Part I

Climatic trends

For many key parameters, the climate system is moving beyond the patterns of natural variability within which civilisations have developed and thrived…

1

Identifying, monitoring and predicting change in the climate system

'Without the willow, how to know the beauty of the wind'[1]

Weather directly impacts our lives on a minute-to-minute basis. Radio and television channels are devoted to keeping us up to date on current and future weather conditions. These include temperature, barometric pressure, precipitation, severe storms, humidity, wind and more. When we refer to 'climate', we mean average patterns in weather. Thus, climate change is a deviation from the weather patterns that have prevailed over a given period. Taken together, the weather we experience and the weather patterns across the globe are the product of processes occurring in the Earth's 'climate system', which is composed of interactions between the atmosphere, the hydrosphere (including the oceans), the cryosphere (ice and snow), the land surface and the biosphere. Ultimately, this system is controlled by the amount of energy stored as heat at the Earth's surface and the redistribution of this heat energy. Because we humans live in the atmosphere at the surface of the Earth, we (wrongly) assume that changes in air temperature are the only and best indicator of climate change. In fact, relatively little (<5%) of the change in the amount of heat energy stored at the Earth's surface that has taken place in recent decades has occurred in the atmosphere (IPCC, 2007a).

To understand changes in the climate system, the changes in the heat energy content of compartments other than the atmosphere also need to be considered. Regardless of where in the climate system we are looking for evidence of possible change, however, there is one common rule: identifying changes in the climate system requires data series that are collected over several decades – three at a minimum but five or more are better. Newspaper headlines have, in recent years, been eager to declare global warming as a thing of the past on the basis of one or a few years that have been colder than the immediately preceding. However, the presence or absence of global warming cannot be identified on the basis of one or a few years' data.

[1] Attributed to Lao She, Chinese writer (1899–1966).

1.1 The interaction of many different processes make up the climate system

The factors that influence the global climate system are called 'climate forcings'. The most important of these is, of course, the sun and the energy that it transmits to Earth. Human activities do not directly influence the amount of energy produced by the sun. However, there are natural variations in the sun's activity and these variations obviously influence the global climate system.

Also the shape of the Earth's orbit around the sun influences the amount of solar energy reaching the Earth. Much of the climate variability recorded during the Earth's almost 5 billion-year history can be explained by changes in several characteristics of the Earth's orbit around the sun. For example, during the past approximately 12 000 years, the Earth's orbit has been more circular than at any other time during the last half-million years. This has resulted in a particularly stable and – in comparison to a period of many thousands of preceding years prior to this – warm climate on Earth, and it has been suggested that this comparatively warm and stable climate may have been a contributing factor to the rapid development of human societies (van der Leeuw, 2008). Scientists predict that the Earth's orbit around the sun will continue to have a similar orbit for thousands of years into the future (Berger and Loutre, 2002). We can, then, expect that in the absence of other changes in the climate system, the climate will remain relatively warm and stable in the foreseeable future.

In addition to the sun itself, there are a number of climate forcings that influence the amount of solar energy that reaches the Earth's surface, the amount that is retained on the Earth itself, and the amount that is radiated back into the atmosphere and retained there as heat (Figure 1.1). Many of these climate forcings are found in the atmosphere either as greenhouse gases (GHGs) or aerosols (fine particles or liquid droplets).

A part of the sun's energy reaching the Earth is radiated back into the atmosphere in the form of infrared (IR) radiation (heat). Greenhouse gases absorb this radiation and the process results in heat retention in the atmosphere. This 'greenhouse effect' has been well understood since the nineteenth century and it is not unique to the Earth. Every planet with an atmosphere containing greenhouse gases experiences a greenhouse effect; the extreme surface temperatures (440 °C) on Venus, for example, can only be explained by the high concentration of CO_2 in the atmosphere there. Without the greenhouse effect, the average temperature on Earth would be about −19 °C, i.e. approximately 34 °C colder than today.

The most important greenhouse gas in Earth's atmosphere is actually water vapour, which accounts for about 60% of the natural greenhouse effect for clear skies (Kiehl and Trenberth, 1997). Human activities have not directly resulted in a significant change in the absolute amount of water vapour in the atmosphere (Gordon *et al*., 2005). Fast feedbacks within the climate system can, however, change the amount and distribution of water vapour. Because there is no significant *direct* human influence on water vapour concentrations, the importance of water vapour as a greenhouse gas is seldom a topic of discussion in the public debate concerning climate change. Instead, most of the discussion focuses on the greenhouse gases whose concentrations have been directly influenced by human

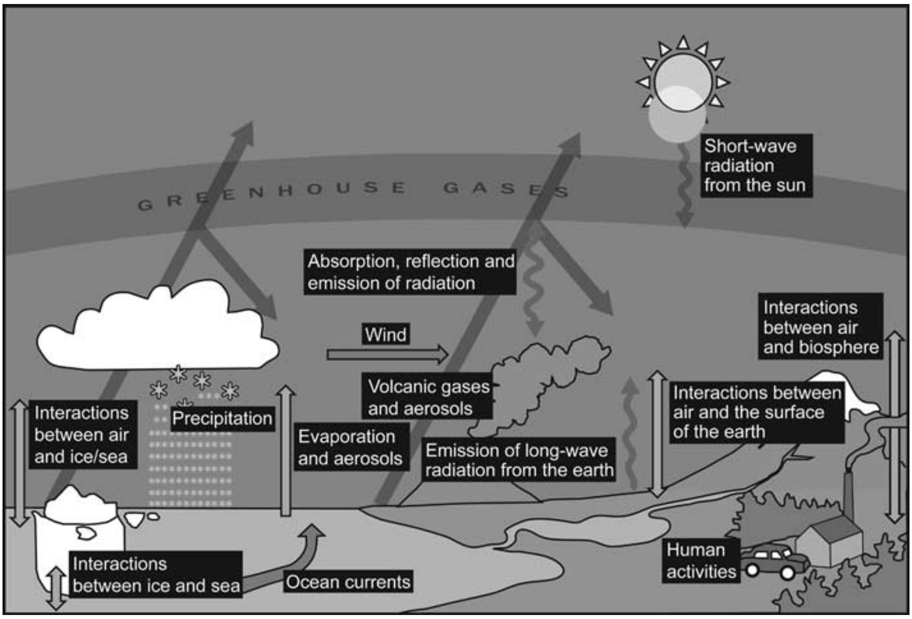

Figure 1.1 Components of the climate system.

activities. Of these, CO_2 is the single most important gas.[2] Human-induced changes in other greenhouse gases are, however, also quantitatively important in terms of their impact on the climate system and it is as important to focus on their reduction of emissions as it is to focus on CO_2 reductions (Chapter 8).

The accumulation of greenhouse gases is not the only change in the atmosphere as a result of human activities. Different types of aerosols are also introduced to the atmosphere via our activities. These different aerosol types have different influences on the climate system – some result in net warming of the planet (because they absorb energy and retain it as heat) and others in net cooling (because they scatter or reflect incoming radiation). Figure 1.2 illustrates the various climate forcings influenced directly by human activities and how they are estimated to have changed in the period 1750–2000. People are often surprised to realise that human-induced changes in aerosol concentrations have had a net cooling effect since the industrial revolution. The flip side of that coin is, however, that any reduction in emission of the aerosol types which have a net cooling effect in the climate

[2] It has become a convention in much of the political discussion concerning greenhouse gas emission to refer to the impact of all greenhouse gases emitted through anthropogenic activities under the heading of ‘CO_2’. To do so, the impact of the non-CO_2 greenhouse gases on warming is converted to the amount of CO_2 that would be required to give the same warming effect. Thus, the concentrations of the non-CO_2 greenhouse gases are converted to ‘CO_2 equivalents’ (CO_2-e). While this convention is convenient, and appears in some chapters of this book, it is important to remember that CO_2 is not the only greenhouse gas impacted by human activities. Other GHGs influenced by human activities include methane, nitrous oxide and ozone.

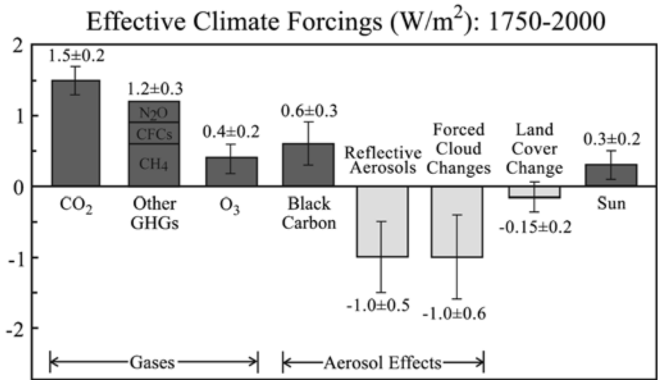

Figure 1.2 Greenhouse gas and aerosol climate forcings influenced by human activities and how they are estimated to have changed in the period 1750–2000. Black carbon is material (e.g. soot) produced by the incomplete combustion of fossil fuels, biomass and biofuels. Source: Hansen *et al*. (2005). Reproduced/modified by permission of American Geophysical Union.

system will result in an additional warming. This means that efforts to reduce many types of air pollution will have as a consequence an increase in global warming. Precisely how much global temperature will increase as a result of a reduction in aerosols stemming from human activities is not yet well known, and is thus currently a topic of enormous interest and active research (Box 1.1).

Box 1.1

Potentially strong sensitivity of late twenty-first century climate to projected changes in short-lived air pollutants

HIRAM LEVY II, M. DANIEL SCHWARZKOPF, DREW SHINDELL, LARRY HOROWITZ, V. RAMASWAMY AND KIRSTEN FINDELL

Previous projections of future climate change have focused primarily on long-lived greenhouse gases such as carbon dioxide, with much less attention paid to the projected emissions of short-lived pollutants, i.e. aerosols and their precursors. When interpolated out to 2050 with a middle-of-the-road IPCC emission scenario (A1B), two of the three climate models in a recent study found that changes in short-lived pollutants contributed 20% of the predicted global warming (CCSP, 2008).

Interpolating out to 2100 with this emission scenario (A1B), one climate model (GFDL – CM2.1) found that projected changes in the emissions of short-lived pollutants (primarily a sharp decrease in sulphur dioxide and a doubling of black carbon) were responsible for

30–40% of the summertime (June–July–August) warming predicted over central North America and southern Europe by the end of the twenty-first century. This leads to a significant decrease in precipitation and increase in soil drying in the summertime central USA. Moreover, the primary increase in radiative forcing from the changing levels of these short-lived pollutants is over Asia (Figure 1.3) while the primary summertime climate response in degrees centigrade (Figure 1.4) is over the central USA and southern Europe (Levy *et al*., 2008).

While this general disconnect between the regional locations of the pollutants and their radiative forcing and the regional climate response is quite robust across a range of climate models (Shindell *et al*., 2008 and references therein), and the particular climate sensitivities of the summertime central USA and southern Europe are also robust across the climate models in the IPCC (2007a), there are two important caveats:

- the magnitude of the climate response to changing emissions of short-lived pollutants depends critically on their projected trajectories, and these projections are highly uncertain (Shindell *et al*., 2008),

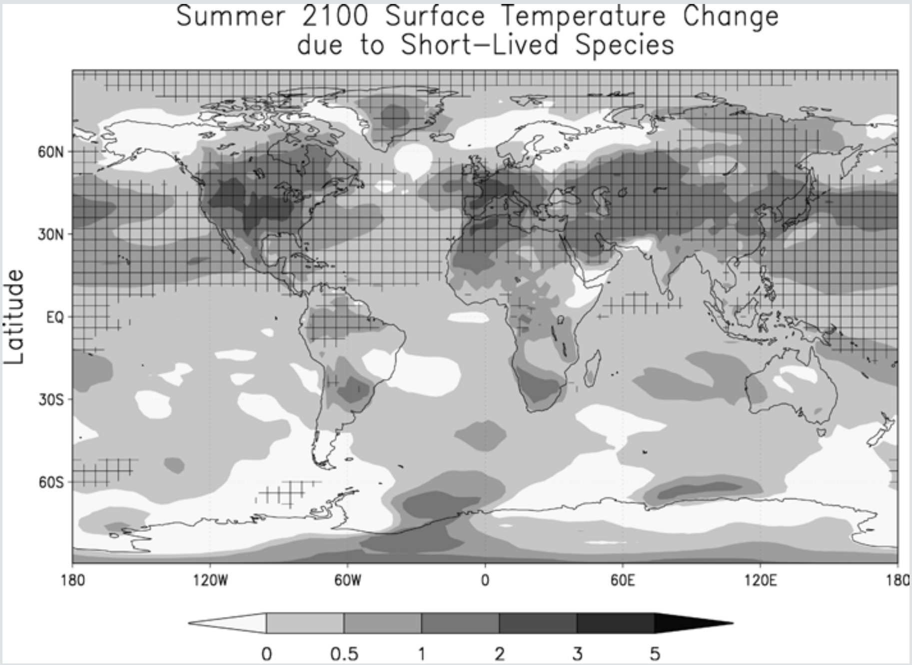

Figure 1.3 Summer (JJA) temperature changes (K) from the 2000s (years 2001–2010) to the 2090s (years 2091–2100) for the forcing only by the short-lived species (A1B(2090s) – A1B*(2090s)) – (A1B(2000s) – A1B*(2000s)). Source: modified from Levy *et al*. (2008).

Box 1.1 (*cont.*)

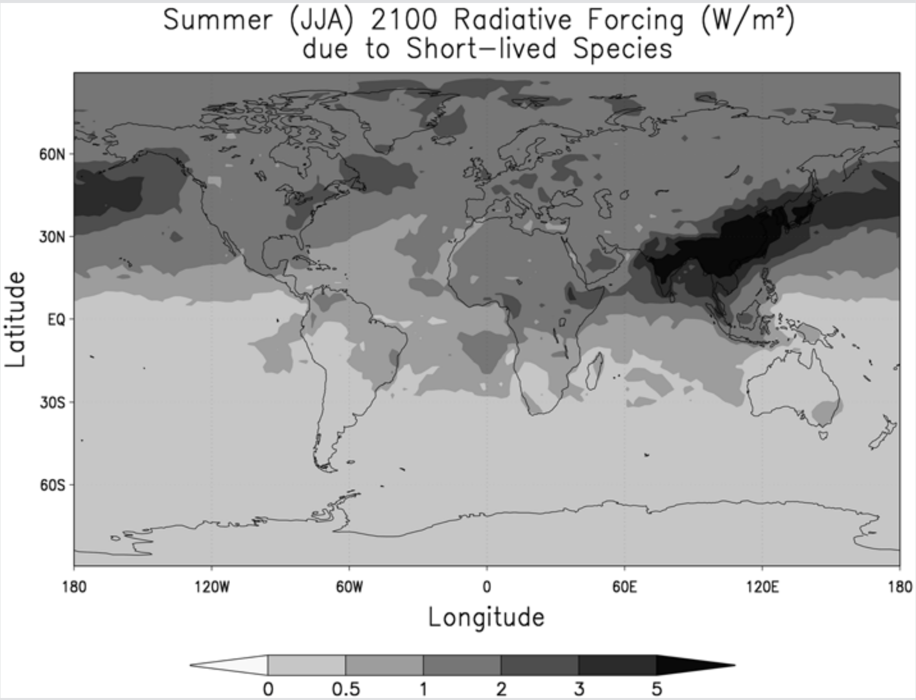

Figure 1.4 Changes in summer-mean adjusted radiative forcing (W m^{-2}) between years 2100 and 2000 for the contribution from short-lived species only. Source: modified from Levy *et al.* (2008).

- this calculation only considered the direct radiative effect of aerosols (i.e. indirect effects such as cloud formation were not considered), and the aerosols were treated as external mixtures (i.e. each particle is assumed to be composed of one pure compound).

Changes on the Earth's surface itself can also influence the climate system. Alterations in land or sea cover can, for example, alter the Earth's ability to reflect sunlight (i.e. cause a change in 'albedo'). The mechanisms causing albedo change are described in Box 1.2. With respect to human-induced albedo changes on the Earth, one of the most worrying of those occurring is the melting of sea-ice (Box 7.2), as ice reflects most of the light that impinges upon it and water absorbs the majority of this energy. In addition, boreal forests are moving northwards into tundra ecosystems as the climate warms. This means that during winter, less snow is exposed directly to the sky because more of it lies underneath the forest canopy than before. These two phenomena lead to a decrease in the reflectance of incoming solar radiation, and thus act to accelerate regional warming.

Box 1.2
Albedo

KEVIN J. NOONE

The overall energy balance of the Earth is very simple: at steady state, the amount of incoming energy from the sun that is absorbed by the Earth is matched by the amount of energy that the Earth radiates back to space. Mathematically, this simple energy balance is written as:

$$(1-A)S_0 = 4\sigma T_e^4 \tag{1.1}$$

where S_0 is the solar constant (the amount of energy per square metre from the sun that reaches the Earth's orbit; 1360 W m^{-2}), σ is the Stephan–Boltzmann constant ($5.67*10^{-8}$ W m^{-2} K^{-4}), T_e is the Earth's *effective temperature* (related to, but not the same as, the surface temperature) and *A* is the planetary albedo – the fraction of incoming solar radiation that is reflected back to space (making 1–*A* the amount that the Earth absorbs).

If the albedo increases, less energy is absorbed, and the effective temperature will decrease; if the albedo decreases, more energy is absorbed and the effective temperature will increase.

The Earth's albedo is determined by how reflective different land and ocean surfaces are, as well as by clouds and particles in the atmosphere. Feedbacks and interactions between incoming solar radiation and snow and ice cover on both land and oceans are thought to be main drivers of the natural glacial/interglacial oscillations that we have observed over the past 800 000 years. However, human activities have also altered the Earth's albedo and affected the energy balance.

Human-induced land-use changes and desertification have changed the reflectivity of the land surface. Most of our land-use activities tend to increase the reflectivity of the surface. Replacing trees with grasslands or crops through deforestation, and replacing grasslands with bare soil or sand due to overgrazing and desertification, are examples of land-use changes that increase the surface albedo. Betts *et al*. (2007) estimated that the present global mean radiative forcing due to surface albedo changes relative to 'natural' (i.e. pre-1750) conditions is –0.2 W m^{-2}. This value is comparable with the global mean radiative forcing due to N_2O of 0.16 W m^{-2} (IPCC, 2007b). While this global mean cooling may be relatively small compared to the warming of all the greenhouse gases, on a regional basis the forcing may be much larger (Betts *et al*., 2007).

As the planet warms due to human activities, the surface area covered by snow and ice is decreasing. Arctic sea-ice has already been observed to be decreasing in area much faster than expected (Box 7.2). Ice is very reflective (*A* is between about 0.7 and 0.9), while ocean water absorbs most of the incoming solar radiation (*A* is less than about 0.1). Replacing a very reflective surface with a very absorptive one results in more energy being absorbed and retained by the surface, further accelerating surface warming. This becomes an amplifying feedback, as a warmer surface will result in even less snow and ice cover. Humans can also change the albedo of snow and ice surfaces through the deposition of absorbing particles. Black carbon deposited on snow and ice surfaces has been estimated to have a global mean warming effect of about +0.1 W m^{-2} (IPCC, 2007b); however, this value remains uncertain.

In addition to changes in surface albedo, human activities have also changed the overall reflectivity of the atmosphere by modifying the properties of aerosol particles and clouds

Box 1.2 (*cont.*)

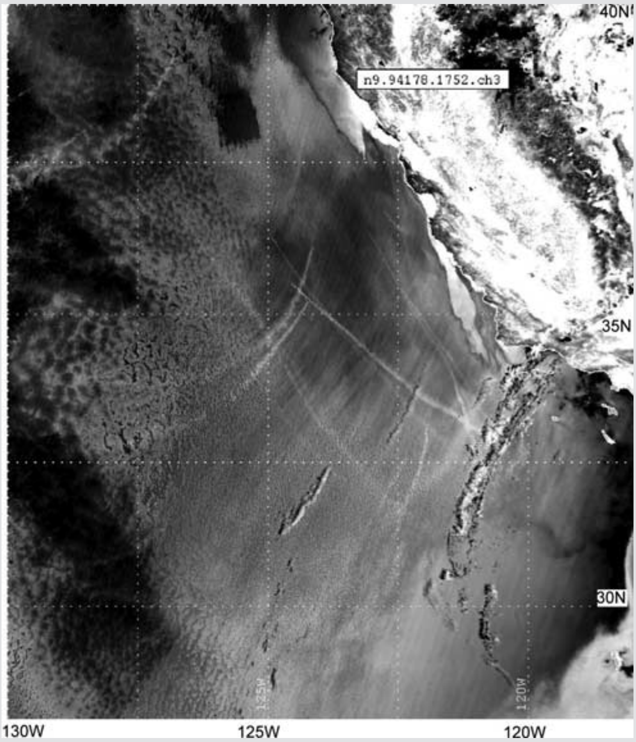

Figure 1.5 Image of 'ship tracks' in clouds off the coast of California, USA. Source: adapted from Noone *et al.* (2000).

(Box 1.1). 'Ship tracks' (Figure 1.5) are a striking example of how human particulate emissions (from individual ships) can increase the albedo of marine clouds (Noone *et al.*, 2000). The global result of this 'indirect cloud albedo forcing' is estimated to be –0.7 W m^{-2} (range of –0.3 to –1.8; IPCC, 2007b). Particles can directly alter the planetary albedo by absorbing or scattering incoming solar radiation. The overall global direct radiative forcing due to aerosols is estimated to be negative (–0.5 W m^{-2}, range of –0.1 to –0.9; IPCC, 2007b). However, as particles can both scatter and absorb solar radiation depending on their chemical composition, and as composition varies widely across the globe, the regional radiative effects of aerosols can be very different (Ramanathan and Feng, 2008). These regional differences can lead to different outcomes if particle abatement strategies are implemented. As one example, particulate pollution over the eastern seaboard of North America has a net cooling effect on both the atmosphere and the surface by scattering incoming solar radiation back to space. 'Atmospheric brown clouds' over parts of Asia containing high concentrations of black carbon aerosols can cool the surface by absorbing incoming radiation, but heat the atmosphere (Ramanathan and Carmichael, 2008). Reducing the amount of particulate emissions in these regions by the same amount could lead to very different results in terms of the energy balance in the regions.

A complete description of the climate system would require a book in itself. Therefore, the focus in this brief discussion has been on the climate forcings that are influenced by human activities. These are many and, as we have seen, influence the climate system in opposing ways. In the following sections, we examine how scientists identify changes in the functioning of the climate system and their probable causes.

1.2 Identifying changes in the climate system

That large-scale burning of fossil fuels (coal) would lead to global warming was already predicted by the Swedish chemist, Svante Arrhenius, in 1896 (Arrhenius, 1896).[3] Thus, the theoretical understanding of the potential for humans to influence the climate system has been in place for over a century. However, because of natural variability in the system, demonstrating that a change has occurred requires the accumulation of data time series that span decades.

Perhaps the most convincing evidence that there is a strong relationship between atmospheric CO_2 concentration and temperature was published in 1999 when a Russian and French research team published an ice core record from Antarctica that provided a time-series of data describing the atmospheric concentration of CO_2 and methane, as well as a proxy for temperature, from 420 000 years ago until the near-present (Petit *et al*., 1999). A more recent, longer ice core pushes the data record back to almost 800 000 years (EPICA community members, 2004). When put together with data collected in the recent past, the picture clearly emerges of a major, rapid change in the atmospheric concentrations of CO_2 and other important greenhouse gases (Chapter 4) since the advent of the industrial revolution. Several lines of evidence confirm that the additional CO_2 that has accumulated in the atmosphere since the beginning of the industrial revolution is almost entirely caused by human activities (Prentice *et al*., 2001).

However, because there are so many climate forcings and they can work in opposite directions, identifying a change in one forcing – in this case, greenhouse gas forcing – does not necessarily imply a significant change in the climate system as a whole. Identifying such a change requires demonstration of a change in the total amount of heat stored at the surface of the Earth. As we live in the surface atmosphere and are directly affected by its temperature, we have long been routinely measuring surface air temperature. These data are now extremely valuable in identifying significant changes in the climate system. Figure 1.6a shows proxy-based estimates of the near-surface air temperature in the northern hemisphere since about 200 AD. There is considerable uncertainty in temperature records in the period before the thermometer was invented. Nevertheless, it is clear that there has been rapid warming in recent decades.

Despite an upward trend in temperatures in recent decades, year-to-year temperature fluctuations are obvious when we look closely at the annual global average for near-surface air temperature from 1970 to the present (inset in Figure 1.6b). The causes of these year-to-year temperature differences are, in many cases, well understood. It is well known, for example, that strong El Niño and La Niña events can influence global air temperature in a

[3] A timeline for the discovery of human-induced climate change is found in Chapter 17.