). This standard welfare-economic approach has no room, for example, for ethical dimensions concerning the processes by which outcomes are reached. Some different notions of ethics, including those based on concepts of rights, justice and freedoms, do consider process. Others, such as sustainability, and stewardship, emphasise particular aspects of the consequences of decisions for others and for the future, as explained in the technical appendix.

Nevertheless, the consequences on which most of these notions would focus for each generation often have strong similarities: above all, with respect to the attention they pay to consumption, education, health and the environment.

And all the perspectives would take into account the distribution of outcomes within and across generations, together with the risks involved in different actions, now and over time. Hence the Review focuses on the implications of action or inaction on climate change for these four dimensions.

How the implications for these four dimensions are assessed, will, of course, vary according to the ethical position adopted. How policy-makers aggregate over consequences (i) within generations, (ii) over time, and (iii) according to risk will be crucial to policy design and choice. Aggregation requires being quantitative in comparing consequences of different kinds and for different people. The Review pays special attention to all three forms of aggregation. In arriving at decisions, or a view, it is not, however, always necessary to derive a single number that gives full quantitative content and appropriate weight to all the dimensions and elements involved (see below).

Climate change is an externality that is global in both its causes and consequences. Both involve deep inequalities that are relevant for policy.

The incremental impact of a tonne of GHG is independent of where in the world it is emitted. But the volume of GHGs emitted globally is not uniform. Historically, rich countries have produced the majority of GHG emissions. Though all countries are affected by climate change, they are affected in different ways and to different extents. Developing countries will be particularly badly hit, for three reasons: their geography; their stronger dependence on agriculture; and because with their fewer resources comes greater vulnerability. There is therefore a double inequity in climate change: the rich countries have special responsibility for where the world is now, and thus for the consequences which flow from this difficult starting point, whereas poor countries will be particularly badly hit.

The standard welfare-economics framework has a single criterion, and implicitly, a single governmental decision-maker. It can be useful in providing a benchmark for what a 'good' global policy would look like. But the global nature of climate change implies that the simple economic theory with one jurisdiction, one decision-maker, and one social welfare function cannot be taken literally. Instead, it is necessary to model how different players or countries will interact (see Section 2.8 below and Pt VI) and to ask ethical questions about how people in one country or region should react to the impacts of their actions on those in another. This raises questions of how the welfare of people with very different standards of living should be assessed and combined in forming judgements on policy.

There are particular challenges in valuing social welfare across countries at different stages of development and across different income or consumption levels.

The ethical question of how consequences for people in very different circumstances should be aggregated must be faced directly. For the sake of simplicity and clarity, we shall adopt the perspective of the 'social welfare function' approach, as explained in Box 2.1.

Box 2.1 The 'social welfare function' approach to 'adding up' the wellbeing of different people.

The stripped-down approach that we shall adopt when we attempt to assess the potential costs of climate change uses the standard framework of welfare economics. The objective of policy is taken to be the maximisation of the sum across individuals of social utilities of consumption. Thus, in this framework, aggregation of impacts across individuals using social value judgements is assumed to be possible. In particular, we consider consumption as involving a broad range of goods and services that includes education, health and the environment. The relationship between the measure of social wellbeing – the sum of social utilities in this argument – and the goods and services consumed by each household, on which it depends, is called the social welfare function.

In drawing up a social welfare function, we have to make explicit value judgements about the distribution of consumption across individuals – how much difference should it make, for example, if a given loss of consumption opportunities affects a rich person rather than a poor person, or someone today rather than in a hundred years' time?[6] Aggregating social utility across individuals to come up with a measure of social welfare has its problems. Different value judgements can lead to different rankings of possible outcomes, and deciding what values should be applied is difficult in democratic societies[7]. It is not always consistent with ethical perspectives based on rights and freedoms. But the approach has the virtue of clarity and simplicity, making it easy to test the sensitivity of the policy choice that emerges to the value judgements made. It is fairly standard in the economics of applied policy problems and allows for a consistent treatment of aggregation within and across generations and for uncertainty. The social welfare function's treatment of income differences can be calibrated by simple thought experiments. For example, suppose the decision-maker is considering two possible policy outcomes. In the second outcome, a poor person receives an income $X more than in the first, but a rich person receives $Y less; how much bigger than X would Y have to be for the decision-maker to decide that the second outcome is worse than the first?

Aggregation across education, health, income and environment raises profound difficulties, particularly when comparisons are made across individuals. Some common currency or 'numeraire' is necessary: the most common way of expressing an aggregate measure of wellbeing is in terms of real income. That immediately raises the challenge of expressing health (including mortality) and environmental quality in terms of income. There have been many attempts to do just that. These should not be lightly dismissed, since nations often decide how much to allocate to, for example, accident and emergency services or environmental protection in the knowledge that a little extra money saves lives and improves the environment. Indeed, individuals make similar choices in their own lives.

Nevertheless, there are significant difficulties inherent in the valuation of health and the environment, many of which are magnified across countries where major differences in income affect individuals' willingness and ability to pay for them. For example, a very poor person may not be 'willing-to-pay' very much money to insure her life, whereas a rich person may be prepared to pay a very large sum. Can it be right to conclude that a poor person's life

[6] Effectively, in putting it this way, we resist the interpretation that this is a strict utilitarian sum of 'actual utility'. On some of the difficulties and attractions of consequentialism, welfarism, utilitarianism and other approaches, see e.g. Sen and Williams (1982) and Sen (1999).

[7] The difficulties of this type of aggregation using democratic methods have been examined by Kenneth Arrow (1951, 1963) using his famous 'impossibility theorem'. It has been examined in a series of studies by Amartya Sen (see, for example, Sen (1970, 1986 and 1999)).

or health is therefore less valuable?[8] It is surely within the realms of sensible discourse to think of the consequences of different strategies simultaneously in terms of income, lives and the environment: that is the approach we adopt where possible. At some points (such as in Chapter 6), however, we present models from the literature that do embody estimates of the monetary equivalent of the impacts of climate change on broader dimensions of welfare (although generally in these contexts increments in income are valued differently at different levels in income – see Box 2.1). Such exercises should be viewed with some circumspection.

2.4 The long-run impacts of climate change: evaluation over time and discounting

The effects of GHGs emitted today will be felt for a very long time. That makes some form of evaluation or aggregation across generations unavoidable. The ethical decisions on, and approaches to, this issue have major consequences for the assessment of policy.

The approach we adopt here is similar to that for assessing impacts that fall on different people or nations, and in some respects continues the discussion of ethics in the preceding section. When we do this formally, we work in terms of sums of utilities of consumption. Again there is a problem of calibrating the social welfare function for this purpose but, as with aggregating across people with different incomes at a moment in time, one can use a series of 'thought experiments' to help (see Box 2.1).

Typically, in the application of the theory of welfare economics to project and policy appraisal, an increment in future consumption is held to be worth less than an increment in present consumption, for two reasons. First, if consumption grows, people are better off in the future than they are now and an extra unit of consumption is generally taken to be worth less, the richer people are. Second, it is sometimes suggested that people prefer to have good things earlier rather than later – 'pure time preference' – based presumably in some part on an assessment of the chances of being alive to enjoy consumption later and in some part 'impatience'.

Yet assessing impacts over a very long time period emphasises the problem that future generations are not fully represented in current discussion. Thus we have to ask how they should be represented in the views and decisions of current generations. This throws the second rationale for 'discounting' future consumption mentioned above – pure time preference – into question. We take a simple approach in this Review: if a future generation will be present, we suppose that it has the same claim on our ethical attention as the current one.

Thus, while we do allow, for example, for the possibility that, say, a meteorite might obliterate the world, and for the possibility that future generations might be richer (or poorer), we treat the *welfare* of future generations on a par with our own. It is, of course, possible that people actually do place less value on the welfare of future generations, simply on the grounds that they are more distant in time. But it is hard to see any ethical justification for this. It raises logical difficulties, too. The discussion of the issue of pure time preference has a long and distinguished history in economics, particularly among those economists with a strong interest and involvement in philosophy[9]. It has produced some powerful assertions. Ramsey (1928, p.543) described pure time discounting as 'ethically indefensible and [arising] merely from the weakness of the imagination'. Pigou (1932, pp 24-25) referred to it as implying that 'our telescopic faculty is defective'. Harrod (1948, pp 37-40) described it as a 'human infirmity' and 'a polite expression for rapacity and the conquest of reason by passion'. Solow (1974, p.9) said 'we ought to act as if the social rate of time preference were zero (though we would simultaneously discount future *consumption* if we expected the future to be richer than the

[8] Notice however that if the valuation of life in money terms in country A is twice that of country B, where income in A is twice that in B, we may choose to value increases in income in A half as much as for B (see Box 2.1 and Chapter 6). In that case, extra mortality would be valued in the way for both countries.

[9] See Anand and Sen (2000) for a technical discussion of these issues, and further references and quotes beyond those here. And see Broome (1991) and (2004) for an extended discussion. We are grateful to Sudhir Anand and John Broome for discussions of these issues.

present)'. Anand and Sen (2000) take a similar view. The appendix to this chapter explores these issues in more technical detail, and includes references to one or two dissenting views.

However, we must emphasise that the approach we adopt, aggregating utility of consumption, does take directly into account the possibility that future generations may be richer or poorer, the first rationale for discounting above. Uncertainty about future prospects plays an important role in the analysis of the Review. How well off we may be when a cost or benefit arrives does matter to its evaluation, as does the probability of the occurrence of costs and benefits. Those issues, *per se*, are not reasons for discounting (other than the case of uncertainty about existence).

A formal discussion of discounting inevitably becomes mathematically technical, as one must be explicit about growth paths and intertemporal allocations. The simple techniques of comparing future incomes or consumption with those occurring now using discount rates (other than for 'pure time preference') is not valid for comparing across paths that are very different. Further, where comparisons are for marginal decisions and the use of discount rates is valid, then, for a number of reasons, particularly uncertainty, discount rates may fall over time. a formal discussion is provided in the appendix to this chapter: the results are summarised in Box 2.2.

Box 2.2 Discounting

Discounting, as generally used in economics, is a technique relevant for marginal perturbations around a given growth path. A discount rate that is common across projects can be used only for assessing projects that involve perturbations around a path and not for comparing across very different paths.

With marginal perturbations, the key concept is the discount factor: the value of an increment in consumption at a time in the future relative to now. The discount factor will generally depend on the consumption level in the future relative to that now, i.e. on growth, and on the social utility or welfare function used to evaluate consumption (see Box 2.1).

The discount rate is the rate of fall of the discount factor. There is no presumption that it is constant over time, as it depends on the way in which consumption grows over time.

- If consumption falls along a path, the discount rate can be negative.
- If inequality rises over time, this would work to reduce the discount rate, for the social welfare functions typically used.
- If uncertainty rises as outcomes further into the future are contemplated, this would work to reduce the discount rate, with the welfare functions typically used. Quantification of this effect requires specification of the form of uncertainty, and how it changes, and of the utility function.

With many goods and many households, there will be many discount rates. For example, if conventional consumption is growing but the environment is deteriorating, then the discount rate for consumption would be positive but for the environment it would be negative. Similarly, if the consumption of one group is rising but another is falling, the discount rate would be positive for the former but negative for the latter.

Taking the analysis of this section and that of the appendix to this chapter together with the discussion of ethics earlier in this chapter, it can be seen that the standard welfare framework is highly relevant as a theoretical basis for assessing strategies and projects in the context of climate change. However, the implications of that theory are very different from those of the techniques often used in cost-benefit analysis. For example, a single constant discount rate would generally be unacceptable for dealing with the long-run, global, non-marginal impacts of climate change.

For further discussion of discounting, and references to the relevant literature, see the technical annex to this chapter.

This approach to discounting and the ethics from which it is derived is of great importance for the analysis of climate change. That is why we have devoted space to it at the beginning of our Review**. If little or no value were placed on prospects for the long-run future, then climate change would be seen as much less of a problem. If, however, one thinks about the ethics in terms of most standard ethical frameworks, there is every reason to take these prospects very seriously.**

2.5 Risk and Uncertainty

The risks and uncertainties around the costs and benefits of climate policy are large; hence the analytical framework should be able to handle risk and uncertainty explicitly.

For the moment, we do not make a distinction between risk and uncertainty, but the distinction is important and we return to it below. Uncertainty affects every link in the chain from emissions of GHGs through to their impacts. There are uncertainties associated, for example, with future rates of economic growth, with the volume of emissions that will follow, with the increases in temperature resulting from emissions, with the impacts of these temperature increases and so on. Similarly, there are uncertainties associated with the economic response to policy measures, and hence about how much it will cost to reduce GHG emissions.

Our treatment of uncertainty follows a similar approach to that for evaluation or aggregation over space and time. Where we embody uncertainty formally in our models, we add utilities over possible states of the world that might result from climate change, weighting by the probability of those states. This yields what is known as 'expected' utility.

This is essentially the extension of the social utility approach to an uncertain or 'stochastic' environment. As in a certain or 'deterministic' environment, it has its ethical difficulties, but it has the virtues of transparency, clarity, and consistency. Again, it is fairly standard in applied economics.

The basis of such probabilities should be up-to-date knowledge from science and economics. This amounts to a 'subjective' probability approach.[10] It is a pragmatic response to the fact that many of the 'true' uncertainties around climate-change policy cannot themselves be observed and quantified precisely, as they can be in many engineering problems, for example.

The standard expected-utility framework involves aversion to risk and in this narrow sense a 'precautionary principle'**.**

This approach to uncertainty, combined with the assumption that the social marginal utility of income declines as income rises, implies that society will be willing to pay a premium (insurance) to avoid a simple actuarially fair gamble where potential losses and gains are large. As Parts II and III show, potential losses from climate change are large and the costs of avoidance (the insurance premium involved in mitigation), we argue, seem modest by comparison.

The analytical approach incorporates aspects of insurance, caution and precaution directly, and does not therefore require a separate 'precautionary principle' to be imposed as an extra ethical criterion.

More modern theories embodying a distinction between uncertainty and risk suggest an explicit 'precautionary principle' beyond that following from standard expected-utility theory.

The distinction between uncertainty and risk is an old one, going back at least to Knight (1921) and Keynes (1921). In their analysis, risk applied when one could make some

[10] Often called a 'Bayesian' approach, after Thomas Bayes, the 18th century mathematician. However, the application of Bayes' ideas to a subjective theory of probability was made in the 20th century. See Ramsey (1931).

assessment of probabilities and uncertainty when one does not have the ability to assess probabilities. In a fascinating paper, Claude Henry (2006) puts these ideas to work on problems in science and links them to modern theories of behaviour towards risk. He uses two important examples to illustrate the relevance of a precautionary principle in the presence of uncertainty. The first is the link between bovine spongiform encephalopathy (BSE) in cows and Creutzfeld-Jacob Disease (CJD) in humans and the second, the link between asbestos and lung disease.

For the first, UK scientists asserted for some time that there could be no link because of 'a barrier between species'. However in 1991 scientists in Bristol succeeded in inoculating a cat with BSE and the hypothesis of 'a barrier' was destroyed. Around the same time, a scientist, Stanley Prusiner, identified protein mutations that could form the basis of a link. These results did not establish probabilities but they destroyed 'certainty'. By introducing uncertainty, the finding opened up the possibility of applying a precautionary principle.

For the second, a possible link between asbestos and lung disease was suggested as early as 1898 by health inspectors in the UK, and in 1911 on a more scientific basis after experiments on rats. Again the work was not of a kind to establish probabilities but provided grounds for precaution. Unfortunately, industry lobbying prevented a ban on asbestos and the delay of fifty years led to considerable loss of life. Application of the precautionary principle could have saved lives.

Henry refers to recent work by Maccheroni et al (2005) and Klibanoff et al (2005) that formalises this type of argument,[11] giving, in effect, a formal description of the precautionary principle. In this formalisation, there are a number of possible probability distributions over outcomes that could follow from some action. But the decision-maker, who is trying to choose which action to take, does not know which of these distributions is more or less likely for any given action. It can be shown under formal but reasonable assumptions[12] that she would act as if she chooses the action that maximises a weighted average of the worst expected utility and the best expected utility, where best and worst are calculated by comparing expected utilities using the different probability distributions. The weight placed on the worst outcome would be influenced by concern of the individual about the magnitude of associated threats, or pessimism, and possibly any hunch about which probability might be more or less plausible. It is an explicit embodiment of 'aversion to uncertainty', sometimes called 'aversion to ambiguity', and is an expression of the 'precautionary principle'. It is different from and additional to the idea of 'aversion to risk' associated with and derived from expected utility.

The ability to work with probability distributions in the analysis of climate change was demonstrated in Chapter 1. But there is genuine uncertainty over which of these distributions should apply. In particular, the science and economics are particularly sparse precisely where the stakes are highest – at the high temperatures we now know may be possible. Uncertainty over probability distributions is precisely the situation we confront in the modelling of Chapter 6. As Claude Henry puts it in the conclusion to his 2006 paper, 'uncertainty should not be inflated and invoked as an alibi for inaction'. We now have a theory that can describe how to act.

2.6 Non-marginal policy decisions

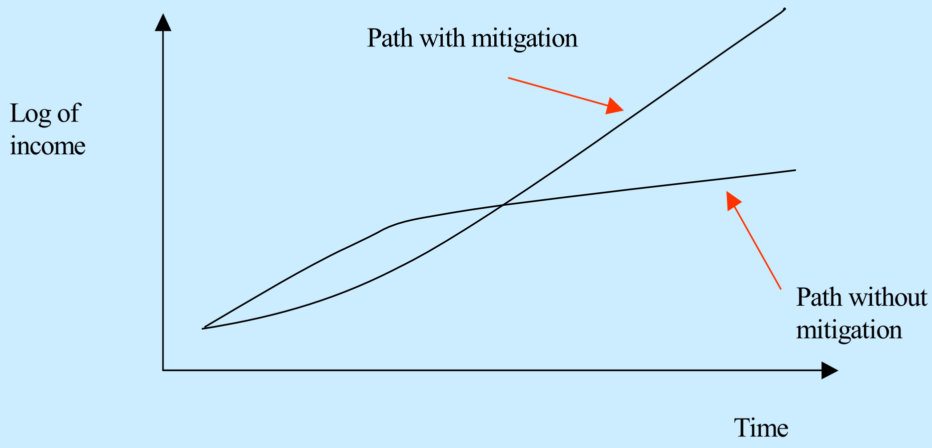
There is a serious risk that, without action to prevent climate change, its impacts will be large relative to the global economy, much more so than for most other environmental problems.

The impacts of climate change on economies and societies worldwide could be large relative to the global economy. Specifically, it cannot be assumed that the global economy, net of the costs of climate change, will grow at a certain rate in the future, regardless of whether nations

[11] See also Chichilnisky (2000)
[12] Essentially the axioms are similar to those of the standard Von Neumann-Morgenstern theorem deriving expected utility except the dependence axiom is relaxed slightly. See Gollier (2001), for example, for a description of the Von Neumann-Morgenstern approach.

follow a 'business as usual' path or choose together to reduce GHG emissions. In this sense, the decision is not a marginal one.

Figure 2.3 Conceptual approach to comparing divergent growth paths over the long-term



The issues are represented schematically in Figure 2.4, which compares two paths, one with mitigation and one without. We should note that, in this diagram, there is uncertainty around each path, which should be analysed using the approaches of the preceding section. This is crucial to the analysis in much of the Review. Income on the 'path with mitigation' is below that on the path without ('business as usual') for the earlier time period, because costs of mitigation are incurred. Later, as the damages from climate change accumulate, growth on the 'path without mitigation' will slow and income will fall below the level on the other path. The analysis of Part III attempts to quantify these effects and finds that the 'greener' path (with mitigation) allows growth to continue but, on the path without mitigation, income will suffer. The analysis requires formal comparison between paths and Part III shows that the losses from mitigation in the near future are strongly outweighed by the later gains in averted damage.

2.7 The public policy of promoting mitigation

Having established the importance of strong mitigation in Parts II and III of the Review, Part IV is devoted to policy to bring it about. The basic theory of externalities identifies the source of the economic problem in untaxed or unpriced emissions of GHGs.

The externality requires a price for emissions: that is the first task of mitigation policy.

The first task of policy is therefore to introduce taxes or prices for GHGs. The Pigou treatment of externalities points to taxes based on the marginal damages caused by carbon emissions. In the diagram shown in Figure 2.1, the appropriate tax would be equal to the social cost of carbon at the point where it is equal to the marginal abatement cost. Faced with this tax, the emitters would choose the appropriate level of abatement.

However, the modern theory of risk indicates that long-term quantity targets may be the right direction for policy, with trading within those targets or regular revision of taxes to keep on course towards the long-run objective (see Chapter 14). Given the long-run nature of many of the relevant decisions, whichever policies are chosen, credibility and predictability of policy will be crucial to effectiveness.

The second task of mitigation policy is to promote research, development and deployment.

However, the inevitable absence of total credibility for GHG pricing policy decades into the future may inhibit investment in emission reduction, particularly the development of new technologies. Action on climate change requires urgency, and there are generally obstacles, due to inadequate property rights, preventing investors reaping the full return to new ideas. Specifically, there are spillovers in learning (another externality), associated with the development and adoption of new low-emission technologies that can affect how much emissions are reduced. Thus the economics of mitigating climate change involves understanding the processes of innovation.

The spillovers occur in a number of ways. A firm is unlikely to be able to appropriate all the benefits, largely because knowledge has some characteristics of a public good. In particular, once new information has been created, it can be virtually costless to copy. This allows a competitor with access to the information to capture the benefits without undertaking the research and development (R&D). Patents are commonly used to reduce this problem. In addition, there are typically 'adoptive externalities' to other firms that arise from the processes whereby technology costs fall as a result of increasing adoption. These spillovers are likely to be particularly important in the case of low-emission technologies that can help to mitigate climate change, as Chapter 16 explains.

Other interacting barriers or problem that are relevant include

- asymmetric and inadequate information – for example, about energy-efficiency measures
- policy-induced uncertainties – such as uncertainty about the implicit price of carbon in the future
- moral hazard or 'gaming' – for example firms might rush to make carbon-emitting investments to avoid the possibility of more stringent regulation in the future
- perverse regulatory incentives – such as the incentive to establish a high baseline of emissions in regimes where carbon quotas are 'grandfathered'
- the endogenous price dynamics of exhaustible natural resources – and the risk that fossil-fuel prices could fall in response to strong climate-change policy, threatening to undermine it.[13]

These issues involve many of the most interesting theoretical questions studied by economists in recent years in industrial, regulatory and natural resource economics.

There are important challenges for public policy to promote mitigation beyond the two tasks just described. That is the subject of Chapter 16. These include regulation and standards and deepening public understanding of responsible behaviour.

Standards and regulation can provide powerful and effective policies to promote action on mitigation.

The learning process for new technologies is uncertain. There are probably important scale effects in this process due to experience or learning-by-doing and the externalities of learning-by-watching. In these circumstances, standards for emissions, for example, can provide a clear sense of direction and reduced uncertainty for investors, allowing these economies of scale to be realised.

In other circumstances, particularly concerning energy efficiency, there will be market imperfections, for example due to the nature of landlord-tenant relations in property, that may inhibit adaptation of beneficial investments or technologies. In these circumstances, regulation can produce results more efficient than those that are available from other instruments alone.

[13] The economic theory of exhaustible natural resources is expounded by Dasgupta and Heal (1979). A seminal reference is Hotelling (1931). See, also, Ulph and Ulph (1994) and Sinclair (1994).

Information, education and public discussion can play a powerful role in shaping understanding of reasonable behaviour.

Economists tend to put most of weight in public-policy analyses and recommendations on market instruments to which firms and households respond. And there are excellent reasons for this – firms and households know more about their own circumstances and can respond strongly to incentives. But the standard 'sticks and carrots' of this line of argument do not constitute the whole story.

Chapter 17 argues that changing attitudes is indeed likely to be a crucial part of a policy package. But it raises ethical difficulties: who has the right or authority to attempt to change preferences or attitudes? We shall adopt the approach of John Stuart Mill and others who have emphasised 'government by discussion' as the way in which individuals can come to decisions individually and collectively as to the ethical and other justifications of different approaches to policy.

2.8 International action for mitigation and adaptation

The principles of public policy for mitigation elaborated so far do not take very explicit account of the international nature of the challenge. This is a global problem and mitigation is a global public good. This means that it is, from some perspectives, 'an international game' and the theory of games does indeed provide powerful insights. The challenge is to promote and sustain international collective action in a context where 'free-riding' is a serious problem. Adaptation, like mitigation, raises strong and difficult international issues of responsibility and equity, and also has some elements of the problem of providing public goods.

Aspects of adaptation to climate change also have some of the characteristics of public goods and require public policy intervention.

Concerns about the provision of public goods affect policy to guide adaptation to the adverse impacts of climate change. This is the subject of Part V of the Review. Compared with efforts to reduce emissions, adaptation provides immediate, local benefits for which there is some degree of private return. Nevertheless, efficient adaptation to climate change is also hindered by market failures, notably inadequate information on future climate change and positive externalities in the provision of adaptation (where the social return remains higher than the return that will be captured by private investors). These market failures may limit the amount of adaptation undertaken – even where it would be cost-effective.

The ethics of adaptation imply strong support from the rich countries to the most vulnerable.

The poorest in society are likely to have the least capacity to adapt, partly because of resource constraints on upfront investment in adaptive capacity. Given that the greatest need for adaptation will be in low-income countries, overcoming financial constraints is also a key objective. This will involve transfers from rich countries to poor countries. The argument is strongly reinforced by the historical responsibility of rich countries for the bulk of accumulated stocks of GHGs. Poor countries are suffering and will suffer from climate change generated in the past by consumption and growth in rich countries.

Action on climate change that is up to the scale of the challenge requires countries to participate voluntarily in a sustained, coordinated, international effort.

Climate change shares some characteristics with other environmental challenges linked to the management of common international resources, including the protection of the ozone layer and the depletion of fisheries. Crucially, there is no global single authority with the legal, moral, practical or other capacity to manage the climate resource.

This is particularly challenging, because, as Chapter 8 makes clear, no one country, region or sector alone can achieve the reductions in GHG emissions required to stabilise atmospheric concentrations of GHGs at the necessary level. In addition, there are significant gains to co-operating across borders, for example in undertaking emission reductions in the most cost-effective way. The economics and science point to the need for emitters to face a common price of emissions at the margin. And, although adaptation to climate change will often deliver some local reduction in its impact, those countries most vulnerable to climate change are particularly short of the resources to invest in adaptation. Hence international collective action on both mitigation and adaptation is required, and Part VI of the Review discusses the challenges and options.

Economic tools such as game theory, as well as insights from international relations, can aid the understanding of how different countries, with differing incentives, preferences and cost structures, can reach agreement. The problem of free-riding on the actions of others is severe. International collective action on any issue rests on the voluntary co-operation of sovereign states. Economic analysis suggests that multilateral regimes succeed when they are able to define the gain to co-operation, share it equitably and can sustain co-operation in ways that overcome incentives for free-riding.

Our response to climate change as a world is about the choices we make about development, growth, the kind of society we want to live in, and the opportunities it affords this and future generations. The challenge requires focusing on outcomes that promote wealth, consumption, health, reduced mortality and greater social justice.

The empirical analysis of impacts and costs, together with the ethical frameworks we have examined, points to strong action to mitigate GHG emissions. And, given the responsibility of the rich countries for the bulk of the current stock of GHGs, and the poverty and vulnerability of developing countries that would be hardest hit, the analysis suggests that rich countries should bear the major responsibility for providing the resources for adjustment, at least for the next few years. The reasons for strong action by the rich countries are similar to those for aid:

- the moral consequences which flow from a recognition of a common humanity of deep poverty;
- the desire to build a more collaborative, inclusive and better world;
- common interest in the climate and in avoiding dislocation;
- historical responsibility.

2.9 Conclusions

Much of the economics we have begun to describe here and that is put to use in the subsequent parts of this Review is not simple. But the structure of this economics is essentially dictated by the structure of the science. And we have seen that it is not possible to provide a coherent and serious account of the economics of climate change without close attention to the ethics underlying economic policy raised by the challenges of climate change.

The economics of climate change is as broad ranging, deep and complicated as any other area of economics. Indeed, it combines most of the difficulties of other areas of economics. It is unavoidably technical in places. It is the task of this Review to explore the economics of climate change in the depth that is possible given the current state of economic and scientific knowledge. And it should already be clear that much more research is necessary. In many ways, the science has progressed further than the economics.

The scope and depth of the subject require us to put the tools of economics to work across the whole range of the subject. Indeed they point to the importance of tools we wish we had. Nevertheless, the economics can be very powerful in pointing us towards important policy conclusions, as we have already begun to see in this chapter. The urgency of the problems established by the science points to the urgency of translating what we can already show with the economic analysis into concrete policy actions. In doing so, the international dimension must be at centre stage.

References

This chapter touches on many important topics in ethics, social choice and economic theory. On social choice theory, Sen (1986) is a thorough guide, while Sen (1970) is a classic analysis of collective choice and social welfare. Broome (2004) examines the complexities of assessing inter-generational welfare. Henry (2006) considers the distinction between risk aversion and aversion to ambiguity or Knightian uncertainty. Gollier (2001) also raises many important issues concerning discounting of the future. Dasgupta and Heal (1979) investigate the economics of exhaustible resources and its implications for price theory, not all of which are intuitive.

Anand,S and A.K. Sen (2000): 'Human development and economic sustainability'. World Development, **28**(12): 2029-2049

Arrow, K. (1951): 'Individual Values and Social Choice', New York: Wiley

Arrow, K. (1963): 'Individual Values and Social Choice', 2nd edition, New York: Wiley

Beckerman, W. and J. Pasek (2001): 'Justice, Posterity and the Environment', Oxford: Oxford University Press.

Broome, J. (1992): 'Counting the Cost of Global Warming', Cambridge: The White Horse Press.

Broome, J. (1994): 'Discounting the future', Philosophy and Public Affairs **23**: 128–56

Broome, J. (2004): 'Weighing lives', Oxford: Oxford University Press.

Broome, J. (2005): 'Should we value population?', The Journal of Political Philosophy. **13**(4): 399-413

Chichilnisky , G. (2000): 'An axiomatic approach to choice under uncertainty with catastrophic risk', Resource and Energy Economics, **22**, 221-31

Dasgupta, P. S. and G. M. Heal (1979): 'Economic theory and exhaustible resources', Cambridge: Cambridge University Press.

Fankhauser, S. (1998): 'The costs of adapting to climate change', Global Environment Facility Working Paper 16, Washington, DC: Global Environment Facility.

Gardiner, S. (2004): 'Ethics and global climate change', Ethics **114:** 555-600

Gollier, C. (2001): 'The Economics of Risk and Time', Cambridge, MA: MIT Press.

Harrod, R.F. (1948): 'Towards a Dynamic Economics', London: Macmillan.

Henry, C. (2006): 'Decision – Making Under Scientific, Policitcal and Economic Uncertainty', Cahier no. DDX-06-12, Chaire Developpement Durable, Paris; Laboratoire d'Econométrie de l'Ecole Polytechnique.

Hills, J. and K. Stewart (2005): 'A More Equal Society: New Labour, Poverty, Inequality and Exclusion', Bristol: Policy Press.

Hotelling, H. (1931): 'The economics of exhaustible resources', Journal of Political Economy **39**(2): 137-175

Keynes, J.M. (1921: 'A Treatise on Probability', London: Macmillan.

Klibanoff, P., M. Marinacci and S.Mukerji (2005): 'A smooth model of decision-making under ambiguity' Econometrica, **73**: 1849-1892

Knight, F. (1921): 'Risk, Uncertainty and Profit', New York: Kelly.

Maccheroni, F., Marinacci, A. Rustichini (2005): 'Ambiguity aversion', robustness and the variational representation of preferences', available from http://web.econ.unito.it/gma/fabio/mmr-r.pdf

Mueller, B. (2006): 'Adaptation Funding and the World Bank Investment Framework Initiative'. Background Report prepared for the Gleneagles Dialogue Government Working Groups Mexico, 7-9 June 2006.

Pigou, A. C. (1912): 'Wealth and Welfare', London: Macmillan.

Pigou, A. C. (1932): 'The Economics of Welfare', (4th ed), London: Macmillan.

Ramsey, F.P. (1928): 'A Mathematical Theory of Saving', Economics Journal, **38** (December): 543-559

Ramsey, F.P. (1931): 'Foundations of Mathematics and Other Logical Essays', New York: Harcourt Brace.

Samuelson, P. (1954): 'The pure theory of public expenditure'. Review of Economics and Statistics **36**(4): 387-389

Sen, A.K. (1970): 'Collective Choice and Social Welfare', San Francisco: Holden-Day.

Sen, A.K. (1986): 'Social Choice Theory', Handbook of Mathematical Economics, K.J. Arrow and M. Intriligator, Vol3. Amsterdam: North-Holland.

Sen, A.K. (1999): 'The Possibility of Social Choice', American Economic Review **89**(3): 349-378

Sen, A. and B. Williams (eds.) (1982): 'Utilitarianism and Beyond', Cambridge: Cambridge University Press/Maison des Sciences de l'Homme.

Sinclair, P. J. N. (1994): 'On the optimum trend of fossil fuel taxation'. Oxford Economic Papers **46**: 869-877.

Solow, R.M. (1974): 'The economics of resources or the resources of economics'. American Economic Review, **64**(2) pp1-14.

Ulph, A. and D. Ulph (1994). 'The optimal time path of a carbon tax'. Oxford Economic Papers **46**: 857-868

2A Ethical Frameworks and Intertemporal Equity

2A.1 Ethical frameworks for climate change

The 'consequentialist' and 'welfarist' approach, the assessment of a policy in terms of its consequences for individual welfare, that is embodied in standard welfare economics, is highly relevant to the ethics of climate change.

In Section 2.3 we described the standard approach to ethics in welfare economics i.e. the evaluation of actions in terms of their consequences for consumption by individuals of goods and services. We emphasised that "goods and services" in consumption were multi-dimensional and should be interpreted broadly. In this appendix we examine that approach in a little more detail and compare it with different ethical perspectives of relevance to the economics of climate change.

For many applications of the standard theory, the community is defined as the nation-state and the decision-maker is interpreted as the government. Indeed this is often seen as sufficiently obvious as to go unstated. This is not, of course, intended to deny the complexities and pressures of political systems: the results of this approach should be seen as an ethical benchmark rather than a descriptive model of how political decisions are actually taken.

Nevertheless, questions such as 'what do individuals value', 'what should be their relation to decisions and decision-making', 'what is the decision-making process' and 'who are the decision-makers' arise immediately and strongly in the ethical analysis of climate change. These questions take us immediately to different perspectives on ethics.

Economics, together with the other social sciences, has in fact embraced a much broader perspective on the objectives of policy than that of standard welfare-economic analysis. Amartya Sen[1], for example, has focussed on the capabilities and freedoms of individuals to live a life they have reason to value, rather than narrowly on the bundles of goods and services they consume. His focus is on opportunities and the processes that create them, rather than on outcomes only. Similar emphases come from discussions of equity[2] (with its focus on opportunity), empowerment[3], or social inclusion[4].

Whilst such perspectives are indeed different, in practice many of the indicators arising from them would overlap strongly with the areas of focus in the Millennium Development Goals (MDGs) and other indicators commonly used by international institutions. Indeed, the MDGs were the outcome of analyses and discussions which themselves embraced a range of ethical approaches.

Impacts of climate change on future generations and other nations raise very firmly questions of rights. Protection from harm done by others lies at the heart of many philosophical approaches to liberty, freedom and justice.[5]

Protection from harm is also expressed in many legal structures round the world in terms of legal responsibility for damage to the property or well-being of others. This is often applied whether or not the individual or firm was knowingly doing harm. A clear example is asbestos, whose use was not prohibited[6] when it was placed in buildings with the worthy purpose of protecting against the spread of fire. Nevertheless insurance companies are still today paying large sums as compensation for its consequences.

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[1] Sen (1999).
[2] e.g. *World Development Report 2006*.
[3] e.g. Stern *et. al.* (2005).
[4] Atkinson and Hills (1998), Atkinson *et al*. (2002), Hills and Stewart (2005).
[5] See, for example, Shue (1999) on the 'no-harm principle' in the context of climate change and Gardiner (2004) for a link with John Rawls theory of justice. From the point of view of jurisprudence, and for a discussion of links with notions of retribution, see Hart (1968).
[6] As Henry (2006) argued, the possibility of harmful effects had been discovered around 100 years go but this would not necessarily be generally known by those whose used it.

This is a version of the 'polluter pays' principle that is derived from notions of rights, although, as we saw, for example, in the discussion of Fig. 2.1 above, it also arises from an efficiency perspective within the standard economic framework. If this interpretation of rights were applied to climate change, it would place at least a moral, if not a legal, responsibility on those groups or nations whose past consumption has led to climate change.

Looking at the moral responsibilities of this generation, many would argue that future generations have the right to enjoy a world whose climate has not been transformed in a way that makes human life much more difficult; or that current generations across the world have the right to be protected from environmental damage inflicted by the consumption and production patterns of others.

The notions of the right to climate protection or climate security of future generations and of shared responsibilities in a common world can be combined to assert that, collectively, we have the right only to emit some very small amount of GHGs, equal for all, and that no-one has the right to emit beyond that level without incurring the duty to compensate. We are therefore obliged to pay for the right to emit above that common level. This can be seen as one argument in favour of the 'contract and converge' proposition, whereby 'large emitters' should contract emissions and all individuals in the world should either converge to a common (low) level or pay for the excess (and those below that level could sell rights).

There are problems with this approach, however. One is that this right, whilst it might seem natural to some, is essentially asserted. It is not clear why a common humanity in a shared world automatically implies that there are equal rights to emit GHGs (however low). Equality of rights, for example to basic education and health, or to common treatment in voting, can be related to notions of capabilities, empowerment, or the ability to participate in a society. Further, they have very powerful consequences in terms of law, policy and structures of society. How does the 'right to emit' stand in relation to these rights? Rights are of great importance in ethics but they should be argued rather than merely asserted. More pragmatically, as we shall examine in Part VI of this report, action on climate change requires international agreement and this is not a proposition likely to gain the approval necessary for it to be widely adopted.

A concept related to the idea of the rights of future generations is that of sustainable development: future generations should have a right to a standard of living no lower than the current one.

In other words, the current generation does not have the right to consume or damage the environment and the planet in a way that gives its successor worse life chances than it itself enjoyed. The life chances of the next generation, it is understood here, are assessed assuming that it behaves in a sustainable way, as defined here, in relation to its own successor generation[7].

Expressed in this form, however, the principle need not imply that the whole natural environment and endowment of resources should be preserved by this generation for the next generation in a form exactly as received from the previous generation. The capital stock passed on to the next generation consists of many things, mostly in the form of stocks covering, for example, education, health, capital equipment, buildings, natural resources, the natural environment etc. The standard of living available to the next generation depends on this whole collection of stocks. A decline in one of them, say copper, might be compensated by another stock, say education or infrastructure, which has increased.

On the other hand, it seems quite clear that, at a basic level, the global environmental and ecological system, which provides us with life support functions such as stable and tolerable climatic conditions, cannot be substituted. The relation between emissions of GHGs and the risks to these functions is examined in detail in the Review, particularly Part II. The commitment of Article 2 of the United Nations Framework Convention on Climate Change

[7] A valuable summary of the analytic background and foundations of sustainability is given by Anand and Sen (2000)

(UNFCCC) to 'achieve stabilisation of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic [i.e. human-induced] interference with the climate system' can be interpreted as just such a sustainability rule.

The notion of 'stewardship' can be seen as a special form of sustainability. It points to particular aspects of the world, which should themselves be passed on in a state at least as good as that inherited from the previous generation.

Examples might be historic buildings, particular pieces of countryside, such as National Parks, or even whole ecosystems such as tracts of primary tropical rainforest. This involves a particular interpretation of the responsibilities of the current generation in terms of a limit on its rights to property. Essentially, in this approach each generation has the responsibility of stewardship. Some would see the climate in this way since it shapes so much of all the natural environment and is not straightforwardly substitutable with other capital. Others[8] might ask still more basic questions as to how we ought to live, particularly in relation to nature.

These different notions of ethics emphasise different aspects of the consequences of decisions for others and for the future. Nevertheless, the list of consequences on which they would focus for each generation are similar: above all consumption, education, health and environment.

And all the perspectives would take into account the distribution of outcomes within and across generations, together with the risks involved in different actions, now and over time. Hence in the Review we shall focus our analysis on the implications of action or inaction on climate change for these four dimensions.

How the implications on these four dimensions are assessed, will, of course, vary according to the ethical position adopted. How and whether, in making assessments, we attempt to aggregate over consequences (i) within generations, (ii) over time, and (iii) according to risk will be crucial to policy design and choice. When we do aggregate explicitly we have to be quantitative in comparing consequences of different kinds and for different people. We shall be paying special attention to all three forms of aggregation. Aggregation across dimensions poses different kinds of questions and problems, as was discussed in Section 2.3 above.

2A.2 Intertemporal appraisals and discounting[9]

Introduction: the underlying welfare framework for appraisal and cost-benefit analysis

Different strategies for climate change will yield different patterns of consumption over time. We assume that a choice between strategies will depend on their consequences for households now and in the future (see Chapter 2 and 2A.1 above, for a brief discussion of 'consequentialism'). The households to be included and examined in this weighting of consequences will depend on the perspective of those making the judgements: we assume here that the assessment is done from the perspective of the world as a whole. Narrower perspectives would include, for example, only those households associated with a particular country or region and would follow similar reasoning except that net benefits would be assessed for a narrower group. If all the perspectives are from narrow groups, one country, or just the next one or two generations, it is likely that little action would be taken on global warming. As is emphasised throughout this Review, this is a global and long-run issue.

An analysis of how to carry out an intertemporal assessment of consequences of strategies or actions is inevitable if somewhat formal: usually there would be first a modelling of the consequences, second an aggregation of the consequences into overall welfare indicators for households, and third an aggregation across households within generations, across generations and across uncertain outcomes. We focus here on the second and third elements, particularly the third.

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[8] Jamieson (1992).

[9] This section has benefited from discussions with Cameron Hepburn and Paul Klemperer, although they are not responsible for the views expressed here. See also Hepburn (2006).

We can compare the consequences of different strategies and actions by thinking of overall welfare, W, calculated across households (and generations) as a function of the welfare of these households, where we write welfare of household h as u^h. The joint specification of W and u^h constitutes a set of value judgements which will guide the assessment of consequences. We think of h as ranging across households now and in the future and can allow (via specification of W and u^h) for the possibility that a household does not live forever. Then, if we are comparing a strategy indexed by the number 1 with that indexed by zero we will prefer strategy 1 if

$$W^1 > W^0 \tag{1}$$

where W^1 is evaluated across the path 1 with its consequences for all households now and in the future, and similarly W^0.

In the above, the two strategies can yield very different patterns of outcomes across individuals and over time – they can differ in a non-marginal way. There is, however, a major part of economic theory that works in terms of a marginal change, for example an investment project. Then we can write, where W^1 is welfare in the world with the project and W^0 is welfare in the world without the project

$$\Delta W \equiv W^1 - W^0 = \sum_h \frac{\partial W}{\partial u^h} \Delta u^h \tag{2}$$

where Δu^h is the change in household welfare for h as a result of the project. Calculating Δu^h will then depend on the structure of the economic model and the characteristics of the project. This is the theory of cost-benefit analysis set out clearly by James Meade (1955) and explored in some detail by Drèze and Stern (1987) and (1990) for imperfect economies.

As we have argued strategies on climate change cannot be reduced to marginal comparisons so we have to examine W^1 and W^0 (for different strategies) and for many climate change questions, we must compare the two without using the very special case of marginal comparisons as in equation (2).

Nevertheless there will be investment projects which can be considered as small variations around a particular path e.g. a new technique in electricity generation. In this case marginal analysis can be appropriate. In this context we can think about comparing benefits occurring at different points in time, in terms of how we should value small changes around a particular path. This leads to the subject of discounting and how we value marginal benefits which are similar in nature but which occur at different points in time. We must emphasise very strongly that these valuations occur with respect to variations around a particular path. If the path is shifted so too are the marginal valuations and thus discount factors and rates (see below).

An investment carried out now may yield returns which are dependent on which strategy, and thus which growth paths, might be followed. If we are uncertain about these strategies, for example, we do not know whether the world would follow a strong mitigation strategy or not, then we should evaluate the project for each of the relevant scenarios arising from the strategies. Each of these evaluations would then be relative to a different growth path. The next step would not be straightforward. We could aggregate across the scenarios or growth paths using probabilities and relative values of social marginal utilities relevant for the different paths (i.e. we would have to compare the numeraire used for each path) but only if we are in a position to assign probabilities. Further a related discussion over strategies may be going on at the same time as the projection evaluation.

Discounting: a very simple case

Discounting and discount rates have been controversial in environmental economics and the economics of climate change, because a high rate of discounting of the future will favour avoiding the costs of reducing emissions now, since the gains from a safer and better climate in the future are a long way off and heavily discounted (and vice versa for low discount rates). Our first and crucial point has been made already: discounting is in general a marginal approach where the evaluation of marginal changes depends on the path under consideration. If the two paths are very different, a marginal/discounting approach for comparing the two is unacceptable in logic – we have to go back to an evaluation of the underlying W for each path.

The discounting approach is, however, relevant for small changes around a given path and, since some of the literature has been somewhat confused on the issue and because it brings out some important issues relevant for this Review, we provide a brief description of the main principles here. To do this we narrow down the relevant determinants of utility to just consumption at each point in time and take a very special additive form of W. Thus we think of the overall objective as the sum (or integral) across all households and all time of the utility of consumption. In order to establish principles as clearly as possible we simplify still further to write

$$W = \int_0^\infty u(c)e^{-\delta t}dt \qquad (3)$$

We assume here that there is just one individual at each point in time (or a group of identical individuals) and that the utility or valuation function is unchanging over time. We introduce population and its change later in the discussion.

In Chapter 2 we argued, following distinguished economists from Frank Ramsey in the 1920s to Amartya Sen and Robert Solow more recently, the only sound ethical basis for placing less value on the utility (as opposed to consumption) of future generations was the uncertainty over whether or not the world will exist, or whether those generations will all be present. Thus we should interpret the factor $e^{-\delta t}$ in (3) as the probability that the world exists at that time. In fact this is exactly the probability of survival that would apply if the destruction of the world was the first event in a Poisson process with parameter δ (i.e. the probability of an event occurring in a small time interval Δt is $\delta\Delta t$). Of course, there are other possible stochastic processes that could be used to model this probability of survival, in which case the probability would take a different form. The probability reduces at rate δ. With or without the stochastic interpretation here, δ is sometimes called 'the pure time discount rate.' We discuss possible parameter values below.

The key concept for discounting is the marginal valuation of an extra unit of consumption at time t, or discount factor, which we denote by λ. We can normalise utility so that the value of λ at time 0 along the path under consideration is l. We are considering a project which perturbs consumption over time around this particular path. Then, following the basic criterion, equation 2, for marginal changes we have to sum the net incremental benefits accruing at each point in time, weighting those accruing at time t by λ. Thus, from the basic marginal criteria (2), in the special case (3), we accept the project if

$$\Delta W = \int_0^\infty \lambda \Delta c dt > 0 \qquad (4)$$

where λ and c are each evaluated at time t, Δc is the perturbation to consumption at time t arising from the project and λ is the marginal utility of consumption where

$$\lambda = u'(c)e^{-\delta t} \qquad (5)$$

If, for example, we have to invest to gain benefits then Δc will be negative for early time periods and positive later.

The rate of fall of the discount factor is the discount rate which we denote by ρ. These definitions and the special form of λ as in (5) are in the context of the very strong simplifications used. Under uncertainty or with many goods or with many individuals there will be a number of relevant concepts of discount factors and discount rates.

The discount factors and rates depend on the numeraire that is chosen for the calculation. Here it is consumption and we examine how the present value of a unit of consumption changes over time. If there are many goods, households, or uses of revenue we must be explicit about choice of numeraire. There will, in principle, be different discount factors and rates associated with different choices of numeraire –- see below.

Even in this very special case there is no reason to assume the discount rate is constant. On the contrary it will depend on the underlying pattern of consumption for the path being examined; remember that λ is essentially the discounted marginal utility of consumption along the path.

Let us simplify further and assume the very special 'isoelastic' function for utility

$$u(c) = \frac{c^{1-\eta}}{1-\eta} \qquad (6)$$

(where, for η=1, u(c) = log c). Then

$$\lambda = c^{-\eta} e^{-\delta t} \qquad (7)$$

and the discount rate ρ, defined as $-\dot{\lambda}/\lambda$ is given by

$$\rho = \eta \frac{\dot{c}}{c} + \delta \qquad (8)$$

To work out the discount rate in this very simple formulation we must consider three things. The first is η which is the elasticity of the marginal utility of consumption.[10] In this context it is essentially a value judgement. If, for example η=1, then we would value an increment in consumption occurring when utility was 2c as half as valuable as if it occurred when consumption was c. The second is ċ/c, the growth rate of consumption along the path: this is a specification of the path itself or the scenario or forecast of the path of consumption as we look to the future. The third is δ, the pure time discount rate, which generates, as discussed, a probability of existence of $e^{-\delta t}$ at time t (thus δ is the rate of fall of this probability).

The advantage of (8) as an expression for the discount rate is that it is very simple and we can discuss its value in terms of the three elements above. The Treasury's Green Book (2003) focuses on projects or programmes that have only a marginal effect relative to the overall growth path and thus uses the expression (8) for the discount rate. The disadvantage of (8) is that it depends on the very specific assumptions involved in simplifying the social welfare function into the form (3).

There is, however, one aspect of the argument that will be important for us in the analysis that follows in the Review and that is the appropriate pure time discount rate. We have argued that it should be present for a particular reason, i.e. uncertainty about existence of future generations arising from some possible shock which is exogenous to the issues and choices under examination (we used the metaphor of the meteorite).

But what then would be appropriate levels for δ? That is not an easy question but the consequences for the probability for existence of different δs can illuminate – see Table 2A.1

[10] See e.g. Stern (1977), Pearce and Ulph (1999) or HM Treasury (2003) for a discussion of some of the issues.

Table 2A.1				
	Probability of human race surviving 10 years	Not surviving 10 years	Probability of human race surviving 100 years	Not surviving 100 years
δ = 0.1	0.990	0.010	0.905	0.095
0.5	0.951	0.049	0.607	0.393
1.0	0.905	0.095	0.368	0.632
1.5	0.861	0.139	0.223	0.777

For δ=0.1 per cent there is an almost 10% chance of extinction by the end of a century. That itself seems high – indeed if this were true, and had been true in the past, it would be remarkable that the human race had lasted this long. Nevertheless that is the case we shall focus on later in the review, arguing that there is a weak case for still higher levels.[11] Using δ=1.5 per cent, for example, i.e. 0.015, the probability of the human race being extinct by the end of a century would be as high as 78%, indeed there would be a probability of extinction in the next decade of 14%. That seems implausibly, indeed unacceptably, high as a description of the chances of extinction.

However, we should examine other interpretations of 'extinction'. We have expressed survival or extinction of the human race as either one or the other and have used the metaphor of the devastating meteorite. There are also possibilities of partial extinction by some exogenous or man-made force which has little to do with climate change. Nuclear war would be one possibility or a devastating outbreak of some disease which 'took out' a significant fraction of the world's population.

In the context of *project uncertainty* rather different issues arise. Individual projects can and do collapse for various reasons and in modelling this type of process we might indeed consider values of δ rather higher than shown in this table. This type of issue is relevant for the assessment of public sector projects, see, for example HM Treasury (2003), the Green Book.

A different perspective on the pure time preference rate comes from Arrow (1995). He argues that one problem with the absence of pure time discounting is that it gives an implausibly high optimum savings rate a particular model using for the utility functions as described above, where output is proportional to capital. If δ=0 then one can show that the optimum savings rate in such a model[12] is 1/η; for η between 1 and 1.5 this looks very high. From a discussion of 'plausible' savings rates he suggests a δ of 1%. The problem with Arrow's argument is first that there are other aspects influencing optimum savings in possible models that could lower the optimum savings rate and second that his way of 'solving' the 'over-saving' complication is very ad hoc. Thus the argument is not convincing.

Arrow does in his article draw the very important distinction between the 'prescriptive' and the 'descriptive' approach to judgements of how to 'weigh the welfare' of future generations. He, like the authors described in Chapter 2 on this issue, is very clear that this should be seen as a prescriptive or ethical issue rather than one which depends on the revealed preference of individuals in allocating their own consumption and wealth (the descriptive approach). The allocation an individual makes in her own lifetime may well reflect the possibility of her death and the probability that she will survive a hundred years may indeed be very small. But this intertemporal allocation by the individual has only limited relevance for the long-run ethical question associated with climate change.

There is nevertheless an interesting question here of combining short-term and long-term discounting. If a project's costs and benefits affect only this generation then it is reasonable

[11] See also Hepburn (2006)
[12] This uses the optimality condition that the discount rate (as in (8)) should be equal to the marginal product of capital.

to argue that the revealed relative valuations across periods has strong relevance (as it does across goods). On the other hand, as we have emphasised allocation across generations and centuries is an ethical issue for which the arguments for low pure time discount rates are strong.

Further, we should emphasise that using a low δ does not imply a low discount rate. From (8) we see, e.g., that if η were, say, 1.5, and $\dot{c}/c$ were 2.5% the discount rate would be, for δ= 0, 3.75%. Growing consumption is a reason for discounting. Similarly if consumption were falling the discount rate would negative.

As the table shows the issue of pure time discounting is important. If the ethical judgement is that future generations count very little *regardless of their consumption level* then investments with mainly long-run pay-offs would not be favoured. In other words, if you care little about future generations you will care little about climate change. As we have argued that is not a position which has much foundation in ethics and which many would find unacceptable.

Beyond the very simple case

We examine in summary form the key simplifying assumptions associated with the formulation giving equations (3) and (8) above, and ask how the form and time pattern of the various discount factors and discount rates might change when these assumptions are relaxed.

Case 1 Changing population

With population N at time t and total consumption of C we may write the social welfare function to generalise (3) as

$$W = \int_0^\infty Nu(C/N)e^{-\delta t}dt \qquad (9)$$

In words we add, over time, the utility of consumption per head times the number of people with that consumption: i.e. we simply add across people in this generation just as in (3) we added across time; we abstract here from inequality within the generation (see below). Then the social marginal utility of an increment in total consumption at time t is again given by (5) where c is now C/N consumption per head. Thus the expression (8) for the discount rate is unchanged. We should emphasise here that expression (9) is the appropriate form for the welfare function where population is exogenous. In other words we know that there will be N people at time t. Where population is endogenous some difficult ethical issues arise – see, for example, Dasgupta (2001) and Broome (2004, 2005).

Case 2 Inequality within generations

Suppose group i has consumption C_i and population N_i. We write the utility of consumption at time t as

$$\sum_i N_i u(C_i / N_i)e^{-\delta t} \qquad (10)$$

and integrate this over time: in the same spirit as for (9) we are adding utility across sub-groups in this generation. Then we have, replacing (5), where c_i is consumption per head for group i,

$$\lambda_i = u'(c_i)e^{-\delta t} \qquad (11)$$

as the discount factor for weighting increments of consumption to group i. Note that in principle the probability of extinction could vary across groups, thus making δ_i dependent on i.

An increment in aggregate consumption can be evaluated only if we specify how it is distributed. Let us assume a unit increment is distributed across groups in proportions α_i. Then

$$\lambda = \sum_i \alpha_i u'(c_i) e^{-\delta t} \qquad (12)$$

For some cases α_i may depend on c_i, for example, if the increment were distributed just as total consumption, so that $\alpha_i = C_i/C$ where C is total consumption. In this case the direction of movement of the discount rate will depend on the form of the utility function. For example, in this last case, if $\eta=1$, the discount rate would be unaffected by changing inequality.

If $\alpha_i = 1/N$ this is essentially "expected utility" for a "utility function" given by u′( ). Hence the Atkinson theorem (1970) tells us that if $\{c_i\}$ becomes more unequal[13] then λ will rise and the discount rate will fall if u′ is convex (and vice versa if it is concave). The convexity of u′ ( ) is essentially the condition that the third derivative of u is positive: all the isoelastic utility functions considered here satisfy this condition[14].

For α_i 'tilted' towards the bottom end of the income distribution the rise is reinforced. Conversely, it is muted or reversed if α_i is 'tilted' towards the top end of the income distribution. For example, where $\alpha_i = 1$ for the poorest subset of households then λ will rise where rising inequality makes the poorest worse off. But where $\alpha_N = 1$ for the richest household, λ will fall if rising income inequality makes the richest better off. Note that in the above specification the contribution of individual i to overall social welfare depends only on the consumption of that individual. Thus we are assuming away consumption externalities such as envy.

Case 3 Uncertainty over the growth path

We cannot forecast, for a given set of policies, future growth with certainty. In this case we have to replace the right-hand side of (5) in the expression for λ by its expectation. This then gives us an expression similar to (12) where we can now interpret α_i as the probability of having consumption in period t, denoted as p_i in equation (13). We would expect uncertainty to grow over time in the sense that the dispersion would increase. Under the same assumptions, i.e. convexity of u′, as for the increasing inequality case this increasing dispersion would reduce the discount rate over time. Increased uncertainty (see Rothschild and Stiglitz, 1976 and also Gollier, 2001) increases λ if u′ is convex since λ is essentially expected utility with u′ as the utility function.

$$\lambda = \sum_i p_i u'(c_i) e^{-\delta t} \qquad (13)$$

Figure 2A.1 shows a simple example of how the discount factor falls as consumption increases over time, when the utility function takes the simple form given in equation (6). The chart plots the discount factor along a range of growth paths for consumption; along each path the growth rate of consumption is constant, ranging from 0 per cent to 6 per cent per year. The value of δ is taken to be 0.1 per cent and of η 1.05. The paths with the lowest growth rates of consumption are the ones towards the top of the chart, along which the discount factor declines at the slowest rate. Figure 2A.2 shows the average discount rate over time corresponding to the discount factor given by equation (13), assuming that all the paths are equally likely. This falls over time. For further discussion of declining discount rates, see Hepburn (2006).

[13] This property can be defined via distribution functions and Lorenz curves. It is also called second-order stochastic domination or Lorenz-dominance: see e.g. Gollier (2001), Atkinson (1970) and Rothschild and Stiglitz (1970).
[14] Applying the same theory to the utility function shows that total utility will be lower under greater inequality for a concave utility function.

Figure 2A.1

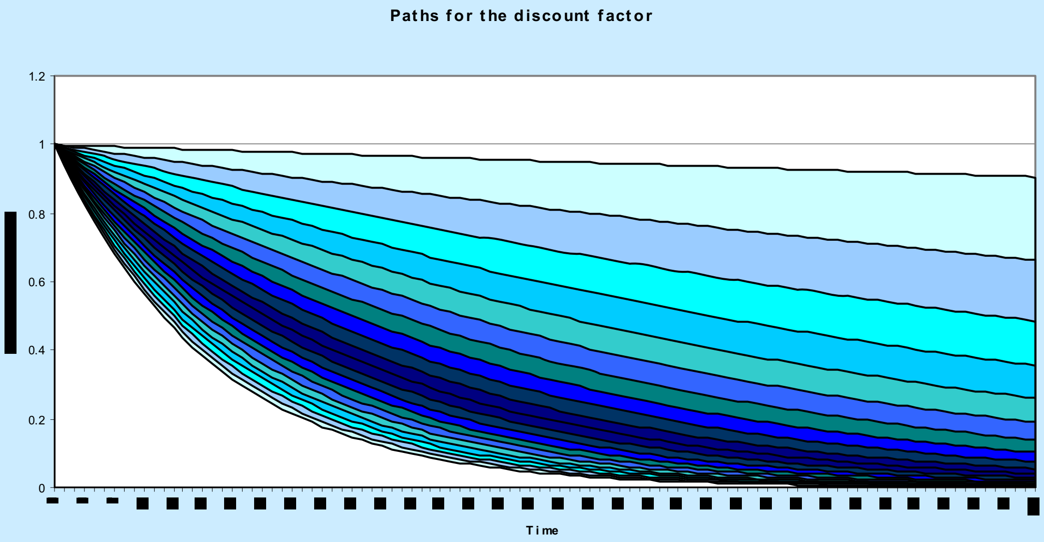
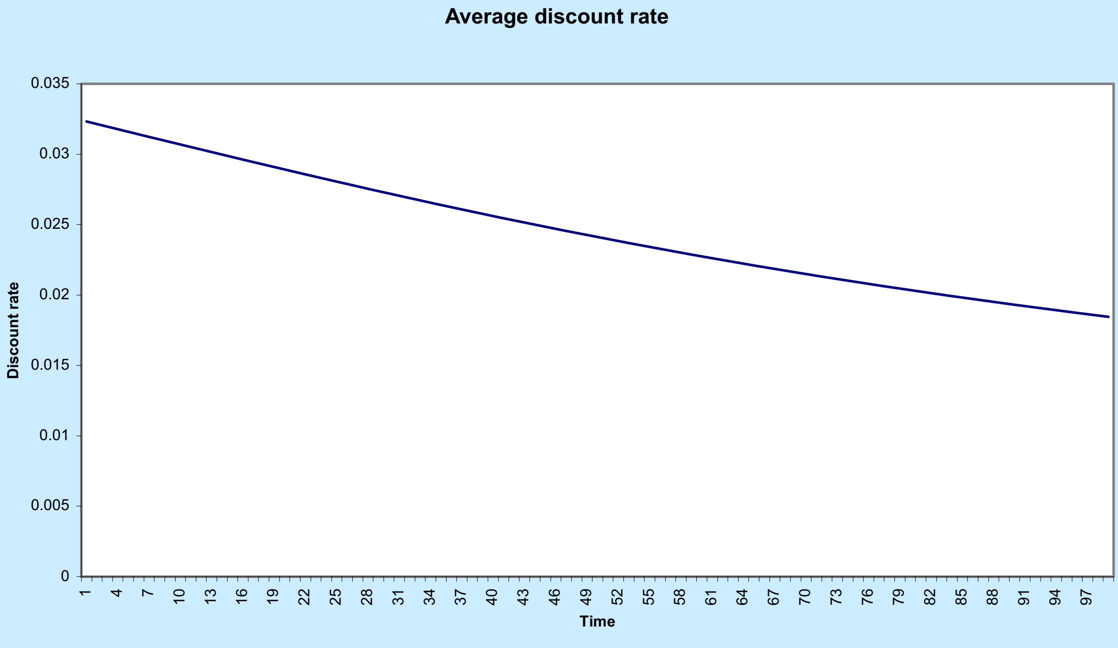


Figure 2A.2



Further complications

The above treatment has kept things very simple and focussed on a case with one consumption good and one type of consumer and says little about markets.

Where there are <u>many goods</u>, and <u>different types of household</u> and <u>market imperfections</u> we have to go back to the basic marginal criterion specified in (2) and evaluate Δu^h for each household taking into account these complications: for a discussion see Drèze and Stern (1990). There will generally be a different discount rate for each good and for each consumer. One can, however, work in terms of a discount rate for aggregate (shadow) public revenue.

A case of particular relevance in this context would be where utility depended on both current consumption and the natural environment. Then it is highly likely that the relative 'price' of consumption and the environment (in terms of willingness-to-pay) will change over time. The changing price should be explicit and the discount rate used will differ according to whether consumption or the environment is numeraire (see below on Arrow (1966)).

Growing benefits in a growing economy: convergence of integrals.

We examine the special case (4) of the basic marginal criteria (2). The convergence of the integral requires λ to fall faster than the net benefits Δc are rising. Without convergence it will appear from (4) that the project has infinite value. Suppose consumption grows at rate g and the net benefits at $\hat{g}$. From (8) and (4) we have that for convergence we need, in the limit into the distant future,

$$\eta g + \delta > \hat{g} \tag{14}$$

If, for example, g and $\hat{g}$ are the same (benefits are proportional to consumption) then for convergence we need, in the limit,

$$\delta > (1-\eta)g \tag{15}$$

Where $\eta \geq 1$ and $\delta > 0$ this will be satisfied. But for $\eta < 1$ there can be problems. Given that infinite aggregate net benefits are implausible this could be interpreted as an argument for a high η or more precisely a high limiting value of η. We have so far assumed that η is constant (the isoelastic case) but it could, however, in principle be higher for very high c. As we have indicated, arguments for a high δ should be conducted on a separate basis concerning the probability of existence, and we have, in this context argued for a low value of δ.

Market rates, capital market imperfections and intergenerational welfare

Some may object that the discount rates which would arise from (8), e.g. 3-4% or lower, may not directly reflect market interest rates[15]. Further, it may be argued, market interest rates give the terms under which individuals actually do make intertemporal allocations and thus these market rates reflect individual marginal rates of substitution between goods now and in the future. Thus, in this argument, market rates should be used as discount rates.

There are a number of reasons why this argument may be misleading including capital market imperfections and myopia. And the argument begs the question of which of the many different market rates of interest and return might be relevant. In this context, however, we would emphasise as argued in Chapter 2, that the decisions at issue for the long-run analyses concern allocation across generations rather than within. One can confront these only by looking carefully at the ethical issues themselves. The intertemporal valuations of individuals over their own lifetimes, as we have argued, is not the same issue. They do not constitute a market revealed preference of the trade-offs at stake here.

This is not the place for a detailed analysis of market imperfections, "crowding out of investment" and discount rates. The reader may wish to consult Drèze and Stern (1987 and 1990) and some of the references therein, in particular Arrow (1966). An intuitive expression of the Arrow argument is as follows. The issue concerns the relative value of two forms of income, call this relative value μ. These different forms of income can be, e.g. consumption, investment or government income. If μ is constant over time then the discount rates, whether we work in terms of consumption, investment or government income, should be the same. The reason is that the difference between the two discount rates for the two forms of income is simply the rate of change of μ (since $\mu = \lambda^A / \lambda^B$ where λ are the discount factors for incomes type A and B respectively). The reason that μ is not unity arises from various market imperfections and constraints on the tax system (otherwise the government would shift resources so that λ^A is equal to λ^B). And if the intensities of these imperfections and

[15] However, these values are not far away from real long-run returns on government bonds or on equities.

constraints are unchanged over time then μ will be constant and the relevant discount rates will be equal.

2A.3 Conclusions

Discounting is a technique relevant for marginal perturbations around a given growth path. Where the strategies being compared involve very different paths, then discounting can be used only for assessing projects which involve perturbations around a path and not for comparing across paths. There will be important decisions for which marginal analysis is appropriate, including, for example, technological choices to sustain given paths of emission reduction. We must emphasise, however, that, as with any marginal analysis, the marginal valuations will depend on the paths under consideration. Which path or paths are relevant will depend on the overall strategies adopted.

Within the case of marginal perturbations, the key concept is the discount factor, i.e. the present value of the numeraire good: here the discount factor is the relative value of an increment in consumption at a time in the future relative to now. The discount factor will generally depend on the consumption level in the future relative to that now, i.e. on the growth path, and on the social utility or welfare function used to evaluate consumption. The discount rate is the rate of fall of the discount factor. It depends on the way in which consumption grows over time. If consumption falls along a path then the discount rate can be negative. There is no presumption that it is constant over time.

- If inequality rises over time then this would work to reduce the discount rate, for the welfare functions standardly used.

- If uncertainty rises as we go into the future this would work to reduce the discount rate, for the welfare functions standardly used. Quantification of this effect requires specification of the form of uncertainty, and how it changes, and of the utility function.

- With many goods and many households there will be many discount rates. For example if conventional consumption is growing but the environment is deteriorating then the discount rate for consumption would be positive but for the environment it will be negative. Similarly, if the consumption of one group is rising but another is falling then the discount rate would be positive for the former but negative for the latter.

Taken together with our discussion of ethics we see that the standard welfare framework is highly relevant as a theoretical basis for assessing strategies and projects in the context of climate change. However, the implications of that theory are very different from those of the techniques often used in cost-benefit analysis. For example, a single constant discount rate would generally be unacceptable.

Whether we are considering marginal or non-marginal changes or strategies the “pure time discount rate” is of great importance for a long-run challenge such as climate change. The argument in the chapter and in the appendix and that of many other economists and philosophers who have examined these long-run, ethical issues, is that ”pure time discounting” is relevant only to account for the exogenous possibility of extinction. From this perspective it should be small. On the other hand, those who would put little weight on the future (regardless of how living standards develop) would similarly show little concern for the problem of climate change.

References

Anand,S and A.K. Sen (2000). 'Human development and economic sustainability'. World Development, **28**(12): 2029-2049

Arrow, K.J. (1966): 'Discounting and public investment criteria', in Water Research, A.V. Kneese and S.C. Smith, (eds.), John Hopkins University Press.

Arrow, K.J. (1995): 'Inter-generational equity and the rate of discount in long-term social investment' paper at IEA World Congress (December), available at www.econ.stanford.adu/faculty/workp/swp97005.htm

Atkinson, A. B. (1970): 'On the measurement of inequality', Journal of Economic Theory, **2**(3): 244-263

Atkinson, A.B. and J. Hills (1998): 'Social exclusion, poverty and unemployment', Exclusion, Employment and Opportunity, A.B. Atkinson and J. Hills, London: London School of Economics. CASE Paper 4.

Atkinson, A.B., B. Cantillon, E. Marlier and B.Nolan (2002): 'Social Indicators:The EU and Social Inclusion'. Oxford: Oxford University Press.

Broome, J. (2004): 'Weighing Lives', Oxford: Oxford University Press.

Broome, J. (2005): 'Should we value population', The Journal of Political Philosophy: **13**(4): 399-413

Dasgupta, P. (2001):'Human Well-Being and the Natural Environment', Oxford: Oxford University Press.

Drèze, J.P. and N.H. Stern (1987): 'The Theory of Cost-Benefit Analysis' in (ed.) Auerback and Feldstein, Handbook of Public Economics, Vol12, North Holland.

Drèze, J.P. and N.H. Stern (1990): 'Policy reform, Shadow Prices and Market Prices', Journal of Public Economics, **42**: 1-45

Gardiner, S. (2004): 'Ethics and global climate change', Ethics **114:** 555-600

Gollier, C. (2001):'The Economics of Risk and Time', Cambridge, MA: MIT Press.

Hart, H.L.A. (1968): 'Punishment and Responsibility', Oxford: Oxford University Press.

Hepburn (2006): 'Discounting climate change damages', Overview for the Stern Review, St Hugh's College, Oxford.

Henry, C. (2006): 'Decision – Making Under Scientific, Policitcal and Economic Uncertainty', Cahier no. DDX-06-12, Chaire Developpement Durable, Paris; Laboratoire d'Econométrie de l'Ecole Polytechnique.

Hills, J. and K. Stewart (2005) '*A More Equal Society: New Labour, Poverty, Inequality and Exclusion'*. Bristol: Policy Press.

HM Treasury (2003): 'The Green Book – Appraisal and Evaluation in Central Government', HM Treasury, London

Jamieson, D. (1992): 'Ethics, public policy and global warming'. Science, Technology and Human Values **17**:139–53. Reprinted in Jamieson, D. (2003), Morality's Progress, Oxford: Oxford University Press.

Meade, J.E. (1955): 'Trade and Welfare: A mathematical supplement', Oxford: Oxford University Press.

Pearce, D.W. and A. Ulph (1999): 'A social discount rate for the United Kingdom'. Economics and the Environment: Essays in Ecological Economics and Sustainable Development, D.W. Pearce, Cheltenham: Edward Elgar.

Rothschild, M.D. and J.E. Stiglitz (1970): 'Increasing Risk: I. A Definition', Journal of Economic Theory, September 2 pp. 255-243.

Shue, H. (1999): 'Bequeathing Hazards: Security Rights and Property Rights of Future Humans'. M. Dore and T. Mount. *Global Environmental Economics: Equity and the Limits to Markets*. Oxford: Blackwell: 38-53.

Sen, A (1999) : 'Development as Freedom', Anchor Books, London

Stern, N.H. (1977): 'Welfare weights and the elasticity of the marginal valuation of income'. Published as Chapter 8 in M. Artis and R. Nobay. Proceedings of the AUTE Edinburgh Meeting of April 1976. Basil Blackwell.

Stern, N.H., J-J Dethier and F.H. Rogers (2005): 'Growth and Empowerment: Making Development Happen'. Munich Lectures in Economics. Massachusetts: MIT Press.

World Development Report (2006) :'Equity and Development', World Bank, Washington DC.