

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

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).

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, CO₂ equivalent or CO₂e)³ (Figure 1.1) and rising at around 2.3 ppm per year⁴. Current levels of greenhouse gases are higher now than at any time in at least the past 650,000 years.⁵

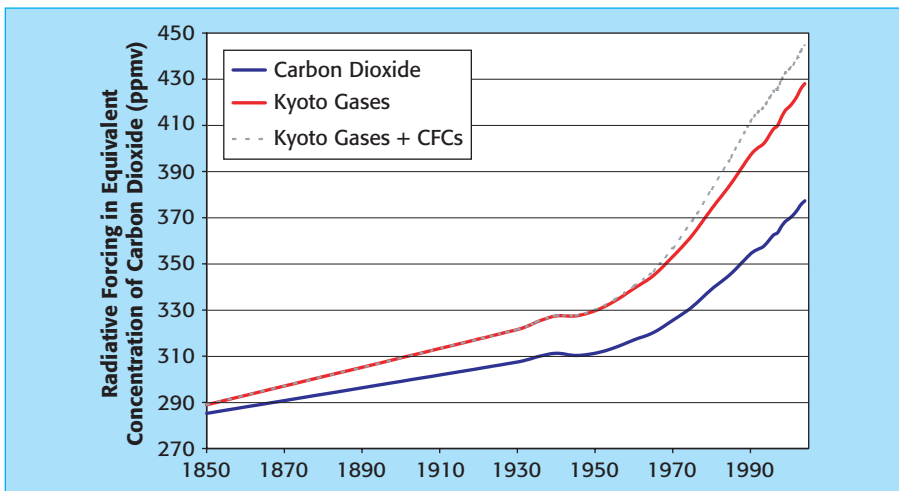
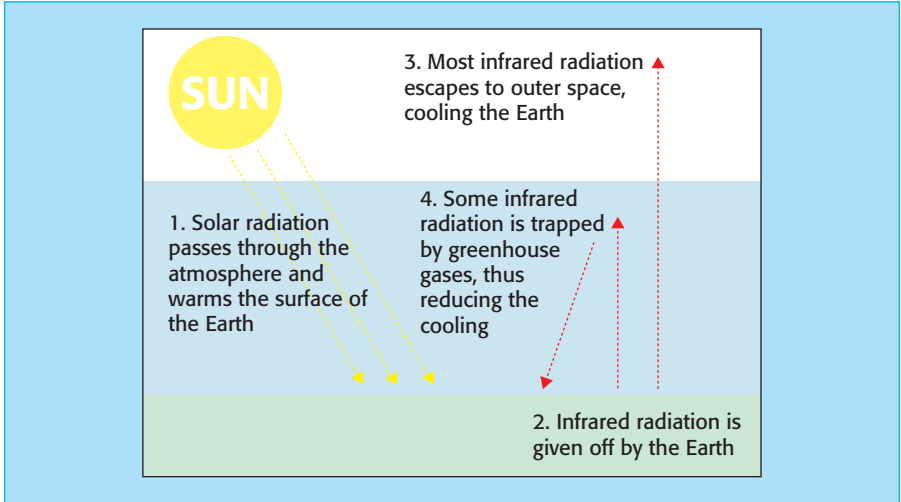


Figure 1.1 Rising levels of greenhouse gases

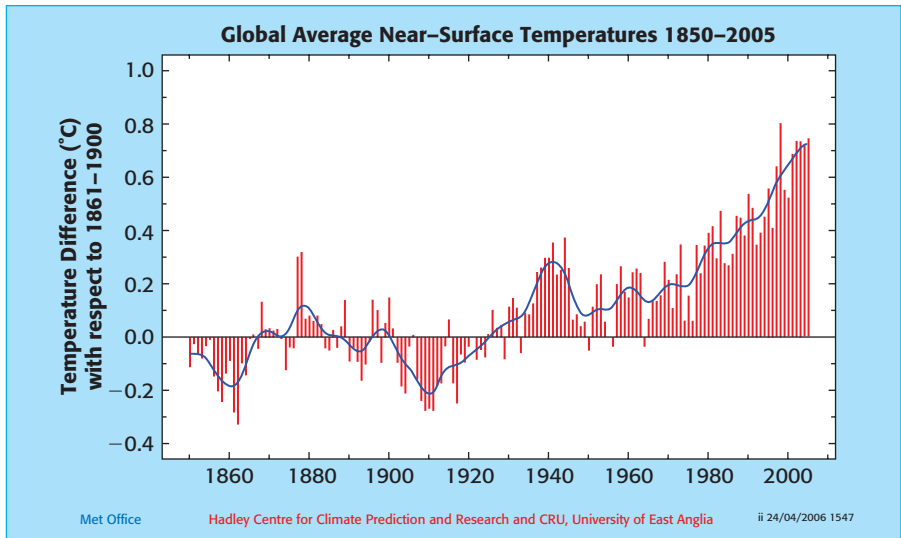
The figure shows the warming effect of greenhouse gases (the ‘radiative forcing’) in terms of the equivalent concentration of carbon dioxide (a quantity known as the CO₂ equivalent). The blue line shows the value for carbon dioxide only. The red line is the value for the six Kyoto greenhouse gases (carbon dioxide, methane, nitrous oxide, PFCs, HFCs and SF₆)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

- 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 CO₂ 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.
- 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 CO₂ equivalent) of all long-lived greenhouse gases from Figure 6.6, IPCC (2001b).

**Figure 1.2** The Greenhouse Effect

Source: Based on DEFRA (2005)

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

The figure above 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)

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 ago⁸. 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

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 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.

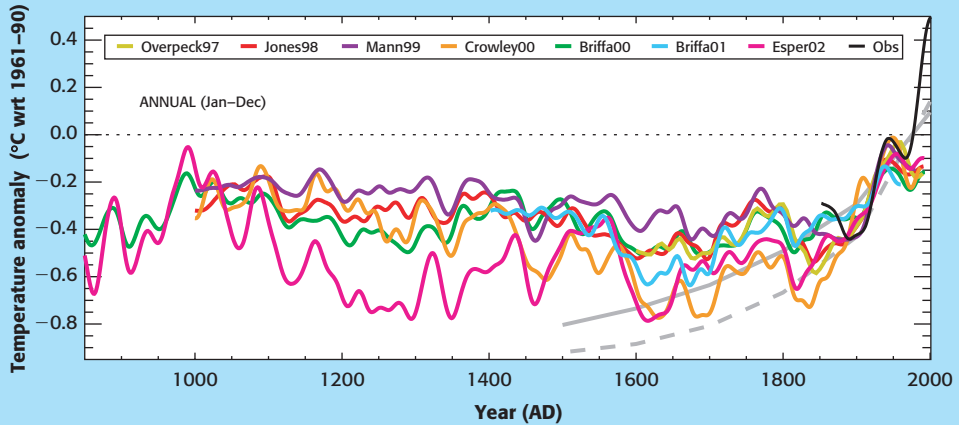
Climate change arguments do not rest on “proving” that the warming trend is unprecedented over the past Millennium. Whether or not this debate is now settled, this is only one in a number of lines of evidence for human induced climate change. The key conclusion, that the build-up of greenhouse gases 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.

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).

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 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 oceans¹², as well as the spatial distribution of warming¹³, 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.

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

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.

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 Arrhenius¹⁵. 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 atmosphere¹⁶. 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

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 600 ppm, a quarter at 1200 ppm and an eighth at 2400 ppm. 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.

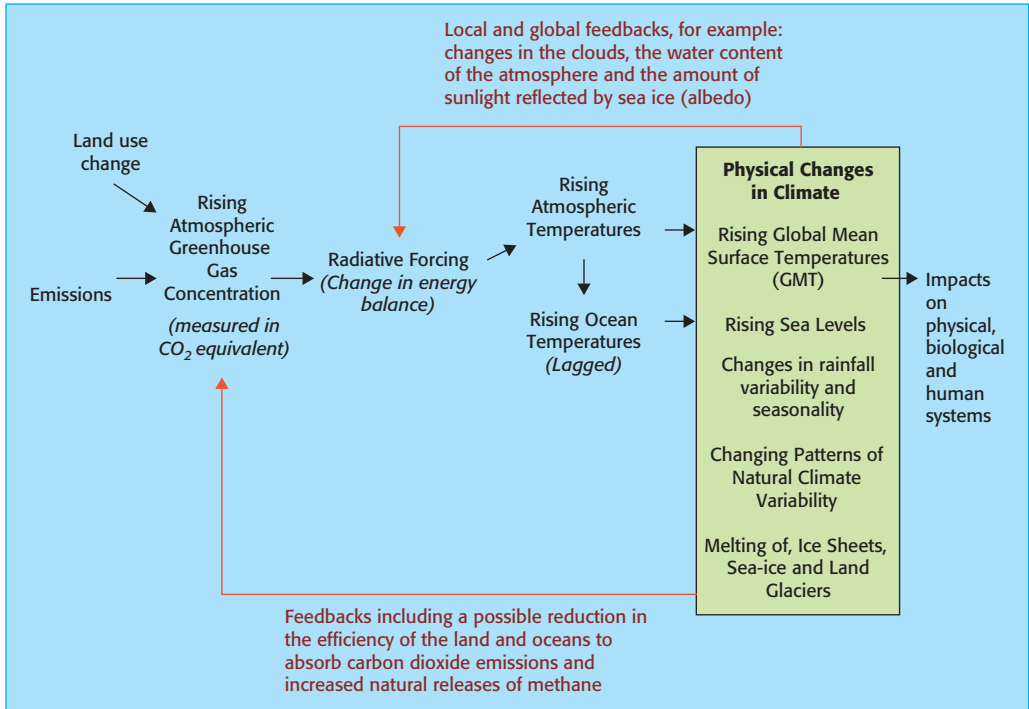


Figure 1.4 The link between greenhouse gases and climate change.

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.

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 CO₂e). 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 CO₂e), 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 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°C¹⁹. These sensitivities imply that there is up to a one-in-five chance that the world would experience a warming

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. Meinshausen (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.

¹⁸ Calculated using method shown in Meinshausen (2006).

¹⁹ Meinshausen (2006)