PART One

Introduction to Climate Change Issues and Consequences

CHAPTER 1

The Science of Climate Change

Richard A. Betts, PhD

Climate change is a complex scientific problem, but its implications could have major consequences for the human species and indeed the rest of the world. Moreover, human actions to reduce climate change and adapt to its effects could also have major consequences. In order to make informed decisions about our responses to the issue, we require robust scientific understanding of the issue and the likely consequences of our actions, or at least some grasp of the range of potential consequences if we are unable to be certain.

This chapter reviews the latest scientific conclusions about recent climate change and its causes, and discusses the implications of different levels and timing of emissions reductions. Climate science issues relating to adaptation to climate change are also discussed. Most of this chapter is grounded in the science described in detail in the volume "The Physical Science Basis" in the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC 2007), which is widely known as "AR4."[1] More recent work from the Met Office Hadley Centre is also discussed.

HUMAN-CAUSED CLIMATE CHANGE: THE EVIDENCE

A vast body of evidence demonstrates that the world is becoming warmer and that this is not a natural phenomenon—beyond reasonable doubt, humans are to blame. By gathering data from a wide range of sources, from weather stations to tree rings, from ice cores to computer models, we can

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Richard A. Betts is head of climate impacts at the Met Office Hadley Centre.

clearly see that the climate has already moved out of its previous natural state. This forms the bedrock of evidence that the human species is already influencing its own environment and can now choose whether to continue to increase this influence or reduce it.

The World Is Warming

One of the iconic measures of climate change is the global average temperature near the surface. This can be established for roughly the last 150 years from a worldwide network of weather stations on land and observations made aboard ships. In some places the observed temperature record extends farther back, but before 1860 the worldwide coverage was not sufficiently dense to provide a credible global average of thermometer-based measurements. The records show that global average temperature has risen by more than 0.7 degrees Celsius since the start of the twentieth century (Figure 1.1). The rise has not been steady; before 1940 there was a warming of around 0.3 degrees Celsius, then there was a cooling of approximately 0.2 degrees Celsius until 1950, followed by a renewed warming of 0.13 degrees Celsius per decade since then.

The world has been warmer over the last decade than at any time since measurements began. This warming is observed over the oceans as well as over land, suggesting that it is a truly global phenomenon and not a conglomeration of "local" warmings caused by some small-scale process such as the urban heat island effect. In AR4, the IPCC concluded that "warming of the climate system is unequivocal."

This Warming Is Unusual

But what about before our global network of thermometers was established? In the history of the Earth, 150 years is not long, and to establish whether the current warming is unusual we need to know more about temperatures farther into the past. Temperatures can be estimated from a variety of "proxy" evidence such as the patterns of growth in the rings of ancient trees, the distribution of particular species as indicated by their pollen found in the soil, and the chemical composition of air bubbles trapped in ancient ice. A number of independent studies have used these lines of evidence to reconstruct northern-hemisphere temperatures over the last 1,000 years or more (Figure 1.1), and while they do not agree with each other perfectly, they all indicate that the temperatures of the last 50 years are likely to be the highest in any 50-year period in the last 1,300 years. (The IPCC indicates an outcome or result as "very likely" if expert judgment assesses the probability

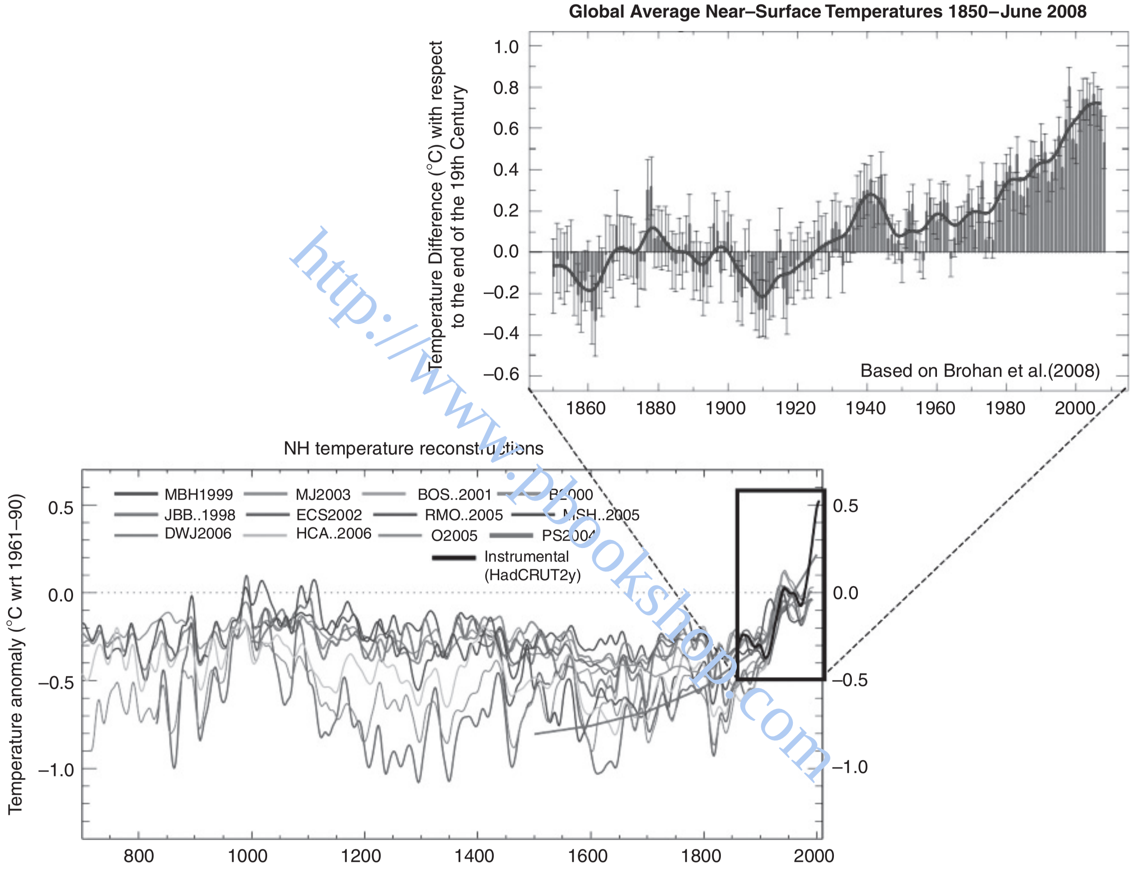

FIGURE 1.1 Historical records and reconstructions of past climate change and variability.
Sources: IPCC, 2007 (main figure), Met Office, British Crown Copyright (inset).

of occurrence to be greater than 90 percent. "Likely" is defined as a greater than 66 percent probability.)

The millennial reconstructions in Figure 1.1 include the famous "Hockey Stick" graph of Mann, Bradley, and Hughes (1999) (here labeled MBH99), which was targeted by climate skeptics following its publication in the IPCC Third Assessment Report. Although subsequent studies and reanalysis led to slightly different reconstructions of past temperatures, all studies show the common feature of the twentieth-century warming being highly unusual in comparison with the previous millennium.

Other Changes Are Consistent with Warming

Changes have also been seen in other aspects of the climate system. Snow cover and mountain glaciers have shrunk, and some melting of the Greenland and Antarctic ice sheets has been measured. Global average sea level rose by approximately 17 cm over the twentieth century, partly because of the additional water in the ocean basins arising from the melting of ice on land, and partly because water expands when it warms. Patterns of precipitation (rainfall and snowfall) have also changed, with parts of North and South America, Europe, and northern and central Asia becoming wetter while the Sahel, southern Africa, the Mediterranean, and southern Asia have become drier. Intense rainfall events have become more frequent. In Europe, Asia, and North America, growing seasons have extended, with flowers emerging and trees coming into leaf several days earlier in the year than in the mid-twentieth century.

Carbon Dioxide and Other Greenhouse Gases

Some gases such as water vapor, carbon dioxide (CO_2), methane, and nitrous oxide are known as greenhouse gases (GHGs). They absorb and re-emit some of the heat radiation given off by the Earth's surface, hence warming the lower atmosphere. These gases occur naturally in the atmosphere, and without their warming presence in the atmosphere the Earth's average surface temperature would be around −20 degrees Celsius. In terms of its contribution to the natural greenhouse effect, the most important is water vapor, followed by CO_2. However, the concentrations of CO_2, methane, and nitrous oxide have shown a rapid increase over the past 200 years, and this increase is accelerating (Figure 1.2). Records extending back 10,000 years have been obtained by analyzing the chemical composition of air bubbles trapped in ancient ice (Figure 1.2, main panels), and in the 1950s, actual instrumental measurements of CO_2 and other GHGs began to be taken. These are now routinely taken at a number of locations around the world,

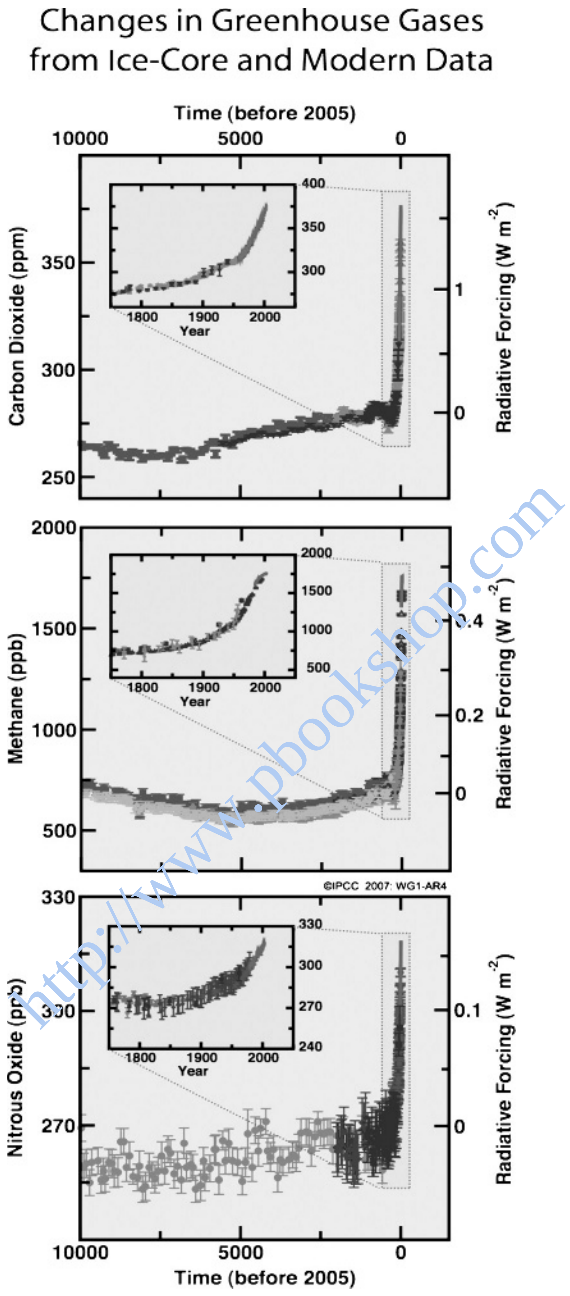

FIGURE 1.2 Historical records of the atmospheric concentrations of three major greenhouse gases: CO_2, methane, and nitrous oxide.
Source: IPCC, 2007.

including Mauna Loa observatory in Hawaii, the South Pole, and Cape Grim in Tasmania (Figure 1.2, insets). Together, these records show that the concentrations of these greenhouse gases are all rising rapidly, and that these rises are unique in the past 10,000 years. It is this increasing concentration of these gases, rather than the background levels, that is of relevance to the issue of climate change.

Changes in the atmospheric concentration of CO_2 are a consequence of shifts in the balance of very large flows of carbon into and out of the atmosphere. In the natural system, CO_2 is produced through the chemical combination of carbon with oxygen in the process of respiration, most of which is a natural part of biological processes in soils, vegetation, plankton, and animals, such as breathing and decay. Some CO_2 is also produced by combustion of vegetation—in other words, forest fires. These are natural sources of CO_2. Opposing these are the processes that take up CO_2 from the atmosphere, such as photosynthesis by plants, which combines CO_2 with water to produce sugars that store the energy absorbed from the sun during the process. Further uptake of CO_2 involves the dissolving of CO_2 in water (mostly in the oceans) from which it can then be extracted by plankton. These latter processes provide sinks of CO_2. All life on earth contains carbon, and indeed the vegetation, soil microbes, plankton, and higher life forms collectively store more carbon than is present in the atmosphere. Very large quantities of carbon are also held as dissolved CO_2 in seawater. So the "carbon cycle" as described here consists of flows of carbon between large stores in the atmosphere, ocean, and life.

The rates of release and removal of CO_2 by these processes are affected by environmental conditions, such as the concentration of CO_2 in the atmosphere, the temperature, and the availability of moisture for plant growth. Hypothetically, if environmental conditions were unchanging, the natural flows of CO_2 into and out of the atmosphere would balance out and the atmospheric CO_2 concentration would not be changed. Even though the flows in each direction are large, in a balanced system they could in theory cancel each other out.

However, the balance is currently being upset by the addition of further sources of CO_2, particularly the combustion of fossil fuels—coal, oil, and natural gas. These substances are the remains of vegetation and plankton from millions of years in the past, which were buried underground or beneath the ocean floor. The carbon stored within them, as described above, becomes coal and oil. The energy that was stored as sugars as a result of photosynthesis is held within these substances and their concentrated form means that a small quantity of coal or oil can hold considerable quantities of energy that can then be released when the coal or oil is burned, hence their value as fuels. However, burning of these fuels rapidly releases CO_2

that was previously removed over millions of years and held away from the atmosphere underground. This is therefore an extra release of CO_2 that tips the balance between sinks and sources.

Greenhouse Gas Concentrations Are Increasing Due to Our Emissions

Further records of air bubbles in ancient ice show us that CO_2 is now at its highest concentration for more than 650,000 years. We know for certain that combustion produces CO_2, and we know for certain that we have been burning fossil fuels at ever-increasing rates over the last 200 to 300 years. From international records of energy consumption, it is easy to calculate the quantity of CO_2 that has been produced by burning fossil fuels; by 2000 this had reached around billion tonnes of CO_2 per year, having risen by over 1 percent per year over the previous 20 years. In total, we have emitted over a trillion tonnes of CO_2 since fossil fuel burning began, which is more than enough to account for the rise in CO_2 in the atmosphere. Indeed, the rate of rise of CO_2 in the atmosphere is only about 60 percent of the rate of emission from fossil fuel burning (Figure 1.3a); some of the additional CO_2 is absorbed through an increase in photosynthesis by vegetation and an increased dissolving of CO_2 in ocean waters (Figure 1.3b). It is worth noting

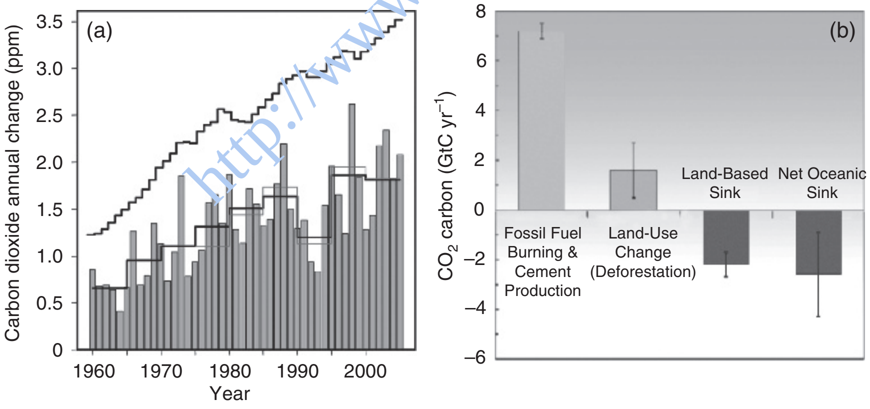

FIGURE 1.3 The role of carbon sinks in buffering us from the full effect of our CO_2 emissions. (a) Annual emissions of CO_2 from fossil fuel burning (upper stepped line), and annual change in atmospheric CO_2 concentration (lower bars). (b) Emissions from fossil fuel and deforestation, partly offset by uptake of carbon by land ecosystems and the oceans.
Source: IPCC, 2007.

that this uptake is affected by the climate itself, so if this changes as a result of climate change, this would be a feedback on the atmospheric CO_2 rise.

Moreover, we have also been clearing the world's forests to make way for farmland or degrading them through logging, and since forests lock up carbon within their biomass, their removal (which again often involves combustion) inevitably leads to a further release of CO_2 to the atmosphere. Therefore, we are certain that the observed increase in CO_2 in the atmosphere has resulted from a combination of burning fossil fuels and deforestation. It is less easy to determine the exact contribution of each of these sources, but the current best estimate is that fossil fuel burning has contributed approximately three quarters of the current excess of CO_2 above preindustrial levels, and deforestation has provided approximately the remaining quarter. Cement production also makes a small contribution.

Methane and nitrous oxide, two other GHGs, are also at record high levels. Most methane emissions and one third of nitrous oxide emissions are from human activities, largely agriculture.

Humans have also introduced new GHGs of their own, the "halocarbons" such as chlorofluorocarbons or CFCs (which, incidentally, have also damaged the ozone layer in the stratosphere). While CO_2, methane, nitrous oxide, and the halocarbons by themselves do not contribute as much to the overall greenhouse effect as water vapor, they are increasing because of human activity. However, water vapor is not directly affected by humans to any appreciable degree. The fact that CO_2 and the other human-affected GHGs are increasing leads to an enhancement of the greenhouse effect and hence a warming influence on climate.

The Observed Warming Is Very Likely to Be Human Caused

Because an unusual rise in temperatures across the globe has coincided with a unique and man-made rise in the concentration of gases known to exert a warming influence on the Earth, this suggests a role of human-induced GHG concentrations in this warming. However, while this provides strong circumstantial evidence for a human influence on climate, it does not provide a rigorous scientific test of the theory. There are many other processes that could cause climate change and have done so at various times in the history of the Earth—for example, changes in the output of energy from the sun, or changes in the Earth's orbit or the tilt of its axis, which affect how much of the sun's energy is received by the Earth and its distribution across the Earth's surface. Large volcanic eruptions can inject very large quantities of aerosol high into the atmosphere, where they can spread around the globe and cool the Earth by blocking solar radiation. Also, as well as these "externally forced" variations in the energy received from the sun, natural "internal" variability in the climate such as shifts in ocean currents and wind patterns can lead to warmer and cooler periods over years, decades, and longer. To be confident in the causes of the current warming, and hence make predictions about the future, it is necessary to go beyond mere correlations and do more rigorous scientific studies.

The established scientific method for explaining a phenomenon is to carry out a controlled experiment in which two (or more) samples are examined, with one sample being subject to a deliberate change while another is held unchanged. Clearly, this method cannot be applied to the Earth, since we have only one! However, it is possible to construct a "virtual Earth" using well-established laws of physics and measured chemical and biological processes, and conduct controlled experiments on this instead. Such a virtual Earth takes the form of a computer model, which brings together a vast array of understanding of the Earth's atmosphere, oceans, and life, and represents the physical, chemical, and biological processes in the form of mathematical equations solved by a computer program. For example, the models simulate the global patterns of wind; the flows and changes of water, energy, and chemical compounds between atmosphere, land, and ocean; and the biological processes that affect these. They simulate the cycling of water through precipitation on the land and ocean, the flow of rivers to the ocean, evaporation back to the atmosphere from land and ocean, the condensation of water vapor back to liquid water ready for precipitation again, and the freezing and melting of ice at various points in the water cycle. The models simulate the energy that the planet receives from the sun, the proportions that are reflected back to space by clouds or that reach the surface, and the proportions of the latter that are absorbed by the surface or reflected. They also simulate the emission of energy from the Earth's surface and the proportion that is absorbed in the atmosphere through the "greenhouse effect"; again, clouds are also important here, as they also reduce the loss of energy to space. These processes are affected by the chemical composition of the atmosphere, particularly the concentrations of GHGs such as water vapor, CO_2, and methane, and again this chemical composition is simulated by the models. Large-scale ecosystem changes such as deforestation are also included in many models, and these affect the absorption of energy at the surface, the evaporation of water, and the release and uptake of CO_2 and some other GHGs.

The equations themselves have been established through careful observations, measurements, and experiments both in laboratories and in the outside world, by countless scientists from Isaac Newton onward. They are central to other aspects of physics, chemistry, and biology, as well as being the building blocks of computer models of climate. The climate models bring these equations together to provide an integrated view of the workings of the planet, and once again the models are tested and refined by comparison against observations. The very same computer models are used to provide weather forecasts on a daily basis, and the fact that such models are now able to generally provide accurate weather forecasts lends confidence to the idea that they are reasonably good representations of how the world works.

With our virtual Earth, we can now "play God" and subject our mathematical planet to changes such as increases in the concentrations of GHGs and aerosols, changes in forest cover, and changes in the energy received from the sun. We can examine the effects of these acting together and in isolation from each other (Figure 1.4). Climate models can be used to estimate how the climate of the twentieth century should have evolved in the absence of human influence, driven only by natural forcings (changes in the sun and volcanoes) (pink bands in Figure 1.4). These simulations do not account for the warming seen in the last decades of the twentieth century (black lines in Figure 1.4). The climate models agree with the observed past climate change only when they additionally include the human-induced forcing of increasing concentrations of GHGs and aerosols (blue bands in Figure 1.4), hence suggesting that the observed warming is human induced.

We can also examine a climate state with no external influences, to assess the magnitude and rate of the year-to-year and decade-to-decade natural cycles of warming and cooling associated with shifts in wind patterns and ocean circulation. By comparing a variety of such simulations with the observed record of past climate, and seeing which model setup agrees best with reality, we can establish further evidence for the causes of climate change. This technique is more sophisticated than simply comparing year-by-year global average temperatures; the geographical patterns of change are also compared, allowing the "climate fingerprint" of different causes of change to be examined against the "fingerprint" of the real change, and climate change is only attributed to a particular cause (or set of causes) if the fingerprints agree within established bounds of statistical significance. While this technique obviously relies on the model's being realistic, it should be remembered that the models are grounded in well-established science and are tested against other data.

Such "detection and attribution" studies have been carried out by a number of independent groups of climate scientists around the world and all agree that the rise in temperature observed over the last 30 to 40 years cannot be explained without the rise in GHG concentrations (Figure 1.4). If only natural factors are taken into account, the computer models do not produce a warming over this period. Although the energy received from the sun (solar irradiance) has increased slightly relative to preindustrial times, the warming influence of this is less than one thirteenth of that due to the total effect of man-made changes. Moreover, solar irradiance has not increased since the 1970s and so cannot account for the warming seen more recently.

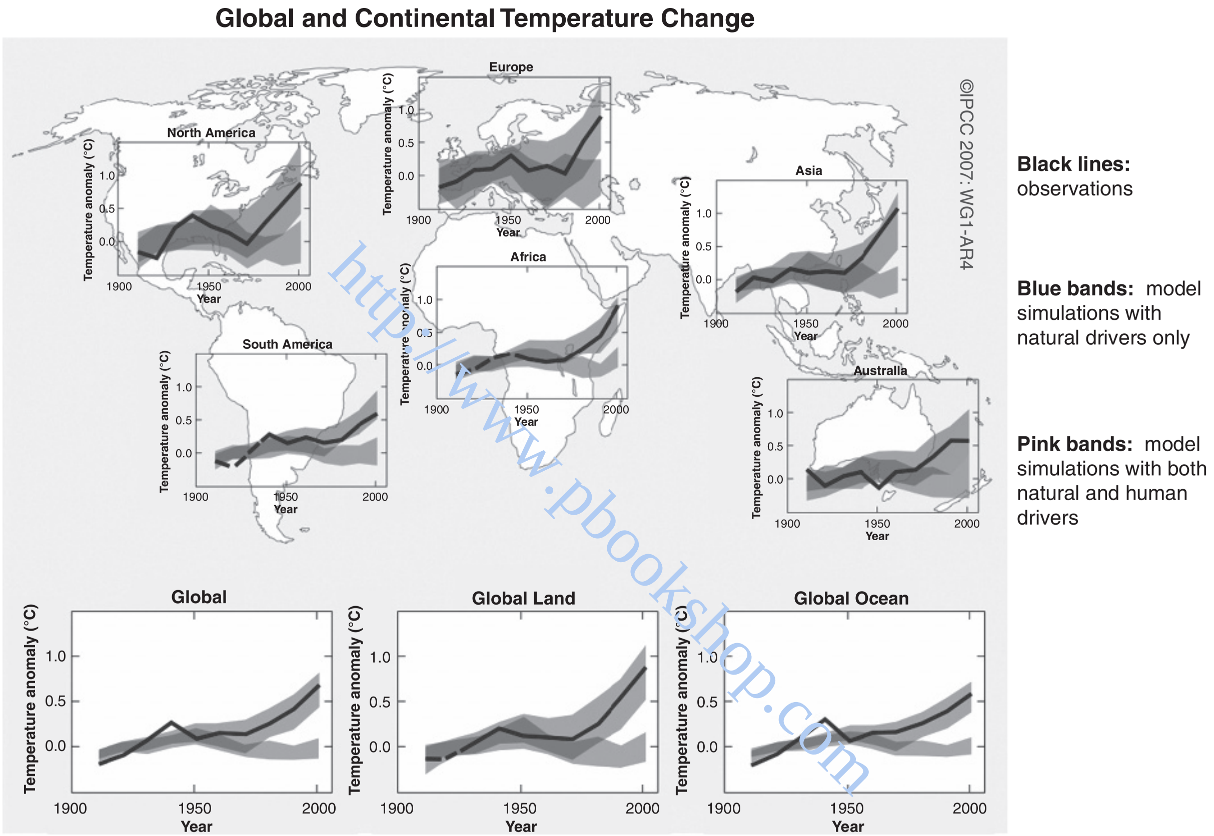

FIGURE 1.4 Using climate models to explain the observed rise in temperature (black lines). Simulations without human influence on climate (pink bands) do not reproduce the observed changes; this requires simulations with human influence through greenhouse gases and aerosol emissions (blue bands).
Source: IPCC, 2007.

Internal variability in the climate system does not appear to produce such rates of warming. The conclusion of the IPCC AR4 is therefore that "most of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic GHG concentrations" (IPCC 2007).

We Are Shielded from the Full Warming by Other Pollution

At the same time as increasing GHG concentrations, we are also increasing the already-vast number of particles in the atmosphere. These particles are technically known as "aerosols," but are not to be confused with the spray cans of the same name. As with GHGs, some kinds of aerosols occur naturally, examples being dust, volcanic ash, sea salt, spora from plants and dimethylsulphide (DMS) from plankton. However, many are produced by human activity, mostly from burning fossil fuels. Burning wood also produces aerosols, so forest clearance and its use as fuel both increase aerosol concentrations. Additionally, desertification can increase the release of dust.

Aerosols have complex effects on climate. One effect is a cooling, since many of the particles cause some of the sun's energy to be reflected back into space, either directly through their own brightness or indirectly by increasing the brightness or lifetime of clouds. But aerosols can also absorb some of the sun's energy or some of that given off by the Earth's surface, with both processes giving rise to a warming effect. The overall effect of all aerosols is to exert a cooling influence, although the precise strength of this cooling is less certain than the warming effect of GHGs since it is more difficult to measure.

Somewhat ironically, the full rate of warming due to GHGs has not been realized because of the corresponding increase in aerosol concentrations, which is exerting a cooling effect to partly offset the greenhouse warming. Moreover, the rate of rise of CO_2 in the atmosphere is only about half of the rate of emissions from fossil fuel burning because some of the CO_2 is being absorbed by the world's vegetation and ocean waters (see Figure 1.3b). Therefore, we have been buffered from the full effect of our GHG emissions, partly by a service provided by the biosphere, and partly by a further consequence of our own pollution.

OTHER HUMAN INFLUENCES ON CLIMATE

While human-caused increases in GHGs are the main influence on current climate change, with aerosol pollution having a secondary influence, humans are also exerting other effects on climate through our transformation of the land surface and our release of energy into the environment. While land cover change and urbanization do not contribute significantly to global warming, they do influence climate at a local level, especially in the most densely inhabited parts of the world. These effects therefore need to be accounted for when assessing the impacts of future climate change on human health and our society's infrastructure.

Land Cover Change

The world's vegetation cover plays other vital roles in the climate system. As well as providing carbon sinks and stores, land ecosystems also affect climate through their influence on the character of the Earth's surface. For example, forested landscape absorbs more of the sun's energy than unforested land, so it can exert a warming influence in comparison with the unforested land, which reflects more of the sun's energy back to space. However, forests also evaporate water more than unforested land, so they can also exert a cooling influence. The relative importance of these effects depends on the local background climate. In regions where snow lies for much of the year, the difference in albedo between forests and open land are more accentuated; if you have ever flown over Canada or Siberia in winter, you may have seen how the forests stand out as black against the bright, white snow fields. In these cold regions, relatively little evaporation is occurring and the albedo effect dominates, so forests exert an overall warming influence. In contrast, tropical forests are in regions of very high evaporation and the difference between their albedo and that of snow-free tropical grasslands is not as significant, so the overall effect of tropical forests is to cool their local environment. Tropical forests also recycle significant quantities of rainwater back to the atmosphere, which maintains high rainfall in those regions.

Changes in land cover through deforestation and afforestation therefore affect climate through the changes in these physical properties of the land surface. In particular, tropical deforestation exerts two warming influences on climate, the first through the release of CO_2 to the atmosphere, adding to the enhanced greenhouse effect, and the second by reducing evaporation (and the associated cloud cover).

Urban Effects

Urban areas affect their own local climate both through the physical properties of the landscape and partly from the release of heat into the environment by the use of energy for human activities such as heating buildings and powering appliances and vehicles. As a result, urban areas tend to be warmer than their rural surroundings, a phenomenon known as the “urban heat island” effect. The contribution of urban heat islands to the global average temperature rise is negligible; cities cover an estimated 0.046 percent of the Earth’s surface (Loveland et al. 2000), so the aggregate effect of all the local urban heat islands to the global average temperature is small. Averaged over the entire globe, the heat flux from urban areas is estimated as 0.03 watts per square meter of the Earth’s surface (Nakićenović, Grübler, and McDonald 1998), which is less than 1 percent of the total perturbation to the Earth’s energy balance (“radiative forcing”) through human-induced increases in GHGs. Weather stations in or near urban areas are excluded from the records used to monitor global average temperature, in order to avoid contaminating the record with urban effects. Moreover, warming is also observed in sea surface temperatures thousands of kilometers from any city, so it is clear that urban effects are not a significant contributor to global warming.

However, urban effects do need to be taken into account if projections of local climate change are required, for example, for planning for adaptation to climate change. The local effects of human energy production can be very large indeed; in central London, the heat release is approximately 60 W m^{-2}, and daytime values in central Tokyo typically exceed 400 W m^{-2}, with a maximum of 1,590 W m^{-2} in winter (Ichinose, Shimodozono, and Hanaki 1999). Therefore, plans to adapt urban infrastructure or protect human health in a changing climate need to consider urban effects as well as greenhouse-forced climate change.

CHALLENGES IN PROJECTING FUTURE CLIMATE CHANGE

The implication of the evidence is that continued deforestation and burning of fossil fuels will inevitably lead to further changes in climate. The complexity of the climate system is such that the extent of such warming is difficult to predict, but the same computer models that are used to attribute climate change to its causes can be used to provide an estimate of future warming if provided with scenarios of GHG and aerosol emissions.

There are large uncertainties in the rate and extent of future warming, as is evident from the fact that the IPCC gives a range of figures for the warming rather than a single number. While there is sufficient confidence in our understanding of the climate system to make generalized projections for the future, there are still major gaps in our scientific understanding. Therefore, the approach is more one of assessing risks of particular changes and their rates, rather than making firm predictions.

The uncertainties in predictions of climate change arise from four main reasons:

1. The unknown future of GHG emissions. To a large extent this depends on whether action is taken to halt and reverse the current trend for increasing emissions. However, even if "business-as-usual" continued, it is not clear what this would mean for emissions—even in the absence of specific climate policy, emissions will depend on factors such as population growth, development of technology, and the nature and condition of the global economy.
2. Uncertainties in translating emissions into GHG concentrations, especially since this depends on the ecosystem's service of carbon reabsorption described earlier, which itself is affected by climate change.
3. Uncertainties in the response of the global climate to a given change in GHG concentrations.
4. Uncertainties in climate change and variability at local scales.

Emissions Scenarios

A key factor for future climate change will be the quantity of GHG emissions. These will depend on the population, their lifestyle, and the way this is supported by the production of energy and the use of the land. A large population whose lifestyle demands high energy consumption and the farming of large areas of land, in a world with its main energy source being fossil fuel consumption, will inevitably produce more GHG emissions than a smaller population requiring less land and energy and deriving the latter from nonfossil sources. These factors could vary in a multitude of ways; the international community is already examining how energy demand and production can be modified to cause lower emissions, but the implementation of this will depend on both the international political process and the actions of individuals. Even if no specific action is taken to reduce emissions, the future rates of emissions are uncertain since the future changes in population, technology, and economic state are difficult if not impossible to forecast. Therefore, rather than make predictions of future emissions, climate science examines a range of plausible scenarios in order to examine the implications of each scenario and inform decisions on reducing emissions and/or dealing with their consequences.

The IPCC's climate models have generally used a set of scenarios from the Special Report on Emissions Scenarios (SRES; Nakićenović et al. 2000). These scenarios were grounded in plausible story lines of the human socioeconomic future, with differences in economy, technology, and population but no explicit inclusion of emissions reductions policies. A large number of

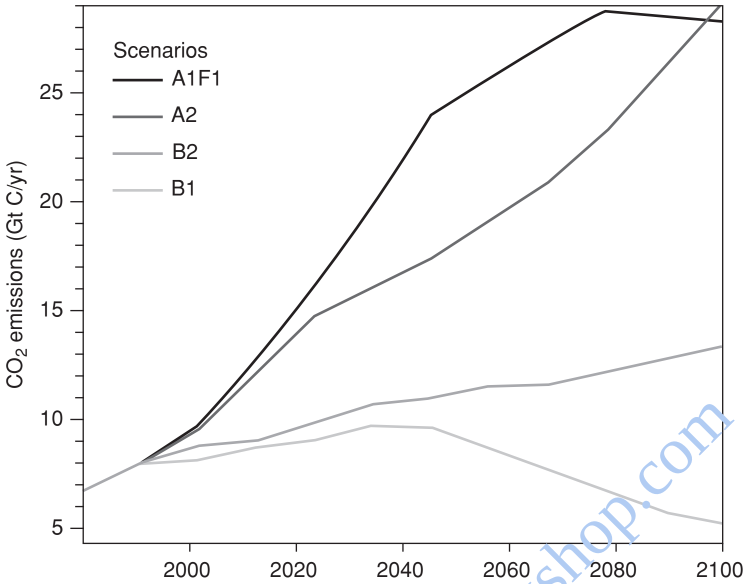

FIGURE 1.5 Four of the IPCC SRES CO_2 emissions scenarios used to drive climate models out to 2100, expressing emissions as gigatonnes (billion tonnes) of carbon per year (Nakićenović et al., 2000).
Source: Met Office, British Crown Copyright.

these scenarios were developed in the mid-1990s, and four particular scenarios shown in Figure 1.5 illustrate the range of futures assessed and have been used to drive climate models to assess their climatic consequences. These scenarios extend out to 2100 and vary widely in their projected emissions by that time (Figure 1.5), although none of them include a reduction in emissions through climate policy. The A1FI scenario describes a future world of very rapid economic growth, global population that peaks in midcentury and declines thereafter, with convergence among regions and decreasing global differences in per capita income. New technologies are introduced rapidly, but with a continued intensive use of fossil fuels. The B1 scenario describes the same pattern of population change as A1FI but with much greater emphasis on clean and resource-efficient technologies, with global solutions to economic, social, and environmental sustainability and improved equity. The A2 scenario describes a heterogeneous world with a continuously increasing population, regionally oriented economic development, and fragmented per capita economic growth and technological change. The B2 scenario also features ongoing population growth but at a lower rate than A2, and with less rapid and more diverse technological change than A1FI and B1. As with B1, B2 is oriented toward environmental protection and social equity, but focuses on local and regional levels.

So far, actual emissions have been near the upper end of the range suggested by the scenarios,[2] but emissions reductions are now high on the international political agenda. There is a need to examine a wider range of scenarios, both above and below the main SRES range, in order to help determine the effects of different levels of emissions cuts or of potential further acceleration of emissions. New scenarios will be used in the IPCC Fifth Assessment Report in order to assess the consequences of different levels of ongoing emissions, from a high rate of “business as usual” to scenarios of deep emissions cuts.

Translating Emissions to Concentrations: Importance of a Weakening Natural Carbon Sink

It is important to recognize the distinction between GHG emissions and the concentration of GHGs in the atmosphere. These are not the same thing and they do relate to each other in a simple way. CO_2 does not undergo chemical reactions in the atmosphere, so emissions to the atmosphere are only countered by removal by vegetation growth, dissolving in ocean waters or rock weathering. These are slow processes, so a large proportion of a given quantity of emissions remains in the atmosphere for decades to centuries. The concentration of CO_2 in the atmosphere at any time depends not only on the recent emissions but also the history of emissions and removals over many previous decades. A key consequence of this is that changes in emissions, such as reductions that may result from international agreements, are unlikely to significantly affect the ongoing rise in CO_2 concentration for many years. Since global temperatures take decades to respond in full to a given change in GHG concentrations, we are therefore largely committed to ongoing CO_2 rise and warming for some time. However, beyond a few decades away, the rate of CO_2 rise and warming would be impacted by any emissions cuts that began now. Therefore, while some further change is already unavoidable, action to reduce emissions in the near future could still reduce climate change in the longer term.

A key uncertainty in translating emissions into concentrations arises from uncertainty in the strength of the land and ocean carbon sinks. Since these sinks currently slow the rate of CO_2 rise, the rise in concentrations would be more rapid if the natural carbon reabsorption service is weakened. There is evidence that this may occur through three processes: photosynthesis ceasing to increase as CO_2 rises, some areas of forest dying as a result of a drying climate, and plant respiration and rates of decay in the soil increasing more rapidly with warming. At current levels, an increase in CO_2

concentration leads to an increase in photosynthesis, resulting in an uptake of CO_2 from the atmosphere by plants across the world. This process partly offsets our emissions of CO_2 and helps to slow the rise of CO_2 concentrations in the atmosphere. However, experimental studies demonstrate that this process has a limit, and the increase in photosynthesis becomes smaller and smaller as CO_2 concentrations become higher. The ecosystem service of an uptake of CO_2 therefore becomes weaker. Moreover, climate models project changes in local climates, which themselves could affect the ability of global vegetation to buffer us against the CO_2 rise. One key example is the possible reduction in rainfall over Amazonia. About 1,500 mm of rainfall per year are required to support a rainforest, and some models project the rainfall to fall well below this level during the second half of the twenty-first century. Such a drying would increase the frequency of forest fires and prevent the subsequent regrowth of dense rainforest vegetation. The carbon currently locked up within the forest biomass would therefore be released to the atmosphere, accelerating the CO_2 rise.

Finally, experimental studies suggest that the process of decay in the soil becomes more rapid under warming temperatures. Decay involves a release of CO_2 to the atmosphere, and since the world's soils currently contain more than twice as much carbon as the atmosphere, such an increase in decay worldwide could potentially be a very large feedback on the CO_2 rise and climate warming.

Just How Responsive *Is* the Climate System?
Uncertainties in Climate Sensitivity

Another source of uncertainty in projecting future climate change arises from difficulties in establishing the response of global temperatures to a given rise in GHG concentrations. This may seem like an easy problem to solve because we can measure GHG concentrations and temperatures well enough to be very confident that both are increasing. In theory, the problem can be expressed as a simple equation with three terms: radiative forcing, climate sensitivity, and climate response. In this conceptual model, radiative forcing is the driving force of change, in the form of a change imposed on the Earth's energy balance. The climate sensitivity is the change in global average temperature to a given radiative forcing, representing how responsive the climate is to an imposed change. The climate response is the final result. However, although we can estimate the radiative forcing due to GHGs quite precisely, the problem is made more difficult by the other contributions to the overall radiative forcing such as aerosols. As described above, the extent of the cooling influence of aerosols has not yet been established with much precision, which means that the net radiative forcing of GHGs and aerosols together is also not very well known. Therefore, although we know the final climate response from our temperature measurements, we do not precisely know the forcing causing this response and therefore cannot estimate climate sensitivity precisely, either. Different climate models give different estimates of climate sensitivity, often related to the strength of cloud feedbacks.

A key issue arising from this is that we do not know the extent to which aerosols are masking the true effect of GHGs. If the current aerosol cooling is strong, this implies that the greenhouse warming that it is partly counteracting must also be strong. This is an issue because aerosol emissions can be reduced more easily than GHGs, and also aerosol particles are washed out of the atmosphere within days, whereas CO_2 is gradually taken up by the ocean and land ecosystems over decades and centuries. Therefore, it would be relatively easy to reduce the aerosol cooling effect, and therefore unveil the full warming effect of GHGs.

Butterflies and Pooh Sticks: Challenges in Predicting Regional Climate Change

A further difficulty for climate scientists arises from the inherently chaotic nature of the atmosphere and oceans. While the processes in the atmosphere and oceans are governed by the laws of physics, these laws include those of "chaos theory" in which very small differences at the start of a process can lead to enormous differences in the final outcome. This was illustrated by Ed Lorenz with the classic "butterfly effect," asking "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" Tiny changes in wind, such as would be caused by the butterfly's wings, can influence other, larger wind flows, which in turn influence still larger winds until some major event is affected. While a tornado could be "set off" from such a small start, equally another tornado could be prevented from happening.

The reason this is relevant to weather and climate modeling is that it is impossible to measure and model the atmosphere to infinite precision, and even the small approximations necessary in the measurements and models can lead to differences in the outcome. Minuscule changes in the numbers put into a model lead to different results, so this poses a limit on what is predictable, at least in terms of day-to-day weather. This is why weather forecasts for individual days are currently given only up to about a week ahead—any farther ahead and the effects of today's butterflies are magnified so much as make precise forecasting impossible. Since we do not include butterflies in our measurements of today's weather, we cannot hope to capture their effects when they become large enough to matter. And even if we could know where all the butterflies are and how hard they are flapping, there would still be some further level of detail we cannot capture.

But while day-to-day local weather cannot be forecast very far ahead, average or likely conditions over longer times and larger scales can be more predictable when large, slow oceanic changes or large drivers of change from outside are involved. A good example is the game of "Pooh Sticks"—we can throw several sticks into a river and know that they will all be carried downstream with the current, and run to the other side of the bridge to watch them come out, but it is much harder (if not impossible) to predict which one will win the race because that depends on the individual swirlings in the water. Similarly, we can be confident that trapping more heat radiation from the Earth by increased GHG concentrations will cause a general warming on average over the coming decades, and can make projections of the general nature of changes in the atmospheric circulation. However, the local details of weather depend on smaller-scale processes that again are much harder to predict even on average, let alone for particular years or months in the future. Understanding these processes and using them to improve predictability is a major focus for climate research.

FUTURE CLIMATE CHANGE WITH AND WITHOUT EMISSIONS REDUCTIONS

So far, the main focus of IPCC climate projections has been to assess the long-term impacts of climate change over the coming century if no action is taken to reduce emissions, in order to assess the consequences of "business as usual" and establish whether there is indeed a need to reduce emissions. More recently, with the need for emissions reductions now widely accepted, there are new requirements to assess the consequences of different levels of emissions cuts, in order to inform climate policy negotiations in more detail. Again, these studies focus on the long-term timescales of the middle to the end of the century. However, with adaptation to climate change also becoming recognized as necessary even if emissions are reduced, there is also a further need to assess the local-scale climate changes to which we need to adapt. In many cases, decisions for adaptation planning require projections of changes and variability in the nearer term, over the next few years or decades, as these are the timescales for which planning needs to begin now. Consequently, climate models are now being used for an increasing variety of projections, to inform an expanding portfolio of decisions.

Projections of Change if No Action Is Taken

The IPCC SRES emissions scenarios have been widely used as input to climate models to project likely further global warming over the coming century if no action is taken to reduce emissions; these models project warming

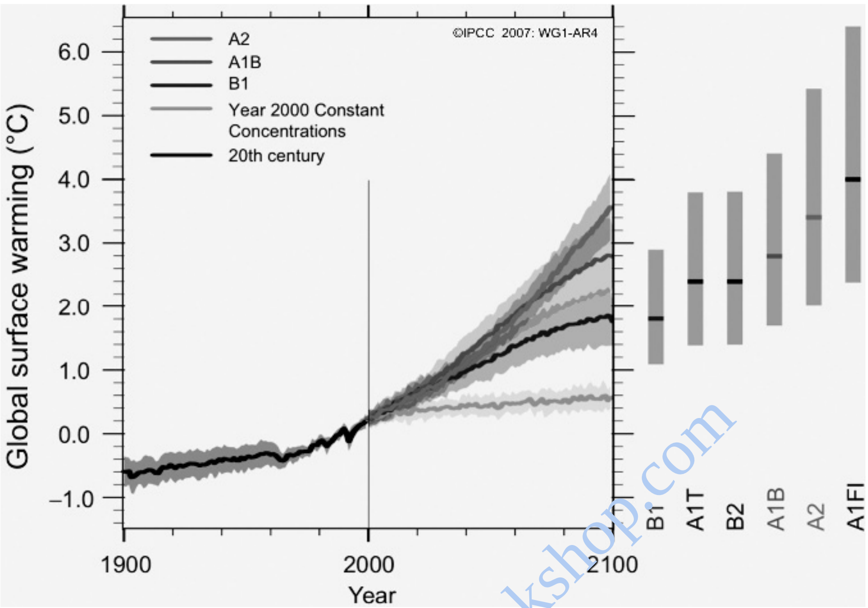

FIGURE 1.6 Projected changes in global mean temperature resulting from the main IPCC SRES emissions scenarios.
Source: IPCC, 2007.

of between 1.0 and 6.4 degrees Celsius by the end of the twenty-first century (Figure 1.6). The range of results reflects the uncertainties in "business as usual" emissions, uncertainties in translating emissions to concentrations, and uncertainties in the climate response to a given level of GHG concentration increases.

Sea level is projected to rise by between 28 cm and 58 cm, and snow and sea ice cover are projected to shrink. Some models suggest that the Arctic could be ice free in late summer by the latter part of the twenty-first century. Heat waves and extreme rainfall events are projected to increase. Although the number of tropical cyclones is tentatively projected to decrease, their intensity is projected to increase.

These changes would not be spread uniformly around the world. Some regions will warm faster than the global average, while others will warm less. Faster warming is expected near the poles, as the melting snow and sea ice exposes the darker underlying land and ocean surfaces, which absorb more of the sun's radiation instead of reflecting it back to space as bright ice and snow do. Indeed, such "polar amplification" of global warming is already being seen. Changes in precipitation are also expected to vary from place to place (Figure 1.7).

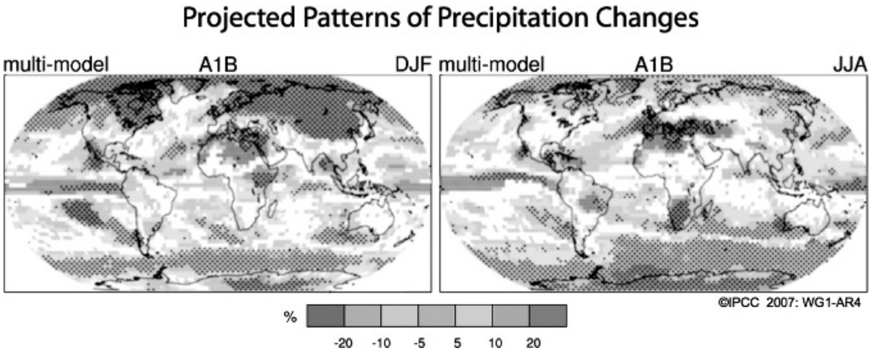

FIGURE 1.7 Changes in precipitation projected for the 2080s by a number of climate models, including an indication of the level of agreement. Shadings show where more than 66 percent of models agree on the sign of the change, white areas show where less than 66 percent agree. Black dots show where 90 percent of models agree on the sign of the change. Contours show the average change projected by all models. Results are shown for the seasons of December-January-February (DJF, left) and June-July-August (JJA, right).
Source: IPCC, 2007.

In the high-latitude regions (central and northern regions of Europe, Asia, and North America) the year-round average precipitation is projected to increase, while in most subtropical land regions the precipitation is projected to decrease by as much as 20 percent. Some climate models (but not all) project a particularly strong decrease in rainfall in Amazonia, due to changes in atmospheric circulation caused by particular patterns of warming in the north Atlantic and equatorial east Pacific oceans.

The projections used for long-term assessments represent the overall trend of global mean temperatures, but not the precise year-to-year variations. While the models do include year-to-year variations that are realistic in a statistical sense—they simulate relatively warmer and cooler years with about the right frequency—they are not expected to be realistic for individual years. Progress in forecasting shorter-term changes for informing adaptation, including year-to-year variations, is discussed below.

Informing Mitigation: Assessing the Impact of Different Emissions Cuts

With AR4 having established that ongoing greenhouse emissions would cause major climate changes, the policy focus is now turning to the question of how deeply and how quickly emissions should be reduced.

Jason Lowe at the Met Office Hadley Centre used a simple climate model calibrated against more complex models to address issues relevant to this question (Met Office 2007). Many climate policy makers and stakeholders focus on a global mean temperature rise of 2 degrees Celsius relative to preindustrial as a threshold to avoid surpassing; Lowe estimated the likelihood of exceeding this 2 degrees Celsius rise with different illustrative scenarios of emissions reductions, shown in Figure 1.8.

The simple model estimated the uncertainty in the climate response to given GHG concentrations, and also included feedbacks between climate change and the carbon cycle as described earlier. In one scenario, emissions reductions begin in 2012 and are reduced to zero in the 2060s. The model suggested that the most likely result was that a global warming of 2 degrees Celsius would be avoided with this hypothetical scenario; however, the model also suggested a significant probability of exceeding 2 degrees Celsius. A key result was that the peak warming was significantly delayed after the peak emissions; in the "best estimate," the peak in global mean temperature occurred in the 2060s, approximately half a century after the peak in emissions.

In the maximum sensitivity case, ongoing warming continued until the end of the simulation at 2200, as a result of ongoing release of carbon from natural stores as a consequence of climate change itself. As described earlier, climate change itself is altering the balance of uptake and release of carbon by ecosystems and the ocean waters. The net sink of carbon is weakening and is expected to continue to do so in the future, particularly as warming continues to increase the release of carbon from soils. This means that stabilizing and recovering atmospheric CO_2 concentrations is likely to be more difficult than would otherwise be expected, because once the CO_2 is in the atmosphere the resulting climate change could weaken the natural carbon sink and hence reduce the removal of CO_2 from the atmosphere (Jones, Cox, and Huntingford 2006). So, despite a reduction in emissions, if climate change leads to large carbon cycle feedbacks, CO_2 concentrations could continue to rise even while emissions are being reduced.

In a second scenario, emissions cuts begin in 2036 and are reduced to zero by the 2080s. Again, peak warming lags behind peak emissions by several decades, with the world continuing to warm until the 2080s and the "best estimate" showing 2 degrees Celsius being exceeded. Uncertainties in the warming are significant, again largely due to uncertainties in carbon cycle feedbacks, and while the "best estimate" scenario shows temperatures declining over the twenty-second century, the upper estimate shows ongoing warming, which reaches 7 degrees Celsius by 2200. As the strength of the carbon sink decreases as the climate warms, stabilization of concentrations requires increasingly large emissions cuts to compensate for the weaker sink.

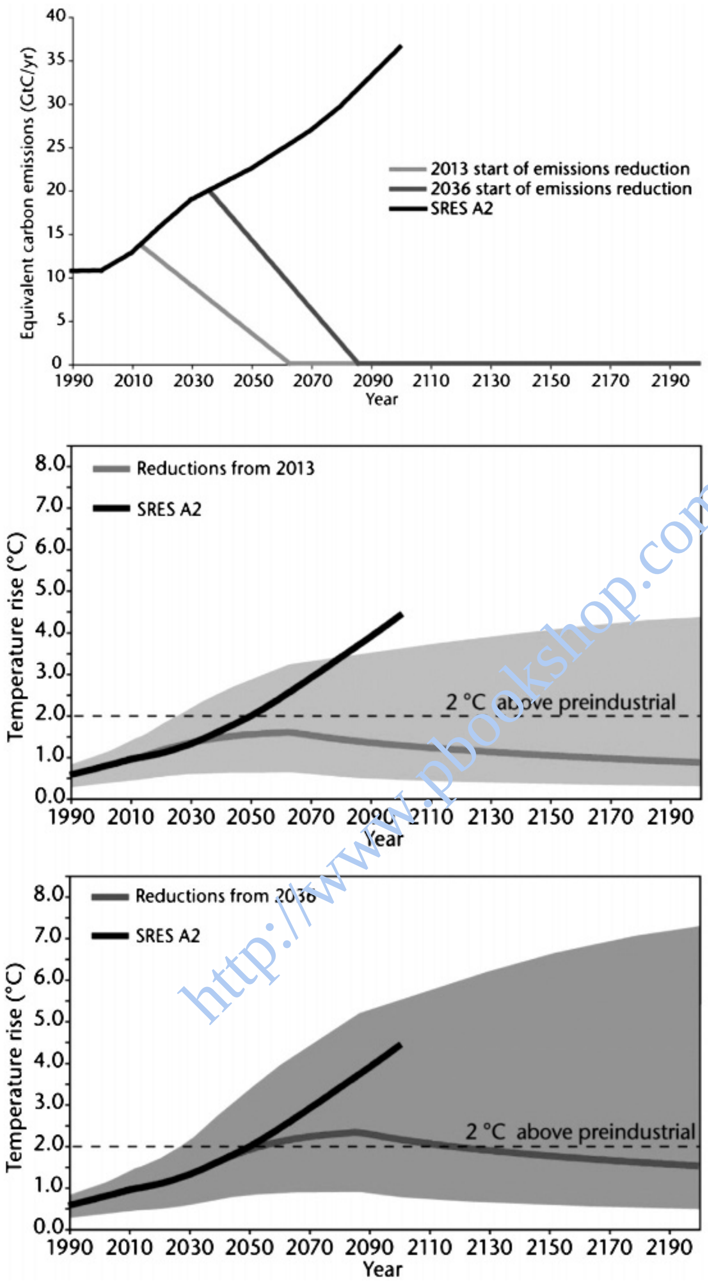

FIGURE 1.8 Simple climate model study of the effects of emissions reductions begun earlier and later. Lines show best estimates of global temperature changes, bands show estimated uncertainties due to uncertainties in the resulting CO_2 concentrations and climate change.
Source: Met Office, British Crown Copyright.

The implication of this illustrative study is that delays in emissions cuts increase the commitment to large warming and also the risk of feedbacks becoming large. There is a lag of several decades between instigating emissions cuts and seeing the benefit of these cuts, so it is not possible to wait to see the outcome of past emissions before deciding on the level of emissions reductions. Some further changes are already inevitable, but there is still a possibility that global warming could remain below 2 degrees Celsius—but this will require early action in reducing emissions significantly. The longer the delay in reducing emissions, the greater the likelihood of exceeding 2 degrees Celsius warming.

Having seen the importance of carbon sinks for stabilizing CO_2 concentrations, it is also worth noting that forests are an important carbon sink, so deforestation also makes stabilization and recovery of CO_2 concentrations more difficult. Not only does deforestation add to emissions, it reduces the removal of CO_2 from the atmosphere by decreasing the size of the forest carbon sink (Betts et al. 2008). The farther deforestation is allowed to advance, the weaker the carbon sink and the more deeply fossil fuel emissions will need to be reduced.

Informing Adaptation: Forecasting Unavoidable Climate Change

As is evident from the preceding discussion, some further climate change is already unavoidable simply due to the laws of physics. Note, for example, the bottom line in Figure 1.6, which shows a simulation of the ongoing rise in temperature that would occur even if CO_2 concentrations had ceased to rise in the year 2000. The Earth takes time to respond fully to a change in GHG concentrations, so it is still “catching up” with the increased concentrations over the twentieth century. Even more climate change seems inevitable for social, political, and economic reasons: An immediate total shutting down of emissions would require an abandonment of the modern lifestyle overnight. Note again in Figure 1.6 how the projected climate changes are similar for all the main SRES emissions scenarios up until approximately 2040, despite the large differences in actual emissions by then (Figure 1.5). This is because, as described above, concentrations are affected more by previous emissions than current emissions, and because the Earth’s temperature also takes time to fully respond. We already appear to be seeing impacts of climate change; many plant species are flowering or leafing out earlier in the year due to warmer springs (Fischlin et al. 2007), and it has been estimated that European summer temperatures as high as those experienced in the heat wave of 2003 are probably now twice as likely (Stott, Stone, and Allen 2004). Therefore, with further changes already in the pipeline, there is a need to adapt. Those who plan ahead are more likely to be able to minimize damages and even exploit opportunities, and in competitive fields, those who act first would be expected to gain the edge.

In an ideal world, adaptation plans would be based on robust forecasts of the potential impacts of climate change on a specific activity in a specific place at a specific time. For example, a decision on siting a new piece of infrastructure such as a dam or a power station would take account of the climate changes projected for that site over the lifetime of the investment, which could be several decades or longer. In the nearer term, a commodity trader may wish to know which crops will do well and which will fail in the coming season or next few years. In practice, these kinds of questions push the current scientific capability to its absolute limits, but it seems that useful advice can be given even with this aspect of the science in its infancy.

Climate prediction in the near term (years to a few decades) is made more difficult by the fact that natural variations are still relatively important on this timescale, whereas on multidecadal timescales we expect the increased greenhouse warming to lead to long-term changes that are greater than the natural year-to-year variability. This poses a huge challenge when attempting to forecast on these timescales in order to inform adaptation. This area of climate science is only just beginning to demonstrate predictive skill, but nevertheless some skill is there. The key lies in good measurements of the current state of the climate (especially ocean temperatures), including the direction of any trends in the system, in order to set off the forecast in the right direction. Returning to the Pooh Sticks analogy, imagine that you are about to drop your sticks into the river and you see a large, slow-moving swirl of water making its way down the river. You can be reasonably confident that a stick dropped on the arm of the swirl moving in the same direction of the main stream flow will probably move faster than a stick dropped in the arm of the swirl moving against the main flow. Similarly, measurements of ocean temperatures can help capture the natural variations within the climate system and allow them to be factored into the models. Forecasts of global temperatures on decadal timescales have been shown to be credible, with techniques developed by Smith et al. (2007) in the Met Office Hadley Centre having been used to reproduce decadal temperature changes over the 1980s–1990s and 1990s–2000s using only the information that would have been available to forecasters at the start of those periods. Moreover, a forecast issued by Smith et al. in 2005 predicted that global temperatures would stall over the following few years, and only then begin to rise again. Since 2005, the rise in temperature has indeed stalled, with a La Niña event in 2007–2008 being a major feature temporarily counteracting the greenhouse-forced warming. However, Smith et al. forecast the warming to begin again before the end of the decade, and they forecast the warming

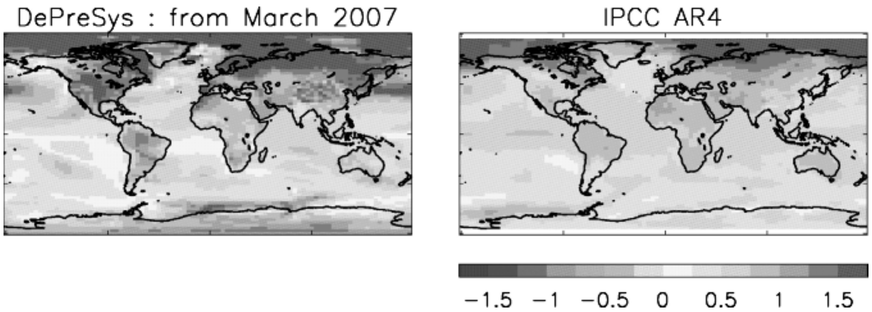

FIGURE 1.9 Forecast of temperature changes by 2020 using the Met Office Hadley Centre decadal forecasting system starting from the actual observed state in 2007 (left) and standard climate models initialized from the long-term average climate (right). Initialization from the current observed state rather than the long-term average improves the ability to forecast year-by-year variations. *Source:* Met Office, British Crown Copyright.

between 2005 and 2014 to be 0.3 degrees Celsius. This is half of the warming observed over the twentieth century. Figure 1.9 shows that this forecast suggests different rates of warming to those projected by the standard climate models, which do not set their forecasts in motion using observations of recent trends in ocean temperature.

Decadal forecasting is still in its early stages, and significant challenges remain, especially for forecasting of local rather than global changes. However, rapid progress is being made, and such forecasts are likely to be invaluable to adaptation planners in the coming years.

SUMMARY

It is clear that the world is now warming at a highly unusual rate and, consequently, snow and ice are melting, sea levels are rising, and patterns of rainfall are changing. This is very likely to be the result of the very high atmospheric concentrations of CO_2 and other GHGs, which are undeniably a result of deforestation and the burning of fossil fuels by humans.

The effects of our CO_2 emissions have not been fully realized, partly because of a feedback mechanism of carbon uptake by the biosphere and partly because fossil fuel burning also produces aerosol particles, which exert a cooling effect by reflecting sunlight. Continued emissions of GHGs are confidently expected to lead to further warming, resulting in further sea level rise and rainfall pattern changes with consequent impacts on society. The precise magnitude and nature of future changes is difficult to predict, partly because feedback mechanisms (which have buffered us from the full effect of our emissions) may weaken by an uncertain extent in the future. While some level of change is now inevitable, and hence must be faced up to and adapted to, there is still the possibility of reducing the magnitude of future change later in this century by reducing emissions of GHGs.

NOTES

1. IPCC Assessment Reports are prepared by a large international team of leading scientists, with several rounds of very extensive peer review, and provide a thorough assessment of the recent peer-reviewed literature. Reports and further information are available online at www.ipcc.ch.
2. Suggestions that actual emissions have been greater than the IPCC SRES range are based on a comparison with the averages of different versions of the scenarios from different sources (Raupach et al., 2007) rather than with the individual scenarios that were actually used in climate models. The emissions scenarios were generated from plausible “story lines” of future population, gross domestic products, energy sources, technology, and other socioeconomic factors, and several different versions of each scenario were produced by a number of Integrated Assessment Models (IAMs). From the group of versions of each scenario, one particular version was chosen as the “marker scenario” and was used to drive climate models for the IPCC Third and Fourth Assessment Reports (IPCC, 2001, 2007). Raupach et al. compared actual emissions with the averages of the versions of each scenario, rather than with the marker scenarios. Actual emissions have been within the range of the marker scenarios (van Vuuren and Riahi 2008).

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