2 Atmosphere and weather

In this chapter you will learn:

- → How energy from the sun is gained, lost and transferred in the earth-atmosphere system at a local scale and how it varies from day to night.
- → About variations in the global energy budget, how energy is transferred from areas of surplus to areas of deficit and how it is linked to seasonal variations in temperature, pressure and wind belts.
- → How atmospheric moisture processes cause different types of precipitation.
- → How human activity is having an impact on weather and climate at both global and city scales.

The atmosphere

The **atmosphere** is a mixture of gases held to Earth by gravity; it increases in density, and therefore pressure, towards the Earth's surface and is divided into zones based on temperature variations. Only the lower two zones are relevant to our study.

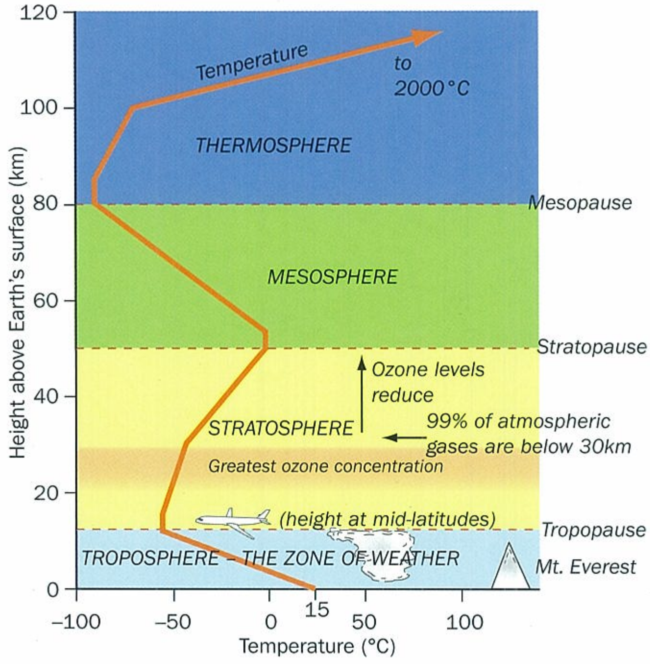

Fig. 2.1 The vertical structure of the atmosphere

Weather results from processes at work in the **troposphere.** At the **tropopause** a **temperature inversion** prevents air rising into the stratosphere. In the troposphere the air normally cools with increased altitude but the air above the tropopause is warmer than the air immediately below it. Cooler air is denser and cannot rise into warmer air. The tropopause varies in height from about 8 km at the poles to 18 km at the Equator.

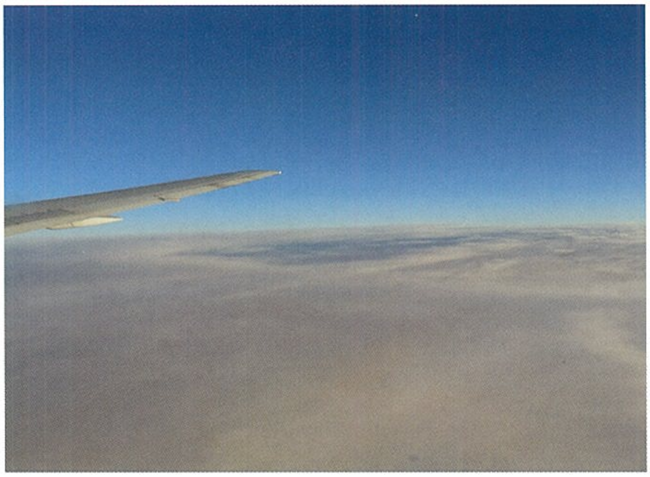

Fig. 2.2 Flat upper surfaces of cloud at the tropopause indicate the temperature inversion

Both troposphere and stratosphere consist of 78 per cent nitrogen and 20 per cent oxygen but trace amounts of other gases, such as methane and low-level ozone, also occur in the troposphere, whereas the stratosphere has important concentrations of ozone. Almost all the water vapour and suspended **aerosols** are in the troposphere.

Local diurnal energy budgets

Factors affecting the daytime energy budget

The sun provides the energy source to drive all atmospheric processes. The atmosphere derives little heat from the sun's rays passing through it. Most atmospheric heat is gained from the Earth. The daytime energy budget shown in Fig. 2.3 is a model of the average situation, based on 2013 revised estimates by NASA.

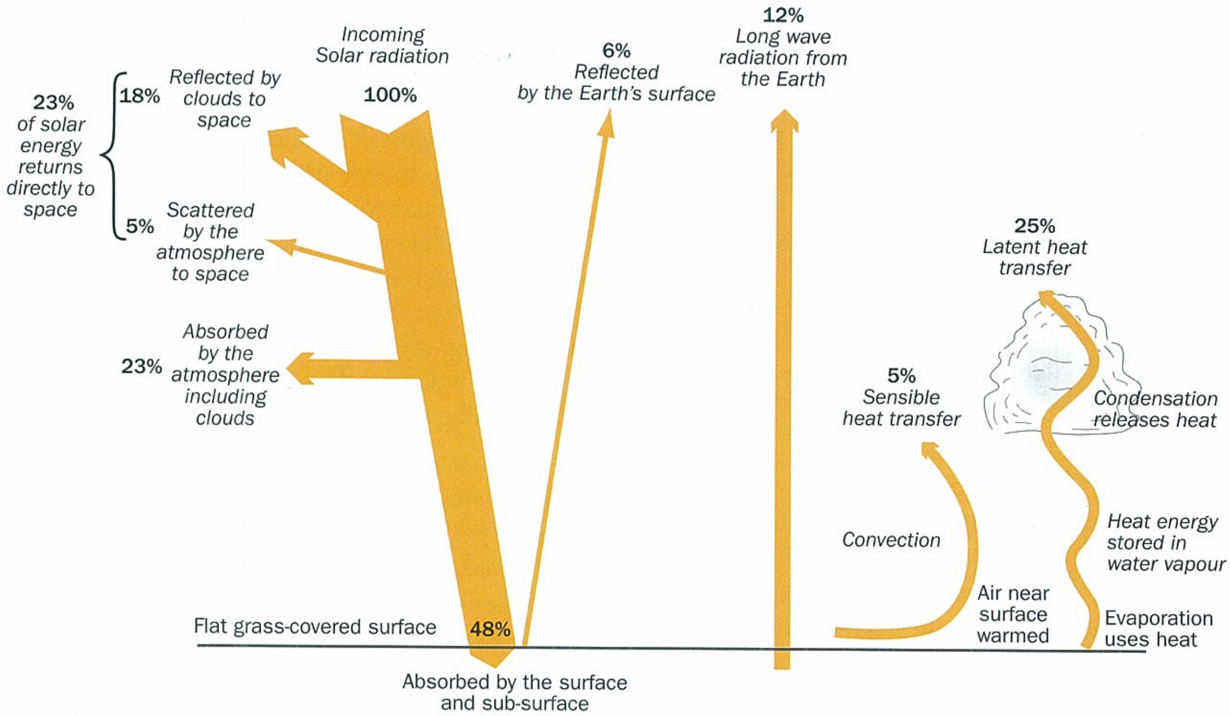

Fig. 2.3 The daytime energy budget

Incoming solar radiation (insolation)

The very hot sun emits short-wave (ultraviolet) **radiation**. Radiation is the transfer of heat from one body to another by electro-magnetic waves. At any time, the half of the Earth facing the sun is in daylight and being heated while the other side remains unheated.

Not all the energy emitted by the sun reaches the Earth's surface. During its passage through the atmosphere it is estimated that:

- 5 per cent is **scattered** straight back to space by dust and smoke particles.
- 24 per cent is **reflected** back to space, 18 per cent by the white upper surface of clouds and the water droplets within them and 6 per cent by the Earth's surface, mainly by snow, ice and water surfaces.
- 23 per cent is **absorbed** by atmospheric gases, mainly by ozone and oxygen at high levels, with small amounts by carbon dioxide and water vapour near the Earth's surface.

The remaining 48 per cent reaches the Earth's surface directly and heats it. The intensity of heating by incoming solar radiation depends on the angle of the sun's rays, being greatest where they reach the surface at 90° and reducing as their angle becomes smaller.

Dust and smoke particles also scatter another 5 per cent of solar radiation within the atmosphere. The short-wave bluer light rays are more easily scattered than the longer-wave red rays so, when the sun is low near the horizon, passing through a thicker atmosphere, more scattering occurs and only red rays remain. The thick stratus cloud in Fig. 2.4 limits radiation received at the surface to about 10 per cent.

Fig. 2.4 Red evening sky caused by scattering of the sun's rays

Solar radiation reflected by the Earth's surface

The percentage of solar radiation that is reflected back to space by the Earth's surface is known as its **albedo**. Lighter-coloured surfaces reflect more solar radiation, while darker-coloured surfaces absorb more of it.

Surface	Average albedo (%)
Thick cumulonimbus cloud	92
Fresh snow	80
Thick stratus cloud	65
Sandy surfaces	40
Thin cloud	32
Concrete	22
Deciduous forest	18
Green grass	15
Coniferous forest	12
Asphalt	10
Dark soil	7

Table 2.1 Average albedo values

The albedo of oceans varies remarkably according to the time of day; when the sun is at a high angle near midday it has very low albedo (about 4 per cent) but reflection can reach 80 per cent when the evening sun is very low in the sky.

The total amount of energy lost to space by scattering and reflection, from both Earth and atmosphere, is the **planetary** or **global albedo**.

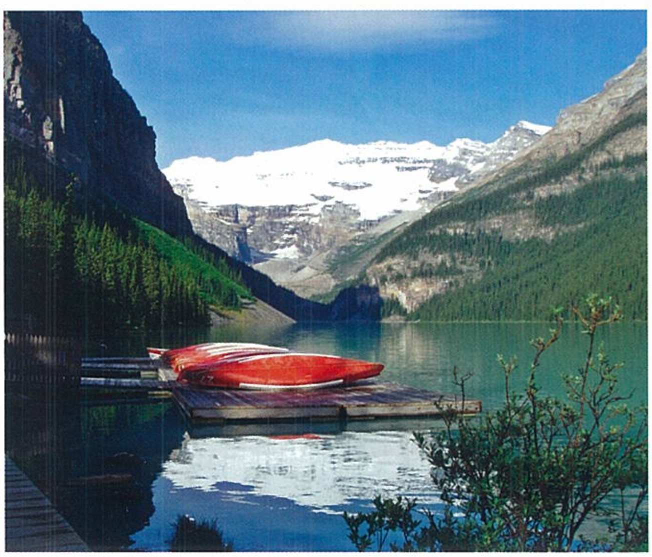

Fig. 2.5 Local variations in albedo in the Canadian Rocky Mountains

1. Rank, from highest to lowest, the variations in albedo of the different surfaces shown in the sunny areas on Fig. 2.5. The sun was at an angle of about 50° above the horizontal.
2. Explain why:
   (a) dirty snow melts faster than fresh snow
   (b) the albedo of crops can vary from 15 to 25 per cent
   (c) some parts of urban areas will have lower than the average albedo for an urban area (15 per cent) and others will have higher albedos. Give examples to illustrate each.

Energy absorbed into the surface and sub-surface

Dark surfaces absorb much more radiation than surfaces with a high albedo. Some of the absorbed energy is transferred a short depth into the soil and rocks by **conduction**. This is achieved by contact with the heated surface in the same way as heat transfers along the handle of a spoon left in a hot liquid, as metal is a good conductor of heat. Light-coloured rock, like limestone, is a poor conductor, so heating is confined to the surface, giving very high rock surface temperatures (45 °C) in hot deserts in daytime. By contrast, darker rock like granite, with a low albedo, absorbs heat well.

The conductivity of soils also varies according to their moisture content. Anyone who has walked barefooted on a dry sandy beach in early afternoon in low latitudes will have experienced great heat on the soles of their feet. The air in the pores of dry sand is a poor conductor, so heat remains concentrated at the surface, whereas water in soil increases heat flow. In a wet sandy soil conduction transfers the heat down and the surface is cooler.

Long-wave Earth radiation

Short-wave radiation from the sun is absorbed by the Earth and re-radiated as long-wave (infra-red) radiation because the Earth is a cool body. This is much more easily absorbed by 'greenhouse' gases in the atmosphere – mainly by water vapour and carbon dioxide – than short-wave radiation, and is the most important way in which the atmosphere is heated. Clouds absorb long-wave radiation very efficiently and continuously re-radiate it back to Earth – keeping heat in by the **greenhouse effect**. Heat loss is greatest in dry air but, in general, only small amounts escape directly to space through '**radiation windows**'.

Sensible heat transfer

Sensible heat transfer occurs when heat energy is transferred by direct conduction or **convection**.

- Air is a very poor conductor of heat, so only a thin layer next to the surface is warmed by conduction.
- Warming causes the air molecules to expand, become lighter and rise through air that is cooler and denser. This process of convection transfers heat to higher altitudes and, on very hot summer days, the strongly rising air currents can reach the tropopause. Cooler air moves down to replace the rising air and is, in turn, heated.
- Warm winds near the surface can be deflected upwards by an obstacle and can reach 600 m above the surface if the wind turbulence is very strong.

Latent heat transfer

Latent heat transfer occurs when water on the Earth's surface **evaporates** to water vapour or ice melts to water vapour.

The heat needed to make these changes is absorbed from the air, leaving less energy for heating at the surface. This latent heat is stored in the water vapour and may be carried upwards in convection currents until it cools sufficiently for the water vapour to condense into water droplets or change into ice crystals. During this change the stored heat is released into the air, warming it. This is known as the **latent heat of condensation** and increases the speed and extent of convection. Much solar radiation is lost by latent heat being used to convert snow and ice back to water in high latitudes in spring and early summer.

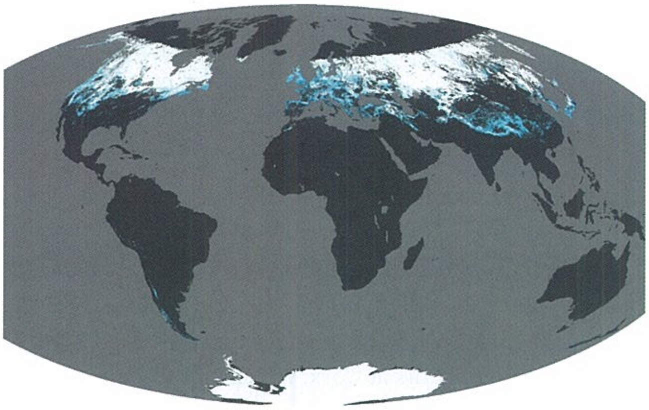

Fig. 2.6 Satellite image showing snow cover in December

Fig. 2.6 does not show the snow and ice in the most northerly latitudes which were in darkness at the time the image was received. Where snow cover is permanent, as in Greenland and Antarctica, its albedo is so great that the net radiation balance is zero or slightly negative, even on summer days when there is maximum insolation during the 24 hours of daylight.

The daytime energy budget has a surplus of energy, as shown in Table 2.2.

3 (a) Describe two types of latent heat transfer that would be occurring when the photograph, Fig. 2.5, was taken.

(b) Describe and explain the atmospheric process occurring in Fig. 2.7.

Fig. 2.7 Ice crystals after sunrise in winter in mid-latitudes

The influence of clouds on the daytime energy budget

The model shown in Fig. 2.3 (page 35) does not include the influences different clouds have on daytime energy transfers.

- High thin clouds, such as cirrus, allow incoming solar radiation to pass through but absorb some long-wave radiation, so warming the Earth's surface.
- Deep convective clouds, especially cumulonimbus, neither heat nor cool overall.
- An overcast sky with complete cloud cover of low, thick clouds, such as stratus and stratocumulus, can reflect 80 per cent of solar radiation and cool the Earth's surface.
- Clouds usually have higher albedos than the surface below them, so more short-wave radiation is reflected back to space than would be the case if there were no clouds. So, clouds have a net cooling effect.

4. Using a different example for each, describe how, and explain why, a daytime energy budget will vary:

(a) from time to time.

(b) from place to place.

The daytime energy budget			
Input		**Outputs**	
Incoming short-wave solar radiation	minus	Reflected solar radiation + outgoing long-wave terrestrial radiation + energy absorbed into the Earth's surface + sensible heat transfer + latent heat transfer	= Surplus energy available at the surface (variable from place to place and time to time).

Table 2.2 The daytime energy budget

Fig. 2.8 About 80 per cent of solar radiation is reflected back to space from the white upper surfaces of thick clouds

The night-time energy budget

Whereas the daytime energy budget model has six factors, the night-time model lacks two components - it has no short-wave radiation from the sun, so has a deficit of energy, and it has no reflected solar radiation, making it a four factor model. As insolation stops, the ground loses heat and cools and the air next to it also cools. At night the budget is in deficit.

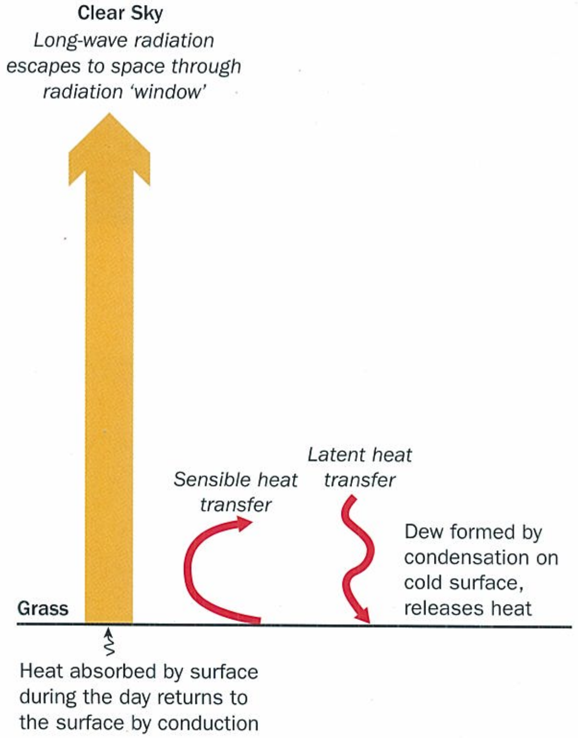

Fig. 2.9a The night-time energy budget

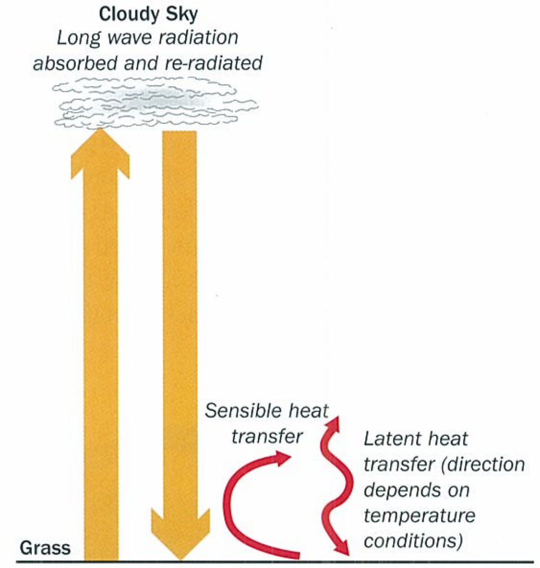

Fig. 2.9b How cloud changes the model

Conduction of heat to the surface

Heat that was absorbed into the soil and rocks during the day, returns to the surface at night and offsets to a small extent the other factors at work, which all cause heat loss.

Long-wave Earth radiation

The amount of long-wave radiation escaping to space from the Earth depends on the cloud cover. Clear skies result in very cold nights. Without cloud to stop the long-wave radiation escaping to space, temperatures fall quickly, leading to large temperature differences between night and day, especially if the daytime was also cloudless.

5. Look at Fig. 2.10 of temperature changes during a cloudless day.

(a) In mid-latitudes how many minutes after dawn is the minimum temperature and how many hours after noon is the maximum temperature of the day? What is the relationship between the incoming solar radiation and the outgoing long-wave radiation at these times?

(b) Describe and explain the two trends in temperature over 24 hours.

Sensible heat transfer

Although convectional uplift may continue after dark in the tropics and sub-tropics, it is unimportant in higher latitudes where air often sinks at night. There may also be some sensible heat transfer by **advection** - horizontal transfers of air from a warmer to a colder area.

Latent heat transfer

On cloudless nights, the Earth's surface rapidly loses heat by long-wave radiation. Cooling is very intense if the air is also

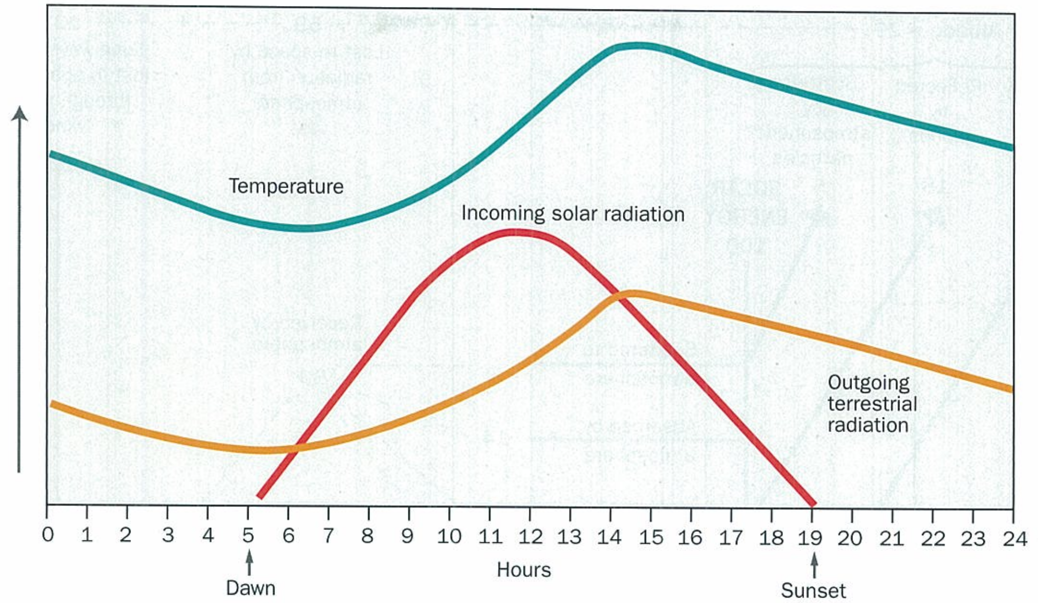

Fig. 2.10 Multiple line graph showing the influence of solar and terrestrial radiation on temperature during a day in mid-latitudes

calm because there is no warmer air coming in to mix with it. When water vapour comes into contact with a cold object whose temperature is below the **dew point** of the air, such as a leaf or spider's web, the water vapour will condense on the object, forming small water droplets known as **dew**. Latent heat, absorbed during evaporation, is released during the condensation process, adding warmth to the air near the ground.

The influence of cloud on night-time energy budgets: absorbed energy returned to Earth

A thick cloud cover at night acts as a 'blanket', keeping the Earth and lower atmosphere warm by absorbing and re-radiating the emissions of long-wave radiation from Earth to atmosphere and back to Earth. This results in little difference in temperature between day and night, especially when the day has also been cloudy.

Some of the Earth's long-wave radiation absorbed by clouds is re-radiated to space. The warmer the cloud, the more long-wave radiation is re-radiated. Little is radiated from high level clouds, such as those in Fig. 2.8, because their upper surfaces are cold.

Eventually a balance is achieved between incoming solar radiation and long-wave radiation to space.

The global energy budget

Variations in the energy budget occur from place to place and time to time. However, globally and in general, incoming solar radiation must have been balanced by outgoing terrestrial radiation because, if that was not so, the Earth's atmosphere would have been getting hotter or colder. As 71 per cent of incoming solar radiation is absorbed (48 per cent by the Earth and 23 per cent by 'greenhouse' gases in its atmosphere), those amounts must be radiated back to space to keep the balance, as shown in Tables 2.3 and 2.4. If global warming (page 62) is now occurring, these processes are no longer in balance.

Incoming short-wave radiation at the Earth's surface (estimates)	**Outgoing radiation (estimates)**	
absorbed by the Earth = 48%	latent heat transfer (evaporation):	25%
	sensible heat transfer (convection):	5%
	long-wave radiation direct to space:	12%
	total =	42%
	long-wave radiation absorbed by greenhouse gases in the atmosphere:	6%
	total =	**48%**

Table 2.3 The surface energy budget of the Earth's surface

Gains		**Losses**
absorbed solar radiation:	23%	long-wave radiation from the atmosphere to space = **59%**
latent heat transfer (evaporation):	25%	
sensible heat transfer (convection):	5%	
absorbed long-wave radiation:	6%	
Total =	**59%**	

Table 2.4 The energy budget of the atmosphere