Vegetation and soils at the *land surface* control how energy received from the Sun is returned to the atmosphere. Some is returned as long-wave (infrared) radiation, heating the atmosphere as the land surface warms. Some serves to evaporate water, either in the soil or in the leaves of plants, bringing water back into the atmosphere. Because the evaporation of soil moisture requires energy, soil moisture has a strong influence on the surface temperature. The texture of the land surface (its roughness) influences the atmosphere dynamically as winds blow over the land's surface. Roughness is determined by both topography and vegetation. Wind also blows dust from the surface into the atmosphere, which interacts with the atmospheric radiation.

The marine and terrestrial *biospheres* have a major impact on the atmosphere's composition. The biota influence the uptake and release of greenhouse gases. Through the photosynthetic process, both marine and terrestrial plants (especially forests) store significant amounts of carbon from carbon dioxide. Thus, the biosphere plays a central role in the carbon cycle, as well as in the budgets of many other gases, such as methane and nitrous oxide. Other biospheric emissions are the so-called volatile organic compounds (VOC) which may have important effects on atmospheric chemistry, on aerosol formation and therefore on climate. Because the storage of carbon and the exchange of trace gases are influenced by climate, feedbacks between climate change and atmospheric concentrations of trace gases can occur. The influence of climate on the biosphere is preserved as fossils, tree rings, pollen and other records, so that much of what is known of past climates comes from such biotic indicators.

Interactions among the components
Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the system extremely complex. Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behaviour, they are all linked by fluxes of mass, heat and momentum: all subsystems are open and interrelated.

As an example, the atmosphere and the oceans are strongly coupled and exchange, among others, water vapour and heat through evaporation. This is part of the hydrological cycle and leads to condensation, cloud formation, precipitation and runoff, and supplies energy to weather systems. On the other hand, precipitation has an influence on salinity, its distribution and the thermohaline circulation. Atmosphere and oceans also exchange, among other gases, carbon dioxide, maintaining a balance by dissolving it in cold polar water which sinks into the deep ocean and by outgassing in relatively warm upwelling water near the equator.

Some other examples: sea ice hinders the exchanges between atmosphere and oceans; the biosphere influences the carbon dioxide concentration by photosynthesis and respiration, which in turn is influenced by climate change. The biosphere also affects the input of water in the atmosphere through evapotranspiration, and the atmosphere's radiative balance through the amount of sunlight reflected back to the sky (albedo).

These are just a few examples from a virtually inexhaustible list of complex interactions some of which are poorly known or perhaps even unknown. Chapter 7 provides an assessment of the present knowledge of physical climate processes and feedbacks, whilst Chapter 3 deals with biological feedbacks.

Any change, whether natural or anthropogenic, in the components of the climate system and their interactions, or in the external forcing, may result in climate variations. The following sections introduce various aspects of natural climate variations, followed by an introduction to the human influence on the climate system.

1.2 Natural Climate Variations

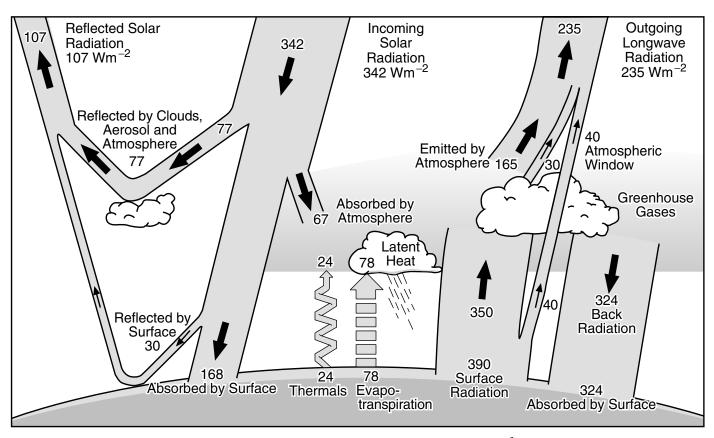### 1.2.1 Natural Forcing of the Climate System

The Sun and the global energy balance
The ultimate source of energy that drives the climate system is radiation from the Sun. About half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum. Each square metre of the Earth's spherical surface outside the atmosphere receives an average throughout the year of 342 Watts of solar radiation, 31% of which is immediately reflected back into space by clouds, by the atmosphere, and by the Earth's surface. The remaining 235 Wm^{-2} is partly absorbed by the atmosphere but most (168 Wm^{-2}) warms the Earth's surface: the land and the ocean. The Earth's surface returns that heat to the atmosphere, partly as infrared radiation, partly as sensible heat and as water vapour which releases its heat when it condenses higher up in the atmosphere. This exchange of energy between surface and atmosphere maintains under present conditions a global mean temperature near the surface of 14°C, decreasing rapidly with height and reaching a mean temperature of –58°C at the top of the troposphere.

For a stable climate, a balance is required between incoming solar radiation and the outgoing radiation emitted by the climate system. Therefore the climate system itself must radiate on average 235 Wm^{-2} back into space. Details of this energy balance can be seen in Figure 1.2, which shows on the left hand side what happens with the incoming solar radiation, and on the right hand side how the atmosphere emits the outgoing infrared radiation. Any physical object radiates energy of an amount and at wavelengths typical for the temperature of the object: at higher temperatures more energy is radiated at shorter wavelengths. For the Earth to radiate 235 Wm^{-2}, it should radiate at an effective emission temperature of –19°C with typical wavelengths in the infrared part of the spectrum. This is 33°C lower than the average temperature of 14°C at the Earth's surface. To understand why this is so, one must take into account the radiative properties of the atmosphere in the infrared part of the spectrum.

The natural greenhouse effect
The atmosphere contains several trace gases which absorb and emit infrared radiation. These so-called greenhouse gases absorb infrared radiation, emitted by the Earth's surface, the atmosphere

Figure 1.2: The Earth's annual and global mean energy balance. Of the incoming solar radiation, 49% (168 Wm^{-2}) is absorbed by the surface. That heat is returned to the atmosphere as sensible heat, as evapotranspiration (latent heat) and as thermal infrared radiation. Most of this radiation is absorbed by the atmosphere, which in turn emits radiation both up and down. The radiation lost to space comes from cloud tops and atmospheric regions much colder than the surface. This causes a greenhouse effect. Source: Kiehl and Trenberth, 1997: Earth's Annual Global Mean Energy Budget, *Bull. Am. Met. Soc.* 78, 197-208.

and clouds, except in a transparent part of the spectrum called the "atmospheric window", as shown in Figure 1.2. They emit in turn infrared radiation in all directions including downward to the Earth's surface. Thus greenhouse gases trap heat within the atmosphere. This mechanism is called the natural greenhouse effect. The net result is an upward transfer of infrared radiation from warmer levels near the Earth's surface to colder levels at higher altitudes. The infrared radiation is effectively radiated back into space from an altitude with a temperature of, on average, −19°C, in balance with the incoming radiation, whereas the Earth's surface is kept at a much higher temperature of on average 14°C. This effective emission temperature of −19°C corresponds in mid-latitudes with a height of approximately 5 km. Note that it is essential for the greenhouse effect that the temperature of the lower atmosphere is not constant (isothermal) but decreases with height. The natural greenhouse effect is part of the energy balance of the Earth, as can be seen schematically in Figure 1.2.

Clouds also play an important role in the Earth's energy balance and in particular in the natural greenhouse effect. Clouds absorb and emit infrared radiation and thus contribute to warming the Earth's surface, just like the greenhouse gases. On the other hand, most clouds are bright reflectors of solar radiation and tend to cool the climate system. The net average effect of the Earth's cloud cover in the present climate is a slight cooling: the

reflection of radiation more than compensates for the greenhouse effect of clouds. However this effect is highly variable, depending on height, type and optical properties of clouds.

This introduction to the global energy balance and the natural greenhouse effect is entirely in terms of the global mean and in radiative terms. However, for a full understanding of the greenhouse effect and of its impact on the climate system, dynamical feedbacks and energy transfer processes should also be taken into account. Chapter 7 presents a more detailed analysis and assessment.

Radiative forcing and forcing variability
In an equilibrium climate state the average net radiation at the top of the atmosphere is zero. A change in either the solar radiation or the infrared radiation changes the net radiation. The corresponding imbalance is called "radiative forcing". In practice, for this purpose, the top of the troposphere (the tropopause) is taken as the top of the atmosphere, because the stratosphere adjusts in a matter of months to changes in the radiative balance, whereas the surface-troposphere system adjusts much more slowly, owing principally to the large thermal inertia of the oceans. The radiative forcing of the surface troposphere system is then the change in net irradiance at the tropopause after allowing for stratospheric temperatures to re-adjust to radiative equilibrium, but with surface and tropospheric temperatures and state held