converted into units of CO_2e using their respective 100-year DGWPs of 25 and 298 (from Table 1.2). To convert 17 Mt of methane into its equivalent in CO_2e, multiply by 25: i.e. $17 \times 25 = 425$ Mt CO_2e. To convert 1.3 Mt of nitrous oxide into its equivalent in CO_2e, multiply by 298: i.e. $1.3 \times 298 = 387$ Mt CO_2e. The total contribution of the six gases expressed in Mt CO_2e can now be added up. This comes to 4644 Mt CO_2e.

(b) How important were emissions of each of the categories of greenhouse gases listed above expressed as a percentage in relation to the grand total for all six gases?

Answer

The relative contribution of carbon dioxide is $3755 \div 4644 \times 100 = 80.9\%$.

The figures for methane and nitrous oxide are 9.2% and 8.3%, respectively. The relative contribution of HFCs, PFCs and SF_6 was 1.7%.

In other words, statistics for the European Union in 2006 show that emissions of carbon dioxide were responsible for over 80% of the region's total contribution to global warming. Emissions of methane and nitrous oxide were each responsible for around 8–9% of Europe's contribution to global warming in 2006. The combined contribution of the other three greenhouse gases was only 1.7%. The emissions profile of Europe is typical of other industrialised countries. Carbon dioxide is the main contributor to the enhanced greenhouse effect not because it is a particularly powerful greenhouse gas, but simply because so very much more of it is produced than any of the other gases.

In summary, to find out what the sum total effect of the emissions of various anthropogenic greenhouse gases is having on the internal rate of heat exchange between the surface and the atmosphere, we need to take into account:

- the relative contribution of each different gas to infrared absorption – how 'powerful' the greenhouse gas is (the DGWP value);
- the relative amounts of each gas released into the atmosphere.

1.6 Other factors affecting net radiative forcing

How sure are we about the relationship between the atmospheric CO_2 concentration and temperature increases? The best estimate of the increase in GMST for a doubling of the atmospheric CO_2 concentration from 280 p.p.m. (the pre-industrial CO_2 concentration) to 560 p.p.m. is 1.5 °C to 4.5 °C. The term used for the best estimate of how much the world might warm for a doubling of carbon dioxide concentrations is **climate sensitivity**. The IPCC AR4 estimates that stabilisation of carbon dioxide at 350 p.p.m. would result in an eventual temperature rise from 1990 to 2100 of 2.0 °C and that stabilisation of carbon dioxide at 790 p.p.m. would result in an equilibrium temperature rise from 1990 to 2100 of 6.1 °C. Increases in the concentrations of other greenhouse gases would increase these estimates.

Increasing greenhouse gas concentrations produce a net positive radiative-forcing effect and therefore lead to global warming. However, GMST is influenced by several other factors that each have various effects on radiative forcing. GMST is really just an abstract statistic. It is true that what actually contributes to the climate (wind, clouds, rain storms, etc.) is differences in temperature between one region and another. However, for our purposes, GMST is a useful device for understanding how various factors influence the climate. It is an accessible way of understanding uncertainties in simple climate prediction models.

There are many aspects of the functioning of the Earth's climate that are still not properly understood. However, we are gaining an increasingly better understanding of how various factors affect the Earth's GMST and therefore a variety of aspects of the climate.

GMST is particularly important in determining other climatic variables. Many climate variables (precipitation, extreme events, cloud cover, sea level) are closely related to GMST. This is why so much effort and care goes into refining models of natural and enhanced radiative forcing. All modelling and policy making rests firmly in the first instance on radiative forcing. It will be very important later on to understand what affects GMST when it comes to asking reasonable questions about what we know and don't know about climate change. Overall, the Earth's GMST is determined by several diverse factors (explained in more detail later), including:

- atmospheric properties that affect solar radiation – aerosols (content, type, altitude) and clouds (cover, type, altitude and thickness)
- atmospheric properties that affect infrared radiation – clouds and aerosols again as well as greenhouse gas concentrations
- surface properties that affect solar radiation – **albedo** (the reflectivity of a surface to sunlight) of surfaces free of ice and snow; fraction of surface covered by ice and snow
- 'external' or 'natural' factors – solar variability and volcanic eruptions.

Figure 1.20 summarises knowledge about the radiative forcing (RF) effects of the various factors that affect GMST. The most important point to glean from Figure 1.20 is that direct forcing from the four main groups of anthropogenic greenhouse gases is by far the most significant effect (2.64 W m^{-2}) and the one we know with the highest certainty. There are many smaller forcings that we are much less sure about, for example we are still not very sure about the role of:

- tropospheric ozone
- the impact of land-use changes on albedo
- aerosols
- stratospheric water vapour from CH_4
- the contribution of linear contrails from aircraft
- solar variation.

These are discussed briefly below.

1 Tropospheric ozone

In the stratosphere, ozone has a small negative (cooling) effect. Tropospheric ozone has a relatively large warming effect, though there is only medium LOSU.

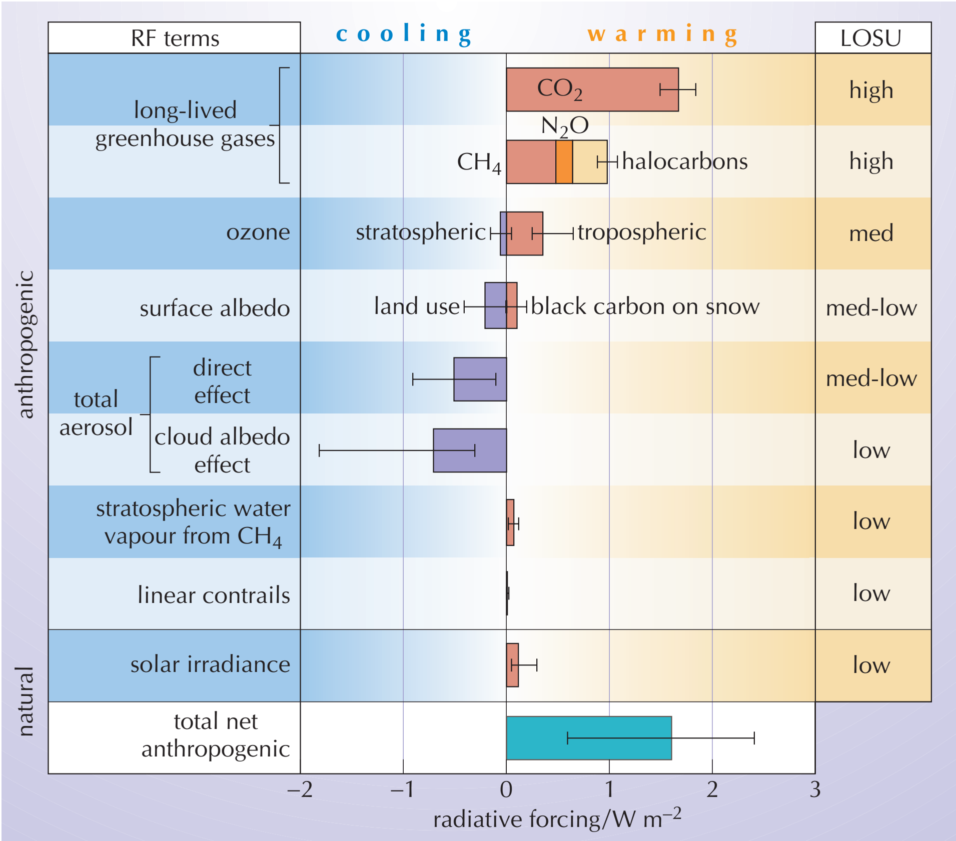

Figure 1.20 The radiative forcing (RF) effects of various factors, arranged in order of level of scientific understanding (LOSU). Positive radiative forcing effects are shown in orange and negative effects in blue. The black vertical lines indicate the range of estimates for these forcings. (IPCC, 2007a)

2 *Change in surface albedo*

Changes in various surface properties of the Earth can affect albedo (the amount of reflected solar radiation). Snow-covered forested areas reflect less light back to the atmosphere than open, deforested, snow-covered areas. Cutting down trees in snow-covered areas can have a cooling effect because more radiation is reflected back to space. Sea ice reflects more incoming radiation than seawater. It also insulates the sea from heat loss during the winter. Overall, a reduction in the area of sea ice has a positive effect on radiative forcing, and so has a warming effect.

3 *Aerosols – direct effect*

Aerosols include, for example, dust from volcanic eruptions, soot and sulfates from the burning of fossil fuels and biomass. The effect of aerosols on the climate is complex and not well understood. Some aerosols can be hard to observe and model as they have very short residence times in the atmosphere (weeks) and show strong regional variations. Aerosols do various things, including:

- scattering part of the incoming solar radiation back into space, and therefore having a cooling effect (or direct negative radiative forcing effect) on GMST
- absorbing and re-emitting infrared radiation (a direct warming effect)
- affecting the formation and properties of clouds, which in turn affects the climate in various ways (aerosol cloud albedo effect).

The physics and chemistry of atmospheric aerosols are complex. There are several different 'species' of atmospheric aerosols, including sulfates, black carbon, organic carbon, biomass burning and mineral dust. The current estimate is that sulfates (largely derived from fossil fuel and biomass combustion), wood burning and the release of organic carbon (a by-product of burning fossil fuel and biomass) have a negative radiative effect (i.e. a cooling effect), whereas black carbon from fossil-fuel combustion produces a positive effect (Figure 1.20).

Explosive volcanic eruptions are an external factor that affect radiative forcing and create a 2–3 year cooling (negative forcing) effect by temporarily increasing sulfate concentrations in the stratosphere. The major volcanic eruptions that occurred between 1880 and 1991 will therefore have had a net negative radiative-forcing effect.

The net direct forcing combined across all kinds of aerosols is negative with medium to low level of scientific understanding. The contribution of aerosols to the creation of clouds, and in turn an indirect cloud albedo effect, is much less well understood but is believed to be negative.

4 Aerosols – cloud albedo effect

Clouds reflect sunlight back into space. Think about what happens to you on a spring day as the Sun goes behind a cloud. You can instantly feel chilly. Where did that lovely heat go? Some of it was reflected back into space off the cloud. Clouds can also trap heat: starry nights are generally colder than cloudy ones. As clouds are made of tiny water droplets, they also contribute to the thermal warming of the atmosphere through infrared absorption and re-emittance. High clouds have a net warming effect, whereas low clouds have a net cooling effect. The net effect of a cloud on the balance of radiative forcing depends on the type of cloud and its altitude.

The effect of clouds (either naturally occurring or created by anthropogenic aerosols) on radiative forcing is a major uncertainty in climate prediction. AR4 notes that the indirect radiative-forcing effect of aerosols through cloud modification is poorly understood.

5 Stratospheric water vapour

Trends in changes in water vapour concentrations in the stratosphere due to increased concentrations of CH_4 are not well understood.

6 Variation in solar irradiance

One of the natural factors that has an influence on radiative forcing is changes in the level of the Sun's solar activity Scientists calculate that changes in the Sun's solar radiation may have increased radiative forcing by +0.12 W m^{-2} since 1750.

1.7 Conclusion: a chain of causes and effects

To consolidate our understanding of different aspects of the mechanisms at play in the greenhouse effect that contribute to climate change, briefly consider for a moment the mechanisms at work in other environmental issues. Think about a classic environmental pollution problem – pollution in a river, particulate matter