Climate change

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Contents

Introduction

This course explores the topic of climate change and global warming. We will begin by exploring how the Earth's global mean surface temperature is determined through a global “balancing act” of the rate of energy that comes from the Sun and the rate at which the planet returns that energy into space. We will also discuss the natural greenhouse effect, and how this contributes to a balanced global climate. We will then go on to consider the human impact on the atmosphere, including the impact of industrialisation, other sources of greenhouse gases that are connected to humans and the numerous and varied means of measuring climate change that are available.

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Learning Outcomes

After studying this course, you should be able to:

- understand the physical basis of the natural greenhouse effect, including the meaning of the term radiative forcing
- know something of the way various human activities are increasing emmissions of the natural greenhouse gases, and are also contributing to sulphate aerosols in the troposphere
- demonstrate an awareness of the difficulties involved in the detection of any unusual global warming ‘signal’ above the ‘background noise’ of natural variability in the Eath's climate and of attributing (in whole or in part) any such signal to human activity
- understand that although a growing scientific consensus has become established through the IPCC, the complexities and uncertainties of the science provide opportunity for climate sceptics to challenge the Panel's findings.

1 Global climate and the greenhouse effect

1.1 Introduction

At the beginning of the 21st century, terms such as the 'greenhouse effect', 'greenhouse gases' and 'greenhouse warming' are printed or spoken thousands of times a week in the context of climate change caused by human activities. This section is designed to consolidate your understanding of the basic science behind these terms, and then to review what is known about the human impact on the composition of the atmosphere since the dawn of the industrial age, commonly put (in this context) at around AD 1750.

We start with a couple of fundamental questions about global climate. What determines the Earth's global mean surface temperature (GMST)? And how does the composition of the atmosphere come into that equation?

Box 1 Electromagnetic radiation

Electromagnetic radiation is the only form of energy transfer that travels through the vacuum of space, propagating as a wave. By convention, the full spectrum of electromagnetic radiation is carved up into regions, each characterised by a particular range of wavelengths (Figure 1). The **wavelength** (symbol λ) is just the distance between successive crests of a wave.

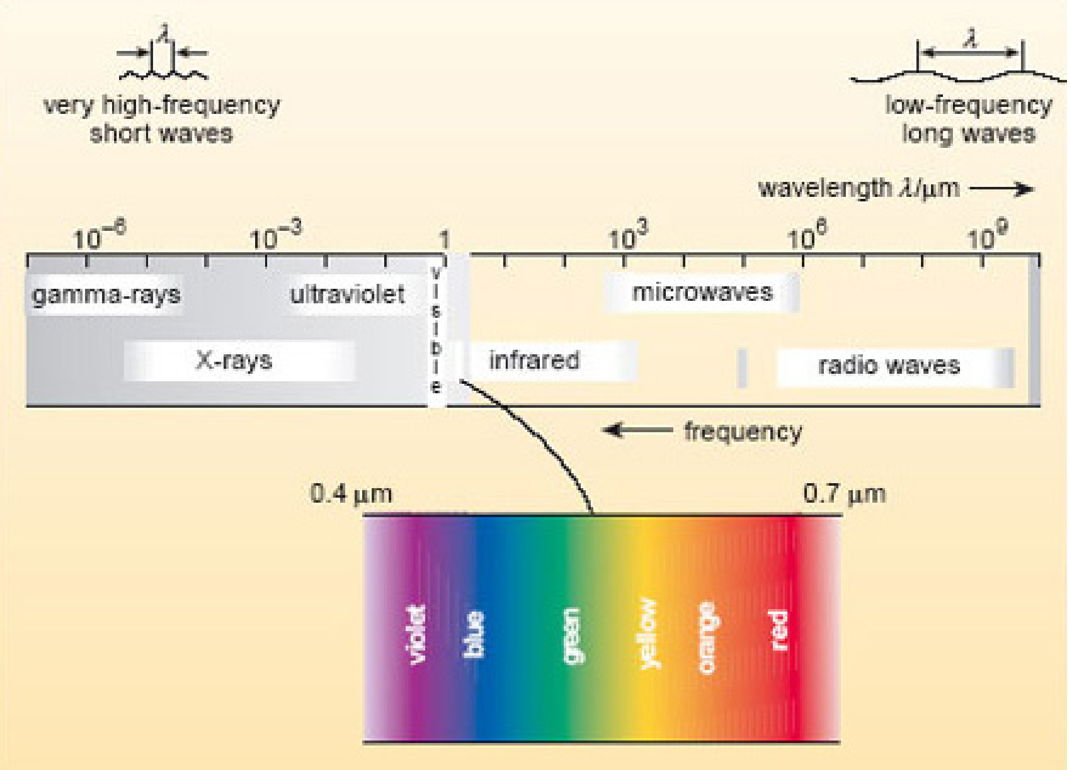

Figure 1 A portion of the electromagnetic spectrum. Wavelength is given in micrometres, μm: 1 μm = 10^{-6} m. Note that the wavelength changes by *a factor of 10* for each division along the top scale, so this is a *logarithmic* scale.

Our eyes are sensitive to **visible radiation**, which corresponds to the wavelength range from about 0.4 μm (violet light) to 0.7 μm (red light). When all wavelengths in this range are present, we perceive this as 'white light'. To either side of the visible band lie the ranges known as **ultraviolet (uv) radiation** (with wavelengths *below* that of violet light) and **infrared (ir) radiation** (with wavelengths *above* that of red light).

As with any propagating waves, the shorter the wavelength, the higher the frequency (f) (i.e. the higher the number of waves passing a point in a given time). For electromagnetic radiation, the two multiplied together give the speed of light (c): $c = f\lambda$.

1.2 What determines the Earth's GMST?

The Sun is the ultimate source of energy for the Earth's climate. A planet such as the Earth will have a stable temperature as long as there is a balance between the rate at which energy comes in from the Sun and the rate at which it is returned to space by the planet. If the two rates fail to match, the planet will either warm up or cool down until a balance is restored. Thus, it is appropriate to begin with a review of this global balancing act. The heart of the matter is that the energy flows to and from space are in the form of radiation - or to be more precise, **electromagnetic radiation**. You should consult Box 1 (Section 1.1) if you need to refresh your memory about this form of energy transfer.

1.2.1 Heating and cooling the Earth: the overall radiation balance

The Sun emits electromagnetic radiation with a range of wavelengths, but its peak emission is in the visible band - the sunlight that allows us to see. The wavelength of radiation has important climatic implications, as we shall see shortly. For now, we are mainly interested in the overall *rate* at which energy in the form of **solar radiation** reaches the Earth.

SAQ 1

What is the SI unit for the rate of energy transfer, or 'power'?

Answer

The watt (W), defined as 1 W=1 J s^{-1} (joule per second).

Radiation streams out of the Sun at the prodigious rate of 3.85×10^{26} W. Located at an average distance from the Sun of some 150×10^{6} km, the Earth intercepts only a tiny fraction of this - an amount equivalent to the solar radiation falling on the flat, circular disc depicted in Figure 2. Note that we imagine the disc to be just outside the Earth's atmosphere and aligned at right angles to the Sun's rays: the solar input *per unit area* (a square metre, say) of this disc is called the **solar constant**. Measurements from satellite-borne radiation sensors give the solar constant an average value over recent years of 1368 W m^{-2}. Of course, the Earth is a rotating sphere, not a flat disc. As explained in the paragraph below Figure 2, when averaged over the surface of the whole globe, the solar input per unit area at the top of the atmosphere comes down by a factor of four, to 342 W m^{-2}. For simplicity, we shall refer to this globally averaged value as '100 units', though you should remember that these are units of 'energy per unit time per unit area'.

Not all of the incoming solar radiation is available to heat the Earth: some of it is reflected directly back to space. The proportion of incident solar radiation that is reflected by a given surface is called the **albedo**. Now have a look at Figure 3. This is an image of the Earth from space formed from reflected sunlight (solar radiation at visible wavelengths). Clouds and the ice-covered mass of Antarctica (at the bottom of the image) appear bright because they reflect strongly; i.e. they have a high albedo - up to 90% in the case of fresh snow and sea-ice. By contrast, the oceans have a low albedo (typically less than 5%) and appear dark in this image. In general, most land surfaces have moderate albedo, with values ranging from 10-20% for forests to around 35% for grasslands and deserts.

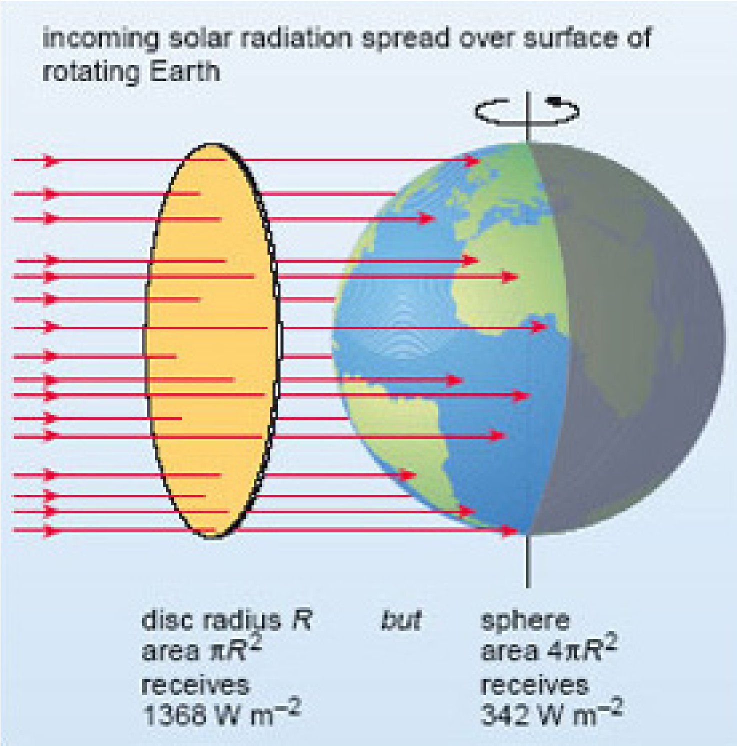

Figure 2

Figure 2 The Earth intercepts an amount of solar radiation equivalent to that falling on a disc with the same radius (R) as the Earth, facing the Sun: this comes to (1368 × πR^2) W, where πR^2 is the area of the disc (in m^2). However, the Earth is *spherical* , so the area presented to the incoming solar radiation by the rotating Earth (over a period of 24 hours or more) is $4\pi R^2$; i.e. four times as great. Thus, the solar input per unit area *averaged over the surface area of the whole Earth* is a quarter of the solar constant; i.e. 1368 Wm^{-2}/4=342 Wm^{-2}.

Figure 3 The Earth from space formed from reflected sunlight

Evidently, the albedo can vary markedly around the world, depending on the cloud cover and surface characteristics. The **planetary albedo** is the combined figure for the Earth as a whole: on average, it has a measured value of 31% (31 units). The remainder (69 units) is absorbed by the atmosphere and materials at the Earth's surface (the oceans, soils, vegetation and so on).

SAQ 2

What is the rate per unit area at which solar energy is absorbed by the Earth's atmosphere and surface?

Answer

69 units is 69% of 342 W m^{-2} or (342 W m^{-2}) × (69/100)=236 W m^{-2}.

Suppose now that the Earth's atmosphere is stripped away, but the planetary albedo is unchanged. (This may strike you as a curious proposition, but it will help to expose just how important the atmosphere really is.) The energy flows at the surface of this 'airless' world are shown in Figure 4. To the left of the figure, a nominal 100 units of solar radiation reach the planet; 31 units are reflected away and *all* of the remaining 69 units are absorbed by the surface.

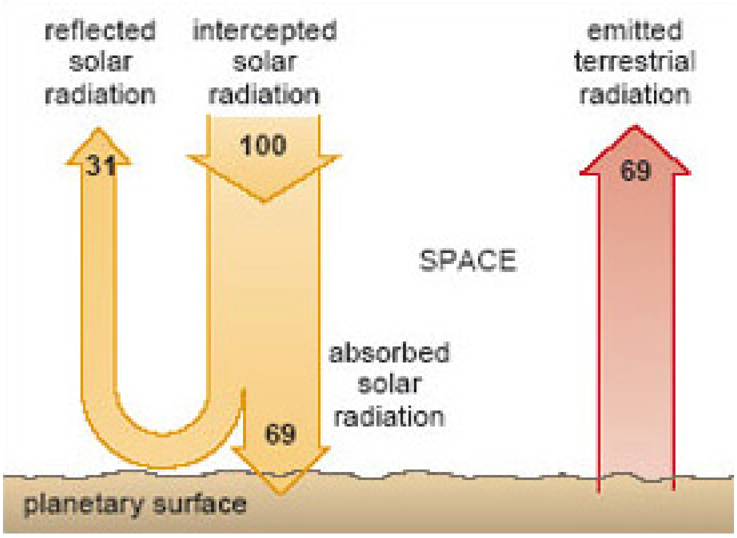

Figure 4 The steady-state balance between incoming and reflected solar radiation (orange arrows) and outgoing terrestrial radiation (reddish arrow) for an Earth-like planet without an atmosphere. 100 units represent the globally averaged rate per unit area at which solar radiation reaches the planet; i.e. 342 W m^{-2}.

SAQ 3

By itself, what would be the effect of this continual input of solar energy?

Answer

The surface would warm up; indeed, it would get progressively hotter and hotter.

Fortunately, there is a compensating cooling effect. Like the Sun, *all* objects (you and I included) emit electromagnetic radiation. Further, they do so at a rate that depends on the temperature of the object: the hotter an object becomes, the higher its radiative power - the rate at which it emits radiation. For our planet, a steady or *equilibrium* temperature is maintained by a dynamic balance: the rate at which solar energy is absorbed (the 69 units to the left in Figure 4) must be balanced by the rate at which the planet loses energy to space as emitted radiation (the 69 units to the right in Figure 4). Note that this *emitted* radiation originates with the 'jostling about' of atoms within the surface; it is *not* the same thing as the *reflected* solar radiation, which merely 'bounces off' the surface. To emphasise the distinction, we shall refer to the radiation emitted by the planet as **terrestrial radiation**.

Expressed in quantitative terms, the relationship between temperature and radiative power is the basis for a well-established law of physics. The appropriate calculations tell us that, for an Earth-like planet to emit radiation to space at a steady rate of 236 W m^{-2} (the 69 units depicted in Figure 4), it should have an equilibrium temperature of -19 °C.

This equilibrium temperature is known as the **effective radiating temperature** and, were it not for the atmosphere, this would also be the Earth's global mean *surface* temperature. Conditions would certainly be inimical to life as we know it. But how does the atmosphere perform the vital trick of keeping the GMST at a more temperate 15 °C (? The answer is bound up with an important difference between 'solar' and 'terrestrial' radiation - one that again depends on the temperature of the source.

Question 1

Heated in an ordinary fire, a metal poker glows 'red-hot'; if heated to a higher temperature (in an oxy-acetylene flame, say), it would glow 'white-hot'. Generalising from this example, does the average wavelength of emitted radiation increase or decrease as the temperature of the emitting body rises? Include your reasoning.

Answer

White light contains all visible wavelengths (Box 1), whereas red light is at the long wavelength end of the visible band (Figure 1). 'White-hot' objects therefore emit light of shorter average wavelength than cooler 'red-hot' ones. Generalising, as the temperature of an object rises, so the average wavelength of the radiation it emits will decrease.

The trend you identified in Question 1 is evident in Figure 5. Here, the curves record the distribution, or *spectrum*, of wavelengths emitted by the Sun (with an average surface temperature of some 5500 °C) and the Earth (with a GMST of 15 °C). The plots are schematic, in the sense that the vertical scale is not defined, but each shows how the radiative power is apportioned among the range of wavelengths emitted.

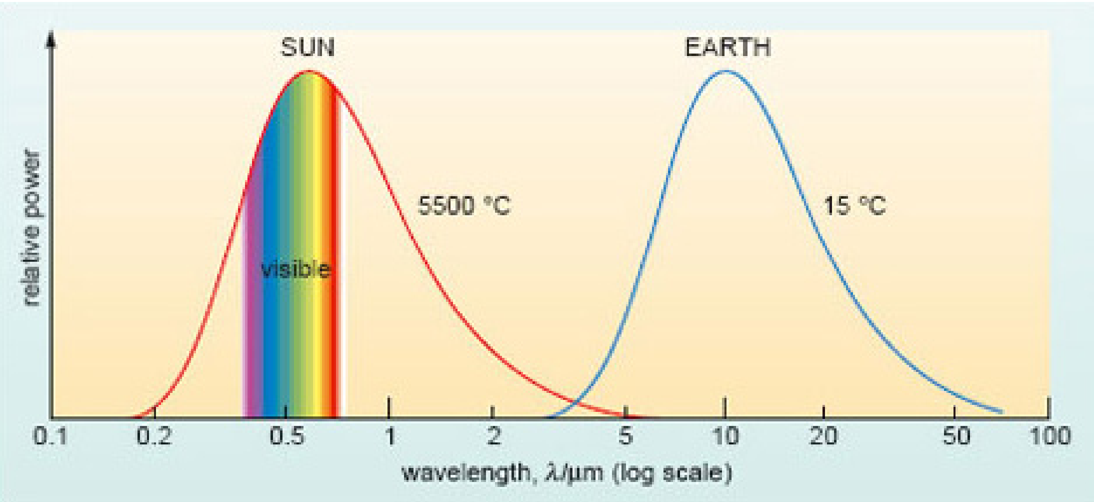

Figure 5 Wavelength spectrum of solar radiation (red) and terrestrial radiation (blue). The solar spectrum has been simplified and is for the solar radiation *intercepted* by the Earth (as in Figure 2), not the total power emitted by the Sun. Note again that the wavelength scale is logarithmic.

SAQ 4

With reference to Figure 5, is it reasonable to use 'shortwave' and 'longwave' as a shorthand for incoming solar radiation and outgoing terrestrial radiation, respectively?

Answer

Yes. The two curves in Figure 5 barely overlap: solar radiation peaks in the visible band, although there are contributions at both shorter wavelengths (in the ultraviolet, uv) and longer wavelengths (in a region often called the 'near' infrared). By contrast, radiation emitted at cooler terrestrial temperatures lies entirely at longer infrared (ir) wavelengths.

This pattern is important because the atmosphere is relatively transparent to incoming shortwave radiation, but *not* to outgoing longwave radiation. And that has a profound effect on the actual energy balance at the Earth's surface.

1.2.2 Bringing in the atmosphere: the natural greenhouse effect

> As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the Earth's surface.
>
> (Tyndall, 1862, quoted in Weart, 2004)

Thus, writing in 1862, John Tyndall (Figure 6) described the key to our modern understanding of why the Earth's surface is so much warmer than the effective radiating temperature. Tyndall's careful experimental work had established what others only suspected: expressed in modern scientific terms, certain atmospheric gases absorb infrared radiation with wavelengths in the range spanned by outgoing terrestrial radiation (about 4 to 100 μm; Figure 5). These are the **greenhouse gases**. Tyndall identified water vapour and CO_2, but the list of *natural* greenhouse gases (naturally present in the atmosphere long before human activities began to make their mark) also includes methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). The main mechanism by which these gases absorb infrared radiation is through the vibrations of their molecules. We shall not pursue the scientific principles that underlie this mechanism in any detail, but the key points we shall need are summarised in Box 2.

Figure 6 John Tyndall (1820-1893).

Like many Victorian scientists, Tyndall was interested in a great many questions - contributing to such diverse areas as heat transfer, glacier motion and scattering of light in the atmosphere, where he is honoured for his explanation of why the sky is blue (the Tyndall effect). He was a keen alpinist, and attracted by one of the great riddles of his day: if vast sheets of ice had once covered all of northern Europe (hotly debated at the time), how could climate have changed so radically? One then-current hypothesis was a change in atmospheric composition, and it was this possibility that led to Tyndall's pioneering work on the physics of the greenhouse effect. He was also a committed communicator; during his time at the Royal Institution, he earned great renown for presenting science to the public. So it is fitting that one of the climate change research institutes in the UK, with a particular focus on an interdisciplinary approach and communication with the public, local authorities, business, etc., is named after him - the Tyndall Centre in Norwich.

Box 2 'Exciting' molecular vibrations

- The chemical bonds that hold a molecule together are like springs and, like them, they can stretch and flex, making the molecule vibrate. Molecular vibrations always have a characteristic frequency. If a molecule absorbs radiation of a matching frequency - *and hence with a characteristic wavelength* (see Box 1) - the energy it gains makes it vibrate more vigorously. The frequencies of molecular vibrations invariably correspond to wavelengths in the infrared part of the spectrum.
- To be 'infrared active' (i.e. to absorb infrared radiation through changes in the way it vibrates), a molecule must contain more than two atoms or, if there are just two atoms, these are of different elements. More complex molecules, such as the greenhouse gases, can vibrate in several ways, each with its own characteristic frequency. So they can absorb a range of wavelengths in the infrared.

- Once 'excited' by absorbing infrared radiation, a greenhouse gas molecule can lose energy again by *re-emitting* radiation of the *same* wavelength. Alternatively, it can pass energy on to other molecules in the air by bumping into them: the net effect is to increase the total 'energy content' of the air, warming it up.

Taken together, the natural greenhouse gases absorb infrared wavelengths throughout most of the terrestrial range; there is only one region, between 8 and 13 μm, where absorption is weak. Known as the 'atmospheric window', this allows some of the longwave radiation from the surface to escape *directly* to space, but most of it is intercepted by the atmosphere. That changes the simple picture in Figure 4 substantially. A better representation is shown in Figure 7. Now most of the longwave radiation from the surface is effectively 'trapped' and recycled by the atmosphere, being repeatedly absorbed and *re-emitted* in all directions by the greenhouse gases. This warms the atmosphere. Some of the re-emitted radiation ultimately goes out to space, maintaining an overall **radiation balance** *at the top of the atmosphere*, as shown in Figure 7. This prevents the whole Earth-atmosphere system from heating up without limit. The crucial difference is that much of the re-emitted radiation goes back down and is absorbed by the surface. It is this additional energy input - over and above the absorbed solar radiation - that keeps the Earth's GMST over 30 °C warmer than it otherwise would be.

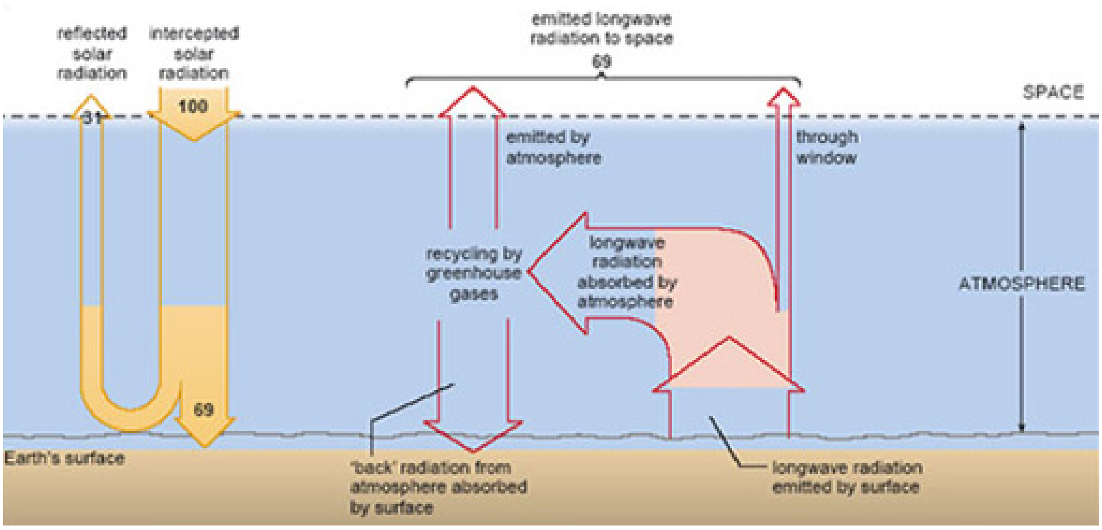

Figure 7 Schematic representation of the globally averaged radiation balance for an Earth-like planet with an atmosphere that absorbs and re-emits (both downward and upward) longwave radiation from the surface (reddish arrows).

As in Figure 4, Figure 7 shows that 69 units of solar radiation are absorbed by the planet and 69 units of longwave radiation go back out to space. However, this overall radiation balance is now at the top of the atmosphere, *not at the surface*, which receives an extra input of energy through the 'back radiation' from the atmosphere.

The surface warming attributed to the back radiation from the atmosphere is called the **greenhouse effect**.

The contribution each of the greenhouse gases makes to the total effect depends on two main factors: how efficient it is at absorbing outgoing longwave radiation, and its atmospheric concentration. The striking thing is that most of these gases are only minor atmospheric constituents, as shown by the information collected in Table 1. Here, concentrations are given as 'mixing ratios' - the measure of atmospheric composition that has become familiar to policy makers and other stakeholders in the climate change debate (Figure 8). The term is explained in Box 3.

Figure 8 According to the 500 PPM company, 'Our name is our mission: 500 PPM means 500 parts per million - a critical value for climate protection, because it describes the point at which the concentrations of greenhouse gases in the atmosphere should be stabilized'.

Box 3 Mixing ratios

Strictly, the mixing ratio (by volume) tells us about the 'fractional abundance' or proportion of a given atmospheric gas, although you will often find it referred to as the 'atmospheric concentration' (and we shall follow this practice). Taking oxygen (O_2) as an example, the formal definition is as follows:

$$\text{mixing ratio} = \frac{N(O_2)}{N_{\text{total}}} \qquad (2.1)$$

where N_{total} is the total number of molecules in a given volume of air (a cubic metre, say) and $N(O_2)$ is the number of molecules of oxygen in the *same* volume of air. Expressing the fraction in decimal form or as a percentage (by multiplying by 100) is fine for the major atmospheric constituents (see the entries in Table 1), but it becomes unwieldy for minor constituents like the greenhouse gases. In this case, values are usually recorded as **ppm (parts per million, 10^6)** or as **ppb (parts per billion, 10^9)** - or even as **ppt (parts per trillion, 10^{12})** for the least abundant species.

SAQ 5

In Table 1, the mixing ratio of CO_2 is given as 368 ppm. Express this value as a number (in scientific notation), and then as a percentage.

Answer

A value of 368 ppm means that in every million molecules of air, 368 will, on average, be molecules of CO_2. So 368 ppm is equivalent to $368/10^6 = 368 \times 10^{-6} = 3.68 \times 10^{-4}$ (in scientific notation). Multiplying by 100, this becomes 3.68×10^{-2}% or 0.0368%.

SAQ 6

Now express the mixing ratio of CO_2 in ppb.

Answer

If there are 368 molecules of CO_2 per million in total, there would be 368 000 per billion, so the answer is 368 000 ppb.

Thus, 1 ppm=10^3 ppb, and similarly 1 ppb=10^3 ppt.

Table 1 Recent (1998) average mixing ratios of some of the gases in (absolutely) dry air in the lower atmosphere - the region up to about 10 km, known as the troposphere (see Section 1.2.1).

Gas (and formula)	Mixing ratio
major constituents	
nitrogen (N_2)	0.78
oxygen (O_2)	0.21
argon (Ar)	0.0093
trace gases	
carbon dioxide (CO_2)	368 ppm
methane (CH_4)	1745 ppb
nitrous oxide (N_2O)	314 ppb
ozone (O_3)	10-100 ppb

SAQ 7

Given the information in Table 1, how would you describe the bulk composition of the lower atmosphere?

Answer

99% is nitrogen and oxygen (roughly in a 4 : 1 ratio), and most of the rest (0.93%) is argon.

SAQ 8

Is any one of these major components a greenhouse gas?

Answer

No. The chemically inert noble gas argon exists as individual atoms; nitrogen and oxygen molecules each consist of two atoms of the same element. None of them fulfils the criterion for being infrared-active (Box 2).

Note that the mixing ratios in Table 1 are for *dry* air. The contribution from water vapour is not included because the amount in the air is highly variable - from practically none at all up to about 4% (by volume). Part of the explanation is that air can 'hold' only a certain amount of water vapour: it has a 'saturation' limit, which depends mainly on temperature. The variable humidity of the air (a measure of its water vapour content) is part of our everyday experience: it affects the ability of sweat to evaporate, for example, and the drying of clothes on the line.

Averaged over time and around the globe, water vapour represents about 0.5% of the total atmospheric gas. This relatively high abundance makes water vapour the single most important natural greenhouse gas: it contributes about 60% of the surface warming attributed to the natural greenhouse effect. Carbon dioxide, the second most abundant, contributes a further 25% or so; most of the rest is due to the other three trace gases in Table 1, which have much lower atmospheric concentrations. (One further contribution is noted in Section 1.3.3.)

The fact that the Earth is not a frozen and lifeless rock shows that the *natural* greenhouse effect is not a 'bad thing'; indeed, it is a 'good thing'! It is the extra warming produced by an *enhanced* or amplified greenhouse effect, due to an increase in the atmospheric concentration of CO_2 (and indeed other greenhouse gases), that lies at the heart of current concerns. We shall sometimes refer to this as an increase in the atmospheric 'burden' of CO_2 (or of greenhouse gases in general), since an increase in concentration necessarily implies an increase in the total amount (or number of molecules) of the gas in the atmosphere.

Question 2

Analogies are a useful aid to understanding, and can be a powerful means of communicating scientific ideas to a lay audience. However, they can be misleading. Look back at the quote from John Tyndall at the beginning of Section 1.2.2. In what way is the analogy used there a misleading one? Explain your reservations, making reference to the mechanism that actually creates the Earth's greenhouse effect.

Answer

The basic problem is the notion of a 'barrier across the terrestrial rays'. This could suggest that the atmosphere somehow 'reflects' back outgoing radiation (an error that sometimes appears in newspaper accounts to this day) and/or that *none* of it ever goes out to space - in which case the planet would simply heat up without limit! In reality, some of the longwave radiation from the surface escapes directly to space (at wavelengths in the 'atmospheric window'). The rest is *absorbed and re-emitted* (up and down) by greenhouse gases in the atmosphere. Back radiation from the atmosphere keeps the surface warmer than it otherwise would be (the natural greenhouse effect). But some of the re-emitted radiation ultimately goes out to space, maintaining an overall radiation balance at the top of the atmosphere.

1.3 Energy flows within the Earth-atmosphere system

Before we focus on the enhanced greenhouse effect, we need to refine the schematic representation in Figure 7 and draw in some of the other processes that influence the Earth's temperature - not only at the surface, but also at different levels within the atmosphere.

1.3.1 The vertical 'structure' of the atmosphere

The atmosphere is not a simple, uniform slab of absorbing material. On the contrary, it gets progressively 'thinner' or less dense with increasing altitude (height above mean sea level); i.e. the *total* number of molecules in a given volume of air is lower, and so is the pressure. About 80% of the total mass of the atmosphere is within some 10 km of the surface; 99.9% lies below 50 km.

The important corollary is that the key greenhouse gas molecules (H_2O and CO_2) are also more abundant close to ground level, and increasingly scarce at higher altitudes. So a better picture of radiation trapping in the real atmosphere is to imagine it happening in a series of stages. Outgoing longwave radiation is repeatedly absorbed and re-emitted as it 'works up' through the atmosphere; it is re-radiated to space only from levels high enough (i.e. thin enough) for absorption to have become weak. This suggests that the atmosphere should be warmer at ground level - close to the source of the outgoing radiation, and where the absorbing molecules are more abundant. Everyday experience confirms this expectation; it generally gets colder as you walk up a mountain, for example.

Figure 9 is a typical temperature profile of the atmosphere. It shows that air temperature does indeed fall with increasing altitude throughout the lower atmosphere or **troposphere**, reaching a minimum value (of about −55 °C) at the **tropopause**. This lies 8-15 km above the ground, depending mainly on latitude: it is higher (and colder) at the Equator than at the poles. No mountains rise above the troposphere; it is where we live and where almost all weather phenomena (rain, clouds, winds, etc.) occur. However, if you could travel higher up (without the protection of a jet aircraft), you would find that the temperature soon starts to increase again - and continues to do so up to the stratopause at the top of the **stratosphere**. Why is this?

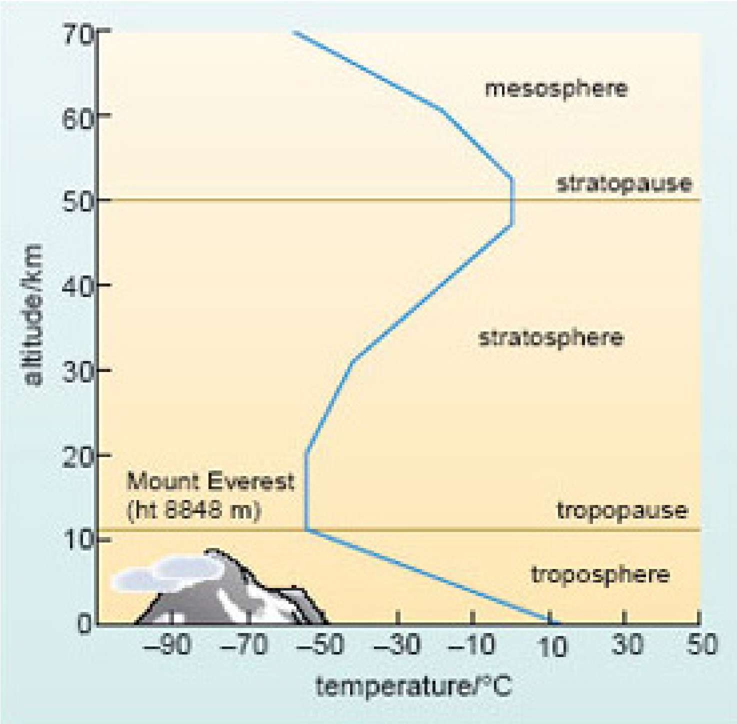

Figure 9 The characteristic temperature profile of the atmosphere produces a vertical structure like a series of concentric shells. The successive regions or 'spheres' are separated by 'pauses' where the change in temperature with altitude switches from decreasing to increasing, or vice versa. The outer more-rarefied reaches of the atmosphere (which extends up to 100 km or so) are not included.

1.3.2 The fate of incoming solar radiation

SAQ 9

Look back at Figure 7. In this schematic representation, what is the fate of incoming solar radiation?

Answer

It is either reflected back to space (31 units) or absorbed by the surface (69 units).

Some solar radiation is, in fact, absorbed as it travels down through the atmosphere. Mostly, this is radiation at wavelengths in the two 'tails' of the solar spectrum (Figure 5) - the ultraviolet and the near infrared.

Like water vapour and CO_2, the ozone in the troposphere acts as a greenhouse gas. Unlike those two gases, however, very little of the Earth's ozone is, in fact, in the lower atmosphere; the bulk of it (some 90%) is in the stratosphere, where it forms the so-called **ozone layer**. In this more-rarefied region, ozone plays a different role because it also absorbs the shorter ultraviolet wavelengths in the solar spectrum - radiation that is lethal to many micro-organisms and can damage important biological molecules, leading to conditions such as skin cancer in humans. Fortunately for life on Earth, most of this radiation is absorbed by the ozone layer, preventing it from penetrating deeper into the atmosphere. More pertinent here, the absorption of incoming solar energy by stratospheric ozone heats this region of the atmosphere *directly*. In effect, the stratosphere is heated from *above*, whereas the troposphere is heated from *below*. This is why the highest temperatures are found at the top of the stratosphere, but at the bottom of the troposphere (as shown in Figure 9).

About half of the incoming near-infrared radiation is also absorbed, mainly by water vapour low down in the troposphere. In addition, the atmosphere contains a huge assortment of **aerosols** - fine solid particles and liquid droplets suspended in the air. Except in the aftermath of a major volcanic eruption (of which more in Section 1.5), aerosols are also most abundant in the lower atmosphere; natural sources include desert dust wafted into the air by wind, smoke and soot from wildfires, salt from sea-spray, and so on. Depending on their make-up, aerosols can absorb solar radiation - or (and this is usually more important) scatter some of it back to space. Globally, aerosols make a significant contribution to the Earth's albedo (included in the figure of 31% quoted earlier). They also play another important role. Many aerosols act as **cloud condensation nuclei**, providing surfaces that promote the condensation of water vapour to form the liquid droplets (or ice crystals, at higher and colder altitudes) suspended in clouds - a process that occurs less readily in 'clean' (i.e. aerosol-free) air.

1.3.3 The role of clouds

We have already identified one role that clouds play in the Earth's climate: they are highly reflective (Section 1.2.1). At any given time, about half of our planet is covered by clouds; the sunlight they reflect back to space accounts for about 55% of the total planetary albedo. However, clouds also absorb and re-emit *outgoing* longwave radiation; i.e. they contribute to the back radiation from the atmosphere, and hence to the natural greenhouse effect. This is why temperatures tend to be lower under clear night skies than on nights with extensive cloud cover.

Thus, clouds present something of a paradox: they both warm and cool the Earth. The balance between these two opposing effects is a delicate one - dependent on factors such as the type and thickness of the clouds, their altitude, whether they consist of water droplets or ice crystals, and so on (Figure 10). Averaged over time and around the world, satellite data indicate that the net effect of clouds in our current climate is a slight cooling of the surface. As you will see, predicting how the balance between warming and cooling might shift in a warmer world remains one of the biggest headaches for climate scientists.

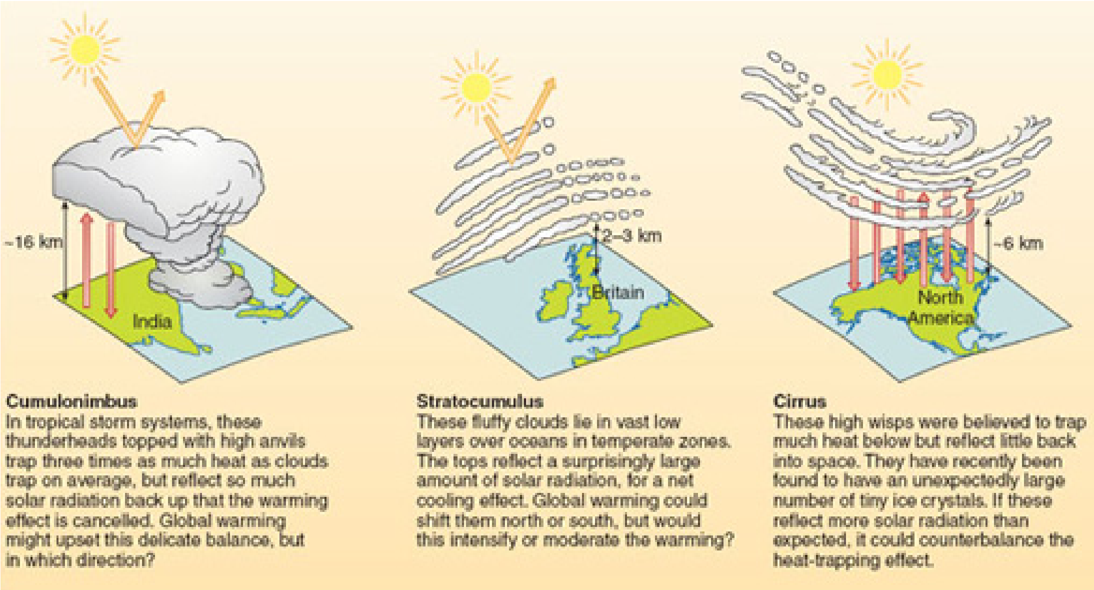

Figure 10 Researchers are only beginning to understand the complex role clouds play in modulating the planet's temperature. The figure summarises some key points, stressing how different types of clouds affect the Earth's radiation balance differently. How these variations fit together to produce a global cooling effect, and how that might change in a warmer world, remains uncertain.

1.3.4 The role of convection in the atmosphere

We come now to our final refinement to the simple picture in Figure 7. Recall that the troposphere is heated from below, with temperature then falling with increasing altitude. This situation sets the scene for the onset of convection - the bulk flow or circulation of a fluid driven by differences in temperature. Convection in the atmosphere plays a vital role in two further mechanisms - *quite apart from the emission of longwave radiation* - whereby energy is transferred from the Earth's surface to the atmosphere.

The first is the transfer of 'thermal' energy (often referred to rather loosely as 'heat') by a combination of conduction and convection. This is essentially the same mechanism that heats a saucepan of water on the stove; see Box 4. The situation in the atmosphere is more complicated, but the basic principle is the same. Warm air, heated by contact with the ground or a warm sea, rises upwards carrying heat transferred from the surface aloft. This allows more cool air to come into contact with the surface and be heated in its turn. Working together, conduction/convection drive a significant flow of heat across the boundary between the surface and the air.

Box 4 Heating water by conduction and convection

Anyone who tries to pick up a metal spoon left in contact with a hot pan quickly learns that metals are good conductors of heat. **Conduction** is the transfer of heat through matter by molecular activity; i.e. the energy is transferred through contact between individual molecules. By contrast, **convection** is the transfer of heat by bulk movement or circulation within a fluid (a liquid like water or a gas like the air).

In Figure 11, heat is transmitted from the electric element, through the pan to the water in contact with the base of the pan by conduction. As water in this layer warms up, it expands - this is called **thermal expansion** - and so becomes less dense than the water above.

Because of this new buoyancy, the warm water begins to rise, to be replaced by cooler, denser water from above which is heated in its turn. On reaching the surface, the warmed water begins to lose heat to the air; it cools, becomes denser and sinks, then is heated again and rises, and so on. As long as the water is heated unequally (i.e. from the bottom up), the water will continue to 'turn over' in a convective circulation so that eventually all of it becomes warm.

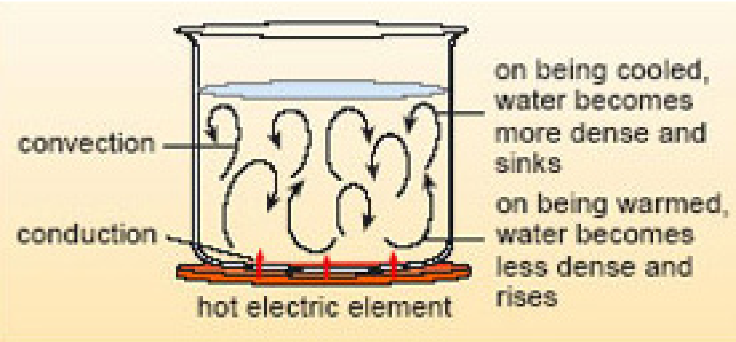

Figure 11 The circulatory pattern in a pan of water heated on an electric element.

The second form of energy transfer is indirect, but even more important on a global scale. It involves the evaporation of water - mainly from the oceans, but also from lakes and rivers, soils, rocks and vegetation on land. Evaporation requires energy, known as the **latent heat of vaporisation**, which is extracted from the surface involved. This is why the evaporation of sweat acts to cool the body. The latent heat of vaporisation of water, i.e. the amount of heat needed to convert 1 kg of liquid water to water vapour at the same temperature (and the amount of heat *released to* the surrounding environment when 1 kg of water vapour condenses) is 2.25×10^6 J kg^{-1} - higher than the value for any other substance.

SAQ 10

How does convection in the overlying air help to promote the evaporation of water?

Answer

Convection carries air containing water vapour upwards, so the air just above the surface does not become 'saturated' (Section 1.2.2), enabling more water to evaporate.

As we noted earlier, the saturation limit of air depends on temperature: *cool air can carry less water vapour than warm air*. As moisture-laden air is carried upwards, it cools and may become saturated. Continued rise and further cooling then results in the condensation of water vapour onto aerosols in the air: clouds form and latent heat is released to the atmosphere. Clouds, the turbulence of atmospheric convection and the winds that redistribute heat around the world are largely confined to the troposphere (*tropos* is Greek for 'turning').

SAQ 11

Look back at Figure 9. It is often said that the tropopause acts like a lid, preventing convection in the lower atmosphere from reaching any higher. Can you suggest why?

Answer

With (less dense) warm air lying above (more dense) cooler air, conditions in the stratosphere are not conducive to convection. (*Stratos* is Latin for 'layered'.)

Rapidly rising air can (and does) overshoot the tropopause, mostly in the updraught of violent storms over the tropics. And there are return routes as well, mainly at middle latitudes. In general, though, the circulation of air in the stratosphere does not interact strongly with the wind systems in the lower atmosphere. It is within the troposphere that the full drama of the Earth's weather occurs.

1.4 An overview of the global energy budget

Figure 12 incorporates the additional factors considered in Section 1.3, including the non-radiative energy transfers across the surface-air boundary (green arrow). Essentially a more detailed version of Figure 7, this figure gives quantified estimates of the globally averaged energy budget for the whole Earth-atmosphere system, and its component parts. Question 3 should help you to find your way around Figure 12, and to draw together many of the key points developed so far in this chapter. Make sure to try answering it before moving on.

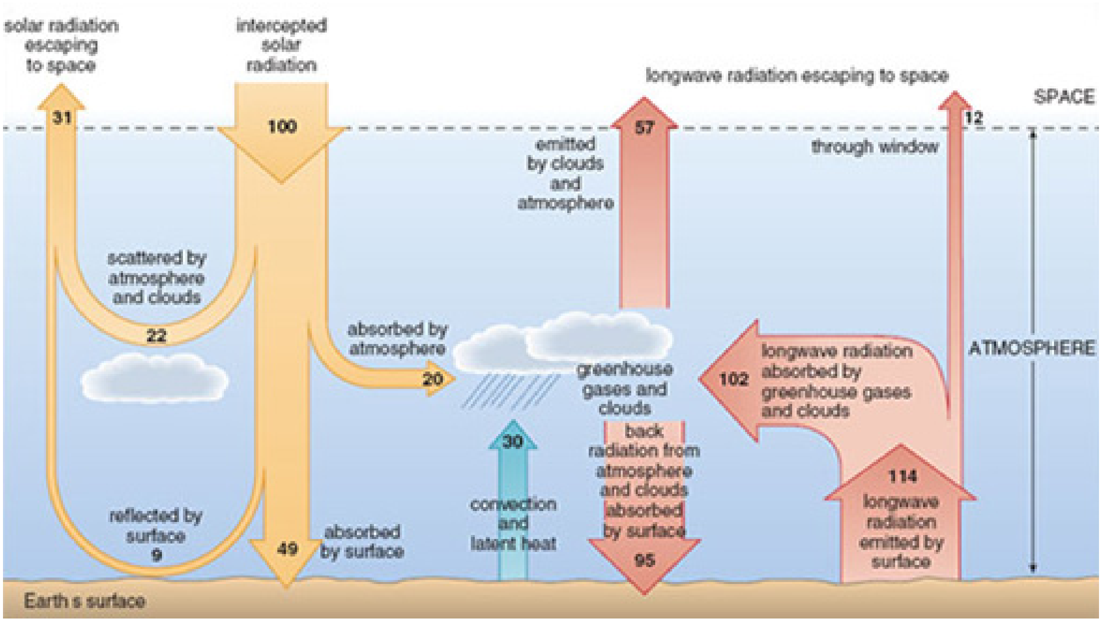

Figure 12 Schematic representation of the overall energy budget for the Earth and its atmosphere. Figures are global annual averages expressed as a percentage of the rate per unit area at which solar radiation is intercepted by the Earth; i.e. 100 units is equivalent to 342 W m^{-2}, as in Figure 4.

Question 3

With reference to Figure 12:

(a) What proportion (as a percentage) of the Earth's planetary albedo is due to solar radiation reflected by the surface? Which regions of the world are likely to be mainly responsible for this contribution?

(b) Calculate the difference between the rate of energy gain and the rate of loss for: (i) the Earth's surface; (ii) the atmosphere; and (iii) the whole Earth-atmosphere system (i.e. at the top of the atmosphere). What do you conclude about the Earth's GMST?

(c) What proportion (as a percentage) of the longwave radiation emitted by the surface is absorbed by the atmosphere?

(d) Translate the 114 units of longwave radiation emitted by the surface into a rate of energy transfer (in W m^{-2}). Explain why your answer is consistent with the fact that the Earth's GMST is higher than its effective radiating temperature (−19 °C).

Answer

(a) The planetary albedo is the proportion of incoming solar radiation reflected or (scattered) directly back to space - 31 units according to Figure 12. Surface reflection contributes 9 units or (9/31) × 100% = 29%. Snow- or ice-covered surfaces (predominantly at high latitudes) are likely to be mainly responsible, given their high albedo.

(b) (i) The total rate of energy gain by the Earth's surface is the sum of the appropriate downward-pointing arrows in Figure 2.12; i.e. (49 + 95) units = 144 units. The total loss rate is the sum of the upward-pointing arrows that originate at the Earth's surface: (30 + 114) units = 144 units. The difference is zero, so the surface is in a steady state; the GMST is not changing.

(ii) Proceeding as in (i), the total rate of energy gain by the atmosphere is: (20 + 30 + 102) units = 152 units. The total rate of loss is: (95 + 57) units = 152 units. The difference is again zero.

(iii) For the whole Earth-atmosphere system, the total rate of energy gain (solar radiation intercepted) is 100 units, and the total rate of loss is (31 + 57 + 12) units = 100 units, confirming that the whole system is also in a steady state.

(c) The proportion is (102/114) × 100% = 89% (to 2 significant figures).

(d) 100 units is equivalent to 342 W m^{-2}, so 114 units is equivalent to (342 W m^{-2}/100) × 114 = 390 W m^{-2}. This is significantly higher than the rate of emission (236 W m^{-2}; Section 1.2.1) from a body with an effective radiating temperature of −19°C. Since the rate of emission increases with increasing temperature, this implies that the Earth's GMST is higher than −19 °C.

To sum up: in Figure 12, the whole Earth-atmosphere system is in a dynamic **steady state** or equilibrium. Most (89%) of the outgoing longwave radiation is absorbed and recycled by the atmosphere, and ultimately re-emitted to space from higher, colder levels (Figure 9). As a result, energy circulates *within* the system at a higher rate than the rate of input or output at the top of the atmosphere: this is why the Earth's surface is warmer than it otherwise would be. But in a balanced state, there is no net accumulation of energy in any part of the system, and no net loss. In short, Figure 12 depicts a world where the GMST is not changing. So what might cause the Earth's GMST to change?

1.5 'Radiative forcing' as an agent of climate change

Since its first major report in 1990, the IPCC has used the concept of 'radiative forcing' as a simple measure of the importance of a potential climate change mechanism. The basic idea is straightforward. Any factor that disturbs the radiation balance *at the top of the atmosphere* has the potential to 'force' the global climate to change: it will either warm up or cool down until a balance is restored. The perturbation to the energy balance of the whole Earth-atmosphere system is called **radiative forcing**, and is given in the units W m^{-2}.

SAQ 11a

Look back at Figure 12. What three factors could disturb the radiation balance at the top of the atmosphere?

Answer

A change in the Sun's output, and hence in the solar constant; a change in the Earth's albedo; and a change in the longwave emission to space.

Among the more enduring hypotheses to account for climate change are those based on the idea that the Sun is a variable star and that its output of energy varies through time. Indeed, this idea underlies the sceptical view that recent global warming has little to do with human activities; rather, the argument goes, solar variability is the main culprit. We shall come back to that issue in Section 2. For now, we use the possibility of solar variability to put some flesh on the notion of radiative forcing.

To that end, Figure 13 illustrates the effect of a 1% change (up or down) in the solar constant, and hence in the globally averaged solar radiation intercepted by the Earth (the 100 units in Figure 13a). Assuming that the planetary albedo is unchanged (at 31%), an increase in the solar constant (Figure 13b) produces a **positive radiative forcing**: the rate at which the Earth-atmosphere system absorbs solar radiation (69.69 units) is now greater than the rate at which it emits longwave radiation to space (69 units). This has a warming effect. Conversely, a reduction in the solar constant (Figure 13c) produces a **negative radiative forcing**, which has a cooling effect.

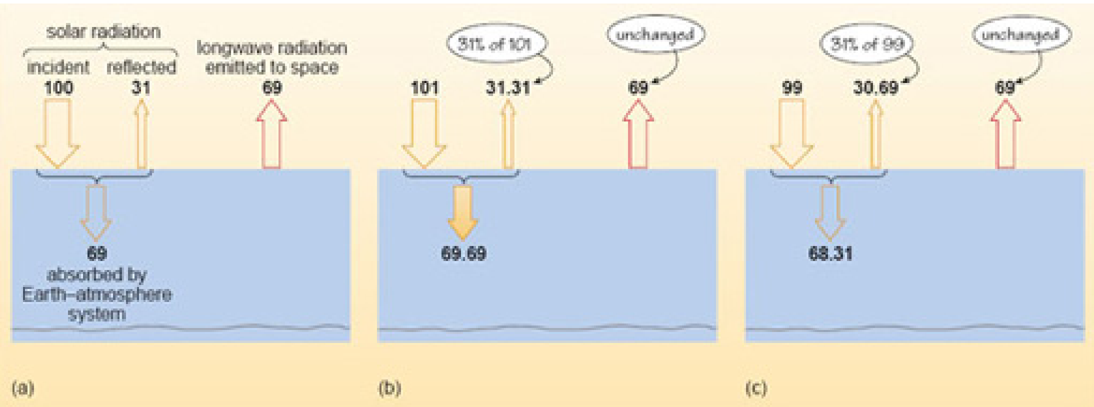

Figure 13 (a) The globally averaged radiation balance at the top of the atmosphere from Figure 12 (i.e. 100 units is equivalent to 342 W m^{-2}). (b) and (c) The imbalance induced by a 1% increase or decrease, respectively, in the solar constant, assuming no change in the planetary albedo.

Question 4

According to Figure 13, what is the radiative forcing, in W m^{-2}, associated with a ±1% change in the solar constant?

Answer

The radiative forcing is the difference between the rate at which the Earth-atmosphere system absorbs solar radiation and the rate at which it emits longwave radiation to space. From parts (b) and (c) of Figure 13, the magnitude of the radiative forcing is (69.69 − 69) units or (69 − 68.31) units = 0.69 units, which is equivalent to (342 W m^{-2}/ 100) × 0.69 = 2.4 W m^{-2} (to 2 significant figures). The forcing is positive for a 1% increase in the solar constant (Figure 13b) and negative for a 1% decrease (Figure 13c).

Explosive volcanic eruptions spew vast quantities of gases and fine-grained debris (volcanic ash) into the atmosphere. The greatest eruptions are sufficiently powerful to inject material high into the stratosphere, where it gradually spreads around the world. The result can be a significant and widespread cooling effect on climate (see Box 5).

Box 5 1816: the 'year without a summer'

The bright sun was extinguish'd, and the stars

Did wander darkling in the eternal space,

Rayless, and pathless, and the icy earth

Swung blind and blackening in the moonless air;

Morn came and went - and came, and brought no day,

And men forgot their passions in the dread

Of this their desolation.

(Lord Byron, *Darkness*, 1816)

The largest volcanic event of modern times was the eruption of Mount Tambora in Indonesia in April 1815. Where records exist, they reveal a period of abnormally cold weather that prevailed during the spring and summer of 1816 in many parts of the Northern Hemisphere. The effects were especially severe in the northeastern United States, with average temperatures in New England up to 3.5 °C below normal in June, for instance, and unseasonal frosts and snowfalls. Europe was also badly affected, leading to crop failures and famine in England, France and Germany. The below-average temperatures lasted for about two years.

In the summer of 1816, there were also widespread reports of a dim Sun, or persistent haze that was not dispersed by surface wind or rain (since it was actually up in the stratosphere) - though few captured its effects as powerfully as Byron's poem.

SAQ 12

Why might a major volcanic eruption be expected to have a cooling effect on climate at the Earth's surface?

Answer

It increases the load of aerosols in the stratosphere, potentially increasing the absorption of incoming solar radiation in this region and/or scattering more of it back to space (Section 1.3). Both effects cause a cooling at the surface

Although one of the more dramatic features of a major eruption (Figure 14), volcanic ash has little enduring impact on climate because it settles out of the stratosphere within a few months. Far more important is the amount of sulfur dioxide (SO_2), one of the volcanic gases, emitted during the eruption. Chemical reactions rapidly convert the gas to droplets of sulfuric acid, and these **sulfate aerosols** can remain in the stratosphere for several years (the persistent haze of Box 5). Their main effect is to increase the back-scattering of solar radiation.

Figure 14 The explosive eruption of Mount Pinatubo in the Philippines in June 1991 devastated the surrounding area and sent about 25×10^9 kg of SO_2 into the stratosphere. Over the following year, the haze of sulfate aerosols travelled around the world and lowered the average surface temperature in the Northern Hemisphere by about 0.5 °C.

SAQ 13

With this in mind, how would you describe the climatic effects of a major volcanic eruption in terms of radiative forcing?

Answer

The extra load of stratospheric aerosols effectively increases the planetary albedo (the second of the three factors identified at the beginning of this section), and this constitutes a *negative* radiative forcing. (The effect is analogous to a reduction in the solar input.)

The resulting cooling effect can be significant (as noted in connection with the Pinatubo eruption in Figure 14), but only on a relatively short-term basis - typically, 1-3 years at most. Air movements gradually carry the sulfate aerosols down into the troposphere, where they are usually washed out by rain within a few weeks.

But how does an increase in the atmospheric burden of greenhouse gases lead to a radiative forcing of climate? Again we use an illustrative example. Suppose the atmospheric concentration of CO_2 is doubled instantaneously (known as a **CO_2-doubling)**, but everything else (the solar input, planetary albedo, concentrations of other greenhouse gases, etc.) remains the same. What would be the immediate effect? With more molecules of CO_2 in the atmosphere, a higher proportion of the outgoing longwave radiation would be absorbed, *reducing* the net emission to space. Complicated, but well-understood, calculations give a reduction by about 4 W m^{-2} (from 236 W m^{-2} to 232 W m^{-2}) for a CO_2-doubling.

SAQ 14

Does this change represent a positive or negative radiative forcing?

Answer

The forcing is positive. The effect is analogous to an increase in the solar constant (by rather more than 1%, according to Question 4).

There is no dispute about this central conclusion. Increasing the atmospheric concentration of CO_2, or any other greenhouse gas, *will* force the global climate to warm up; we shall often refer to this as '**greenhouse forcing**'. However, the weighty tomes issued by the IPCC bear witness to the fact that 'the devil is in the detail'! In particular, there is still major uncertainty about what is perhaps the most fundamental question in the whole climate change debate: how much will the Earth's GMST rise in response to a given amount of greenhouse forcing? We shall revisit this question many times as the topic unfolds. Here, we focus next on what is known about the amount of greenhouse forcing to date.

1.6 The human impact on the atmosphere: the coming of the industrial age

There is no doubt that CO_2 is accumulating in the atmosphere. The record from Mauna Loa charts a continuing rise in CO_2 concentration since measurements began in 1958, when the level was 315 ppm; the value had reached about 370 ppm by the end of the 20th century, and hit more than 378 ppm in 2004. Important as changes in atmospheric CO_2 undoubtedly are (see below), we need to be aware that this is not the whole story of human-induced greenhouse forcing. In particular, monitoring programmes established during the 1980s reveal an upward trend in the levels of two other natural greenhouse gases as well - methane (CH_4) and nitrous oxide (N_2O). But how do we know that the build up of all three gases over recent decades is due to human intervention?

One strong line of evidence that it is comes from an unlikely source - the vast ice sheets of Greenland and Antarctica. As glacier ice is formed by compaction of successive layers of snow, small bubbles of air become trapped. When a sample of ice is drilled out (Figure 15), these air bubbles can be dated quite accurately, and when analysed, provide an archive of past atmospheric composition - including the levels of CO_2, CH_4 and N_2O. Figure 16 (adapted from IPCC, 2001a) sets the current situation in the context of ice-core data that trace variations in the atmospheric concentrations of these three gases over the past millennium.

Figure 15 Scientists at the US National Ice Core Laboratory examine an ice-core sample. Faint lines in the sample are annual dust layers (deposited in summer months), and counting these allows air bubbles trapped in successive layers to be dated.

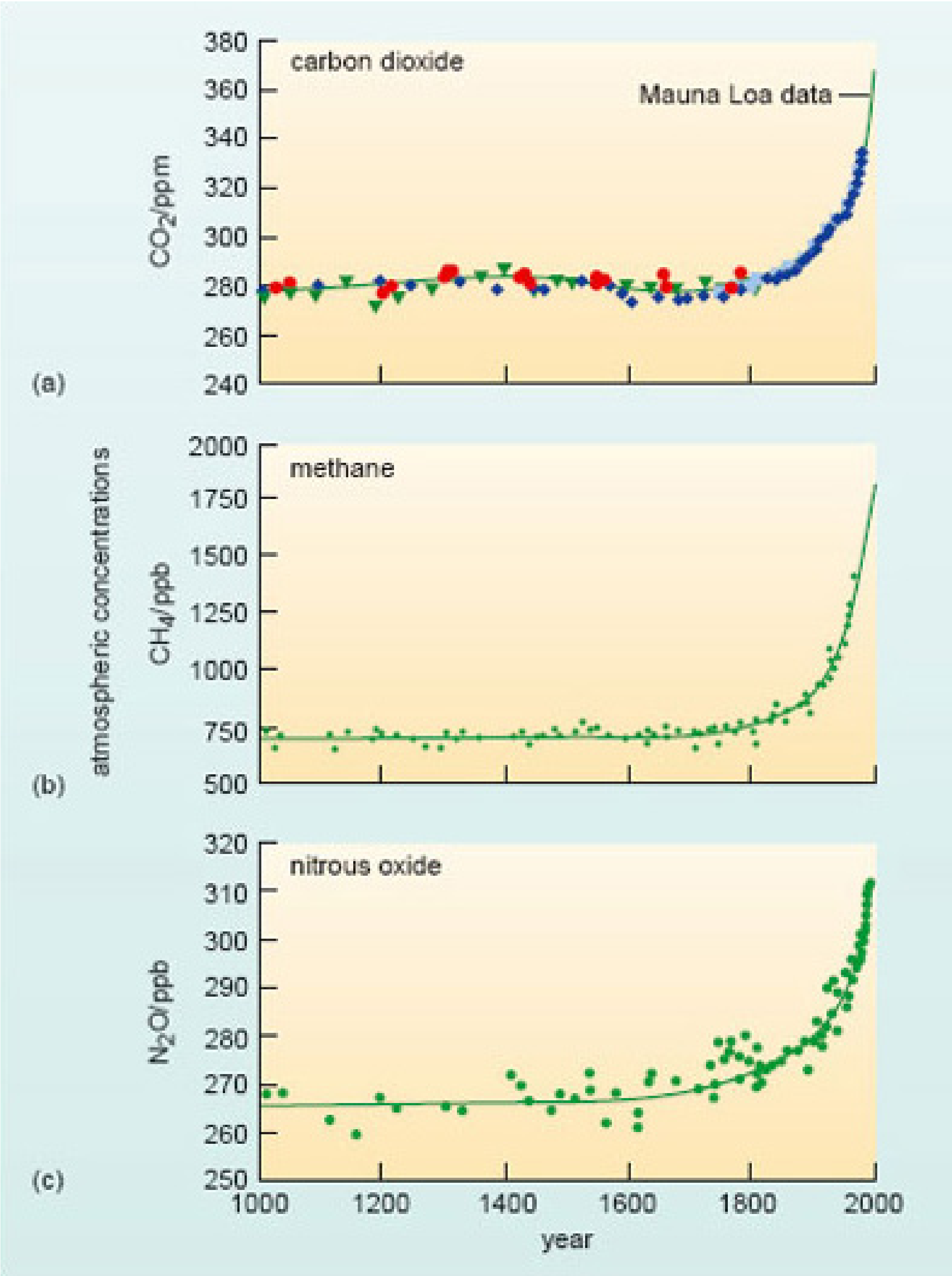

Figure 16

Figure 16 shows changes in the atmospheric concentration of (a) CO_2, (b) CH_4 and (c) N_2O over the past 1000 years. Ice-core data from several sites in Antarctica and Greenland (shown by different symbols in (a)) are supplemented with data from direct atmospheric measurements over recent decades - shown by the line for CO_2 (labelled the Mauna Loa data) and included in smoothed curves for CH_4 and N_2O.

SAQ 15

With this longer-term perspective in mind, what does Figure 16a suggest about the change in atmospheric CO_2 during the period covered by the Mauna Loa record?

Answer

It continues a rising trend that seems to have started towards the end of the 18th century. For some 800 years before that, the CO_2 level fluctuated little about a mean value close to 280 ppm.

Similar patterns are evident for both methane (Figure 16b) and nitrous oxide (Figure 16c). For each gas, the average level over the first 750 years of these ice-core records (i.e. up to 1750) is taken as a measure of its 'pre-industrial' concentration; these values are collected in Table 2, along with some other pertinent information we shall come on to shortly.

Table 2 Information on 'well-mixed' greenhouse gases influenced by human activities. (Source: IPCC, 2001a.)

Concentration				
Gas	**Pre-industrial**	**1998**	**Atmospheric lifetime/ years**	**Global Warming Potential**
natural greenhouse gases				
CO_2	280 ppm	368 ppm	~100	1
CH_4	700 ppb	1745 ppb	12	23
N_2O	270 ppb	314 ppb	114	296
synthetic halocarbons				
CFC-11($CFCl_3$)	**0**	268 ppt	45	4600
CFC-12 (CF_2Cl_2)	**0**	533 ppt	100	101600
HCFC-22 (CHF_2Cl)	**0**	132 ppt	12	1700

SAQ 16

Using the information in Table 2, calculate the percentage change in the atmospheric concentrations of (i) CO_2; (ii) CH_4; and (iii) N_2O since the pre-industrial period 1750 up to 1998.

Answer

There has been an increase by (i) 31%; (ii) 149%; and (iii) 16%. For CO_2, for example, the concentration has increased by (368-280) ppm=88 ppm, so the percentage increase has been (88/280) × 100%=31%. Similar calculations for CH_4 and N_2O give the other values.

There is one further point to note about the plots in Figure 16. The increase in the atmospheric burden of these gases since pre-industrial times is not linear; rather it appears to be accelerating. For example, it took over 200 years for the level of CO_2 to rise from 280 to 330 ppm (1750 to around 1975); it has taken just 30 years for it to increase by the same amount, i.e. a further 50 ppm.

As indicated in the heading to Table 2, these three natural greenhouse gases are described as being 'well-mixed', which means that they are distributed fairly uniformly throughout the troposphere. This is because they persist in the atmosphere long enough to be moved around the world by large-scale air movements and 'mixed up' with other atmospheric constituents, so their concentrations do not vary much from place to place. Current estimates of the **atmospheric lifetimes** of CO_2, CH_4 and N_2O are also given in Table 2 - along with comparable information for some of the infrared-absorbing **halocarbons** that do not occur naturally, but are now found in trace amounts in the atmosphere (albeit at the level of only a few tens to hundreds of parts per *trillion* , ppt; Box 3) as a result of their manufacture and use for various purposes. As a group of compounds, halocarbons can be thought of as derived from hydrocarbons (methane, for the examples in Table 2), but with some or all of the hydrogen atoms in the molecule replaced by halogen atoms - usually some combination of fluorine (F) and chlorine (Cl), as in the **chlorofluorocarbons (CFCs)** and hydrochlorofluorocarbons (HCFCs).

Indicted for their role in stratospheric ozone loss, the use of all CFCs has now been phased out under the evolving provisions of the Montreal Protocol on Substances that Deplete the Ozone Layer (first agreed in 1987). The two main CFCs are included in Table 2 for two reasons. First, these compounds are eventually destroyed by chemical reactions within the atmosphere, but this is a slow process - whence their long atmospheric lifetimes. It will take many decades to remove all trace of these compounds from the atmosphere (e.g. see Figure 17). Secondly, CFCs are also potent greenhouse gases - and so, unfortunately, are many of the other halocarbons (typified by HCFC-22 in Table 2) that have come on stream as CFC-substitutes in some key areas (e.g. refrigeration), and are now building up in the atmosphere. Basically, this can be traced back to the fact that halocarbons tend to absorb strongly at infrared wavelengths within the 'atmospheric window' (Section 1.2.2), where absorption by the natural greenhouse gases is weak.

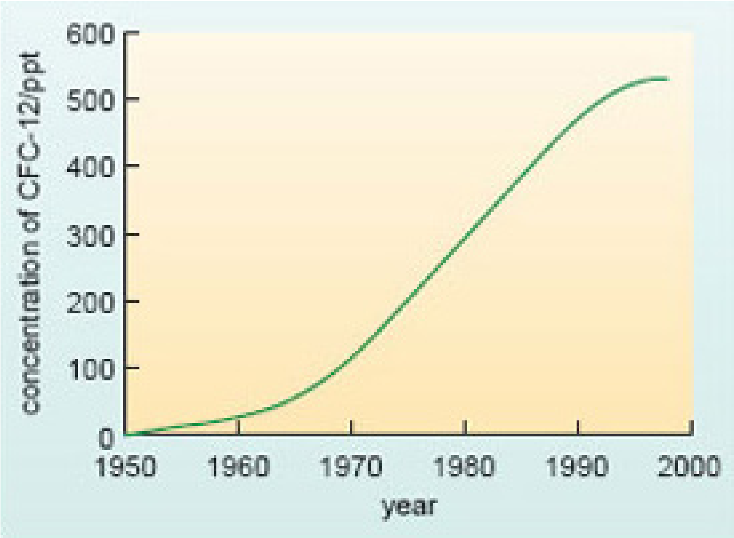

Figure 17 The trend in the atmospheric concentration of CFC-12 over the period 1950 to 1998. Thanks to the Montreal Protocol, the growth rate has slowed and then levelled off, but it will take many decades for natural processes to remove all of the CFC-12 already stored in the atmosphere.

This point is made more forcibly by the information collected under the heading 'Global Warming Potential' (GWP) in the final column of Table 2. This is a complicated index, designed mainly for use in a policy-making context. Put simply, it is a measure of the radiative forcing induced by adding to the atmosphere a given mass (1 kg, say) of a particular greenhouse gas *relative to* that induced by adding the *same* mass of carbon dioxide; this is why the entry for CO_2 is '1'. So we can think of the GWP value as a measure of the 'effectiveness' of a greenhouse gas as a climate change agent *relative to carbon dioxide* - but only on a mass-for-mass basis. This proviso is important. At first sight, the GWP values listed in Table 2 would suggest that CO_2 is a relatively weak greenhouse gas; certainly the halocarbons are a factor of at least 10^3 times more effective, when comparing the release of equal masses of the compounds. The reason CO_2 is given such prominence is that humans are responsible for generating so much more of this gas than any other.

SAQ 17

How do the concentration data in Table 2 provide evidence to support this statement?

Answer

In *absolute* terms (rather than the percentage terms noted above), the increase in atmospheric CO_2 has been much greater than that for any of the other greenhouse gases (natural or synthetic); it has risen by close to 100 ppm since pre-industrial times, while the CH_4 level, for example, has gone up by around 1000 ppb or just 1 ppm (Box 3).

The atmospheric content of purely synthetic compounds like the halocarbons can be wholly ascribed to human activities. But what about the greenhouse gases that do occur naturally? Atmospheric CO_2 is part of the global carbon cycle - and so too is the methane in the atmosphere, though this is probably a less familiar idea. Likewise, N_2O is part of the natural nitrogen cycle.

For each of these gases, there are natural processes that release it into the atmosphere (**sources**), and other natural processes that remove it again (**sinks**). The relatively stable atmospheric concentrations that prevailed in the pre-industrial world tell us that these sources and sinks were in balance (more or less) at that time. Clearly, this natural balance has been disturbed over the past 200 years or so - a period marked by an explosive growth in the human population. At the end of the 18th century, there were fewer than 1 billion people on the planet; there are over 6.3 billion today, and official estimates suggest that the upward trend is likely to continue for some time to come (Figure 18).

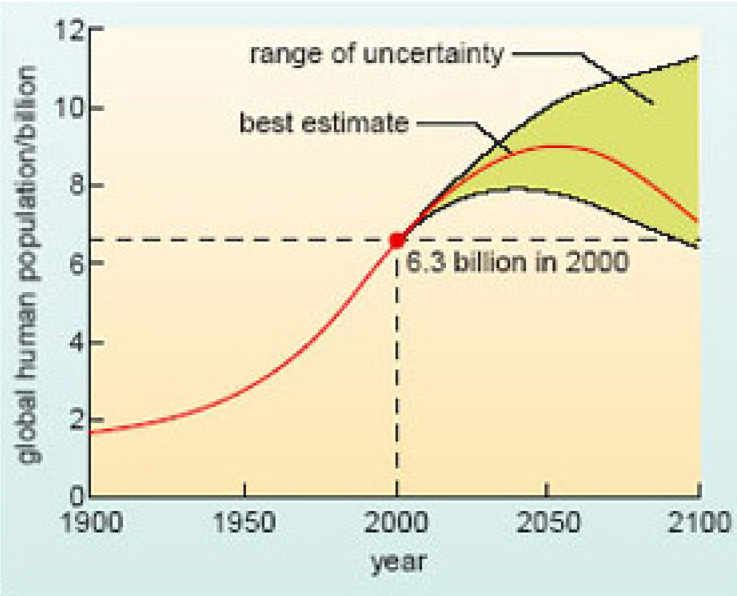

Figure 18 According to current best estimates, the human population is projected to peak at around nine billion by 2050, though some experts believe that it could go on increasing throughout the 21st century.

For the most part, the human impact on the atmospheric burden of natural greenhouse gases can be traced back to activities that effectively add a new source of the gas and/or increase natural emissions in various ways. Take CO_2, for example. Despite being the feature that characterises the industrial age, burning fossil fuels is not the only anthropogenic source of CO_2. For centuries, people have been clearing forests, burning the wood and turning vast tracts of land over to agricultural use in order to feed an ever-expanding population. The process of **'deforestation and land-use change'** also adds to the CO_2 content of the atmosphere. The range of human activities that have augmented natural emissions of CH_4 and N_2O are summarised in Box 6, along with a brief comment about another natural greenhouse gas - tropospheric ozone. Study the material in the box, and then work through the following questions.

Box 6 Sources of other greenhouse gases - the human connection

Methane is generated during the breakdown of organic matter by bacteria that thrive in *anaerobic* (i.e. oxygen-free) environments - principally in waterlogged soils (bogs, swamps and other wetlands, whence methane's common name of 'marsh gas') and in the guts of termites and grazing animals. But today, only some 30% of global CH_4 emissions come from natural sources, with natural wetlands accounting for about two-thirds of the total. Rice paddies, effectively artificial marshes, contribute a further 11%, and an astonishing 16% is due to the flatulence of grazing livestock (cattle, sheep, etc.)! While such sources are undoubtedly biogenic in origin, they also clearly have an anthropogenic element - closely linked to human food production, in this case.

Waste management (e.g. organic matter rotting in landfill sites) adds a further anthropogenic source of CH_4 (around 17% of global emissions). And since natural gas is mainly methane, so too does leakage from natural gas pipelines and the common practice of venting the gas to the atmosphere at oil production sites and from coal mines (a further 19%). Finally, burning vegetation can also generate CH_4, depending on the way it burns (i.e. smouldering as opposed to flaming).

Nitrous oxide is part of the natural nitrogen cycle; it is produced by the activities of micro-organisms in soils and sediments. Again, the increase in its atmospheric concentration is thought to result mainly from agricultural activities, such as the application of nitrogenous fertilisers to boost crop yields; some of the nitrogen ends up in the air as N_2O. In addition, the high-temperature combustion of fossil fuels (or indeed, any kind of vegetation) in air produces some N_2O (through reaction between N_2 and O_2 in the air), along with other nitrogen oxides (notably nitric oxide, NO).

Ozone is also a natural component of the lower atmosphere (due in part to transport down from the stratosphere), but the normal background level is low. However, enhanced concentrations of tropospheric ozone are now found in many polluted environments, especially over densely populated industrialised regions. Here, ozone is generated close to the surface by the action of sunlight on the mix of gaseous pollutants that is typically found in vehicle exhaust fumes - unburnt hydrocarbons, carbon monoxide (CO) and nitric oxide (NO). Ozone is one of the more noxious components of 'photochemical smog' , since exposure to enhanced levels of the gas is harmful to both human health and plant growth.

Unfortunately, gains made in reducing vehicle emissions of the key ozone 'precursors' (by fitting catalytic converters) are being outweighed by the worldwide growth in car usage. And there are many other anthropogenic sources of these pollutants as well - including power stations, industrial processes, and the burning of vegetation.

SAQ 18

How does the extraction, distribution and burning of fossil fuels add to the atmospheric burden of other greenhouse gases, as well as CO_2?

Answer

It does so both directly (e.g. N_2O formed during combustion; CH_4 released at fuel extraction sites and through leakage from gas pipelines) and indirectly (emissions of O_3 precursors from vehicles and power stations).

SAQ 19

What other activity that is fundamental to human welfare also seems to have played a major role?

Answer

Food production. Agricultural activities increase emissions of both CH_4 (rice paddies and livestock) and N_2O (fertiliser use). Since burning vegetation often goes along with clearing land for agricultural use, we can add that in as well (a source of CH_4, N_2O and O_3 precursors, as well as CO_2).

Unlike the well-mixed greenhouse gases in Table 2, tropospheric ozone is relatively short-lived and there are marked regional variations in its concentration. This has made it difficult to track long-term changes in the *total* amount of ozone in the troposphere, though recent estimates (reported in the TAR) suggest a significant increase since pre-industrial times, by an estimated 36%.

Translating the build up of each of the greenhouse gases into an estimate of the corresponding positive radiative forcing gives the figures collected in Table 3; the relative contributions are shown in a more immediately striking form in the 'pie diagram' in Figure 19. Evidently, the dominant contribution to date has indeed come from the large increase in atmospheric CO_2. Nevertheless, the build up of the other gases, coupled with their greenhouse efficiency, means that they too are now playing a significant role as climate change agents; together they account for nearly 50% of the historical greenhouse forcing. This is why the Kyoto Protocol does, in fact, cover a 'basket' of greenhouse gases (including CH_4, N_2O and halocarbons not included in the Montreal Protocol) as well as CO_2. In later discussions focusing chiefly on carbon dioxide, it is important not to forget the additional contributions of the other greenhouse gases.

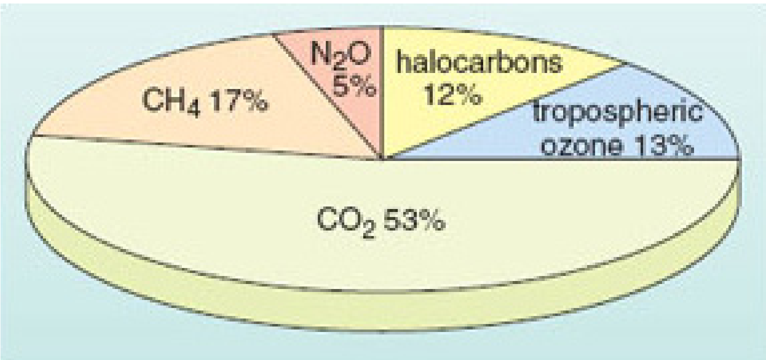

Figure 19 Relative contributions of various gases to the total greenhouse forcing of climate over the period 1750 to 2000.

Table 3 Estimated contributions to the greenhouse forcing of climate over the period 1750 to 2000 (IPCC, 2001a).

Gas	Radiative forcing/W m^{-2}	% Contribution
long-lived		
CO_2	1.46	53
CH_4	0.48	17
N_2O	0.15	5
halocarbons	0.34	12
short-lived		
tropospheric O_3	0.35	13

total	2.78	100

SAQ 20

What other natural greenhouse gas has not been mentioned in this section?

Answer

Water vapour, the most important of all (Section 1.3).

As noted earlier, the water vapour content of the air depends on temperature, and on very little else. The total amount of water vapour in the atmosphere is not directly affected by human actions. However, it can be affected *indirectly* - and in a way that has important implications for the global climatic response to the build up of other greenhouse gases.

There is also something else to think about in the context of 'the human impact on the atmosphere'. Since the dawn of the industrial age, human activities have been pumping a cocktail of particulate matter, as well as greenhouse gases, into the lower atmosphere. In particular, coal often has a high sulfur content, released as SO_2 when the fuel burns (in a power station, industrial process, fireplace, etc.). The 'unpolluted' troposphere naturally contains a certain background level of sulfate aerosols derived from various sulfur-containing gases of both volcanic and biogenic origin. Anthropogenic emissions of SO_2 add to the background aerosol load, and that has the same direct radiative effect as the episodic injection of volcanic aerosols into the stratosphere: it increases the back-scattering of solar radiation.

The 'urban haze' typical of many industrialised regions with a high traffic density also contains 'carbon-based' particulate matter derived from fossil-fuel combustion - including droplets of organic compounds, together with varying amounts of black graphitic and tarry carbon particles (collectively known as '**black carbon**'). Similar **'carbonaceous' aerosols** are found in the dense smoke plumes generated by the large-scale burning of vegetation that occurs on a regular basis in many parts of the world. In some regions, natural wildfires (ignited by a lightning strike) are supplemented by fires set deliberately for forest clearance (e.g. in Amazonia and parts of southeast Asia), or as part of the annual agricultural cycle (e.g. to stimulate a flush of new grass for livestock in the savannah grasslands of southern Africa). Data from satellite-borne instruments (Figure 20) are helping researchers to map the distribution of fine aerosols (whether sulfates or carbonaceous material) typical of anthropogenic sources (Figure 20a) - and to distinguish these from the coarser particles (dust and salt-spray) that have largely natural origins (Figure 20b).

The radiative forcing produced by the build up of well-mixed greenhouse gases is both positive (i.e. it has a warming effect) and occurs everywhere around the globe. The climatic effects of an increased load of tropospheric aerosols are different in three important ways.

1. Like sulfates, most aerosols are highly reflective, so they effectively increase the planet's albedo, producing a *negative* forcing (i.e. they cool the surface). Black carbon is an exception to this general rule: it strongly absorbs both incoming sunlight *and* outgoing longwave radiation, and it is thought that this has a warming effect at the surface.
2. Anthropogenic aerosols are short-lived in the lower atmosphere (sulfates return to the surface as 'acid rain'), so concentrations vary considerably by region (a pattern

evident in Figure 20a) and over time. The radiative effects of an increased load of tropospheric aerosols therefore act on a regional, rather than a truly global, scale.

3. Anthropogenic aerosols (especially sulfates) also have a potentially important *indirect* effect on the Earth's radiation balance, linked to their role as cloud condensation nuclei (Section 1.3.2). In polluted regions, the numerous aerosol particles share the condensed water during cloud formation, producing a higher number of small liquid droplets; such clouds are more reflective (i.e. they have a higher albedo), which makes for an additional cooling effect at the surface. This is known as the **indirect aerosol effect**.

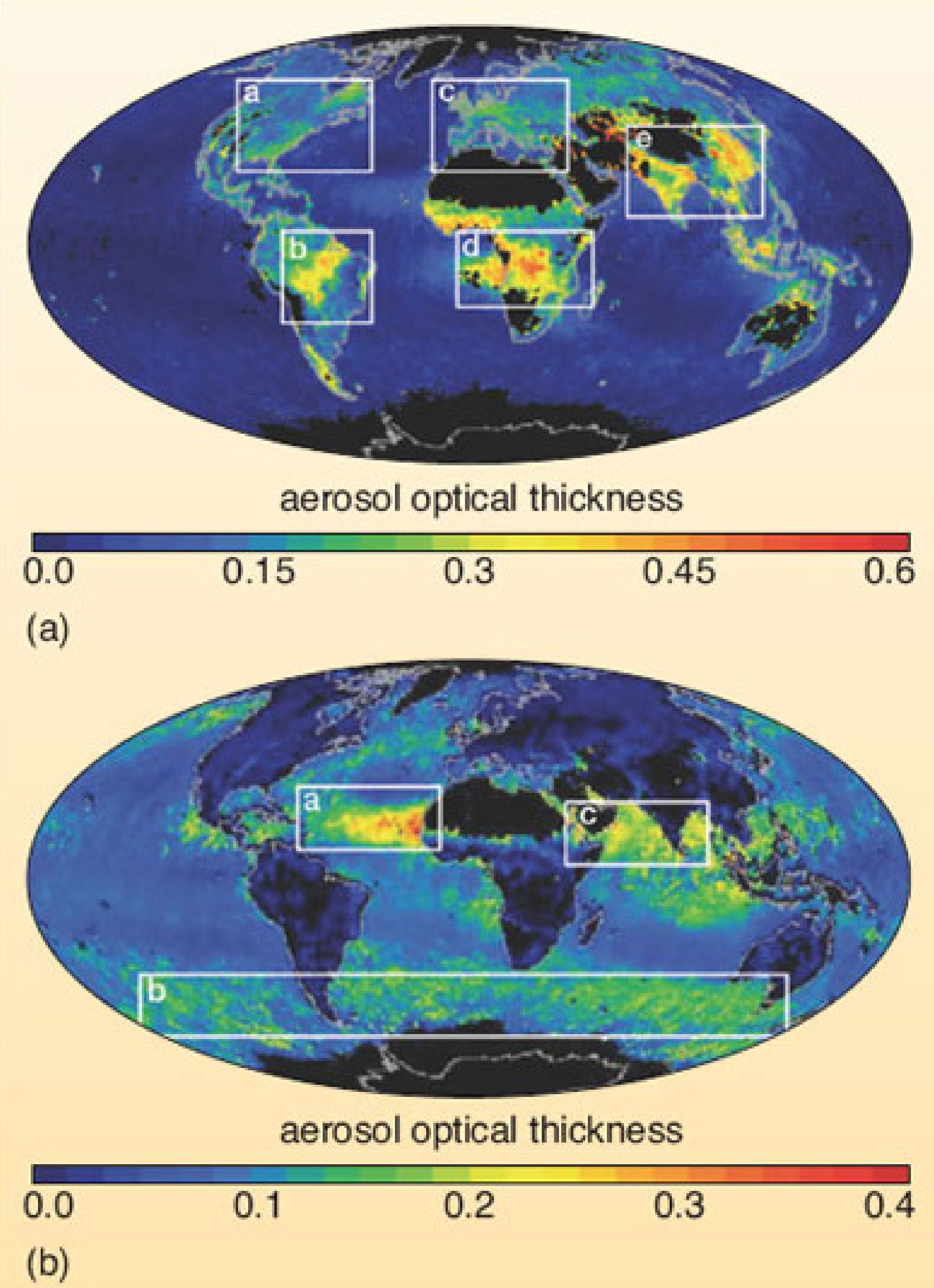

Figure 20 Distribution of (a) fine and (b) coarse aerosols from measurements taken by the

NASA Terra satellite for September 2000.

The aerosol optical thickness is a measure of the total aerosol load (in each size group) in the lower atmosphere, and is represented by the colour scale. In Figure 20 the white boxes indicate regions with high aerosol concentrations. (a) The image shows fine particles in pollution from North America, Europe and south and east Asia (regions 1, 2 and 3), and in dense plumes downwind from vegetation fires in South America and southern Africa (regions 4 and 5). (b) The image shows coarse dust from Africa (region 6), salt particles generated in the windy conditions of the Southern Ocean (region 8) and desert dust (region 7).1.

The cooling influence (both direct and indirect) of sulfate aerosols in the troposphere has been appreciated for over a decade: it featured in the first IPCC report in 1990, for example. Research since then has begun to unravel the climatic effects of other anthropogenic aerosols, but the extraordinary diversity of these particles (in size, chemical composition, radiative properties, etc.) means that this is turning out to be another complicated and uncertain part of the climate change puzzle. The general view is that tropospheric aerosols mostly produce negative forcing, but there is little confidence in the ability to quantify the *total* human-related effect, and the way it has evolved over time during the industrial age.

SAQ 21

Given the fundamental question we highlighted at the end of Section 1.5, why is this an important issue?

Answer

The cooling influence of most anthropogenic aerosols could have acted to mask (i.e. partially offset) the full warming effect of the build up of greenhouse gases since pre-industrial times.

We shall come back to this issue towards the end of Section 2, once we have examined the evidence that the Earth really is warming up.

1.7 Summary

1. Figure 12 summarises the ways in which the Earth's surface and atmosphere gain and lose energy. The main points are as follows:
   - A proportion (the planetary albedo) of the incoming shortwave radiation from the Sun is reflected (or scattered) directly back to space, mainly by clouds and the Earth's surface (especially snow and ice cover), but also by aerosols (e.g. dust, salt particles, etc.). Most of the rest is absorbed by the surface, thereby warming it.
   - Outgoing longwave (infrared) radiation from the Earth's surface is repeatedly absorbed and re-emitted by greenhouse gases naturally present in the atmosphere (mainly water vapour and CO_2, but also methane, nitrous oxide and ozone); this warms the lower atmosphere (or troposphere). Some of the re-emitted radiation ultimately goes out to space, maintaining an overall radiation balance at the top of the atmosphere. But back radiation from the atmosphere

keeps the Earth's surface over 30 °C warmer than it otherwise would be - the natural greenhouse effect.
- Clouds both cool the surface (by reflecting solar radiation) and warm it (by absorbing and re-emitting outgoing longwave radiation). Globally, the net effect is a slight cooling of the planet.
- Energy is also transferred from the surface to the atmosphere as heat (through conduction and convection) and through the evaporation/condensation of water (latent heat transfer).

2. The troposphere is heated from below whereas the stratosphere is heated from above, mainly by the absorption of incoming uv radiation from the Sun by the ozone layer. This produces the characteristic variation of temperature with altitude from the surface up to the stratopause (Figure 9).
3. Radiative forcing is an imbalance between the solar radiation absorbed by the Earth-atmosphere system and the longwave radiation emitted to space. It can be either positive (which has a warming effect) or negative (which has a cooling effect). Natural sources of radiative forcing include variations in the solar constant (either up or down) and episodic injections of large amounts of volcanic sulfate aerosols into the stratosphere (which has a short-term cooling effect at the surface).
4. Various human activities (including the extraction, distribution and burning of fossil fuels; industry; burning vegetation and land-use change; agriculture; waste management, etc.) have increased emissions of natural greenhouse gases (or their precursors in the case of tropospheric ozone). As a result, the atmospheric concentrations of these gases have increased since pre-industrial times, by about 31% for CO_2, 149% for CH_4, 16% for N_2O and 36% for O_3. The use of entirely synthetic compounds (halocarbons, e.g. CFCs) has also added new (and potent) greenhouse gases to the atmosphere. This has produced a positive radiative forcing (greenhouse forcing) of climate, which is expected to lead to global warming.
5. Human activities also increase the tropospheric load of sulfate aerosols (due to SO_2 emissions) and various carbonaceous particles (from fossil fuel and vegetation burning). Anthropogenic aerosols mostly produce negative forcing, both directly (by back-scattering solar radiation) and indirectly (through their influence on cloud albedo).
6. Long-lived gases (CO_2, CH_4, N_2O and halocarbons) are well-mixed in the troposphere. By contrast, the concentrations of relatively short-lived species (e.g. ozone and aerosols) are variable in both space and time.

1.8 End of section questions

Question 5

Information on the different albedos of various types of surface was given in Section 1.2.1. Given that information:

(a) Explain how a cover of snow or ice is likely to affect the amount of incident solar radiation *absorbed* by land or sea.

(b) According to the TAR, there has been a 20% decrease in global forest area since 1850. If we assume that dark forest cover (with an average albedo of 10 -

20%) has been replaced by farmland and pasture with an albedo similar to that of grassland (say, 35%), why might this have contributed to the radiative forcing of climate over the past 150 years? Would the forcing be positive or negative?

Answer

(a) Both snow- or ice-cover on land and sea ice have a very high albedo (up to 90%), and so will reduce the amount of solar radiation absorbed.

(b) Replacing large areas of dark forest cover with vegetation that reflects ahigher proportion of incident solar radiation effectively increases the planetary albedo; this constitutes a negative radiative forcing. (See Figure 36, Section 2.6.1 for an estimate of the effect this has had.)

Question 6

One suggested strategy for reducing anthropogenic emissions of methane is to capture the gas generated in landfill sites, and pipe this away for use as a fuel (for local domestic needs, say). But burning methane produces CO_2. Why might this still be a sensible option if the overall aim is to reduce the *total* greenhouse forcing of climate in future?

Answer

The main point here is that methane is a more powerful greenhouse gas than CO_2 (at least on a mass-for-mass basis; Table 2, Section 1.6).

Question 7

Draw a simple annotated diagram to illustrate the radiative effects (both direct and indirect) of tropospheric sulfate aerosols. Include in your diagram the link with human activities.

Answer

Something along the lines shown in Figure 21 would be appropriate. Note how a simple annotated diagram like this can communicate a lot of information, much of which would not need to be repeated in detail in the accompanying text (useful if you are working to a tight word limit). Note too that diagrams should always have a caption.

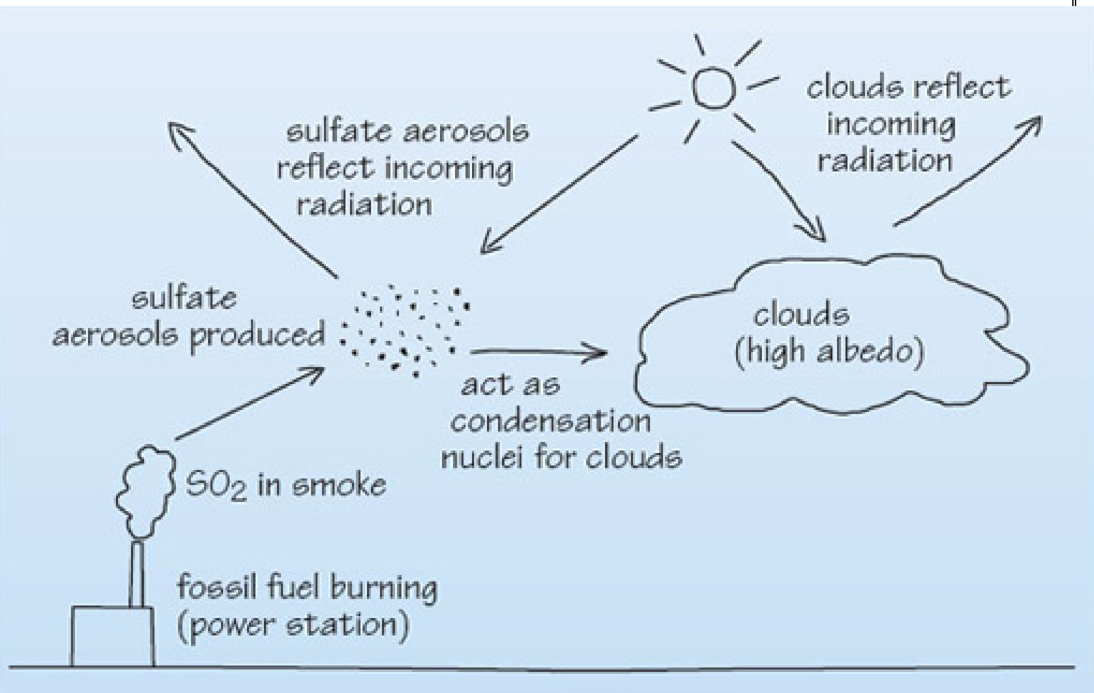

Figure 21 Diagram showing the direct and indirect cooling effects of sulphate aerosols in the lower atmosphere.

2 What do we know about recent climate change?

2.1 Preamble

Here are some quotes from the 'Summary for Policymakers' (SPM) included in the report from the scientific working group in the IPCC TAR (IPCC, 2001a):

- The Earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities.
- Globally, it is very likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record [1861-2000].
- New analyses of proxy data for the Northern Hemisphere indicate that the increase in temperature in the 20th century is likely to have been the largest of any century during the past 1000 years. It is also likely that […] the 1990s was the warmest decade and 1998 the warmest year [of the millennium].
- In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.

The overall aim of this section is to review the scientific evidence supporting these conclusions. For example, how sure are scientists that the Earth really is warming up? Specifically, what do terms such as 'very likely' and 'likely' actually mean? And how do we know that the record warmth of recent decades is not just some naturally occurring fluctuation in the Earth's temperature that has little, if anything, to do with human activities?

As you will see, the 'background noise' of natural variability makes establishing the existence of a 'significant' global warming trend - one that *could be* due to rising levels of greenhouse gases in the atmosphere - not only difficult, but also highly contentious. Work that challenges the mainstream view on this issue, embodied in the IPCC consensus, is commonly cited by those who remain sceptical about the link between climate change and human activity. We look at one recent example, set in the political context of the day, later on in the section. First, we focus on what is known about variations in the Earth's temperature over a range of past time-scales.

2.2 Records of the Earth's temperature

To put the temperature records reported by the IPCC in context, we start with a longer-term geological perspective on the Earth's GMST.

2.2.1 Long-term rhythms in the climate

The instrumental record referred to above is based on direct temperature measurements (using thermometers), and extends back only 150 years or so. Temperatures further back in time are reconstructed from a variety of **proxy data**. These include historical documents, together with natural archives of climate-sensitive phenomena, such as the growth or retreat of glaciers, tree rings, corals, sediments and ice cores (see Box 7). In general, the proxy data record becomes more sparse and more imprecise the further back in time we go. Nevertheless, it has proved possible to produce a reasonably reliable reconstruction of how global temperature has varied throughout most of the Earth's history; this is known as the **palaeoclimate** record (from the Greek *palaios* for 'ancient').

Box 7 Proxy data: ways to reconstruct past climates (Stokstad, 2001)

People have recorded the vicissitudes of climate and their impact on human affairs for centuries, so archaeological inscriptions and historical documents (diaries, ship's logs, etc.) are a valuable, if somewhat anecdotal, source of climate information. In addition, a variety of techniques - ranging from counting pollen types in lake sediments to analysis of isotope ratios in ancient ice (recall Figure 15)- yields rich, if sometimes ambiguous, climate information from many natural sources.

For example, *dendroclimatology* depends on the fact that trees in many parts of the world experience an annual growth cycle (Figure 22). Each year's growth (the thickness and/or density of a ring) depends on the local temperature and moisture conditions, creating a unique record that can then be matched with overlapping records from other trees to produce longer time series. Annual records typically go back 500 to 700 years. In a few cases, the preservation of fossil trees has allowed continuous records from 11 000 years ago to the present to be constructed.

Figure 22 Unlocking the secrets of past climates. Each year, a growing tree produces a layer of new cells beneath the bark. If the tree is felled and the trunk examined (or if a core is taken), the growth pattern from year to year appears as a series of rings.

In a similar way, cyclical responses lead to annual banding in corals, which can provide information about sea-surface temperatures, sea level and other ocean conditions - typically back to some 400 years ago.

Layered sediments on lake and ocean floors are another rich source. The types of pollen trapped in lake sediments reveal shifting patterns of vegetation, and thus indirect information about temperature and moisture conditions. Records can go back some 100

000 years. In marine sediments, analysis of microfossils can provide data on seawater temperature and salinity (salt content), atmospheric CO_2 and ocean circulation. Less common deposits of coarse debris can point to the break up of ice sheets and the release of detritus from melting icebergs. Marine sediments provide information from time periods ranging from 20 000 years to 180 million years ago.

Finally, long ice cores drilled out of the Greenland and Antarctic ice sheets yield a wealth of information. For example, past temperatures can be determined by *oxygen isotope analysis* . 99% of the oxygen on Earth is the isotope ^{16}O; most of the rest is ^{18}O. Because water molecules containing the different isotopes (i.e. $H_2\,^{16}O$ and $H_2\,^{18}O$) have slightly different physical properties, it turns out that the $^{18}O/^{16}O$ ratio in ice locked up on land is affected by the ambient temperature at the time when the ice formed. Thus, fluctuations in the oxygen isotope ratio in an ice core provide a proxy for temperature changes back through time (see Figure 23). The cores also include atmospheric fallout such as wind-blown dust, volcanic ash, pollen, etc. - along with trapped air bubbles (as discussed in Section 1.6).

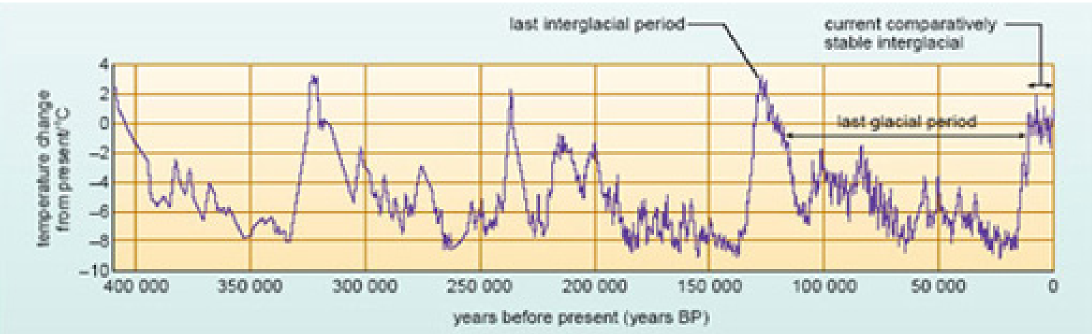

Figure 23 Temperature changes over the past 400 000 years reconstructed from the Vostok ice core, the longest continuous ice-core record to date.

This record tells us, for example, that the Earth entered into the most recent comparatively cold period of its history (known as the Pleistocene Ice Age) around 2.6 million years ago. On a geological time-scale, these Ice Ages are relatively rare, covering only 2-3% of the history of our planet. The characteristic feature of the current one (and there is no reason to suppose that it is finished) is evident in Figure 23. Drilled in Antarctica, the Vostok ice core provides a temperature record that goes back several hundreds of thousands of years. Beyond about 10 000 years ago, it tells a story of an unstable climate oscillating between short warm **interglacial periods** and longer cold **glacial periods** about every 100 000 years - with global temperatures varying by as much as 5 to 8 °C - interspersed by many more short-term fluctuations.

By contrast, global temperatures over the last 10 000 years or so seem to have been much less variable, fluctuating by little more than one or two degrees. In short, the interglacial period in which we live, known as the **Holocene**, appears (on available evidence) to have provided the longest period of relatively stable global climate for at least 400 000 years. It is almost certainly no coincidence that this is also when many human societies developed agriculture and when the beginnings of modern civilisations occurred. We now shift the focus to the more recent past - the period during which human population growth and the coming of the industrial age began to make their mark on the composition of the atmosphere.

2.2.2 Temperature changes over the past millennium

One of the most striking images in the IPCC TAR is reproduced (in adapted form) in Figure 24. Together, these two temperature records tell a compelling story, crystallised in our earlier quotes from the SPM. So let's just pause to take a closer look at each of them.

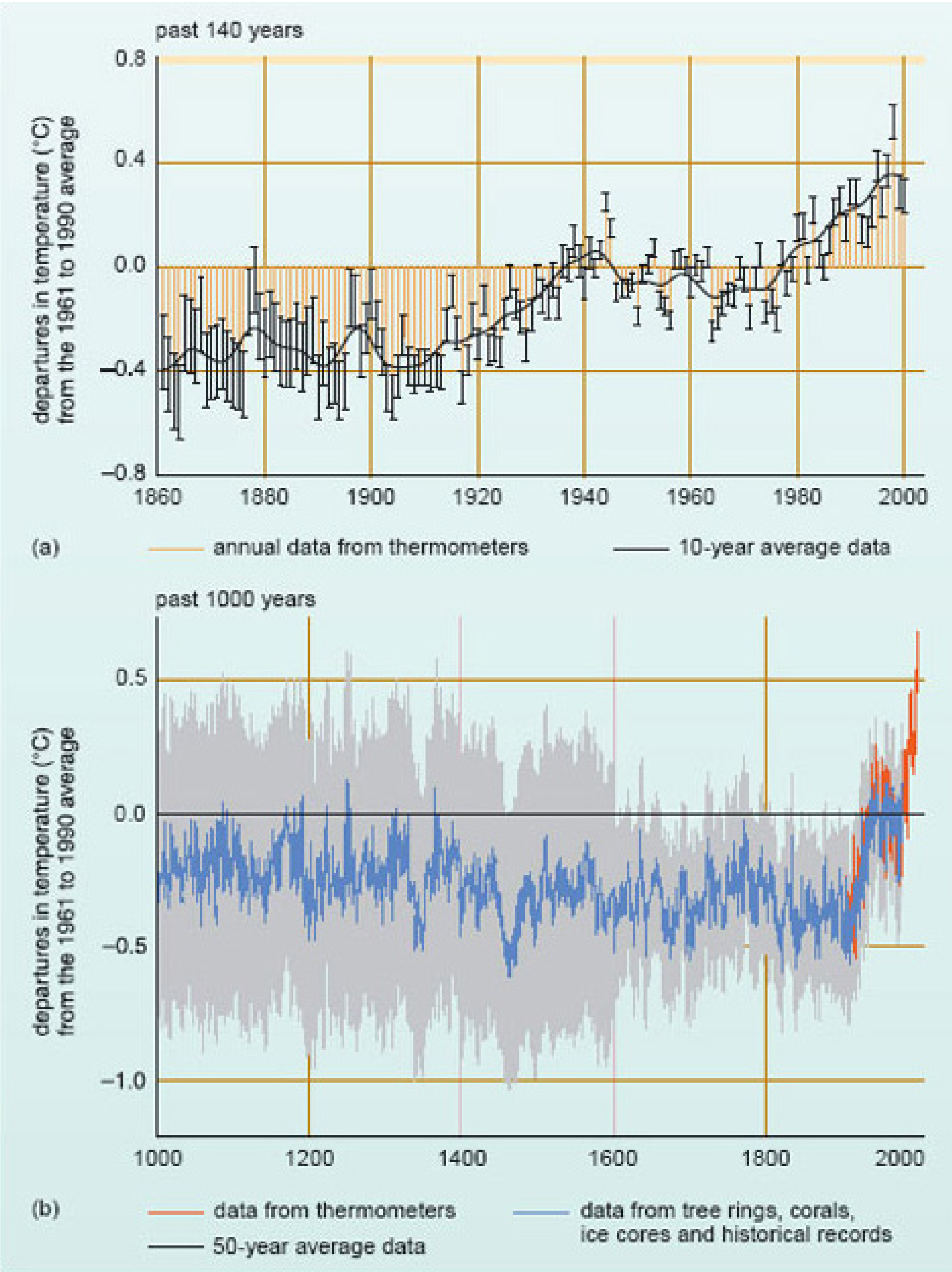

Figure 24 Variations of the mean surface temperature: (a) globally over the period 1860-2000; (b) in the Northern Hemisphere over the past 1000 years. In both cases, data are plotted as 'deviations' from the mean value, or *climatological average* , for a particular 30-year period (here 1961-1990). This is a convention widely used by climatologists. In (a), error bars are attached to values for each individual year and don't always overlap with

the 'smoothed' curve (black line). (Source: IPCC, 2001a.)

The instrumental record of the Earth's GMST

Immediately striking in Figure 24a are the marked fluctuations in global temperature from year to year. Equally, the averaging that produced the smoothed curve brings out considerable variability over periods of a decade or so as well. Set against this 'background noise' however, there clearly has been a general warming over the past 140 years.

SAQ 22

Use the smoothed curve in Figure 24a to estimate the overall warming.

Answer

The curve starts about 0.40°C below the climatological average, and ends up about 0.35°C above it. So the overall warming amounts to some $\{0.35-(-0.40)\}°C=0.75°C$.

Before engaging further with the details of that trend, it is pertinent to ask about the uncertainties in the instrumental record, indicated by the error bars attached to the annual data. In practice, it is a complex and time-consuming business to 'aggregate' weather observations (be they on land or at sea) from around the world into global averages, and hence construct the kind of climatological time series shown in Figure 24a. Uncertainty can arise for various reasons, collected here under two broad headings.

1. *Sampling errors* Even today, land-based weather stations tend to be concentrated in heavily populated regions of the industrialised world (Figure 25). More remote areas and large parts of the ocean are often poorly monitored - and this was even more Figure in the past. For example, until fairly recently most marine observations were made by 'ships of opportunity'. An uneven spatial coverage effectively 'samples' the Earth's temperature non-uniformly. And as the spatial coverage changes over time, spurious trends and biases can become embedded in the historical record.
2. *Data reliability* Apparent jumps or trends in the record from a particular station may be an artefact of some local effect. Changes in instrumentation or observing times, or in precise location or the local environment, can all affect the reliability of the data. An important example here is the spurious warming associated with the growth of towns and cities around (or near) a weather station - the so-called 'urban heat island effect'.

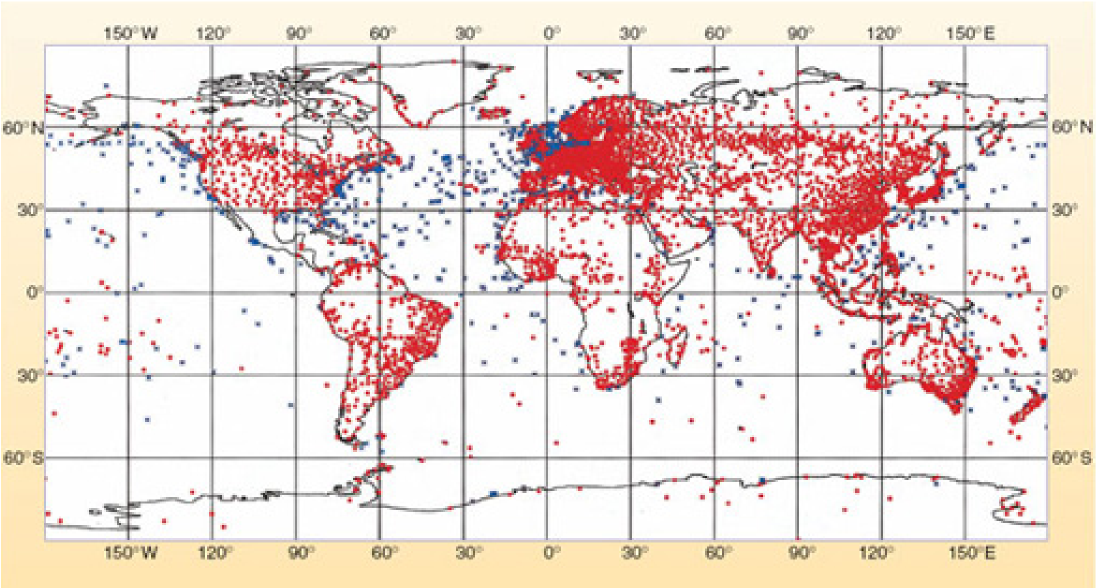

Figure 25 Today, the WMO (World Meteorological Organisation) oversees the free international exchange of meteorological data, as well as promoting properly taken observations from a worldwide network of land and marine monitoring stations, including moored buoys and fixed platforms at sea (e.g. oil rigs). The map shows the distribution of these various surface stations.

Figure 24a is the result of a painstaking effort to screen the available records (both land-based and marine) - applying corrections where possible or simply rejecting unreliable data - and then to estimate and quantify the uncertainty in the final global averages. Thus, the top (or bottom) of each little orange bar represents the central or 'best' estimate for each year's reconstructed temperature. The error bars represent the 95% confidence interval or range; i.e. there is a 95% probability that the 'Figure' value lies within this range (see Box 8).

Box 8 Measures of uncertainty

Probabilistic statements are based on a 'formal' statistical analysis of observational data (e.g. the temperature measurements that feed into estimates of GMST). Where IPCC scientists were unable to estimate and quantify the uncertainties in their conclusions in this way, they adopted a ' likelihood' language, originally proposed by Moss and Schneider. This was intended to convey their level of confidence in the validity of a conclusion, based on their collective *subjective* judgement. This is fairly unfamiliar territory for most scientists, but reflects the 'policy relevant' context in which the IPCC operates. In other words, if the expert community does not attempt to make such judgements, then someone else will! The translation is as follows:

virtually certain: greater than 99% probability that a conclusion or finding is valid

very likely: 90-99% probability

likely: 66-90% probability

medium likelihood: 33-66% probability

unlikely: 10-33% probability

very unlikely: 1-10% probability

exceptionally unlikely: less than 1% probability.

By applying a standard statistical technique (rather than the rough-and-ready judgement 'by eye' that you used above), the IPCC concluded (IPCC, 2001a): 'Over the 20th century, the increase [in GMST] has been 0.6 ± 0.2°C'.

SAQ 23

The 95% confidence level applies to this statement as well. Describe in your own words what this means.

Answer

The central (or best) estimate of the temperature rise is 0.6°C; there is a 95% probability that it lies between 0.4°C and 0.8°C, and only a 5% probability that it is less than 0.4°C or greater than 0.8°C.

Averaged over the whole century, this estimate translates into a *rate* of warming of 0.06 °C per decade. However, the smoothed curve in Figure 24a makes it abundantly clear that there were two periods of sustained warming and two periods when the GMST fluctuated without any overall warming or cooling trend. Deciding where the fluctuations end and the warming begins is open to debate. The IPCC's verdict? Most of the warming occurred in the periods 1910 to 1945 and since 1976. The rate of warming for both periods is about 0.15°C per decade, more than twice the century-long average.

On a regional scale, the most recent warming has been almost global in extent (i.e. it has been happening almost everywhere), but is most marked over the continental landmasses at mid- and high latitudes in the Northern Hemisphere.

And there are some notable 'hot spots', especially in the coldest regions of the far northern Arctic fringe. For the past few decades, parts of Siberia, Alaska and Canada have been warming much faster than the global average rate. In Point Barrow, Alaska, for instance, the annual mean temperature has gone up by 2.3°C over the past 30 years. Meanwhile, at the other end of the planet, the Antarctic peninsula (the long finger of land that sticks up towards the southern tip of South America in Figure 25) has experienced a warming of about 2.5°C since 1950; average *winter* temperatures are up by nearly 5°C.

SAQ 24

Now have another look at the second bullet point in our opening remarks to this chapter. Given the 'likelihood' language adopted in the TAR (Box 8) and the information in Figure 24a, does this seem a reasonable conclusion?

Answer

Yes. It does indeed seem 'very likely' (90-99% probability) that the 1990s was the warmest decade (and 1998 the warmest year) in the instrumental record.

In the early years of the 21st century, there is no immediate sign that global temperatures have taken a downturn. At the time of writing (2006), 2002, 2003 and 2004 stand as the second, third and fourth warmest years, respectively, in the instrumental record. Indeed, the top ten warmest years have all occurred since 1990.

Question 8

In its second major report (published in 1996), the IPCC assessed the instrumental record up to (and including) 1994. At that stage, the Panel's best estimate of the increase in GMST since the late 19th century was 0.45°C - the same as its original estimate (in 1990). How does this compare with the more recent estimate in the TAR, and what is likely to be the main reason for the difference?

Answer

The more recent estimate (0.6°C) is 0.15°C larger than that estimated in the IPCC's second report for the period up to 1994 (0.45°C), mainly due to the exceptional warmth of the additional years (1995 to 2000; see Figure 24a). [According to the IPCC TAR, the recent estimate also involved improved methods of processing the data.]

The proxy data record for the past millennium

To establish whether 20th century warming is unusual, we need to place it in the context of longer-term climate variability during the Holocene. Because of the scarcity of proxy data from the Southern Hemisphere, the IPCC TAR focused on reviewing a number of reconstructions of the average surface temperature for the Northern Hemisphere, not the whole globe. Figure 24b is the record they endorsed as the most reliable guide to how temperatures averaged across the whole hemisphere changed during the course of the last 1000 years. Like the instrumental record (shown in red), the proxy record includes annual data and a smoothed curve that brings out variability on a time-scale of several decades. The grey region is the 95% confidence range in the annual data. Note that the uncertainty is much greater than for the period covered by the instrumental record, and increases further back in time.

SAQ 25

How would you summarise, in a sentence, the overall long-term trend brought out by the smoothed curve in Figure 24b?

Answer

There is no one 'correct' answer to a question like this, and if you get a chance to discuss the figure with other students, don't be surprised if you come up with slightly different descriptions.

Here is the formulation the IPCC came up with (IPCC, 2001a):

> The long-term hemispheric trend is best described as a modest and irregular cooling from AD 1000 to around 1850-1900, followed by an abrupt 20th century warming.

This description and the record it is based on challenge a widely held belief. Conventional wisdom has it that the Northern Hemisphere experienced a 'Medieval Warm Period' (roughly the 11th to 14th centuries) - when vineyards flourished in southern Britain and the Vikings colonised Greenland, for example - followed by a 'Little Ice Age' that lasted well into the 19th century (Figure 26); icebergs became common off Norway, ice fairs were sometimes held in London on the frozen River Thames in winter, and advancing mountain glaciers crushed entire villages in the Alps.

Figure 26 'Hunters in the snow', an imaginary landscape painted by Peter Bruegel the Elder in February 1565, during the first of the great winters of the next 200 years. This seems to have been the most severe period of the Little Ice Age in Europe.

There is no doubt that the landmasses bordering the northern North Atlantic (NE America, Iceland, Greenland and NW Europe) did experience more genial climes during the Middle Ages, followed by several centuries of a generally colder regime than now. These climate changes were often pronounced, but they did not always occur at the *same* time in different regions. As a result, when conditions are averaged over the whole hemisphere, the changes no longer appear exceptional. In other words, current evidence does not support hemisphere-wide *synchronous* periods of anomalous warmth or cold over this timeframe. Such periods appear to have been mainly a regional phenomenon, and are thought to have been associated with changes in the state of the atmosphere-ocean system centred on the northern North Atlantic. Natural fluctuations such as this occur on almost all time-scales. They can have a profound effect on climate on local or regional scales, but are greatly diminished in their influence on hemispheric or global mean temperatures.

The shape marked out by the smoothed curve in Figure 24b has seen this reconstruction dubbed the 'hockey stick', especially in the US (think of the graph turned through 90°). Its significance is that the warmth of the last few decades appears to be *unprecedented* in this 1000-year period; i.e. it rises above the range of natural variability, and exceeds the uncertainty in the proxy data record (at the 95% confidence level).

SAQ 26

Here is a reminder of one of the quotes from the beginning of the chapter:

New analyses of proxy data for the Northern Hemisphere indicate that the increase in temperature in the 20th century is likely to have been the largest of any century during the past 1000 years. It is also likely that […] the 1990s was the warmest decade and 1998 the warmest year [of the millennium].

What do you make of the language used there?

Answer

It is more cautious. Use of the word 'likely' implies a 66-90% probability (Box 8) that the statements are Figure (i.e. a greater than 2 in 3 probability), based on the collective judgement of the IPCC scientists. Presumably this acknowledges residual concerns about the very large uncertainty associated with proxy data records.

Bearing in mind that every dot and comma in the SPM is pored over, this is still a pretty strong conclusion - the more so, since it was the first time the IPCC had put the warmth of the late 20th century in the context of changes over a millennial time-scale. *Detection* of a warming 'signal' above the 'noise' of natural variability does not prove that human activity is the probable cause (the question of *attribution* is taken up in Section 3.5), but it is an important first step in that process. As a consequence, it is fraught with political significance.

2.3 Contested science: a case study

For complex issues such as global climate change, there are many opportunities for scientists to take issue with the findings of their colleagues. They can disagree about the procedures for gathering data, the completeness or coverage of the data, how the data are analysed and interpreted, and then finally the conclusions. The assumptions that shape a particular piece of research and inform the kind of questions that will be asked can be no less contentious than the quality of the data gathered.

Such contention is not unique to climate science, of course. Fuelled in part by very human concerns such as a desire to protect one's reputation, competition for funding, etc., vigorous debate is the lifeblood of science; it helps to drive further investigation and innovation. In scientific areas where society has pressing concerns, however, influences beyond the normal cut and thrust of scientific debate come into play. Scientists are typically aware of the potential policy implications of their research, and may shape their work accordingly. Often, such research is stimulated or funded by organisations with an interest in the outcome of the policy debate. In turn, interest groups and policy makers tend to adopt a 'pick n'mix' approach to the available scientific evidence, promoting research that reinforces their existing arguments and beliefs, and neglecting or criticising more uncomfortable findings. Equally, the influence of individual scientists sometimes owes more to their access to decision makers or the media than to the reliability of their knowledge.

In short, the science associated with policy-sensitive areas like climate change is almost bound to be hotly contested, with disputes within the scientific community being extensively reported by the media. In the early years of this century, the 'hockey stick' reconstruction (Figure 24b, first published by Professor Michael Mann and colleagues in *Nature* in 1998) became the target for a sustained (and at times, vitriolic) attack that had a high public profile in the US. This is not altogether surprising. It is a potent image - and has become, for some, an icon of what we are doing to the climate. Equally, we should bear in mind the political circumstances of the day. Shortly after he took office in 2001, President George W. Bush withdrew the US from the Kyoto Protocol on the grounds that it would harm the US economy. Given the link between fossil fuels, CO_2emissions and economic activity, this is a legitimate concern; it may well be shared (privately) by other world leaders. Nevertheless, rejection of this landmark agreement to curb CO_2 emissions from industrialised countries set the tone for the Bush Administration. It was widely seen as hostile to any mandatory cutbacks in CO_2 emissions, and open to the influence of sceptical scientific opinion on global warming - either directly (Figure 27) or through the activities of various business-backed lobby groups.


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21 September 2003 The Observer

The World

'The code rules that women and dogs are half the value of men'

Albania's murderous blood feuds, page 23

Bush covers up climate research

White House officials play down its own scientists' evidence of global warming

Figure 27 In September 2003, *The Observer* reported allegations that White House officials had sought to interfere with a report from the US Environmental Protection Agency (EPA) in order to play down the message that climate change is a serious problem.

2.4 The meaning of 'consensus': peer review and the IPCC process

At the time of writing (2006), debate about the 'hockey stick' reconstruction continues to rumble on. In this and other controversial areas, it is natural that scientists who are not part of the IPCC process should scrutinise its assessments and continue to ask probing questions about its conclusions. At the same time, however, it's important to keep claims that run counter to the mainstream view in perspective - and to bear in mind that there may well be a political agenda behind the *selective* promotion of such claims. In the US, for example, Congress had already refused to ratify the Kyoto Protocol before the Bush Administration took office. A sustained campaign, stressing the uncertainties in the science, by the notorious and now largely defunct Global Climate Coalition (a business NGO comprising several large multinational fossil fuel companies) is credited with having played an important role in that decision.

The IPCC's remit is to analyse and evaluate the existing peer-reviewed literature, pertinent to the many scientific, technical and socioeconomic aspects of human-induced climate change. This huge interdisciplinary task depends on the work of thousands of collaborating natural and social scientists - a significant proportion of the academic community engaged in climate change-related research. To put the sensitivity of the IPCC's role into sharper focus (Edwards and Schneider, 2001):

> As a hybrid science-policy body, the IPCC must maintain credibility and trust *vis-à-vis* two rather different communities: the scientists who make up its primary membership, and the global climate policy community to which it

> provides input […] The IPCC's rules of procedure spell out a variety of methods designed to ensure its reports include the best available scientific knowledge and that they represent this knowledge fairly and accurately. Chief among these is the principle of peer review, traditionally one of the most important safeguards against bias and error in science.

As far as the peer review of scientific literature is concerned, scientists write articles (papers) and submit them to a journal. The journal editor sends the paper to several referees, all of them experts in the authors' field (i.e. their 'peers'). Referees can typically chose one of three recommendations: acceptance, rejection or acceptance after certain specified changes are made. The third option ('revise and resubmit') is by far the most common. The process usually goes back and forth a few times, with several rounds of revisions, until an acceptable compromise is achieved.

This highlights one of the perceived problems with peer review; different referees can come up with radically different conclusions about the merits of a particular piece of work. Some commentators see this as a fundamental weakness of the whole system. Others have concluded that most reviewer differences probably result from 'real and legitimate differences of opinion among experts about what good science is or should be'.

As we said earlier, disagreement is healthy; it moves science on. But, as Edwards and Schneider go on to say:

> if expert judgement varies too widely to provide a quasi-mechanical means of winnowing out bad science from good, why is peer review important? […] We maintain that peer review ought to be regarded as a [sometimes fallible] human process whose primary functions are to improve the quality of scientific work, to maintain accountability both inside and outside the scientific community, and to build a scientific community that shares core principles and beliefs even when it does not agree in detail.

This perspective on what peer review is 'for' bears directly on its role in the IPCC process. Recall that IPCC reports are not primary science, but assessments of the state of the field based on a critical evaluation of existing work. Nevertheless, draft chapters and other IPCC documents are subjected to their own peer review process. This is more open, extensive and inclusive than most, involving non-specialists (government advisers, business lobby groups, etc.) as well as expert scientific reviewers. Typically, hundreds or even thousands of changes are made as each document goes through several drafts.

This exhaustive process has played a major role in building a broad-based scientific consensus on the causes and implications of recent climate change, and in establishing the credibility of IPCC reports for policy purposes. These days, most of the world's leading climate researchers are involved in one way or another - as authors or reviewers, or because their work is used and cited. Over the years, some of the more outspoken scientific sceptics have been drawn in as well, so their views are now represented in the process that produces eventual consensus on the 'current state of knowledge'. In effect, then, the IPCC has become the voice of the expert climate science community, and is now regarded as an authority by most (if not all!) governments around the world. Its assessments are a major driving force behind international climate policy.

Yet there are critics who charge that the very notion of 'consensus science' is a nonsense, commonly citing those giants of the past (e.g. Galileo, Einstein) who have challenged and revolutionised the scientific dogma of the day. If controversy and robust debate is the lifeblood of science, the argument goes, then 'consensus' must surely be its death knell, and deeply anti-scientific.

The counter argument is that the IPCC consensus is not some unassailable 'truth'; it is simply a fair representation of the expert scientific community's current general opinion, based on the available evidence and subject to revision. Behind the public, government-negotiated and carefully crafted face of this consensus (in the SPMs) is a lot of messy and uncertain science. The highly technical bulk of each report documents limitations of current understanding, areas of disagreement, caveats about uncertainties, etc. There is no point pretending this is not the case. As stated at the outset, in a field as complex as climate change, uncertainty is unavoidable. Moreover, ongoing research may help to reduce uncertainties in some areas while at the same time uncover new sources of uncertainty elsewhere. We have already encountered one example - growing awareness of the complicated climatic effects of tropospheric aerosols - and doubtless many more will come to light in the years ahead.

To return to the original focus of this section, few researchers base their underlying concern about the build up of atmospheric CO_2 on the Earth's recent temperature history. Rather, it is rooted in what might be termed the 'relentless logic' of the physics of the greenhouse effect (Section 1.5), and fuelled by the dramatic rise in greenhouse gas concentrations over the past 200 years or so (Figure 16). On the other hand, there is little doubt that the record-breaking warmth of the 1980s and 1990s has lent warnings about the 'greenhouse problem' a popular credibility they previously lacked. Activity 1 invites you to ponder on that popular perception.

Activity 1

0 hour(s) 20 minute(s)

The theory that we were heading into another 'ice age' was quite topical and scientifically respectable in the 1970s. Indeed, this was one of the concerns on the agenda at the first World Climate Conference, along with the prospect of greenhouse warming. Here are a couple of quotes, which give you a feel for how the issue was presented at the time:

> The threat of a new ice age must now stand alongside nuclear war as a likely source of wholesale death and misery for mankind.
>
> (Nigel Calder, International Wildlife, July 1975)

> This cooling has already killed hundreds of thousands of people. If it continues and no strong action is taken, it will cause world famine, world chaos and world war, and this could all come about before the year 2000.
>
> (Lowell Ponte, The Cooling, 1976)

(a) Look back at Figure 24a. Can you suggest why the idea that the world was headed for a cooler regime might have gained credence at the time?

(b) What devices are used in the quotes above in order to communicate the implications of'global cooling'?

(c) In the 1970s, some scientists argued that the cooling was due to expanding industrial activity. What do you think was the basis for this suggestion?

(d) What salutary lessons can be drawn from this episode that are relevant to the current debate about global warming?

Answer

(a) If you cover up the last bit of the record in Figure 24a, it's fairly easy to see how the slight cooling in the post-war years (from the early 1940s to the mid1970s, say) could be interpreted as evidence that a long-term downward trend in global temperature might be underway.

[In fact, cooling during this period was stronger in the Northern Hemisphere, and particularly marked in the well-monitored regions around the North Atlantic. This northern cooling was offset to some extent by a slight warming in the Southern Hemisphere, but this only became apparent with the generation of the first reliable records of global temperature (i.e. GMST) in the mid-1980s.]

(b) The language used conjures images of wholesale (doom and gloom), made more potent still by reference to the deepest fear of the 'Cold War' years - the threat of nuclear war. Indeed, the devices used in these quotes are strikingly similar to those sometimes used today to communicate the implications of global warming. Recall, for example, the image of 'a world riven by water wars, famine and anarchy' in the recent Pentagon report, and references to the 'threat of terrorism' by Sir David King and the Prime Minister of Tuvalu.

(c) The most likely basis for a cooling influence from expanding industrial activity is the large amount of particulate matter (sulfate and carbonaceous aerosols) pumped out by burning fossil fuels, especially coal. [See Section 2.6 for the part this has played in 20th century climate change.]

(d) This episode exemplifies points flagged up at the beginning of Section 2.1. Given evidence of an apparent, but relatively short-term, trend in global temperature, we need to be wary of jumping to conclusions - both about the significance of that trend (i.e. it needs to be set in a long-term context, the message of Sections 2.2 and 2.3), and about the underlying cause or causes (the issue taken up in Section 2.6).

[It is worth noting that this episode would continue to haunt the climate science community. In the years that followed, it was often used to cast doubt on the credibility of climate science and the emerging consensus that greenhouse warming would, sooner or later, prove to be a major factor in the Earth's climate future.]

2.5 A 'collective picture of a warming world'

The observed increase in GMST may be the key global indicator of greenhouse warming, but it is far from being the only tangible sign of climate change during the 20th century. This brings us back to the first bullet point at the beginning of Section 2.1. Here, we take a brief look at the growing body of evidence that many different climate variables, as well as physical and biological systems around the world, have been affected by recent climate warming. The examples collected in Box 9 will give you a flavour of the sorts of reports that are now emerging from research programmes, though for the most part we focus on the overall picture summarised in the TAR.

Box 9 'Global warming: early warning signs' (UCS, 2004)

1. *The Himalaya* The Khumbu Glacier (on a popular climbing route to the summit of Mount Everest) has retreated by over 5 km since 1953. In the central and eastern Himalaya, glaciers are contracting at an average rate of 15 m per year, and could be gone by 2035 if this trend continues - with serious implications for populations who depend on glacial meltwater for drinking supplies, etc. Meanwhile, glacial lakes are swelling in Bhutan, increasing the risk of catastrophic flooding downstream.
2. *Alaska, USA* Most of the state is underlain by **permafrost** (permanently frozen soil). Thawing permafrost is causing the ground to subside (by 4-10 m in some places), undermining buildings, roads and other infrastructure. In some coastal areas, wave action is undermining cliffs softened by permafrost melt, increasing the risk of flooding for native communities. In the interior, forests of spruce and birch are taking on a 'drunken' appearance (Figure 28) on softening ground, and trees are dying as they succumb to waterlogged conditions.
3. *Chokoria Sundarbans, Bangladesh* Rising sea levels have flooded about 7500 hectares of coastal mangrove forest during the past three decades. Global sea-level rise is aggravated by substantial deltaic subsidence in the area due mainly to human activities, such as reduced sediment supply following dam construction upstream for irrigation schemes, and the over-extraction of groundwater.
4. *United Kingdom* The average flowering date of 385 British plant species has advanced by $4^1/_2$ days during the 1990s compared with the previous four decades; 16% of the species flowered 15 days earlier on average. Over a 20-year period (between 1968-72 and 1988-91), many bird species have extended the northern margins of their breeding ranges in the UK by an average of 19 km.
5. *Monteverde Cloud Forest, Costa Rica* A reduction in dry-season mists due to warmer Pacific Ocean temperatures has been linked to the disappearance of 20 species of frogs and toads, upward shifts in the ranges of mountain birds, and declines in lizard populations.
6. *Antarctic peninsula* Adélie penguin populations have shrunk by 33% over the past 25 years in response to declines in their winter sea-ice habitat. Adélies depend on sea ice as a resting and feeding platform. They are being replaced by gentoo penguins (a sub-Antarctic species that has begun to migrate towards the pole) which thrive in open water.

Figure 28 A 'drunken' forest on ground softened by melting permafrost, outside Fairbanks, Alaska.

2.5.1 Physical and weather-related indicators

The indicators collected in Table 4 have been observed to change over large regions of the Earth during the 20th century. According to the TAR, there is now a good level of confidence that what is being recorded is the result of long-term change rather than short-term natural fluctuations. As we noted earlier (Section 2.2.2), the most recent period of warming has been almost global in extent, but particularly marked at high latitudes. So are the changes in Table 4 consistent with rising temperatures on both a regional and global scale?

Table 4 Twentieth century changes in the Earth's climate system.

Weather indicators	Observed changes*
hot days/heat index†	increased (likely)
cold/frost days	decreased over most land areas during 20th century (very likely)
continental precipitation	increased by 5-10% over 20th century in Northern Hemisphere (very likely), although it has decreased in some regions (e.g. N and W Africa and parts of Mediterranean)
heavy precipitation events	increased at mid- and high northern latitudes (likely)
frequency and severity of drought	increased summer drying and associated incidence of drought in a few areas (likely); in recent decades, frequency and intensity of droughts have increased in parts of Asia and Africa

Physical indicators	Observed changes*
global-mean sea level	increased at average annual rate of 1-2 mm during 20th century

duration of ice cover on rivers and lakes	in mid- and high latitudes of Northern Hemisphere, decreased by 2 weeks during 20th century (very likely); many lakes now freeze later in autumn and thaw earlier in spring than in 19th century
Arctic sea-ice extent and thickness	thinned by 40% in recent decades in late summer (likely), and decreased in extent by 10-15% since 1950s in spring and summer
non-polar glaciers	widespread retreat during 20th century
snow cover	decreased in area by 10% since satellite observations began in 1960s (very likely)
permafrost	thawed, warmed and degraded in parts of polar and sub-polar regions

* Levels of confidence (Box 8) where available are given in brackets.

† Heat index is a measure of how humidity acts along with high temperature to reduce the body's ability to cool itself.

Question 9

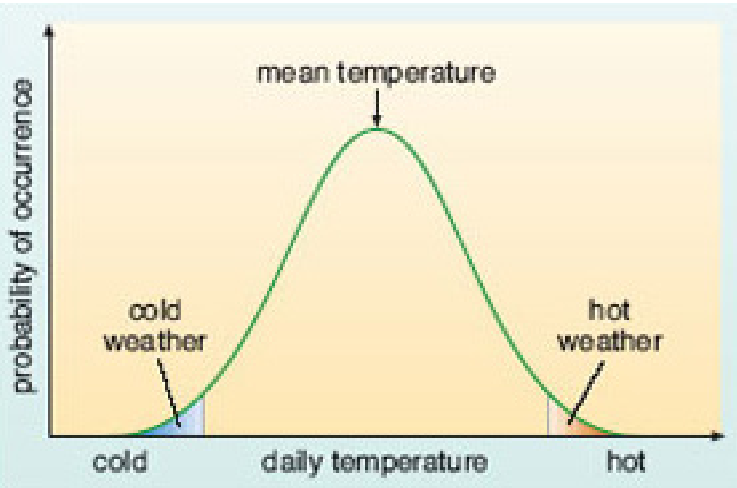

Figure 29 The distribution of daily temperatures around the mean value for a fictional location; see Question 9.

(a) Figure 29 is a schematic representation of the distribution of daily temperatures (for a fictional location), scattered around the mean value according to a bell-shaped curve (a 'normal' distribution). At the tail ends of the distribution, the shaded areas represent the frequency of occurrence of unusually cold (left) and unusually hot (right) days. Suppose now that the mean temperature increases, but the distribution of temperatures around the mean (i.e. the shape of the curve) is unchanged. Sketch a second curve on Figure 29 to represent this 'new' climate, and use it to explain the first two weather-related entries in Table 4.

(b) Drawing on your own experience, how might the shifts you identified in part (a) be expected to affect the human death-toll due to temperature extremes?

Answer

(a) Figure 30 shows how an increase in mean temperature shifts the wholebell-shaped curve to the right. This reduces the frequency of unusually cold days (effectively to zero, in the somewhat exaggerated situation depicted to the left in

Figure 30), and increases the frequency of unusually hot days (i.e. the area under the curve above a given temperature, to the right in Figure 30, is now much larger). This pattern is consistent with the first two entries in Table 4.

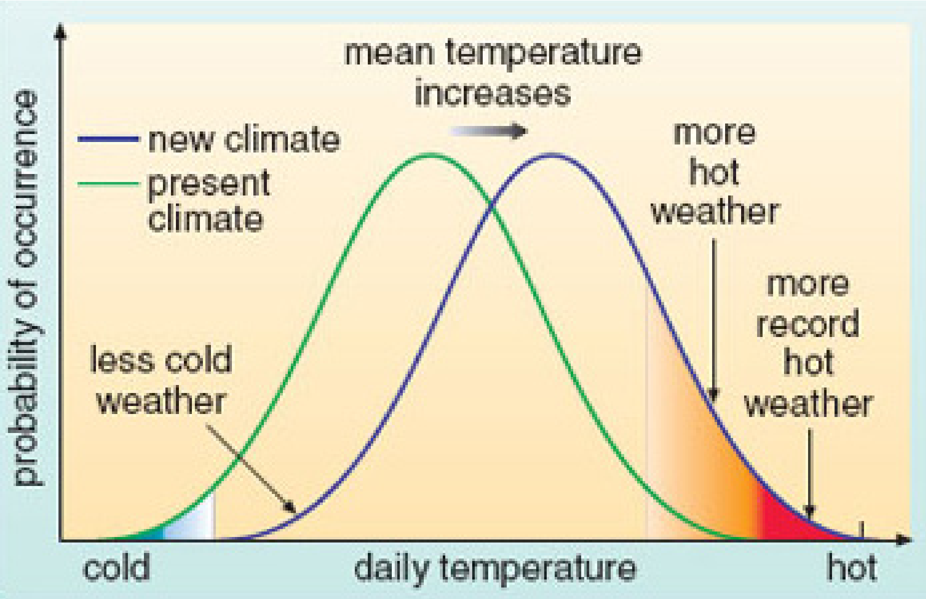

Figure 30 Schematic diagram showing the effect on extreme temperatures when the mean temperature increases.

(b) Shifts of the kind identified in (a) could have both beneficial effects (reducing the number of cold-related deaths in winter in some regions) and adverse effects (increasing the number of deaths due to heat stress).

The remaining weather indicators in Table 4 (changes to precipitation and droughts) are less easy to link directly with a rise in GMST. However, they do bear directly on one of the major reasons for concern about regional climate change - a possible increase in extreme events

SAQ 27

What about the changes in physical systems collected in Table 4? How might these be explained by rising temperatures?

Answer

The thinning and reduced extent of snow and ice cover over land and sea, and the melting of permafrost (Box 9), are all consistent with a warming of the climate. We might also expect that this warming has, in turn, contributed to the observed sea-level rise, both through direct warming and thermal expansion of seawater (Box 4; Section 1.3.4), and because the widespread melting of glaciers has added more water to the oceans.

Sea-level rise is one of the most feared aspects of global warming for island nations like Tuvalu, and for inhabitants of other low-lying parts of the planet. Yet keeping tabs on *global mean* sea level (the indicator included in Table 4) is, if anything, an even more complicated problem than monitoring the Earth's temperature - and again provides scope for disagreement and controversy among scientists.

Today, sea-levels are recorded by coastal tide gauges *relative* to a fixed benchmark on land. Averaged over a period of time (a year, say, to remove short-term effects due to waves, tides, weather conditions, etc.), the result is the local 'mean sea level'. The difficulty in interpreting changes in mean sea level at a particular locality is that the land moves up and down as well. These vertical land movements can result from human activities (of the kind noted in connection with Bangladesh in Box 9), or more generally from natural causes - including tectonic processes (e.g. earthquakes) and very slow adjustments to major changes in ice-loading. For instance, the UK is still adjusting to the melting of ice at the end of the last glacial period; Scotland is rising a few mm a year and the south of England is sinking at a similar rate.

With this in mind, you can begin to see why it might be difficult to establish how global mean sea level (sea level averaged across the globe) has varied over the past century due solely to changes in the total *volume* of water in the oceans. It is this so-called 'eustatic' sea-level change that is linked to the climate-related factors identified above: thermal expansion of seawater and melting of land ice. All the historical records from tide gauges around the world measure only relative sea level. Not only is the spatial distribution of high-quality long-term records decidedly patchy, but individual records must also be adjusted for local land movements. This is a major source of uncertainty in the IPCC estimate included in Table 4.

SAQ 28

What does this estimate imply about the total sea-level rise over the 20th century?

Answer

A rate of increase of 1-2 mm per year translates into a rise of 10-20 cm in the past 100 years.

But is this linked to 20th century climate warming? There is no independent evidence of this. All scientists can do is to *estimate* the contributions due to the observed warming, and see whether this matches the *observed* sea-level rise. The IPCC TAR estimates of the various temperature-linked contributions are collected in Table 5. Some background information on these estimates is given in Box 10. Read through that material, and then try Question 10.

Table 5 Estimated contributions to mean rate of sea-level rise (in mm y^{-1}) from thermal expansion and land-ice change, averaged over the period 1910-1990. See Box 10 for significance of negative values, and entry for 'long-term ice sheet adjustment'. Estimates for the *observed* rate of increase are included for comparison. (Source: IPCC, 2001a.)

	Low	Central estimate	High
effects due to 20th century warming:			
thermal expansion	0.3	0.5	0.7

glaciers	0.2	0.3	0.4
Greenland ice sheet	0.0	0.05	0.1
Antarctic ice sheet	−0.2	−0.1	0.0
long-term ice-sheet adjustment	0.0	0.25	0.5
total estimated	**0.3**	**1.0**	**1.7**
observed	**1.0**	**1.5**	**2.0**

Box 10 Glaciers and ice sheets: how do they respond to climate warming?

The ice stored on land is usually carved up into two broad categories:

1. **Glaciers** (and small ice caps) in mountainous areas (such as the Alps, Andes, Himalayas, etc.) and at high latitudes (in places like Iceland, Alaska, the Canadian Arctic and Scandinavia).
2. The vast **ice sheets** in Greenland and Antarctica.

A glacier or ice sheet gains mass by *accumulation* of snow (which is gradually transformed to ice) and loses mass (known as *ablation*) mainly by melting at the surface or base, with subsequent runoff or evaporation of the meltwater. Bodies of ice have their own internal dynamics as well. Ice is deformed and flows within them - down a mountain for example, or in vast slow-moving 'ice streams' within the major ice sheets. Where a glacier or ice stream meets the sea, ice may be removed by the calving of icebergs or by discharge into a floating ice shelf (Figure 31), from which it is lost by basal melting and calving of icebergs.

Figure 31 Virtually all ice shelves appear as huge walls of ice towering up to 40 m above the ocean. During the 'heroic age' of Antarctic exploration, the Ross Ice Shelf (the largest on the fringes of the continent) was known as the 'Great Ice Barrier'.

How climate warming affects the total mass of an individual glacier or ice sheet depends on how the balance between accumulation (through snowfall) and ablation (through melting and discharge) responds to rising temperatures. On the face of it, this is a simple task of relating climate to accumulation and loss rates. In practice, numerous factors conspire to complicate this simple picture - not least the internal dynamics of the ice body.

Nevertheless, estimates of glacier and ice-sheet sensitivity to climate change have been made. On the basis of such estimates, a warmer climate is judged to result in a shrinkage of glaciers and the Greenland ice sheet, due to increased ablation. By contrast, Antarctic temperatures are currently so low that modest warming is expected to *increase* the overall mass of ice, due to increased accumulation accompanying a warmer atmosphere with increased moisture availability.

One final, very important complicating factor: the mass balance of a body of ice is essentially always attempting to catch up with climate. There is a time lag between climate change and the corresponding effect on a glacier or ice sheet, known as the response time.

In general, glaciers are not only pretty sensitive to climate change, they also have relatively short response times - typically 50 years or so, though the actual value varies depending on surface area, ice thickness and other factors. By contrast, changes in ice discharge from ice sheets have response times of 1000 years or more. Hence, it is likely that the Greenland and Antarctic ice sheets are still adjusting to their past history, especially the last glacial/ interglacial transition. Table 5 includes an estimate of the contribution this long-term adjustment has made to 20th century sea-level rise.

Question 10

(a) Using the central estimates in Table 5, work out the percentage contribution each factor has made to the mean rate of sea-level rise during the 20th century. Which of these factors appears to have made the major contribution?

(b) In broad terms, are the estimated contributions from glaciers and the major ice sheets (due to 20th century warming) consistent with the background information in Box 10?

Answer

(a) From the central estimates in Table 5, the major contribution to the observed rate of sea-level rise has come from the thermal expansion of seawater; this accounts for (0.5/1.5) × 100% = 33%. The next-largest contribution was due to melting glaciers (20%), followed by 'long-term icesheet adjustment' (17%; this is something that will continue to make a significant contribution in future), and then loss of ice from the Greenland ice sheet due to 20th century warming (just 3%).

(b) The short answer is 'yes'. According to Box 10, glaciers and the Greenland ice sheet are expected to lose mass in a warmer climate (greater ablation exceeds any gains from increased precipitation), but glaciers respond much more quickly. By contrast, the Antarctic ice sheet is expected to gain mass (due to increased precipitation), which is consistent with the negative entry in Table 5 (i.e. this has partly offset the loss of ice elsewhere).

Clearly, there are large uncertainties associated with the estimates collected in Table 5. This reflects a lack of sufficient observational data, inadequate understanding of the complex processes involved and shortcomings in the models used to produce some of these estimates. For instance, there is abundant evidence that the 20th century saw widespread glacier retreat across the globe: from the Arctic to Peru and New Zealand, from Switzerland to the Himalaya (Box 9) and the famed snows of Mount Kilimanjaro (Figure 32), vast ice fields and glaciers are shrinking. Yet it is still a difficult and uncertain business to quantify the loss of ice and assess its impact on the total volume of water in the world's oceans.

Meanwhile, the sheer physical size and inaccessibility of the ice sheets, the extreme climates and the occurrence of long periods of polar darkness have long rendered the acquisition of representative measurements extremely difficult. For example, the lack of suitable long-term data means there is no *direct* evidence that the whole Greenland ice sheet did actually shrink during the last 100 years; the estimate in Table 5 is based entirely on modelling studies driven by the observed warming over the ice sheet. However, satellite surveillance has been in place since 1990, and this short-term record does indicate a rapid thinning of the edges of the ice sheet.

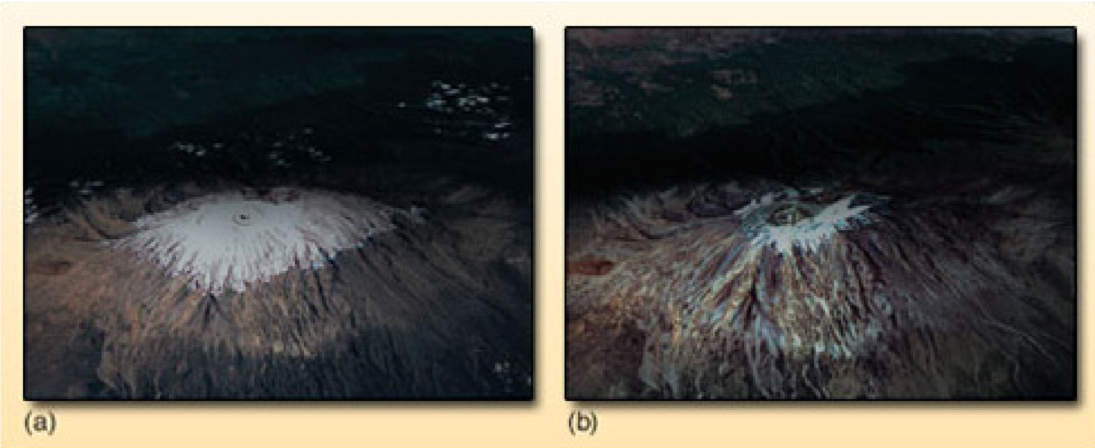

Figure 32 Satellite images of Mount Kilimanjaro, Tanzania, in (a) February 1993 and (b) February 2000. Around 82% of the snow and ice on the summit has disappeared since 1912, with about one-third melting since 1990. At current rates, scientists believe the ice cap could be gone by 2015, with important implications for tourism in Tanzania.

Summaries of available data for the whole of Antarctica have tended to find small positive net mass balances overall (in line with the estimate in Table 5), though with high degrees of uncertainty. But once again, there are signs that dramatic change is underway in some parts of the continent - not least the recent rapid collapse of several ice shelves around the Antarctic peninsula (Figure 33). Despite the newspaper headlines that accompany such an event, bear in mind that disintegration of a *floating* ice shelf does not, by itself, contribute to sea-level rise. (If you want to prove this for yourself, try floating ice cubes in a tumbler brimful of water to see if it overflows as they melt.) However, there is concern that, without ice shelves to act as dams, the continent's ice streams and glaciers might migrate faster towards the coast, ultimately contributing to sea-level rise. There are early indications that this may be happening in some parts of western Antarctica.

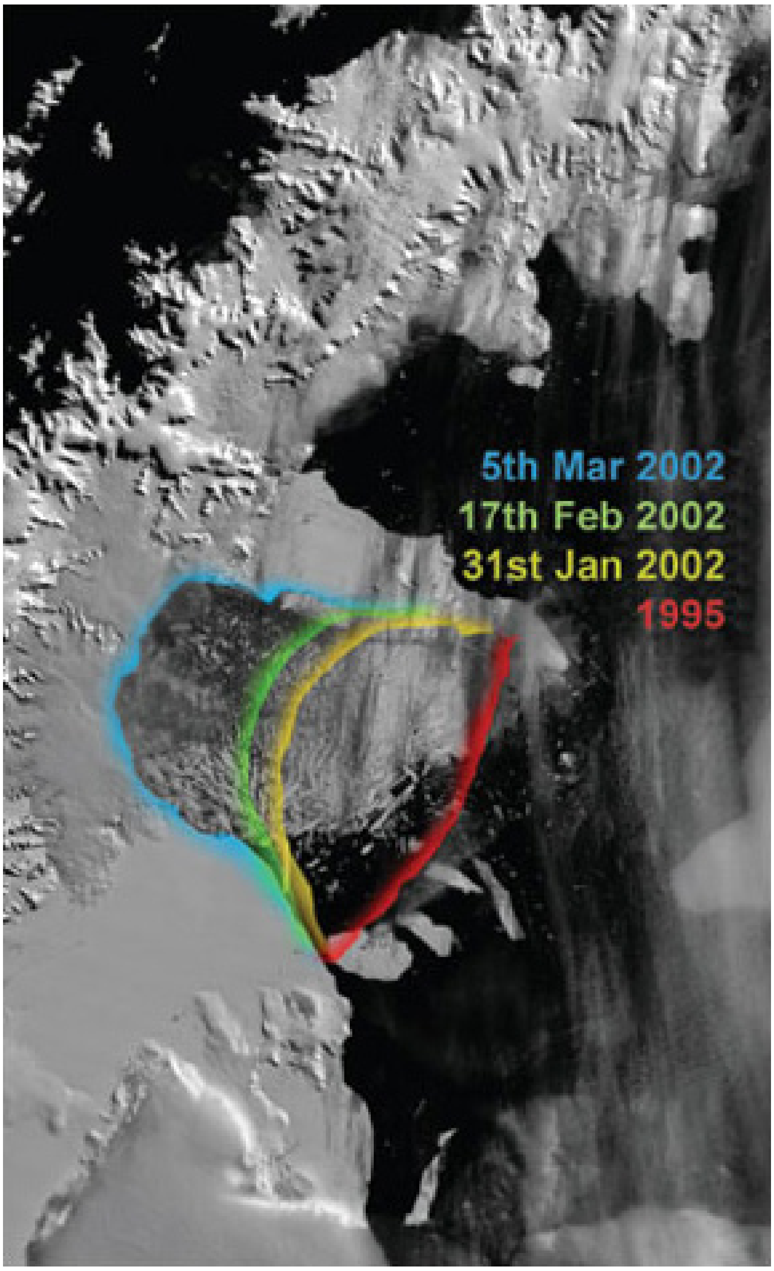

Figure 33 Satellite images tracking the spectacular collapse of part of the Larsen-B ice shelf on the eastern side of the Antarctic peninsula. In 2002, a huge area (about 3200 km^2) of ice disintegrated in just 35 days. This was the largest collapse event of the last 30 years, bringing the total loss of ice extent from seven ice shelves to 17 500 km^2 since 1974. The ice retreat is attributed to the region's strong warming trend (Section 2.2.2).

SAQ 29

Now have another look at the estimates in Table 5. Taken together, do they tell the whole story of sea-level rise during the 20th century?

Answer

Probably not. The uncertainties are large, but (based on the central estimates) these climate-related contributions make up only some 67% of the observed rate of increase. However, the high estimate does account for the observed rise.

The IPCC identified the influence of some additional factors (*not* directly related to climate change, such as the extraction of groundwater), but were still left with a discrepancy between the estimated and observed rate of sea-level rise. Given the uncertainties that pervade this issue on all fronts, this is not altogether surprising. Nevertheless, the TAR concluded that 'it is very likely [90-99% probability; Box 8] that the 20th century warming has contributed significantly to the observed sea-level rise'.

2.5.2 Environmental indicators

The notion of a link between climatic conditions and the behaviour of plants and animals (e.g. the growth of trees or coral) and the composition of natural communities or ecosystems (the type of vegetation in a given area, say) is fundamental to the use of proxy data to reconstruct past climates. Some examples of biological responses to recent climate change were included in Box 9. Here we should be wary of jumping to conclusions. Such changes involve complex living systems that can respond in complicated ways to a great variety of other pressures. Particular caution is necessary wherever records are of short duration, which in this context means less than a few decades.

Well aware of this stricture, and having conducted a literature survey of papers documenting biological and ecosystem changes on this sort of time-scale, the IPCC concluded (with high confidence) that the following observations are related to recent climate change:

- earlier flowering of plants, budding of trees, emergence of insects and egg-laying in birds and amphibians;
- lengthening of the growing season in mid- to high latitudes;
- shifts of plant and animal ranges to higher latitudes and higher altitudes;
- decline of some plant and animal populations.

You may well have noticed the kind of 'phenological' changes referred to in the first two points - shifts in the timing of life cycle events in plants and animals. Many biological phenomena (e.g. leaf bud burst and flowering in plants) cannot proceed until a minimum temperature has been reached over an adequate length of time. Changes in the timing of such events are easy to observe and monitor, and can provide sensitive indicators of climate change. Studies from various regions and ecosystem types tell a consistent story. For example, from Scandinavia to the Mediterranean and across North America, the growing season for plants has increased by 1-4 weeks over the past 50 years; spring comes earlier, but leaf fall in deciduous plants is delayed. Many animal life cycles also depend on temperature; in the UK, for instance, it seems that aphids now appear on average a week earlier than 25 years ago.

Migrating animals, especially butterflies and birds, benefit from keeping pace with the changes by arriving earlier in their summer habitat, so that food such as pollen and insects is available at the right time. Many are responding in just such a manner. However, there are signs that, in some cases, important inter-dependencies may be slipping 'out of sync' as the species involved respond to changed conditions in different ways; one example is included in Figure 34.

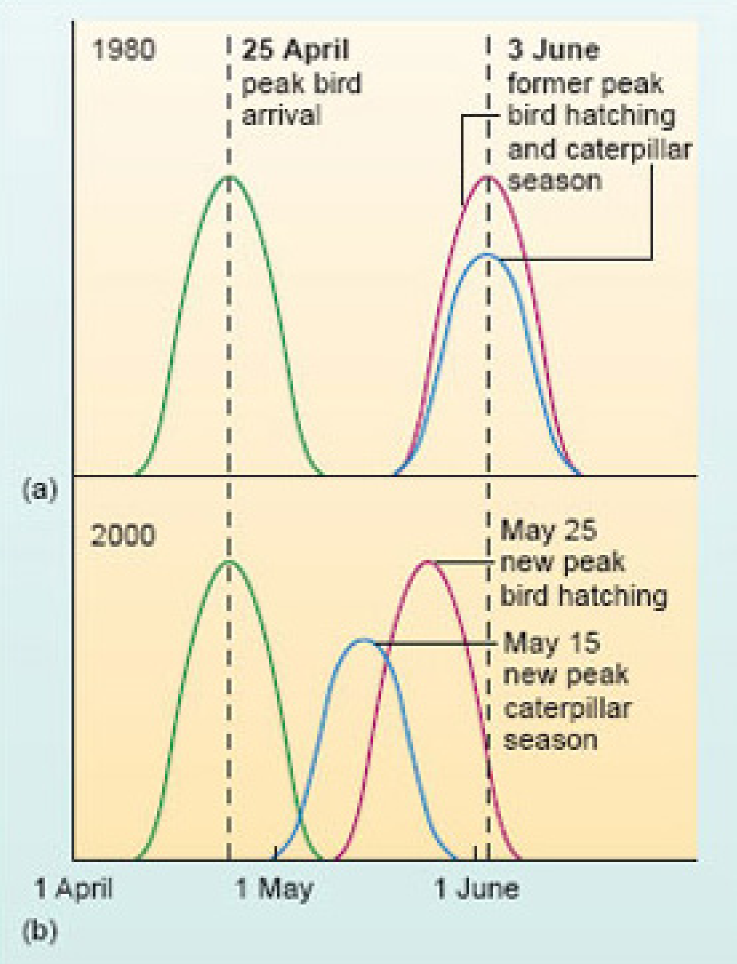

Figure 34 An example of emerging 'desynchrony' between bird behaviour (in migrating flycatchers) and insects (moth caterpillars), an important food source for their nestlings. Flycatchers that migrate from Africa to The Netherlands to breed still arrived at the same time (on average) in 2000 (b) as they did 20 years earlier (a). Because of higher temperatures, however, the caterpillars now emerge about 2 weeks earlier than before. The birds' peak egg-hatching date has also shifted, but not enough. So nestlings now miss peak caterpillar emergence, and may go hungry. (In each part of the figure, the curves are schematic representations of the distribution of dates for each of the key events.)

Other plants and animals are adapting by extending their ranges - an example of the type of response referred to in the third bullet point above. Put simply, the underlying principle here is that the geographical limits of many plants and animals are determined very largely by temperature. In the Northern Hemisphere, for instance, it may be too cold for some species further north (or at higher altitudes), and too warm for other species further south (or at lower altitudes; alpine plants come to mind). Either way, shifts of the kind that appear to be underway (Box 9, points 4-6) are broadly consistent with a warmer climate.

Natural communities of plants and animals are in a constant state of change, and their composition is often strongly influenced by climatic factors. In a warmer climate, crucial interactions in the complicated dynamics of natural systems can be disrupted; some species will fare better than others. Those that are particularly sensitive to environmental change and/or unable to adapt in various ways (e.g. by colonising new areas) may suffer a decline in population (the final bullet point above), or be lost altogether (Box 9, point 5).

To sum up: the IPCC TAR is confident that a large proportion (over 80%) of the observed changes in these environmental indicators are in the direction consistent with well-established temperature relationships. In other words, there is a negligible probability that they happened by chance, given what is known about the various mechanisms of change in biological systems. Taken together with all the other indicators reviewed earlier in this section, they do indeed add up to a 'collective picture of a warming world' (IPCC, 2001a). At the same time, they serve as a portent of the kinds of changes that could lie ahead.

The threat of mass extinctions and loss of biodiversity regularly hits the headlines. We shall not attempt to grapple with the complexities of this issue - another potent and contested area of the climate change debate. Bear in mind, though, that ecological systems around the world are already under siege from countless other pressures linked with human activities: loss or fragmentation of habitat due to deforestation, urban and industrial development, demand for agricultural land, etc.; air and water pollution; overfishing and marine pollution; and so on. While some species may increase in abundance or range, climate change is likely to increase existing threats to other more vulnerable species, and some may literally have nowhere to go as the world warms up. Examples include plants and animals that thrive only in the coldest parts of the planet - at high latitudes and/or high altitudes. Like the Adélie penguins of Antarctica (Box 9), the polar bears, walrus and ringed seals of the far north all depend on Arctic sea ice in one way or another.

2.6 An evolving consensus on attribution

The fact that the Earth really is warming up now commands near-universal support. However, it is one thing to detect a global warming trend that appears to be unprecedented in the past millennium (Subsection 2.2.2), and quite another to establish with a given level of confidence that it has been *caused by* (i.e. can be attributed to) human activity - specifically, the increase in greenhouse gas concentrations and associated radiative forcing since pre-industrial times (reviewed in Section 1.6). Establishing 'cause-and-effect' relationships in the behaviour of complex natural systems is always difficult, and often controversial. With such high stakes in the present context, the 'question of attribution' is probably *the* most sensitive area of the IPCC's remit. Certainly, it is an area where the Panel has always exercised particular caution over its pronouncements, well aware that these will make headline news around the world. As scientists involved in the IPCC process have put it (Allen et al., 2001):

> We should recall that the IPCC was under considerable pressure in 1990 to make a statement attributing observed climate changes to human influence 'because if they don't, someone else will' (and indeed, did). The IPCC is a cautious body, and if the evidence is not available in the peer-reviewed literature to support a statement, it will not make it, no matter how great the interest in that statement might be. In the end, this caution resulted in the attribution statement made in the Second Assessment Report [in 1996] having much more impact than if it had been made prematurely.

The reference here is to the much-quoted statement: 'The balance of evidence suggests that there is a discernible human influence on global climate'. Even this decidedly equivocal language was sufficient to trigger charges that the IPCC process had been 'corrupted', and a high-profile campaign (again, especially in the US) aimed at discrediting the Panel's conclusions. Just five years later, however, the TAR pointed to humans as the culprits in more robust terms: it is 'likely' (66-90% probability; Box 8) that 'most of the warming over the last 50 years' is attributable to 'the increase in greenhouse gas concentrations' - the final bullet point at the beginning of this section.

Before we take a closer look at the evidence behind this statement, it is worth pausing to consider why there might be grounds for scepticism about there being a causal link between 20th century climate change and human activity - a stance that a few scientists continue to maintain. With this in mind, try Question 11 before moving on.

Question 11

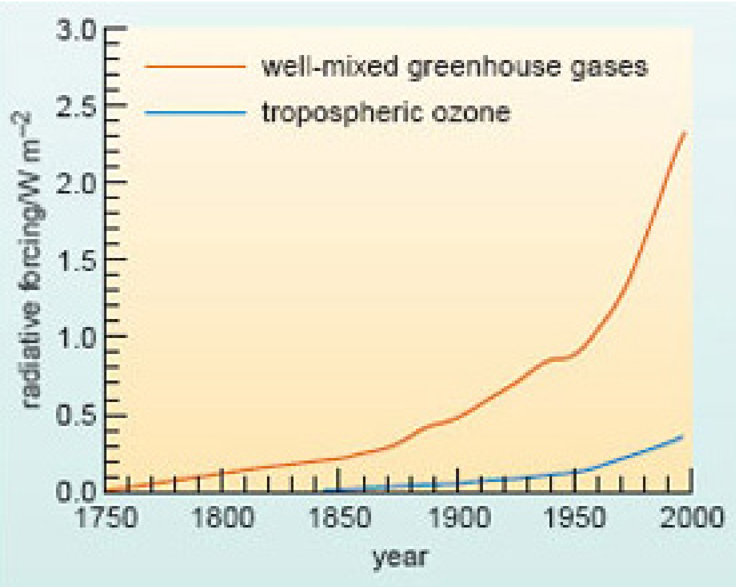

Figure 35 Time evolution of the radiative forcing during the industrial age, due to rising levels of well-mixed greenhouse gases (CO2, CH4, N2O and halocarbons) and tropospheric ozone.

(a) Figure 36 shows how the greenhouse forcing of climate (summarised in Table 2, Section 1.6) has evolved over time since 1750. Compare the pattern of change in this figure with that marked out by the smoothed curve in the instrumental record of the Earth's GMST, Figure 24a. Why might this comparison raise doubts about attributing the development of global warming to the build up of greenhouse gases in the atmosphere?

(b) What other sources of radiative forcing, both natural and anthropogenic, could also have influenced global temperature over the past century? In each case, indicate whether the forcing would be positive or negative, or whether it could act either way.

Answer

(a) As noted in Subsection 2.2.2, the smoothed curve in the instrumental record (Figure 3.3a) traces a very irregular pattern of warming during the course of the 20th century. There is little direct correlation with the observed build up of greenhouse gases, which translates into a relatively smooth and accelerating increase in radiative forcing since pre-industrial times (Figure 35). In this context, the most striking inconsistency is the pause in the upward trend in GMST (or even a slight cooling; Activity 1) from the mid-1940s to the mid1970s - whereas the greenhouse forcing shows the steepest increase from around 1950.

(b) Natural sources of radiative forcing include possible variations in the solarconstant during the 20th century (could be either positive or negative forcing), together with the short-term negative forcing associated with volcanic activity. Other anthropogenic factors include: the cooling effects (both direct and indirect) of sulfates and most carbonaceous aerosols; the warming effects of 'black carbon' (Section 1.6); and the effect on surface albedo of widespread deforestation (likely to be negative forcing; Question 5b).

[The important general point is that variations in the Earth's GMST reflect the influence of the total radiative forcing of climate, and how this has evolved over time during the past century: deviations from the 'expected' steady warming trend due to greenhouse forcing alone are only to be expected. Keep this in mind as you work through the rest of Section 2.6.]

2.6.1 Weighing up the evidence: the full cast of suspects

Figure 36 (again adapted from the TAR) takes your thoughts on Question 11 on a stage. It gives estimates of the cumulative effect since pre-industrial times of the various climate change agents, with the contributions expressed in terms of radiative forcing. Note that the figure also includes yet another device for communicating the IPCC's confidence in a particular finding - an indication of the 'level of scientific understanding' that accompanies each estimate. This reflects the authors' subjective judgement about the reliability of the forcing estimate, based on what is known about the factors that determine the forcing, the assumptions involved, and so on. Of the anthropogenic factors included in Figure 36, it is not surprising that there are large uncertainties, and generally very low confidence, in the estimates for various aerosols, given the difficulties touched on in Section 1.6. Clearly, this goes for the impact on surface albedo of historical changes in land use (e.g. deforestation; Question 5) as well. Only for the well-mixed greenhouse gases is confidence high.

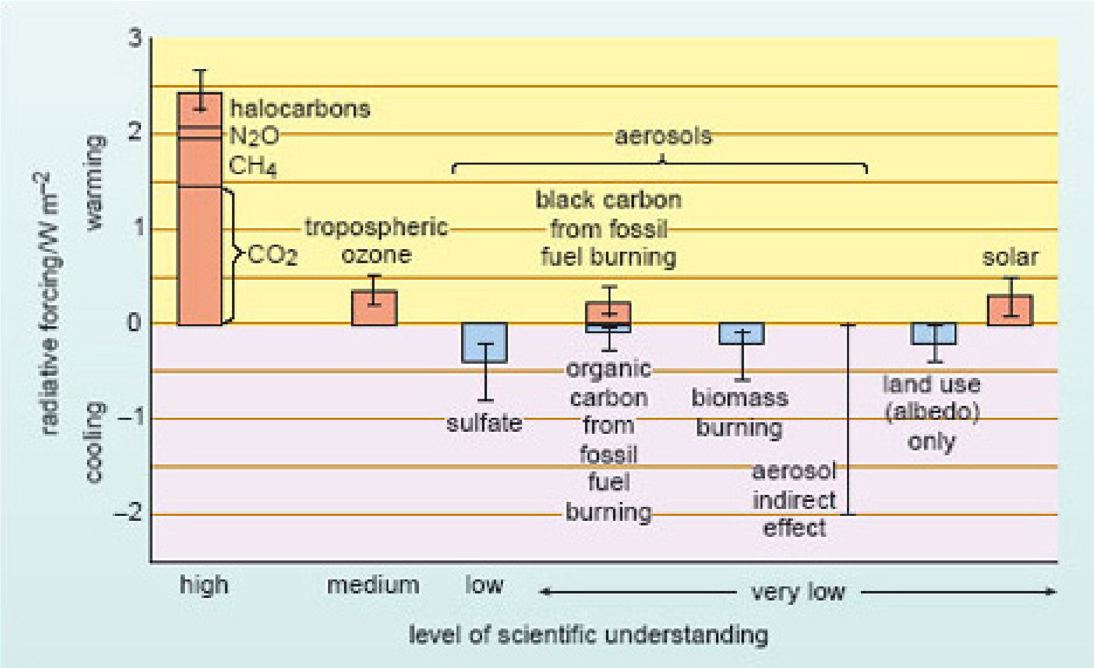

Figure 36 Estimated contributions to the radiative forcing of climate between 1750 and 2000, due to various anthropogenic factors (greenhouse gases, aerosols and land-use change) and to solar variability. Vertical lines represent subjective judgements of the uncertainty range in each estimate. They are not error bars (e.g. 95% confidence limits) in a conventional statistical sense. Note that it is not yet possible to give a 'best guess' estimate for the *indirect* cooling effect of aerosols (due to their influence on cloud albedo; Section 1.6). Note that 'organic carbon' refers to carbonaceous aerosols from fossil fuel burning, other than black carbon.

But what about the issue we flagged up earlier (Section 1.5) - the claim by some scientists that variations in the Sun's output (and hence the solar constant), and not higher levels of greenhouse gases, have been the main driving force behind 20th century global warming? This is a complicated and controversial area, and we do not have the space to go into it in any detail. However, it's important to be aware that the estimate of **solar forcing** included in Figure 36 is not based on direct measurements of variations in the solar constant. Such measurements became available only with the advent of satellite-borne radiation sensors in the late 1970s. These data reveal that the solar 'constant' does, in fact, vary slightly, fluctuating up and down (by about 0.08%) on an 11-year cycle. Unfortunately, the sensors degrade over time, and it is not yet clear whether these small rapid fluctuations (which are thought to have little effect on the Earth's climate) are superimposed on an underlying trend in the *average* value of the solar constant (given as 1368 W m^{-2} in Section 1.2.1) since the measurements began.

Reconstructions of what might have been happening to the solar constant further back in time rely on various proxy indicators of changes in solar activity (such as variations in the number of sunspots), and the relationship between such proxies and possible trends in the output of *energy* from the Sun (the key issue) is only poorly understood. Marked differences between the available reconstructions, together with uncertainties about the satellite record, account for the very low confidence in the 'best guess' estimate of historical solar forcing in Figure 36.

SAQ 30

Given the information in Figure 36, why is it difficult to sustain an argument that the observed global warming is *entirely* due to solar variability?

Answer

Although solar variability appears to have made a positive contribution to climate forcing during the industrial age, the 'best guess' estimate is 0.3 W m^{-2} - only a small fraction of that contributed by the well-mixed greenhouse gases alone (2.4 W m^{-2}); i.e. not counting the additional contribution from tropospheric ozone. It is inconsistent to argue that the Earth's GMST has been highly sensitive to very modest radiative forcing by the Sun, yet unaffected by substantial greenhouse forcing.

In short, the estimates in Figure 36 strongly implicate the chief 'suspect' for recent global warming - the enhanced greenhouse effect. But that does not, by itself, explain the bumpy rise in global temperature evident in Figure 24a, especially the puzzling pause in the upward trend in the middle of the 20th century (identified as a major inconsistency in Question 11). To address this issue, the starting point is a set of 'forcing histories' (i.e. reconstructions of the *time-evolving* change in radiative forcing like that in Figure 35) - one for each of the natural and anthropogenic factors that could have influenced global climate over the past century or so.

SAQ 31

Since the aim is to construct a history of the *total* radiative forcing of climate, what other natural factor needs to be included in the analysis?

Answer

It should also include the history of **volcanic forcing**; i.e. the significant, though episodic and transient, negative forcing (cooling effect) from major volcanic eruptions.

In fact, volcanic activity was particularly strong at the end of the 19th century (e.g. the Krakatau eruption in 1883), and again since 1963 (culminating in the Pinatubo eruption in 1991; Figure 14, Section 1.5). By contrast, the first half of the 20th century was a quiet period for the major events that inject large amounts of volcanic aerosol into the stratosphere.

SAQ 32

Look back at Figure 24a. Does the influence of the Pinatubo eruption show up in that record?

Answer

The annual values do indeed show a downturn in GMST in the years following this eruption (especially 1992 and 1993), so it is tempting to answer with a resounding 'yes'.

Here, detailed analysis has confirmed this conclusion. In general, though, we should again be wary of jumping to conclusions. When it comes to the detailed interpretation of the Earth's recent temperature history, we need to be mindful of the influence of yet another natural factor. Even in the absence of an external 'push' provided by radiative forcing, the GMST would not remain constant year after year. Interactions *within* the climate system generate spontaneous, and inherently unpredictable, fluctuations in global temperature on a variety of time-scales, especially from year-to-year and over periods of a decade or so. This **internally generated natural variability** is a major source of the 'background noise' we referred to earlier (Section 2.2.2), and will always be superimposed on the global temperature response to any particular pattern of radiative forcing.

So, how do climate scientists assess *in a quantitative way* how the GMST might have responded to the history of radiative forcing over the past century - and thus gain a deeper insight into the underlying causes of the observed temperature changes? This is where climate modelling studies come into the picture.

2.6.2 The role of modelling studies

State-of-the-art models are designed to simulate the workings of the climate system (in so far as this is currently understood), and include the 'internal' interactions that generate short-term natural variability in the real world. They provide modellers with a means of carrying out 'virtual' experiments on the climate system. In the present context, an important aim of these experiments is to identify the 'signal' of a human influence on climate, so studies typically involve 'feeding' into a model the time-evolving history of radiative forcing due to:

- natural factors (solar variations and volcanic activity) alone;
- anthropogenic factors (usually just greenhouse gases and aerosols) alone; and
- both natural and anthropogenic factors combined.

In each case, the model simulates the time-evolving change in GMST in response to that particular history of radiative forcing, and this is then compared with the observed temperature record (i.e. Figure 24a). The results of modelling studies of this kind reported in the IPCC TAR are shown in Figure 37. Study the figure and its caption carefully, and then work through the following questions.

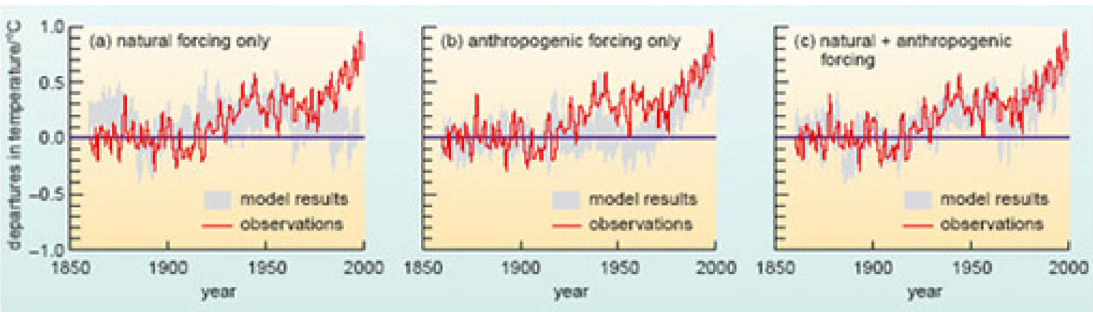

Figure 37

Figure 37 Complex climate models have been used to simulate the Earth's temperature variations over the past 140 years in response to both natural and anthropogenic forcings. The figure shows comparisons between the observed changes and the results of model simulations done with: (a) natural forcing (solar variations and volcanic activity) only; (b) anthropogenic forcing (greenhouse gases and sulfate aerosols) only; and (c) both combined. In each case, the grey band encompasses the results of several model runs and gives an idea of the uncertainty in the simulated response (including that in the 'internal' variability generated by the model). The simulations in (b) and (c) include estimates of the direct and indirect effects of sulfate aerosols. Note that temperature changes are given relative to (i.e. as 'departures from') the climatological average for 1880-1920, not 1961-1990 as in Figure 24a. (Source: IPCC, 2001d.)

SAQ 33

What does the comparison in Figure 34a suggest about the influence of natural forcings during the course of the 20th century?

Answer

The *net* effect of solar variations and volcanic activity seems to have produced a positive forcing of climate during the first half of the century, and probably contributed to the observed warming at that time. However, natural factors alone would have resulted in a slight cooling of the planet thereafter (i.e. the net forcing was negative).

In other words, natural factors cannot explain the observed warming over the last 50 years.

SAQ 34

How does the comparison in Figure 34b support the IPCC's conclusion that most of this warming was due to human activities?

Answer

The model-simulated response to anthropogenic forcing shows a persistent upward trend in GMST from around 1950 (when the greenhouse forcing accelerated; Figure 32). Further, the rate and magnitude of the simulated warming over recent decades is broadly consistent with the observed changes.

Note that the 'compensating' cooling effect (both direct and indirect) of the tropospheric load of sulfate aerosols, which increased throughout this period, is included in the study in Figure 37b. In experiments done with greenhouse forcing alone, the simulated warming over recent decades is typically larger than that observed in the real world.

Finally, Figure 37c shows that the best match with observations over the whole century is obtained in simulations that include both natural and anthropogenic forcings. This suggests that these forcings are sufficient to explain the major features of the Earth's recent temperature history. And that, in turn, adds weight to the case for an identifiable greenhouse warming signal over the past 50 years. The inconsistencies noted earlier (Question 11) then come down to the way this warming effect has been offset to some extent by the cooling influence of natural factors (especially around the middle of the century, evident in Figure 37a) and sulfate aerosols, together with the noise of internally generated natural variability.

Still, a word of caution is in order. For example, the simulations in Figure 37 do not include the influence of non-sulfate aerosols or past land-use changes. Bear in mind too the considerable uncertainty about the natural and anthropogenic forcings that *are* included - for all bar the contribution from increased greenhouse gas concentrations (Figure 36). Equally, it is pertinent to ask probing questions about the climate models used in studies like this (as we shall in Chapter 6: how confident should we be about the simulated response to radiative forcing?

The IPCC is well aware of these concerns - a major reason for caution over its pronouncements on the attribution question. The relevant chapter in the TAR documents the sophisticated statistical techniques that have been brought to bear on the significance of the similarities (or indeed, differences) between model simulated and observed changes - not only in the GMST, but also in other climate variables around the world (e.g. those included in Table 4). According to the IPCC, these more detailed studies 'consistently find evidence for an anthropogenic signal in the climate record of the last 35 to 50 years', even when uncertainties of the kind noted above are taken into account. Put this together with a longer and more closely scrutinised temperature record (Question 8), and the unprecedented warmth of recent decades (Section 2.2.2), and you can begin to see why the Panel finally felt able to endorse a less equivocal attribution statement. In the words that appeared in countless press reports when the TAR came out in 2001 (taken from one of the headings in the SPM): 'There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities'.

The IPCC is not alone in its conclusions. As one recent article in the journal *Science* put it (Oreskes, 2004):

> In recent years, all major scientific bodies in the United States whose members' expertise bears directly on the matter have issued similar statements […] concluding that the evidence for human modification of climate is compelling.

In short, the overwhelming scientific consensus is that the human impact on the atmospheric burden of greenhouse gases has made a significant contribution to recent climate warming - and hence, by implication, to the observed changes in other climate variables, and in physical and biological systems reviewed in Section 2.5. But what of the future? What further climate changes might lie ahead in a future that could see an extra three billion people on the planet by 2050 (Figure 18, Section 1.6)?

Just as simulations with climate models have provided insight into the human influence on climate in the past, so they are fundamental to projections of future human-induced climate change. A climate model is just what the name implies: a 'model' of the 'climate system'. But what do we actually mean by the Earth's climate system? This question has been lurking in the background in this and earlier sections and needs to be addressed, but is beyond the scope of this unt.

2.7 Summary

1. Reconstructions based on direct temperature measurements (back to 1860) and proxy data (Box 7) reveal that the Earth's GMST varies naturally on many different time-scales: from year-to-year, over periods of several decades and, in the longer term, according to the roughly 100 000-year rhythm of glacial/interglacial cycles. The past 10 000 years has been marked by the relatively stable global climate of the present interglacial (the Holocene).
2. This section has looked at one of the most politically sensitive issues in the IPCC's remit: the detection of an unusual global warming 'signal' above the 'background noise' of natural variability, and its attribution (in whole or in part) to human activities. The Panel's pronouncements on this issue gain authority from the exhaustive peer review process that underpins the production of its reports, together with the caution implicit in formulating consensus statements that are a fair representation of the collective 'expert judgement' of the climate science community. In the TAR, the IPCC

used various devices (notably the 'likelihood' language in Box 8) in order to communicate levels of confidence in its conclusions (e.g. the bullet points at the beginning of this section).

3. From the instrumental record (Figure 24a), GMST is estimated to have risen by 0.6 ± 0.2 °C over the past century. The upward trend has been irregular, with most of the warming during two periods: 1910 to 1945 and since 1976. During recent decades, the local warming rate has been greatest at high latitudes, where it has been accompanied by the thinning and reduced extent of snow and ice cover over land and sea, and the thawing of permafrost (Table 3.1 and Box 9).
4. Based on the proxy data record for the Northern Hemisphere in the IPCC TAR (the 'hockey stick' reconstruction, Figure 22b), 20th century warming and the record temperatures of recent decades appear (66-90% probability) to have been unprecedented during the past millennium.
5. There is mounting evidence that many different climate variables (Table 3.1), as well as physical and biological systems around the world (Table 4 and Box 9), have been affected by 20th century climate warming. It is judged to have contributed significantly to the observed sea-level rise over the past 100 years (in the range 10-20 cm), mainly due to the thermal expansion of seawater and the widespread retreat of glaciers. Most of the observed changes in various environmental indicators (phenological changes, shifts in plant and animal ranges, population declines, etc.) are broadly consistent with a warmer climate, and are harbingers of the kinds of changes that could lie ahead.
6. Successive IPCC reports trace an evolving consensus on the 'question of attribution', culminating in the statement in the TAR: 'There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities'. Along with the evidence summarised in points 3-5 above, this statement is supported by critical appraisal of climate modelling studies that can reproduce the bumpy rise in GMST over the past century, in response to estimates of the historical radiative forcing from both natural factors (solar variability and volcanic activity) and anthropogenic factors (greenhouse gases and aerosols).

2.8 End of course question

Question 12

The writer and campaigner George Monbiot wrote the following (in *The Guardian Weekly*, 10 February 2000): 'Every time someone in the West switches on a kettle, he or she is helpting to flood Bangladesh'. What is the link between switching on a kettle and sea level rise? Write down the various steps in the chain of cause and effects as a set of bullet points. Do you feel confident that you could cover all the links, if asked by a friend or colleague, say?

Answer

'Switching on a kettle' is linked to sea-level rise by the following chain of