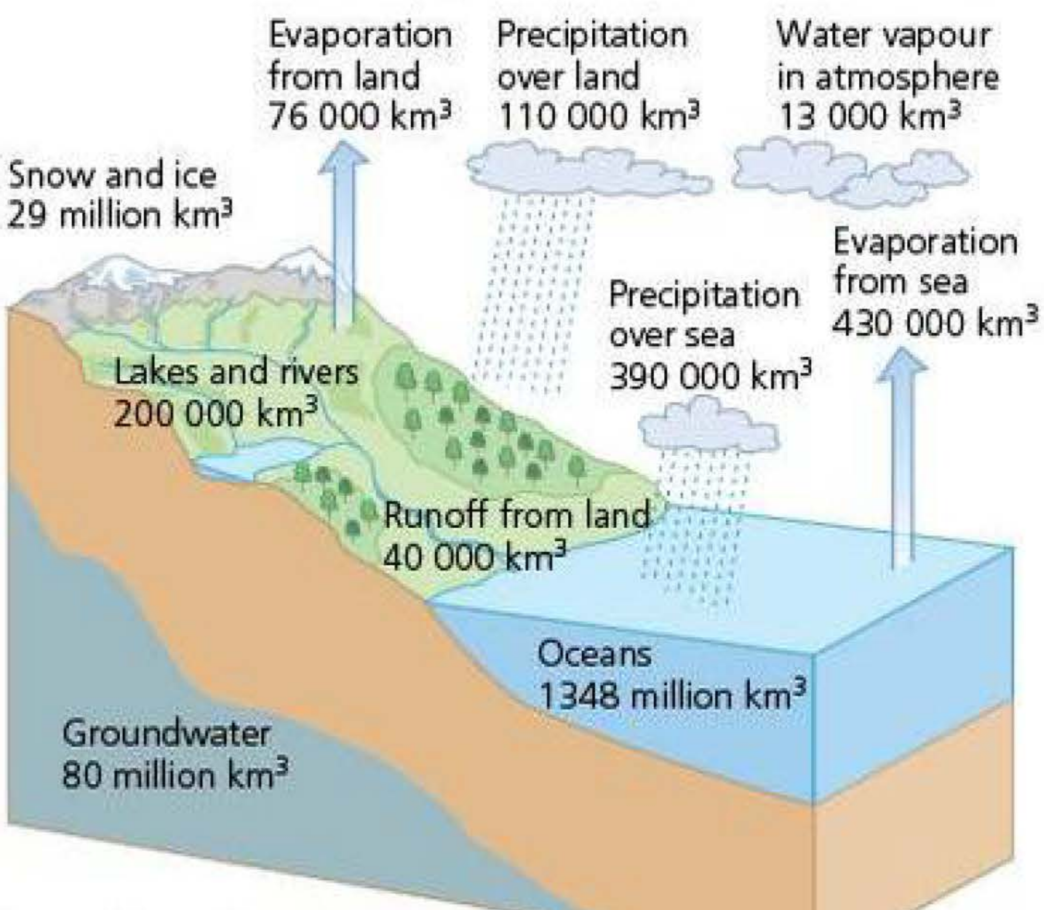
1 Hydrology and fluvial geomorphology

1.1 The drainage basin system

The hydrological cycle refers to the cycle of water between atmosphere, lithosphere and biosphere (Figure 1.1). At a local scale – the drainage basin (Figure 1.2) – the cycle has a single input, precipitation (PPT), and two major losses (outputs): evapotranspiration (EVT) and runoff. A third output, leakage, may also occur from the deeper subsurface to other basins. The drainage basin system is an open system as it allows the movement of energy and matter across its boundaries.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.245

Figure 1.1 The global hydrological cycle

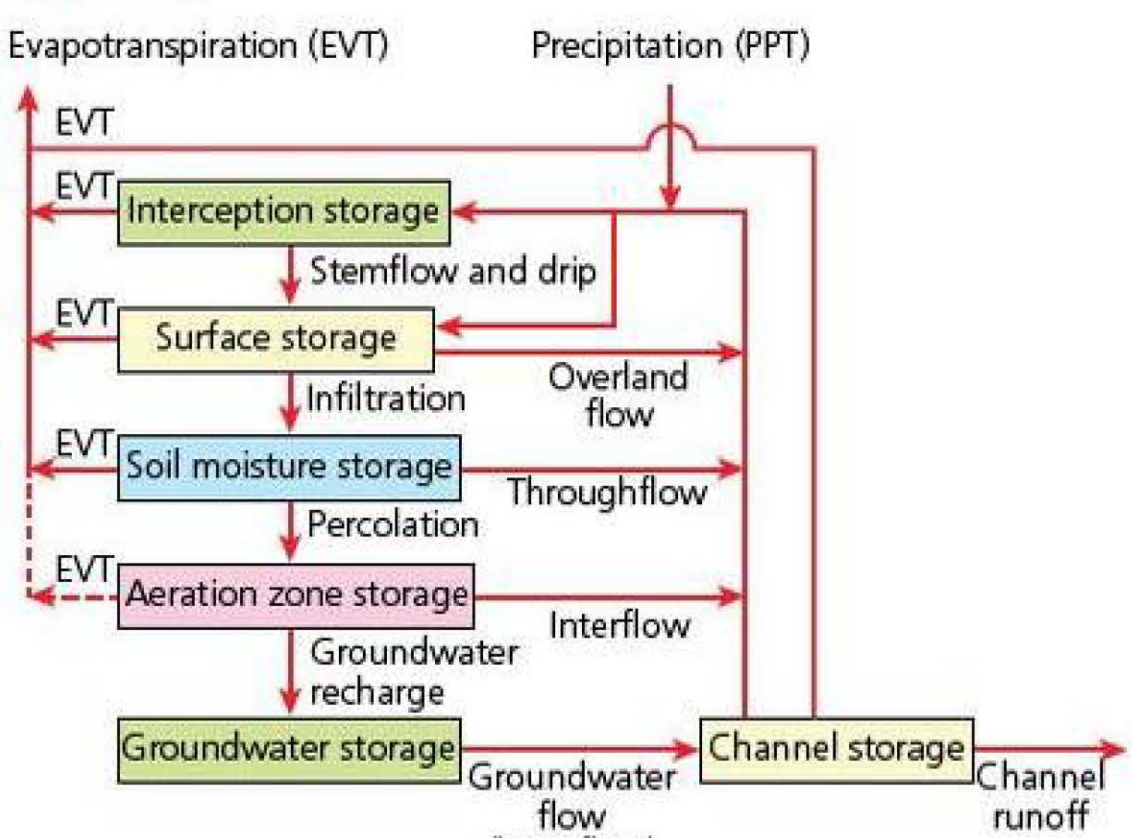


Figure 1.2 The drainage basin hydrological cycle

Water can be stored at a number of stages or levels within the cycle. These stores include vegetation, surface, soil moisture, groundwater and water channels.

Human modifications are made at every scale. Relevant examples include large-scale changes of channel flow and storage, irrigation and land drainage, and large-scale abstraction of groundwater and surface water for domestic and industrial use.

Outputs

Evaporation

Evaporation is the process by which a liquid is changed into a gas. The process by which a solid is changed into a gas is sublimation. These terms refer to the conversion of solid and liquid precipitation (snow, ice and water) to water vapour in the atmosphere. Evaporation is most important from oceans and seas. It increases under warm, dry conditions and decreases under cold, calm conditions. Evaporation losses are greater in arid and semi-arid climates than in polar regions.

Factors affecting evaporation include meteorological factors such as temperature, humidity and wind speed. Of these, temperature is the most important factor. Other factors include the amount of water available, vegetation cover and colour of the surface (albedo or reflectivity of the surface).

Evapotranspiration

Transpiration is the process by which water vapour escapes from a living plant, principally the leaves, and enters the atmosphere. The combined effects of evaporation and transpiration are normally referred to as evapotranspiration (EVT). EVT represents the most important aspect of water loss, accounting for the loss of nearly 100 per cent of the annual precipitation in arid areas and 75 per cent in humid areas. Only over ice and snow fields, bare rock slopes, desert areas, water surfaces and bare soil will purely evaporative losses occur.

Potential evapotranspiration (P.EVT)

The distinction between actual EVT and P.EVT lies in the concept of moisture availability. Potential evapotranspiration is the water loss that would occur if there were an unlimited supply of water in the soil for use by the vegetation. For example, the actual evapotranspiration rate in Egypt is less than 250 mm, because there is less than 250 mm of rain annually. However, given the high temperatures experienced in Egypt, if the rainfall were as high as 2000 mm, there would be sufficient heat to evaporate that water. Hence the potential evapotranspiration rate there is 2000 mm. The factors affecting evapotranspiration include all those that affect evaporation. In addition, some plants, such as cacti, have adaptations to help them reduce moisture loss.

River discharge

River discharge refers to the movement of water in channels such as streams and rivers. The water may enter the river as direct channel precipitation (it falls on the channel) or it may reach the channel by surface runoff, groundwater flow (baseflow), or throughflow (water flowing through the soil).

Stores

Interception

Interception refers to water that is caught and stored by vegetation. There are three main components:

- interception loss – water that is retained by plant surfaces and that is later evaporated away or absorbed by the plant
- throughfall – water that either falls through gaps in the vegetation or that drops from leaves or twigs
- stemflow – water that trickles along twigs and branches and finally down the main trunk.

Interception loss varies with different types of vegetation (Figure 1.3). Interception is less from grasses than from deciduous woodland owing to the smaller surface area of the grass shoots. From agricultural crops, and from cereals in particular, interception increases with crop density. Coniferous trees intercept more than deciduous trees in winter, but this is reversed in summer.

Soil water

Soil water (soil moisture) is the subsurface water in soil and subsurface layers above the water table. From here water may be:

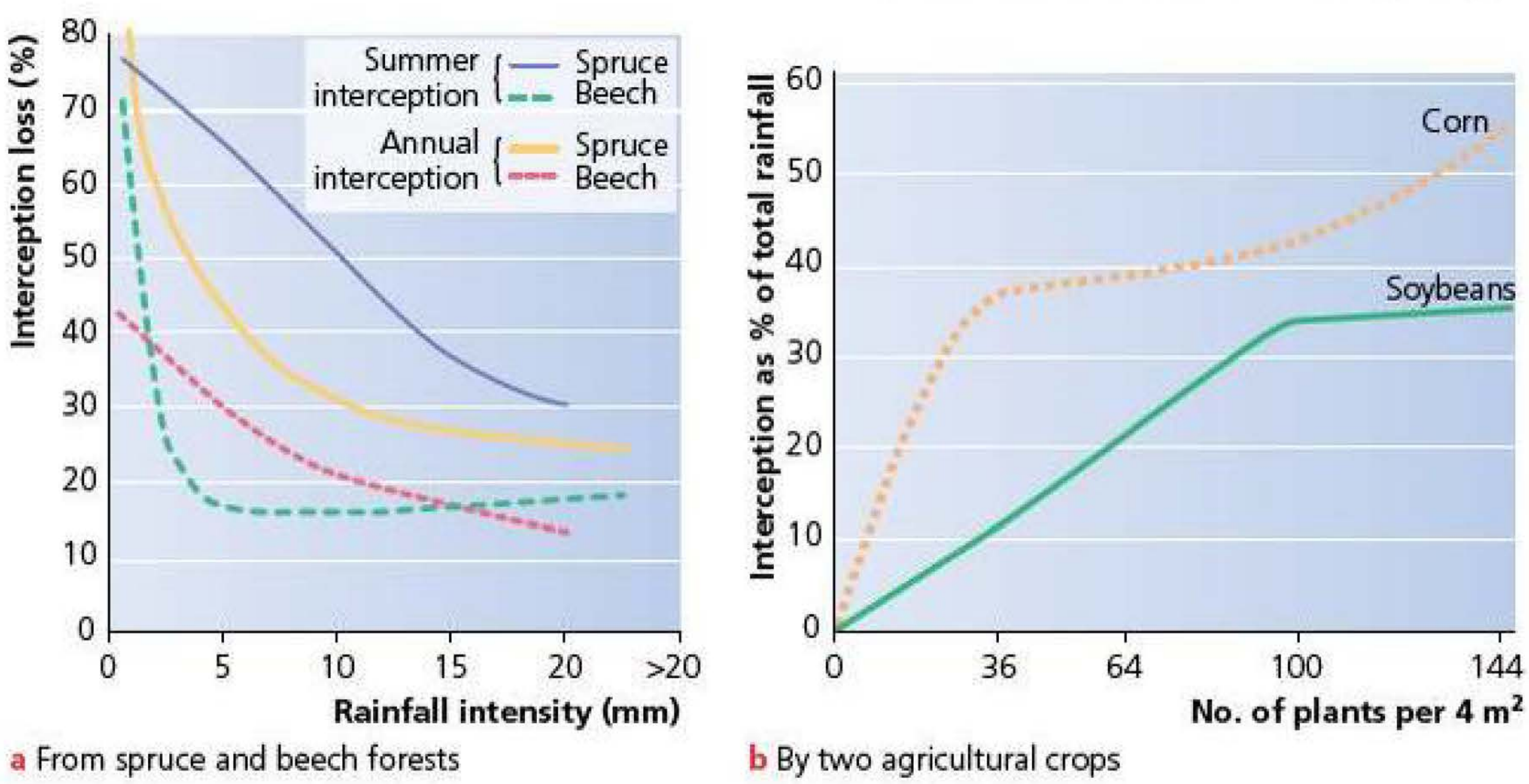
- absorbed
- held
- transmitted downwards towards the water table, or
- transmitted upwards towards the soil surface and the atmosphere.

In coarse-textured soils much of the water is held in fairly large pores at fairly low suctions, while very little is held in small pores. In the finer-textured clay soils the range of pore sizes is much greater and, in particular, there is a higher proportion of small pores in which the water is held at very high suctions.

Field capacity refers to the amount of water held in the soil after excess water drains away; that is, saturation or near saturation. Wilting point refers to the range of moisture content in which permanent wilting of plants occurs.

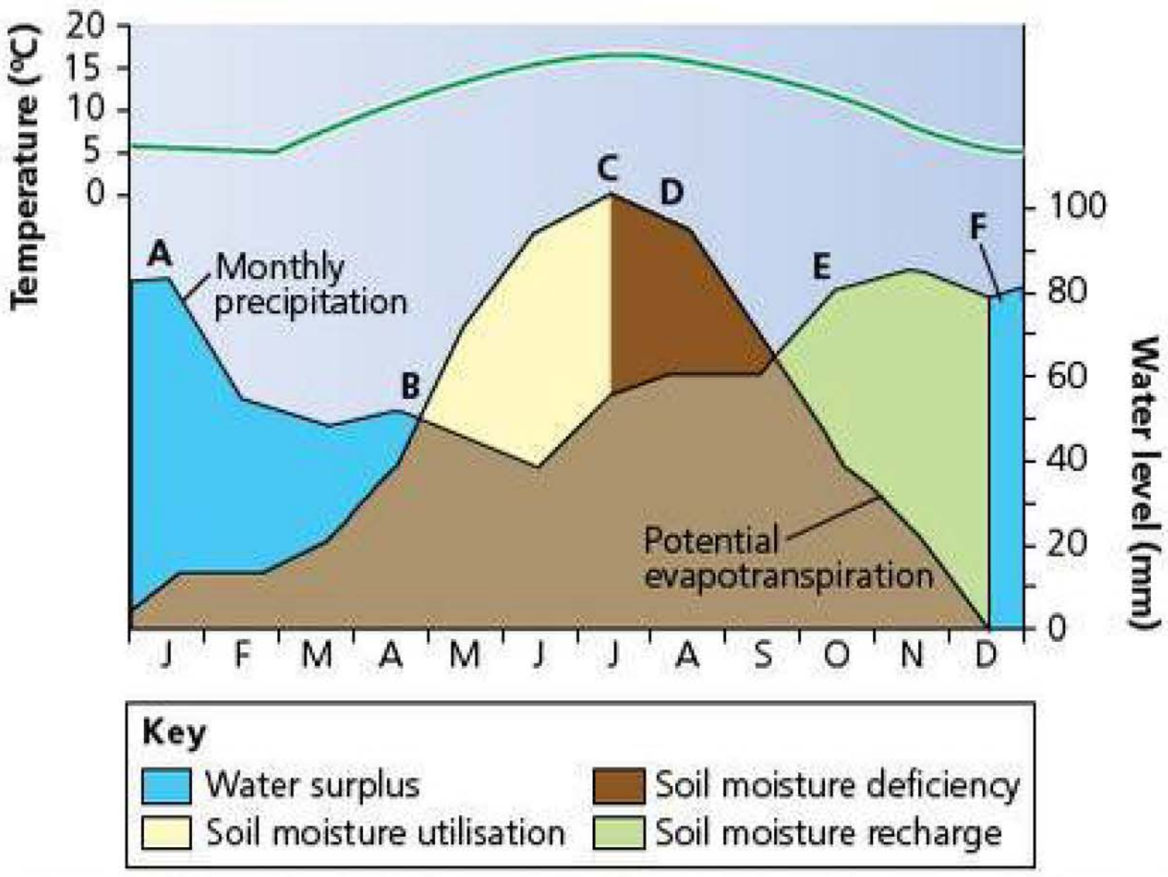
There are a number of important seasonal variations in soil moisture budgets (Figure 1.4):

- Soil moisture deficit is the degree to which soil moisture falls below field capacity. In temperate areas, during late winter and early spring, soil moisture deficit is very low, due to high levels of precipitation and limited evapotranspiration.
- Soil moisture recharge occurs when precipitation exceeds potential evapotranspiration – there is some refilling of water in the dried-up pores of the soil.
- Soil moisture surplus is the period when soil is saturated and water cannot enter, and so flows over the surface.
- Soil moisture utilisation is the process by which water is drawn to the surface through capillary action.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.245

Figure 1.3 Interception losses for different types of vegetation



A Precipitation > potential evapotranspiration. Soil water store is full and there is a soil moisture surplus for plant use, runoff and groundwater recharge.

B Potential evapotranspiration > precipitation. Water store is being used up by plants or lost by evaporation (soil moisture utilisation).

C Soil moisture store is now used up. Any precipitation is likely to be absorbed by the soil rather than produce runoff. River levels will fall or dry up completely.

D There is a deficiency of soil water as the store is used up and potential evapotranspiration > precipitation. Plants must adapt to survive; crops must be irrigated.

E Precipitation > potential evapotranspiration. Soil water store will start to fill again (soil moisture recharge).

F Soil water store is full. Field capacity has been reached. Additional rainfall will percolate down to the water table and groundwater stores will be recharged.

Figure 1.4 Soil moisture status

Surface water

There are a number of types of surface water, some of which are temporary and some are permanent. Temporary sources include small puddles following a rainstorm and turloughs (seasonal lakes in limestone in the west of Ireland), while permanent stores include lakes, wetlands, swamps, peat bogs and marshes.

Groundwater

Groundwater refers to subsurface water that is stored under the surface in rocks. Groundwater accounts for 96.5 per cent of all freshwater on the Earth (Table 1.1). However, while some soil moisture may be recycled by evaporation into atmospheric moisture within a matter of days or weeks, groundwater may not be recycled for as long as 20000 years. Recharge refers to the refilling of water in pores where the water has dried up or been extracted by human activity. Hence, in some places where recharge is not taking place, groundwater is considered a non-renewable resource.

Table 1.1 Global water reservoirs

Reservoir		Value (km^{-3} x 10^{-3})	% of total
Ocean		1350000.0	97.403
Atmosphere		13.0	0.00094
Land		35977.8	2.596
Of which	Rivers	1.7	0.00012
	Freshwater lakes	100.0	0.0072
	Inland seas	105.0	0.0076
	Soil water	70.0	0.0051
	Groundwater	8200.0	0.592
	Ice caps/glaciers	27500.0	1.984
	Biota	1.1	0.00088

Channel storage

Channel storage refers to all water that is stored in rivers, streams and other drainage channels. Some rivers are seasonal, and some may disappear underground either naturally, such as in areas of Carboniferous limestone, or in urban areas, where they may be covered (culverted).

Flows

Above ground

Throughfall refers to water that either falls through gaps in vegetation or that drops from leaves or twigs. Stemflow refers to water that trickles along twigs and branches and finally down the main trunk.

Overland flow (surface runoff) is water that flows over the land's surface. Surface runoff (or overland flow) occurs in two main ways:

- when precipitation exceeds the infiltration rate
- when the soil is saturated (all the pore spaces are filled with water).

In areas of high precipitation intensity and low infiltration capacity, overland runoff is common. This is clearly seen in semi-arid areas and in cultivated fields. By contrast, where precipitation intensity is low and infiltration is high, most overland flow occurs close to streams and river channels.

Channel flow or stream flow refers to the movement of water in channels such as streams and rivers. The water may have entered the stream as a result of direct precipitation, overland flow, groundwater flow (baseflow) or throughflow (water flowing through the soil).

Below ground

Porosity is the capacity of a rock to hold water, for example sandstone has a porosity (pore space) of 5–15 per cent, whereas clay may be up to 50 per cent. Permeability is the ability to transmit water through a rock via joints and fissures.

Infiltration

Infiltration is the process by which water soaks into or is absorbed by the soil. The infiltration capacity is the maximum rate at which rain can be absorbed by a soil in a given condition.

Infiltration capacity decreases with time through a period of rainfall until a more or less constant value is reached (Figure 1.5). Infiltration rates of 0–4 mm/hour are common on clays, whereas 3–12 mm/hour are common on sands. Vegetation also increases infiltration. This is because it intercepts some rainfall and slows down the speed at which it arrives at the surface. For example, on bare soils where rainsplash impact occurs, infiltration rates may reach 10 mm/hour. On similar soils covered by vegetation, rates of between 50 and 100 mm/hour have been recorded. Infiltrated water is chemically rich as it picks up minerals and organic acids from vegetation and soil.

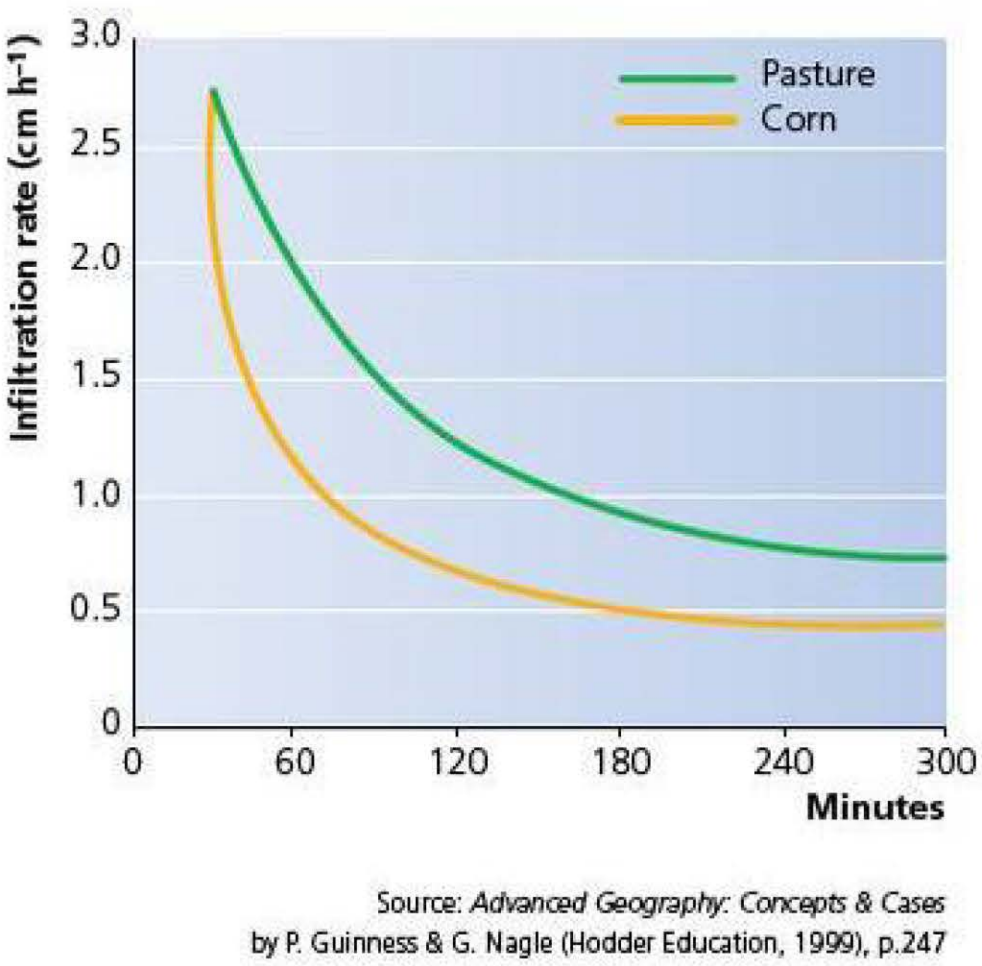


Figure 1.5 Infiltration rates under vegetation

Infiltration is inversely related to overland runoff and is influenced by a variety of factors, such as duration of rainfall, antecedent soil moisture (pre-existing levels of soil moisture), soil porosity, vegetation cover (Table 1.2), raindrop size and slope angle (Figure 1.6). In contrast, overland flow is water that flows over the land's surface.

Table 1.2 Influence of ground cover on infiltration rates

Ground cover	Infiltration rate (mm/hour)
Old permanent pasture	57
Permanent pasture: moderately grazed	19
Permanent pasture: heavily grazed	13
Strip-cropped	10
Weeds or grain	9
Clean tilled	7
Bare, crusted ground	6

Percolation

Water moves slowly downwards from the soil into the bedrock – this is known as percolation. Depending on the permeability of the rock, this may be very slow or in some rocks, such as Carboniferous limestone and chalk, it may be quite fast, locally.

Throughflow

Throughflow refers to water flowing through the soil in natural pipes and percolines (lines of concentrated water flow between soil horizons).

Groundwater and baseflow

Most groundwater is found within a few hundred metres of the surface but has been found at depths of up to 4 kilometres beneath the surface. Baseflow refers to the part of a river's discharge that is provided by groundwater seeping into the bed of a river. It is a relatively constant flow although it increases slightly following a wet period.

Underground water

The permanently saturated zone within solid rocks and sediments is known as the phreatic zone. The upper layer of this is known as the water table. The water table varies seasonally. In temperate zones it is higher in winter following increased levels of precipitation. The zone that is seasonally wetted and seasonally dries out is known as the aeration zone.

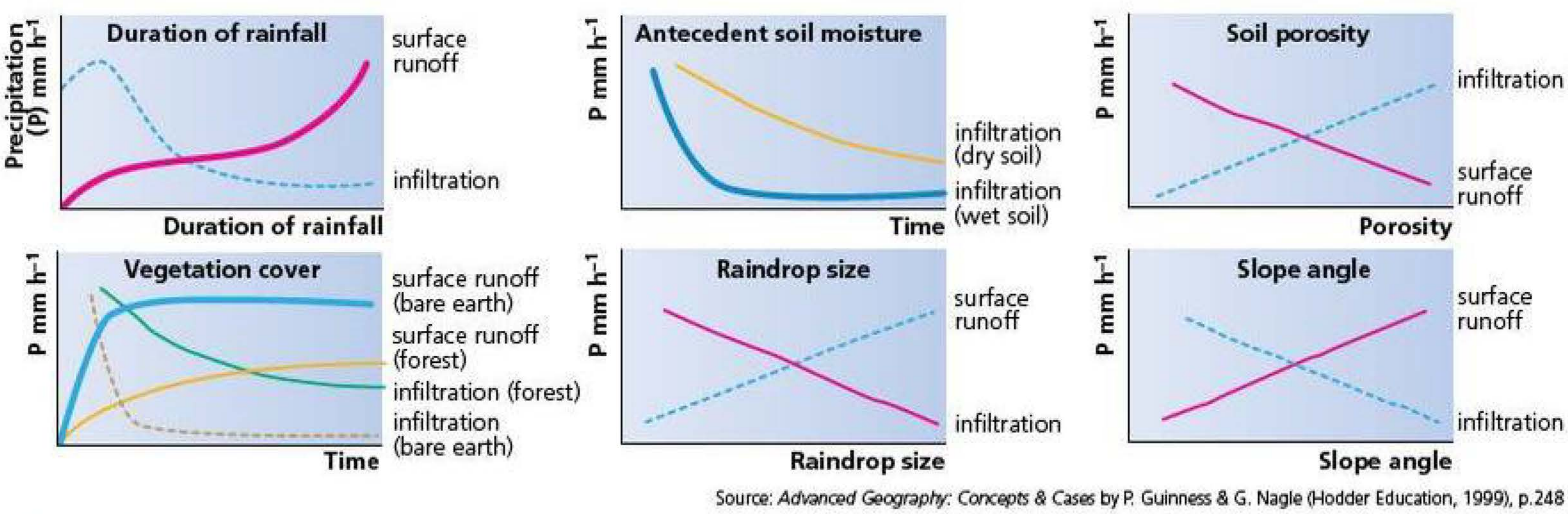
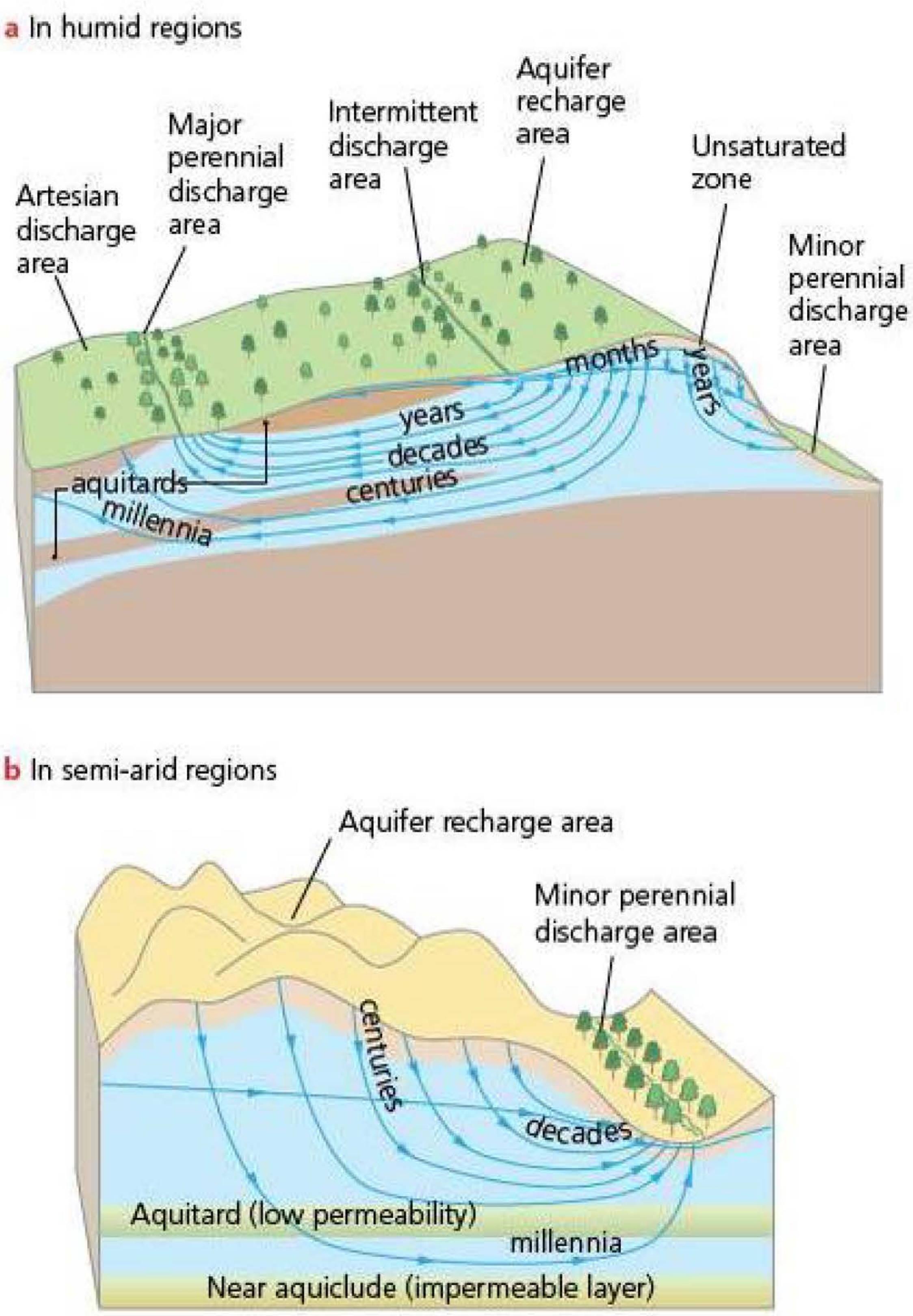


Figure 1.6 Factors affecting infiltration and surface runoff

Aquifers (rocks that contain significant quantities of water) provide a great reservoir of water. Aquifers are permeable rocks such as sandstones and limestones. The water in aquifers moves very slowly and acts as a natural regulator in the hydrological cycle by absorbing rainfall that otherwise would reach streams rapidly. In addition, aquifers maintain stream flow during long dry periods. Where water flow reaches the surface (as shown by the discharge areas in Figure 1.7), **springs** may be found. These may be substantial enough to become the source of a stream or river.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.248

Figure 1.7 Groundwater and aquifer characteristics

Groundwater recharge occurs as a result of:

- **infiltration** of part of the total precipitation at the ground surface
- **seepage** through the banks and bed of surface water bodies such as ditches, rivers, lakes and oceans
- **groundwater leakage and inflow** from adjacent rocks and aquifers
- **artificial recharge** from irrigation, reservoirs, and so on.

Losses of groundwater result from:

- **evapotranspiration**, particularly in low-lying areas where the water table is close to the ground surface
- **natural discharge**, by means of spring flow and seepage into surface water bodies
- **groundwater leakage and outflow**, along aquicludes and into adjacent aquifers
- **artificial abstraction**, for example the water table near Lubbock on the High Plains of Texas (USA) has declined by 30–50m in just 50years, and in Saudi Arabia the groundwater reserve in 2010 was 42per cent less than in 1985.

Section 1.1 Activities

1. Define the following hydrological characteristics:
   a interception b evaporation c infiltration.
2. Study Figure 1.2.
   a Define the terms *overland flow* and *throughflow*.
   b Compare the nature of water movement in these two flows.
   c Suggest reasons for the differences you have noted.
3. Figure 1.3 shows interception losses from spruce and beech forests and from three agricultural crops. Describe and comment on the relationship between the number of plants and interception, and the type of plants and interception.
4. Figure 1.6 shows the relationship between infiltration, overland flow (surface runoff) and six factors. Write a paragraph on each of the factors, describing and explaining the effect it has on infiltration and overland runoff.
5. Comment on the relationship between ground cover and infiltration, as shown in Table 1.2.
6. Define the terms *groundwater* and *baseflow*.
7. Outline the ways in which human activities have affected groundwater.

1.2 Discharge relationships within drainage basins

Hydrographs

A **storm hydrograph** shows how the discharge of a river varies over a short time (Figure 1.8). Normally it refers to an individual storm or group of storms of not more than a few days in length. Before the storm starts, the main supply of water to the stream is through groundwater flow or baseflow. This is the main supplier of water to rivers. During the storm, some water infiltrates into the soil while some flows over the surface as overland flow or runoff. This reaches the river quickly as **quickflow**, which causes a rapid rise in the level of the river. The **rising limb** shows us how quickly the **flood** waters begin to rise, whereas the **recessional limb** is the speed with which the water level in the river declines after the peak. The **peak flow** is the maximum discharge of the river as a result of the storm, and the **time lag** is the time between the height of the storm (not the start or the end) and the maximum flow in the river.

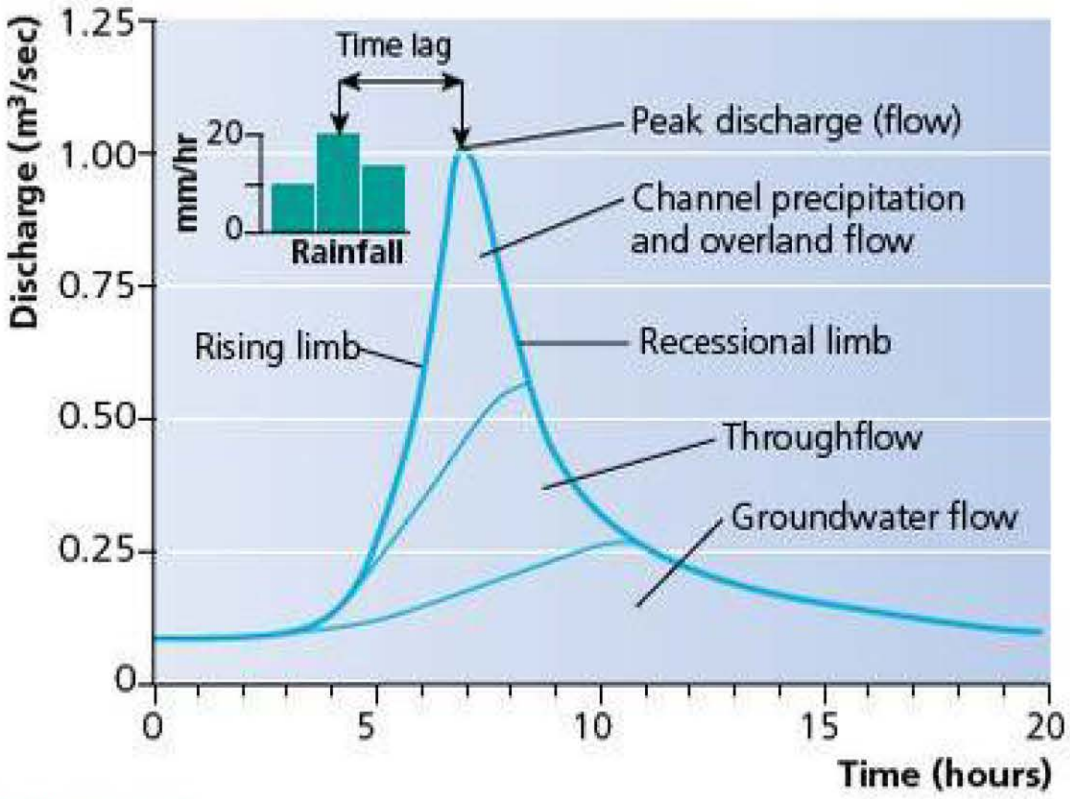


Figure 1.8 A simple hydrograph

In contrast, a river regime is the annual variation in the discharge of a river. Stream discharge occurs as a result of overland runoff and groundwater springs, and from lakes and meltwater in mountainous or sub-polar environments. The character or regime of the resulting stream or river is influenced by several variable factors:

- the amount and nature of precipitation
- the local rocks, especially porosity and permeability
- the shape or morphology of the drainage basin, its area and slope
- the amount and type of vegetation cover
- the amount and type of soil cover.

On an annual basis, the most important factor determining stream regime is climate. Figure 1.9 shows generalised regimes for Europe. Notice how the regime for the Shannon at Killaloe (Ireland) has a typical temperate regime, with a clear winter maximum. By contrast, Arctic areas such as the Gloma in Norway and the Kemi in Finland have a peak in spring associated with snowmelt. Others, such as the Po near Venice, have two main maxima – autumn and winter rains (Mediterranean climate) and spring snowmelt from Alpine tributaries.

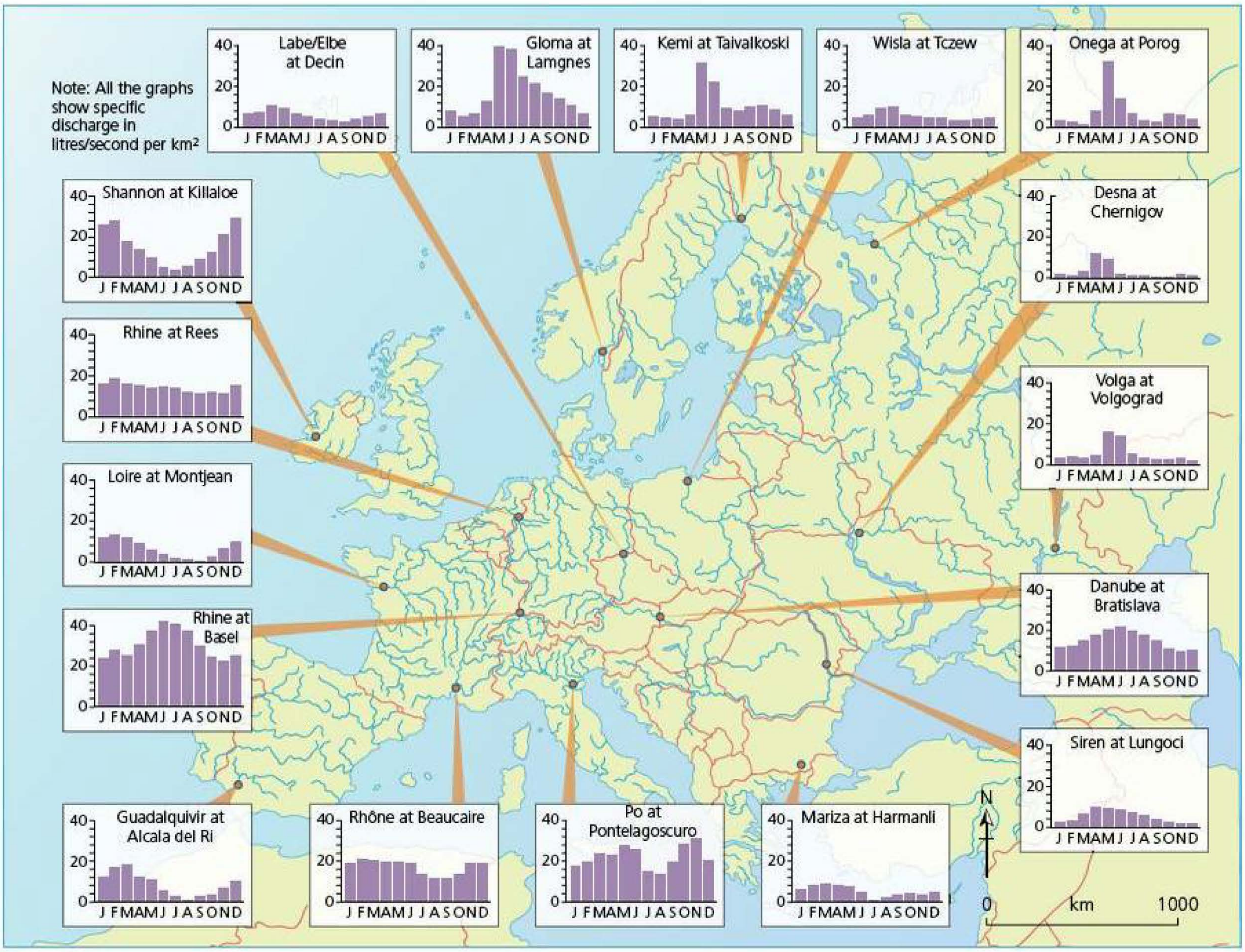
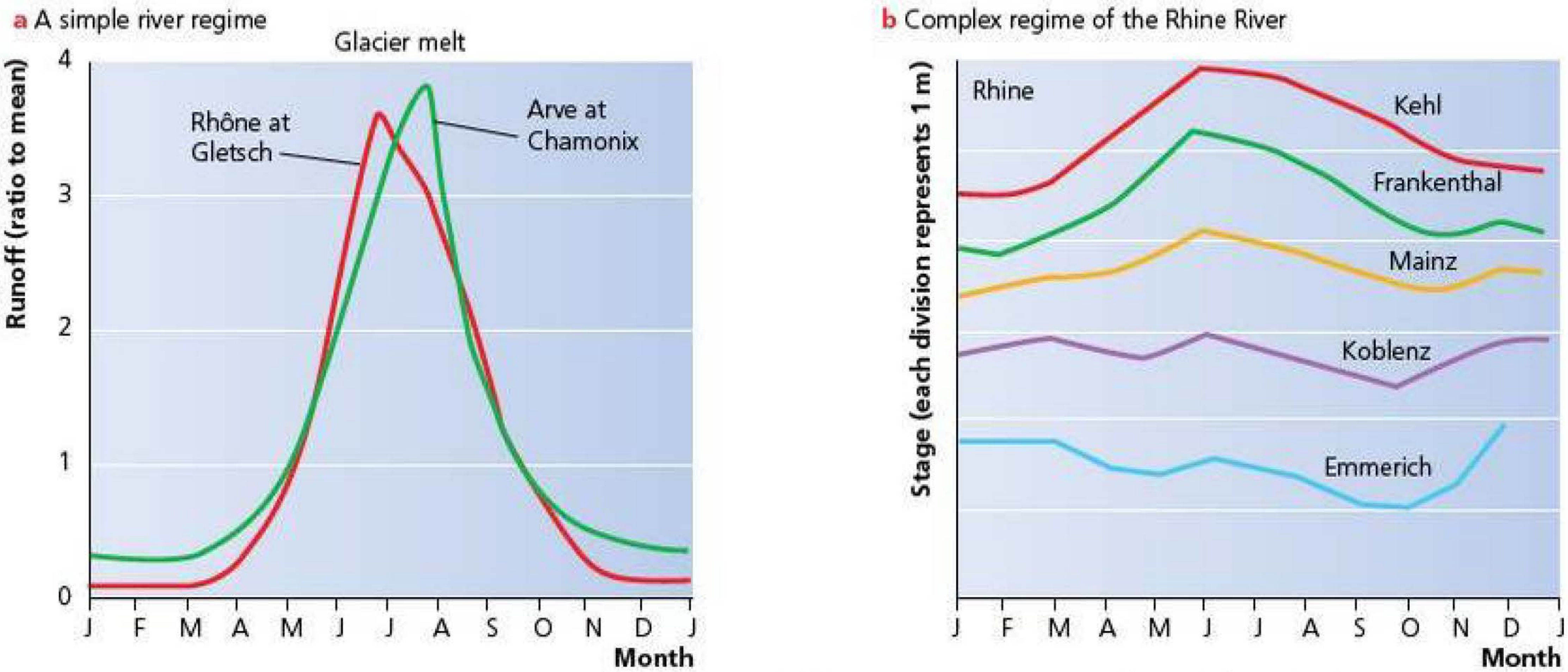


Figure 1.9 River regimes in Europe



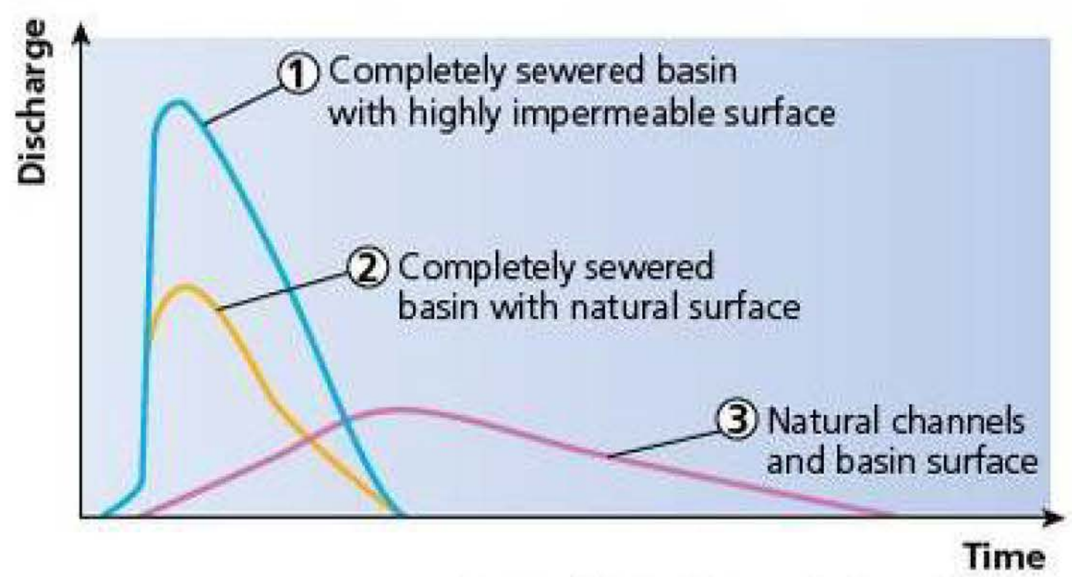
Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.262

Figure 1.10 Simple and complex river regimes

Figure 1.10a shows a simple regime, based upon a single river with one major peak flow. By contrast, Figure 1.10b shows a complex regime for the River Rhine. It has a number of large tributaries that flow in a variety of environments, including alpine, Mediterranean and temperate. By the time the Rhine has travelled downstream, it is influenced by many, at times contrasting, regimes.

Influences on hydrographs

The effect of urban development on hydrographs is to increase peak flow and decrease time lag (Figure 1.11). This is due to an increase in the proportion of impermeable ground in a drainage basin, as well as an increase in the drainage density. Storm hydrographs also vary, with a number of other factors (Table 1.3) such as basin shape, drainage density and gradient.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.255

Figure 1.11 The effects of urban development on storm hydrographs

Table 1.3 Factors affecting storm hydrographs

Factor	Influence on storm hydrograph
Climate	
Precipitation type and intensity	Highly intensive rainfall is likely to produce overland flow, a steep rising limb and high peak flow. Low-intensity rainfall is likely to infiltrate into the soil and percolate slowly into the rock, thereby increasing the time lag and reducing the peak flow. Precipitation that falls as snow sits on the ground until it melts. Sudden, rapid melting can cause flooding and lead to high rates of overland flow, and high peak flows.
Temperature, evaporation, transpiration and evapotranspiration	Not only does temperature affect the type of precipitation, it also affects the evaporation rate (higher temperatures lead to more evaporation and so less water getting into rivers). On the other hand, warm air can hold more water so the potential for high peak flows in hot areas is raised. Increased vegetation cover intercepts more rainfall and may return a proportion of it through transpiration, thereby reducing the amount of water reaching stream channels. The greater the return through evapotranspiration, the less water is able to reach stream channels, and therefore the peak of the hydrograph is reduced.
Antecedent moisture	If it has been raining previously and the ground is saturated or nearly saturated, rainfall will quickly produce overland flow, a high peak flow and short time lag.

⇨

Factor	Influence on storm hydrograph
Drainage basin characteristics	
Drainage basin size and shape	Smaller drainage basins respond more quickly to rainfall conditions. For example, the Boscastle (UK) floods of 2004 drained an area of less than 15 km². This meant that the peak of the flood occurred soon after the peak of the storm. In contrast, the Mississippi River is over 3700 km long – it takes much longer for the lower part of the river to respond to an event that might occur in the upper course of the river. Circular basins respond more quickly than linear basins, where the response is more drawn out.
Drainage density	Basins with a high drainage density, such as urban basins with a network of sewers and drains, respond very quickly. Networks with a low drainage density have a very long time lag.
Porosity and impermeability of rocks and soils	Impermeable surfaces cause more water to flow overland. This causes greater peak flows. Urban areas contain large areas of impermeable surfaces. In contrast, rocks such as chalk and gravel are permeable and allow water to infiltrate and percolate. This reduces the peak flow and increases the time lag. Sandy soils allow water to infiltrate, whereas clay is much more impermeable and causes water to pass overland.
Rock type	Impermeable rocks such as granite and clay produce greater peak flows with a more flashy response. In contrast, more permeable rocks such as chalk and limestone produce storm hydrographs with a much lower peak flow (if at all) and with a much delayed/ less flashy response (greater time lag).
Slopes	Steeper slopes create more overland flow, shorter time lags and higher peak flows.
Vegetation type	Forest vegetation intercepts more rainfall, especially in summer, and so reduces the amount of overland flow and peak flow and increases time lag. In winter, deciduous trees lose their leaves and so intercept less.
Land use	Land uses that create impermeable surfaces, or reduce vegetation cover, reduce interception and increase overland flow. If more drainage channels are built (sewers, ditches, drains), the water is carried to rivers very quickly. This means that peak flows are increased and time lags reduced.

Section 1.2 Activities

1. Compare the river regimes of the Gloma (Norway), Shannon (Ireland) and Rhine (Switzerland). Suggest reasons for their differences.
2. Table 1.4 shows precipitation and runoff data for a storm on the Delaware River, New York. Using this data, plot the storm hydrograph for this storm. Describe the main characteristics of the hydrograph you have drawn.
3. Define the terms *river regime* and *storm hydrograph*.
4. Study Figure 1.11, which shows the impact of urbanisation on storm hydrographs. Describe and explain the differences in the relationship between discharge and time.

Table 1.4 Precipitation and runoff data for a storm on the Delaware River, New York

Date	Time	Duration of rainfall	Total (cm)
29 September	6 a.m.	12 hours	0.1
29 September	6 p.m.	12 hours	0.9
30 September	6 p.m.	24 hours	3.7
30 September	12 p.m.	6 hours	0.1
		Total	**4.8**

Date	Stream runoff (m³/s)
28 September	28.3 (baseflow)
29 September	28.3 (baseflow)
30 September	339.2
1 October	2094.2
2 October	1330.1
3 October	594.3
4 October	367.9
5 October	254.2
6 October	198.1
7 October	176.0
8 October	170.0
9 October	165.2 (baseflow)

1.3 River channel processes and landforms

Erosion

Abrasion (corrasion) is the wearing away of the bed and bank by the load carried by a river. It is the mechanical impact produced by the debris eroding the river's bed and banks. In most rivers it is the principal means of erosion. The effectiveness of abrasion depends on the concentration, hardness and energy of the impacting particles and the resistance of the bedrock. Abrasion increases as velocity increases (kinetic energy is proportional to the square of velocity).

Attrition is the wearing away of the load carried by a river. It creates smaller, rounder particles.

Hydraulic action is the force of air and water on the sides of rivers and in cracks. It includes the direct force of flowing water, and **cavitation** – the force of air exploding. As fluids accelerate, pressure drops and may cause air bubbles to form. Cavitation occurs as bubbles implode and evict tiny jets of water with velocities of up to 130 m/s. These can damage solid rock. Cavitation is an important process in rapids and waterfalls, and is generally accompanied by abrasion.

Corrosion or **solution** is the removal of chemical ions, especially calcium. The key factors controlling the rate of corrosion are bedrock, solute concentration of the stream water, discharge and velocity. Maximum rates of corrosion occur where fast-flowing, undersaturated streams pass over soluble rocks – humid zone streams flowing over mountain limestone.

There are a number of factors affecting rates of erosion. These include:

- load – the heavier and sharper the load the greater the potential for erosion
- velocity – the greater the velocity the greater the potential for erosion (see Figure 1.13)
- gradient – increased gradient increases the rate of erosion
- geology – soft, unconsolidated rocks such as sand and gravel are easily eroded
- pH – rates of solution are increased when the water is more acidic
- human impact – deforestation, dams and bridges interfere with the natural flow of a river and frequently end up increasing the rate of erosion.

Erosion by the river will provide loose material. This eroded material (plus other weathered material that has moved downslope from the upper valley sides) is carried by the river as its load.

Global sediment yield

It is possible to convert a value of mean annual sediment and solute load to an estimate of the rate of land surface lowering by fluvial denudation. This gives a combined sediment and solute load of 250 tonnes/km² per year – that is, an annual rate of lowering of the order of 0.1 mm per year. There is a great deal of variation in sediment yields. These range from 10 tonnes/km² per year in such areas as northern Europe and parts of Australia to in excess of 10 000 tonnes/km² per year in certain areas where conditions are especially conducive to high rates of erosion (Figure 1.12). These include Taiwan, New Zealand's South Island and the Middle Yellow River basin in China.

In the first two cases, steep slopes, high rainfall and tectonic instability are major influences, while in the last case the deep loess deposits and the almost complete lack of natural vegetation cover are important. Rates of land surface lowering vary from less than 0.004 mm per year to over 4 mm per year. The broad pattern of global suspended sediment is shown on the map and it reflects the influence of a wide range of factors, including climate, relief, geology, vegetation cover and land use.

Load transport

Load is transported downstream in a number of ways:

- The smallest particles (silts and clays) are carried in suspension as the suspended load.
- Larger particles (sands, gravels, very small stones) are transported in a series of 'hops' as the saltated load.
- Pebbles are shunted along the bed as the bed or tracted load.
- In areas of calcareous rock, material is carried in solution as the dissolved load.

The load of a river varies with discharge and velocity. The capacity of a stream refers to the largest amount of debris that a stream can carry, while the competence refers to the diameter of the largest particle that can be carried.

Deposition and sedimentation

There are a number of causes of deposition, such as:

- a shallowing of gradient, which decreases velocity and energy
- a decrease in the volume of water in the channel
- an increase in the friction between water and channel.

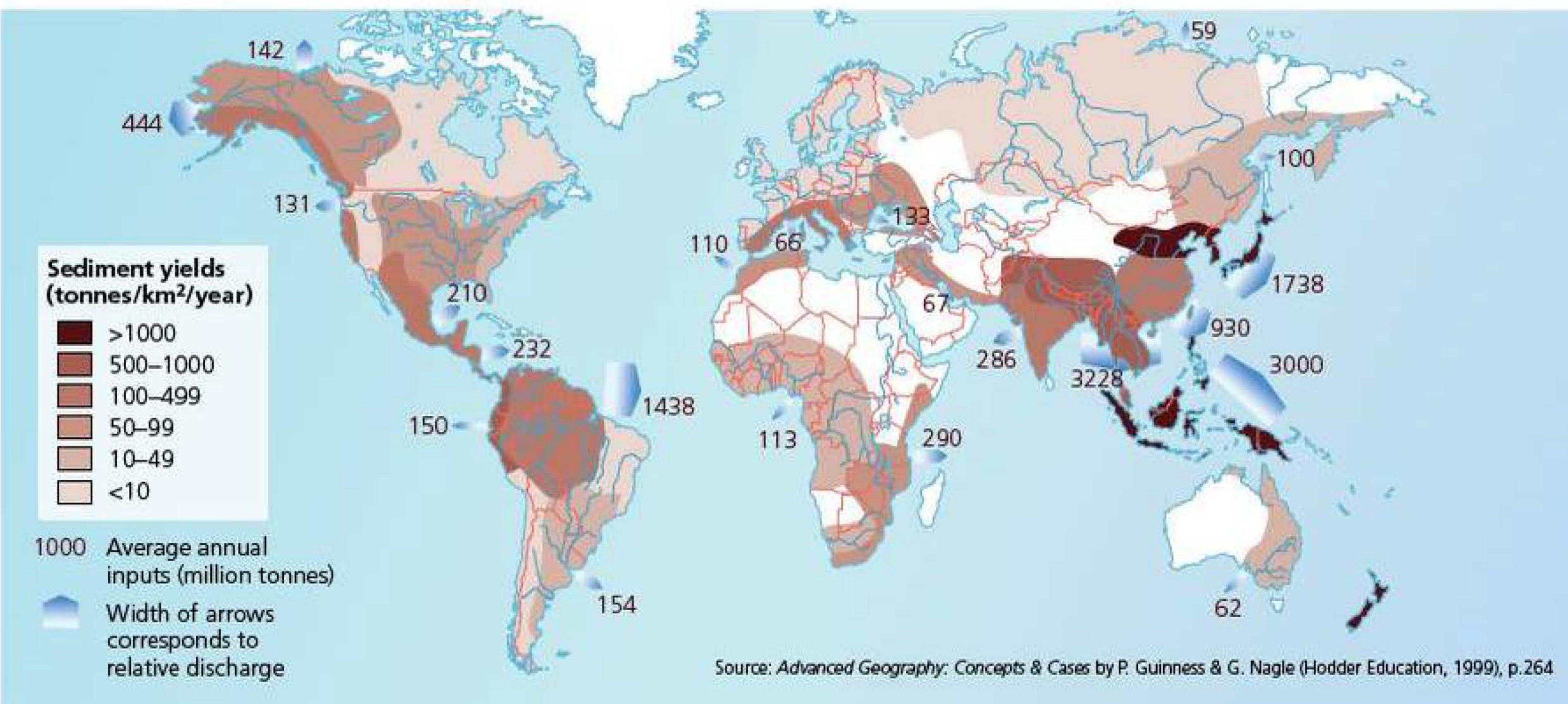
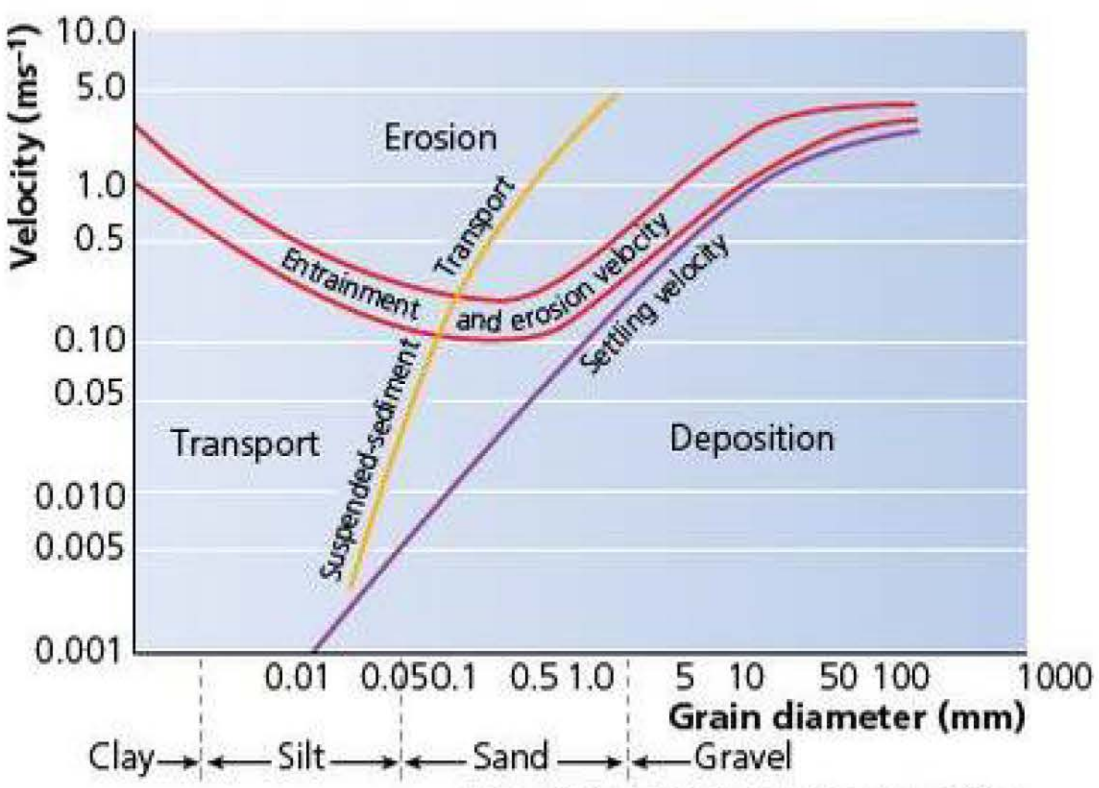


Figure 1.12 Global sediment yield

The Hjülstrom curve

The critical erosion velocity is the lowest velocity at which grains of a given size can be moved. The relationship between these variables is shown by means of a Hjülstrom curve (Figure 1.13). For example, sand can be moved more easily than silt or clay, as fine-grained particles tend to be more cohesive. High velocities are required to move gravel and cobbles because of their large size. The critical velocities tend to be an area rather than a straight line on the graph.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.263

Figure 1.13 Hjülstrom curve

There are three important features on Hjülstrom curves:

- The smallest and largest particles require high velocities to lift them. For example, particles between 0.1 mm and 1 mm require velocities of around 100 mm/s to be entrained, compared with values of over 500 mm/s to lift clay (0.01 mm) and gravel (over 2 mm). Clay resists entrainment due to its cohesion; gravel due to its weight.
- Higher velocities are required for entrainment than for transport.
- When velocity falls below a certain level (settling or fall velocity), those particles are deposited.

Section 1.3 Activities

Study Figure 1.13.

1. Describe the work of the river when sediment size is 1 mm.
2. Comment on the relationship between velocity, sediment size and river process when the river is moving at 0.5 m/s⁻¹.

River flow

Velocity and discharge

River flow and associated features of erosion are complex. The velocity and energy of a stream are controlled by:

- the gradient of the channel bed
- the volume of water within the channel, which is controlled largely by precipitation in the drainage basin (for example bankfull gives rapid flow, whereas low levels give lower flows)
- the shape of the channel
- channel roughness, including friction.

Manning's Equation

$Q = (AR^{2/3} S^{1/2})/n$

where Q = discharge, A = cross-sectional area, R = hydraulic radius, S = channel slope (as a fraction), n = coefficient of bed roughness (the rougher the bed the higher the value).

As water flows over riffles, for example, there are changes in cross-sectional area, slope and hydraulic radius. Slope and velocity increase but depth decreases. Discharge remains the same.

Manning's 'n'

Mountain stream, rocky bed	0.04–0.05
Alluvial channel (large dunes)	0.02–0.035
Alluvial channel (small ripples)	0.014–0.024

Patterns of flow

There are three main types of flow: laminar, turbulent and helicoidal. For laminar flow, a smooth, straight channel with a low velocity is required. This allows water to flow in sheets, or laminae, parallel to the channel bed. It is rare in reality and most commonly occurs in the lower reaches. However, it is more common in groundwater, and in glaciers when one layer of ice moves over another.

Turbulent flow occurs where there are higher velocities and complex channel morphology such as a meandering channel with alternating pools and riffles. Bed roughness also increases turbulence, for example mountain streams with rocky beds create more turbulence than alluvial channels. Turbulence causes marked variations in pressure within the water. As the turbulent water swirls (eddies) against the bed or bank of the river, air is trapped in pores, cracks and crevices and put momentarily under great pressure. As the eddy swirls away, pressure is released; the air expands suddenly, creating a small explosion that weakens the bed or bank material. Thus turbulence is associated with hydraulic action.

Vertical turbulence creates hollows in the channel bed. Hollows may trap pebbles that are then swirled by eddying, grinding at the bed. This is a form of vertical corrasion or abrasion and given time may create potholes (Figure 1.14). Cavitation and vertical abrasion may help to deepen the channel, allowing the river to down-cut its valley. If the down-cutting is dominant over the other forms of erosion (vertical erosion exceeds lateral erosion), then a gulley or gorge will develop.

Figure 1.14 Potholes as seen by the areas occupied by water (dark patches)

Horizontal turbulence often takes the form of helicoidal flow, a 'corkscrewing' motion. This is associated with the presence of alternating pools and riffles in the channel bed, and where the river is carrying large amounts of material. The erosion and deposition by helicoidal flow creates meanders (Figure 1.15). The thalweg is the line of maximum velocity and it travels from outside bank to outside bank of the meanders. The main current strikes the outer bank and creates a return flow to the inner bank, close to the channel bend. The movement transports sediment from the outer bank to the inner bank where it is deposited as a sand bar.

Channel types

Sinuosity is the length of a stream channel expressed as a ratio of the valley length. A low sinuosity has a value of 1.0 (that is, it is straight) whereas a high sinuosity is above 4.4. The main groupings are straight channels (<1.5) and meandering (>1.5). Straight channels are rare. Even when they do occur the thalweg (line of maximum velocity) moves from side to side. These channels generally have a central ridge of deposited material, due to the water flow pattern.

Braiding occurs when the channel is divided by islands or bars (Figure 1.16). Islands are vegetated and long-lived, whereas bars are unvegetated, less stable and often short-term features. Braided channels are formed by various factors, for example:

- a steep channel gradient
- a large proportion of coarse material
- easily erodable bank material
- highly variable discharge.

Braiding tends to occur when a stream does not have the capacity to transport its load in a single channel, whether it is straight or meandering. It occurs when river discharge is very variable and banks are easily erodable. This gives abundant sediment. It is especially common in periglacial and semi-arid areas.

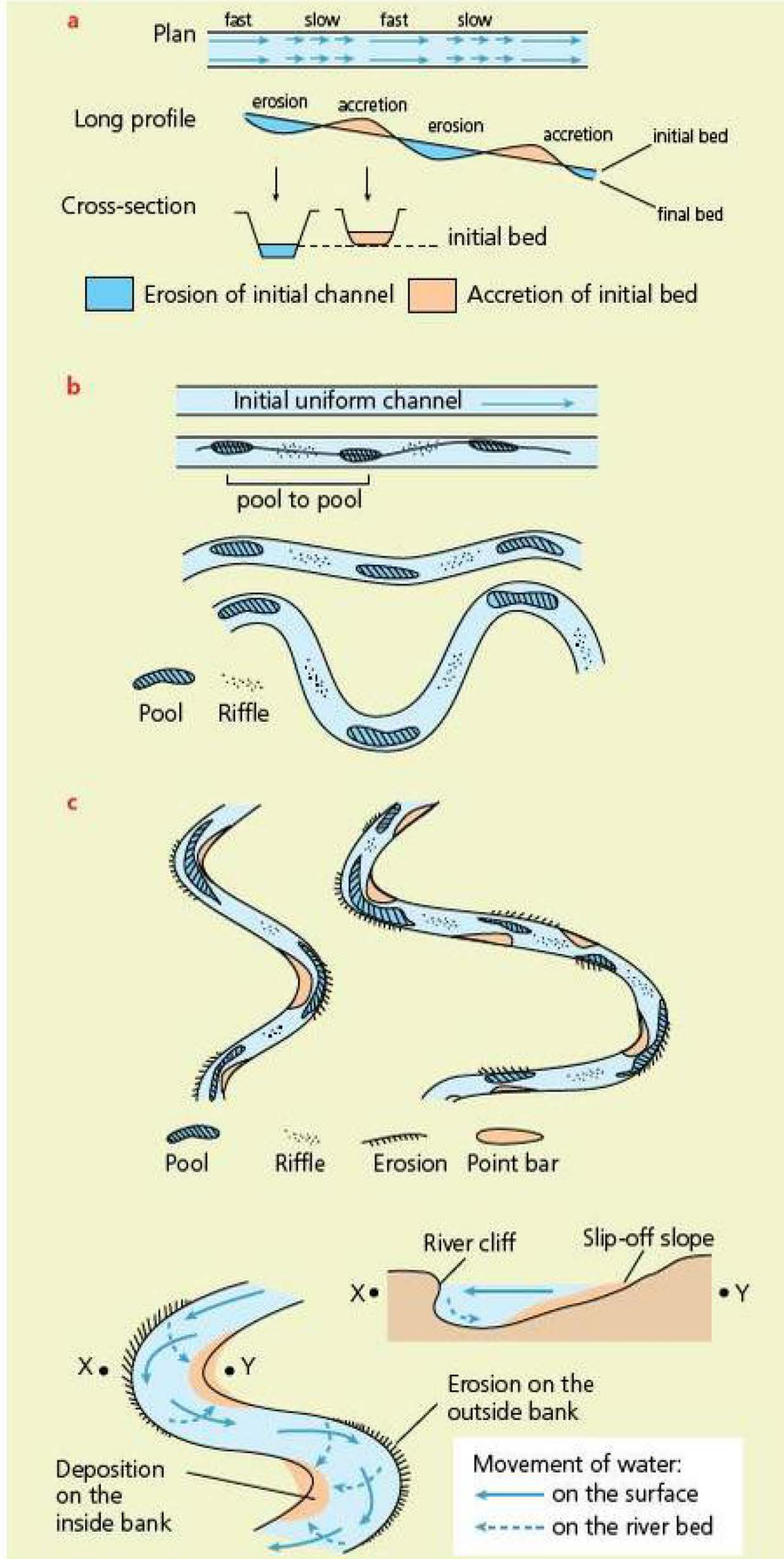


Figure 1.15 Meander formation

Braiding begins with a mid-channel bar that grows downstream. As the discharge decreases following a flood, the coarse bed load is first to be deposited. This forms the basis of bars that grow downstream and, as the flood is reduced, finer sediment is deposited. The upstream end becomes stabilised with vegetation. This island localises and narrows the channel in an attempt to increase the velocity to a point where it can transport its load. Frequently, subdivision sets in.

Figure 1.16 A braided river, Mýrdalsjökull, Iceland

Meanders

Meanders are complex (Figure 1.15). There are a number of relationships, although the reasons are not always very clear. However, they are *not* the result of obstructions in the floodplain. Meandering is the normal behaviour of fluids and gases in motion. Meanders can occur on a variety of materials, from ice to solid rock. Meander development occurs in conditions where channel slope, discharge and load combine to create a situation where meandering is the only way that the stream can use up the energy it possesses equally throughout the channel reach. The wavelength of the meander is dependent upon three main factors: channel width, discharge and the nature of the bed and banks.

Meanders and channel characteristics

- Meander wavelengths are generally 6–10 times channel width and discharge.
- Meander wavelengths are generally 5 times the radius of curvature.
- The meander belt (peak-to-peak amplitude) is generally 14–20 times the channel width.
- Riffles occur at about 6 times the channel width.
- Sinuosity increases as depth of channel increases in relation to width.
- Meandering is more pronounced when the bed load is varied.
- Meander wavelength increases in streams that carry coarse debris.
- Meandering is more likely on shallow slopes.
- Meandering best develops at or near bankfull state.

Natural meanders are rarely 'standard'. This is due, in part, to variations in bed load; where the bed load is coarse, meanders are often very irregular.

Causes of meanders

There is no simple explanation for the creation of meanders, and a number of factors are likely to be important.

- **Friction** with the channel bed and bank causes turbulence, which makes stream flow unstable. This produces bars along the channel, and a helicoidal flow (corkscrew motion), with water being raised on the outer surfaces of pools, and the return flow occurring at depth.
- **Sand bars** in the channel may cause meandering.
- **Sinuosity** is best developed on moderate angles. There is a critical minimum gradient below which straight channels occur. At very low energy (low gradient), helicoidal flow is insufficient to produce alternating pools and riffles. In addition, high-velocity flows in steep gradient channels are too strong to allow cross-channel meandering and the development of alternating pools and riffles. In such circumstances, braided channels are formed.
- **Helicoidal flow** (corkscrewing) causes the line of fastest flow to move from side to side within the channel. This increases the amplitude of the meander.

Change over time

There are a number of possibilities:

- Meanders may migrate downstream and erode river cliffs.
- They may migrate laterally (sideways) and erode the floodplain.
- They may become exaggerated and become cut-offs (ox-bow lakes).
- Under special conditions, they may become intrenched or ingrown.

Intrenched and ingrown meanders

The term incised meanders describes meanders that are especially well developed on horizontally bedded rocks, and form when a river cuts through alluvium and into underlying bedrock. Two main types occur – intrenched and ingrown meanders. Intrenched meanders are symmetrical, and occur when down-cutting is fast enough to offset the lateral migration of meanders. This frequently occurs when there is a significant fall in base level (generally sea level). The Goosenecks of the San Juan in the USA are classic examples of intrenched meanders. Ingrown meanders are the result of lateral meander migration. They are asymmetric in cross-section – examples can be seen in the lower Seine in France.

Landforms

Meanders

Meanders have an asymmetric cross-section (Figure 1.15b). They are deeper on the outside bank and shallower on the inside bank. In between meanders they are more symmetrical. They begin with the development of pools and riffles in a straight channel and the thalweg begins to flow from side to side. Helicoidal flow occurs, whereby surface water flows towards the outer banks, while the bottom flow is towards the inner bank. This causes the variations in the cross-section and variations in erosion and deposition. These variations give rise to river cliffs on the outer bank and point bars on the inner bank.

Pools and riffles

Pools and riffles are formed by turbulence. Eddies cause the deposition of coarse sediment (riffles) at high velocity points and fine sediment (pools) at low velocity. Riffles have a steeper gradient than pools, which leads to variations in subcritical and supercritical flow, and therefore erosion and deposition.

Riffles are small ridges of material deposited where the river velocity is reduced midstream, in between pools (the deep parts of a meander).

Braided rivers

A braided river channel consists of a number of interconnected shallow channels separated by alluvial and shingle bars (islands). These may be exposed during low flow conditions. They are formed in rivers that are heavily laden with sediment and have a pronounced seasonal flow. There are excellent examples on the Eyjafjörður in northern Iceland.

Section 1.3 Activities

Study Figure 1.15.

1 Compare the main characteristics of river cliffs with those of point bars.
2 Briefly explain the meaning of the term *helicoidal flow*.
3 Describe and explain the role of pools and riffles in the development of meanders in a river channel.

Waterfalls and gorges

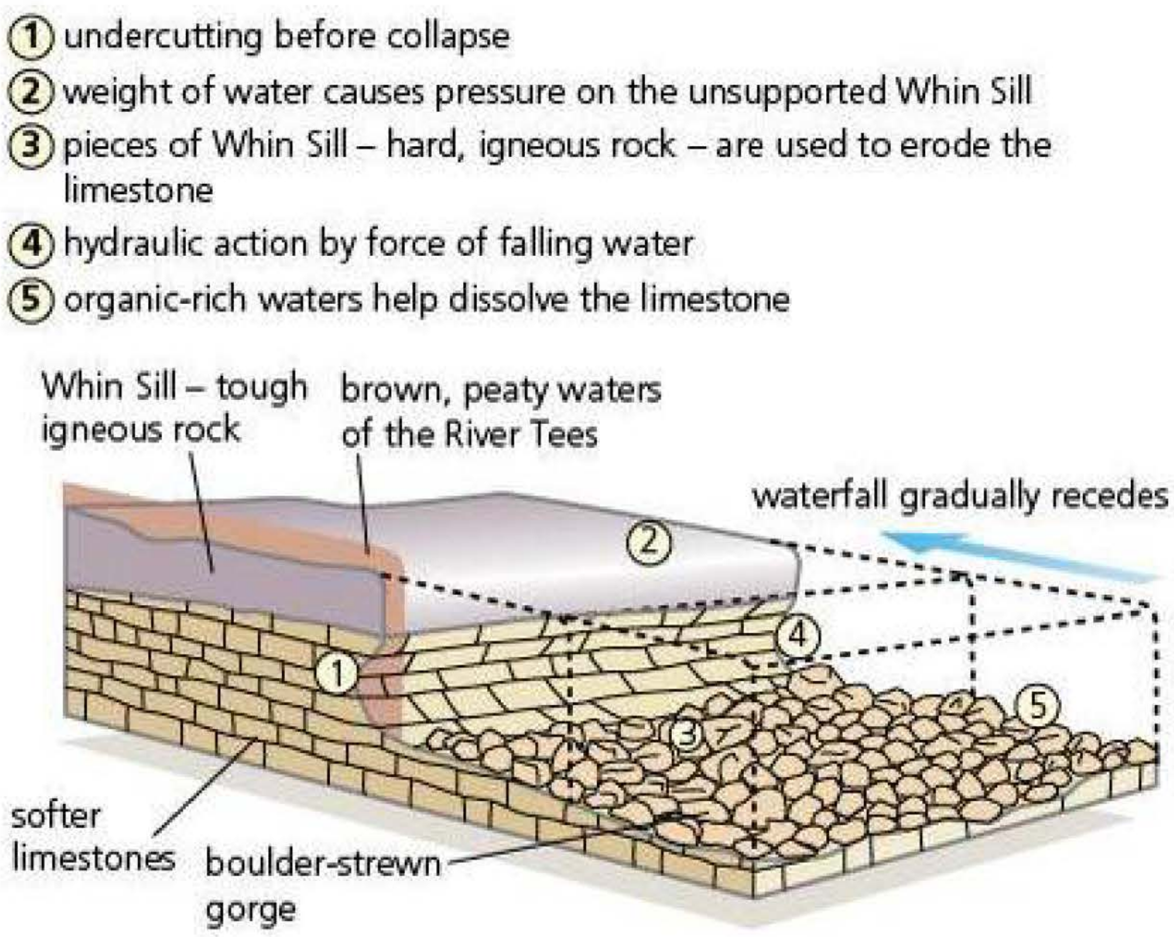
Waterfalls occur where the river spills over a sudden change in gradient, undercutting rocks by hydraulic impact and abrasion, thereby creating a waterfall (Figures 1.17 and 1.18). There are many reasons for this sudden change in gradient along the river:

- a band of resistant strata such as the resistant limestones at Niagara Falls
- a plateau edge such as Victoria Falls on the Zimbabwe–Zambia border
- a fault scarp such as at Gordale, Yorkshire (UK)
- a hanging valley such as at Glencoyne, Cumbria in the UK
- coastal cliffs.

The undercutting at the base of a waterfall creates a precarious overhang, which will ultimately collapse. Thus a waterfall may appear to migrate upstream, leaving a gorge of recession downstream. The Niagara Gorge is 11 kilometres long due to the retreat of Niagara Falls.

Gorge development is common, for example where the local rocks are very resistant to weathering but susceptible to the more powerful river erosion. Similarly, in arid areas where the water necessary for weathering is scarce, gorges are formed by periods of river erosion. A rapid acceleration in down-cutting is also associated when a river is rejuvenated, again creating a gorge-like landscape. Gorges may also be formed as a result of:

- antecedent drainage (Rhine Gorge)
- glacial overflow channelling (Newtondale, UK)
- the collapse of underground caverns in Carboniferous limestone areas
- surface runoff over limestone during a periglacial period
- the retreat of waterfalls (Niagara Falls)
- superimposed drainage (Avon Gorge, UK).



Source: Goudie, A. and Gardner, R., *Discovering Landscapes in England and Wales*, Unwin 1985

Figure 1.17 Waterfall formation

Figure 1.18 Axara waterfall, Iceland

Case Study: Niagara Falls

Most of the world's great waterfalls are the result of the undercutting of resistant cap rocks, and the retreat or recession that follows. The Niagara River flows for about 50 kilometres between Lake Erie and Lake Ontario. In that distance it falls just 108 metres, giving an average gradient of 1:500. However, most of the descent occurs in the 1.5 kilometres above the Niagara Falls (13 metres) and at the Falls themselves (55 metres). The Niagara River flows in a 2 kilometre-wide channel just 1 kilometre above the Falls, and then into a narrow 400 metre-wide gorge, 75 metres deep and 11 kilometres long. Within the gorge the river falls a further 30 metres.

The course of the Niagara River was established about 12 000 years ago when water from Lake Erie began to spill northwards into Lake Ontario. In doing so, it passed over the highly resistant dolomitic (limestone) escarpment. Over the last 12 000 years the Falls have retreated 11 kilometres, giving an average rate of retreat of about 1 metre per year. Water velocity accelerates over the Falls, and decreases at the base of the Falls. Hydraulic action and abrasion have caused the development of a large plunge pool at the base, while the fine spray and eddies in the river help to remove some of the softer rock underneath the resistant dolomite. As the softer rocks are removed, the dolomite is left unsupported and the weight of the water causes the dolomite to collapse. Hence the waterfall retreats, forming a gorge of recession.

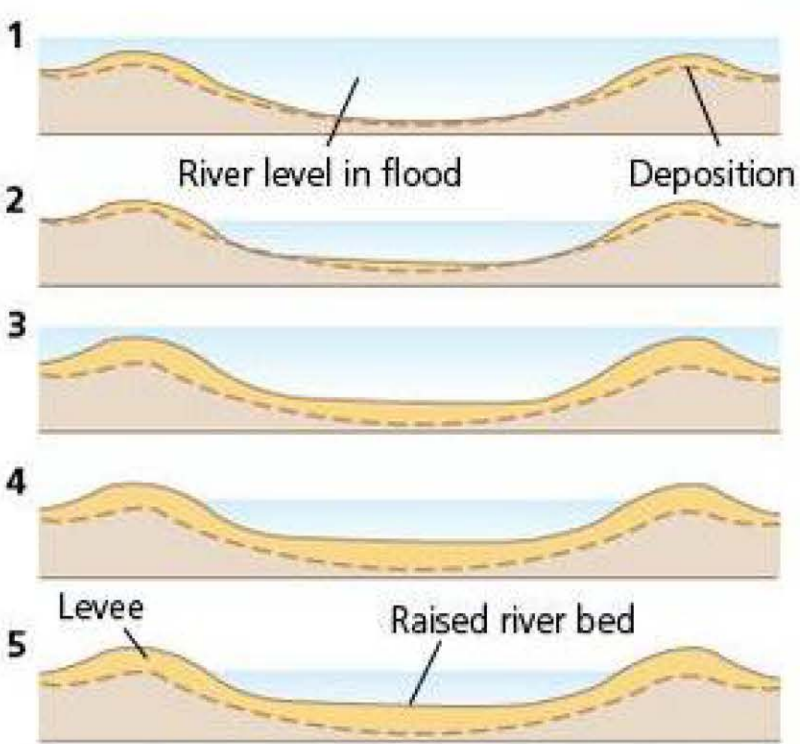
In the nineteenth century, rates of recession were recorded at 1.2 metres per year. However, now that the amount of water flowing over the Falls is controlled (due to the construction of hydro-electric power stations), rates of recession have been reduced. In addition, engineering works in the 1960s reinforced parts of the dolomite that were believed to be at risk of collapse. The Falls remains an important tourist attraction and local residents and business personnel did not want to lose their prized asset!

Section 1.3 Activities

Draw a labelled diagram to show the formation of a waterfall.

Levees, floodplains and bluffs

Levees and floodplain deposits are formed when a river bursts its banks over a long period of time. Water quickly loses velocity, leading to the rapid deposition of coarse material (heavy and difficult to move a great distance) near the channel edge. These coarse deposits build up to form embankments called levees (Figure 1.19). The finer material is carried further away to be dropped on the floodplain (Figure 1.20), sometimes creating backswamps. Repeated annual flooding slowly builds up the floodplain. Old floodplains may be eroded – the remnants are known as terraces. At the edge of the terrace is a line of relatively steep slopes known as river bluffs.



1 When the river floods, it bursts its banks. It deposits its coarsest load (gravel and sand) closest to the bank and the finer load (silt and clay) further away.
2, 3, 4 This continues over a long time, for centuries.
5 The river has built up raised banks, called levees, consisting of coarse material, and a floodplain of fine material.

Figure 1.19 The formation of levees

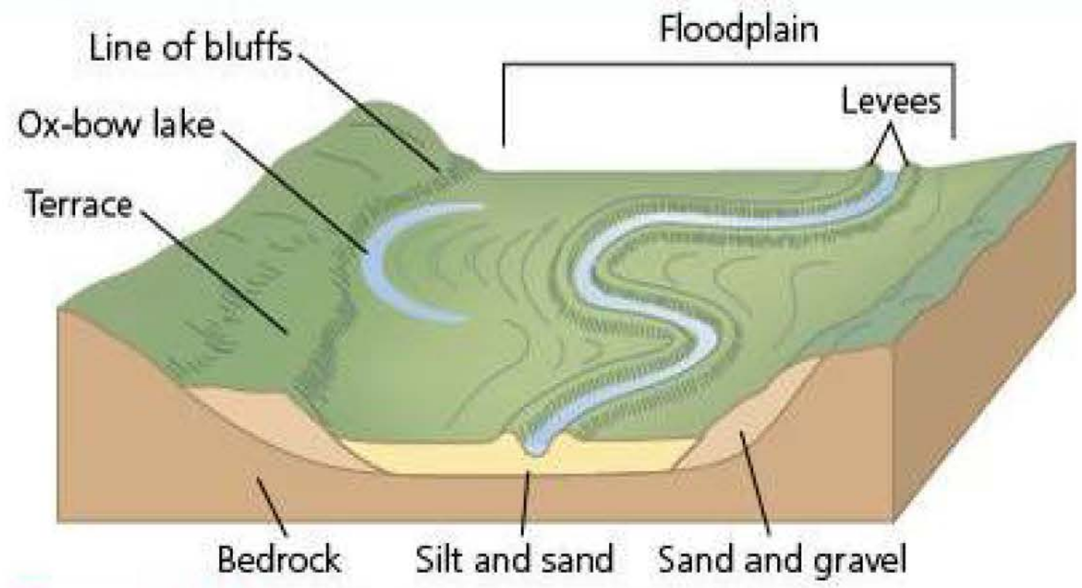
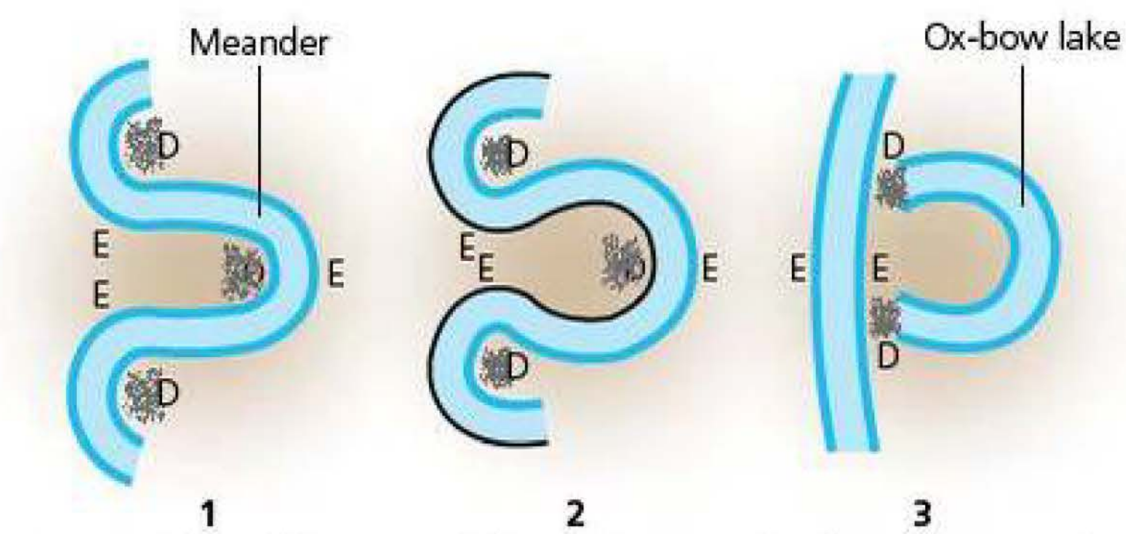


Figure 1.20 Floodplains, levees and bluffs

Ox-bow lakes

Ox-bow lakes are the result of both erosion and deposition. Lateral erosion, caused by helicoidal flow, is concentrated on the outer, deeper bank of a meander. During times of flooding, erosion increases. The river breaks through and creates a new steeper channel. In time, the old meander is closed off by deposition to form an ox-bow lake.

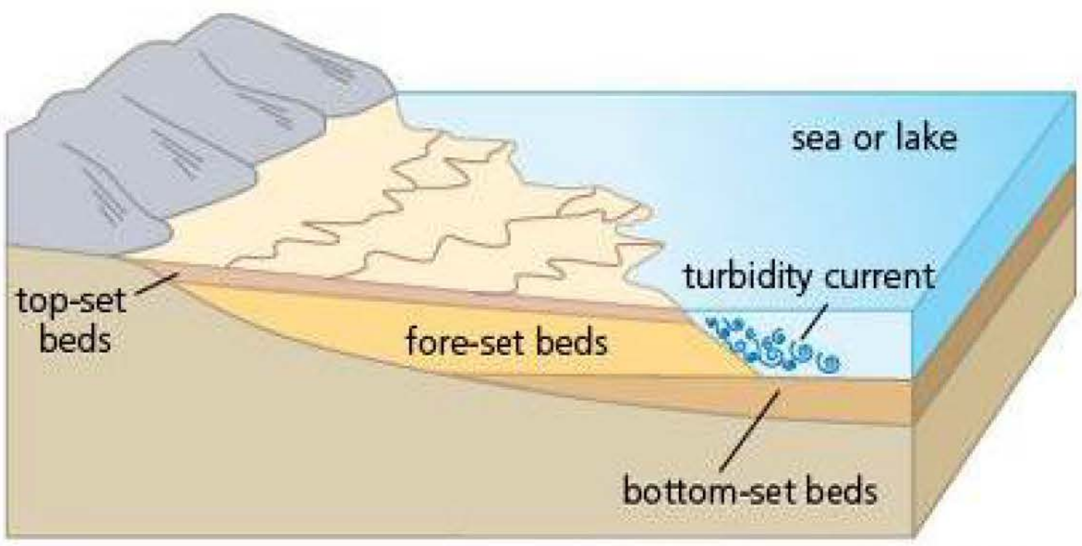


1 Erosion (E) and deposition (D) around a meander (a bend in a river).
2 Increased erosion during flood conditions. The meander becomes exaggerated.
3 The river breaks through during a flood. Further deposition causes the old meander to become an ox-bow lake.

Figure 1.21 Formation of an ox-bow lake

Deltas

Deltas are river sediments deposited when a river enters a standing body of water such as a lake, a lagoon, a sea or an ocean (Figure 1.22). They are the result of the interaction of fluvial and marine processes. For a delta to form there must be a heavily laden river, such as the Nile or the Mississippi, and a standing body of water with negligible currents, such as the Mediterranean or the Gulf of Mexico. Deposition is enhanced if the water is saline, because salty water causes small clay particles to flocculate or adhere together. Other factors include the type of sediment, local geology, sea-level changes, plant growth and human impact.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.268

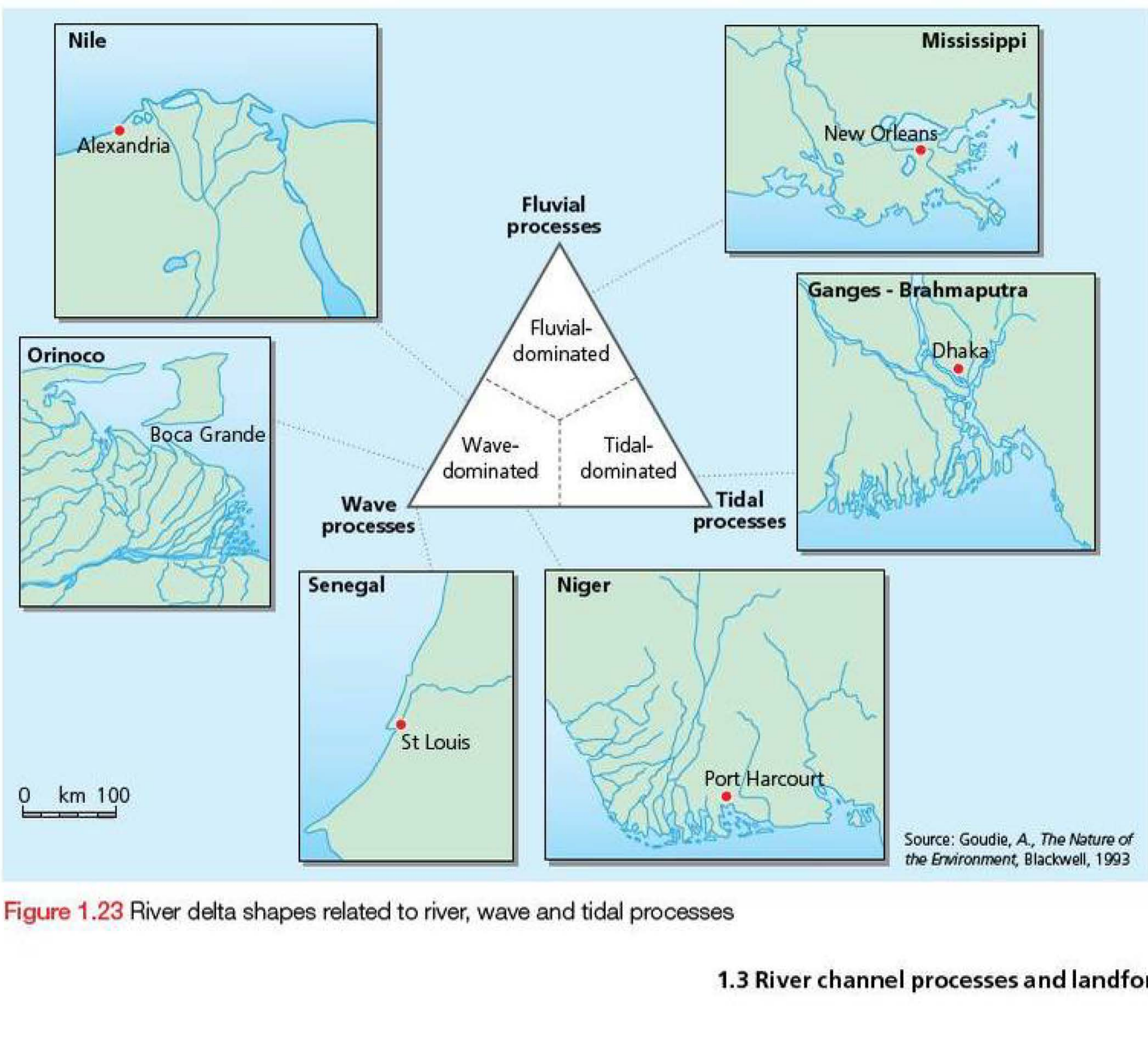
Figure 1.22 Model of a simple delta

The material deposited as a delta can be divided into three types:

- **Bottomset beds** – the lower parts of the delta are built outwards along the sea floor by turbidity currents (currents of water loaded with material). These beds are composed of very fine material.
- **Foreset beds** – over the bottomset beds, inclined/sloping layers of coarse material are deposited. Each bed is deposited above and in front of the previous one, the material moving by rolling and saltation. Thus the delta is built seaward.
- **Topset beds** – composed of fine material, they are really part of the continuation of the river's floodplain. These topset beds are extended and built up by the work of numerous distributaries (where the main river has split into several smaller channels).

The character of any delta is influenced by the complex interaction of several variables (Figure 1.23):

- the rate of river deposition
- the rate of stabilisation by vegetation growth
- tidal currents
- the presence (or absence) of longshore drift
- human activity (deltas often form prime farmland when drained).



Source: Goudie, A., *The Nature of the Environment*, Blackwell, 1993

Figure 1.23 River delta shapes related to river, wave and tidal processes

There are many types of delta, but the three 'classic' ones are:

- **Arcuate delta**, or fan-shaped – these are found in areas where regular longshore drift or other currents keep the seaward edge of the delta trimmed and relatively smooth in shape, such as the Nile and Rhône deltas.
- **Cuspate delta** – pointed like a tooth or cusp, for example the Ebro and Tiber deltas, shaped by regular but opposing gentle water movement.
- **Bird's-foot delta** – where the river brings down enormous amounts of fine silt, deposition can occur in a still sea area, along the edges of the distributaries for a very long distance offshore, such as the Mississippi delta.

Deltas can also be formed inland. When a river enters a lake it will deposit some or all of its load, so forming a **lacustrine delta**. As the delta builds up and out, it may ultimately fill the lake basin. The largest lacustrine deltas are those that are being built out into the Caspian Sea by the Volga, Ural, Kura and other rivers.

Case Study: The future of the Nile delta

The Nile delta is under threat from rising sea levels. Without the food it produces, Egypt faces much hardship. The delta is one of the most fertile tracts of land in the world. However, coastal erosion is steadily eroding it in some places at a rate of almost 100 metres a year. This is partly because the annual deposits from the Nile floods – which balanced coastal erosion – no longer reach the delta, instead being trapped behind the Aswan High Dam. However, erosion of the delta continues, and may be increasing, partly as a result of **global warming** and rising sea levels. The delta is home to about 50 million people, living at densities of up to 4000 people per km^2.

The Intergovernmental Panel on Climate Change has declared Egypt's Nile delta to be among the top three areas most vulnerable to a rise in sea level. Even a small temperature increase will displace millions of Egyptians from one of the most densely populated regions on Earth.

The delta stretches out from the northern reaches of Cairo into 25 000 km^2 of farmland fed by the Nile's branches. It is home to two-thirds of the country's rapidly growing population, and responsible for more than 60 per cent of its food supply. About 270 kilometres of the delta's coastline is at a dangerously low level and a 1 metre rise in the sea level would drown 20 per cent of the delta.

The delta is also suffering from a number of environmental crises, including flooding, coastal erosion, salinisation, industrial/agricultural **pollution** and urban encroachment. Egypt's population of 83 million is set to increase to more than 110 million in the next two decades. More people in the delta means more cars, more pollution and less land to feed them all on, just at a time when increased crop production is needed most.

Saltwater intrusion is destroying crops. Coastal farmland has always been threatened by salt water, but salinity has traditionally been kept at bay by plentiful supplies of fresh water flushing out the salt. It used to happen naturally with the Nile's seasonal floods; after the construction of Egypt's High Dam, these seasonal floods came to an end, but a vast network of irrigation canals continued to bring enough fresh water to ensure salinity levels remained low.

Today, however, Nile water barely reaches the end of the delta. A growing population has extracted water supplies upstream, and what water does make it downriver is increasingly polluted with toxins and other impurities.

The impact of **climate change** is likely to be a 70 per cent drop in the amount of Nile water reaching the delta over the next 50 years, due to increased evaporation and heavier demands on water use upstream. The consequences for food production are ominous: wheat and maize yields could be down 40 per cent and 50 per cent respectively, and farmers could lose around $1000 per hectare for each degree rise in the average temperature.

While politicians, scientists and community workers are trying to educate Egyptians about the dangers of climate change, there is confusion over whether the focus should be on promoting ways to combat climate change, or on accepting climate change as inevitable and instead encouraging new forms of adaptation to the nation's uncertain future.

Egypt's contribution to global carbon emissions is just 0.5 per cent – nine times less per person than for the USA. However, the consequences of climate change are disproportionate and potentially disastrous.

The scale of the crisis – more people, less land, less water, less food – is overwhelming. As a result, many now believe that Egypt's future lies far away from the delta, in land newly reclaimed from the desert. Since the time of the pharaohs, when the delta was first farmed, Egypt's political leaders have tried to harness the Nile. The Egyptian government is creating an array of canals and pumping stations that draw water from the Nile into sandy valleys to the east and west, where the desert is slowly being turned green. The Nile delta may well become history – as a landform and for the people who live and work there.

Section 1.3 Activities

1 Outline the main conditions needed for delta formation.
2 Suggest reasons for the variety of deltas, as shown in Figure 1.23.
3 a Outline the natural and human processes that are operating on the Nile delta.
  b Comment on the advantages and disadvantages for people living in the delta.

1.4 The human impact

☐ Modifications to catchment stores and flows, and to channel flows

Evaporation and evapotranspiration

The human impact on evaporation and evapotranspiration is relatively small in relation to the rest of the hydrological cycle but is nevertheless important. There are a number of impacts:

- Dams – there has been an increase in evaporation due to the construction of large dams. For example, Lake Nasser behind the Aswan Dam loses up to a third of its water due to evaporation. Water loss can be reduced by using chemical sprays on the water, by building sand-fill dams and by covering the dams with some form of plastic.
- Urbanisation leads to a huge reduction in evapotranspiration due to the lack of vegetation. There may also be a slight increase in evaporation because of higher temperatures and increased surface storage (see Figure 1.24).

Urbanising influence	Potential hydrological response
Removal of trees and vegetation	Decreased evapotranspiration and interception; increased stream sedimentation
Initial construction of houses, streets and culverts	Decreased infiltration and lowered groundwater table; increased storm flows and decreased base flows during dry periods
Complete development of residential, commercial and industrial areas	Decreased porosity, reducing time of runoff concentration, thereby increasing peak discharges and compressing the time distribution of the flow; greatly increased volume of runoff and flood damage potential
Construction of storm drains and channel improvements	Local relief from flooding; concentration of floodwaters may aggravate flood problems downstream

Figure 1.24 Potential hydrological effects of urbanisation

Interception

Interception is determined by vegetation, density and type. Most vegetation is not natural but represents some disturbance by human activity. In farmland areas, for example, cereals intercept less than broad leaves. Row crops, such as wheat or corn, leave a lot of soil bare. For example, in the Mississippi basin, while sediment yields in woodland areas are just 1 unit, sediment from soil covered by pasture produces 30 units and areas under corn produce 350 units of sediment. Deforestation leads to:

- a reduction in evapotranspiration
- an increase in surface runoff
- a decline of surface storage
- a decline in time lag.

Afforestation is believed to have the opposite effect, although the evidence does not necessarily support it. For example, in parts of the Severn catchment, sediment loads increased four times after afforestation. Why was this? The result is explained by a combination of an increase in overland runoff, little ground vegetation, young trees, access routes for tractors, and fire- and wind-breaks. All of these allowed a lot of bare ground. However, after only five years the amount of erosion declined.

Infiltration and soil water

Human activity has a great impact on infiltration and soil water. Land-use changes are important. Urbanisation creates an impermeable surface with compacted soil. This reduces infiltration and increases overland runoff and flood peaks (Figure 1.25).

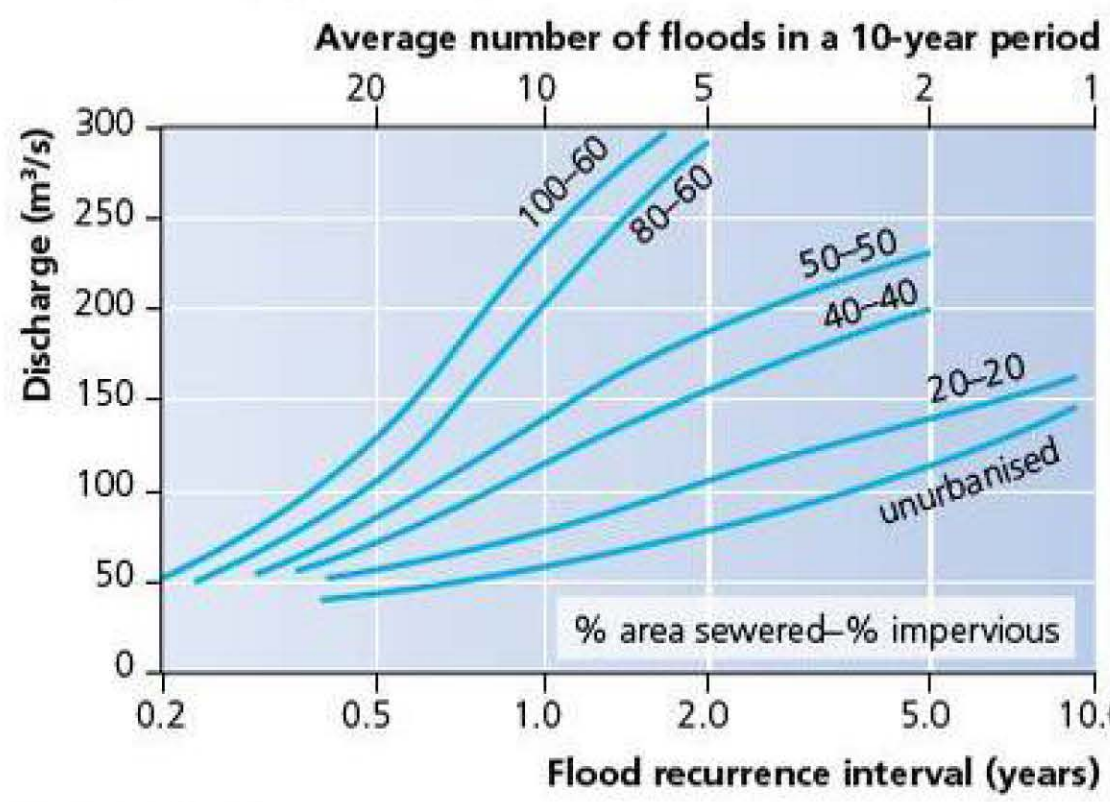


Figure 1.25 Flood frequency and urbanisation

Infiltration is up to five times greater under forest compared with grassland. This is because the forest trees channel water down their roots and stems. With deforestation there is reduced interception, increased soil compaction and more overland flow. Land-use practices are also important. Grazing leads to a decline in infiltration due to compaction and ponding of the soil. By contrast, ploughing increases infiltration because it loosens soils.

Waterlogging and salinisation are common if there is poor drainage. When the water table is close to the surface, evaporation of water leaves salts behind and may form an impermeable crust. Human activity also has an increasing impact on surface storage. There is increased surface storage due to the building of large-scale dams. These dams are being built in increasing numbers, and they are also larger in terms of general size and volume. This leads to:

- increased storage of water
- decreased flood peaks
- low flows in rivers
- decreased sediment yields (clear-water erosion)
- increased losses due to evaporation and seepage, leading to changes in temperature and salinity of the water
- decreased flooding of the land
- triggering of earthquakes
- salinisation, for example in the Indus Valley in Pakistan, 1.9 million hectares are severely saline and up to 0.4 million hectares are lost per annum to salinity
- large dams can cause local changes in climate.

In other areas there is a decline in the surface storage, for example in urban areas water is channelled away very rapidly over impermeable surfaces into drains and gutters.

Section 1.4 Activities

Study Figure 1.25. Describe and explain the changes in flood frequency and flood magnitude that occur as urbanisation increases.

Abstraction

Water availability problems occur when the demand for water exceeds the amount available during a certain period. This happens in areas with low rainfall and high population density, and in areas where there is intensive agricultural or industrial activity. Over-abstraction may lead to the drying up of rivers, falling water tables and saltwater intrusion in coastal areas.

In many parts of Europe, groundwater is the main source of fresh water. However, in many places water is being taken from the ground faster than it is being replenished.

Saline intrusion is widespread along the Mediterranean coastlines of Italy, Spain and Turkey (Figure 1.26), where the demands of tourist resorts are the major cause of over-abstraction. In Malta, most groundwater can no longer be used for domestic consumption or irrigation because it has been contaminated by saline intrusion. Consequently, Malta now has to use desalinated water. Intrusion of saline water due to excessive extraction of water is also a problem in northern countries, notably Denmark.

Irrigation is the main cause of groundwater overexploitation in agricultural areas. In Italy, overexploitation of the Po River in the region of the Milan aquifer has led to a 25 metre decrease in groundwater levels over the last 80 years.

Changing groundwater

Human activity has seriously reduced the long-term viability of irrigated agriculture in the High Plains of Texas. Before irrigation development started in the 1930s, the High Plains groundwater system was stable, in a state of dynamic equilibrium with long-term recharge equal to long-term discharge. However, groundwater is now being used at a rapid rate to supply centre-pivot irrigation schemes. In under 50 years, the water level has declined by 30–50 metres in a large area to the north of Lubbock, Texas. The aquifer has narrowed by more than 50 per cent

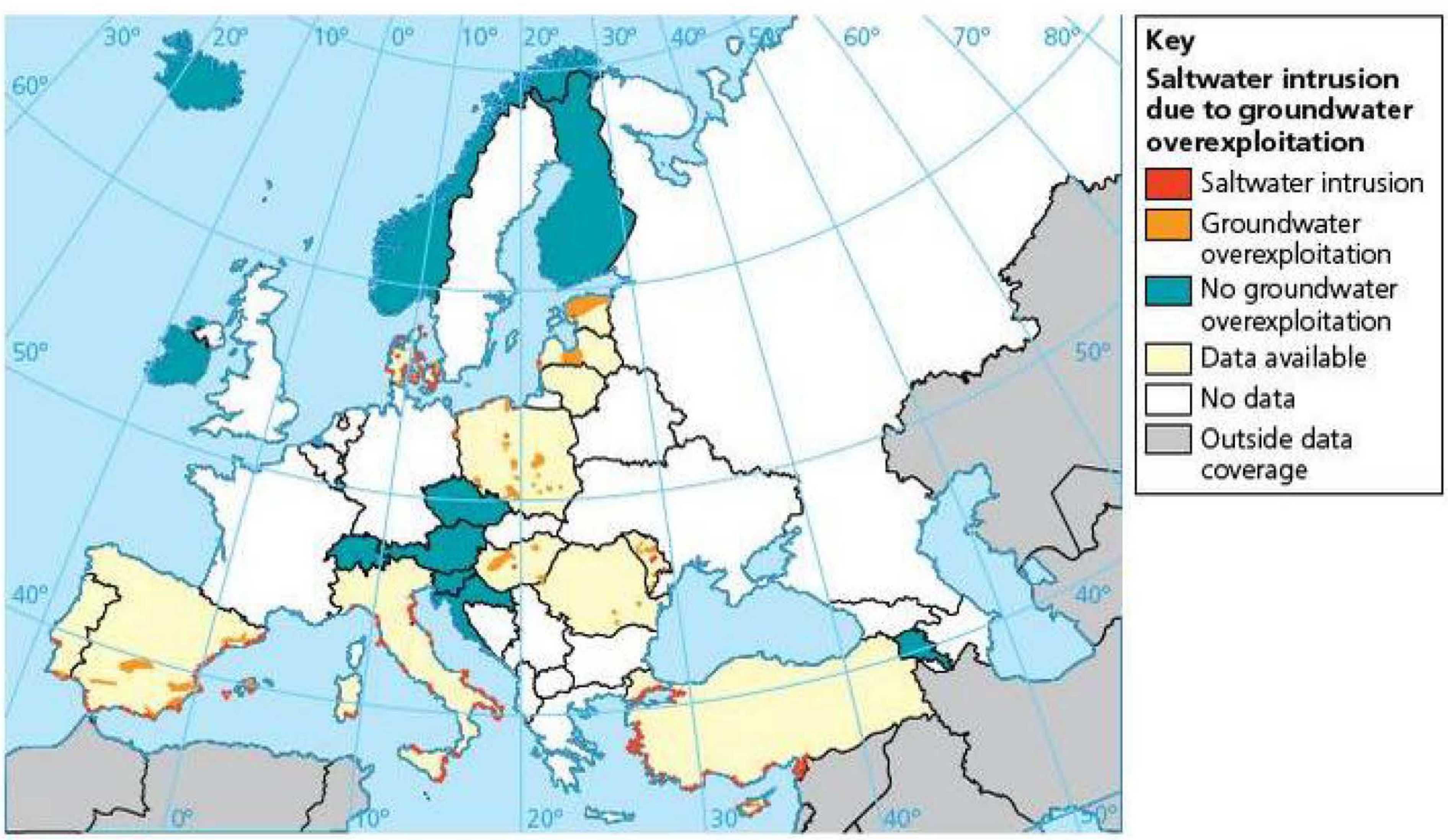


Figure 1.26 Groundwater abstraction and saline intrusion in Western Europe

in large parts of certain counties, and the area irrigated by each well is contracting as well as yields falling.

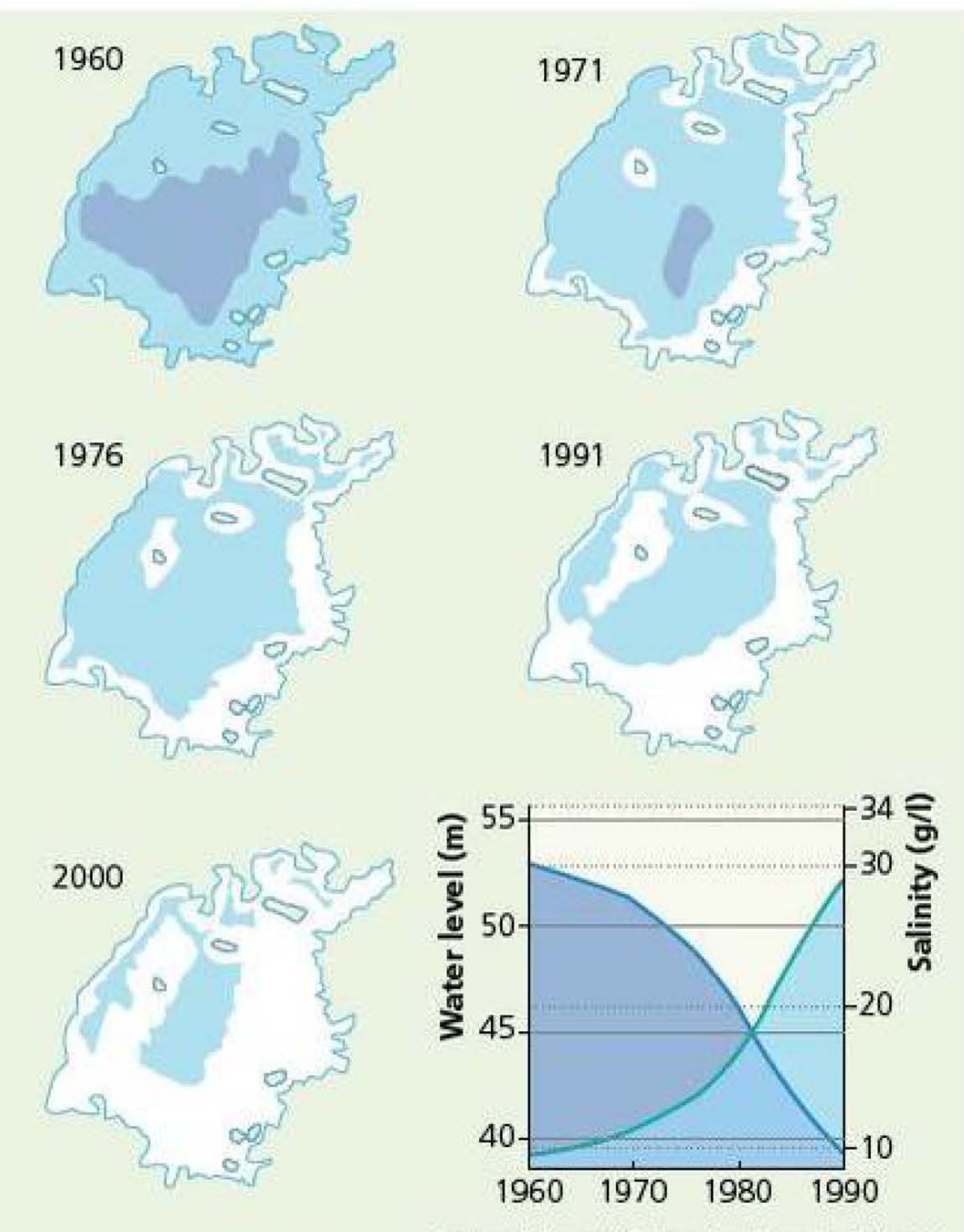
By contrast, in some industrial areas, recent reductions in industrial activity have led to less groundwater being taken out of the ground. As a result, groundwater levels in such areas have begun to rise, adding to the problem caused by leakage from ancient, deteriorating pipe and sewerage systems. Such a rise has numerous implications, including:

- increase in spring and river flows
- re-emergence of flow from 'dry springs'
- surface water flooding
- pollution of surface waters and the spread of underground pollution
- flooding of basements
- increased leakage into tunnels
- reduction in stability of slopes and retaining walls
- reduction in bearing capacity of foundations and piles
- swelling of clays as they absorb water
- chemical attack on building foundations.

There are various methods of recharging groundwater resources, provided that sufficient surface water is available. Where the materials containing the aquifer are permeable (as in some alluvial fans, coastal sand dunes or glacial deposits), water-spreading (a form of infiltration and seepage) is used. By contrast, in sediments with impermeable layers, such water-spreading techniques are not effective, and the appropriate method may then be to pump water into deep pits or into wells. This method is used extensively on the heavily settled coastal plain of Israel, both to replenish the groundwater reservoirs when surplus irrigation water is available, and in an attempt to diminish the problems associated with saltwater intrusions from the Mediterranean.

Case Study: Changing hydrology of the Aral Sea

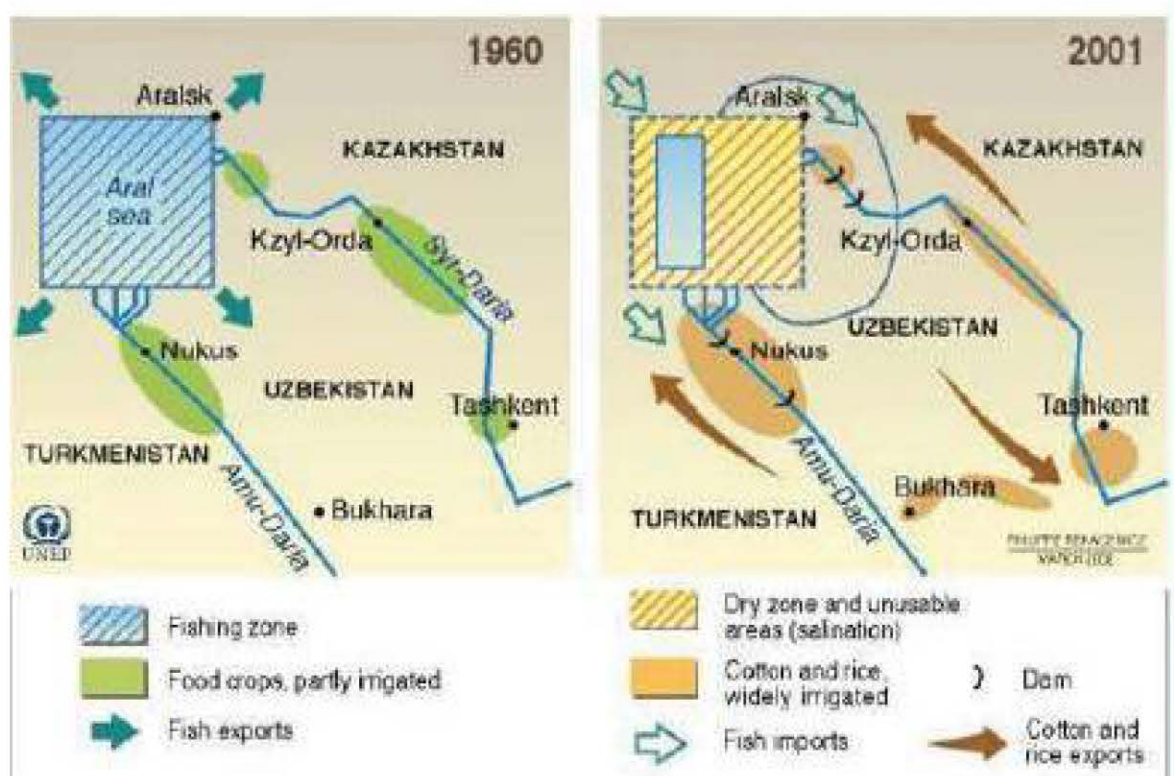
The Aral Sea began shrinking in the 1960s when Soviet irrigation schemes took water from the Syr Darya and the Amu Darya rivers. This greatly reduced the amount of water reaching the Aral Sea. By 1994, the shorelines had fallen by 16 metres, the surface area had declined by 50 per cent and the volume had been reduced by 75 per cent (Figure 1.27). By contrast, salinity levels had increased by 300 per cent.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.251

Figure 1.27 The changing hydrology of the Aral Sea

Increased salinity levels killed off the fishing industry. Moreover, ports such as Muynak are now tens of kilometres from the shore. Salt from the dry seabed has reduced soil fertility and frequent dust storms are ruining the region's cotton production. Drinking water has been polluted by pesticides and fertilisers and the air has been affected by dust and salt. There has been a noticeable rise in respiratory and stomach disorders and the region has one of the highest infant mortality rates in the former Soviet Union.



Source: Philippe Rekacewicz, *An Assassinated Sea*, in Histoire-Géographie, initiation économique, page 333, Classe de Troisième, Hatier, Paris, 1993 (data updated in 2002); *L'état du Monde*, 1992 and 2001 editions, La Découverte, Paris

Source: quoted at www.columbia.edu/~tmt2120/impacts%20to%20life%20in%20the%20region.htm

Figure 1.28 The economic impacts of the shrinking sea

Section 1.4 Activities

Study Figures 1.27 and 1.28.

1 Why do you think the Former Soviet Union (FSU) embarked on such a programme of large-scale irrigation? Use an atlas to produce detailed information.
2 Why have salinity levels increased so much?
3 What problems does the shrinking of the Aral Sea cause for towns such as Aralsk and Muynak?
4 What is the likely effect of the irrigation scheme on the two rivers in terms of velocity, erosion, sediment transport and deposition?

Water storage – dams

The number of large dams (more than 15 metres high) that are being built is increasing rapidly and is reaching a level of almost two completions every day (Figure 1.29).

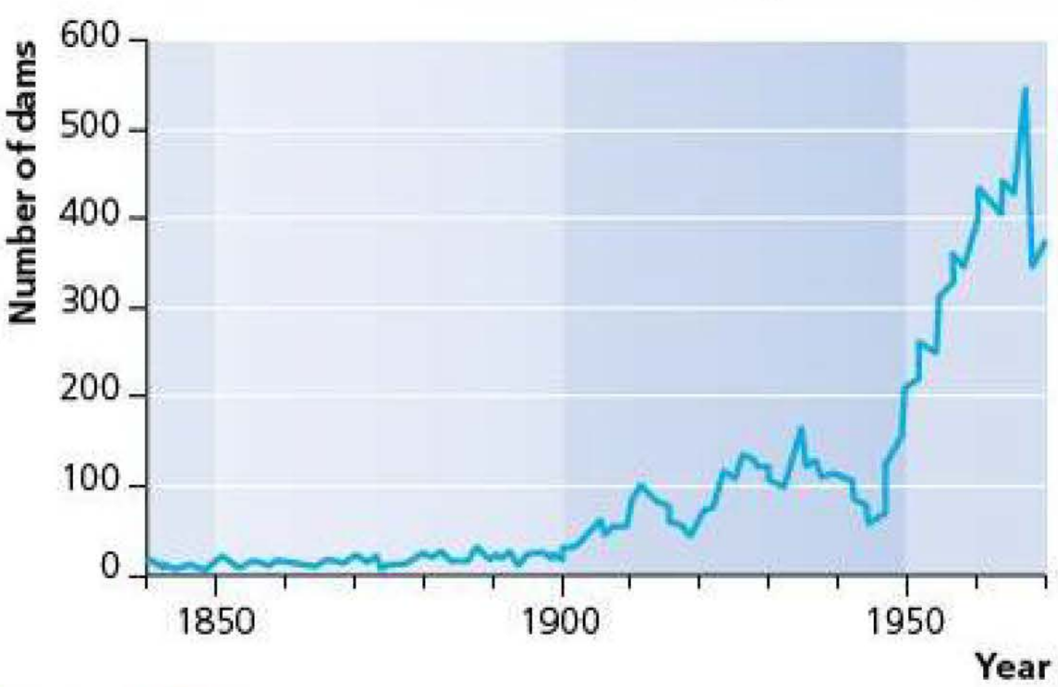


Figure 1.29 The trend in building large dams

The advantages of dams are numerous, as the following examples from the Aswan High Dam on the River Nile, Egypt, show:

- **flood and drought control** – dams allow good crops in dry years as, for example, in Egypt in 1972 and 1973
- **irrigation** – 60 per cent of water from the Aswan Dam is used for irrigation and up to 4000 km of the desert are irrigated
- **hydro-electric power** – this accounts for 7000 million kW hours each year
- **improved navigation**
- **recreation and tourism**.

It is estimated that the value of the Aswan High Dam is about $500 million to the Egyptian economy each year.

On the other hand, there are numerous disadvantages. For example:

- **water losses** – the dam provides less than half the amount of water expected
- **salinisation** – crop yields have been reduced on up to one-third of the area irrigated by water from the Aswan Dam, due to salinisation
- **groundwater changes** – seepage leads to increased groundwater levels and may cause secondary salinisation
- **displacement of population** – up to 100 000 Nubian people have been removed from their ancestral homes
- **drowning of archaeological sites** – the tombs of Ramases II and Nefertari at Abu Simbel had to be removed to safer locations – however, the increase in the humidity of the area has led to an increase in the weathering of ancient monuments
- **seismic stress** – the earthquake of November 1981 is believed to have been caused by the Aswan Dam; as water levels in the Dam increase so too does seismic activity
- **deposition within the lake** – infilling is taking place at about 100 million tonnes each year
- **channel erosion (clear-water erosion) on the channel bed** – lowering the channel by 25 mm over 18 years, a modest amount
- **erosion of the Nile delta** – this is taking place at a rate of about 2.5 cm each year
- **loss of nutrients** – it is estimated that it costs $100 million to buy commercial fertilisers to make up for the lack of nutrients each year
- **decreased fish catches** – sardine yields are down 95 per cent and 3000 jobs in Egyptian fisheries have been lost
- **diseases have spread** – such as schistosomiasis (bilharzia).

Figure 1.30 Paphos dam, Cyprus

Section 1.4 Activities

1 Study Figure 1.29. Describe the pattern shown and suggest reasons to explain the trend.
2 Evaluate the effectiveness of large dams.

Flood risk

Floods are one of the most common of all environmental hazards. This is because so many people live in fertile river valleys and in low-lying coastal areas. For much of the time, rivers act as a resource. However, extremes of too much water – or too little – can be considered a hazard (Figure 1.31).

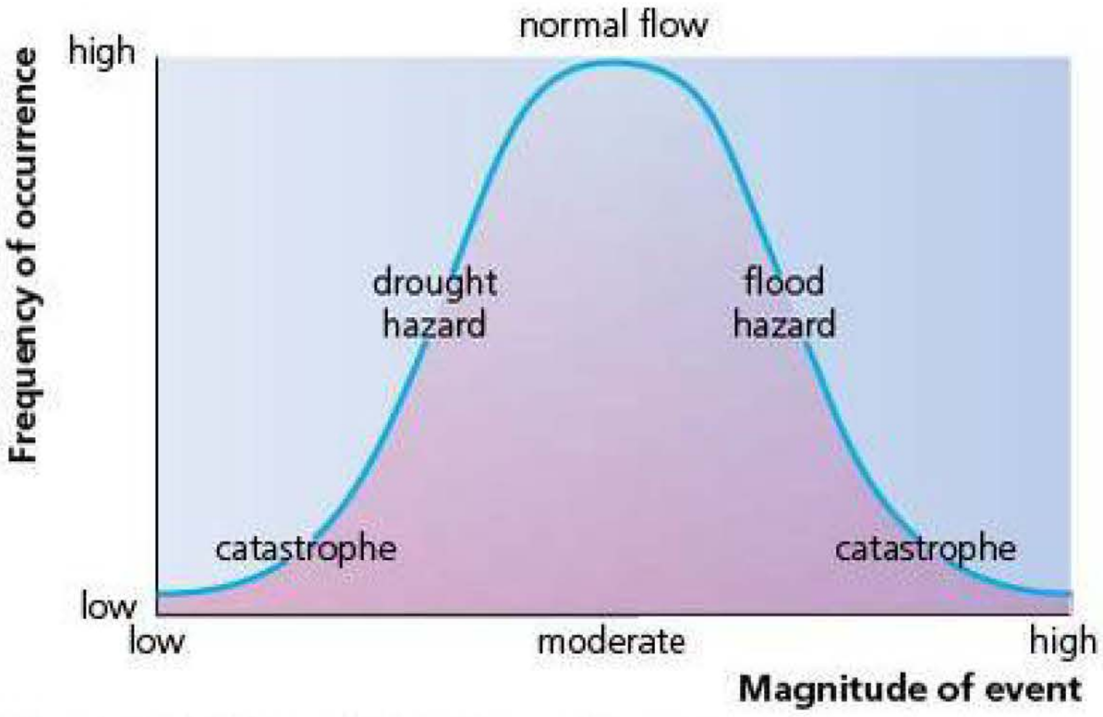


Figure 1.31 River discharge and frequency

In addition, extreme events occur infrequently. Many urban areas are designed to cope with floods that occur on a regular basis, perhaps annually or once in a decade. Most are ill-equipped to deal with the low-frequency/high-magnitude event that may occur once every 100 years or every 500 years (Figure 1.32). The **recurrence interval** refers to the regularity of a flood of a given size. Small floods may be expected to occur regularly. Larger floods occur less often. A 100-year flood is the flood that is expected to occur, *on average*, once every 100 years. Increasingly, larger floods are less common, but more damaging.

The nature and scale of flooding varies greatly. For example, less than 2 per cent of the population of England and Wales and in Australia live in areas exposed to flooding, compared with 10 per cent of the US population. The worst problems occur in Asia where floods damage about 4 million hectares of land each year and affect the lives of over 17 million people. Worst of all is China, where over 5 million people have been killed in floods since 1860.

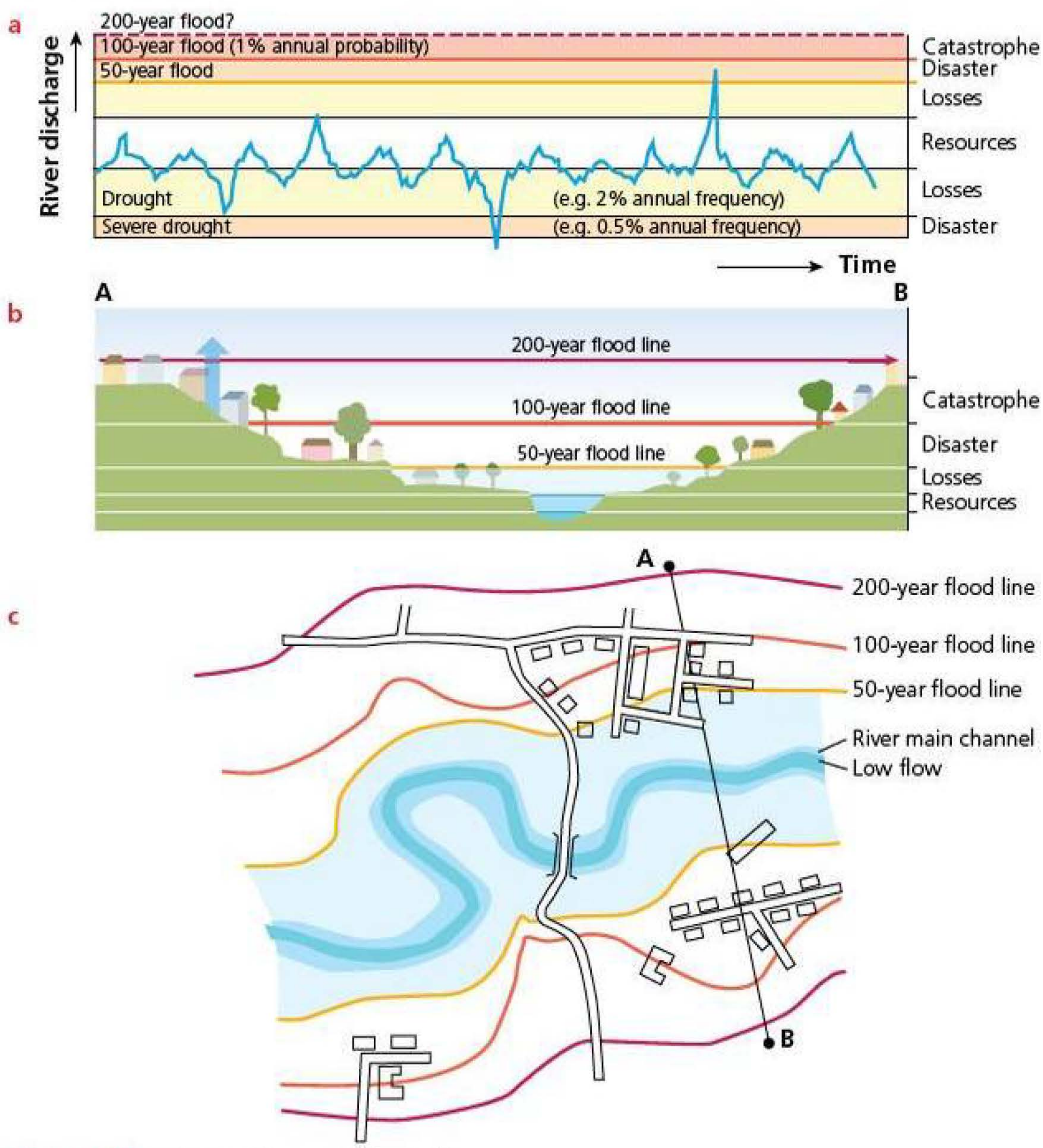


Figure 1.32 Urban land use and flood risk

Some environments are more at risk than others. The most vulnerable include the following:

- Low-lying parts of active floodplains and river estuaries. For example, in Bangladesh 110 million people living on the floodplain of the Ganges and Brahmaputra rivers are relatively unprotected. Floods caused by the monsoon regularly cover 20–30 per cent of the flat delta. In very high floods, up to half of the country may be flooded. In 1988, 46 per cent of the land was flooded and more than 1500 people were killed.
- Small basins subject to flash floods. These are especially common in arid and semi-arid areas. In tropical areas, some 90 per cent of lives lost through drowning are the result of intense rainfall on steep slopes.
- Areas below unsafe dams. In the USA, there are about 30 000 large dams and 2000 communities are at risk from dams. Following the 2008 Sichuan earthquake in China, some 35 quake dams were created by landslides blocking river routes. These were eventually made safe by engineers and the Chinese military.
- Low-lying inland shorelines such as along the Great Lakes and the Great Salt Lake in the USA.

In most high-income countries (HICs), the number of deaths from floods is declining, while in contrast the economic cost of flood damage has been increasing. In low-income countries (LICs), on the other hand, the death rate due to flooding is much greater, although the economic cost is not as great. It is likely that the hazard in LICs will increase over time as more people migrate and settle in low-lying areas and river basins. Often newer migrants are forced into the more hazardous zones.

Since the Second World War (1939–45), there has been a change in the understanding of the flood hazard, in the attitude towards floods and in the policy towards reducing the flood hazard. The response to hazards has moved away from physical control (engineering structures) towards reducing vulnerability through non-structural approaches.

Causes of flooding

A flood is a high flow of water that overtops the bank of a river. The main causes of floods are climatic forces, whereas the flood-intensifying conditions tend to be drainage basin specific (Figure 1.33). Most floods in the UK, for example, are associated with deep depressions (low pressure systems) that are both long-lasting and cover a wide area. By contrast, in India up to 70 per cent of the annual rainfall occurs in three months during the summer monsoon. In Alpine and Arctic areas, melting snow is responsible for widespread flooding.

Flood-intensifying conditions cover a range of factors, which alter the drainage basin response to a given storm (Figure 1.34). The factors that influence the storm hydrograph determine the response of the basin to the storm. These factors include topography, vegetation, soil type, rock type and characteristics of the drainage basin.

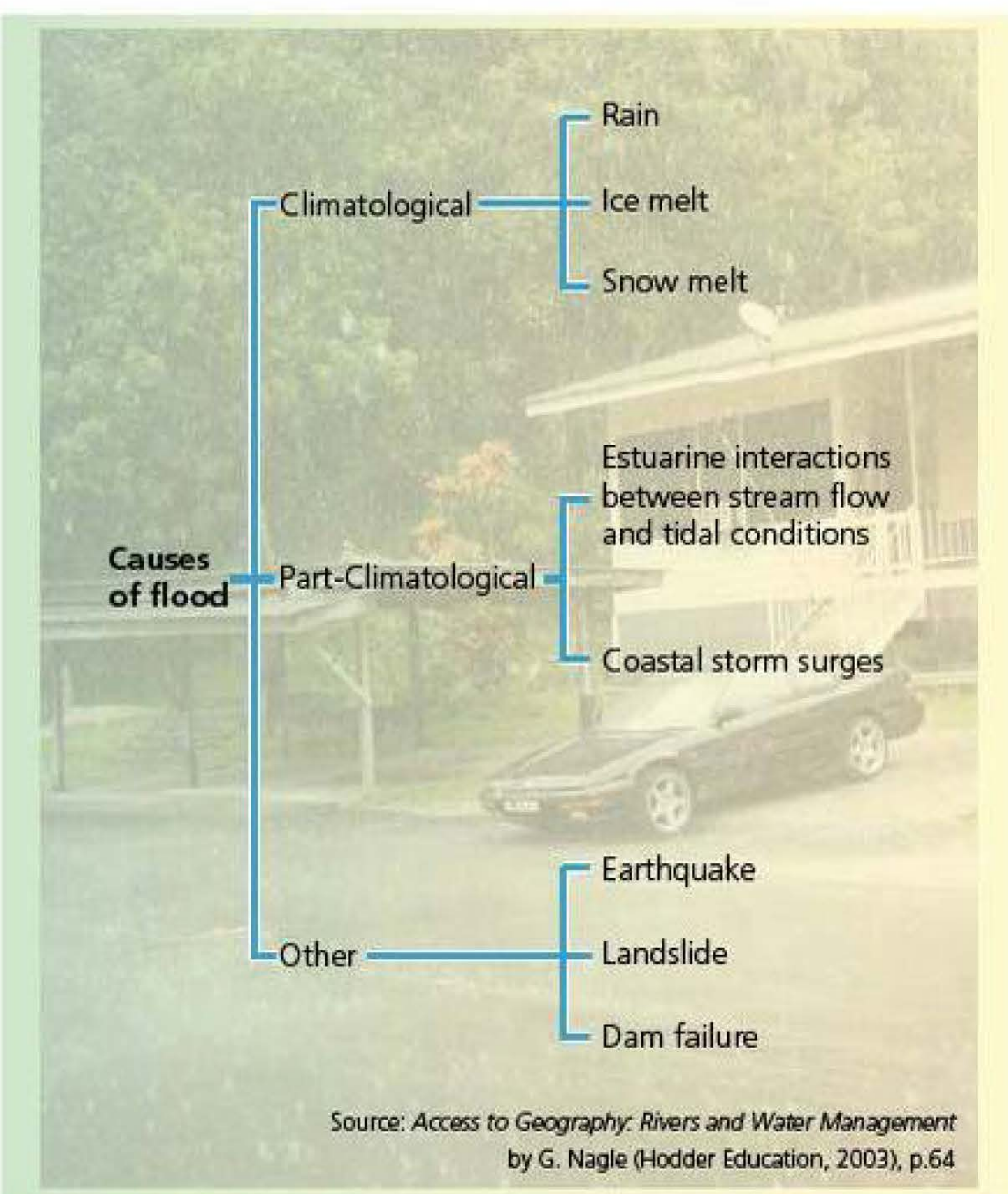


Figure 1.33 The causes of floods

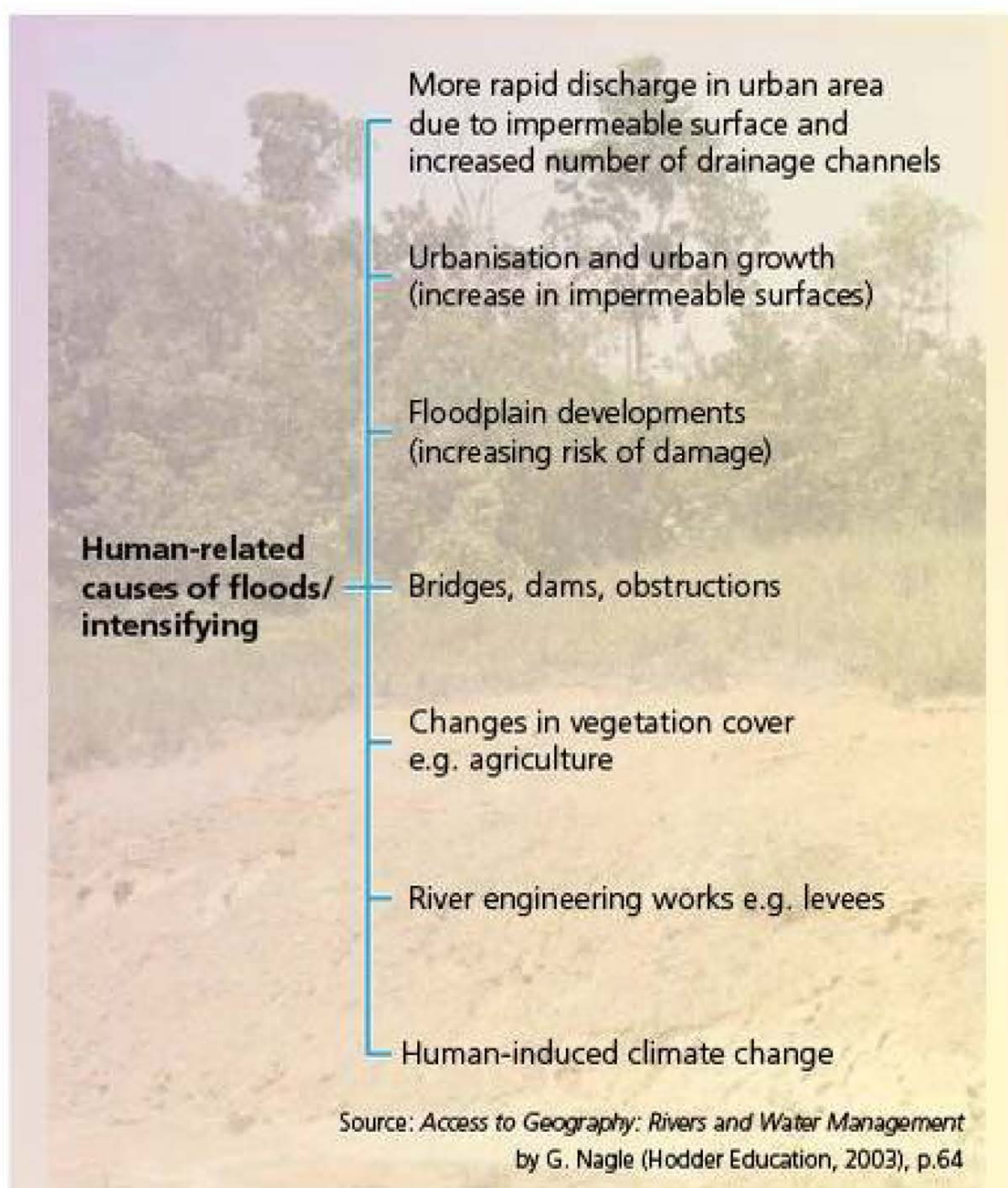


Figure 1.34 Flood-intensifying conditions

The potential for damage by floodwaters increases exponentially with velocity. The physical stresses on buildings are increased even more when rough, rapidly flowing water contains debris such as rocks, sediment and trees.

Other conditions that intensify floods include changes in land use. Urbanisation, for example, increases the magnitude and frequency of floods in at least three ways:

- creation of highly impermeable surfaces, such as roads, roofs, pavements
- smooth surfaces served with a dense network of drains, gutters and underground sewers increase drainage density
- natural river channels are often constricted by bridge supports or riverside facilities, reducing their carrying capacity.

Deforestation is also a cause of increased flood runoff and a decrease in channel capacity. This occurs due to an increase in deposition within the channel. However, the evidence is not always conclusive. In the Himalayas, for example, changes in flooding and increased deposition of silt in parts of the lower Ganges–Brahmaputra are due to the combination of high monsoon rains, steep slopes and the seismically unstable terrain. These ensure that runoff is rapid and sedimentation is high, irrespective of the vegetation cover.

The prevention and amelioration of floods

Forecasting and warning

During the 1980s and 1990s, flood forecasting and warning had become more accurate and these are now among the most widely used measures to reduce the problems caused by flooding. Despite advances in weather satellites and the use of radar for forecasting, over 50 per cent of all unprotected dwellings in England and Wales have less than six hours of flood warning time. In most LICs there is much less effective flood forecasting. An exception is Bangladesh. Most floods in Bangladesh originate in the Himalayas, so authorities have about 72 hours' warning.

According to the United Nations Environment Programme's publication *Early Warning and Assessment*, there are a number of things that could be done to improve flood warnings. These include:

- improved rainfall and snow pack estimates, and better and longer forecasts of rainfall
- better gauging of rivers, collection of meteorological information and mapping of channels
- better and current information about human populations and infrastructure; elevation and stream channels need to be incorporated into flood-risk assessment models
- better sharing of information is needed between forecasters, national agencies, relief organisations and the general public
- more complete and timely sharing of information of meteorological and hydrological information is needed among countries within international drainage basins
- technology should be shared among all agencies involved in flood forecasting and risk assessment, both in the basins and throughout the world.

Loss sharing

Economic growth and population movements throughout the twentieth century have caused many floodplains to be built on. However, for people to live on floodplains there needs to be flood protection. This can take many forms, such as loss-sharing adjustments and event modifications.

Loss-sharing adjustments include disaster aid and insurance. Disaster aid refers to any aid, such as money, equipment, staff and technical assistance, that is given to a community following a disaster. In HICs, insurance is an important loss-sharing strategy. However, not all flood-prone households have insurance and many of those that are insured may be underinsured.

Hard engineering

Traditionally, floods have been managed by methods of 'hard engineering'. This largely means dams, levees, wing dykes and straightened channels that are wider and deeper than the ones they replace. In some cases, new diversion spillways (flood-relief channels and intercepting channels) may be built (Figure 1.35). Although hard engineering may reduce floods in some locations, it may cause unexpected effects elsewhere in the drainage basin, for example decreased water quality, increased sedimentation, bed and bank erosion and loss of habitats.

Levees are the most common form of river engineering. They can also be used to divert and restrict water to low-value land on the floodplain. Over 4500 kilometres of the Mississippi River have levees. Channel improvements such as channel enlargement will increase the carrying capacity of the river. Reservoirs store excess rainwater in the upper drainage basin. However, this may only be appropriate in small drainage networks. It has been estimated that some 66 billion m^3 of storage is needed to make any significant impact on major floods in Bangladesh!

Hazard-resistant design

Flood-proofing includes any adjustments to buildings and their contents that help reduce losses. Some are temporary, such as:

- blocking up entrances
- sealing doors and windows
- removal of damageable goods to higher levels
- use of sandbags.

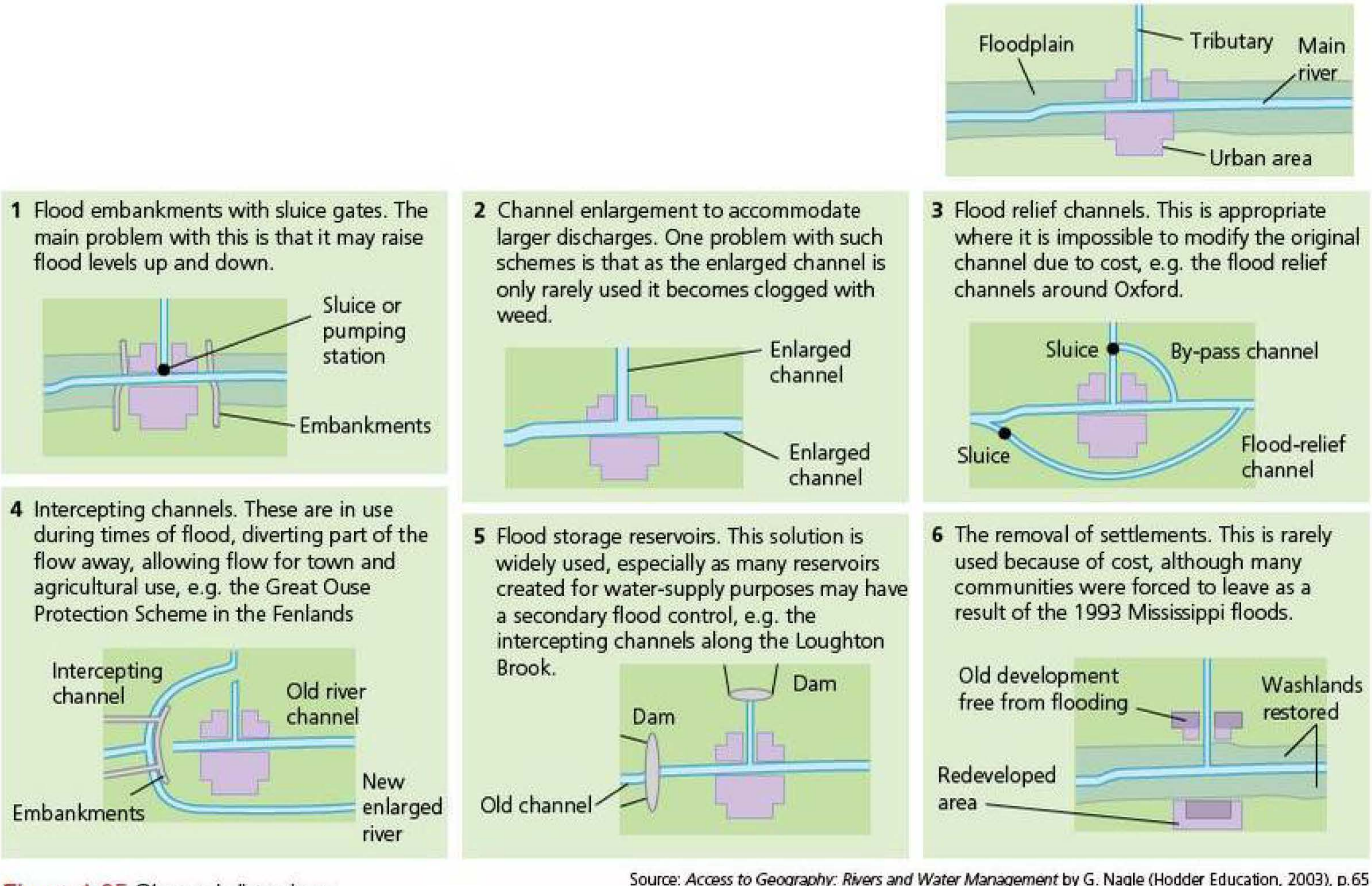


Figure 1.35 Channel diversions

Figure 1.36 Flood-relief channel, Zermatt, Switzerland

By contrast, long-term measures include moving the living spaces above the likely level of the floodplain. This normally means building above the flood level, but could also include building homes on stilts.

Land-use zoning

Most land-use zoning and land-use planning has been introduced since the Second World War. In the USA, land-use management has been effective in protecting new housing developments from 1 in 100-year floods (that is, the size of flood that we would expect to occur once every century).

One example where partial urban relocation has occurred is at Soldier's Grove on the Kickapoo River in south-western Wisconsin, USA. The town experienced a series of floods in the 1970s, and the Army Corps of Engineers proposed building two levees and moving part of the urban area. Following floods in 1978, they decided that relocation of the entire business district would be better than just flood-damage reduction. Although levees would have protected the village from most floods, they would not have provided other opportunities. Relocation allowed energy conservation and an increase in commercial activity in the area.

Soft engineering

Soft engineering generally refers to working with natural processes and features rather than attempts to control them. They include the management of whole catchments (catchment management plans), wetland conservation and river restoration.

Event modification adjustments include environmental control and hazard-resistant design. Physical control of floods depends on two measures: flood abatement and flood diversion. **Flood abatement** involves decreasing the amount of runoff, thereby reducing the flood peak in a drainage basin. There are a number of ways of reducing flood peaks. These include:

- reforestation
- reseeding of sparsely vegetated areas to increase evaporative losses
- treatment of slopes such as by contour ploughing or terracing to reduce runoff
- comprehensive protection of vegetation from wildfires, overgrazing and clear-cutting of forests
- clearance of sediment and other debris from headwater streams
- construction of small water- and sediment-holding areas
- preservation of natural water-storage zones, such as lakes.

Flood diversion refers to the practice of allowing certain areas, such as wetlands and floodplains, to be flooded to a greater extent. Natural flooding may be increased through the use of flood-relief channels (diversion spillways) to direct more water into these areas during times of flood.

River restoration

Case Study: Costs and benefits of the Kissimmee River restoration scheme

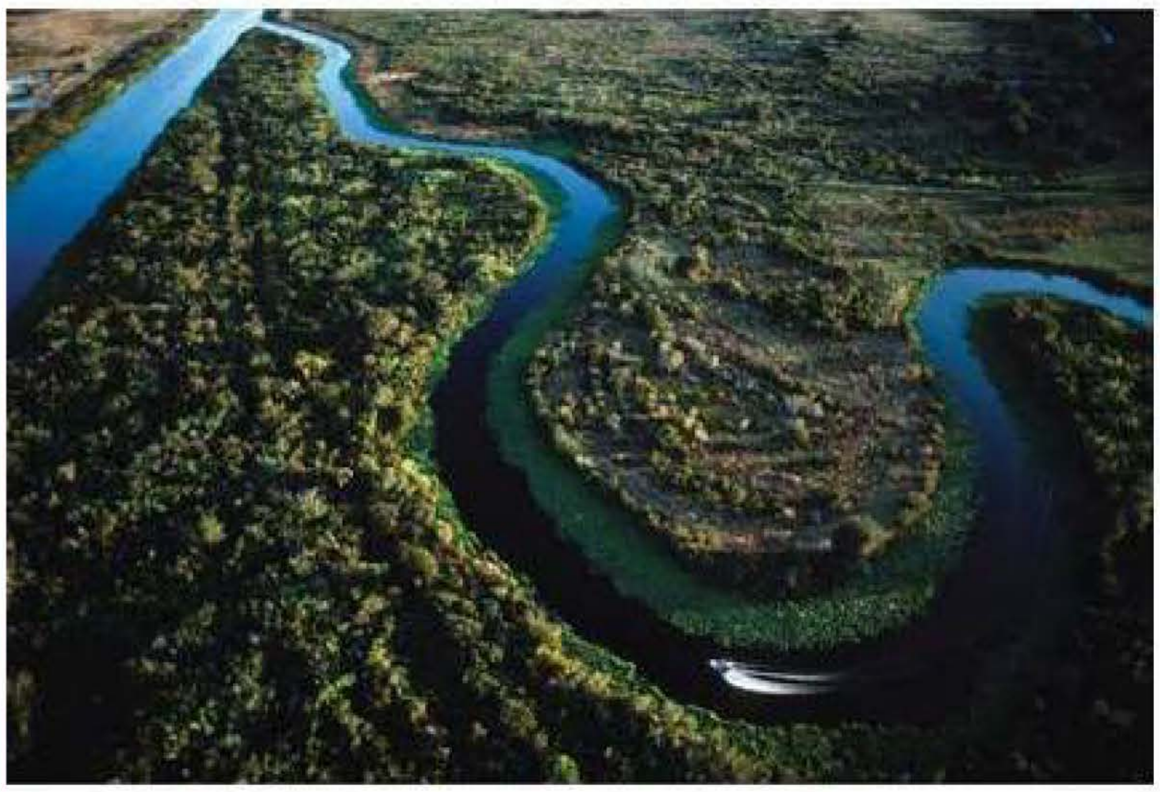


Figure 1.37 Part of the restored Kissimmee Restoration Scheme, Florida, USA

The 165 kilometre Kissimmee River once meandered through central Florida. Its floodplain, reaching up to 5 kilometres wide, was inundated for long periods by heavy seasonal rains. Wetland plants, wading birds and fish thrived there, but the frequent, prolonged flooding caused a severe impact on people.

Between 1962 and 1971, engineering changes were made to deepen, straighten and widen the river, which was transformed into a 90 kilometre, 10 metre-deep drainage canal. The river was channelised to provide an outlet canal for draining floodwaters from the developing upper Kissimmee lakes basin, and to provide flood protection for land adjacent to the river.

Impacts of channelisation

The channelisation of the Kissimee River had several unintended impacts:

- the loss of 2000 to 14 000 hectares of wetlands
- a 90 per cent reduction in wading bird and waterfowl usage
- a continuing long-term decline in game fish populations.

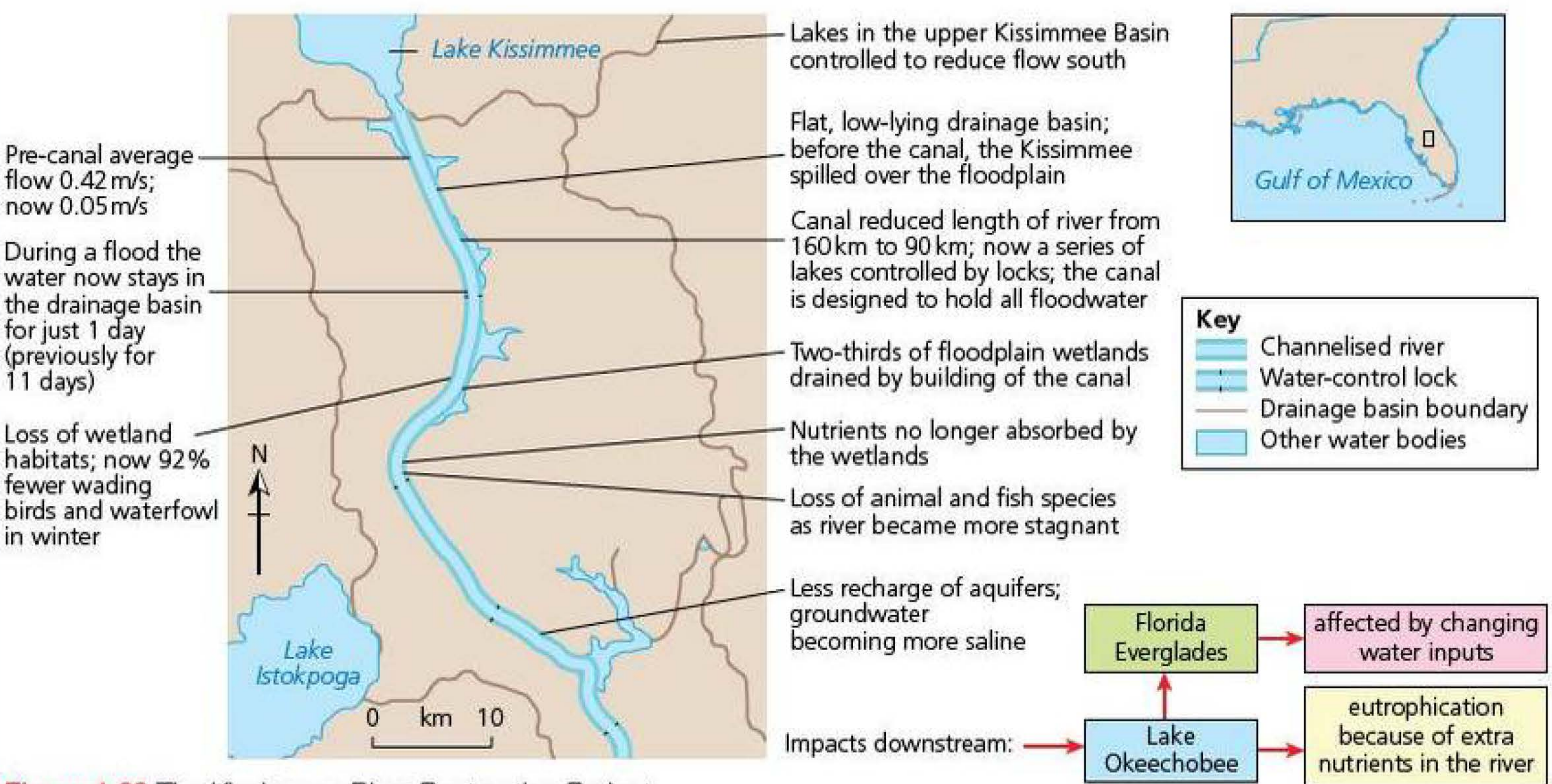


Figure 1.38 The Kissimmee River Restoration Project

Concerns about the **sustainability** of existing ecosystems led to a state and federally supported restoration study. The result was a massive restoration project, on a scale unmatched elsewhere.

The project restored over 100 km² of river and associated floodplain wetlands. It was started in 1999 and completed in 2015. It benefits over 320 fish and wildlife species, including the endangered bald eagle, wood stork and snail kite. It has created over 11 000 hectares of wetlands. Seasonal rains and flows now inundate the floodplain in the restored areas.

Restoration of the river and its associated natural resources required **dechannelisation**. This entailed backfilling approximately half of the flood-control channel and re-establishing the flow of water through the natural river channel. In residential areas, the flood-control channel will remain in place.

The costs of restoration

It is estimated that the project cost over $400 million (initial channelisation cost $20 million), a bill being shared by the state of Florida and the federal government.

Restoration of the river's floodplain could result in higher losses of water due to evapotranspiration during wet periods. In extremely dry spells, navigation may be impeded in some sections of the restored river. It is, however, expected that navigable depths will be maintained at least 90 per cent of the time.

Benefits of restoration

- Higher water levels should ultimately support a natural river ecosystem again.
- Re-establishment of floodplain wetlands and the associated nutrient filtration function is expected to result in decreased nutrient loads to Lake Okeechobee.
- Populations of key avian species, such as wading birds and waterfowl, have returned to the restored area, and in some cases numbers have more than tripled.
- Dissolved oxygen levels have doubled, which is critical for the survival of fish and other aquatic species.
- Potential revenue associated with increased recreational usage (such as hunting and fishing) and ecotourism on the restored river could significantly enhance local and regional economies.

Section 1.4 Activities

1 Outline the natural and human causes of floods.
2 Compare and contrast methods of flood management.
3 To what extent can flood frequency and magnitude be predicted?
4 Outline the disadvantages of channelisation as shown in Figure 1.36.
5 Outline the benefits of wetlands.
6 What is meant by *river restoration*? What are the benefits of river restoration?

Case Study: Flooding in Bangladesh

Figure 1.39 Satellite image of the 1998 floods

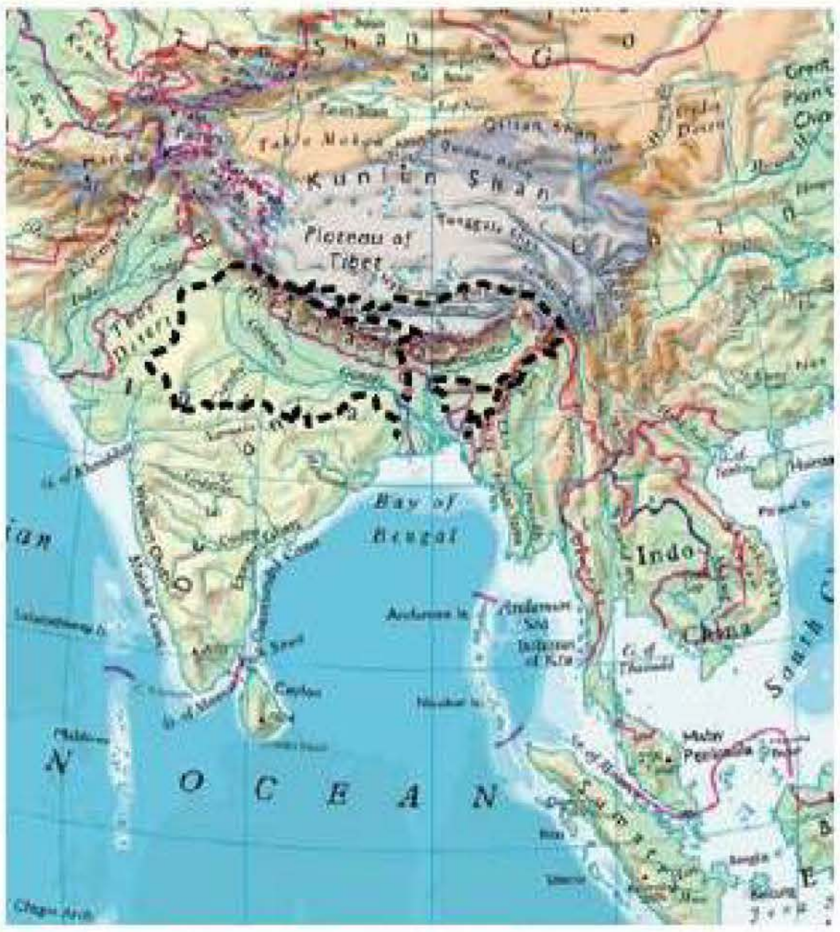
Bangladesh is a small, flat and low-lying country: 60 per cent is less than 6 metres above sea level. For this reason, tides affect one-third of land area. Banglasdesh is located where the Ganga, Brahmaputra (called *Jamuna* in Bangladesh) and Meghna rivers meet. The average gradient of the rivers is 6 cm/km. The country drains an area 12 times its own size. It has a high frequency of floods and cyclones.

Table 1.5 Bangladesh factfile

Area	143 998 km²
Population	166 million (2014)
Age structure	51% under 25 years of age
Population density	1161/km²
Annual growth rate	0.6%
Literacy	58.8%
PPP	$3400
Life expectancy	70.65 years
Employment	Agriculture: 47% Industry: 13% Services: 40%

Source: CIA World Factbook

Bangladesh has a high population density, low human development index (HDI) and a majority of the population is dependent on agriculture. An area of about 150 000 km² is shared by 123 million people.



Source: Philip's Interactive Modern School Atlas by G. Nagle (Hodder Education, 2006) © Philip's

Figure 1.40 The Ganges drainage basin

Several regions affect conditions within Bangladesh:

- **high plateau of Tibet** – the source of the Brahmaputra, where most of the river flow derives from snow melt and glacier melt
- **Himalayas** – source of the Ganga and many of the springs that feed into the Brahmaputra
- **Ganga Plain** – one of the largest lowland areas in the world, and a region of intense cultivation
- **Meghalaya Hills** – located between the floodplain of north-east Bangladesh and the Indian lowlands of Assam; rise to a height of 2500m and act as a barrier to the monsoon winds from the Indian Ocean; Cherrapungee has an annual rainfall of over 11000mm.

Table 1.6 Watershed characteristics of the Ganga and the Brahmaputra/Meghna (Br/M) rivers and a comparison with the Nile, the Amazon and the Mississippi

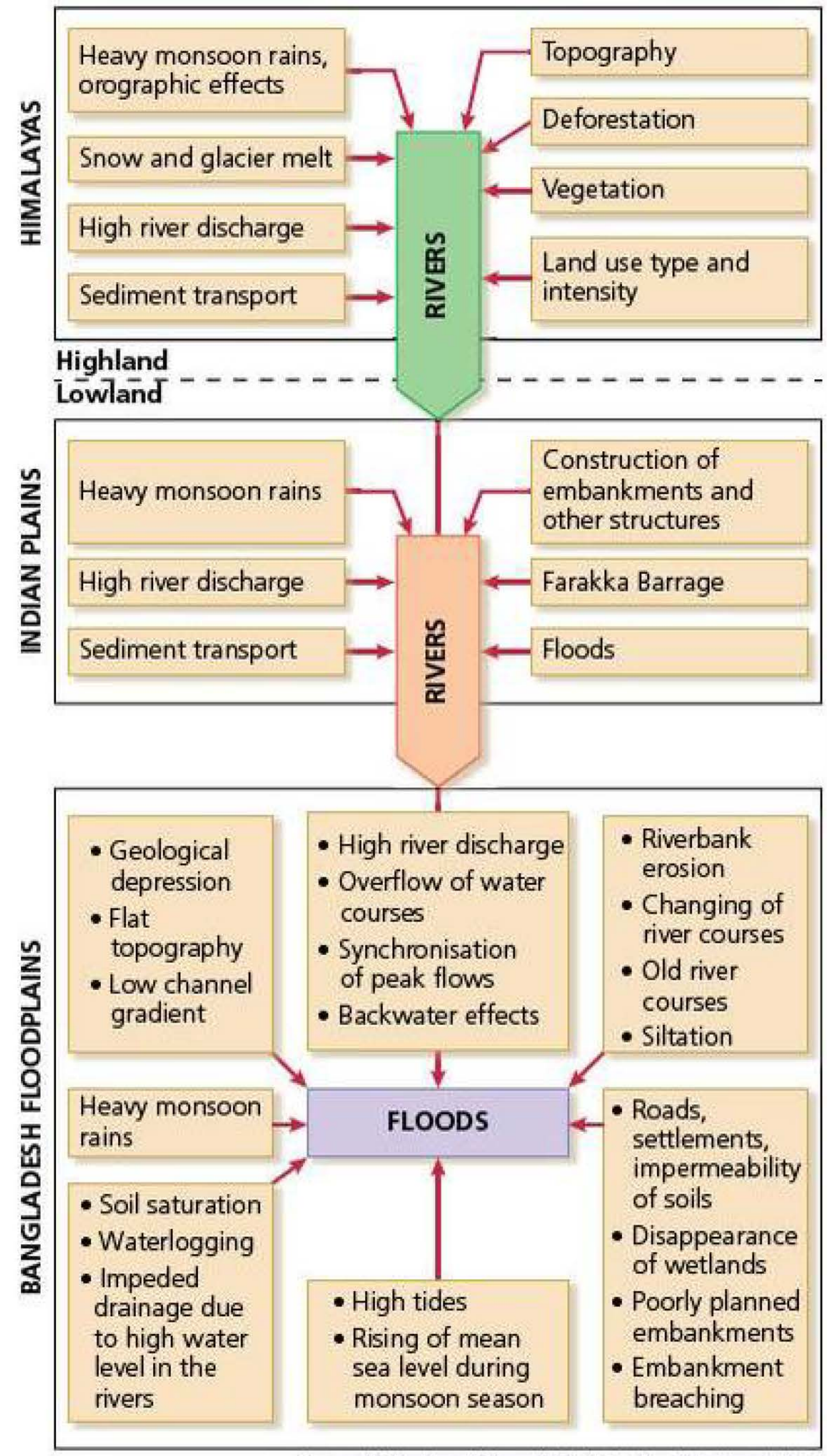
Characteristics	Ganga	Br/M	Nile	Amazon	Mississippi
Basin area (km²)	1016104	651334	3254555	6144727	3202230
Length (km)	2296	2772	5964	4406	4240
Average annual discharge (m^3/s)	11365	19772	2760	176177	17600
Forest (%)	4	19	2	73	22
Cropland (%)	7	29	10	15	35
Cropland irrigated (%)	15	47	5	0	4
Grassland (%)	7	29	52	8	22
Large dams	6	0	7	2	2091

Source: Hofer, T. and Messerli, B, 2006, Floods in Bangladesh, *United Nations University Press, Table 2.2*

The Ganges and the Brahmaputra are two of the world's largest rivers by catchment size, length, amount of flow, sediment discharge (the Brahmaputra carries 540 million tons of sediment per year, the Ganges 520 million tons) and lateral shifting.

Causes of flooding

There are many causes of flooding in Bangladesh (Figure 1.41), which originate in three areas – the highlands (Himalayas); the Indian Plains of the Ganges and the Brahmaputra; and the floodplains of Bangladesh.



Source: Hofer, T and Messerli, B, 2006, *Floods in Bangladesh*, United Nations University Press

Figure 1.41 The causes of floods in the Ganges

Flooding in Bangladesh alternates between periods of high flood frequency and low flood frequency.

- Floods in the western part of Bangladesh were more intensive in the eighteenth and nineteenth centuries than in the twentieth or twenty-first centuries.
- Massive floods occurred regularly long before human impact on the watershed began; there is no evidence that flood frequency is increasing.
- The variation in the extent of flooding year by year has been increasing since the 1950s.

- There is increasing monsoon rain, particularly in the Brahmaputra–Meghna system.
- There is a worsening impact on the Bangladeshi people, but human influence in the Himalayas is not thought to be increasing flooding in Bangladesh.

Flooding is viewed very differently by rural people and by politicians and engineers. For many rural people, flooding is a short-term necessity for their crops; engineers and politicians see the damage it causes to infrastructure and the economy.

The 1998 floods

These were the longest lasting and most devastating floods in 100 years; 1998 was a La Niña year, in which normal circulatory patterns are intensified. The most-affected areas of Bangladesh included the capital Dhaka and other areas close to the main rivers; 53 of the 64 districts of the country – that is, about 50 per cent – were affected, by up to 3 metres of water for up to 67 days. The flooding on 7 September was probably the worst of the twentieth century.

The main causes were:

- the high peaks on all three main rivers occurring at the same time
- high tides causing the river floods to back up
- a strong monsoon that caused excessive flooding, and obstructions by man-made infrastructure.

Table 1.7 Major impacts of the 1998 floods

Number of people affected	c.30 million
Number of deaths	c.780–1500
Number facing malnutrition	25 million
Rice production loss	2.2 million tons
Damage to cultivated area	1.5 million ha
Loss of livestock sector	$500 million
Roads damaged	15 000 km
Embankments damaged	c.4500 km
Bridges/culverts damaged	>20 000
Villages damaged	30 000
Houses damaged	550 000–900 000

Source: Hofer, T. and Messerli, B, 2006, Floods in Bangladesh, *United Nations University Press, Table 2.2*

Coping with flooding in Bangladesh

- Many houses, and also many roads, are built on raised platforms, above the level of the average flood. People who live on islands mainly use bamboo and reeds for their houses, which can be dismantled in about an hour in an emergency.
- Rural people cultivate different varieties of rice, some of which can grow in floodwaters of 1 metre and grow up to 20 centimetres a day to keep up with the rising water level; jute and sugar cane can also withstand submergence.
- It takes up to three days for floodwaters to rise, giving people some time to prepare, such as raising platforms in their homes so that they can sleep on dry ground.
- Levees can prevent overflow but may cause deposition in the channel, which raises the river bed and reduces the capacity of the river.
- Levees can give a false sense of security – they protect against minor floods but not against major ones.
- The Flood Action Plan 1989–95 led to the development of the Bangladesh Water and Flood Management Strategy Report, which stated that there are three main water-resource development options:
  Minimum intervention – improve forecasting and improve existing flood schemes but do not create new ones
  Selective intervention – protect densely populated areas, key infrastructure and water supplies
  Major intervention – build large-scale engineering works on all main rivers.
- In terms of existing measures, there are currently over 10 000 kilometres of levees and a number of raised flood and cyclone shelters.
- Groynes in rivers protect important townships.
- Non-structural measures include flood forecasting, preparation and relief. The Flood Forecasting Warning Centre issues five-day forecasts during the monsoon season.
- Up to 20 per cent of the population is at risk from lateral erosion, which is more predictable on the Ganga than on the braided Brahmaputra. Many families may be forced to move 10 to 15 times during their lifetime.

Social problems

- **Loss of land**, leading to loss of social status and poverty, which can prevent a family's children from being able to marry.
- **Food shortages**, leading to reliance on relatives and neighbours.

Section 1.4 Activities

1. Study Table 1.6. Outline the main differences in watershed characteristics of the rivers. Suggest how these differences may affect the flood hazard.
2. Study Figure 1.41. Outline the main physical and human causes of flooding in Bangladesh.
3. Describe the main impacts of the 1998 floods in Bangladesh. Why were the impacts so great?
4. Evaluate the opportunities for flood control in Bangladesh.

2 Atmosphere and weather

2.1 Diurnal energy budgets

An energy budget refers to the amount of energy entering a system, the amount leaving the system and the transfer of energy within the system. Energy budgets are commonly considered at a global scale (macro-scale) and at a local scale (micro-scale). However, the term microclimate is sometimes used to describe regional climates, such as those associated with large urban areas, coastal areas and mountainous regions.

Figure 2.1 shows a classification of climate and weather phenomena at a variety of spatial and temporal scales. Phenomena vary from small-scale turbulence and eddying (such as dust devils) that cover a small area and last for a very short time, to large-scale anticyclones (high-pressure zones) and jet streams that affect a large area and may last for weeks. The jet stream that carried volcanic dust from underneath the Eyjafjallajökull glacier in Iceland to northern Europe in 2010 is a good example of jet-stream activity (Figure 2.2).

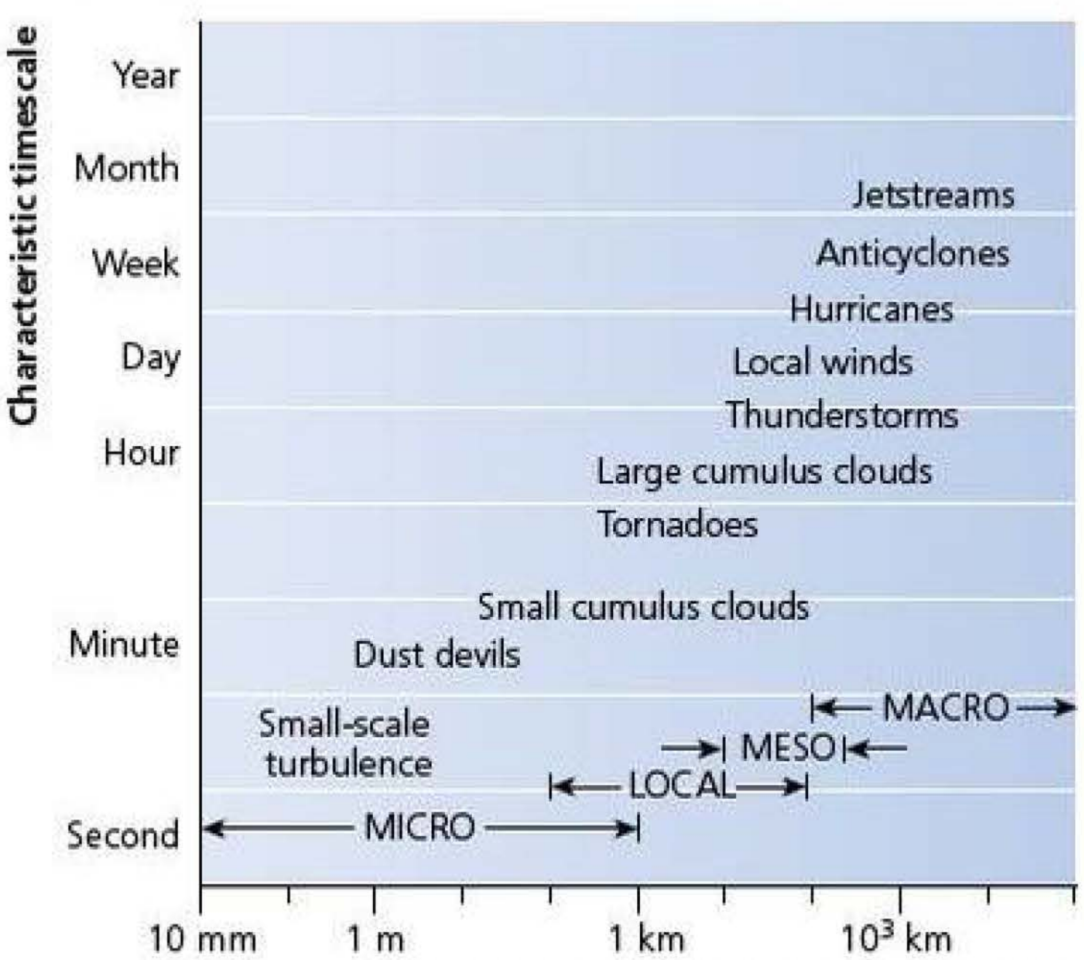


Figure 2.1 Classification of climate and weather phenomena at a variety of spatial and temporal scales

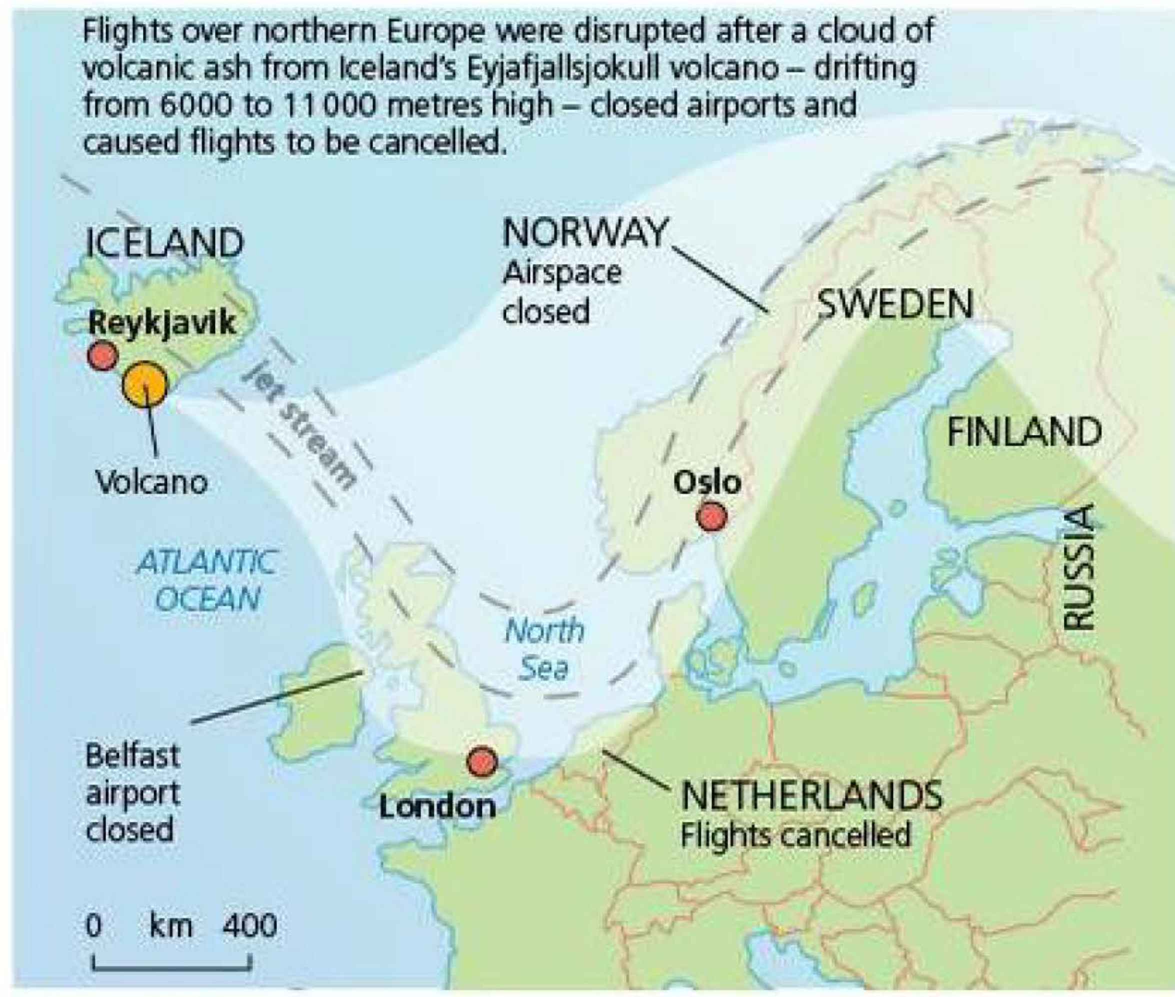


Figure 2.2 Jet-stream activity and the transfer of dust from Eyjafjallajökull, Iceland

These different scales should not be considered as separate scales but as a hierarchy of scales in which smaller phenomena may exist within larger ones. For example, the temperature surrounding a building will be affected by the nature of the building and processes that are taking place within the building. However, it will also be affected by the wider synoptic (weather) conditions, which are affected by latitude, altitude, cloud cover and season, for example.

Daytime and night-time energy budgets

There are six components to the daytime energy budget:

- incoming (shortwave) solar radiation (insolation)
- reflected solar radiation
- surface absorption
- sensible heat transfer
- long-wave radiation (Figure 2.3)
- latent heat (evaporation and condensation).

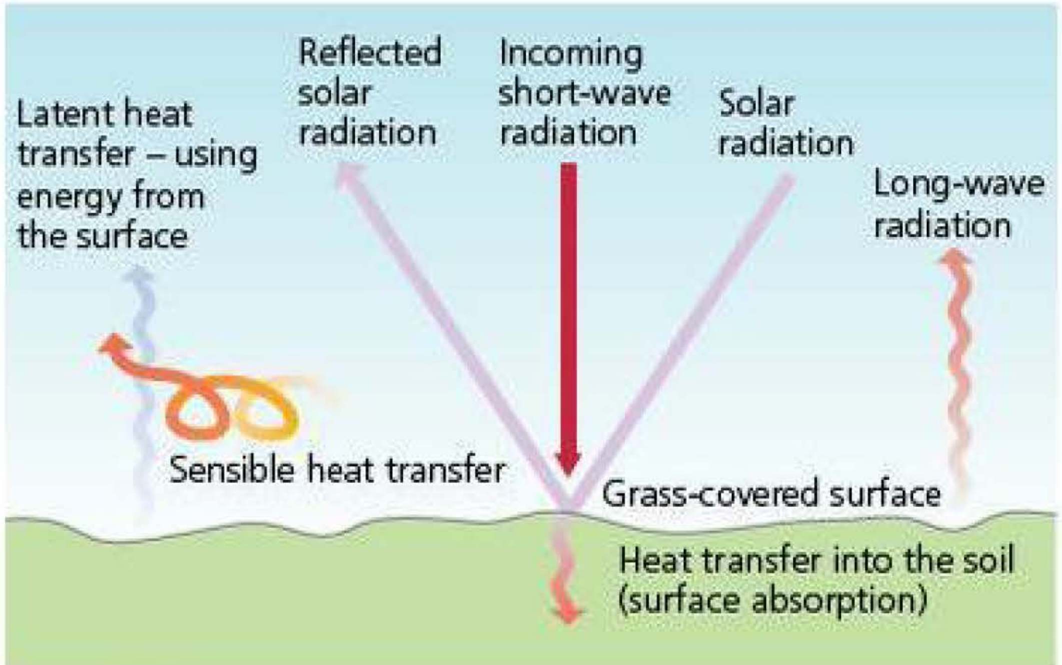


Figure 2.3 Local energy budget – daytime

These influence the gain or loss of energy for a point at the Earth's surface. The daytime energy budget assumes a horizontal surface with grass-covered soil and can be expressed by the formula:

energy available at the surface = incoming solar radiation – (reflected solar radiation + surface absorption + sensible heat transfer + long-wave radiation + latent heat transfers)

In contrast, the night-time energy budget consists of four components:

- long-wave Earth radiation
- latent heat transfer (condensation)
- absorbed energy returned to Earth (sub-surface supply)
- sensible heat transfer (Figure 2.4).

Incoming (shortwave) solar radiation

Incoming solar radiation (insolation) is the main energy input and is affected by latitude, season and cloud cover (Section 2.2). Figure 2.5 shows how the amount of insolation received varies with the angle of the Sun and with cloud type. For example, with strato-cumulus clouds (like those in Figure 2.6) when the Sun is low in the sky, about 23 per cent of the total radiation transmitted is received at the Earth's surface – about 250 watts per m^2. When the Sun is high in the sky, about 40 per cent is received – just over 450 watts per m^2. The less cloud cover there is, and/or the higher the cloud, the more radiation reaches the Earth's surface.

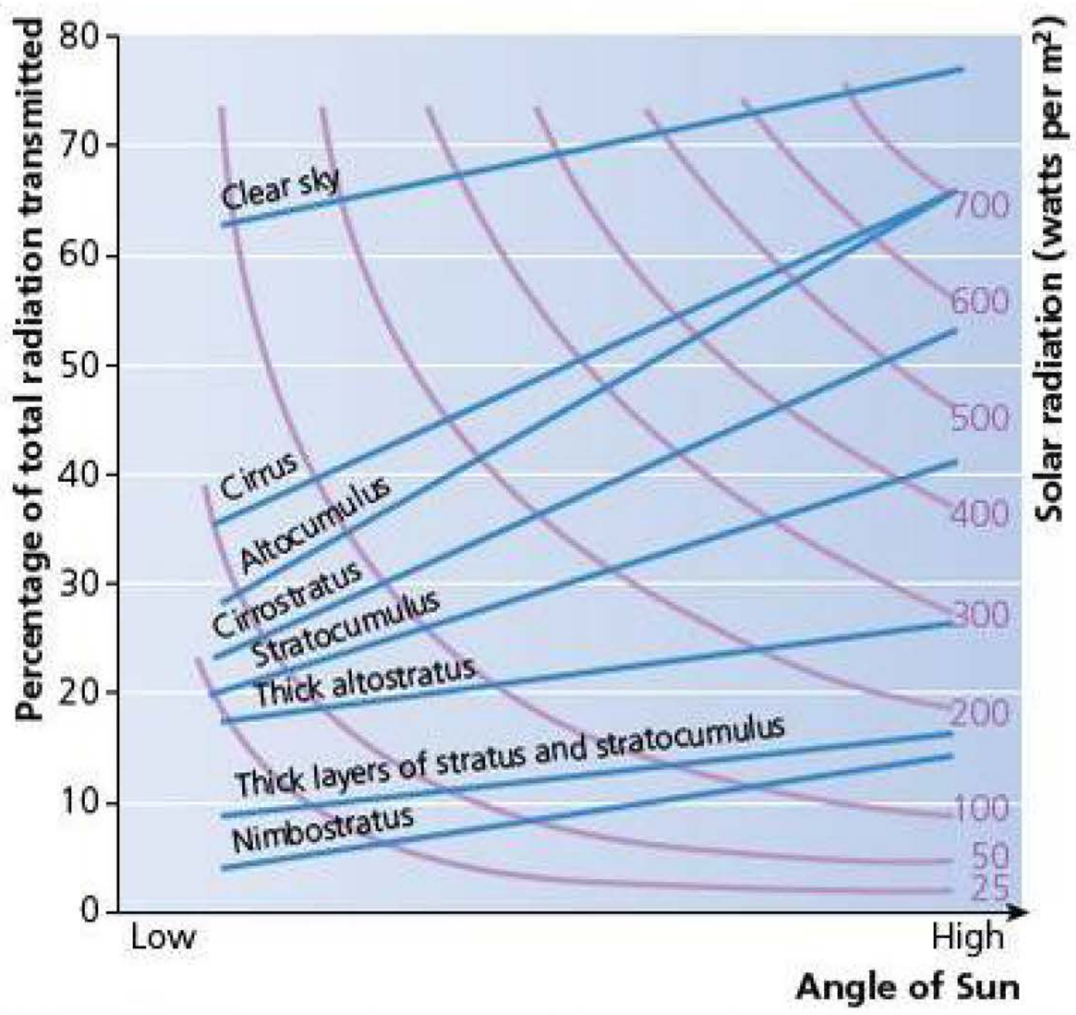


Figure 2.5 Energy, cloud cover/type and the angle of the Sun

Figure 2.6 Stratocumulus clouds

Reflected solar radiation

The proportion of energy that is reflected back to the atmosphere is known as the albedo. The albedo varies with colour – light materials are more reflective than dark materials (Table 2.1). Grass has an average albedo of 20–30 per cent, meaning that it reflects back about 20–30 per cent of the radiation it receives.

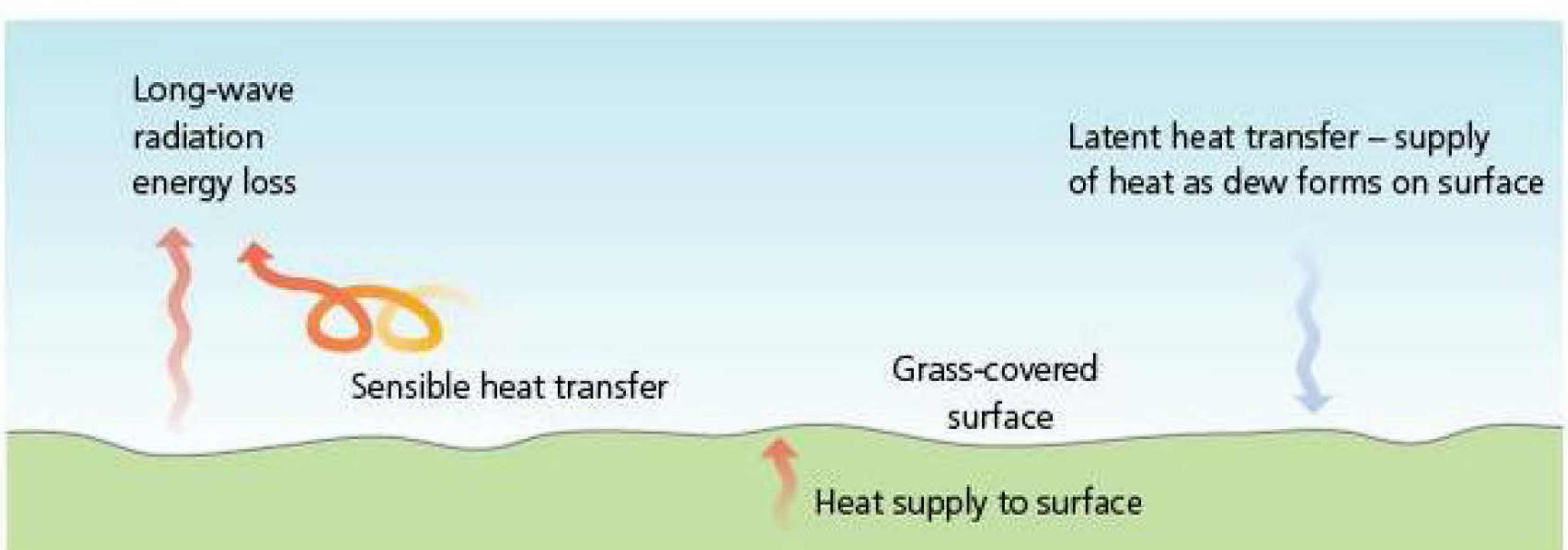


Figure 2.4 Night-time energy budget

Table 2.1 Selected albedo values

Surface	Albedo (%)
Water (Sun's angle over 40°)	2–4
Water (Sun's angle less than 40°)	6–80
Fresh snow	75–90
Old snow	40–70
Dry sand	35–45
Dark, wet soil	5–15
Dry concrete	17–27
Black road surface	5–10
Grass	20–30
Deciduous forest	10–20
Coniferous forest	5–15
Crops	15–25
Tundra	15–20

Section 2.1 Activities

1 The model for the daytime energy budget assumes a flat surface with grass-covered soil. Suggest reasons for this assumption.

2 Study Table 2.1.

  a What is meant by the term *albedo*?

  b Why is albedo important?

Surface and sub-surface absorption

Energy that reaches the Earth's surface has the potential to heat it. Much depends on the nature of the surface. For example, if the surface can conduct heat to lower layers, the surface will remain cool. If the energy is concentrated at the surface, the surface warms up.

The heat transferred to the soil and bedrock during the day may be released back to the surface at night. This can partly offset the night-time cooling at the surface.

Sensible heat transfer

Sensible heat transfer refers to the movement of parcels of air into and out of the area being studied. For example, air that is warmed by the surface may begin to rise (convection) and be replaced by cooler air. This is known as a convective transfer. It is very common in warm areas in the early afternoon. Sensible heat transfer is also part of the night-time energy budget: cold air moving into an area may reduce temperatures, whereas warm air may supply energy and raise temperatures.

Long-wave radiation

Long-wave radiation refers to the radiation of energy from the Earth (a cold body) into the atmosphere and, for some of it, eventually into space. There is, however, a downward movement of long-wave radiation from particles in the atmosphere. The difference between the two flows is known as the net long-wave radiation balance. During the day, the outgoing long-wave radiation transfer is greater than the incoming long-wave radiation transfer, so there is a net loss of energy from the surface.

During a cloudless night, there is a large loss of long-wave radiation from the Earth. There is very little return of long-wave radiation from the atmosphere, due to the lack of clouds. Hence there is a net loss of energy from the surface. In contrast, on a cloudy night the clouds return some long-wave radiation to the surface, hence the overall loss of energy is reduced. Thus in hot desert areas, where there is a lack of cloud cover, the loss of energy at night is maximised. In contrast, in cloudy areas the loss of energy (and change in daytime and night-time temperatures) is less noticeable.

Latent heat transfer (evaporation and condensation)

When liquid water is turned into water vapour, heat energy is used up. In contrast, when water vapour becomes a liquid, heat is released. Thus when water is present at a surface, a proportion of the energy available will be used to evaporate it, and less energy will be available to raise local energy levels and temperature.

During the night, water vapour in the air close to the surface can condense to form water, since the air has been cooled by the cold surface. When water condenses, latent heat is released. This affects the cooling process at the surface. In some cases, evaporation may occur at night, especially in areas where there are local sources of heat.

Dew

Dew refers to condensation on a surface. The air is saturated, generally because the temperature of the surface has dropped enough to cause condensation. Occasionally, condensation occurs because more moisture is introduced, for example by a sea breeze, while the temperature remains constant.

Absorbed energy returned to Earth

The insolation received by the Earth will be reradiated as long-wave radiation. Some of this will be absorbed by water vapour and other greenhouse gases, thereby raising the temperature.

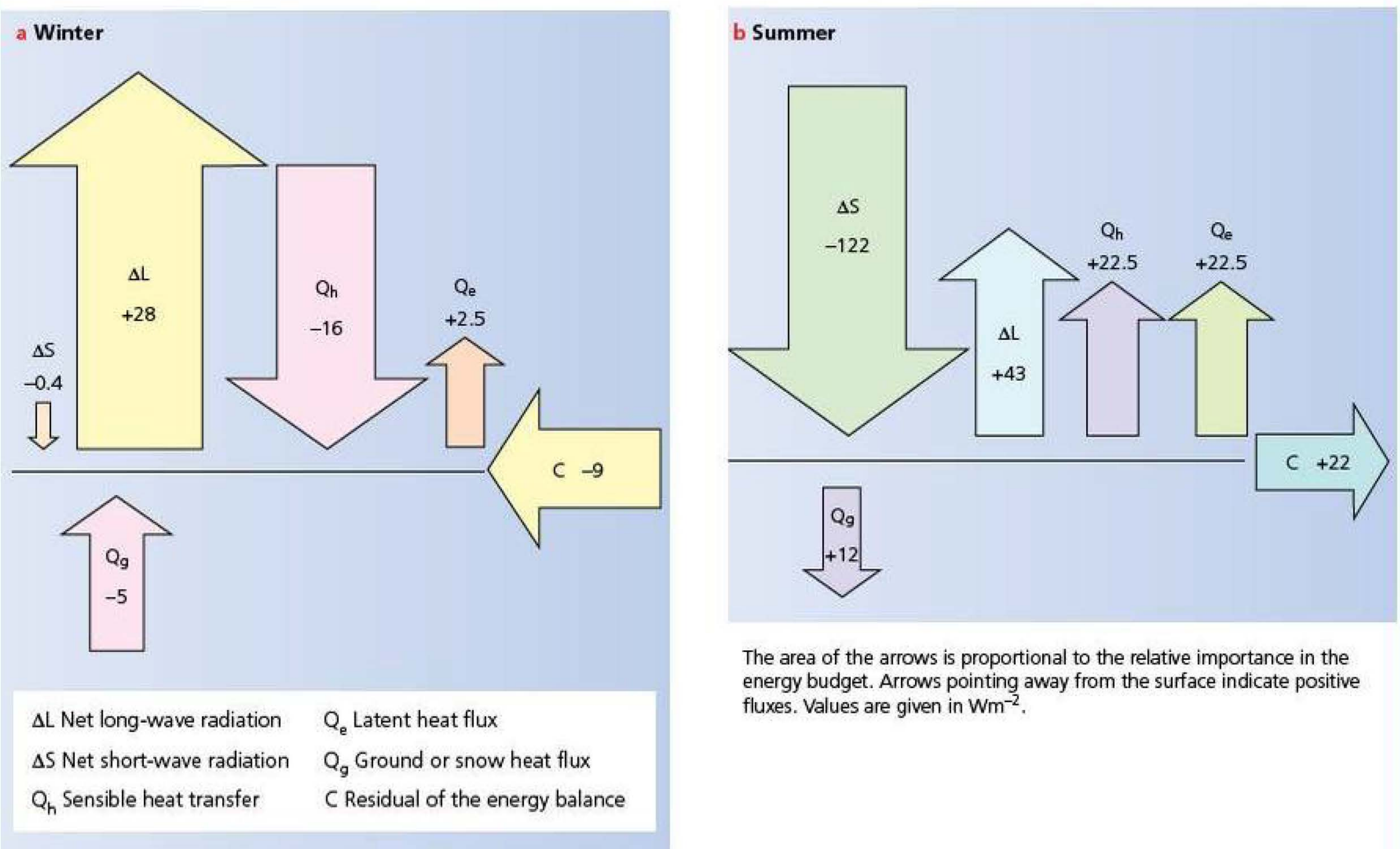
Temperature changes close to the surface

Ground-surface temperatures can vary considerably between day and night. During the day, the ground heats the air by radiation, conduction (contact) and convection. The ground radiates energy and as the air receives more radiation than it emits, the air is warmed. Air close to the ground is also warmed through conduction. Air movement at the surface is slower due to friction with the surface, so there is more time for it to be heated. The combined effect of radiation and conduction is that the air becomes warmer, and rises as a result of convection.

At night, the ground is cooled as a result of radiation. Heat is transferred from the air to the ground.

Case Study: Annual surface energy budget of an Arctic site – Svalbard, Norway

The annual cycle of the surface energy budget at a high-arctic permafrost site on Svalbard shows that during summer, the net short-wave radiation is the dominant energy source (Figure 2.7). In addition, sensible heat transfers and surface absorption in the ground lead to a cooling of the surface. About 15 per cent of the net radiation is used up by the seasonal thawing of the active layer in July and August (the active layer is the layer at the top of the soil that freezes in winter and thaws in summer). During the polar night in winter, the net long-wave radiation is the dominant energy loss channel for the surface, which is mainly compensated by the sensible heat transfer and, to a lesser extent, by the ground heat transfer, which originates from the refreezing of the active layer. The average annual sensible heat transfer of –6.9 Wm^{-2} is composed of strong positive transfers in July and August, while negative transfers dominate during the rest of the year. With 6.8 Wm^{-2}, the latent heat transfer more or less compensates the sensible heat transfer in the annual average. Strong evaporation occurs during the snowmelt period and particularly during the snow-free period in summer and autumn. When the ground is covered by snow, latent heat fluxes through sublimation of snow are recorded, but are insignificant for the average surface energy budget.



The area of the arrows is proportional to the relative importance in the energy budget. Arrows pointing away from the surface indicate positive fluxes. Values are given in Wm^{-2}.

Figure 2.7 Energy budgets for Svalbard

Section 2.1 Activities

1 With reference to Figure 2.7, draw the likely *night-time* energy budgets for Svalbard in summer and in winter.

2 Figure 2.8 shows rural and urban energy budgets for Washington DC (USA) during daytime and night-time. The figures represent the proportions of the original 100 units of incoming solar radiation dispersed in different directions.

a How does the amount of insolation received vary between the rural area and the urban area?

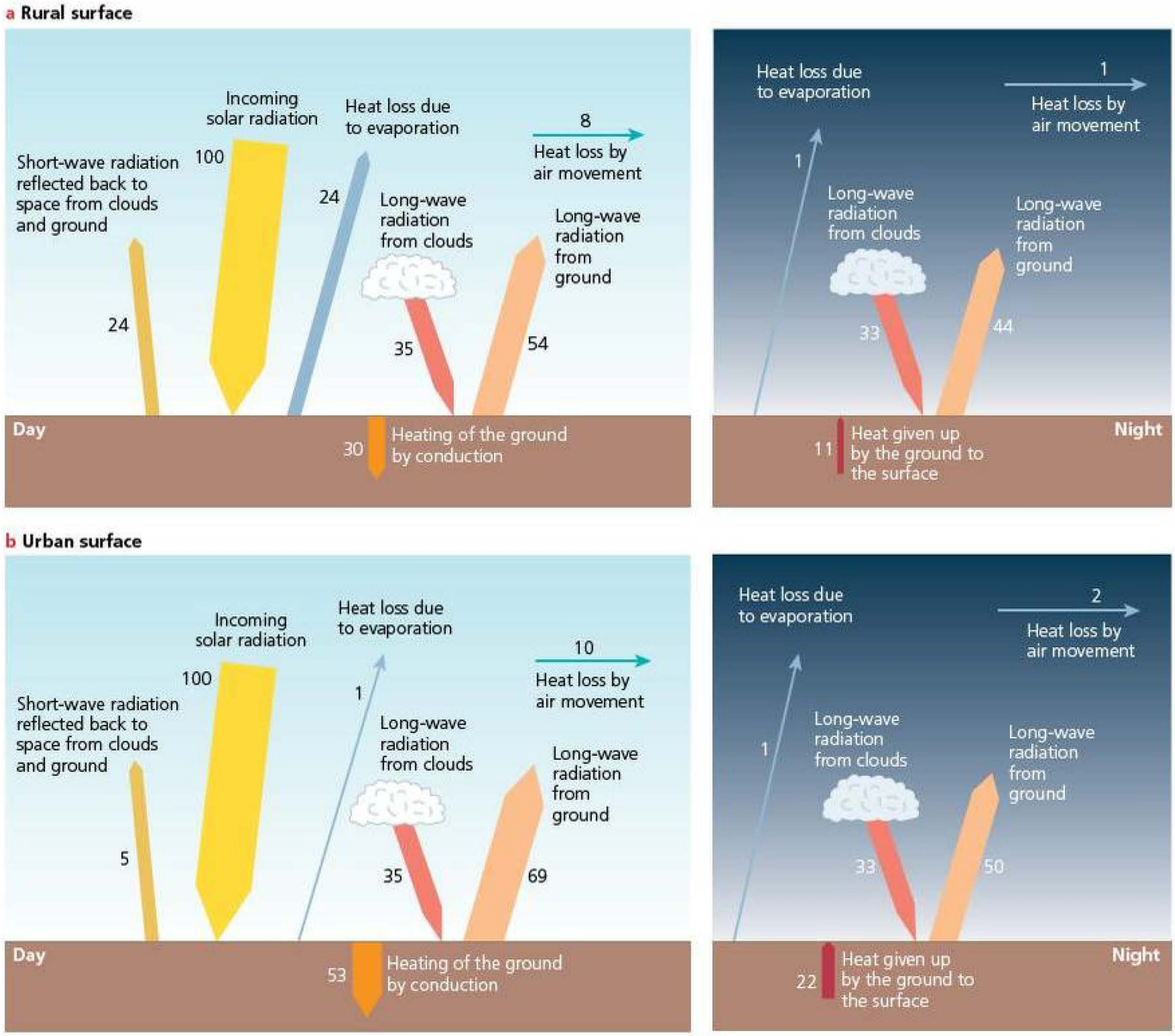
b How does the amount of heat lost through evaporation vary between the areas? Justify your answer.

c Explain the difference between the two areas in terms of short-wave radiation reflected to the atmosphere.

d What are the implications of the answers to **b** and **c** for the heating of the ground by conduction?

e Compare the amount of heat given up by the rural area and the urban area by night. Suggest two reasons for these differences.

f Why is there more long-wave radiation by night from the urban area than from the rural area?



The figures represent the proportions of the original 100 units of incoming solar radiation dispersed in different directions.

Source: University of Oxford, 1989, Entrance examination for Geography

Figure 2.8 Daytime and night-time energy budgets for Washington DC

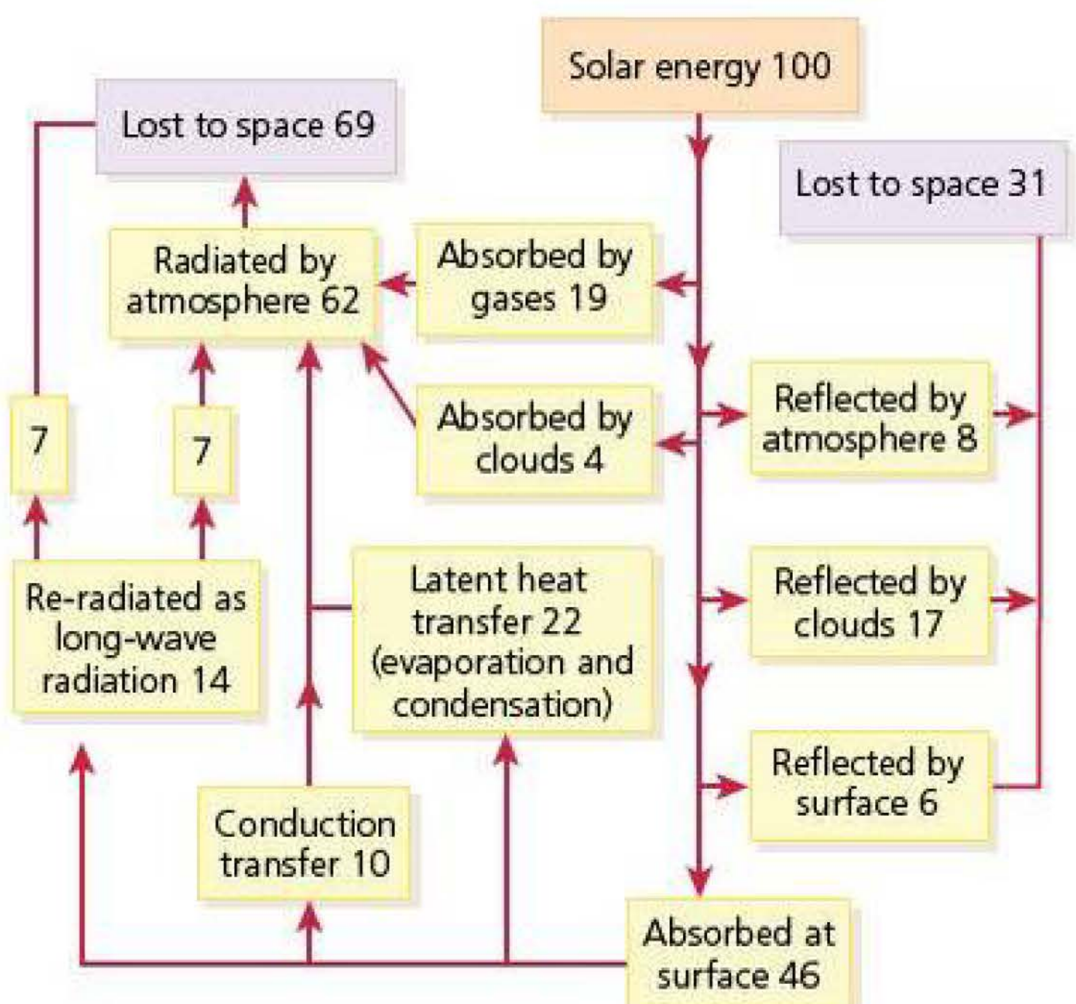
2.2 The global energy budget

The latitudinal pattern of radiation: excesses and deficits

The atmosphere is an open energy system, receiving energy from both Sun and Earth. Although the latter is very small, it has an important local effect, as in the case of urban climates. **In**coming **sol**ar radi**ation** is referred to as insolation.

The atmosphere constantly receives solar energy, yet until recently the atmosphere was not getting any hotter. Therefore there has been a balance between inputs (insolation) and outputs (re-radiation) (Figure 2.9). Under 'natural' conditions the balance is achieved in three main ways:

- **radiation** – the emission of electromagnetic waves such as X-ray, short- and long-wave; as the Sun is a very hot body, radiating at a temperature of about 5700 °C, most of its radiation is in the form of very short wavelengths such as ultraviolet and visible light
- **convection** – the transfer of heat by the movement of a gas or liquid
- **conduction** – the transfer of heat by contact.



Source: *Access to Geography – Climate and Society* by G. Nagle (Hodder Education, 2002) p.15

Figure 2.9 The Earth's energy budget

Of incoming radiation, 19 per cent is absorbed by atmospheric gases, especially oxygen and ozone at high altitudes, and carbon dioxide and water vapour at low altitudes. Reflection by the atmosphere accounts for a net loss of 8 per cent, and clouds and water droplets reflect 23 per cent. Reflection from the Earth's surface (known as the planetary albedo) is generally about 6 per cent. About 36 per cent of insolation is reflected back to space and a further 19 per cent is absorbed by atmospheric gases. So only about 46 per cent of the insolation at the top of the atmosphere actually gets through to the Earth's surface.

Energy received by the Earth is re-radiated at long wavelength. (Very hot bodies such as the Sun emit short-wave radiation, whereas cold bodies such as the Earth emit long-wave radiation.) Of this, 8 per cent is lost to space. Some energy is absorbed by clouds and re-radiated back to Earth. Evaporation and condensation account for a loss of heat of 22 per cent. There is also a small amount of condensation (carried up by turbulence). Thus heat gained by the atmosphere from the ground amounts to 32 per cent of incoming radiation.

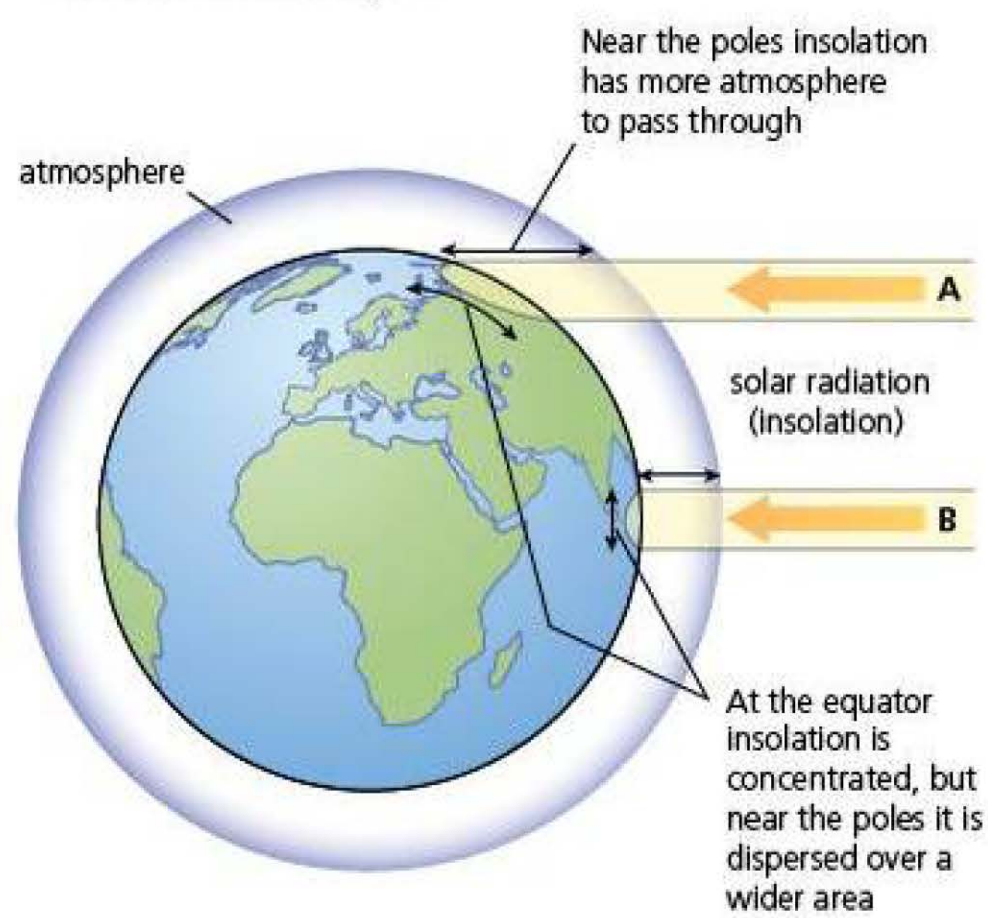
The atmosphere is largely heated from below. Most of the incoming short-wave radiation is let through, but some outgoing long-wave radiation is trapped by greenhouse gases. This is known as the greenhouse principle or greenhouse effect.

There are important variations in the receipt of solar radiation with latitude and season (Figure 2.10). The result is an imbalance: an excess of radiation (positive budget) in the tropics; a deficit of radiation (negative balance) at higher latitudes (Figure 2.11). However, neither region is getting progressively hotter or colder. To achieve this balance, the horizontal transfer of energy from the equator to the poles takes place by winds and ocean currents. This gives rise to an important second energy budget in the atmosphere: the horizontal transfer between low latitudes and high latitudes to compensate for differences in global insolation.

Latitude

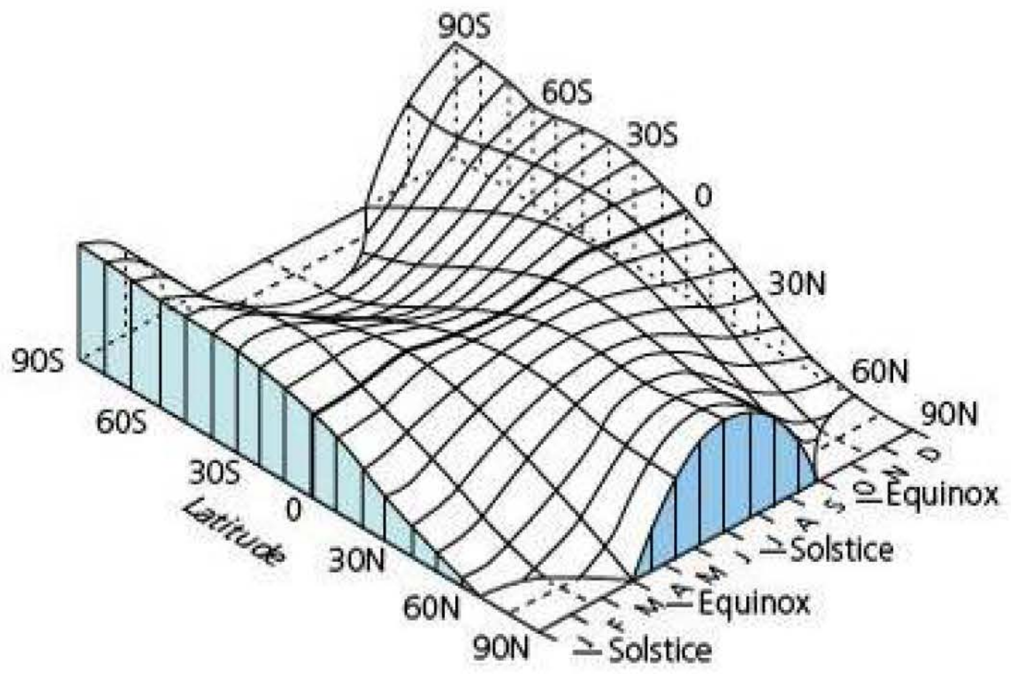
Areas that are close to the equator receive more heat than areas that are close to the poles. This is due to two reasons:

1. Incoming solar radiation (insolation) is concentrated near the equator, but dispersed near the poles.
2. Insolation near the poles has to pass through a greater amount of atmosphere and there is more chance of it being reflected back out to space.



Source: Nagle, G., *Geography through diagrams*, OUP, 1998

Figure 2.10 Latitudinal contrasts in insolation



The variations of solar radiation with latitude and season for the whole globe, assuming no atmosphere. This assumption explains the abnormally high amounts of radiation received at the poles in summer, when daylight lasts for 24 hours each day.

Source: Barry, R. and Chorley, R., *Atmosphere, Weather and Climate*, Routledge, 1998

Figure 2.11 Contrasts in insolation by season and latitude

Section 2.2 Activities

1 Outline the main thermal differences between short-wave and long-wave radiation.
2 Study Figures 2.10 and 2.11. Comment on latitudinal differences in the receipt of solar radiation.

Annual temperature patterns

There are important large-scale north–south temperature zones (Figure 2.12). For example, in January highest temperatures over land (above 30 °C) are found in Australia and southern Africa. By contrast, the lowest temperatures (less than –40 °C) are found over parts of Siberia, Greenland and the Canadian Arctic. In general, there is a decline in temperatures northwards from the Tropic of Capricorn, although there are important anomalies, such as the effect of the Andes in South America, and the effect of the cold current off the coast of Namibia. In July, maximum temperatures are found over the Sahara, Near East, northern India and parts of southern USA and Mexico. By contrast, areas in the southern hemisphere are cooler than in January.

These patterns reflect the general decrease of insolation from the equator to the poles. There is little seasonal variation at the equator, but in mid or high latitudes large seasonal differences occur due to the decrease in insolation from the equator to the poles, and changes in the length of day. There is also a time lag between the overhead Sun and the period of maximum insolation – up to two months in some places – largely because the air is heated from below, not above. The coolest period is after the winter solstice (the shortest day), since the ground continues to lose heat even after insolation has resumed. Over oceans, the lag time is greater than over the land, due to differences in their specific heat capacities.

Section 2.2 Activities

Describe the differences in temperature as shown in Figure 2.12. Suggest reasons for these contrasts.

Atmospheric transfers

There are two main influences on atmospheric transfer: pressure variations and ocean currents. Air blows from high pressure to low pressure, and is important in redistributing heat around the Earth. In addition, the atmosphere is influenced by ocean currents – warm currents raise the temperature of overlying air, while cold currents cool the air above them (see pages 39–40).

Pressure variations

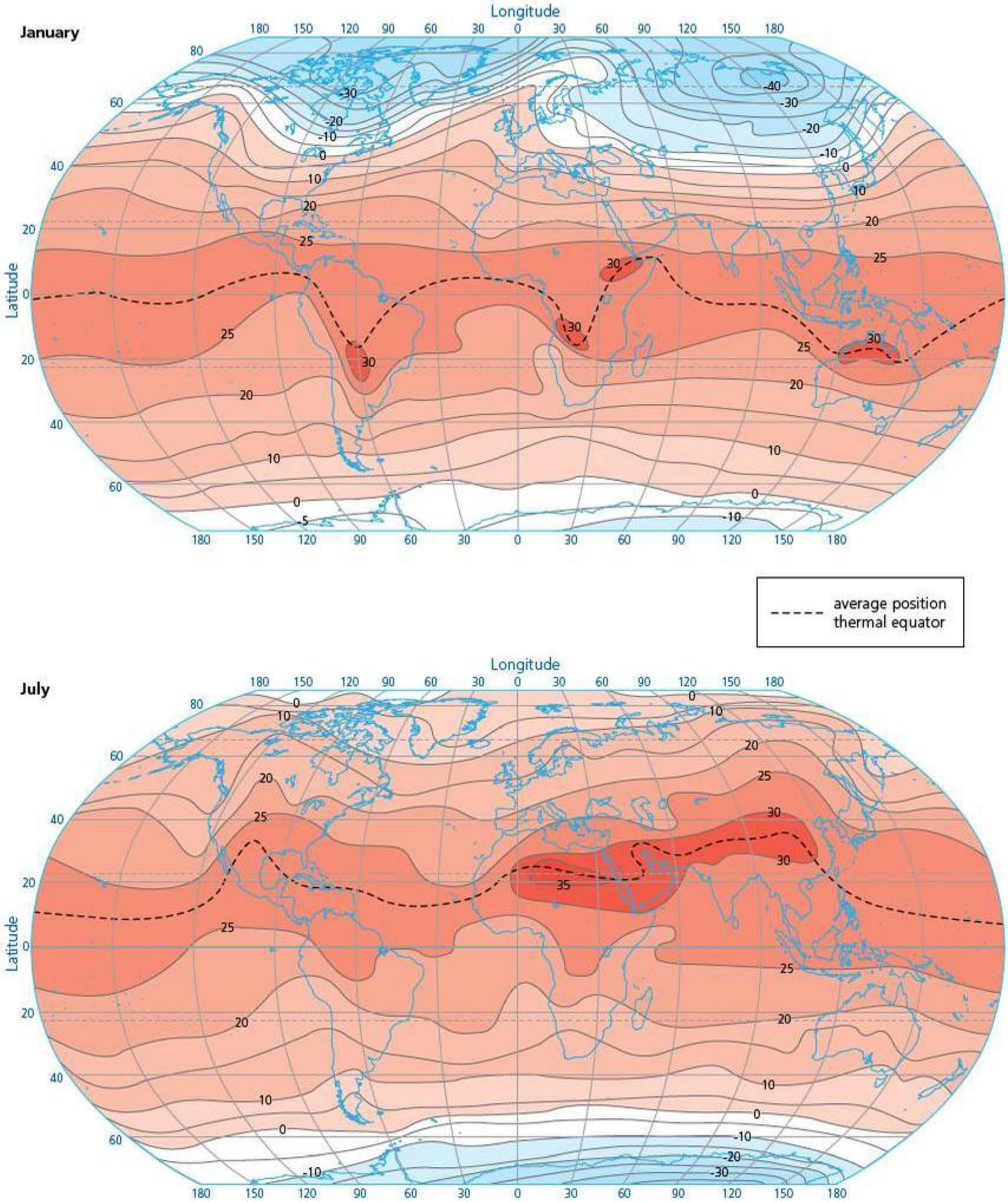
Pressure is measured in millibars (mb) and is represented by isobars, which are lines of equal pressure. On maps, pressure is adjusted to mean sea level (MSL), therefore eliminating elevation as a factor. MSL pressure is 1013 mb, although the mean range is from 1060 mb in the Siberian winter high-pressure system to 940 mb (although some intense low pressure storms may be much lower). The trend of pressure change is more important than the actual reading itself. Decline in pressure indicates poorer weather, and rising pressure better weather.

Surface pressure belts

Sea-level pressure conditions show marked differences between the hemispheres. In the northern hemisphere there are greater seasonal contrasts, whereas in the southern hemisphere much simpler average conditions exist (see Figure 2.13). Over Antarctica there is generally high pressure over the 3–4 kilometre-high eastern Antarctic Plateau, but the high pressure is reduced by altitude. The differences are largely related to unequal distribution of land and sea, because ocean areas are much more equable in terms of temperature and pressure variations.

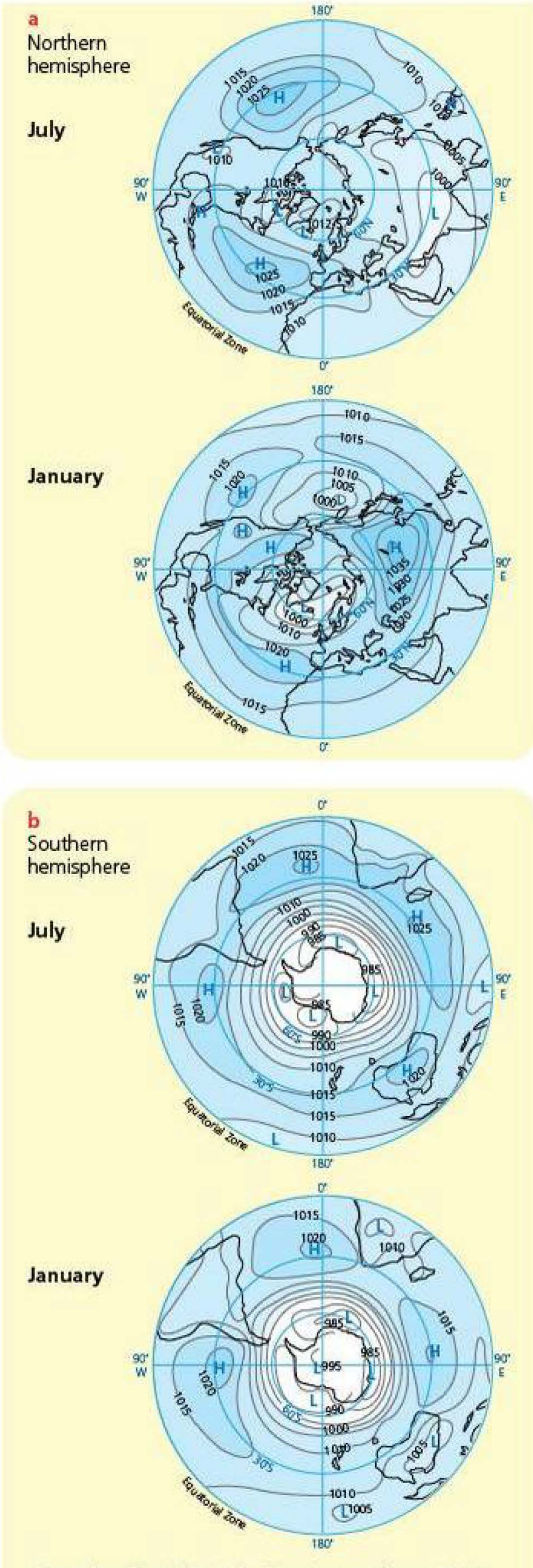
One of the more permanent features is the subtropical high-pressure (STHP) belts, especially over ocean areas. In the southern hemisphere these are almost continuous at about 30° latitude, although in summer over South Africa and Australia they tend to be broken. Generally pressure is about 1026 mb. In the northern hemisphere, by contrast, at 30° the belt is much more discontinuous because of the land. High pressure only occurs over the ocean as discrete cells such as the Azores and Pacific highs. Over continental areas such as south-west USA, southern Asia and the Sahara, major fluctuations occur: high pressure in winter, and summer lows because of overheating.

Over the equatorial trough, pressure is low: 1008–1010 mb. The trough coincides with the zone of maximum insolation. In the northern hemisphere (in July) it is well north of the equator (25 °C over India), whereas in the southern hemisphere (in January) it is just south of the equator because land masses in the southern hemisphere are not



Source: Briggs, D et al., *Fundamentals of the physical environment*, Routledge, 1997

Figure 2.12 Seasonal temperature patterns of sufficient size to displace it southwards. The 'doldrums' refers to the equatorial trough over sea areas, where slack pressure gradients have a becalming effect on sailing ships.



Source: Barry, R. and Chorley, R., *Atmosphere, weather and climate*, Routledge, 1998

Figure 2.13 Variations in pressure

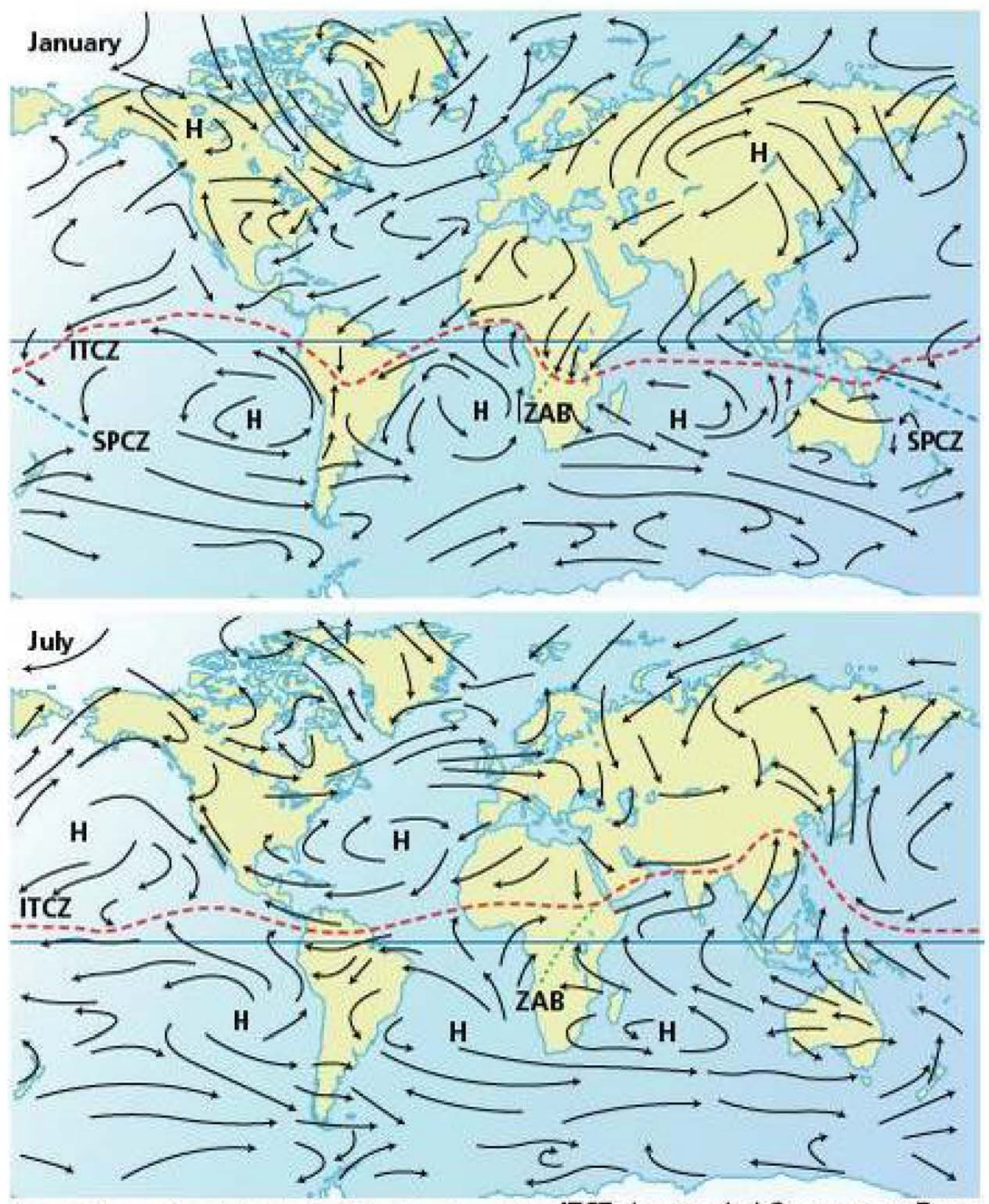
Section 2.2 Activities

Describe the variations in pressure as shown on Figure 2.13.

In temperate latitudes, pressure is generally less than in subtropical areas. The most unique feature is the large number of depressions (low pressure) and anticyclones (high pressure), which do not show up on a map of mean pressure. In the northern hemisphere, there are strong winter low-pressure zones over Icelandic and oceanic areas, but over Canada and Siberia there is high pressure, due to the coldness of the land. In summer, high pressure is reduced. In polar areas pressure is relatively high throughout the year, especially over Antarctica, owing to the coldness of the land mass.

Surface wind belts

Winds between the Tropics converge on a line known as the intertropical convergence zone (ITCZ) or equatorial trough (Figure 2.14). This convergence zone is a few hundred kilometres wide, into which winds blow inwards and subsequently rise (thereby forming an area of low pressure). The rising air releases vast quantities of latent heat, which in turn stimulates convection.



Source: Linacre, E. and Geerts, B., *Climates and Weather Explained*, Routledge, 1997

ITCZ Intertropical Convergence Zone
ZAB Zaïre Air Boundary
SPCZ South Pacific Convergence Zone
H Centre of high pressure
Equator

Figure 2.14 Surface winds

Latitudinal variations in the ITCZ occur as a result of the movement of the overhead Sun. In June the ITCZ lies further north, whereas in December it lies in the southern hemisphere. The seasonal variation in the ITCZ is greatest over Asia, owing to its large land mass. By contrast, over the Atlantic and Pacific Oceans its movement is far less. Winds at the ITCZ are generally light (the doldrums), occasionally broken by strong westerlies, generally in the summer months.

Low-latitude winds between 10° and 30° are mostly easterlies; that is, they flow towards the west. These are the reliable trade winds; they blow over 30 per cent of the world's surface. The weather in this zone is fairly predictable: warm, dry mornings and showery afternoons, caused by the continuous evaporation from tropical seas. Showers are heavier and more frequent in the warmer summer season.

Occasionally there are disruptions to the pattern; easterly waves are small-scale systems in the easterly flow of air. The flow is greatest not at ground level but at the 700 mb level. Ahead of the easterly wave, air is subsiding; hence there is surface divergence. At the easterly wave, there is convergence of air, and ascent – as in a typical low pressure system. Easterly waves are important for the development of tropical cyclones (Section 9.3).

Westerly winds dominate between 35° and 60° of latitude, which accounts for about a quarter of the world's surface. However, unlike the steady trade winds, these contain rapidly evolving and decaying depressions.

The word 'monsoon' means 'reverse'; the monsoon is reversing wind systems. For example, the south-east trades from the southern hemisphere cross the equator in July. Owing to the Coriolis force, these south-east trades are deflected to the right in the northern hemisphere and become south-west winds. The monsoon is induced by Asia – the world's largest continent – which causes winds to blow outwards from high pressure in winter, but pulls the southern trades into low pressure in the summer.

The monsoon is therefore influenced by the reversal of land and sea temperatures between Asia and the Pacific during the summer and winter. In winter, surface temperatures in Asia may be as low as –20 °C. By contrast, the surrounding oceans have temperatures of 20 °C. During the summer, the land heats up quickly and may reach 40 °C. By contrast, the sea remains cooler at about 27 °C. This initiates a land–sea breeze blowing from the cooler sea (high pressure) in summer to the warmer land (low pressure), whereas in winter air flows out of the cold land mass (high pressure) to the warm water (low pressure). The presence of the Himalayan Plateau also disrupts the strong winds of the upper atmosphere, forcing winds either to the north or south and consequently deflecting surface winds.

The uneven pattern shown in Figure 2.14 is the result of seasonal variations in the overhead Sun. Summer in the southern hemisphere means that there is a cooling in the northern hemisphere, thereby increasing the differences between polar and equatorial air. Consequently, high-level westerlies are stronger in the northern hemisphere in winter.

Section 2.2 Activities

Describe the main global wind systems shown in Figure 2.14.

Explaining variations in temperature, pressure and winds

Latitude

On a global scale, latitude is the most important factor determining temperature (Figure 2.10). Two factors affect the temperature: the angle of the overhead Sun and the thickness of the atmosphere. At the equator, the overhead Sun is high in the sky, so the insolation received is of a greater quality or intensity. At the poles, the overhead Sun is low in the sky, so the quality of energy received is poor. Secondly, the thickness of the atmosphere affects temperature. Energy has more atmosphere to pass through at point A on Figure 2.10, so more energy is lost, scattered or reflected by the atmosphere than at B – therefore temperatures are lower at A than at B. In addition, the albedo (reflectivity) is higher in polar regions. This is because snow and ice are very reflective, and low-angle sunlight is easily reflected from water surfaces. However, variations in length of day and season partly offset the lack of intensity in polar and arctic regions. The longer the Sun shines, the greater the amount of insolation received, which may overcome in part the lack of intensity of insolation in polar regions. (On the other hand, the long polar nights in winter lose vast amounts of energy.)

Land–sea distribution

There are important differences in the distribution of land and sea in the northern hemisphere and southern hemisphere. There is much more land in the northern hemisphere. Oceans cover about 50 per cent of the Earth's surface in the northern hemisphere but about 90 per cent of the southern hemisphere (Figure 2.15). This is not always clear when looking at conventional map projections such as the Mercator projection.

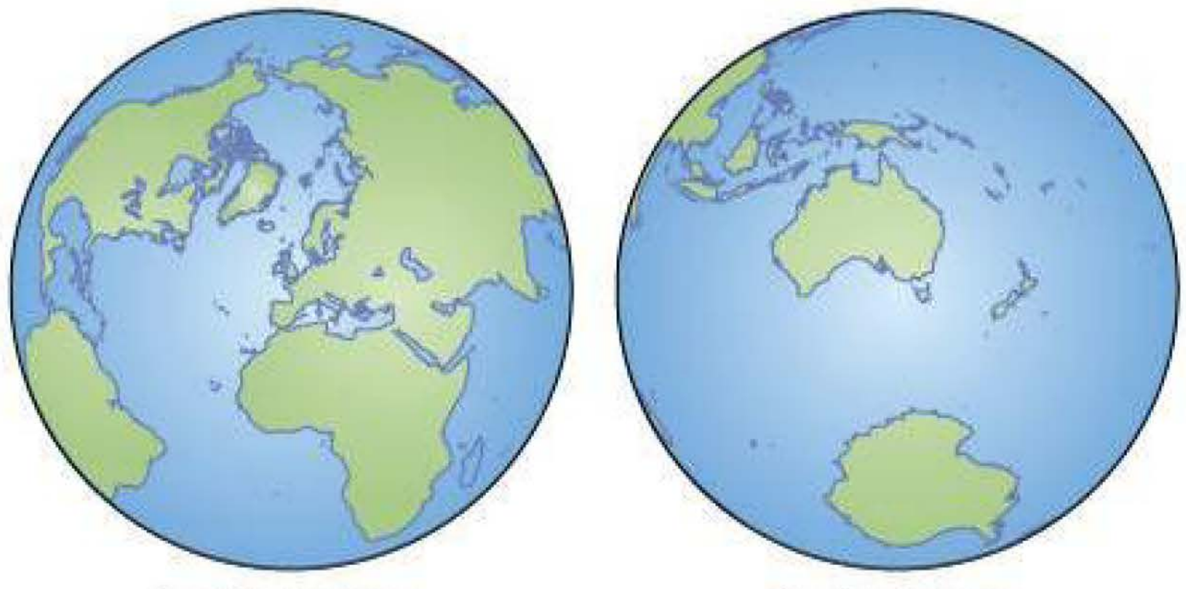


Figure 2.15 Land and sea hemispheres

The distribution of land and sea is important because land and water have different thermal properties. The specific heat capacity is the amount of heat needed to raise the temperature of a body by 1 °C. There are important differences between the heating and cooling of water. Land heats and cools more quickly than water. It takes five times as much heat to raise the temperature of water by 2 °C as it does to raise land temperatures.

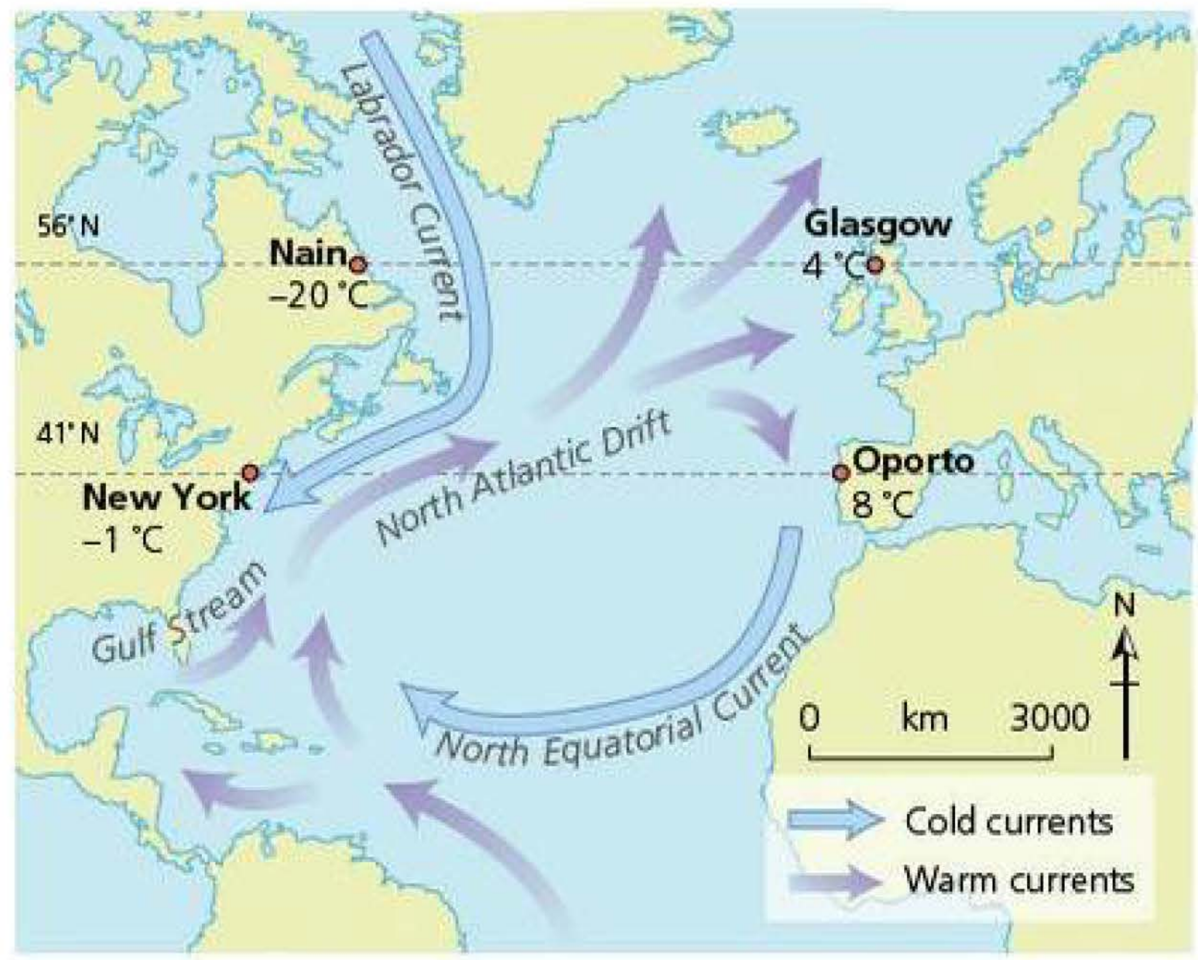
Water heats more slowly because:

- it is clear, so the Sun's rays penetrate to great depth, distributing energy over a wider area
- tides and currents cause the heat to be further distributed.

Therefore a larger volume of water is heated for every unit of energy than the volume of land, so water takes longer to heat up. Distance from the sea has an important influence on temperature. Water takes up heat and gives it back much more slowly than the land. In winter, in mid-latitudes sea air is much warmer than the land air, so onshore winds bring heat to the coastal lands. By contrast, during the summer coastal areas remain much cooler than inland sites. Areas with a coastal influence are termed maritime or oceanic, whereas inland areas are called continental.

Ocean currents

Surface ocean currents are caused by the influence of prevailing winds blowing steadily across the sea. The dominant pattern of surface ocean currents (known as gyres) is roughly a circular flow. The pattern of these currents is clockwise in the northern hemisphere and anti-clockwise in the southern hemisphere. The main exception is the circumpolar current that flows around Antarctica from west to east. There is no equivalent current in the northern hemisphere because of the distribution of land and sea there. Within the circulation of the gyres, water piles up into a dome. The effect of the rotation of the Earth is to cause water in the oceans to push westward; this piles up water on the western edge of ocean basins – rather like water slopping in a bucket. The return flow is often narrow, fast-flowing currents such as the Gulf Stream. The Gulf Stream in particular transports heat northwards and then eastwards across the North Atlantic; the Gulf Stream is the main reason that the British Isles have mild winters and relatively cool summers (Figure 2.16).



The effect of an ocean current depends upon whether it is a warm current or a cold current. Warm currents move away from the equator, whereas cold currents move towards it. The cold Labrador Current reduces the temperatures of the western side of the Atlantic, while the warm North Atlantic Drift raises temperatures on the eastern side.

Source: Nagle, G., *Geography through diagrams*, OUP, 1998

Figure 2.16 The effects of the North Atlantic Drift/Gulf Stream

The effect of ocean currents on temperatures depends upon whether the current is cold or warm. Warm currents from equatorial regions raise the temperature of polar areas (with the aid of prevailing westerly winds). However, the effect is only noticeable in winter. For example, the North Atlantic Drift raises the winter temperatures of north-west Europe. By contrast, other areas are made colder by ocean currents. Cold currents such as the Labrador Current off the north-east coast of North America may reduce summer temperatures, but only if the wind blows from the sea to the land.

In the Pacific Ocean, there are two main atmospheric states. The first is warm surface water in the west with cold surface water in the east; the other is warm surface water in the east with cold in the west. In both cases, the warm surface causes low pressure. As air blows from high pressure to low pressure, there is a movement of water from the colder area to the warmer area. These winds push warm surface water into the warm region, exposing colder deep water behind them and maintaining the pattern.

The ocean conveyor belt

In addition to the transfer of energy by wind and the transfer of energy by ocean currents, there is also a transfer of energy by deep sea currents. Oceanic convection movement is from polar regions where cold salty water sinks into the depths and makes its way towards the equator (Figure 2.17). The densest water is found in the Antarctic, where sea water freezes to form ice at a temperature of around –2 °C. The ice is fresh water, so the sea water that is left behind is much saltier and therefore denser. This cold dense water sweeps around Antarctica at a depth of about 4 kilometres. It then spreads into the deep basins of the Atlantic, the Pacific and the Indian Oceans. In the oceanic conveyor-belt model, surface currents bring warm water to the North Atlantic from the Indian and Pacific Oceans. These waters give up their heat to cold winds that blow from Canada across the North Atlantic. This water then sinks and starts the reverse convection of the deep ocean current. The amount of heat given up is about a third of the energy that is received from the Sun. The pattern is maintained by salt: because the conveyor operates in this way, the North Atlantic is warmer than the North Pacific, so there is proportionally more evaporation there. The water left behind by evaporation is saltier and therefore much denser, which causes it to sink. Eventually, the water is transported into the Pacific where it picks up more water and its density is reduced.

Section 2.2 Activities

Outline the main factors affecting global and regional temperatures.

Factors affecting air movement

Pressure and wind

Vertical air motion is important on a local scale, whereas horizontal motion (wind) is important at many scales, from small-scale eddies to global wind systems. The basic cause of air motion is the unequal heating of the Earth's surface. The major equalising factor is the transfer of heat by air movement. Variable heating of the Earth causes variations in pressure and this in turn sets the air in

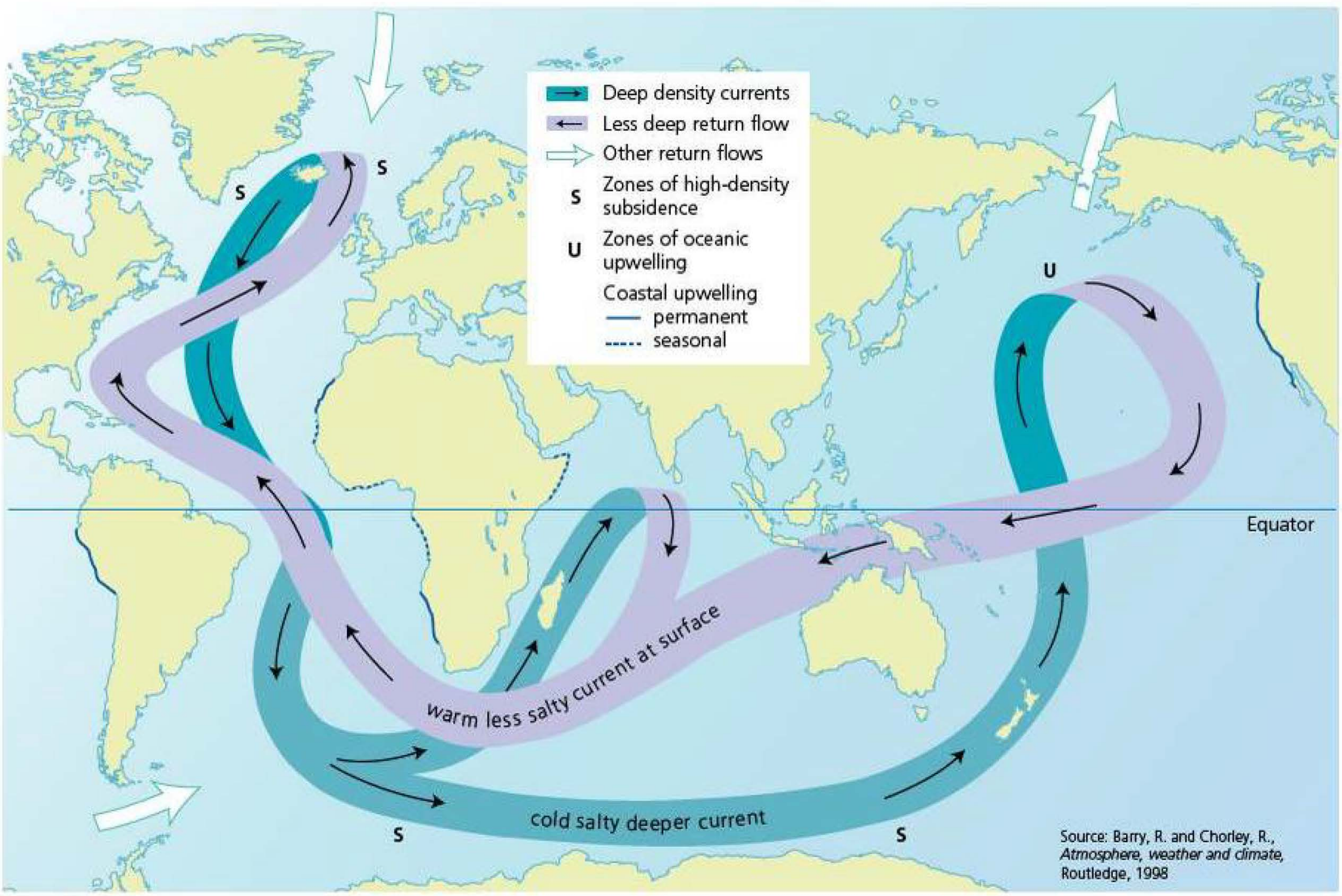
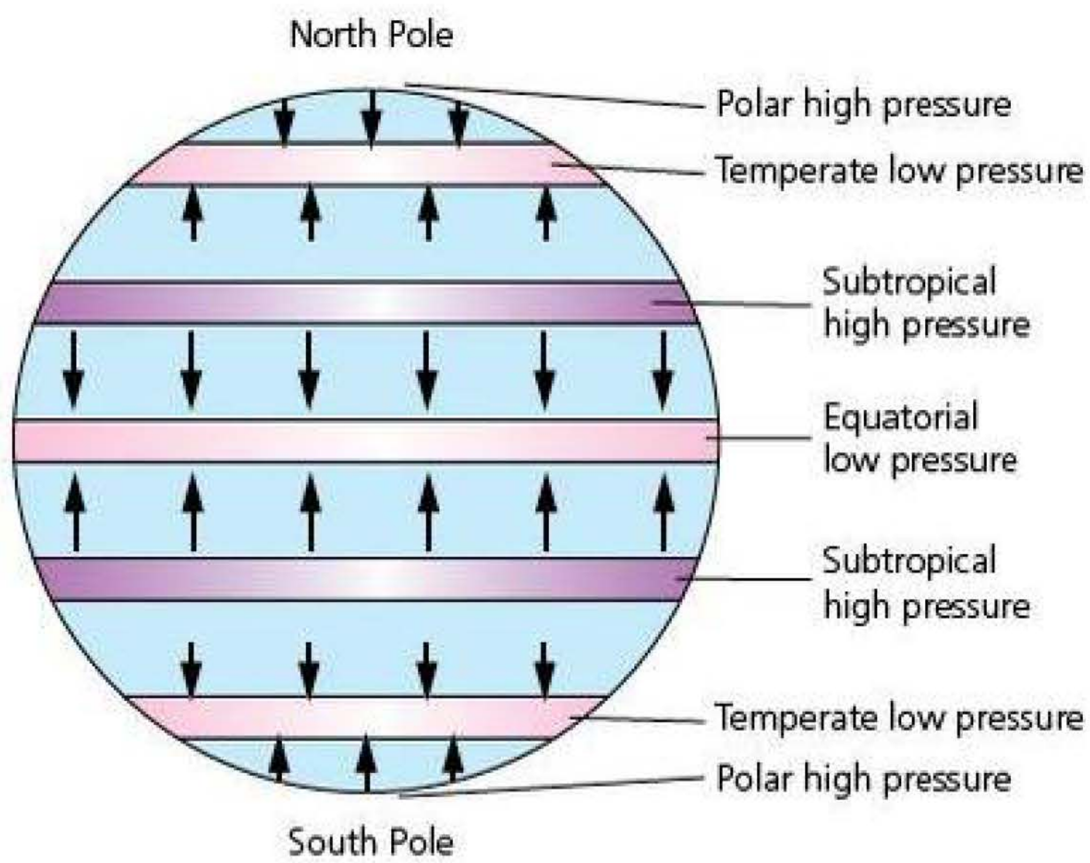


Figure 2.17 The ocean conveyor belt

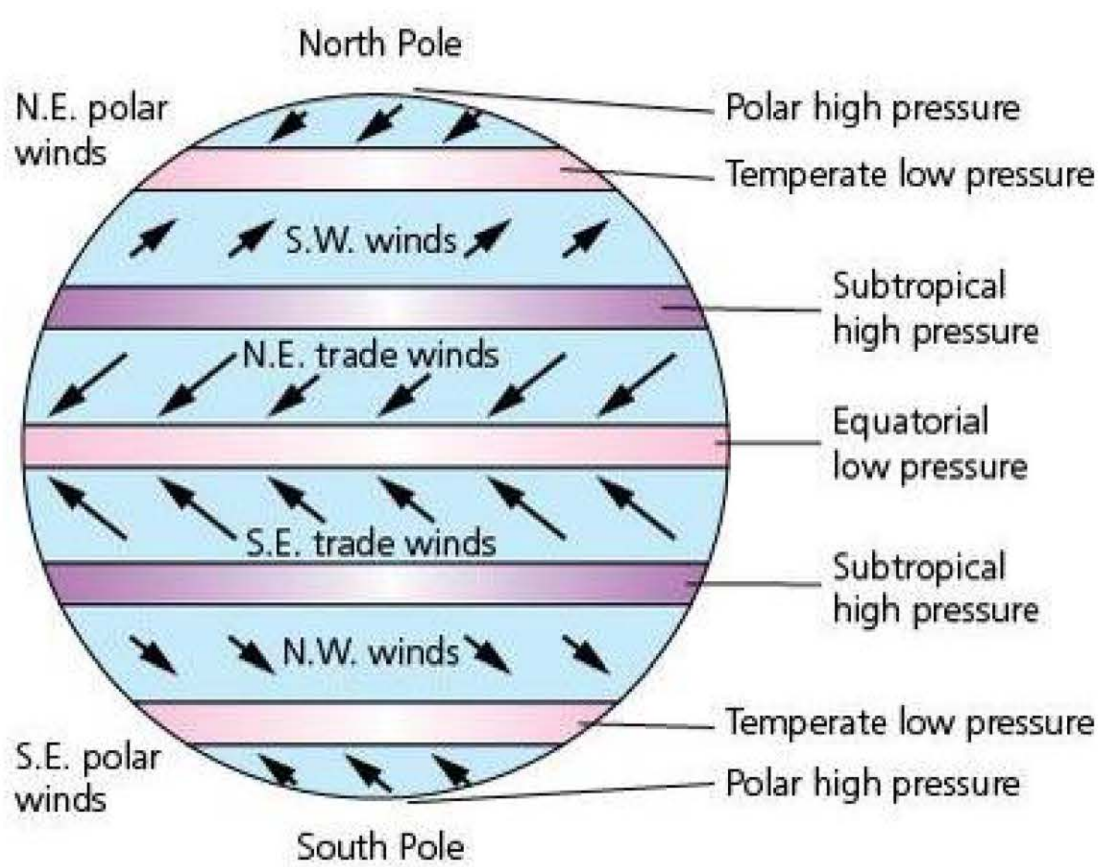
motion. There is thus a basic correlation between winds and pressure.

Pressure gradient

The driving force is the pressure gradient; that is, the difference in pressure between any two points. Air blows from high pressure to low pressure (Figure 2.18). Globally, very high pressure conditions exist over Asia in winter due to the low temperatures. Cold air contracts, leaving room for adjacent air to converge at high altitude, adding to the weight and pressure of the air. By contrast, the mean sea-level pressure is low over continents in summer. High surface temperatures produce atmospheric expansion and therefore a reduction in air pressure. High pressure dominates at around 25–30° latitude. The highs are centred over the oceans in summer and over the continents in winter – whichever is cooler.



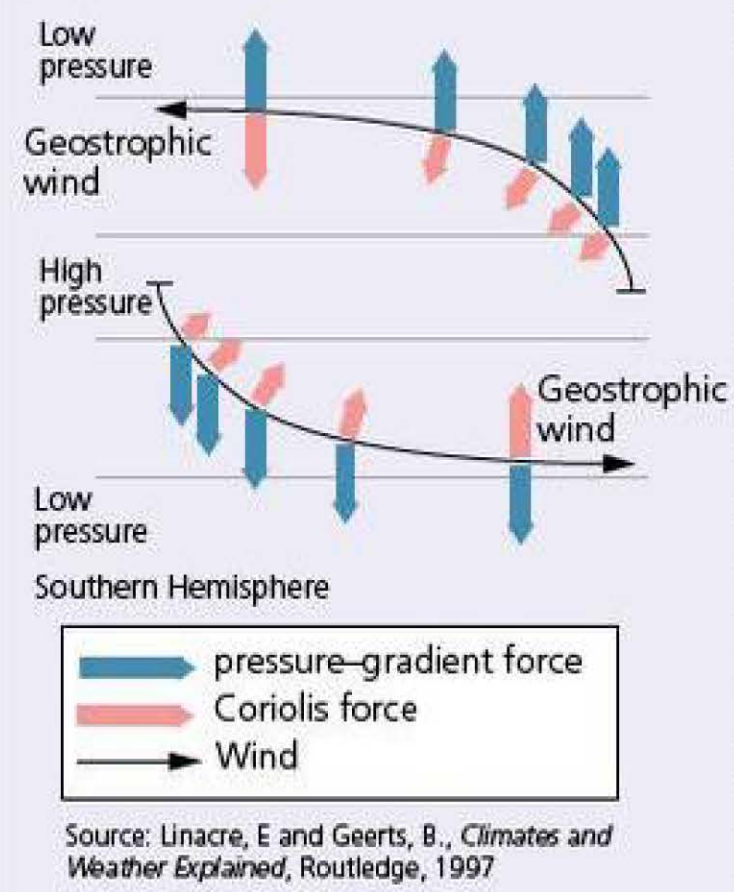
a How the winds would blow on a non-rotating Earth



b How the winds blow on a rotating Earth

Figure 2.18 Pressure gradient winds

The Coriolis force is the deflection of moving objects caused by the easterly rotation of the Earth (Figure 2.19). Air flowing from high pressure to low pressure is deflected to the right of its path in the northern hemisphere and to the left of its path in the southern hemisphere. The Coriolis force is at right angles to wind direction.



The apparent deflection of a parcel of air moving from a belt of high pressure in the southern hemisphere (e.g. from the band of subtropical high pressures). The parcel is assumed stationary initially. As soon as it starts to move, it suffers a sideways Coriolis force, increasing in proportion to its acceleration. The force deflects the parcel until it is travelling along an isobar, with a constant speed such that the Coriolis force balances the pressure–gradient force.

Figure 2.19 The Coriolis force

Every point on the Earth completes one rotation every 24 hours. Air near the equator travels a much greater distance than air near the poles. Air that originates near the equator is carried towards the poles, taking with it a vast momentum. The Coriolis force deflects moving objects to the right of their path in the northern hemisphere and to the left of their path in the southern hemisphere.

The balance of forces between the pressure gradient force and the Coriolis force is known as the geostrophic balance and the resulting wind is known as a geostrophic wind. The geostrophic wind in the northern hemisphere blows anti-clockwise around the centre of low pressure and clockwise around the centre of high pressure.

This centrifugal force is the outward force experienced when you drive a vehicle around a corner. The centrifugal force acts at right angles to the wind, pulling objects outwards, so for a given pressure, airflow is faster around high pressure (because the pressure gradient and centrifugal forces work together rather than in opposite directions).

The drag exerted by the Earth's surface is also important. Friction decreases wind speed, so it decreases the Coriolis force, hence air is more likely to flow towards low pressure.

Section 2.2 Activities

Briefly explain the meaning of the terms **a** *pressure gradient force* and **b** *Coriolis force*.

General circulation model

In general:

- warm air is transferred polewards and is replaced by cold air moving towards the equator
- air that rises is associated with low pressure, whereas air that sinks is associated with high pressure
- low pressure produces rain; high pressure produces dry conditions.

Any circulation model must take into account the meridional (north/south) transfer of heat, and latitudinal variations in rainfall and winds. (Any model is descriptive and static – unlike the atmosphere.) In 1735, George Hadley described the operation of the Hadley cell, produced by the direct heating over the equator. The air here is forced to rise by convection, travels polewards and then sinks at the subtropical anticyclone (high-pressure belt). Hadley suggested that similar cells might exist in mid-latitudes and high latitudes. William Ferrel suggested that Hadley cells interlink with a mid-latitude cell, rotating it in the reverse direction, and these cells in turn rotate the polar cell.

There are very strong differences between surface and upper winds in tropical latitudes. Easterly winds at the surface are replaced by westerly winds above, especially in winter. At the ITCZ, convectional storms lift air into the atmosphere, which increases air pressure near the tropopause, causing winds to diverge at high altitude. They move out of the equatorial regions towards the poles, gradually losing heat by radiation. As they contract, more air moves in and the weight of the air increases the air pressure at the subtropical high-pressure zone (Figure 2.20). The denser air sinks, causing subsidence (stability). The north/south component of the Hadley cell is known as a meridional flow. The Ferrel Cell was originally considered to be a thermally indirect cell (driven by the Hadley cell and polar cell). Now it is known to be more complex, and there is some equator-ward movement of air related to temperate high- and low-pressure systems. These are related to Rossby waves and jet streams (Figure 2.20c).

The zonal flow (east–west) over the Pacific was discovered by Gilbert Walker in the 1920s. The Southern Oscillation Index (SOI) is a measure of how far temperatures vary from the 'average'. A high SOI is associated with strong westward trades (because winds near the equator blow from high pressure to low pressure and are unaffected by the Coriolis force). Tropical cyclones are more common in the South Pacific when there is an El Niño Southern Oscillation warm episode.

The polar cell is found in high latitudes. Winds at the highest latitudes are generally easterly. Air over the North Pole continually cools; and being cold, it is dense and therefore it subsides, creating high pressure. Air above the polar front flows back to the North Pole, creating a polar cell. In between the Hadley cell and the polar cell is an indirect cell, the Ferrel cell, driven by the movement of the other two cells, rather like a cog in a chain.

In the early twentieth century, researchers investigated patterns and mechanisms of upper winds and clouds at an altitude of between 3 and 12 kilometres. They identified large-scale fast-moving belts of westerly winds, which follow a ridge and trough wave-like pattern known as Rossby waves or planetary waves (Figure 2.21). The presence of these winds led to Rossby's 1941 model of the atmosphere. This suggested a three-cell north/south (meridional) circulation, with two thermally direct cells and one thermally indirect cell. The thermally direct cell is driven by the heating at the equator (the Hadley cell) and by the sinking of cold air at the poles (the polar cell). Between them lies the thermally indirect cell whose energy is obtained from the cells to either side by the mixing of the atmosphere at upper levels. The jet streams are therefore key locations in the transfer of energy through the atmosphere. Further modifications of Rossby's models were made by Palmen in 1951.

New models change the relative importance of the three convection cells in each hemisphere. These changes are influenced by jet streams and Rossby waves:

- Jet streams are strong, regular winds that blow in the upper atmosphere about 10 km above the surface; they blow between the poles and tropics (100–300 km/h).
- There are two jet streams in each hemisphere – one between 30° and 50°; the other between 20° and 30°. In the northern hemisphere, the polar jet and the subtropical jet flow eastwards.
- Rossby waves are 'meandering rivers of air' formed by westerly winds. There are three to six waves in each hemisphere. They are formed by major relief barriers such as the Rockies and the Andes, by thermal differences and uneven land–sea interfaces.

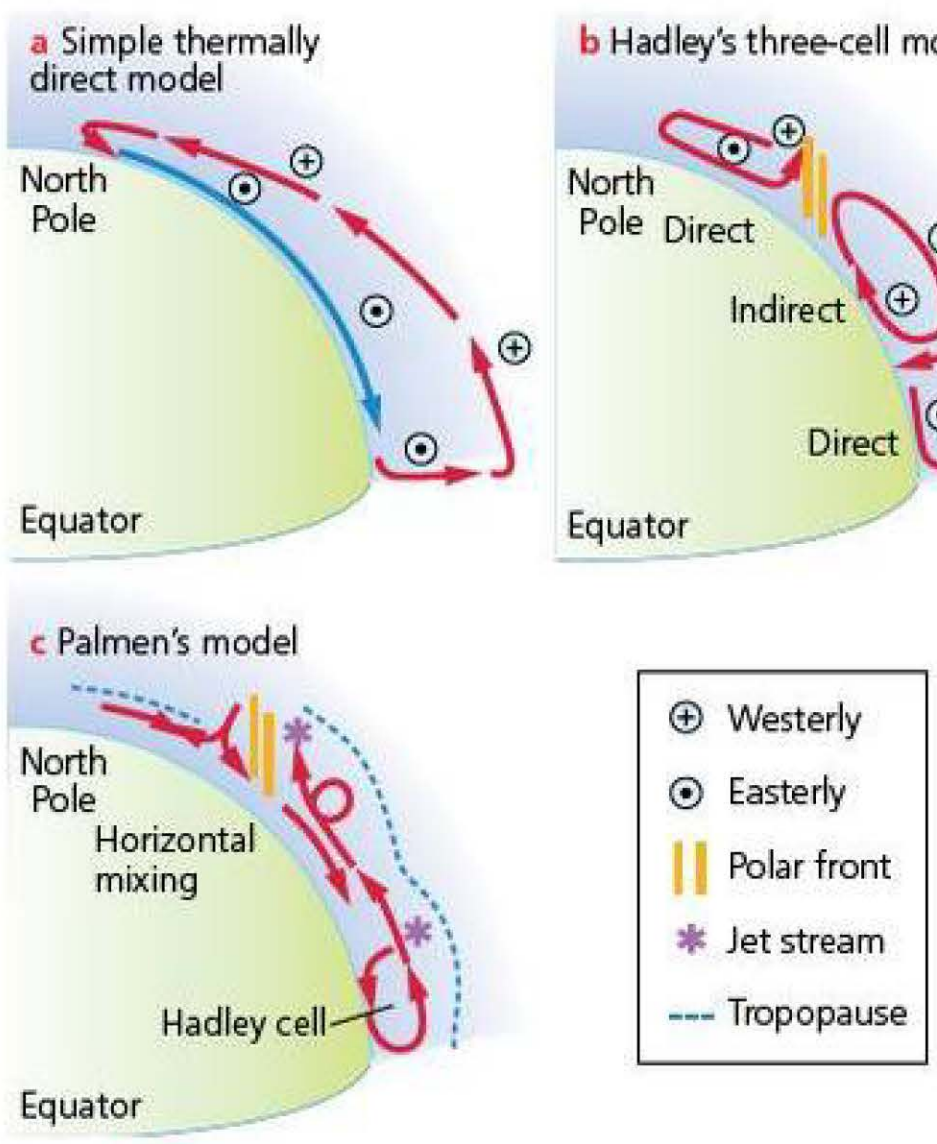


Figure 2.20 General circulation model

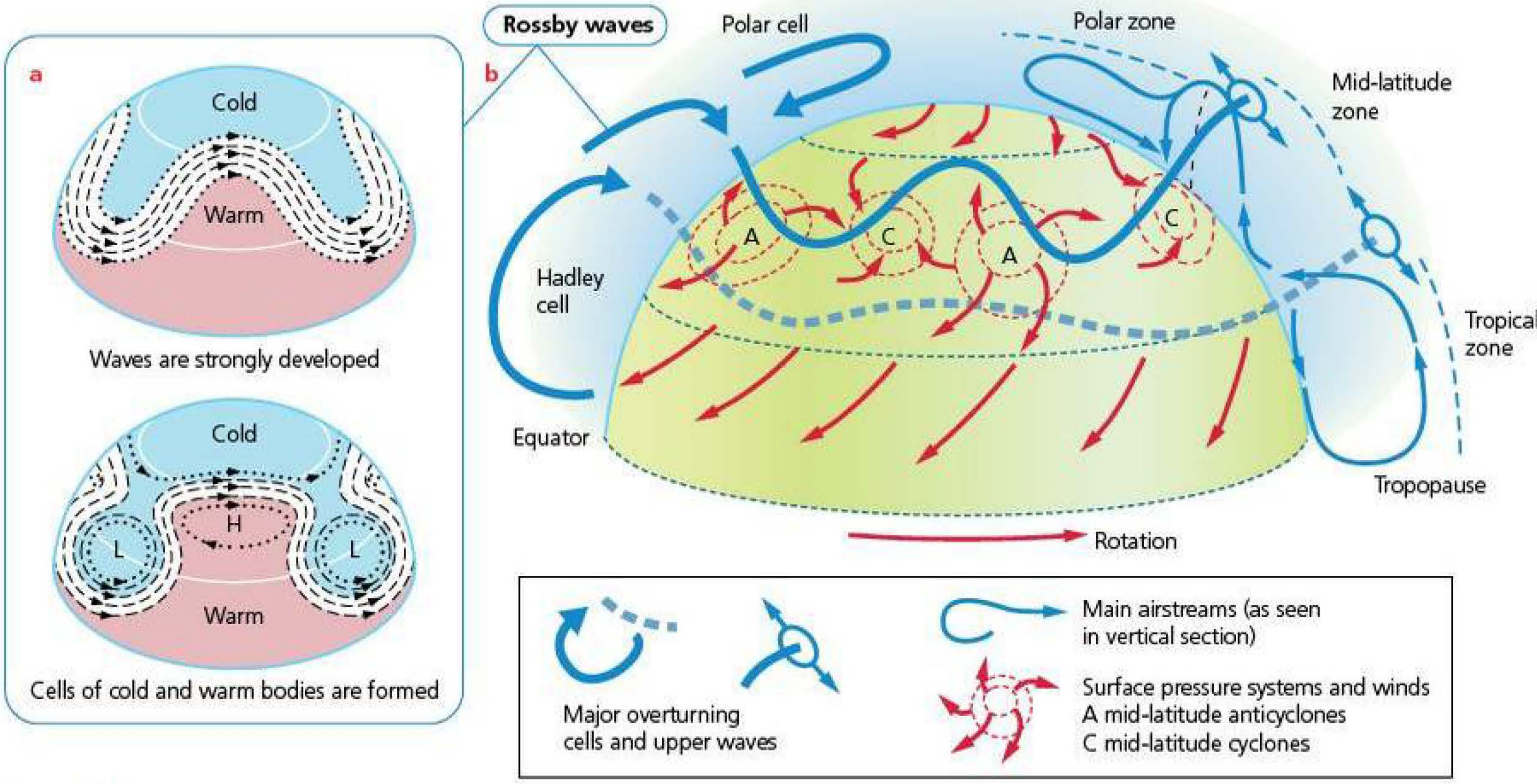


Figure 2.21 Rossby waves

- The jet streams result from differences in equatorial and sub-tropical air, and between polar and sub-tropical air. The greater the temperature difference, the stronger the jet stream.

Rossby waves are affected by major topographic barriers such as the Rockies and the Andes. Mountains create a wave-like pattern, which typically lasts six weeks. As the pattern becomes more exaggerated (Figure 2.21b), it leads to blocking anticyclones (blocking highs) – prolonged periods of unusually warm weather.

Jet streams and Rossby waves are an important means of mixing warm and cold air.

Section 2.2 Activities

1. Describe and explain how the Hadley cell operates.
2. Define the term *Rossby wave*. Suggest how an understanding of Rossby waves may help in our understanding of the general circulation.

2.3 Weather processes and phenomena

Atmospheric moisture processes

Atmospheric moisture exists in all three states – vapour, liquid and solid (Figures 2.22–2.24). Energy is used in the change from one phase to another, for example between a liquid and a gas. In evaporation, heat is absorbed. It takes 600 calories of heat to change 1 gram of water from a liquid to a vapour. Heat loss during evaporation passes into the water as latent heat (of vaporisation). This would cool 1 kilogram of air by 2.5 °C. By contrast, when condensation occurs, latent heat locked in the water vapour is released, causing a rise in temperature. In the changes between vapour and ice, heat is released when vapour is converted to ice (solid), for example rime at high altitudes and high latitudes. In contrast, heat is absorbed in the process of sublimation, for example when snow patches disappear without melting. When liquid water turns to ice, heat is released and temperatures drop. In contrast, in melting ice heat is absorbed and temperatures rise.

Figure 2.22 Atmospheric moisture – condensation

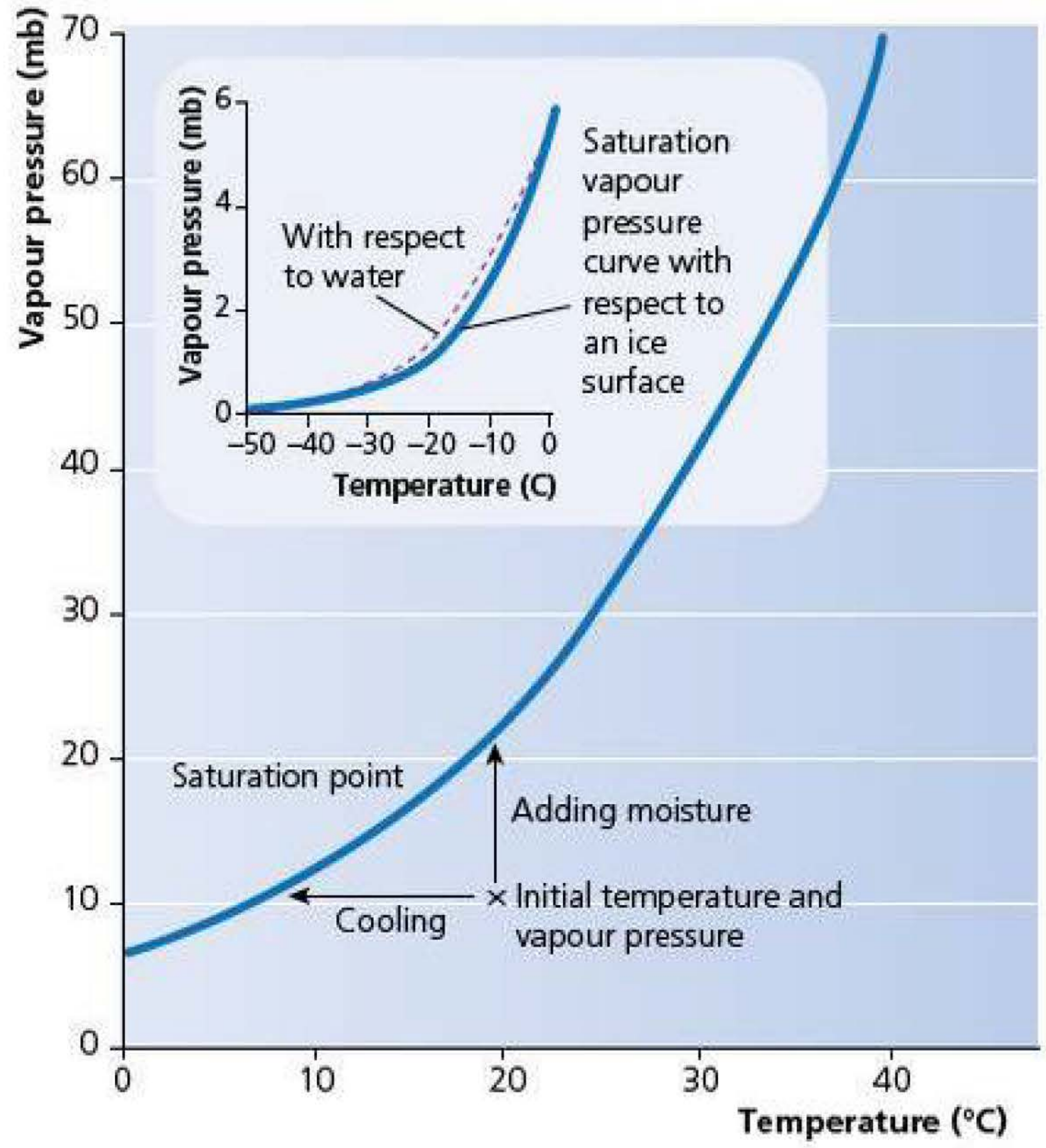
Figure 2.23 Radiation fog in the lower part of alpine valleys

Figure 2.24 Moisture in its liquid state – Augher Lake, Gap of Dunloe, Killarney, Ireland

Factors affecting evaporation

Evaporation occurs when vapour pressure of a water surface exceeds that in the atmosphere. Vapour pressure is the pressure exerted by the water vapour in the atmosphere. The maximum vapour pressure at any temperature occurs when the air is saturated (Figure 2.25). Evaporation aims to equalise the pressures. It depends on three main factors:

- **initial humidity of the air** – if air is very dry then strong evaporation occurs; if it is saturated then very little occurs
- **supply of heat** – the hotter the air, the more evaporation that takes place
- **wind strength** – under calm conditions the air becomes saturated rapidly.



The curves demonstrate how much moisture the air can hold for any temperature. Below 0 °C the curve is slightly different for an ice surface than for a supercooled water droplet.

Source: Briggs et al., *Fundamentals of the physical environment*, Routledge, 1997

Figure 2.25 Maximum vapour pressure

Factors affecting condensation

Condensation occurs when either **a** enough water vapour is evaporated into an air mass for it to become saturated or **b** when the temperature drops so that dew point (the temperature at which air is saturated) is reached. The first is relatively rare; the second common. Such cooling occurs in three main ways:

- radiation cooling of the air
- contact cooling of the air when it rests over a cold surface
- adiabatic (expansive) cooling of air when it rises.

Condensation is very difficult to achieve in pure air. It requires some tiny particle or nucleus onto which the vapour can condense. In the lower atmosphere these are quite common, such as sea salt, dust and pollution particles. Some of these particles are hygroscopic – that is, water-seeking – and condensation may occur when the relative humidity is as low as 80 per cent.

Other processes

Freezing refers to the change of liquid water into a solid, namely ice, once the temperature falls below 0 °C. Melting is the change from a solid to a liquid when the air temperature rises above 0 °C. Sublimation is the conversion of a solid into a vapour with no intermediate liquid state. Under conditions of low humidity, snow can be evaporated directly into water vapour without entering the liquid state. Sublimation is also used to describe the direct deposition of water vapour onto ice. In some cases, water droplets may be deposited directly onto natural features (such as plants and animals) as well as built structures (for example buildings and vehicles).

Precipitation

The term 'precipitation' refers to all forms of deposition of moisture from the atmosphere in either solid or liquid states. It includes rain, hail, snow and dew. Because rain is the most common form of precipitation in many areas, the term is sometimes applied to rainfall alone. For any type of precipitation, except dew, to form, clouds must first be produced.

When minute droplets of water are condensed from water vapour, they float in the atmosphere as clouds. If droplets coalesce, they form large droplets that, when heavy enough to overcome by gravity an ascending current, they fall as rain. Therefore cloud droplets must get much larger to form rain. There are a number of theories to suggest how raindrops are formed.

The Bergeron theory suggests that for rain to form, water and ice must exist in clouds at temperatures below 0 °C. Indeed, the temperature in clouds may be as low as –40 °C. At such temperatures, water droplets and ice droplets form. Ice crystals grow by condensation and become big enough to overcome turbulence and cloud updrafts, so they fall. As they fall, crystals coalesce to form larger snowflakes. These generally melt and become rain as they pass into the warm air layers near the ground. Thus, according to Bergeron, rain comes from clouds that are well below freezing at high altitudes, where the coexistence of water and ice is possible. The snow/ice melts as it passes into clouds at low altitude where the temperatures are above freezing level.

Other mechanisms must also exist as rain also comes from clouds that are not so cold. Mechanisms include:

- condensation on extra-large hygroscopic nuclei
- coalescence by sweeping, whereby a falling droplet sweeps up others in its path
- the growth of droplets by electrical attraction.

Causes of precipitation

The Bergeron theory relates mostly to snow-making. Snow is a single flake of frozen water. Rain and drizzle are found when the temperature is above 0°C (drizzle has a diameter of < 0.5 mm). Sleet is partially melted snow.

There are three main types of rainfall: convectional, frontal (depressional) and orographic (relief) (Figure 2.26).

Convectional rainfall

When the land becomes very hot, it heats the air above it. This air expands and rises. As it rises, cooling and condensation take place. If it continues to rise, rain will fall. It is very common in tropical areas (Figure 2.27) and is associated with the permanence of the ITCZ. In temperate areas, convectional rain is more common in summer.

Frontal or cyclonic rainfall

Frontal rain occurs when warm air meets cold air. The warm air, being lighter and less dense, is forced to rise over the cold, denser air. As it rises, it cools, condenses and forms rain. It is most common in middle and high latitudes where warm tropical air and cold polar air converge.

Orographic (or relief) rainfall

Air may be forced to rise over a barrier such as a mountain. As it rises, it cools, condenses and forms rain. There is often a rainshadow effect, whereby the leeward slope receives a relatively small amount of rain. Altitude is important, especially on a local scale. In general, there are increases of precipitation up to about 2 kilometres. Above this level, rainfall decreases because the air temperature is so low.

Thunderstorms (intense convectional rainfall)

Thunderstorms are special cases of rapid cloud formation and heavy precipitation in unstable air conditions. Absolute or conditional instability exists to great heights, causing strong updraughts to develop within cumulonimbus clouds. Air continues to rise as long as it is saturated (relative humidity is 100 per cent; that is, it has reached its dew point). Thunderstorms are especially common in tropical and warm areas where air can hold large amounts of water. They are rare in polar areas.

Several stages can be identified (Figure 2.28):

1. **Developing stage:** updraught caused by uplift; energy (latent heat) is released as condensation occurs; air becomes very unstable; rainfall occurs as cloud temperature is greater than 0 °C; the great strength of uplift prevents snow and ice from falling.
2. **Mature stage:** sudden onset of heavy rain and maybe thunder and lightning; rainfall drags cold air down with it; upper parts of the cloud may reach the tropopause; the cloud spreads, giving the characteristic anvil shape.
3. **Dissipating stage:** downdraughts prevent any further convective instability; the new cells may be initiated by the meeting of cold downdraughts from cells some distance apart, triggering the rise of warm air in between.

Lightning occurs to relieve the tension between different charged areas, for example between cloud and ground or within the cloud itself. The upper parts of the cloud are positive, whereas the lower parts are negative. The very base of the cloud is positively charged. The origin of the charges is not very clear, although they are thought to be

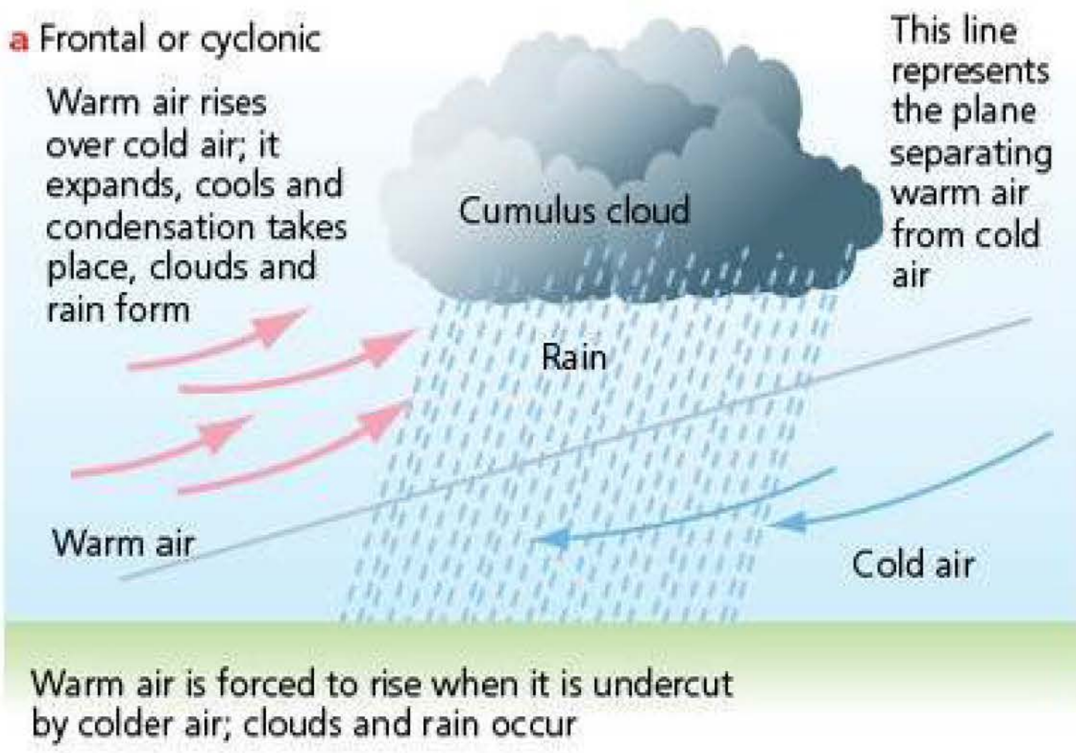
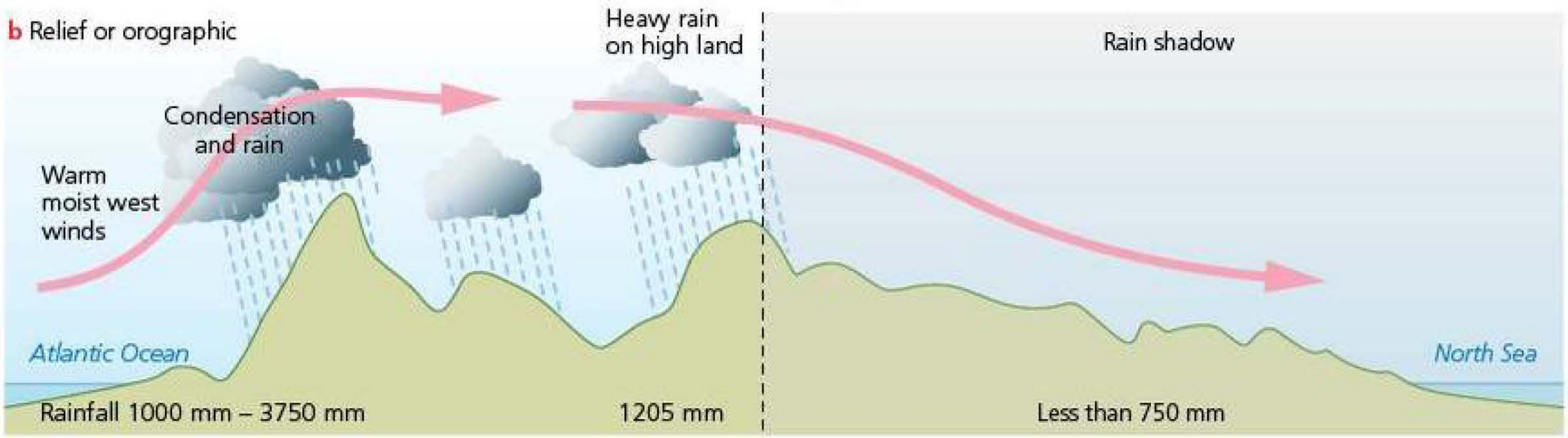


Figure 2.27 Convectional rain in Brunei



Source: Nagle, G. *Geography Through Diagrams*, OUP 1998

Figure 2.26 Types of precipitation

due to condensation and evaporation. Lightning heats the air to very high temperatures. Rapid expansion and vibration of the column of air produces thunder.

Section 2.3 Activities

Using diagrams, explain the meaning of the terms **a** *convectional rainfall*, **b** *orographic rainfall*, **c** *frontal rainfall*.

Clouds

Clouds are formed of millions of tiny water droplets held in suspension. They are classified in a number of ways, the most important being:

- **form or shape**, such as stratiform (layers) and cumuliform (heaped type)
- **height**, such as low (<2000 m), medium or alto (2000–7000 m) and high (7000–13 000 m).

There are a number of different types of clouds (Figure 2.29). High clouds consist mostly of ice crystals. Cirrus are wispy clouds, and include cirrocumulus (mackerel sky) and cirrostratus (halo effect around the Sun or Moon). Alto or middle-height clouds generally consist of water drops. They exist at temperatures lower than 0 °C. Low clouds indicate poor weather. Stratus clouds are dense, grey and low lying (Figure 2.30). Nimbostratus are those that produce rain ('nimbus' means 'storm'). Stratocumulus are long cloud rolls, and a mixture of stratus and cumulus (see Figure 2.6 in Section 2.1).

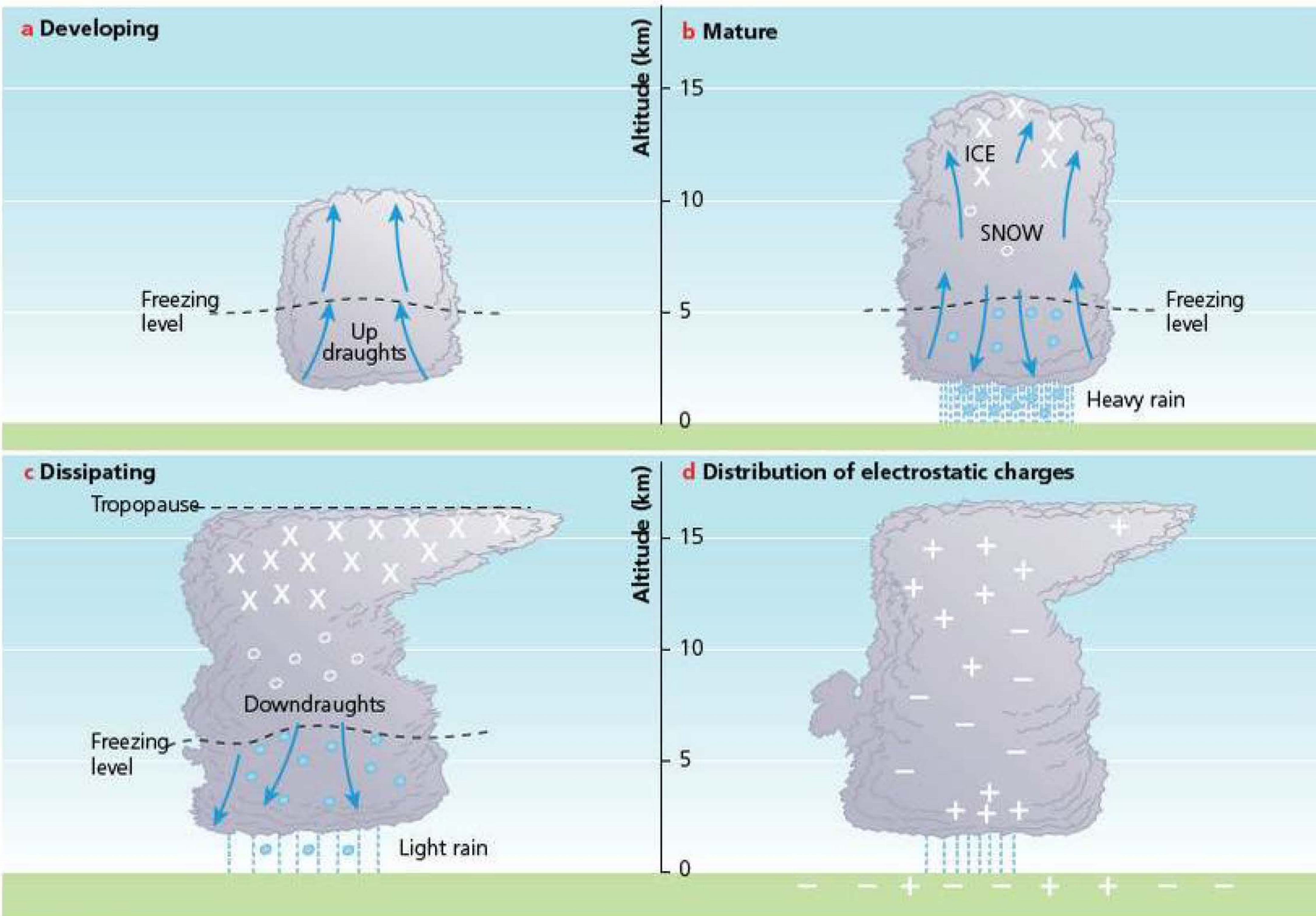


Figure 2.28 Stages in a thunderstorm

Vertical development suggests upward movement. Cumulus clouds are flat-bottomed and heaped. They indicate bright brisk weather. Cumulonimbus clouds produce heavy rainfall and often thunderstorms.

The important facts to keep in mind:

- In unstable conditions, the dominant form of uplift is convection and this may cause cumulus clouds.
- With stable conditions, stratiform clouds generally occur.
- Where fronts are involved, a variety of clouds exist.
- Relief or topography causes stratiform or cumuliform clouds, depending on the stability of the air.

Banner clouds

These are formed by orographic uplift (that is, air forced to rise, over a mountain for example) under stable air conditions. Uplifted moist air streams reach condensation only at the very summit, and form a small cloud. Further downwind the air sinks, and the cloud disappears. Wave clouds reflect the influence of the topography on the flow of air.

Types of precipitation

Rain

Rain refers to liquid drops of water with a diameter of between 0.5 millimetres and 5 millimetres. It is heavy enough to fall to the ground. Drizzle refers to rainfall with a diameter of less than 0.5 millimetres. Rainfall varies in terms of total amount, seasonality, intensity, duration and effectiveness; that is, whether there is more rainfall than potential evapotranspiration. (Refer back to page 45 for more information on the three main types of rainfall.)

Hail

Hail is alternate concentric rings of clear and opaque ice, formed by raindrops being carried up and down in vertical air currents in large cumulonimbus clouds. Freezing and partial melting may occur several times before the pellet is large enough to escape from the cloud. As the raindrops are carried high up in the cumulonimbus cloud they freeze. The hailstones may collide with droplets of supercooled water, which freeze on impact with and form a layer of opaque ice around the hailstone. As the hailstone falls, the outer layer may be melted but may freeze again with further uplift. The process can occur many times before the hail finally falls to ground, when its weight is great enough to overcome the strong updraughts of air.

Snow

Snow is frozen precipitation (Figure 2.31). Snow crystals form when the temperature is below freezing and water vapour is converted into a solid. However, very cold air contains a limited amount of moisture, so the heaviest snowfalls tend to occur when warm moist air is forced over very high mountains or when warm moist air comes into contact with very cold air at a front.

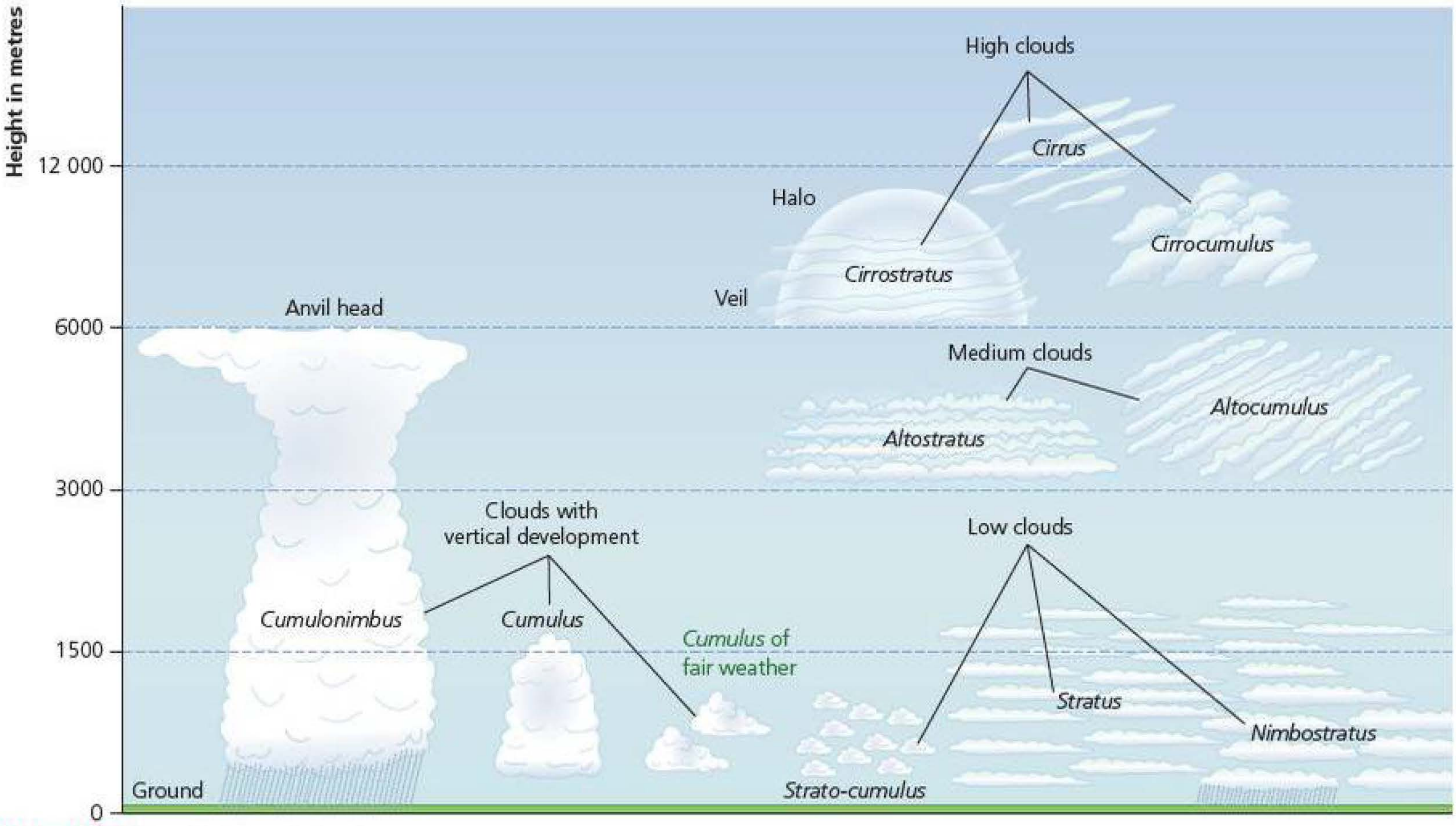


Figure 2.29 Classification of clouds

Figure 2.30 Stratus clouds

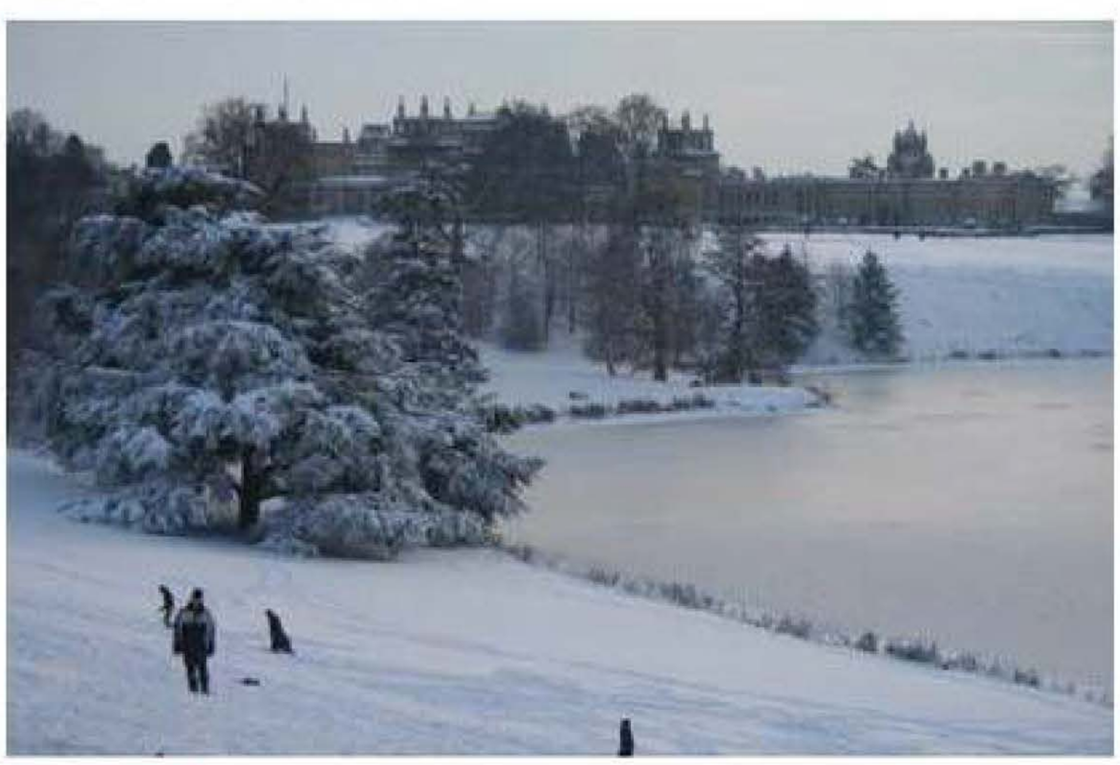


Figure 2.31 Snow at Blenheim Palace, Oxfordshire, UK

Dew

Dew is the direct deposition of water droplets onto a surface. It occurs in clear, calm anticyclonic conditions (high pressure) where there is rapid radiation cooling by night. The temperature reaches dew point, and further cooling causes condensation and direct precipitation onto the ground and vegetation (Figure 2.32).

Figure 2.32 Dew – direct condensation onto vegetation

Fog

Fog is cloud at ground level. Radiation fog (Figure 2.33) is formed in low-lying areas during calm weather, especially during spring and autumn. The surface of the ground, cooled rapidly at night by radiation, cools the air immediately above it. This air then flows into hollows by gravity and is cooled to dew point (the temperature at which condensation occurs). Ideal conditions include a surface layer of moist air and clear skies, which allow rapid radiation cooling.

Figure 2.33 Fog in the Wicklow Mountains, Ireland

The decrease in temperature of the lower layers of the air causes air to go below the dew point. With fairly light winds, the fog forms close to the water surface, but with stronger turbulence the condensed layer may be uplifted to form a low stratus sheet.

As the Sun rises, radiation fog disperses. Under cold anticyclonic conditions in late autumn and winter, fog may be thicker and more persistent, and around large towns smog may develop under an inversion layer. An inversion means that cold air is found at ground level, whereas warm air is above it – unlike the normal conditions in which air temperature declines with height. In industrial areas, emissions of sulphur dioxide act as condensation nuclei and allow fog to form. Along motorways, the heavy concentration of vehicle emissions does the same. By contrast, in coastal areas the higher minimum temperatures means that condensation during high-pressure conditions is less likely.

Fog commonly occurs over the sea in autumn and spring because the contrast in temperature between land and sea is significant. Warm air from over the sea is cooled when it moves on land during anticyclonic conditions. In summer, the sea is cooler than the land so air is not cooled when it blows onto the land. By contrast, in winter there are more low-pressure systems, causing stronger winds and mixing the air.

Fog is more common in anticyclonic conditions. Anticyclones are stable high-pressure systems characterised by clear skies and low wind speeds. Clear skies allow maximum cooling by night. Air is rapidly cooled to dew point, condensation occurs and fog is formed.

Advection fog is formed when warm moist air flows horizontally over a cooler land or sea surface. Steam fog is very localised. Cold air blows over much warmer water. Evaporation from the water quickly saturates the air and the resulting condensation leads to steaming. It occurs when very cold polar air meets the surrounding relatively warm water.

Section 2.3 Activities

1. Distinguish between *radiation fog* and *advection fog*.
2. Under which atmospheric conditions (stability or instability) do mist and fog form? Briefly explain how fog is formed.
3. Under which atmospheric conditions do thunder and lightning form? Briefly explain how thunder is created.

2.4 The human impact

Global warming

The role of greenhouse gases

Greenhouse gases are essential for life on Earth. The Moon is an airless planet that is almost the same distance from the Sun as is the Earth. Average temperatures on the Moon are about −18 °C, compared with about 15 °C on Earth. The Earth's atmosphere therefore raises temperatures by about 33 °C. This is due to the greenhouse gases, such as water vapour, carbon dioxide, methane, ozone, nitrous oxides and chlorofluorocarbons (CFCs). They are called greenhouse gases because, as in a greenhouse, they allow short-wave radiation from the Sun to pass through them, but they trap outgoing long-wave radiation, thereby raising the temperature of the lower atmosphere (Figure 2.34). The greenhouse effect is both natural and good – without it there would be no human life on Earth. On the other hand, there are concerns about the enhanced greenhouse effect.

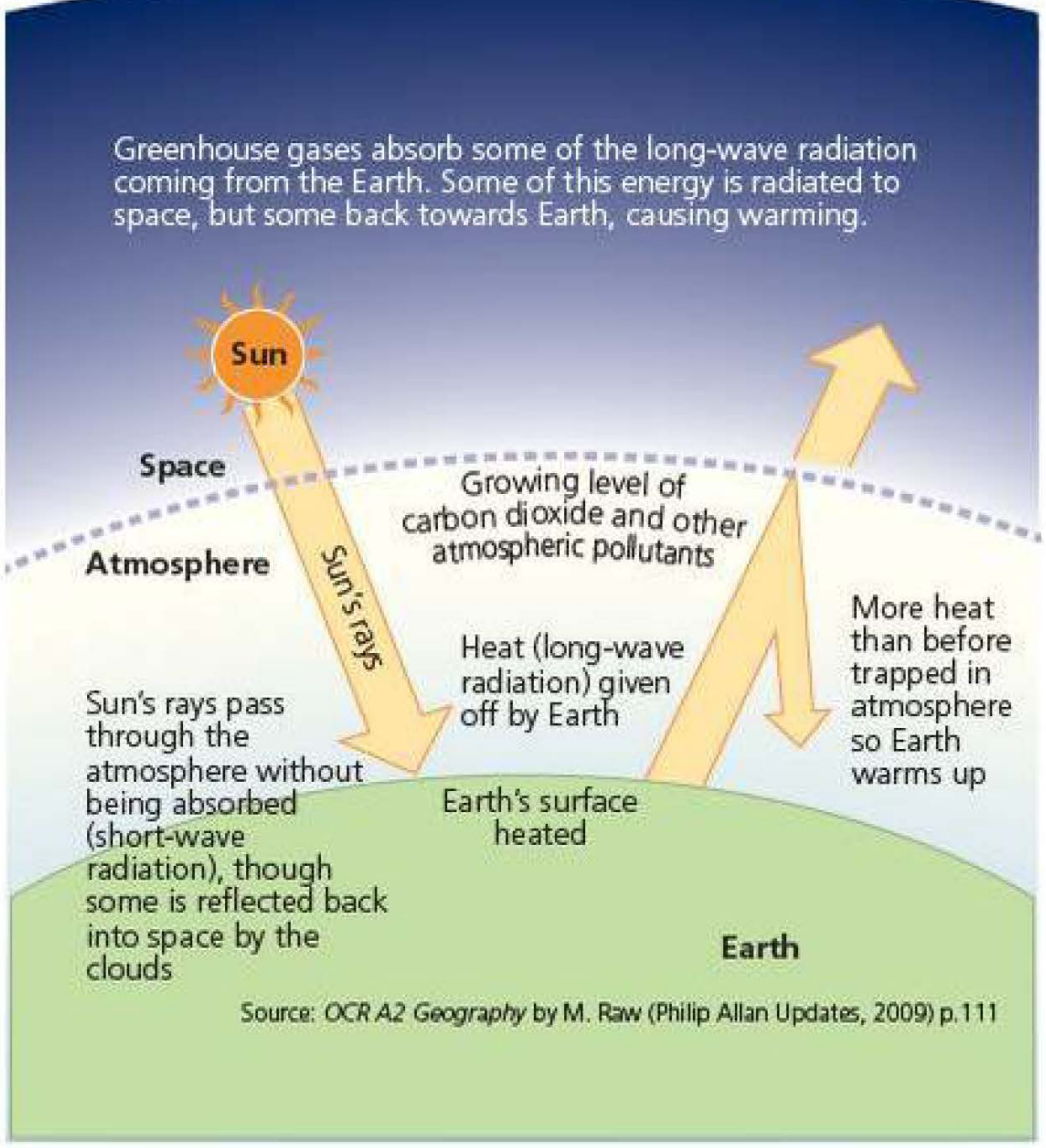


Figure 2.34 The greenhouse effect

The enhanced greenhouse effect is built up of certain greenhouse gases as a result of human activity (Table 2.2). **Carbon dioxide** (CO_2) levels have risen from about 315 ppm (parts per million) in 1950 to over 400 ppm and are expected to reach 600 ppm by 2050. The increase is due to human activities: burning fossil fuels (coal, oil and natural gas) and deforestation. Deforestation of the tropical rainforest is a double blow – not only does it increase atmospheric CO_2 levels, it also removes the trees that convert CO_2 into oxygen.

Methane is the second largest contributor to global warming, and is increasing at a rate of between 0.5 and 2 per cent per annum. Cattle alone give off between 65 and 85 million tonnes of methane per year. Natural wetland and paddy fields are another important source – paddy fields emit up to 150 million tonnes of methane annually. As global warming increases, bogs trapped in permafrost will melt and release vast quantities of methane. **Chlorofluorocarbons** (CFCs) are synthetic chemicals that destroy ozone, as well as absorb long-wave radiation. CFCs are increasing at a rate of 6 per cent per annum, and are up to 10 000 times more efficient at trapping heat than CO_2.

As long as the amount of water vapour and carbon dioxide stay the same and the amount of solar energy remains the same, the temperature of the Earth should remain in equilibrium. However, human activities are upsetting the natural balance by increasing the amount of CO_2 in the atmosphere, as well as the other greenhouse gases.

How human activities add to greenhouse gases

Much of the evidence for the greenhouse effect has been taken from ice cores dating back 160 000 years. These show that the Earth's temperature closely paralleled the levels of CO_2 and methane in the atmosphere. Calculations indicate that changes in these greenhouse gases were part, but not all, of the reason for the large (5°–7°) global temperature swings between ice ages and interglacial periods.

Accurate measurements of the levels of CO_2 in the atmosphere began in 1957 in Hawaii. The site chosen was far away from major sources of industrial pollution and shows a good representation of unpolluted atmosphere. The trend in CO_2 levels shows a clear annual pattern, associated with seasonal changes in vegetation, especially those over the northern hemisphere. By the 1970s there was a second trend, one of a long-term increase in CO_2 levels, superimposed upon the annual trends.

Studies of cores taken from ice packs in Antarctica and Greenland show that the level of CO_2 between 10 000 years ago and the mid-nineteenth century was stable, at about 270 ppm. By 1957, the concentration of CO_2 in the atmosphere was 315 ppm, and it has since risen to about 360 ppm. Most of the extra CO_2 has come

Table 2.2 Properties of key greenhouse gases

	Average atmospheric concentration (ppmv)	Rate of change (% per annum)	Direct global warming potential (GWP)	Lifetime (years)	Type of indirect effect
Carbon dioxide	400	0.5	1	120	None
Methane	1.72	0.6–0.75	11	10.5	Positive
Nitrous oxide	0.31	0.2–0.3	270	132	Uncertain
CFC-11	0.000255	4	3400	55	Negative
CFC-12	0.000453	4	7100	116	Negative
CO				Months	Positive
NOx					Uncertain

from the burning of fossil fuels, especially coal, although some of the increase may be due to the disruption of the rainforests. For every tonne of carbon burned, 4 tonnes of CO_2 are released.

By the early 1980s, 5 gigatonnes (5000 million tonnes, or 5 Gt) of fuel were burned every year. Roughly half the CO_2 produced is absorbed by natural sinks, such as vegetation and plankton.

Other factors have the potential to affect climate too. For example, a change in the albedo (reflectivity of the land brought about by desertification or deforestation) affects the amount of solar energy absorbed at the Earth's surface. Aerosols made from sulphur, emitted largely in fossil-fuel combustion, can modify clouds and may act to lower temperatures. Changes in ozone in the stratosphere due to CFCs may also influence climate.

Since the Industrial Revolution, the combustion of fossil fuels and deforestation have led to an increase of 26 per cent of CO_2 concentration in the atmosphere (Figure 2.35). Emissions of CFCs used as aerosol propellants, solvents, refrigerants and foam-blowing agents are also well known. They were not present in the atmosphere before their invention in the 1930s. The sources of methane and nitrous oxides are less well known. Methane concentrations have more than doubled because of rice production, cattle rearing, biomass burning, coal mining and ventilation of natural gas. Fossil fuel combustion may have also contributed through chemical reactions in the atmosphere, which reduce the rate of removal of methane. Nitrous oxide has increased by about 8 per cent since pre-industrial times, presumably due to human activities. The effect of ozone on climate is strongest in the upper troposphere and lower stratosphere.

- The increasing carbon dioxide in the atmosphere since the pre-industrial era, from about 280 to 382 ppmv (parts per million by volume), makes the largest individual contribution to greenhouse gas radiative forcing: 1.56 W/m^2 (watts per square metre).
- The increase of methane (CH_4) since pre-industrial times (from 0.7 to 1.7 ppmv) contributes about 0.5 W/m^2.
- The increase in nitrous oxide (NOx) since pre-industrial times, from about 275 to 310 ppbv3, contributes about 0.1 W/m^2.
- The observed concentrations of halocarbons, including CFCs, have resulted in direct radiative forcing of about 0.3 W/m^2.

Figure 2.35 Changes in greenhouse gases since pre-industrial times

Arguments surrounding global warming

There are many causes of global warming and climate change. Natural causes include:

- variations in the Earth's orbit around the Sun
- variations in the tilt of the Earth's axis
- changes in the aspect of the poles from towards the Sun to away from it
- variations in solar output (sunspot activity)
- changes in the amount of dust in the atmosphere (partly due to volcanic activity)
- changes in the Earth's ocean currents as a result of continental drift.

All of these have helped cause climate change, and may still be doing so, despite anthropogenic forces.

Complexity of the problem

Climate change is a very complex issue for a number of reasons:

- Scale – it includes the atmosphere, oceans and land masses across the world.
- Interactions between these three areas are complex.
- It includes natural as well as anthropogenic forces.
- There are feedback mechanisms involved, not all of which are fully understood.
- Many of the processes are long term and so the impact of changes may not yet have occurred.

The effects of increased global temperature change

The effects of global warming are varied (see Table 2.3). Much depends on the scale of the changes. For example, some impacts could include:

- a rise in sea levels, causing flooding in low-lying areas such as the Netherlands, Egypt and Bangladesh – up to 200 million people could be displaced
- 200 million people at risk of being driven from their homes by flood or drought by 2050
- 4 million km^2 of land, home to one-twentieth of the world's population, threatened by floods from melting glaciers
- an increase in storm activity, such as more frequent and intense hurricanes (owing to more atmospheric energy)
- changes in agricultural patterns, for example a decline in the USA's grain belt, but an increase in Canada's growing season
- reduced rainfall over the USA, southern Europe and the Commonwealth of Independent States (CIS), leading to widespread drought (Figure 2.36)
- 4 billion people could suffer from water shortages if temperatures rise by 2 °C
- a 35 per cent drop in crop yields across Africa and the Middle East expected if temperatures rise by 3 °C
- 200 million more people could be exposed to hunger if world temperatures rise by 2 °C; 550 million if temperatures rise by 3 °C
- 60 million more Africans could be exposed to malaria if world temperatures rise by 2 °C
- extinction of up to 40 per cent of species of wildlife if temperatures rise by 2 °C.

Table 2.3 Some potential effects of a changing climate in the UK

Positive effects	Negative effects
■ An increase in timber yields (up to 25% by 2050), especially in the north (with perhaps some decrease in the south). ■ A northward shift of farming zones by about 200–300 km per 1°C of warming, or 50–80 km per decade, will improve some forms of agriculture, especially pastoral farming in the north-west. ■ Enhanced potential for tourism and recreation as a result of increased temperatures and reduced precipitation in the summer, especially in the south.	■ Increased damage effects of increased storminess, flooding and erosion on natural and human resources and human resource assets in coastal areas. ■ An increase in animal species, especially insects, as a result of northward migration from the continent and a small decrease in the number of plant species due to the loss of northern and montane (mountain types). ■ An increase in soil drought, soil erosion and the shrinkage of clay soils.

The Stern Review

The Stern Review (2006) was a report by Sir Nicholas Stern that analysed the financial implications of climate change. The report has a simple message:

- Climate change is fundamentally altering the planet.
- The risks of inaction are high.
- Time is running out.

The effects of climate change vary with the degree of temperature change (Figure 2.37). The report states that climate change poses a threat to the world economy and it will be cheaper to address the problem than to deal with the consequences. The global-warming argument seemed a straight fight between the scientific case to act, and the economic case not to. Now, economists are urging action.

The Stern Review says that doing nothing about climate change – the business-as-usual (BAU) approach – would lead to a reduction in global per person consumption of at least 5 per cent now and for ever. According to the report, global warming could deliver an economic blow of between 5 and 20 per cent of GDP to world economies because of natural disasters and the creation of hundreds of millions of climate refugees displaced by sea-level rise. Dealing with the problem, by comparison, will cost just 1 per cent of GDP, equivalent to £184 billion.

Main points

- Carbon emissions have already increased global temperatures by more than 0.5 °C.
- With no action to cut greenhouse gases, we will warm the planet by another 2–3 °C within 50 years.
- Temperature rise will transform the physical geography of the planet and the way we live.
- Floods, disease, storms and water shortages will become more frequent.
- The poorest countries will suffer the earliest and the most.
- The effects of climate change could cost the world between 5 and 20 per cent of GDP.
- Action to reduce greenhouse-gas emissions and the worst of global warming would cost 1 per cent of GDP.
- With no action, each tonne of carbon dioxide we emit will cause at least \$85 (£45) of damage.
- Levels of carbon dioxide in the atmosphere should be limited to the equivalent of 450–550 ppm.
- Action should include carbon pricing, new technology and robust international agreements.

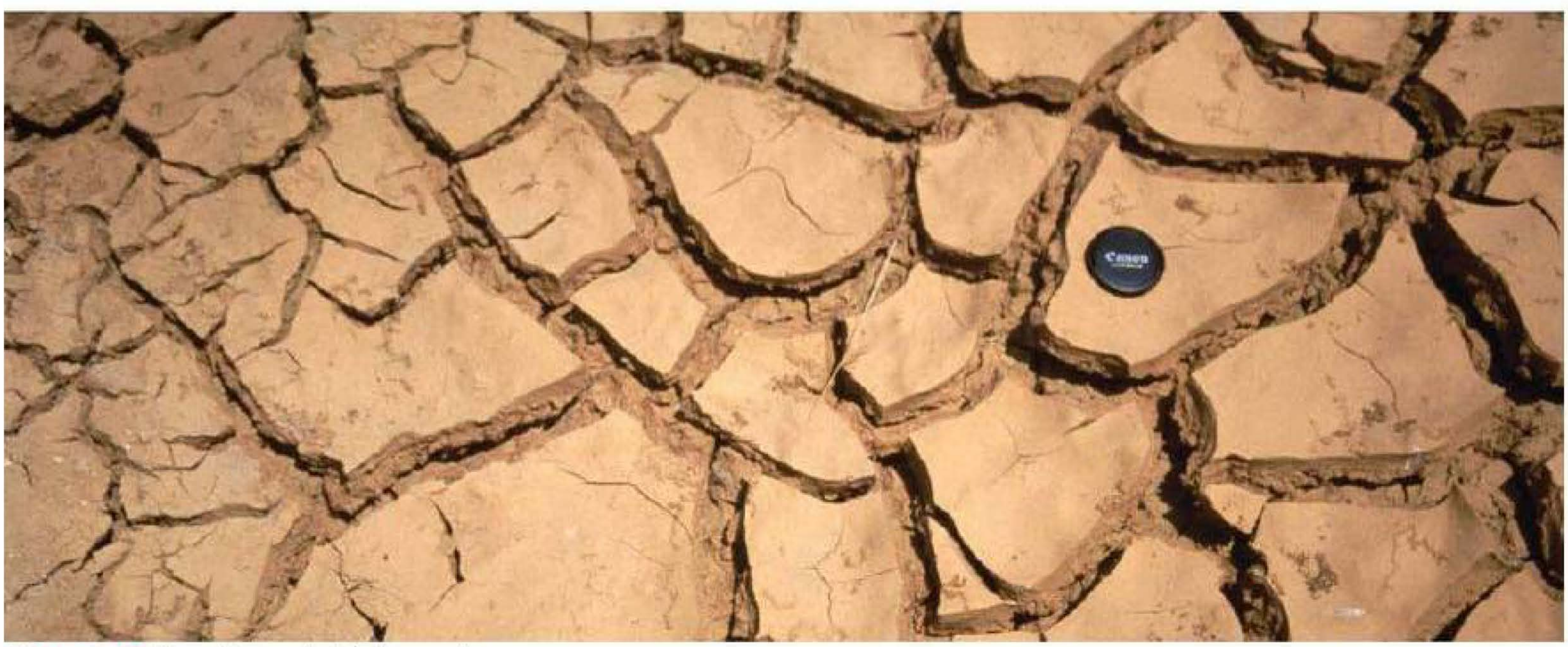


Figure 2.36 The effects of global warming

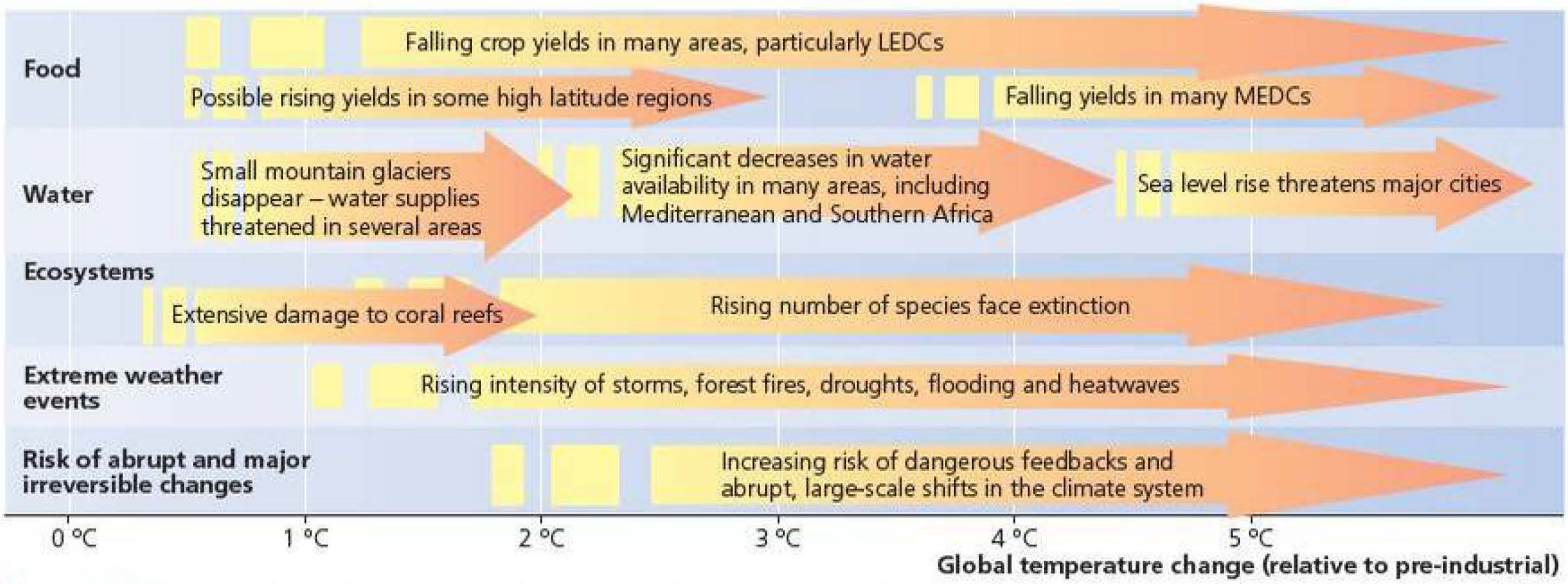


Figure 2.37 Projected impacts of climate change, according to the Stern Review

International policy to protect climate

The first world conference on climate change was held in Geneva in 1979. The Toronto Conference of 1988 called for the reduction of carbon dioxide emissions by 20 per cent of the 1988 levels by 2005. Also in 1988, UNEP and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC).

> 'The ultimate objective is to achieve ... stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.'

The Kyoto Protocol (1997) gave all high-income countries (HICs) legally binding targets for cuts in emissions from the 1990 level by 2008–12. The EU agreed to cut emissions by 8 per cent, Japan 7 per cent and the USA by 6 per cent. The Paris round of global climate-change talks (2015) attempted to bring all countries in line with plans to reduce climate change. However, many of the plans discussed had a very long time frame and there appeared to be little hope for a quick solution.

Section 2.4 Activities

1 Figure 2.37 shows some of the projected impacts related to global warming.
   a Describe the potential changes as a result of a 3 °C rise in temperature.
   b Explain why there is an increased risk of hazards in coastal cities.
   c Outline the ways in which it is possible to manage the impacts of global warming.
   d Evaluate the potential impacts of global warming.
2 Figure 2.38 shows variations in mean air temperature between 1880 and 2000.
   a i Identify the reason that the temperature in the early 1960s fell below 15 °C.
     ii Describe the impact of Pinatubo on global climate in the 1990s.
   b Outline the natural sources of greenhouse gases.
   c Using an annotated diagram, explain what is meant by the term *the greenhouse effect*.
   d Outline the benefits of the greenhouse effect.

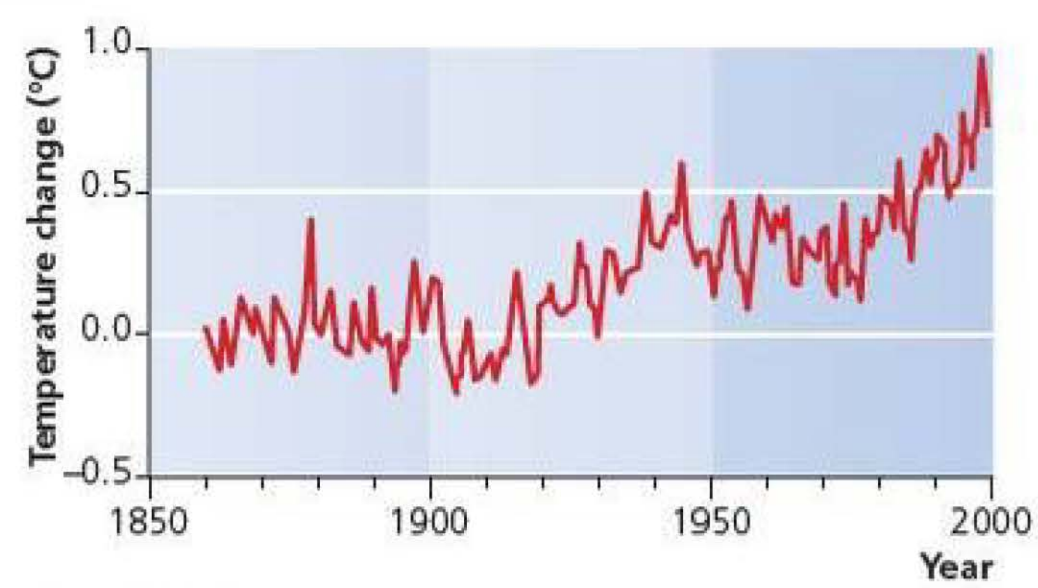


Figure 2.38 Variations in mean air temperature, 1880–2000

Urban climates

Urban climates occur as a result of extra sources of heat released from industry; commercial and residential buildings; as well as from vehicles, concrete, glass, bricks, tarmac – all of these act very differently from soil and vegetation. For example, the albedo (reflectivity) of tarmac is about 5–10 per cent, while that of concrete is 17–27 per cent. In contrast, that of grass is 20–30 per cent.

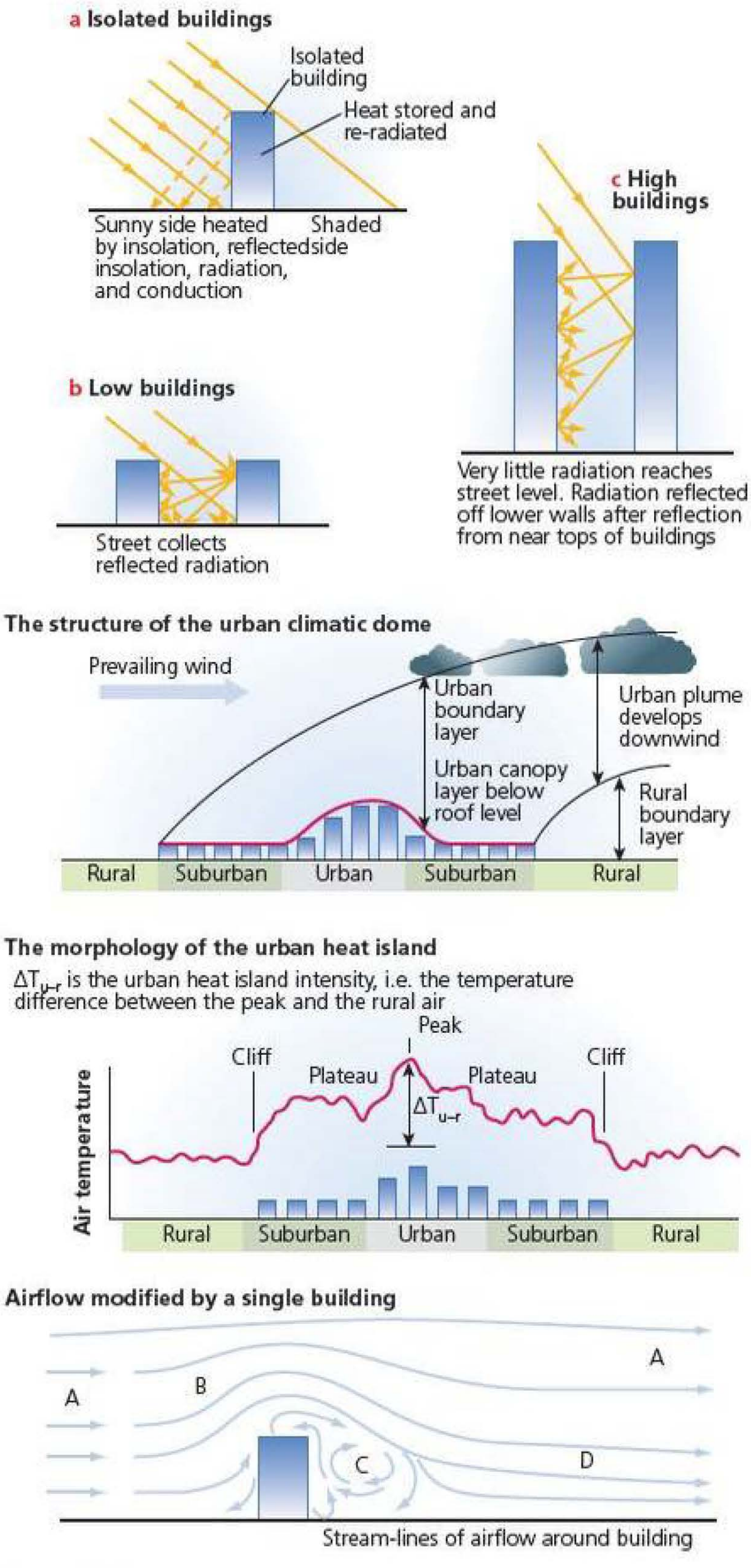


Figure 2.39 Processes in the urban heat island

Some of these – notably dark bricks – absorb large quantities of heat and release them slowly by night (Figure 2.39). In addition, the release of **pollutants** helps trap radiation in urban areas. Consequently, urban microclimates can be very different from rural ones. Greater amounts of dust mean an increasing concentration of hygroscopic particles. There is less water vapour, but more carbon dioxide and higher proportions of noxious fumes owing to combustion of imported fuels. Discharge of waste gases by industry is also increased.

Urban heat budgets differ from rural ones. By day, the major source of heat is solar energy; and in urban areas brick, concrete and stone have high heat capacities. A kilometre of an urban area contains a greater surface area than a kilometre of countryside, and the greater number of surfaces in urban areas allow a greater area to be heated. There are more heat-retaining materials with lower albedo and better radiation-absorbing properties in urban areas than in rural ones.

Moisture and humidity

In urban areas, there is relative lack of moisture. This is due to:

- a lack of vegetation
- a high drainage density (sewers and drains), which removes water.

Thus there are decreases in relative humidity in inner cities due to the lack of available moisture and higher temperatures there. However, this is partly countered in very cold, stable conditions by early onset of condensation in low-lying districts and industrial zones.

Nevertheless, there are more intense storms, particularly during hot summer evenings and nights, owing to greater **instability** and stronger convection above built-up areas. There is a higher incidence of thunder (due to more heating and instability) but less snowfall (due to higher temperatures), and any snow that does fall tends to melt rapidly.

Hence little energy is used for evapotranspiration, so more is available to heat the atmosphere. This is in addition to the sources of heating produced by people, such as in industry and by cars.

At night, the ground radiates heat and cools. In urban areas, the release of heat by buildings offsets the cooling process, and some industries, commercial activities and transport networks continue to release heat throughout the night.

There is greater scattering of shorter-wave radiation by dust, but much higher absorption of longer waves owing to the surfaces and to carbon dioxide. Hence there is more diffuse radiation, with considerable local contrasts owing to variable screening by tall buildings in shaded narrow streets. There is reduced visibility arising from industrial haze.

There is a higher incidence of thicker cloud cover in summer because of increased convection, and radiation fogs or smogs in winter because of air pollution. The concentration of hygroscopic particles accelerates the onset of condensation. Daytime temperatures are, on average, 0.6 °C higher.

Urban heat island effect

The contrast between urban and rural areas is greatest under calm high-pressure conditions. The typical heat profile of an urban **heat island** shows a maximum at the city centre, a plateau across the suburbs and a temperature cliff between the suburban and rural areas (Figure 2.40). Small-scale variations within the urban heat island occur with the distribution of industries, open spaces, rivers, canals, and so on.

The heat island is a feature that is delimited by isotherms (lines of equal temperature), normally in an urban area. This shows that the urban area is warmer than the surrounding rural area, especially by dawn during anticyclonic conditions (Figure 2.41). The heat-island effect is caused by a number of factors:

- heat produced by human activity – a low level of radiant heat can be up to 50per cent of incoming energy in winter
- changes of energy balance – buildings have a high thermal capacity in comparison to rural areas; up to six times greater than agricultural land
- the effect on airflow – turbulence of air may be reduced overall, although buildings may cause funnelling effects
- there are fewer bodies of open water, so less evaporation and fewer plants, therefore less transpiration
- the composition of the atmosphere – the blanketing effect of smog, smoke or haze
- reduction in thermal energy required for evaporation and evapotranspiration due to the surface character, rapid drainage and generally lower wind speeds
- reduction of heat diffusion due to changes in airflow patterns as a result of urban surface roughness.

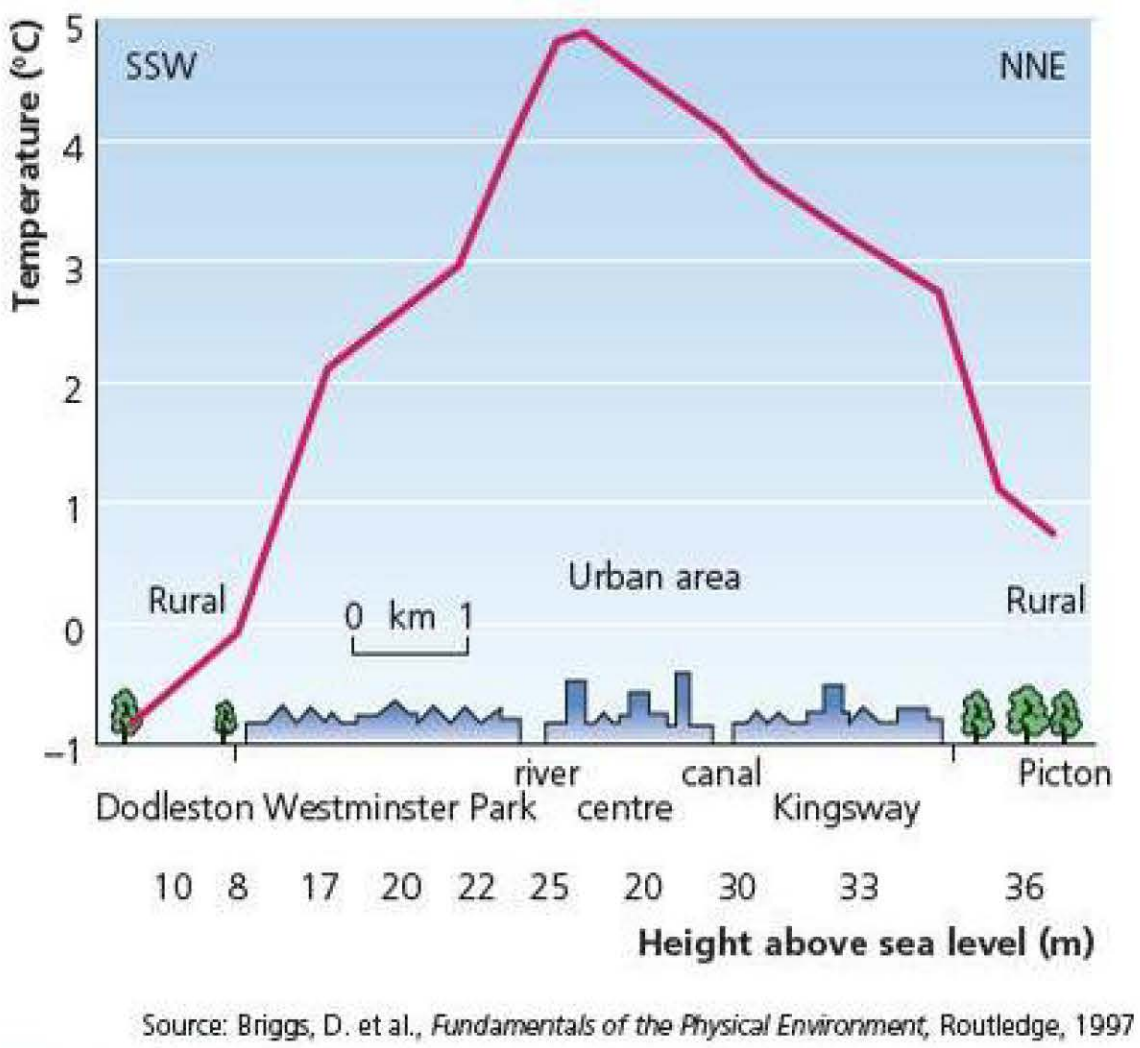


Figure 2.40 The urban heat island (Chester, UK)

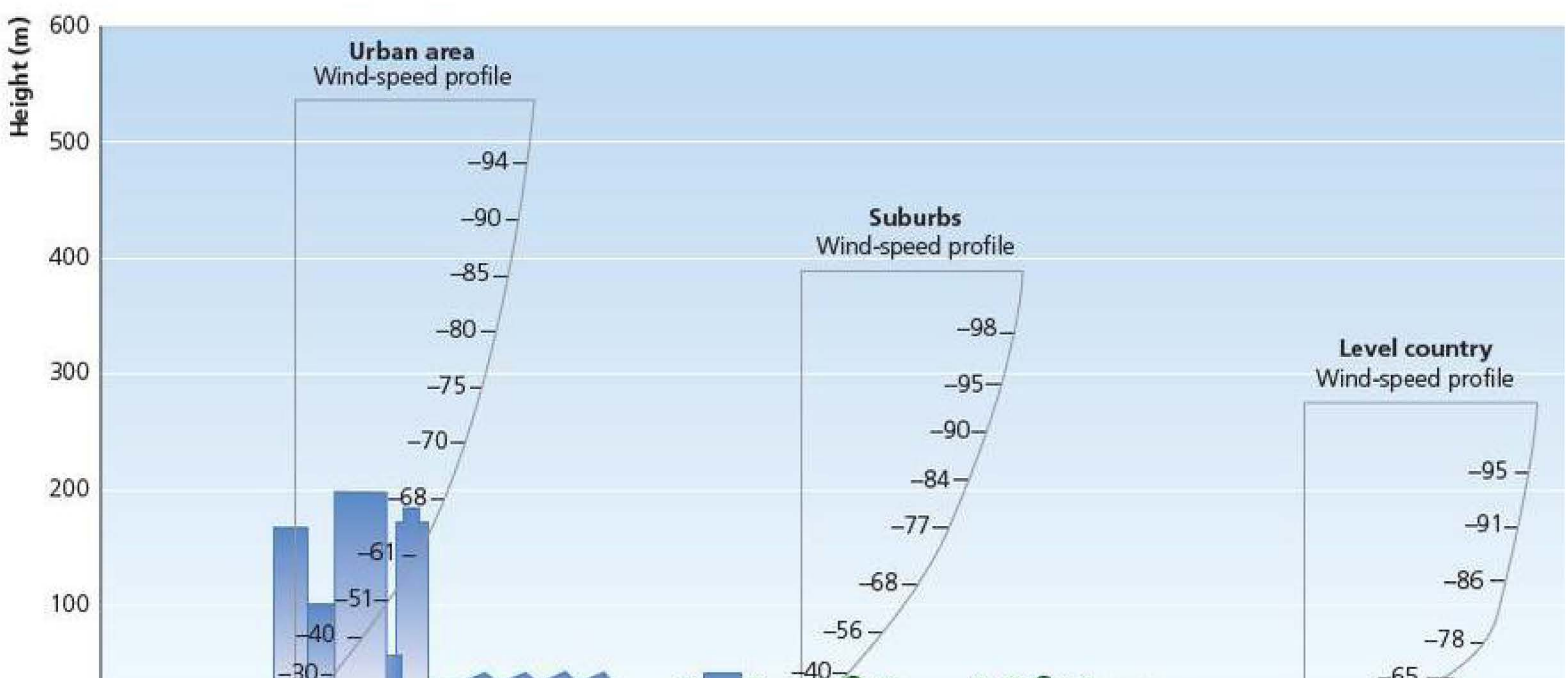


Figure 2.41 The effect of terrain roughness on wind speed – with decreasing roughness, the depth of the affected layer becomes shallower and the profile steeper (numbers refer to wind strength as a percentage of maximum air speed)

Air flow

Urban areas may also develop a pollution dome. Highest temperatures are generally found over the city centre – or downwind of the city centre if there is a breeze present. Pollutants may be trapped under the dome. Cooler air above the dome prevents the pollutants from dispersing. These pollutants may prevent some incoming radiation from passing through, thereby reducing the impact of the heat island. By night, the pollutants may trap some long-wave radiation from escaping, thereby keeping urban areas warmer than surrounding rural areas.

Airflow over an urban area is disrupted; winds are slow and deflected over buildings (Figure 2.41). Large buildings can produce eddying. Severe gusting and turbulence around tall buildings causes strong local pressure gradients from windward to leeward walls. Deep narrow streets are much calmer unless they are aligned with prevailing winds to funnel flows along them – the 'canyon effect'.

The nature of urban climates is changing (Table 2.4). With the decline in coal as a source of energy, there is less sulphur dioxide pollution and so fewer hygroscopic nuclei; there is therefore less fog. However, the increase in cloud cover has occurred for a number of reasons:

- greater heating of the air (rising air, hence condensation)
- increase in pollutants
- frictional and turbulent effects on airflow
- changes in moisture.

Table 2.4 Average changes in climate caused by urbanisation

Factor		Comparison with rural environments
Radiation	Global	2–10% less
	Ultraviolet, winter	30% less
	Ultraviolet, summer	5% less
	Sunshine duration	5–15% less
Temperature	Annual mean	1 °C more
	Sunshine days	2–6 °C more
	Greatest difference at night	11 °C more
	Winter maximum	1.5 °C more
	Frost-free season	2–3 weeks more
Wind speed	Annual mean	10–20% less
	Gusts	10–20% less
	Calms	5–20% more
Relative humidity	Winter	2% less
	Summer	8–10% less
Precipitation	Total	5–30% more
	Number of rain days	10% more
	Snow days	14% less
Cloudiness	Cover	5–10% more
	Fog, winter	100% more
	Fog, summer	30% more
	Condensation nuclei	10 times more
	Gases	5–25 times more

Source: J. Tivy, Agricultural Ecology, *Longman 1990 p.372*

Section 2.4 Activities

1 Describe and account for the main differences in the climates of urban areas and their surrounding rural areas.
2 What is meant by the *urban heat island*?
3 Describe **one** effect that atmospheric pollution may have on urban climates.
4 Explain how buildings, tarmac and concrete can affect the climate in urban areas.
5 Why are microclimates, such as urban heat islands, best observed during high-pressure (anticyclonic) weather conditions?

Case Study: Urban microclimate – London

The heat island effect

Urban microclimates are perhaps the most complex of all microclimates. The general pattern in Figure 2.42 shows the highest temperatures in the city centre, reaching 10–11 °C, compared with the rural fringe temperature of 5 °C. Temperature falls more rapidly along the River Thames to the east of the City. The temperature gradient is more gentle in the west of the city, due to the density of urban infrastructure. Over steep temperature gradients there is a low density of urban infrastructure, for example the river and its vegetated banks. Where there is a gentle temperature gradient, there is a high density of urban infrastructure. Effectively from the map we can see that the east of London is less built up than the west. Temperature remains relatively constant for approximately 15 kilometres west of the city centre before rapidly falling within a 5–6 kilometre distance.

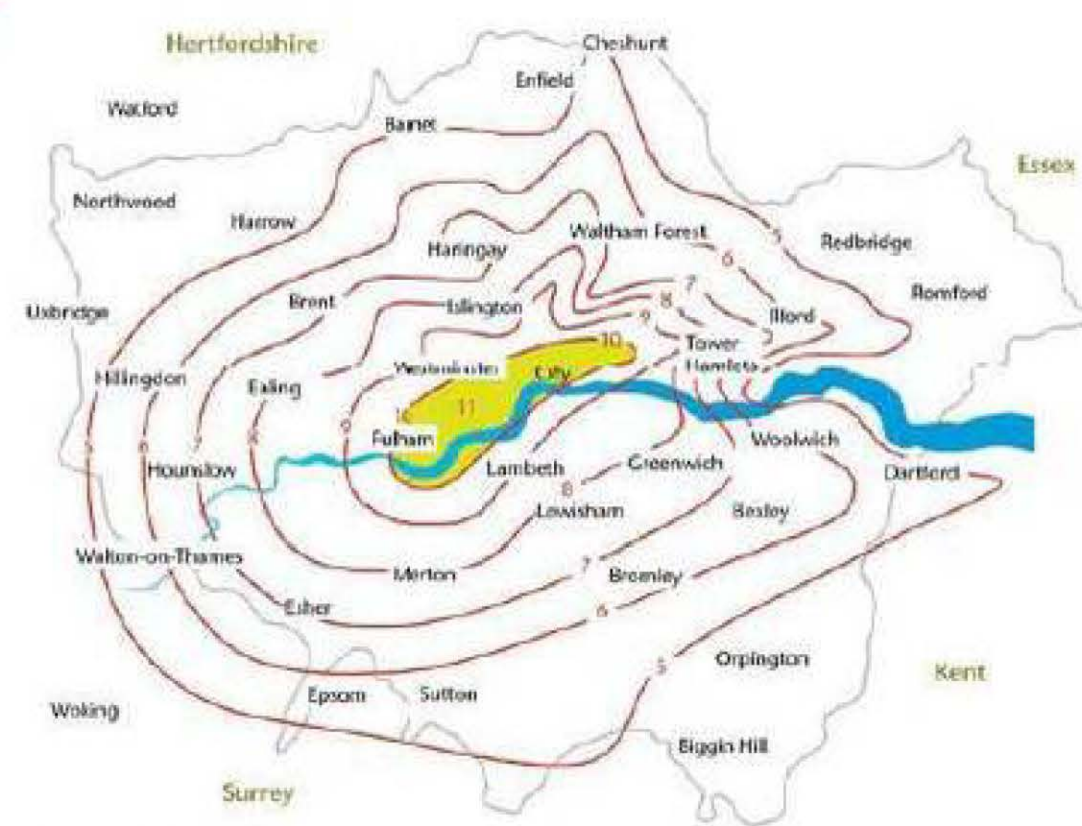
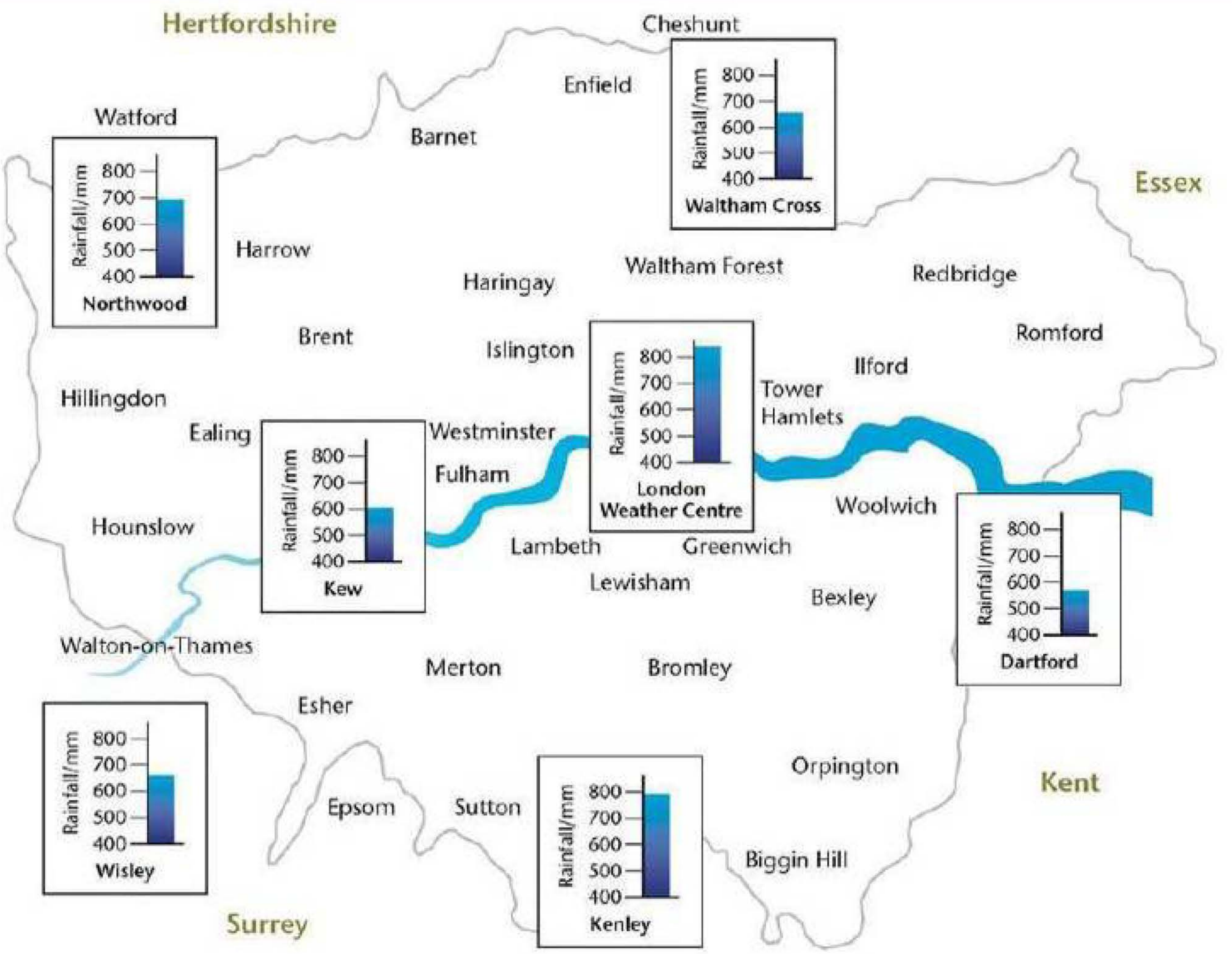


Figure 2.42 London's heat-island effect, showing minimum temperatures (°C) in mid-May



Source: National Meteorological Library and Archive Fact sheet 14 — Microclimates; Figure 16. Mean annual rainfall totals for a number of stations around London. www.metoffice.gov.uk/media/pdf/n/9/Fact_sheet_No._14.pdf

Figure 2.43 Variations in mean annual rainfall around London

Recent research on London's heat island has shown that the pollution domes can also filter incoming solar radiation, thereby reducing the build-up of heat during the day. At night, the dome may trap some of the heat accrued during the day, so these domes might be reducing the sharp differences between urban and rural areas.

There is an absence of strong winds both to disperse the heat and to bring in cooler air from rural and suburban areas. Indeed, urban heat islands are often most clearly defined on calm summer evenings, often under blocking anticyclones.

The distribution of rainfall is very much influenced by topography, with the largest values occurring over the more hilly regions, and lowest values in more low-lying areas. Figure 2.43 illustrates this point quite clearly. Kenley on the North Downs, at an altitude of 170 metres above mean sea-level, has an average annual rainfall of nearly 800 millimetres, whereas London Weather Centre, at 43 metres above mean sea-level, has an average annual rainfall of less than 550 millimetres. Overall, humidity is lower in London than surrounding areas, partly due to higher temperatures (warm air can hold more moisture, hence relative humidity may be lower), but water is removed from large urban areas due to the combination of drains and sewers, the large amount of impermeable surfaces and the reduced vegetation cover.

The urban heat island creates the urban boundary layer, which is a dome of rising warm air and low pressure. As ground surfaces are heated, rapid evapotranspiration takes place. This evapotranspiration, although lower compared to rural areas, occurs more rapidly and can result in cumulus cloud and convectional weather patterns. Due to the low pressure caused by rising air, surface winds are drawn in from the surrounding rural fringe. This air then converges as it is forced to rise over the high urban canopy. The urban boundary essentially creates an orographic process similar to a mountain barrier. The movement of winds contributes to increased rainfall patterns over the city that are most pronounced to the leeward side of the city core. However, as air passes over the urban boundary layer it begins to sink, leading to lower precipitation at the leeward rural area. These differences are also more pronounced in the summer compared to the winter.

Some studies have demonstrated a pattern of increased rain through the week and have shown Saturday rain to be a result of a build-up of pollutants due to five consecutive commutes. By Monday, pollutants have fallen and rainfall is less likely to form.

Case Study: Urban microclimate – Cheong Gye Cheon, Seoul, South Korea

The impact of river restoration on urban microclimates

In Seoul, capital of South Korea, there has been a very marked change in the urban microclimate following the removal of a large, downtown elevated motorway, and the restoration of a river and floodplain that had been built over. Since the restoration of the stream, air temperature has decreased by up to 10–13 per cent; that is, by 3-4 °C during the hottest days. Before the restoration, the area was showing a temperature about 5 °C higher than the average temperature of the city. The decrease in the number of vehicles passing by also contributed to the drop in the temperature. The heat island phenomenon used to be observed in the Cheong Gye Cheon Stream area under the impact of the heavy traffic, concentration of commercial facilities and the impermeable surface.

Following the completion of the restoration, the wind speed has become faster (by 2.2–7.1 per cent). The average wind speed measured at Cheong Gye Cheon is up to 7.8 per cent faster than before, apparently under the influence of the cool air forming along the stream.

Figure 2.44 Cheong Gye Cheon – **a** when the area was developed with an elevated highway and **b** after restoration

Case Study: Urban microclimate – Melbourne, Australia

With increasing distance from the city centre, the amount of tree cover in a suburb decreases, while the amount of green space, such as lawns and parks, increases. In Melbourne, for every 10 kilometres from the city centre, the tree cover drops by more than 2 per cent. That means Melbourne's inner suburbs might have more than 15 per cent cover, but an outer suburb could have less than 10 per cent. A 5 per cent fall in urban tree cover can lead to a 1–2 °C rise in air temperature. This matters for community health and well-being, especially for the vulnerable – the elderly, young children and those with existing health issues.

Trees are missing from back gardens – partly because modern houses in the outer suburbs take up more space, leaving less room for trees – and they are missing from the streets. The property boom led to a gradual thinning out of tree cover in established suburbs, as residential plots were sub-divided.

Melbourne aims to increase tree cover by 75 per cent before 2040, Sydney by 50 per cent before 2030 and Brisbane is targeting tree cover for cycleways and footpaths.

Microclimate mitigation

Increasingly, there are attempts to reverse urban microclimates. Heat-island mitigation strategies include urban forestry, living/green roofs and light surfaces.

In general, substantial reductions in surface and near-surface air temperature can be achieved by implementing heat-island mitigation strategies. Vegetation cools surfaces more effectively than increases in albedo, and curbside planting is the most effective mitigation strategy per unit area redeveloped. However, the greatest absolute temperature reductions are possible with light surfaces.

Table 2.5 Characteristics of the London Plane tree

Characteristic	The London Plane tree
Aesthetic value	A tall elegant tree providing pleasant shade in summer and a pleasing winter silhouette. Flaking bark creates attractive colours on trunk.
Does it make a mess?	Leaves, fruit and bark need clearing from streets and pavements.
Pollution tolerance	Very tolerant of air pollution. Hairs on young shoots and leaves help to trap particulate pollution.
Pests and diseases	Rarely affected by disease and pests (although some shoots are killed each year by fungal infection).
Soil conditions	Very tolerant of poor soil conditions, including compacted soil (although some stunting of growth is caused by road salt).
Space	Grows vigorously and is very tolerant of pruning.
Safety hazards	Trees rarely blow over or shed branches. Fine hairs on young shoots, leaves and fruit may cause irritation and even allergies in some people.
Microclimate	Open canopy produces light shade. Will intercept some rain, especially when in leaf.
Biodiversity	Provides valuable nesting sites for birds. Sufficient light below canopy to allow significant plant growth.

Source: Adapted from the Field Studies Council's Urban Ecosystems website www.field-studies-council.org/urbaneco

The London Plane tree – urban saviour

With an extensive and healthy urban forest, air quality can be drastically improved. Trees help to lower air temperatures through increasing evapotranspiration. This reduction of temperature not only lowers energy use, it also improves air quality, as the formation of ozone is dependent on temperature. Large shade trees can reduce local ambient temperatures by 3 to 5 °C. Maximum midday temperature reductions due to trees range from 0.04 °C to 0.2 °C per 1 per cent canopy cover increase.

Living roofs offer greater cooling per unit area than light surfaces, but less cooling per unit area than curbside planting.

Although street trees provide the greatest cooling potential per unit area, light surfaces provide the greatest overall cooling potential when available area is taken into account because there is more available area in which to implement this strategy compared to the other strategies.

Section 2.4 Activities

1 State the conditions in which London's heat island is most pronounced.
2 Briefly suggest reasons for variations in temperature as shown in Figure 2.42.
3 Describe and explain how the urban microclimate in Seoul changed after river restoration.
4 Explain the advantages of the London Plane tree for urban areas.

3 Rocks and weathering

3.1 Plate tectonics

The Earth's interior

The theory of plate tectonics states that the Earth is made up of a number of layers (Figure 3.1). On the outside, there is a very thin crust, and underneath is a mantle that makes up 82 per cent of the volume of the Earth. Deeper still is a very dense and very hot core. In general, these concentric layers become increasingly more dense towards the centre. Their density is controlled by temperature and pressure. Temperature softens or melts rocks.

Close to the surface, rocks are mainly solid and brittle. This upper surface layer is known as the lithosphere, which includes the crust and the upper mantle, and is about 70 kilometres deep. The Earth's crust is commonly divided up into two main types: continental crust and oceanic crust (Table 3.1). In continental areas, silica and aluminium are very common. When combined with oxygen they make up the most common type of rock: granitic. By contrast, below the oceans the crust consists mainly of basaltic rock in which silica, iron and magnesium are most common.

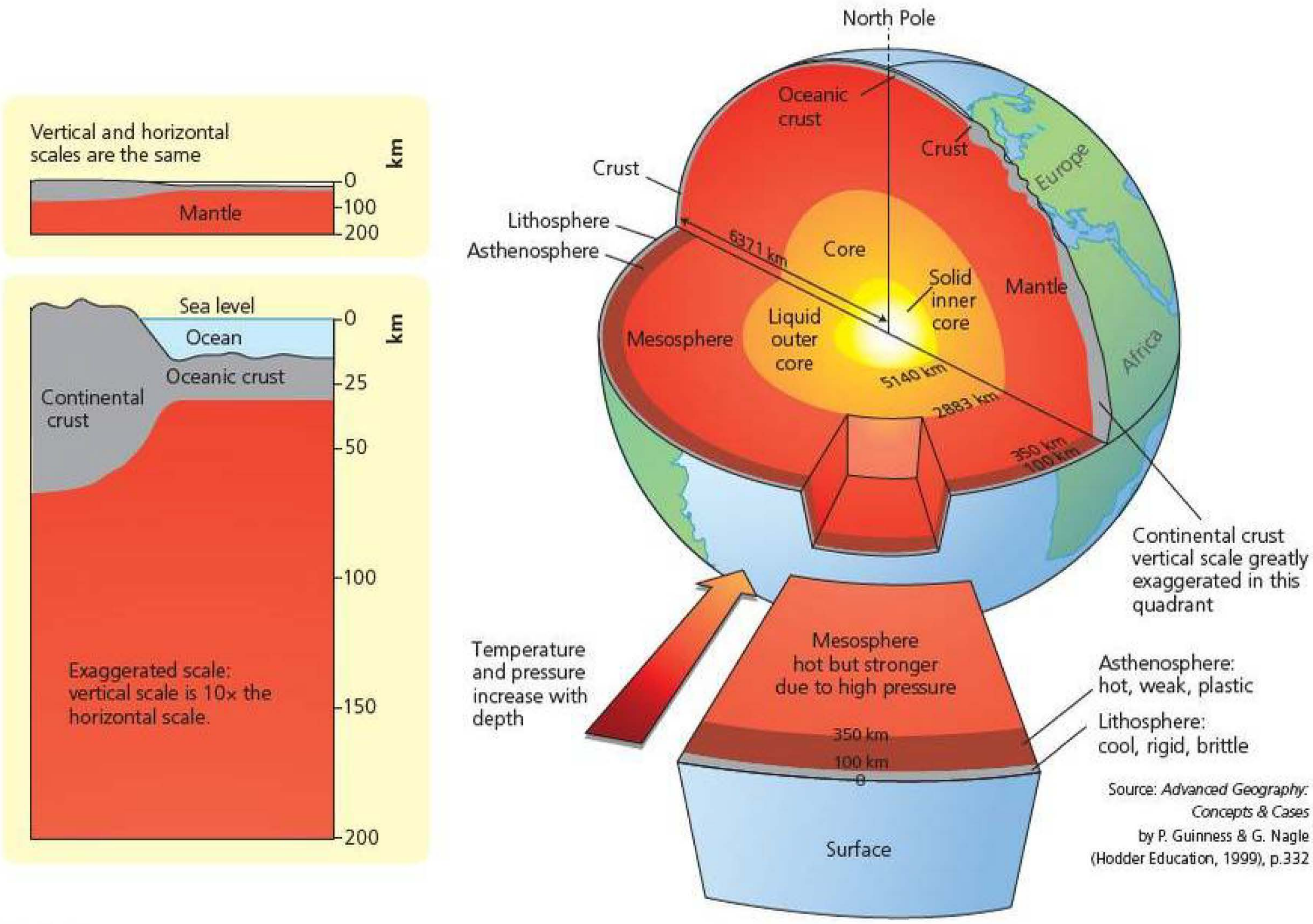


Figure 3.1 The Earth's internal structure

Table 3.1 A comparison of oceanic crust and continental crust

Examples	Continental crust	Oceanic crust
Thickness	35–70 km on average	6–10 km on average
Age of rocks	Very old; mainly over 1500 million years	Very young; mainly under 200 million years
Colour and density of rocks	Lighter, with an average density of 2.6; light in colour	Heavier, with an average density of 3.0; dark in colour
Nature of rocks	Numerous types, many contain silica and oxygen; granitic is the most common	Few types, mainly basaltic

The evidence for plate tectonics and their global patterns

In 1912, Alfred Wegener proposed the idea of continental drift. Others, such as Francis Bacon in 1620, had commented on how the shape of the coast of Africa was similar to that of South America. Wegener proposed that the continents were slowly drifting about the Earth. He suggested that, starting in the Carboniferous period some 250 million years ago, a large single continent, Pangaea, broke up and began to drift apart, forming the continents we know today. Wegener's theory provoked widespread debate initially, but with the lack of a mechanism to cause continental drift, his theory failed to receive widespread support.

In the mid-twentieth century, American Harry Hess suggested that convection currents would force molten rock (magma) to well up in the interior and to crack the crust above and force it apart. In the 1960s, research on rock magnetism supported Hess. The rocks of the Mid-Atlantic Ridge were magnetised in alternate directions in a series of identical bands on both sides of the ridge. This suggested that fresh magma had come up through the centre and forced the rocks apart. In addition, with increasing distance from the ridge the rocks were older. This supported the idea that new rocks were being created at the centre of the ridge and the older rocks were being pushed apart.

In 1965, Canadian geologist J. Wilson linked together the ideas of continental drift and sea-floor spreading into a concept of mobile belts and rigid plates, which formed the basis of plate tectonics.

The evidence of plate tectonics includes:

- the past and present distribution of earthquakes
- changes in the Earth's magnetic field
- the 'fit' of the continents: in 1620 Francis Bacon noted how the continents on either side of the Atlantic could be fitted together like a jigsaw (Figure 3.2)
- glacial deposits in Brazil match those in West Africa
- the fossil remains in India match those of Australia
- the geological sequence of sedimentary and igneous rocks in parts of Scotland match those found in Newfoundland
- ancient mountains can be traced from east Brazil to west Africa, and from Scandinavia through Scotland to Newfoundland and the Appalachians (eastern USA)
- fossil remains of a small aquatic reptile, Mesosaurus, which lived about 270 million years ago, are found only in a restricted part of Brazil and in south-west Africa – it is believed to be a poor swimmer!

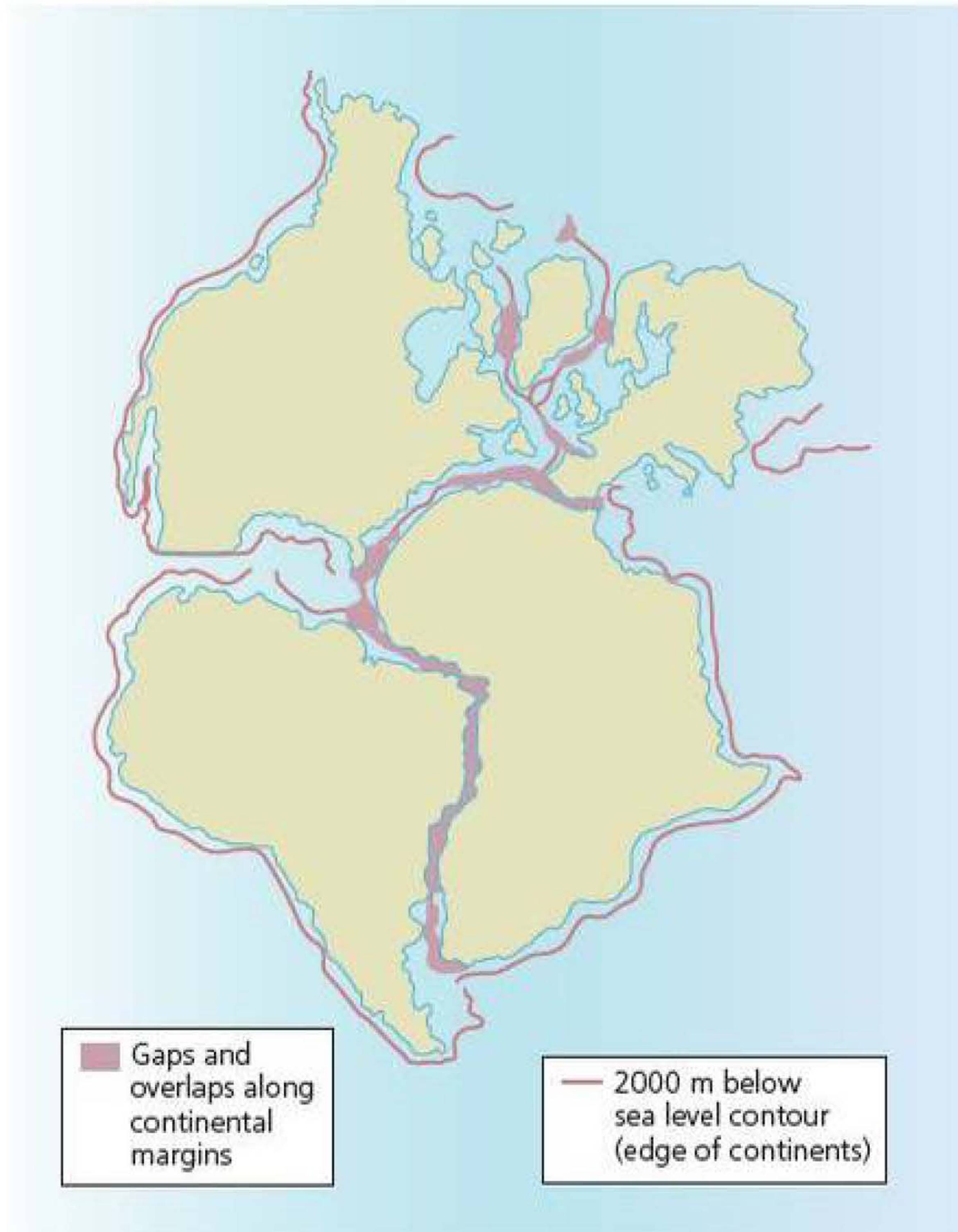
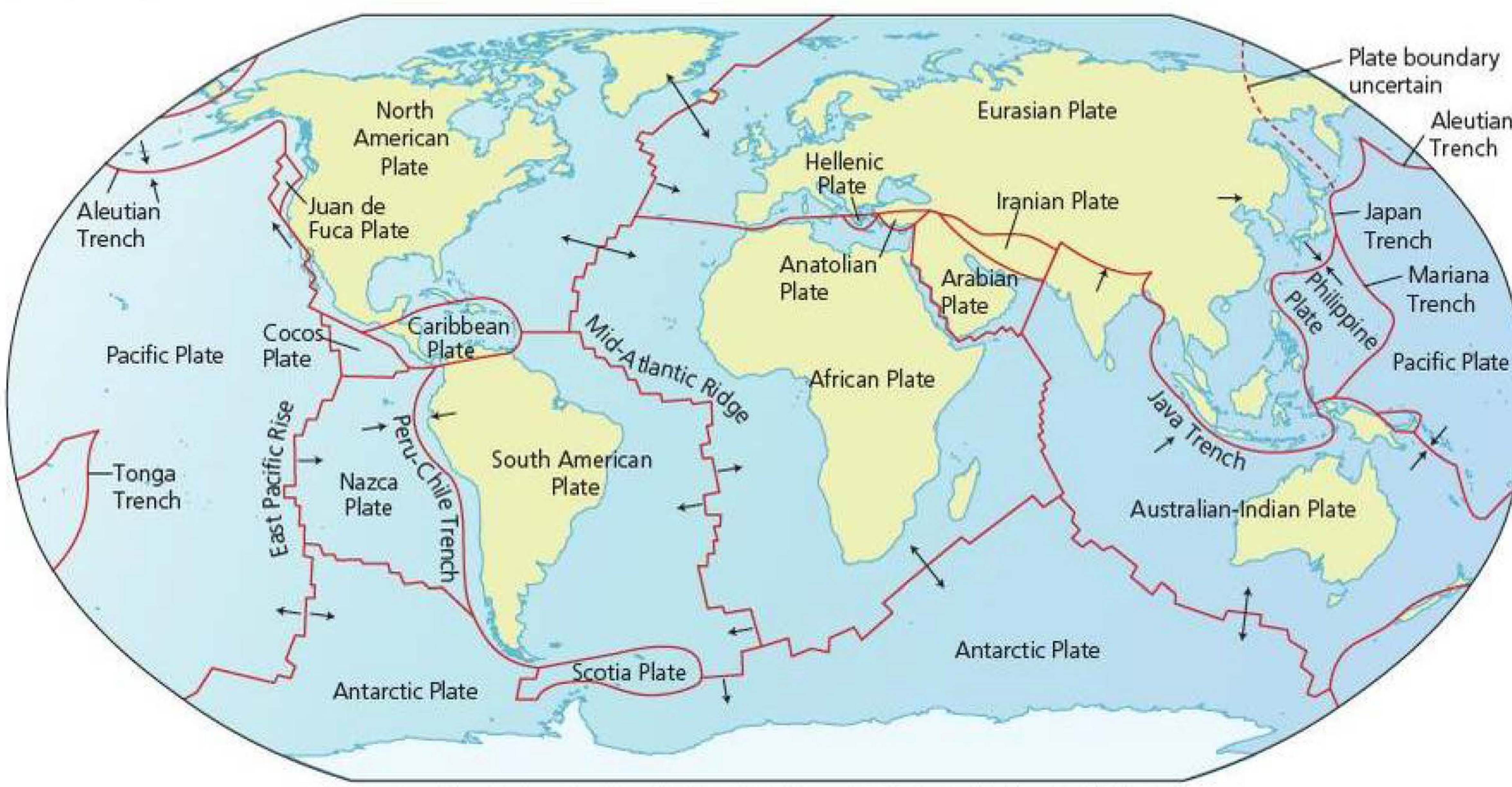


Figure 3.2 Evidence for plate tectonics

Plate boundaries

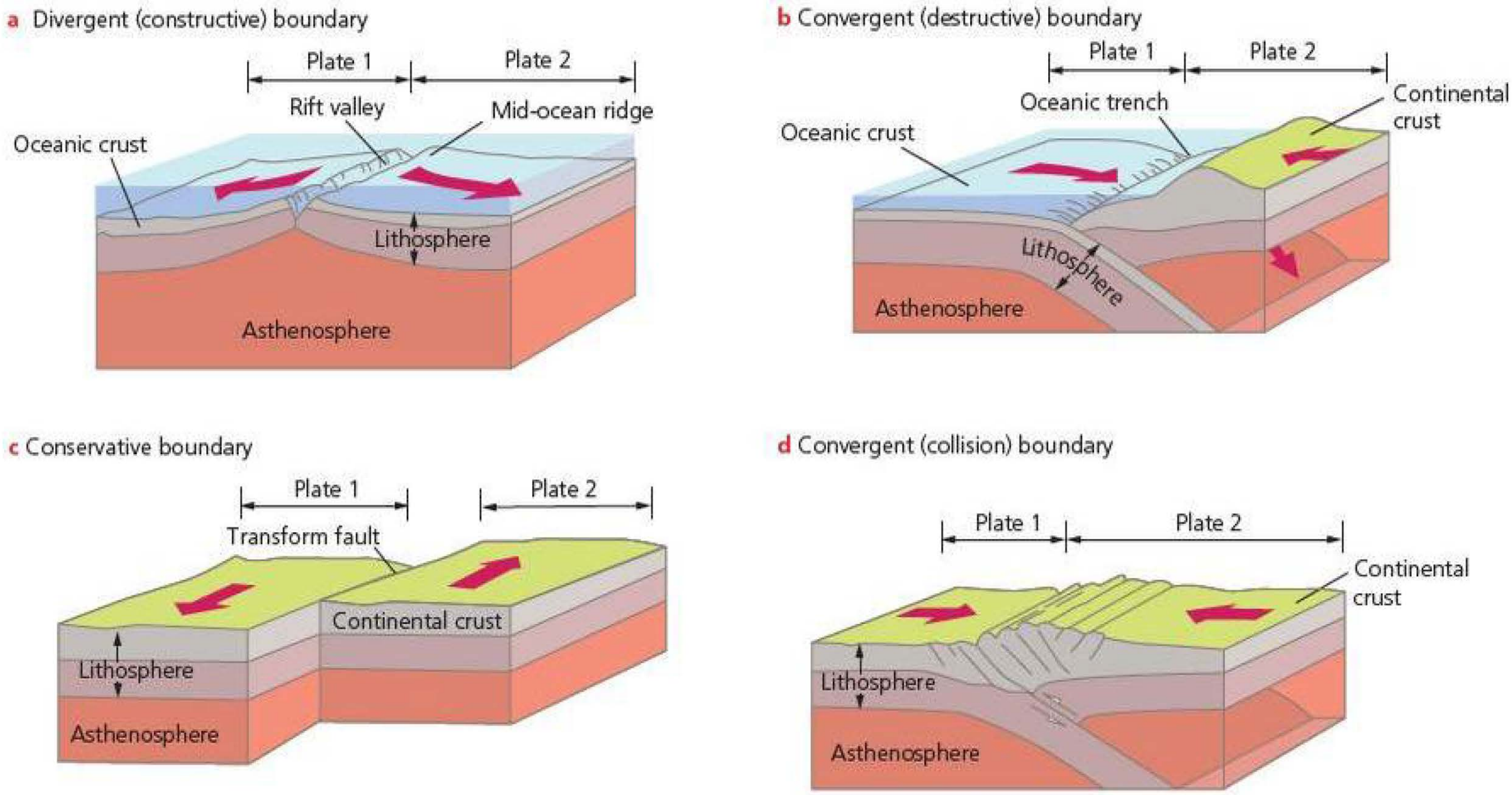
The zone of earthquakes around the world has helped to define six major plates and a number of minor plates (Figures 3.3 and 3.4). The boundaries between plates can be divided into three main types: divergent (constructive) boundaries, convergent plate boundaries (including destructive and collision boundaries) and conservative plate boundaries. Divergent (constructive) plate boundaries, where new crust is formed, are mostly in the middle of oceans (Figure 3.5a). These ridges are zones of shallow earthquakes (less than 50 kilometres below the surface). Where two plates converge, a deep-sea trench may be formed when one of the plates is subducted (forced downwards) into the mantle (Figure 3.5b). Deep earthquakes, up to 700 kilometres below the surface, are common. Good examples include the trenches off the Andes, and the Aleutian Islands that stretch out from Alaska.

Figure 3.3 Thingvellir, Iceland – a constructive plate boundary; here, the North American plate (left) is pulling away from the Eurasian plate (right of picture)



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.334

Figure 3.4 Plate boundaries



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.334

Figure 3.5 Types of plate boundary

Along some plate boundaries, plates slide past one another to create a transform fault (fault zone) without converging or diverging (Figure 3.5c). Again, these are associated with shallow earthquakes, such as the San Andreas Fault in California. Where continents embedded in the plates collide with each other, there is no subduction but collision leading to crushing, and folding may create young fold mountains such as the Himalayas and the Andes (Figure 3.5d).

The movement of plates

There are three main theories about movement:

1. **The convection current theory** – This states that huge convection currents occur in the Earth's interior. Hot magma rises through the core to the surface and then spreads out at mid-ocean ridges. The cold solidified crust sinks back into the Earth's interior, because it is heavier and denser than the surrounding material. The cause of the movement is radioactive decay in the core.
2. **The dragging theory** – Plates are dragged or subducted by their oldest edges, which have become cold and heavy. Plates are hot at the mid-ocean ridge but cool as they move away. Complete cooling takes about a million years. As cold plates descend at the trenches, pressure causes the rock to change and become heavier.
3. A hotspot is a plume of lava that rises vertically through the mantle. Most are found near plate margins and they may be responsible for the original rifting of the crust. However, the world's most abundant source of lava, the Hawaiian Hotspot, is not on a plate margin. Hotspots can cause movement – the outward flow of viscous rock from the centre may create a drag force on the plates and cause them to move.

Section 3.1 Activities

1. Briefly outline the evidence for plate tectonics.
2. Describe how a convection current works. How does it help explain the theory of plate tectonics?
3. What happens at **a** a mid-ocean ridge and **b** a subduction zone?

Processes and associated landforms

Sea-floor spreading

It was not until the early 1960s that R.S. Dietz and H.H. Hess proposed the mechanism of sea-floor spreading to explain continental drift. They suggested that continents moved in response to the growth of oceanic crust between them. Oceanic crust is thus created from the mantle at the crest of the mid-ocean ridge system.

Confirmation of the hypothesis of sea-floor spreading came with the discovery by F.J. Vine and D.H. Matthews that magnetic anomalies across the Mid-Atlantic Ridge were symmetrical on either side of the ridge axis (Figure 3.6). The only acceptable explanation for these magnetic anomalies was in terms of sea-floor spreading and the creation of new oceanic crust. When lava cools on the sea floor, magnetic grains in the rock acquire

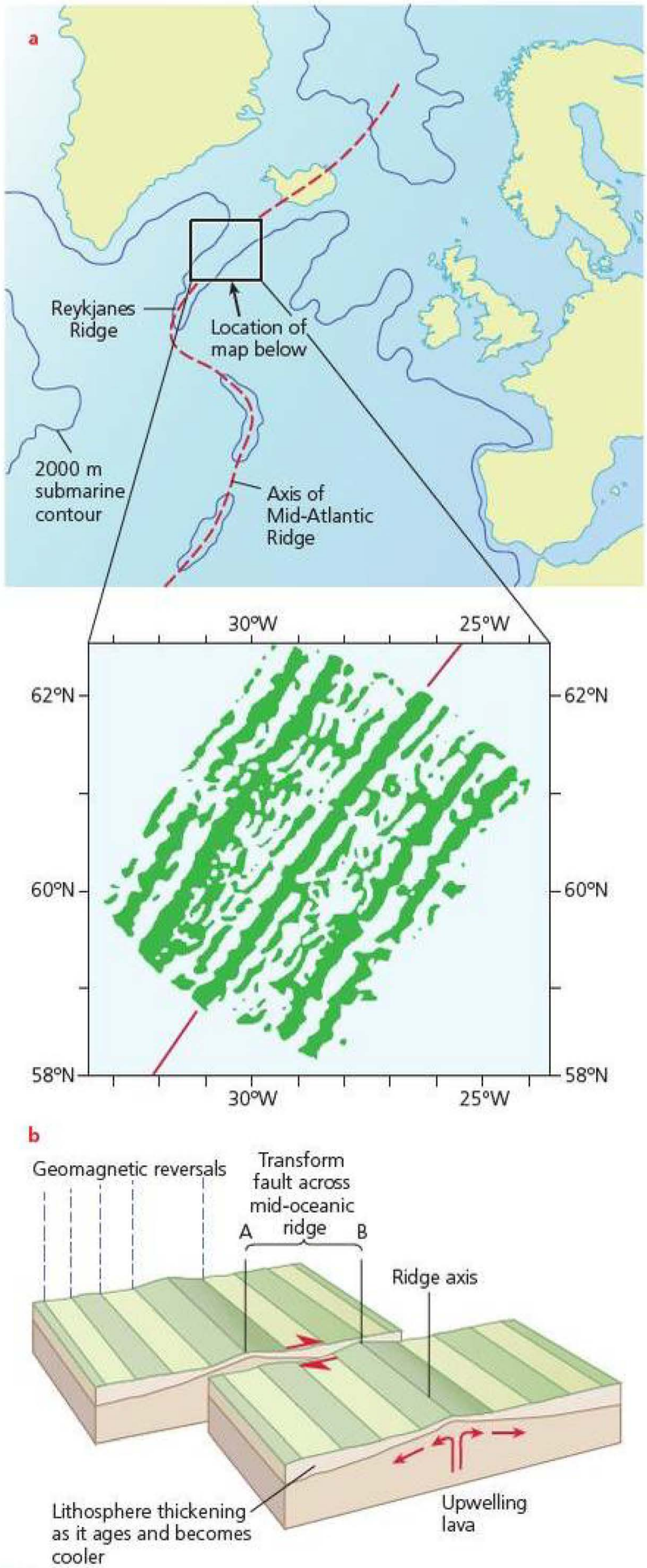


Figure 3.6 Sea-floor spreading and paleomagnetism

the direction of the Earth's magnetic field at the time of cooling. This is known as paleomagnetism.

The anomalies found across the Mid-Atlantic Ridge could, moreover, be matched with similar anomalies that had been discovered in Iceland and other parts of the world where young volcanic rocks could be dated.

The reason that the ridges are elevated above the ocean floor is that they consist of rock that is hotter and less dense than the older, colder plate. Hot mantle material wells up beneath the ridges to fill the gap created by the separating plates; as this material rises, it is decompressed and undergoes partial melting.

Spreading rates are not the same throughout the mid-ocean ridge system, but vary considerably from a few millimetres per year in the Gulf of Aden to 1 centimetre per year in the North Atlantic near Iceland and 6 centimetres per year for the East Pacific Rise. This variation in spreading rates appears to influence the ridge topography. Slow-spreading ridges, such as the Mid-Atlantic Ridge, have a pronounced rift down the centre. Fast-spreading ridges, such as the East Pacific Rise, lack the central rift and have a smooth topography. In addition, spreading rates have not remained constant through time.

The main reason for the differences in spreading rates is that the slow-spreading ridges are fed by small and discontinuous magma chambers, thereby allowing for the eruption of a comparatively wide range of basalt types. Fast-spreading ridges have large, continuous magma chambers that generate comparatively similar magmas. Because of the higher rates of magma discharge, sheet lavas are more common.

Although mid-ocean ridges appear at first sight to be continuous features within the oceans, they are all broken into segments by transverse fractures (faults) that displace the ridges by tens or even hundreds of kilometres.

Section 3.1 Activities

Briefly explain what is meant by **a** *paleomagnetism* and **b** *sea-floor spreading*.

Fractures are narrow, linear features that are marked by near-vertical fault planes.

Subduction zones and ocean trenches

Subduction zones form where an oceanic lithospheric plate collides with another plate, whether continental or oceanic (Figure 3.7). The density of the oceanic plate is similar to that of the **asthenosphere**, so it can be easily pushed down into the upper mantle. Subducted (lithospheric) oceanic crust remains cooler, and therefore denser than the surrounding mantle, for millions of years; so once initiated, subduction carries on, driven, in part, by the weight of the subducting crust. As the Earth has not grown significantly in size – not enough to accommodate

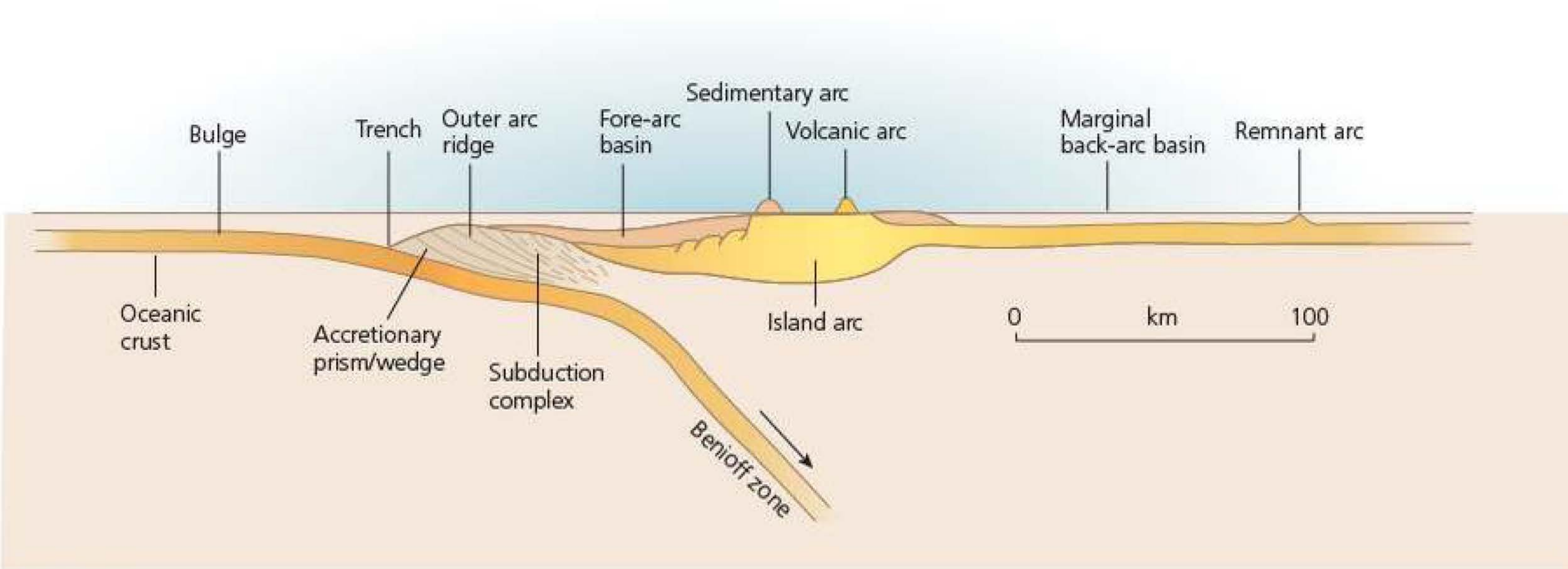


Figure 3.7 Ocean–ocean subduction zone

the new crustal material created at mid-ocean ridges – the amount of subduction roughly balances the amount of production at the constructive plate margins.

Subduction zones dip mostly at angles between 30° and 70°, but individual subduction zones dip more steeply with depth. The dip of the slab is related inversely to the velocity of convergence at the trench, and is a function of the time since the initiation of subduction. The older the crust, the steeper it dips. Because the downgoing slab of lithosphere is heavier than the plastic asthenosphere below, it tends to sink passively; and the older the lithosphere, the steeper the dip.

The evidence for subduction is varied:

- the existence of certain landforms such as deep-sea trenches and folded sediments – normally arc-shaped and containing volcanoes
- the **Benioff zone** – a narrow zone of earthquakes dipping away from the deep-sea trench
- the distribution of temperature at depth – the oceanic slab is surrounded by higher temperatures.

At the subduction zone, deep-sea **ocean trenches** are found. Deep-sea trenches are long, narrow depressions in the ocean floor with depths from 6000 metres to 11 000 metres. Trenches are found adjacent to land areas and associated with island arcs worldwide. They are more numerous in the Pacific Ocean. The trench is usually asymmetric, with the steep side towards the land mass. Where a trench occurs off a continental margin, the turbidites (sediments) from the slope are trapped, forming a hadal plain on the floor of the trench.

Benioff zone

A large number of events take place on a plane that dips on average at an angle of about 45° away from the underthrusting oceanic plate. The plane is known as the Benioff (or Benioff-Wadati) zone, after its discoverer(s), and earthquakes on it extend from the surface, at the trench, down to a maximum depth of about 680 kilometres. For example, shallow, intermediate and deep-focus earthquakes in the south-western Pacific occur at progressively greater distances away from the site of underthrusting at the Tonga Trench.

Section 3.1 Activities

Describe the main characteristics of **a** mid-ocean ridges and **b** subduction zones.

Fold-mountain building

Plate tectonics is associated with mountain building. Linear or arcuate chains – sometimes called 'orogenic mountain belts' – are associated with convergent plate boundaries, and formed on land. Where an ocean plate meets a continental plate, the lighter, less dense continental plate may be folded and buckled into fold mountains, such as the Andes. Where two continental plates meet, both may be folded and buckled, as in the case of the Himalayas, formed by the collision of the Eurasian and Indian plates. Mountain building is often associated with crustal thickening, deformation and volcanic activity, although in the case of the Himalayas, volcanic activity is relatively unimportant.

The Indian subcontinent moved rapidly north during the last 70 million years, eventually colliding with the main body of Asia. A huge ocean (Tethys) has been entirely lost between these continental masses. Figure 3.8a shows the situation just prior to the elimination of the Tethys Ocean by subduction beneath Asia. Note the volcanic arc on the Asian continent (rather like the Andes today).

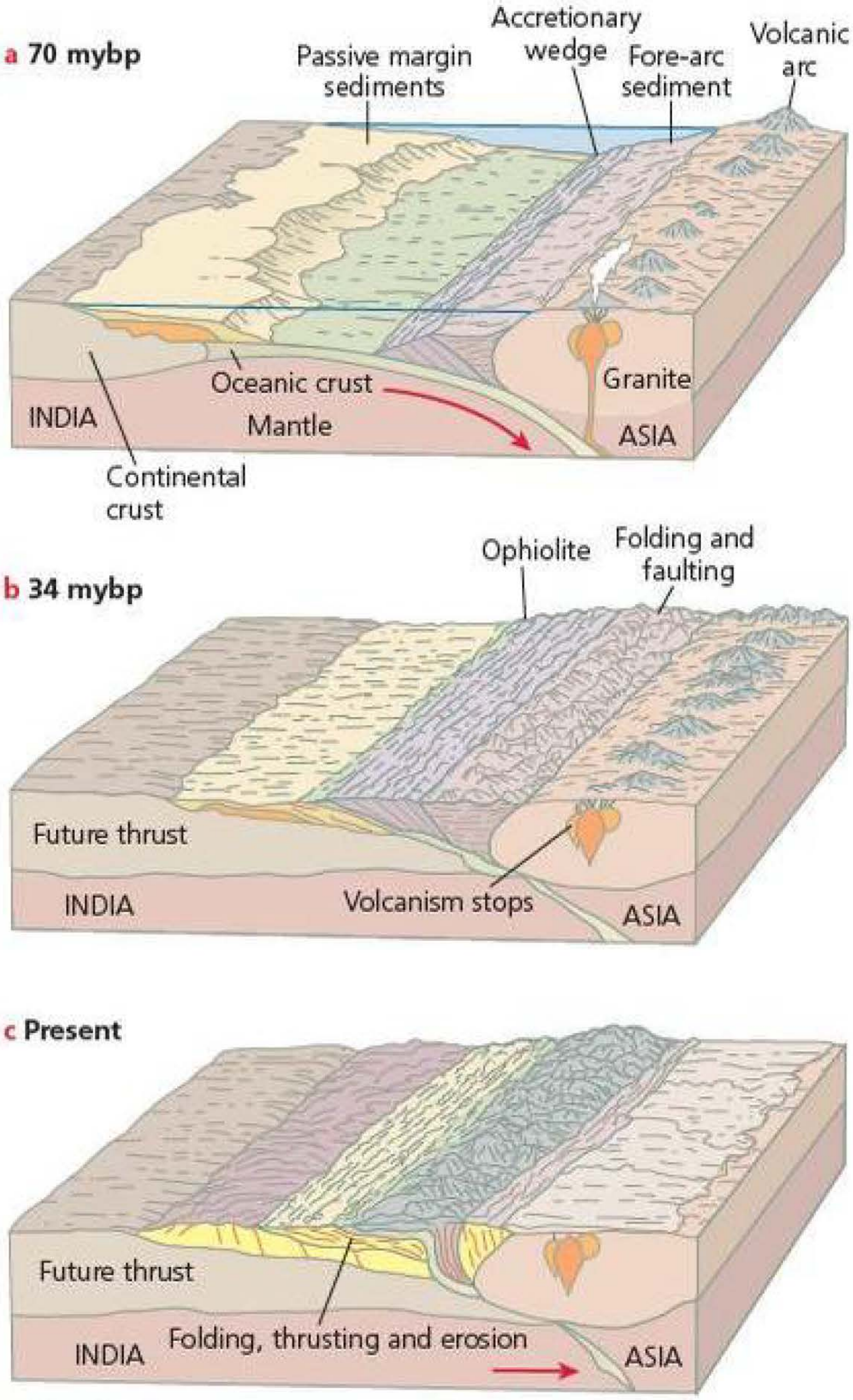


Figure 3.8 Formation of the Himalayas

In Figure 3.8b, the Tethys Ocean has *just* closed. The leading edge of the Indian subcontinent and the sedimentary rocks of its continental shelf have been thrust beneath the edge of the Asian continent. (Ophiolite refers to pieces of ocean crust thrusted onto the edge of the continental crust.)

Finally, in Figure 3.8c the Indian subcontinent continues to move north-eastward relative to the rest of Asia. In the collision zone, the continental crust is thickened because Asia overrides India, and it is this crustal thickening that results in the uplift of the Himalayan mountain range. The red lines show the many locations in the collision zone where thrust faults are active to accommodate the deformation and crustal thickening.

In contrast, the Andes were formed as a result of the subduction of oceanic crust under continental crust. The Andes are the highest mountain range in the Americas, with 49 peaks over 6000 metres high. Unlike the Himalayas, the Andes contain many active volcanoes.

Before about 250 million years ago, the western margin of South America was a passive continental margin. Sediments accumulated on the continental shelf and slope. With the break-up of Pangaea, the South American plate moved westward, and the eastward-moving oceanic lithosphere began subducting beneath the continent.

As subduction continued, rocks of the continental margin and trench were folded and faulted and became part of an accretionary wedge along the west coast of South America. Subduction also resulted in partial melting of the descending plate, producing andesitic volcanoes at the edge of the continent.

The Andes mountains comprise a central core of granitic rocks capped by andesitic volcanoes. To the west of this central core, along the coast, are the deformed rocks of the accretionary wedge; and to the east of the central core are sedimentary rocks that have been intensely folded. Present-day subduction, volcanism and seismicity indicate that the Andes mountains are still actively forming.

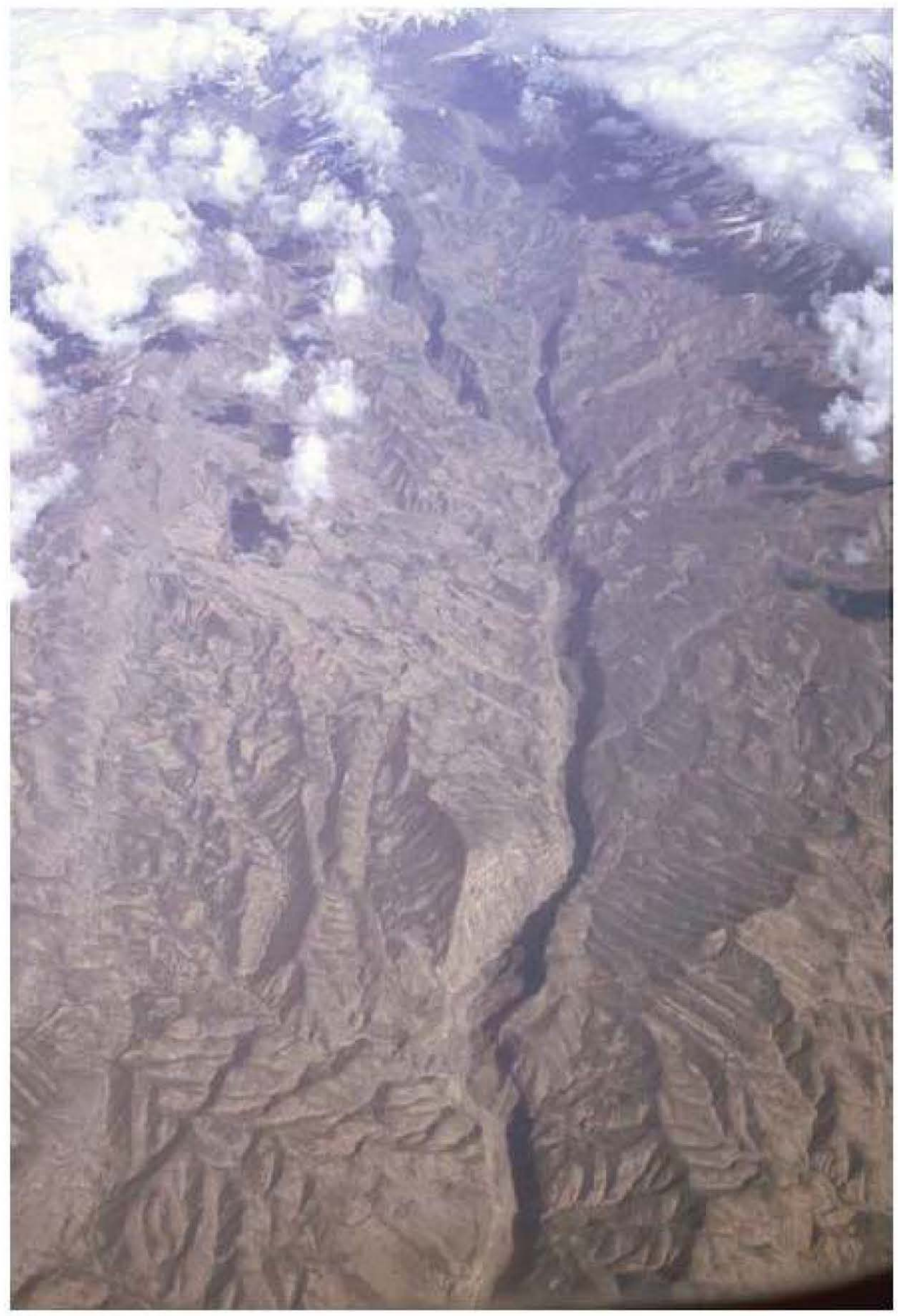


Figure 3.9 Fold mountains

Section 3.1 Activities

Compare and contrast the formation of the Andes and the formation of the Himalayas.

Ocean ridges

The longest linear, uplifted features of the Earth's surface are to be found in the oceans. They are giant submarine mountain chains with a total length of more than 60000 kilometres, between 1000 and 4000 kilometres wide and have crests that rise 2 to 3 kilometres above the surrounding ocean basins, which are 5 kilometres deep. The average depth of water over their crests is thus about 2500 metres. These features are the mid-ocean ridges, famous now not only for their spectacular topography, but because it was with them, in the early 1960s, that the theory of ocean-floor spreading, the precursor of plate tectonic theory, began. We now know that it is at these mid-ocean ridges that new lithosphere is created.

Similar ridges occur at the margins of oceans; the East Pacific Rise is an example. There are other spreading ridges behind the volcanic arcs of subduction zones. These are usually termed 'back-arc spreading centres'. The first ridge to be discovered, the Mid-Atlantic Ridge, was found during attempts to lay a submarine cable across the Atlantic in the mid-nineteenth century.

Volcanic island arcs

Island arc systems are formed when oceanic lithosphere is subducted beneath oceanic lithosphere. They are consequently typical of the margins of shrinking oceans such as the Pacific, where the majority of island arcs are located. They also occur in the western Atlantic, where the Lesser Antilles (Caribbean) and Scotia arcs are formed at the eastern margins of small oceanic plates. The Lesser Antilles (Eastern Caribbean) Arc shows all the features of a typical island arc. Ocean–ocean subduction zones tend to be simpler than ocean–continental subduction zones. In a typical ocean–ocean subduction zone, there are a number of characteristic features (Figure 3.10):

- Ahead of the subduction zone, there is a low bulge on the sea floor (known as the **trench outer rise**) caused by the bending of the plate as it subducts. One of the best-known features is the trench that marks the boundary between the two plates. In the Eastern Caribbean, the trench associated with the subduction zone is largely filled with sediment from the Orinoco River. These sediments, more than 20 kilometres thick, have been deformed and folded into the Barbados Ridge, which emerges above the sea at Barbados.
- The **outer slope** of the trench is generally gentle, but broken by faults as the plate bends. The floor of the trench is often flat and covered by sediment (turbidites) and ash. The trench **inner slope** is steeper and contains fragments of the subducting plate, scraped off like shavings from a carpenter's plane. The **subduction complex** (also known as **accretionary prisms**) is the slice of the descending slab and may form significant landforms – for example in the Lesser Antilles, the islands of Trinidad, Tobago and Barbados are actually the top of the subduction complex.
- Most subduction zones contain an **island arc**, located parallel to a trench on the overriding plate. Typically they are found some 150–200 kilometres from the trench. Volcanic island arcs such as those in the Caribbean, including the islands from Grenada to St Kitts, are island arcs above sea level.

Figure 3.10 Island arcs in the Caribbean

Volcanic activity on Montserrat

Section 3.1 Activities

1 Describe the main features of an island arc system.
2 Briefly explain how island arcs are formed.

3.2 Weathering and rocks

Weathering is the decomposition and disintegration of rocks *in situ*. Decomposition refers to chemical weathering and creates altered rock substances, such as kaolinite (china clay) from granite. By contrast, disintegration or mechanical weathering produces smaller, angular fragments of the same rock, such as scree. A third type, biological weathering, has been identified, whereby plants and animals chemically alter rocks and physically break rocks through their growth and movement. Biological weathering is not a separate type of weathering, but a form of disintegration and decomposition. It is important to note that these processes are interrelated rather than operating in isolation.

Weathering is central to landscape evolution, as it breaks down rock and enables erosion and transport. A number of key features can be recognised:

- Many minerals are formed under high pressure and high temperatures in the Earth's core. As they cool, they become more stable.
- Weathering produces irreversible changes in a rock. Some rocks change from a solid state to a fragmented or clastic state, such as scree. Others are changed to a pliable or plastic state, such as clay.
- Weathering causes changes in volume, density, grain size, surface area, permeability, consolidation and strength.
- Weathering forms new minerals and solutions.
- Some minerals, such as quartz, may resist weathering.
- Minerals and salts may be removed, transported, concentrated or consolidated.
- Weathering prepares rocks for subsequent erosion and transport.
- New landforms and features are produced.

Physical/mechanical weathering

There are four main types of mechanical weathering: freeze–thaw (ice crystal growth), salt crystal growth, disintegration and pressure release. Mechanical weathering operates at or near the Earth's surface, where temperature changes are most frequent.

Freeze–thaw (also called 'ice crystal growth' or 'frost shattering') occurs when water in joints and cracks freezes at 0 °C. It expands by about 10 per cent and exerts pressure up to a maximum of 2100 kg/cm² at −22 °C. These pressures greatly exceed most rocks' resistance (Table 3.2). However, the average pressure reached in freeze–thaw is only 14 kg/cm².

Table 3.2 Resistance to weathering

Rock	Resistance (kg/cm²)
Marble	100
Granite	70
Limestone	35
Sandstone	7–14

Freeze–thaw is most effective in environments where moisture is plentiful and there are frequent fluctuations above and below freezing point. Hence it is most effective in periglacial and alpine regions. Freeze–thaw is most rapid when it operates in connection with other processes, notably pressure release and salt crystallisation.

Salt crystallisation causes the decomposition of rock by solutions of salt. There are two main types of salt crystal growth. First, in areas where temperatures fluctuate around 26–28 °C, sodium sulphate (Na_2SO_4) and sodium carbonate (Na_2CO_3) expand by about 300 per cent. This creates pressure on joints, forcing them to crack. Second, when water evaporates, salt crystals may be left behind. As the temperature rises, the salts expand and exert pressure on rock. Both mechanisms are frequent in hot desert regions where low rainfall and high temperatures cause salts to accumulate just below the surface. It may also occur in polar areas when salts are deposited from snowflakes.

Experiments investigating the effectiveness of saturated salt solutions have shown a number of results.

- The most effective salts are sodium sulphate, magnesium sulphate and calcium chloride.
- Chalk decomposes fastest, followed by limestone, sandstone and shale.
- The rate of disintegration of rocks is closely related to porosity and permeability.
- Surface texture and grain size control the rate of rock breakdown. This diminishes with time for fine materials and increases over time for coarse materials.
- Salt crystallisation is more effective than insolation weathering, hydration or freeze–thaw. However, a combination of freeze–thaw and salt crystallisation produces the highest rates of breakdown.

Heating and cooling may cause disintegration in hot desert areas where there is a large diurnal temperature range. In many desert areas, daytime temperatures exceed 40 °C, whereas night-time ones are little above freezing. Rocks heat up by day and contract by night. As rock is a poor conductor of heat, stresses occur only in the outer layers. This causes peeling or exfoliation to occur. Griggs (1936) showed that moisture is essential for this to happen. In the absence of moisture, temperature change alone did not cause the rocks to break down. The role of salt in insolation weathering has also been studied.

The expansion of many salts such as sodium, calcium, potassium and magnesium has been linked with exfoliation. However, some geographers find little evidence to support this view.

Pressure release (dilatation) is the process whereby overlying rocks are removed by erosion. This causes underlying rocks to expand and fracture parallel to the surface. The removal of a great weight, such as a glacier, has the same effect. Rocks are formed at very high pressure in confined spaces in the Earth's interior. The **unloading** of pressure by the removal of overlying rocks causes cracks or joints to form at right-angles to the unloading surface. These cracks are lines of weakness within the rock. For example, if overlying pressure is released, horizontal **pseudo-bedding planes** will be formed. By contrast, if horizontal pressure is released, as on a cliff face, vertical joints will develop. The size and spacing of cracks varies with distance from the surface: with increasing depth, the cracks become smaller and further apart. Hence the part of the rock that is broken the most is the part that is most subjected to denudation processes, namely at the surface.

Vegetation roots may also physically break down rocks. Figure 3.11 shows the impact of plants roots helping to break up rock.

Figure 3.11 Biological weathering – the physical impact of plant roots

Section 3.2 Activities

1. Define mechanical weathering.
2. Explain how freeze–thaw weathering operates.
3. Comment on the resistance to weathering (Table 3.2) compared with the pressure exerted by ice when it expands.
4. Describe the process of heating/cooling. Explain why it is common in hot, arid environments.

Chemical weathering

Water is the key medium for chemical weathering. Unlike mechanical weathering, chemical weathering is most effective sub-surface since percolating water has gained organic acids from the soil and vegetation. Acidic water helps to break down rocks such as chalk, limestone and granite. The amount of water is important as it removes weathered products by solution. Most weathering therefore takes place above the water table, since weathered material accumulates in the water and saturates it. There are three main types of chemical weathering: carbonation-solution, hydrolysis and hydration.

Carbonation-solution occurs on rocks with calcium carbonate, such as chalk and limestone. Rainfall combines with dissolved carbon dioxide or organic acid to form a weak carbonic acid.

$CO_2 + H_2O \leftrightarrow H_2CO_3$ (carbonic acid)

Calcium carbonate (calcite) reacts with an acid water and forms **calcium bicarbonate** (also termed 'calcium hydrogen carbonate'), which is soluble and removed by percolating water:

$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$
calcite + carbonic acid → calcium bicarbonate

The effectiveness of solution is related to the pH of the water. For example, iron is highly soluble when the pH is 4.5 or less, and alumina (Al_2O_3) is highly soluble below 4.0 or above 9.0 but not in between.

Hydrolysis occurs on rocks with orthoclase feldspar, notably granite. Feldspar reacts with acid water and forms **kaolin** (also termed 'kaolinite' or 'china clay'), silicic acid and potassium hydroxyl:

$2KAlSi_3O_8 + 2\,H_2O \rightarrow Al_2Si_2O_5\,(OH)_4 + K_2O + 4\,SiO_2$
orthoclase feldspar + water → kaolinite + potassium hydroxyl + silicic acid

The acid and hydroxyl are removed in the solution, leaving kaolin behind as the end product. Other minerals in the granite, such as quartz and mica, remain in the kaolin. Hydrolysis also involves solution as the potassium hydroxyl is carbonated and removed in solution.

Hydration is the process whereby certain minerals absorb water, expand and change. For example, anhydrite is changed to gypsum. Although it is often classified as a type of chemical weathering, mechanical stresses occur as well. When anhydrite ($CaSO_4$) absorbs water to become gypsum ($CaSO_4.2H_2O$) it expands by about 0.5 per cent. More extreme is the increase in volume of up to 1600 per cent by shales and mudstones when clay minerals absorb water.

Section 3.2 Activities

1. Compare the character of rocks affected by mechanical weathering with those affected by chemical weathering.
2. Briefly explain the processes of carbonation-solution and hydrolysis.

Controls of weathering

The following factors affect the type and rate of weathering that takes place.

Climate

In the simplest terms, the type and rate of weathering vary with climate (Figure 3.12), but it is very difficult to isolate the exact relationship, at any scale, between climate type and rate of process. Peltier's diagrams (1950) show how weathering is related to moisture availability and average annual temperature (Figure 3.13; see also Table 3.3). In general, frost-shattering increases as the number of freeze–thaw cycles increases. By contrast, chemical weathering increases with moisture and heat. According to **Van't Hoff's Law**, the rate of chemical weathering increases 2–3 times for every increase in temperature of 10 °C (up to a maximum temperature of 60 °C). The efficiency of freeze–thaw, salt crystallisation and insolation weathering is influenced by:

- critical temperature changes
- frequency of cycles
- diurnal and seasonal variations in temperature.

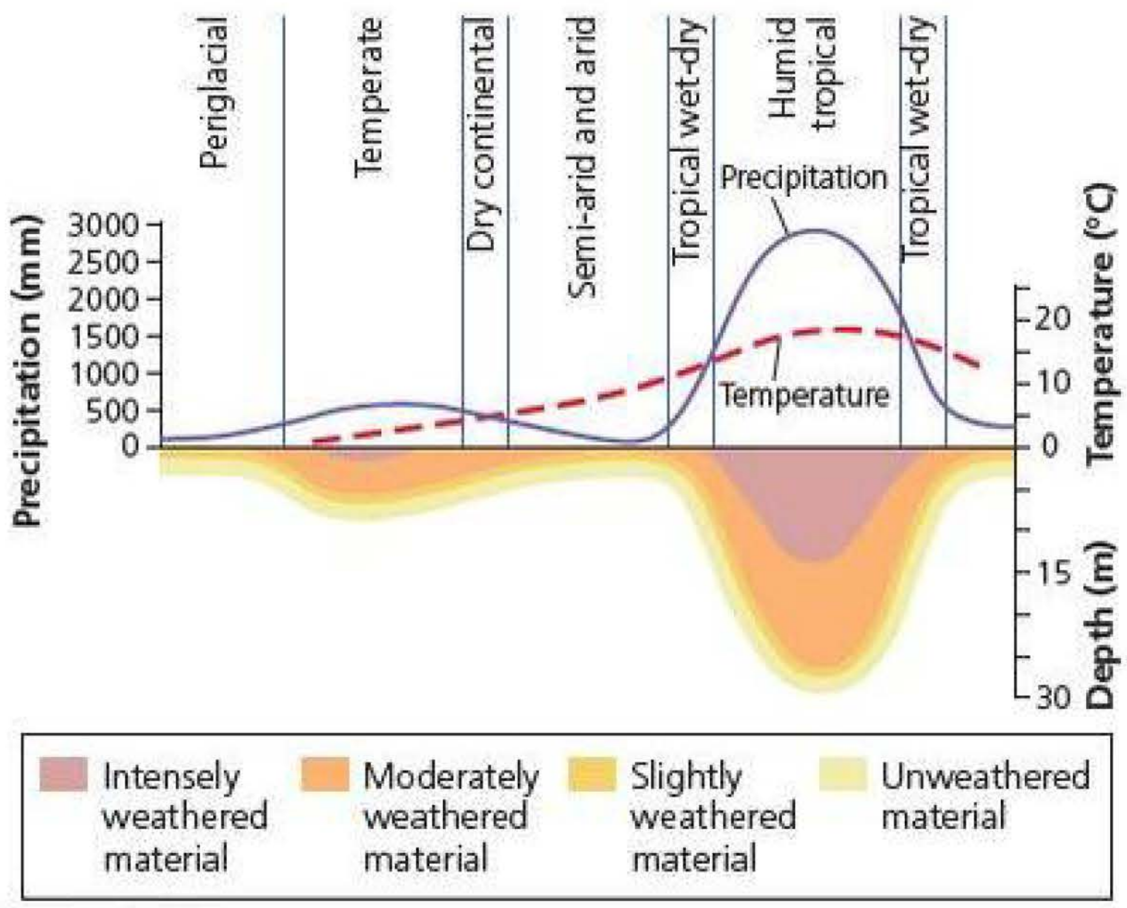


Figure 3.12 Depth of weathering profile and climate

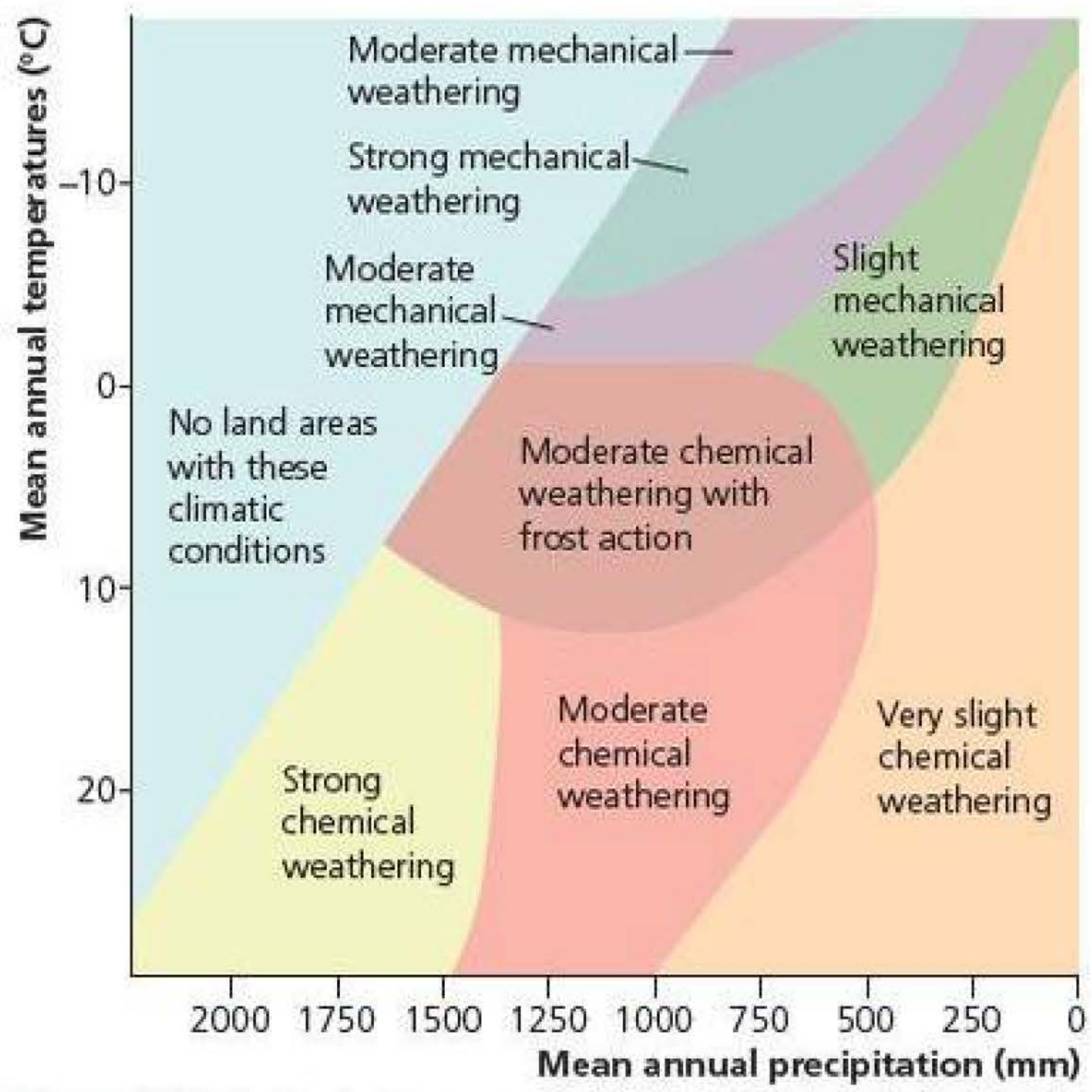


Figure 3.13 Peltier's diagram showing variations of chemical and mechanical weathering with climate

Table 3.3 Generalised weathering characteristics in four climatic regions

Climatic region	Characteristics	Examples – rates of weathering (mm yr^{-1})
Glacial/ Periglacial	Frost very important. Susceptibility to frost increases with increasing grain size. **Taiga:** fairly high soil leaching, low rates organic matter decomposition. **Tundra:** low precipitation, low temperatures, permafrost – moist conditions, slow organic production and breakdown. May have slower chemical weathering. Algal, fungal, bacterial weathering may occur. Granular disintegration occurs. Hydrolytic action reduced on sandstone, quartzite, clay, calcareous shales, phyllites, dolerites. Hydration weathering common due to high moisture. CO_2 is more soluble at low temperatures.	Narvik 0.001 Spitzbergen 0.02–0.2 Alaska 0.04
Temperate	Precipitation and evaporation generally fluctuate. Both mechanical weathering and chemical weathering occur. Iron oxides leached and redeposited. Carbonates deposited in drier areas, leached in wetter areas. Increased precipitation, lower temperatures, reduced evaporation. Organic content moderate to high, breakdown moderate. Silicate clays formed and altered. **Deciduous forest areas:** abundant bases, high nutrient status, biological activity moderate to high. **Coniferous areas:** acidic, low biological activity, leaching common.	Askrigg 0.5–1.6 Austria 0.015–0.04
Arid/semi-arid	Evaporation exceeds precipitation. Rainfall low. Temperatures high, seasonal. Organic content low. Mechanical weathering, salt weathering, granular disintegration, dominant in driest areas. Thermal effects possible. Low organic input relative to decomposition. Slight leaching produces $CaCO_3$ in soil. Sulphates and chlorides may accumulate in driest areas. Increased precipitation and decreased evaporation toward semi-arid areas and steppes yield thick organic layers, moderate leaching and $CaCO_3$ accumulation.	Egypt 0.0001–2.0 Australia 0.6–1.0
Humid tropical	High rainfall often seasonal. Long periods of high temperatures. Moisture availability high. Weathering products **a** removed or **b** accumulate to yield red and black clay soils, ferruginous and aluminous soils (lateritic), calcium-rich soils. Calcareous rocks generally heavily leached where silica content is high, soluble weathering products removed and parent silica in stable products are sandy. Where products remain, iron and aluminium are common. Usually intense deep weathering, iron and alumina oxides and hydroxides predominate. Organic content high but decomposition high.	Florida 0.005

Rock type

Rock type influences the rate and type of weathering in many ways due to:

- chemical composition
- the nature of cements in sedimentary rock
- joints and bedding planes.

For example, limestone consists of calcium carbonate and is therefore susceptible to carbonation-solution. By contrast, granite is prone to hydrolysis because of the presence of feldspar. In sedimentary rocks, the nature of the cement is crucial. Iron-oxide based cements are prone to oxidation, whereas quartz cements are very resistant.

Rock structure

The effect of rock structure varies from large-scale folding and faulting to localised patterns of joints and bedding planes. Joint patterns exert a strong control on water movement. These act as lines of weakness, thereby creating **differential resistance** within the same rock type. Similarly, grain size influences the speed with which rocks weather. Coarse-grained rocks weather quickly owing to a large void space and high permeability (Table 3.4). On the other hand, fine-grained rocks offer a greater surface area for weathering and may be highly susceptible to weathering. The importance of individual minerals was stressed by Goldich in 1938. Rocks formed of resistant minerals, such as quartz, muscovite and feldspar in granite, will resist weathering (Figure 3.14). By contrast, rocks formed of weaker minerals will weather rapidly. The interrelationship of geology and climate on the development of landforms is well illustrated by limestone and granite.

Table 3.4 Average porosity and permeability for common rock types

Rock type	Porosity (%)	Relative permeability
Granite	1	1
Basalt	1	1
Shale	18	5
Sandstone	18	500
Limestone	10	30
Clay	45	10
Silt	40	–
Sand	35	1100
Gravel	25	10000

Source: D. Brunsden, 'Weathering processes' in C. Embleton and J. Thornes (eds), Processes in Geomorphology, *Edward Arnold 1979*

Stability	Dark-coloured minerals	Light-coloured minerals	Susceptibility
Least stable	Olivine		Most susceptible
		Lime plagioclase	
	Augite		
		Lime soda plagioclase	
	Hornblende	Soda lime plagioclase	
		Soda plagioclase	
	Biotite		
Most stable	Orthoclase	Muscovite Quartz	Least susceptible

Figure 3.14 Goldich's weathering system

Vegetation

The influence of vegetation is linked with the type of climate and the nature of the soil. Moisture content, root depth and acidity of humus will influence the nature and rate of weathering. Vegetation weathers rocks in two main ways: through the secretion of organic acids, it helps to chemically weather the soil; and through the growth of roots, it physically weathers the soil.

Depth of soil may have an effect on the amount of weathering that occurs. Soils may protect rocks from further breakdown – or they may increase the rate of breakdown due to the vegetation it supports.

Relief

For weathering to continue, weathered material needs to be removed. If the slope is too shallow, removal might not occur. If the slope is too steep, water may flow over the surface. Hence, intermediate slope angles may produce most weathering.

Aspect is also important, as there may be important temperature differences between south- and north-facing slopes. However, this is important only if the temperature differences are around a critical temperature, for example 0°C for freeze–thaw weathering.

Section 3.2 Activities

1. a Define the terms *porosity* and *permeability*.
   b Choose a suitable method to show the relationship between porosity and permeability.
   c Describe the relationship between porosity and permeability.
   d What are the exceptions, if any, to this relationship?
2. Describe and explain how the type and intensity of mechanical weathering varies with climate.
3. Describe and explain how the type and intensity of chemical weathering varies with climate.
4. How useful are mean annual temperature and mean annual rainfall as a means of explaining variations in the type and intensity of weathering processes?
5. Describe two ways in which vegetation affects the type and rate of weathering.

3.3 Slope processes

Introduction and definitions

The term 'slope' refers to:

- an inclined surface or hillslope
- an angle of inclination or slope angle.

Slopes therefore include any part of the solid land surface, including level surfaces of 0° (Figure 3.15). These can be sub-aerial (exposed) or sub-marine (underwater), aggradational (depositional), degradational (erosional), transportational or any mixture of these. Given the large scope of this definition, geographers generally study the hillslope. This is the area between the watershed (or drainage-basin divide) and the base. It may or may not contain a river or stream.

Slope processes

Many slopes vary with climate. In humid areas, slopes are frequently rounder, due to chemical weathering, soil creep and fluvial transport. By contrast, in arid regions slopes are jagged or straight owing to mechanical weathering and sheetwash (Figure 3.16). Climatic geomorphology is a branch of geography that studies how different processes operate in different climatic zones, and produce different slope forms or shapes (see Table 3.3 in Section 3.2).

Geological structure is another important control on slope development. This includes faults, angle of dip and vulcanicity. These factors influence the strength of a rock and create lines of potential weakness within it. In addition, rock type and character affect vulnerability to weathering and the degree of resistance to downslope movement.

Geological structure can also influence the occurrence of landslips. Slopes composed of many different types of rock are often more vulnerable to landslides due to differential erosion; that is, less resistant rocks are worn away and can lead to the undermining of more resistant rocks.

Figure 3.15 Rounded slopes at Wytham, Oxfordshire, UK – a temperate region

Figure 3.16 Silent Valley, Dolomites, Italy

Soil can be considered as part of the regolith. Its structure and texture will largely determine how much water it can hold. Clay soils can hold more water than sandy soils. A deep clay on a slope where vegetation has been removed will offer very little resistance to mass movement.

Aspect refers to the direction in which a slope faces. In some areas, past climatic conditions varied depending on the direction a slope faced. During the cold periglacial period in the northern hemisphere, in an east–west valley, the southern slope which faced north, remained in the shade. Temperatures rarely rose above freezing. By contrast, the northern slope, facing south, was subjected to many more cycles of freeze–thaw. Solifluction and overland runoff lowered the level of the slope, and streams removed the debris from the valley. The result was an asymmetric valley.

Vegetation can decrease overland runoff through the interception and storage of moisture. Deforested slopes are frequently exposed to intense erosion and gullying. However, vegetation can also increase the chance of major landslips. Dense forests reduce surface wash, causing a build-up of soil between the trees, thus deepening the regolith and increasing the potential for failure.

Section 3.3 Activities

1. Briefly describe **two** ways in which climate affects slope development. What does the term *climatic geomorphology* mean?
2. Briefly describe **two** ways in which geology affects slope development.

Mass movements

Mass movements include any large-scale movement of the Earth's surface that are not accompanied by a moving agent such as a river, glacier or ocean wave. They include:

- **very slow movements**, such as soil creep
- **fast movement**, such as avalanches
- **dry movement**, such as rockfalls
- **very fluid movements**, such as mudflows (Figure 3.17).

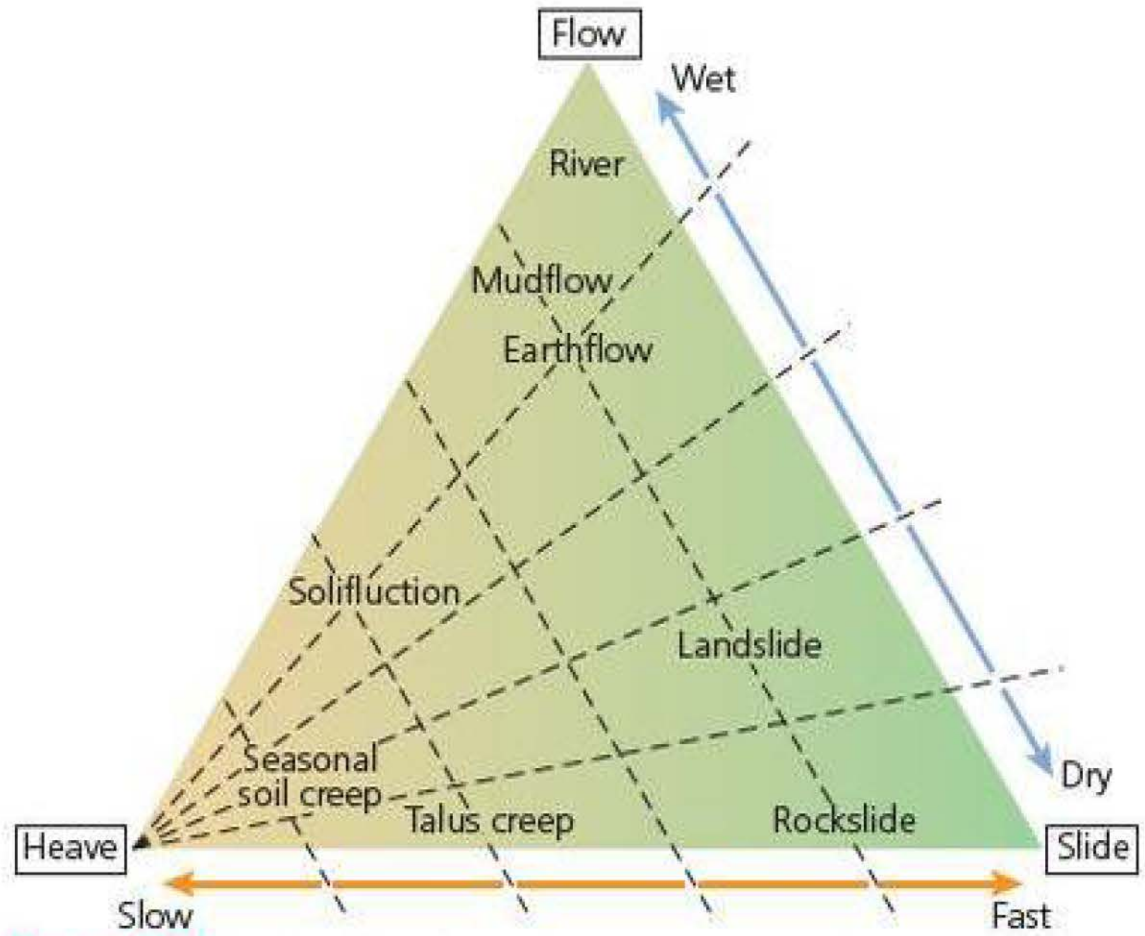


Figure 3.17 A classification of mass movements

A range of slope processes occur that vary in terms of magnitude, frequency and scale. Some are large and occur infrequently, notably rockfalls, whereas others are smaller and more continuous, such as soil creep.

The types of processes can be classified in a number of different ways:

- speed of movement (Figure 3.18)
- water content
- type of movement: flows, slides, slumps
- material.

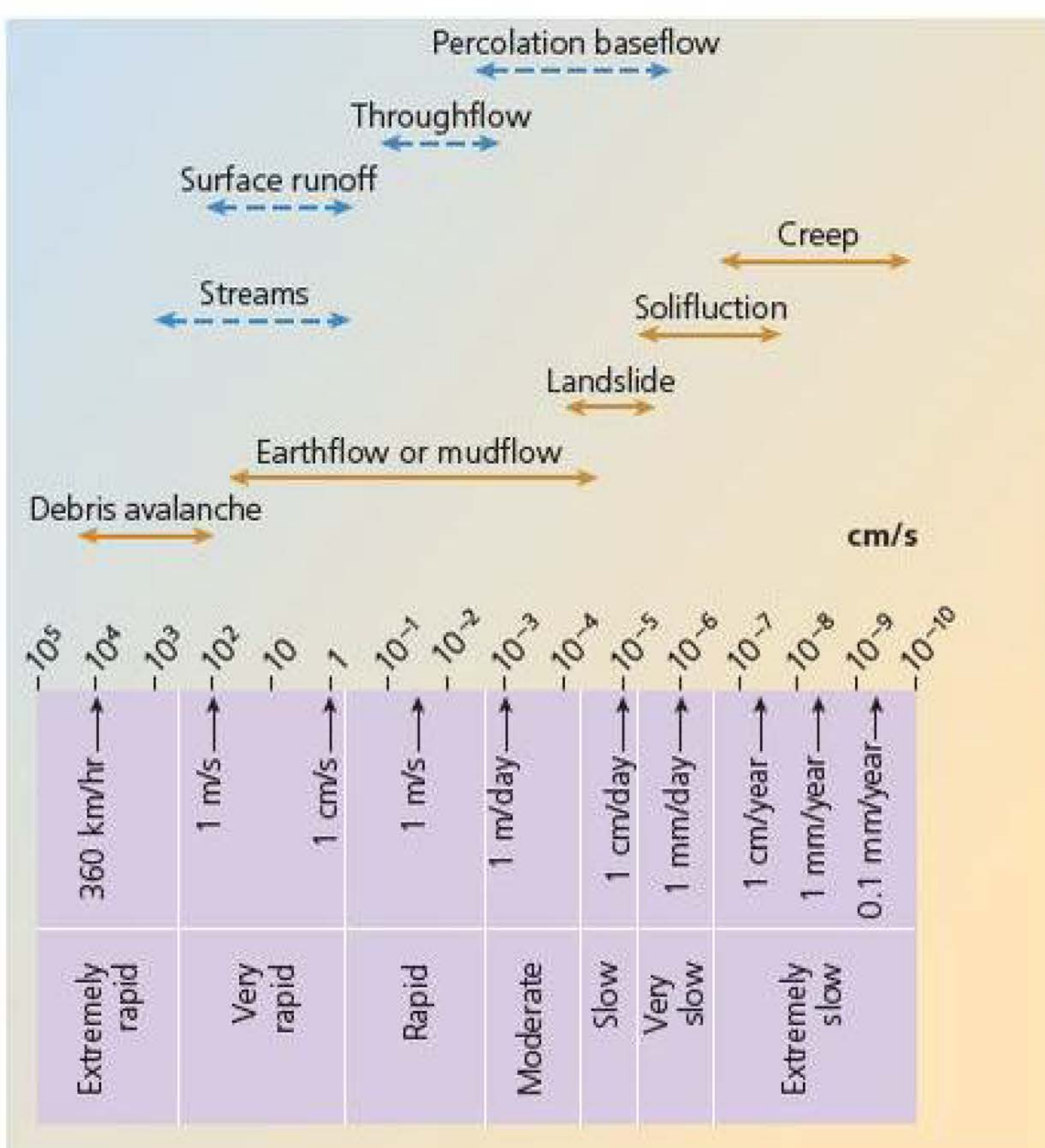


Figure 3.18 Speed of mass movements

Causes of mass movements

The likelihood of a slope failing can be expressed by its safety factor. This is the relative strength or resistance of the slope, compared with the force that is trying to move it. The most important factors that determine movement are gravity, slope angle and pore pressure.

Gravity has two effects. First, it acts to move the material downslope (a slide component). Second, it acts to stick the particle to the slope (a stick component). The downslope movement is proportional to the weight of the particle and slope angle. Water lubricates particles and in some cases fills the spaces between the particles. This forces them apart under pressure. Pore pressure will greatly increase the ability of the material to move. This factor is of particular importance in movements of wet material on low-angle slopes.

Shear strength and shear resistance

Slope failure is caused by two factors:

1. a reduction in the internal resistance, or shear strength, of the slope, or
2. an increase in shear stress; that is, the forces attempting to pull a mass downslope.

Both can occur at the same time.

Increases in shear stress can be caused by a multitude of factors (Table 3.5). These include material

Table 3.5 Increasing stress and decreasing resistance

Factor	Example
Factors that contribute to increased shear stress	
Removal of lateral support through undercutting or slope steepening	Erosion by rivers and glaciers, wave action, faulting, previous rockfalls or slides
Removal of underlying support	Undercutting by rivers and waves, subsurface solution, loss of strength by extrusion of underlying sediments
Loading of slope	Weight of water, vegetation, accumulation of debris
Lateral pressure	Water in cracks, freezing in cracks, swelling (especially through hydration of clays), pressure release
Transient stresses	Earthquakes, movement of trees in wind
Factors that contribute to reduced shear strength	
Weathering effects	Disintegration of granular rocks, hydration of clay minerals, dissolution of cementing minerals in rock or soil
Changes in pore-water pressure	Saturation, softening of material
Changes of structure	Creation of fissures in shales and clays, remoulding of sand and sensitive clays
Organic effects	Burrowing of animals, decay of tree roots

characteristics, weathering processes and changes in water availability. Weaknesses in rocks include joints, bedding planes and faults. Stress may be increased by:

- steepening or undercutting of a slope
- addition of a mass of regolith
- dumping of mining waste
- sliding from higher up the slope
- vibrational shock
- earthquakes.

Weathering may reduce cohesion and resistance. Consequently, material may be more susceptible to movement on slopes, even though the original material was stable.

Water can weaken a slope by increasing shear stress and decreasing shear resistance. The weight of a potentially mobile mass is increased by:

- an increase in the volume of water
- heavy or prolonged rain
- a rising water table
- saturated surface layers.

Moreover, water reduces the cohesion of particles by saturation. Water pressure in saturated soils (pore-water pressure) decreases the frictional strength of the solid material. This weakens the slope. Over time the safety factor for a particular slope will change. These changes may be gradual, for example percolation carrying away finer material. By contrast, some changes are rapid.

There are a number of ways that downslope movement can be opposed:

- **Friction** will vary with the weight of the particle and slope angle. Friction can be overcome on gentle slope angles if water is present. For example, solifluction can occur on slopes as gentle as 3°.
- Cohesive forces act to bind the particles on the slope. Clay may have high cohesion, but this may be reduced if the water content becomes so high that the clay liquefies, when it loses its cohesive strength.
- Pivoting occurs in the debris layers which contain material embedded in the slope.
- **Vegetation** binds the soil and thereby stabilises slopes. However, vegetation may allow soil moisture to build up and make landslides more likely (see pages 75–77).

Section 3.3 Activities

1 a Define the term *mass movement*.
  b Suggest how mass movements can be classified.
2 Define the terms *strength* and *shear stress*.
3 With the use of examples, explain why mass movements occur.

Types of mass movement

Heave or creep is a slow, small-scale process that occurs mostly in winter. It is one of the most important slope processes in environments where flows and slides are not common. Talus creep is the slow movement of fragments on a scree slope.

Individual soil particles are pushed or heaved to the surface by **a** wetting, **b** heating or **c** freezing of water (Figure 3.19). About 75 per cent of the soil-creep movement is induced by moisture changes and associated volume change. Nevertheless, freeze–thaw and normal temperature-controlled expansion and contraction are important in periglacial and tropical climates.

Particles move at right-angles to the surface (2) as it is the zone of least resistance. They fall under the influence of gravity (5) once the particles have dried, cooled, or the water has thawed. Next movement is downslope.

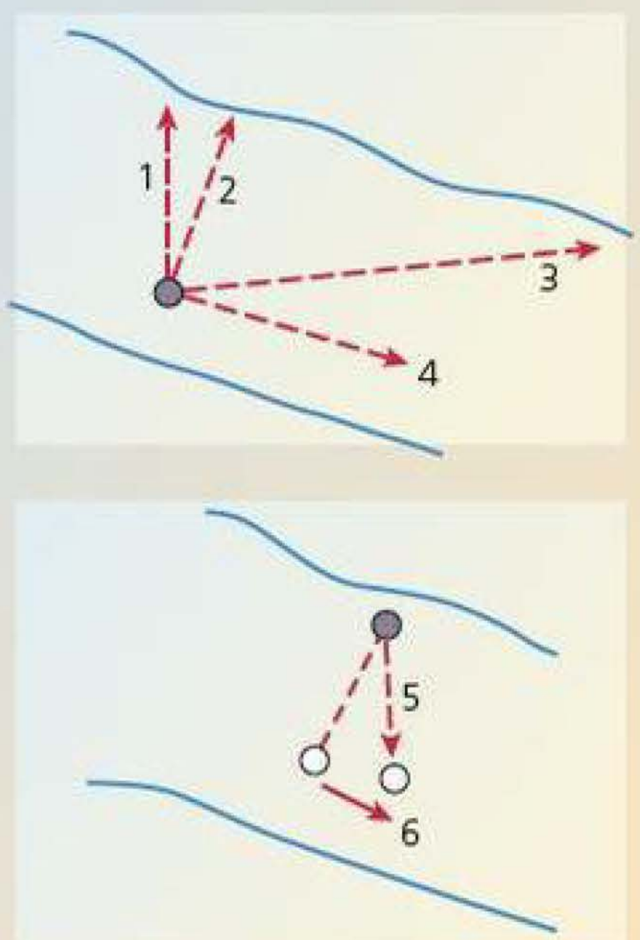


Figure 3.19 Soil creep

Rates of soil creep are slow, at 1–3 millimetres per year in temperate areas and up to 10 millimetres per year in tropical rainforest. They form terracettes. In well-vegetated humid temperate areas, soil creep can be ten times more important than slope wash. In periglacial areas, it can be as much as 300 millimetres per year. By contrast, in arid environments slope wash is more important. Small-scale variations in slope, compaction, cohesion and vegetation will have a significant effect on the rate of creep.

Observation of soil creep is difficult. Traditional qualitative evidence such as bent trees (Figure 3.20) is misleading and now largely discredited. The slow rate of movement may mean that measurement errors are serious.

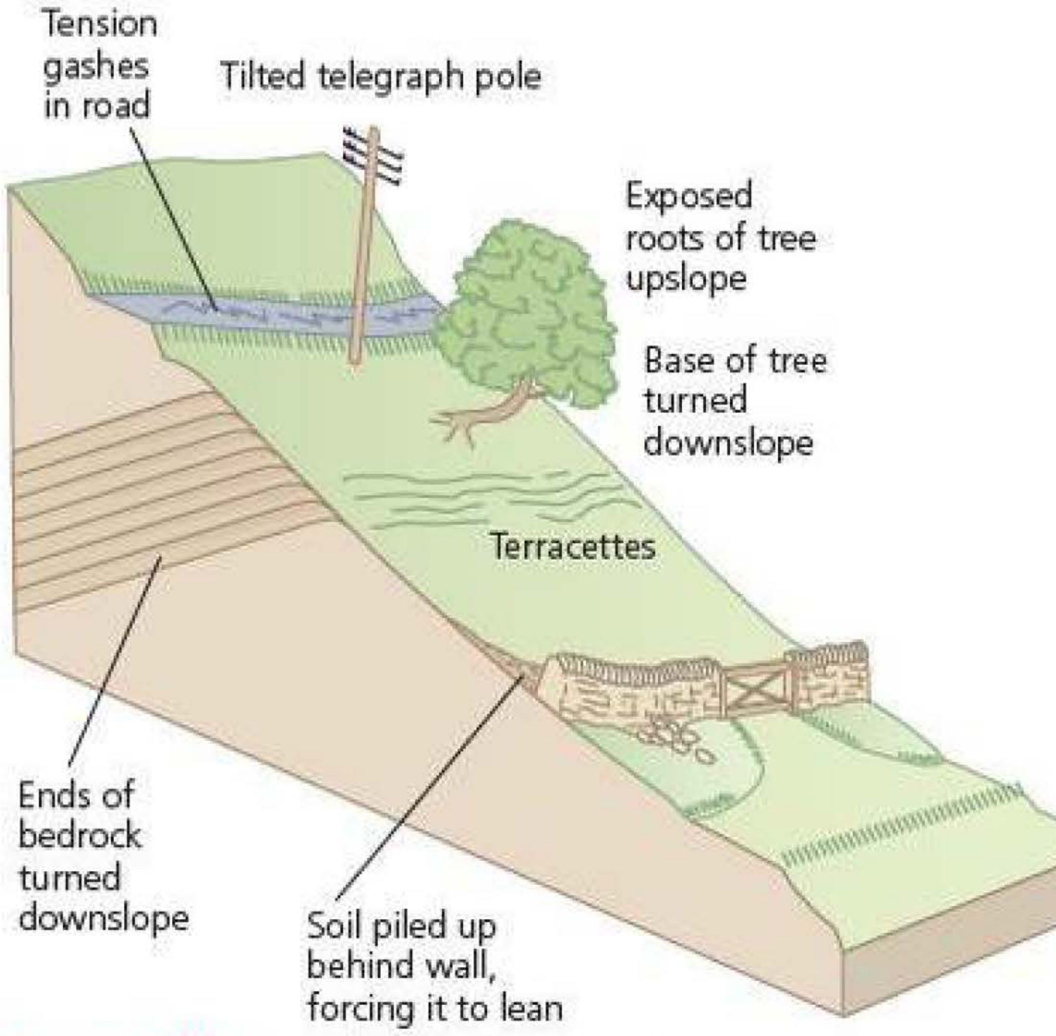


Figure 3.20 The evidence for soil creep

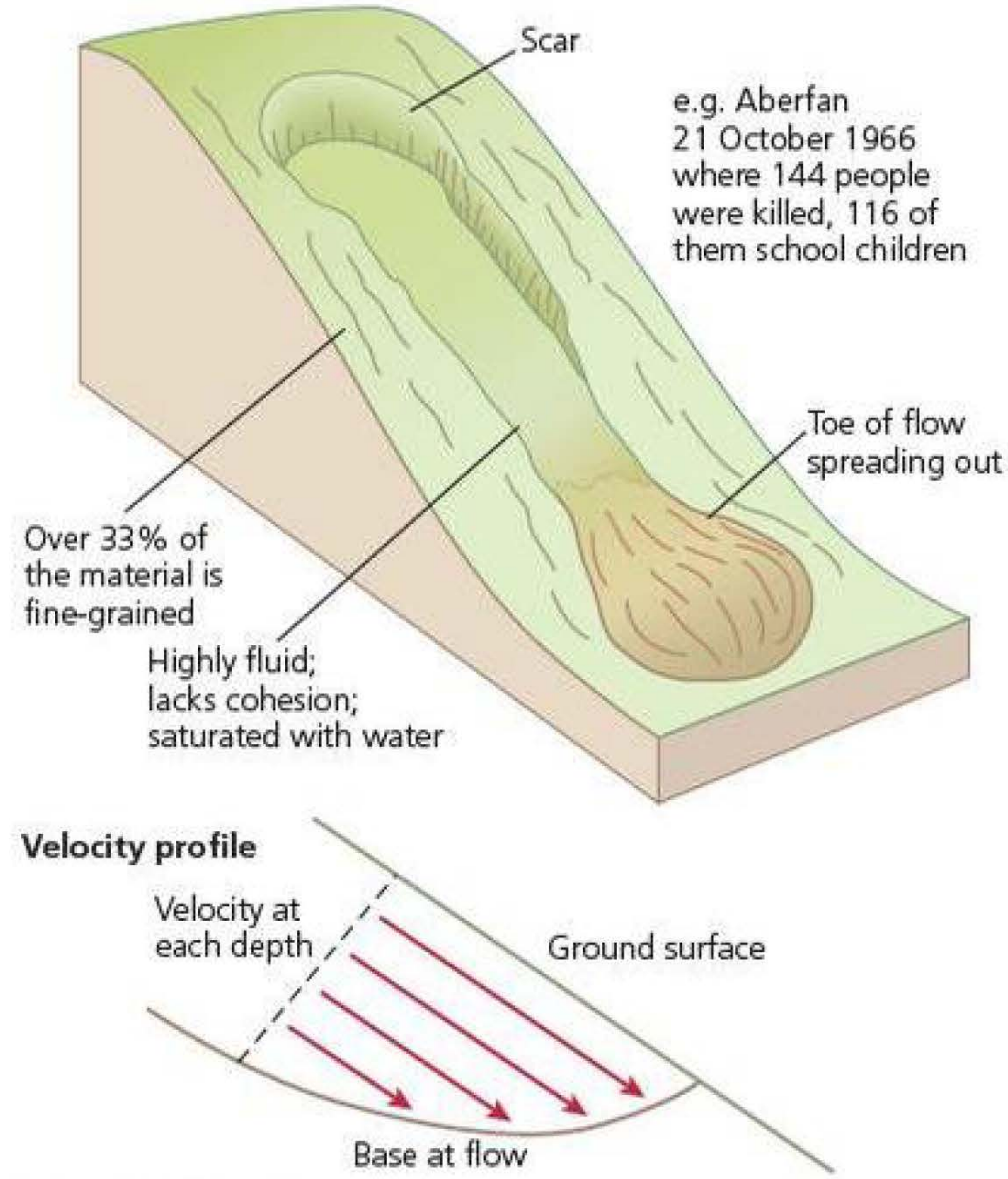


Figure 3.22 Flows

Slumps and flows

Slumps occur on weaker rocks, especially clay, and have a rotational movement along a curved slip plane (Figure 3.21). Clay absorbs water, becomes saturated and exceeds its liquid limit. It then flows along a slip plane. Frequently the base of a cliff has been undercut and weakened by erosion, thereby reducing its strength. By contrast, flows are more continuous, less jerky, and are more likely to contort the mass into a new form (Figure 3.22). Material is predominantly of a small size, such as deeply weathered clays. Particle size involved in flows is generally small, for example sand-sized and smaller.

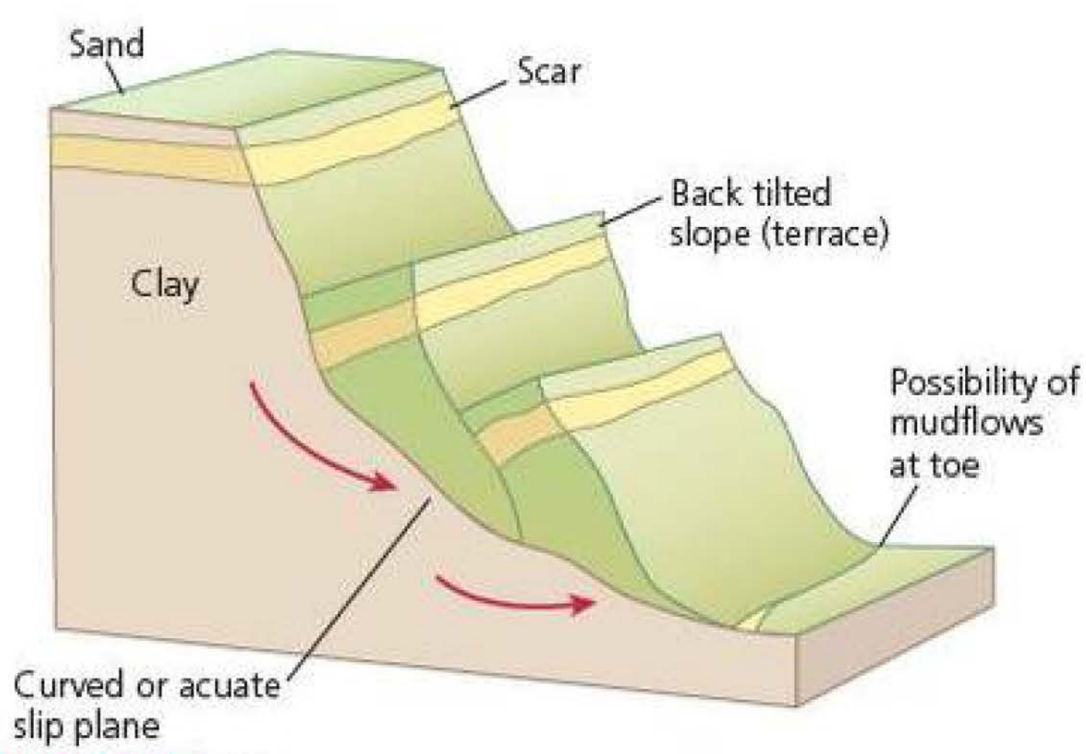


Figure 3.21 Slumps

The speed of a flow varies: mudflows are faster and more fluid than earthflows, which tend to be thicker and deeper. A higher water content will enable material to flow across gentle angles.

Earthflows and mudflows can occur on the saturated toe (end) of a landslide, or may form a distinctive type of mass movement in their own right. Small flows may develop locally, whereas others may be larger and more rapid. In theory, mudflows give way to sediment-laden rivers – but the distinction is very blurred.

Case Study: Sidoarjo mudflow

Since May 2006, more than 50 000 people in Porong District, Indonesia, have been displaced by hot mud flowing from a natural well. Gas and hot mud began spewing out when a drill penetrated a layer of liquid sediment. The amount of material spilling out peaked at 135 000 m^3/day in September 2006. By 2010, the main thoroughfare in Porong was raised 80 cm to avoid further mudflows. The Sidoarjo mudflow is an ongoing eruption of gas and mud.

Slides

Slides occur when an entire mass of material moves along a slip plane. These include:

- **rockslides and landslides** of any material, rock or regolith
- **rotational slides**, which produce a series of massive steps or terraces.

Slides commonly occur where there is a combination of weak rocks, steep slopes and active undercutting. Slides are often caused by a change in the water content of a slope or by very cold conditions. As the mass moves along the slip plane, it tends to retain its shape and structure until it hits the bottom of a slope (Figure 3.23). Slides range from small-scale slides close to roads, to large-scale movements that kill thousands of people.

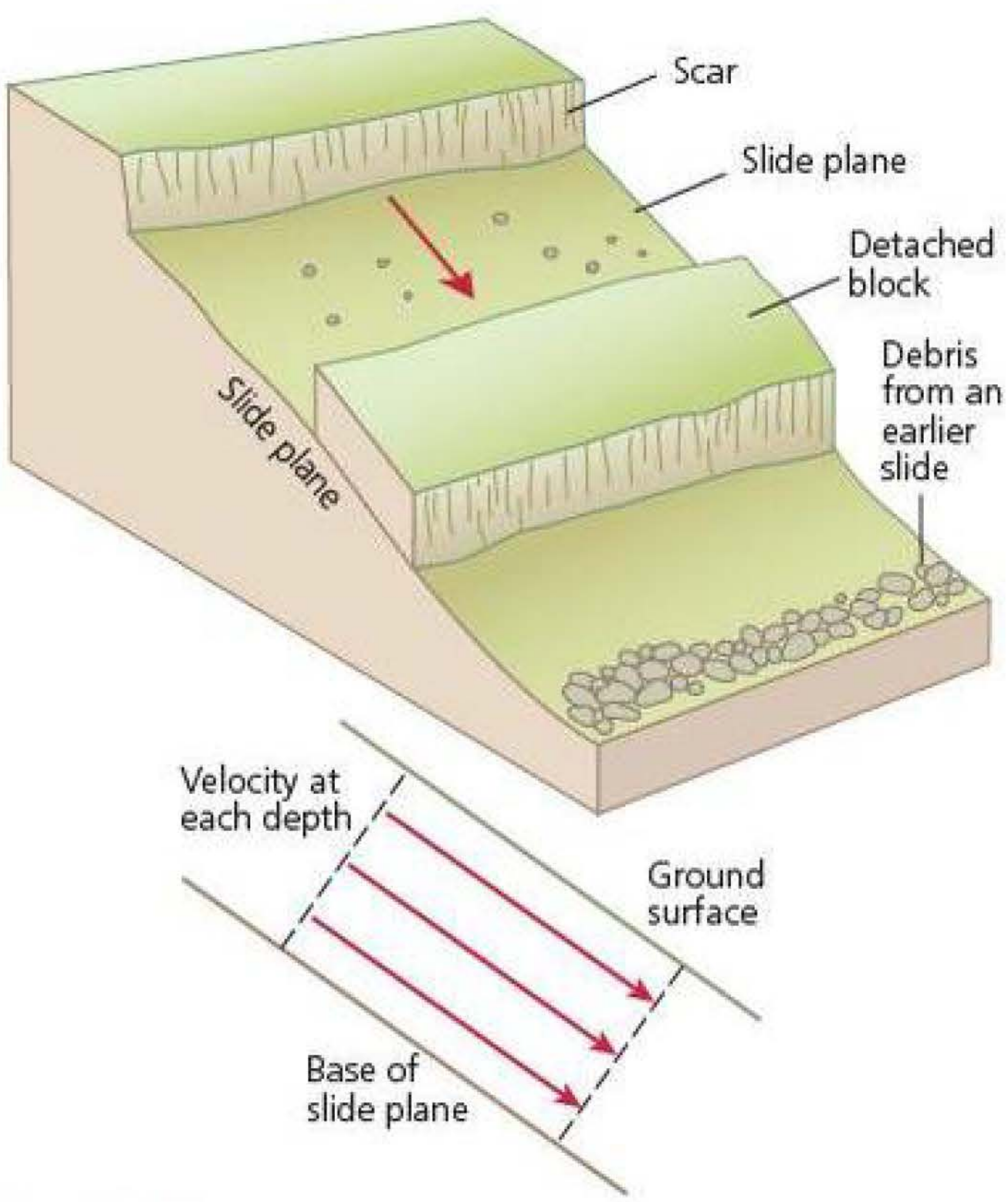


Figure 3.23 Slides

Slip planes occur for a variety of reasons:

- at the junction of two layers
- at a fault line
- where there is a joint
- along a bedding plane
- at the point beneath the surface where the shear stress becomes greater than the shear strength.

Weak rocks such as clay have little shear strength to start with, and are particularly vulnerable to the development of slip planes. The slip plane is typically a concave curve and as the slide occurs the mass will be rotated backwards.

Rockslides

In 1959, the sixth strongest earthquake ever to affect the USA occurred in Montana. Close to the epicentre of the earthquake, in the Madison River valley, a slope of schists and gneiss with slippery mica and clay was supported by a base of dolomite. The earthquake cleanly broke the dolomite. A huge volume of rock, 400 metres high and 1000 metres long, slid into the valley; 80 million tonnes of material moved in less than a minute! The Madison River was dammed and a lake 60 metres deep and 8 kilometres long was created.

Landslides

Loose rock, stones and soil all have a tendency to move downslope. They will do so whenever the downward force exceeds the resistance produced by friction and cohesion. When the material moves downslope as a result of shear failure at the boundary of the moving mass, the term 'landslide' is applied. This may include a flowing movement as well as straightforward sliding. Landslides are very sensitive to water content, which reduces the strength of the material by increasing the water pressure. This effectively pushes particles apart, thereby weakening the links between them. Moreover, water adds weight to the mass, increasing the downslope force.

Case Study: The Abbotsford landslide, Dunedin, New Zealand

The landslide that took place in East Abbotsford, South Island, New Zealand is a very good example of how human and physical factors can interact to produce a hazardous event. It also shows clearly how such hazards can be managed.

From 1978, several families in Abbotsford noticed hairline cracks appearing in their homes – in the brickwork, concrete floors and driveways. During 1979, workmen discovered that a leaking water main had been pulled apart. Geologists discovered that water had made layers of clay on the hill soft, and the sandstone above it was sliding on this slippery surface.

As a result, an early warning system was put in place. A civil defence emergency was declared on 6 August, although the situation wasn't thought to be urgent as geologists believed that landslip would continue to move only slowly. However, on 8 August a 7 hectare section of Abbotsford started down the hill at a rate of over 3 metres a minute (Figure 3.24), with houses and 17 people on board. No-one was killed, although 69 homes were destroyed or damaged and over 200 people were displaced. The total cost from the destruction of the homes, infrastructure and relief operation amounted to over £7 million. An insurance scheme designed to cope with such disasters, and government and voluntary relief measures, meant that many of the residents were compensated for their loss. However, other costs, such as depressed house prices in the surrounding area, psychological trauma and the expense of a prolonged public enquiry, were not immediately appreciated.

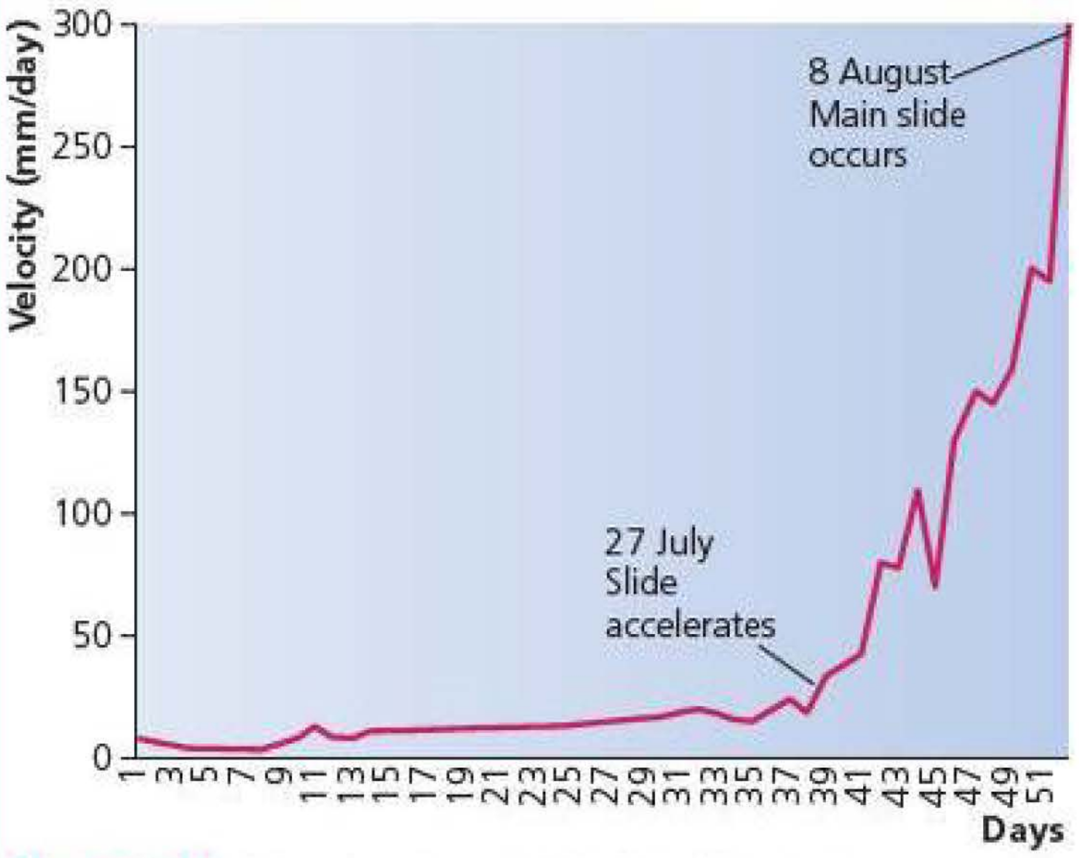


Figure 3.24 Abbotsford landslide, New Zealand

The landslide was essentially a block slide of sandstone resting on a bed of weaker clay. Displacement of 50 metres took place in about 30 minutes, leaving a small rift 30 metres deep at the head of the slope. Such geological conditions – in which a permeable hard rock rests on an impermeable soft rock – are commonly associated with landslides. In addition, the slope was dipping at an angle of 7°. Water collected in the impermeable clay, reduced its strength and cohesion, and caused the sandstone to slip along the boundary of the two rocks.

The landslide involved 5.4 million m^3 of material. At first, the land moved as a slow creep, followed by a rapid movement with speeds of 1.7 metres per minute. Rapid sliding lasted for about 30 minutes. An area of about 18 hectares was affected.

However, other factors are also believed to have made a contribution. Deforestation in the area, even over a century before, had reduced evapotranspiration in the area and there was less binding of the soil by plant roots. Urbanisation in the previous 40 years had modified the slopes by cutting and infilling, and had altered surface drainage (speeding up the removal of surface water). Quarrying of material at the toe of the slope in the 1960s and 1970s had removed support from the base of the slope. The trigger of the landslide is believed to have been a combination of leaking water pipes and heavy rainfall.

A number of lessons can be learnt from the Abbotsford landslide:

- Dangerous landslides can occur on relatively gentle slopes if the right conditions exist.
- Attention to early warning can help preparedness and reduce the loss of life.
- Human activity can destabilise slopes.
- Low-frequency, high-magnitude events may be hard to predict, but mapping and dating of old hazards may indicate areas of potential risk – a regional landslide **hazard assessment** should be made where there is evidence of previous landslide activity.
- A landslide insurance scheme eased the cost of the event – however, money was available only after the event rather than beforehand, and the insurance only covered houses, not land damage.

Section 3.3 Activities

1. What were the causes of the Abbotsford landslide?
2. Describe the impacts of the Abbotsford landslide.
3. What lessons can be learnt from the Abbotsford landslide?

Case Study: Mexican landslides, 2010

In October 2010, mud buried part of a remote town in the southern Mexican state of Oaxaca when a large chunk of a nearby mountain collapsed after three days of relentless rain. Initially, it was thought that the landslide had caused a massive tragedy with up to 1000 people killed. However, the number of deaths was believed to be less than ten. The landslide happened at about four o'clock in the morning. The authorities were unsure how many houses had been buried because it was dark, so they estimated.

The rescue progress along the unpaved mountain road was hampered by smaller landslides and a collapsed bridge. Heavy cloud cover prohibited helicopters from getting a clear view of the situation on the ground. When the first rescue workers and soldiers eventually reached the town, they found considerable destruction in one relatively small part of the town. Two houses were completely interred, two partially buried and thirty more in serious danger because they lay within the path of the still-unstable mudflow.

In 2010, Mexico experienced one of the most intense rainy seasons on record, with large areas under water in lowland regions of Oaxaca as well as in other southern states. Landslides are a major danger in mountainous parts of the country – particularly those, such as Oaxaca, that have long suffered from severe deforestation.

Falls

Falls occur on steep slopes (greater than 40°), especially on bare rock faces where joints are exposed. The initial cause of the fall may be weathering, such as freeze–thaw or disintegration, or erosion prising open lines of weakness. Once the rocks are detached, they fall under the influence of gravity (Figure 3.25). If the fall is short, it produces a relatively straight scree. If it is long, it forms a concave scree. Falls are significant in producing the retreat of steep rock faces and in providing debris for scree slopes and talus slopes.

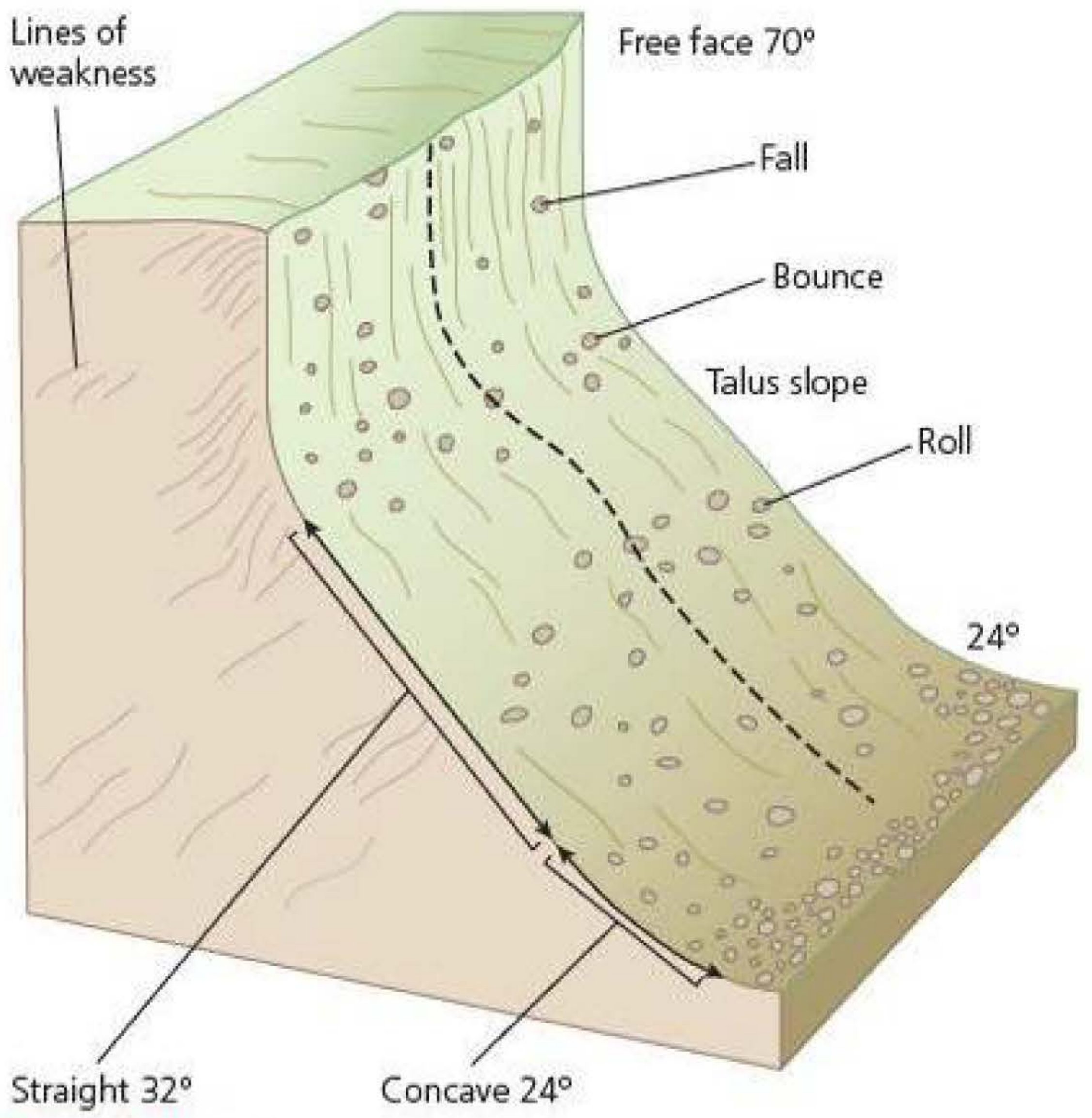


Figure 3.25 Falls

Section 3.3 Activities

1 Explain the terms *mass movement*, *soil creep* and *rotational slide*.
2 Outline the main characteristics of slumps and flows.

Water and sediment movement on hillslopes

Surface wash occurs when the soil's infiltration capacity is exceeded. In the UK, this commonly occurs in winter as water drains across saturated or frozen ground, following prolonged or heavy downpours or the melting of snow. It is also common in arid and semi-arid regions where particle size limits percolation.

Sheetwash is the unchannelled flow of water over a soil surface. On most slopes, sheetwash breaks into areas of high velocity separated by areas of lower velocity. It is capable of transporting material dislodged by rainsplash (see the following section). Sheetwash occurs in the UK on footpaths and moorlands. For example, during the Lynmouth floods of 1952, sheetwash from the shallow moorland peat caused gullies 6 metres deep to form. In the semi-arid areas of south-west USA, it lowers surfaces by 2–5 millimetres per year compared with 0.01 millimetres per year on vegetated slopes in a temperate climate.

Sheetwash erosion of soil occurs through raindrop impact and subsequent transport by water flowing overland rather than in channels. The result is a relatively uniform layer of soil being eroded. A **rill** is a relatively shallow channel, generally less than tens of centimetres deep and carrying water and sediment for only a short period. Rills are common in agricultural areas, following the removal of vegetation during the harvest season, and the ground subsequently being left bare. They are also common in areas following deforestation or land-use changes. Ground compaction by machinery may also lead to the generation of rills during rainfall events.

Throughflow refers to water moving down through the soil. It is channelled into natural pipes in the soil. This gives it sufficient energy to transport material, and added to its solute load, may amount to a considerable volume.

Rainsplash erosion

Raindrops can have an erosive effect on hillslopes (Figure 3.26). On a 5° slope, about 60 per cent of the movement is downslope. This figure increases to 95 per cent on a 25° slope. The amount of erosion depends on the rainfall intensity, velocity and raindrop distribution. It is most effective on slopes of between 33° and 45° and at the start of a rainfall event when the soil is still loose.

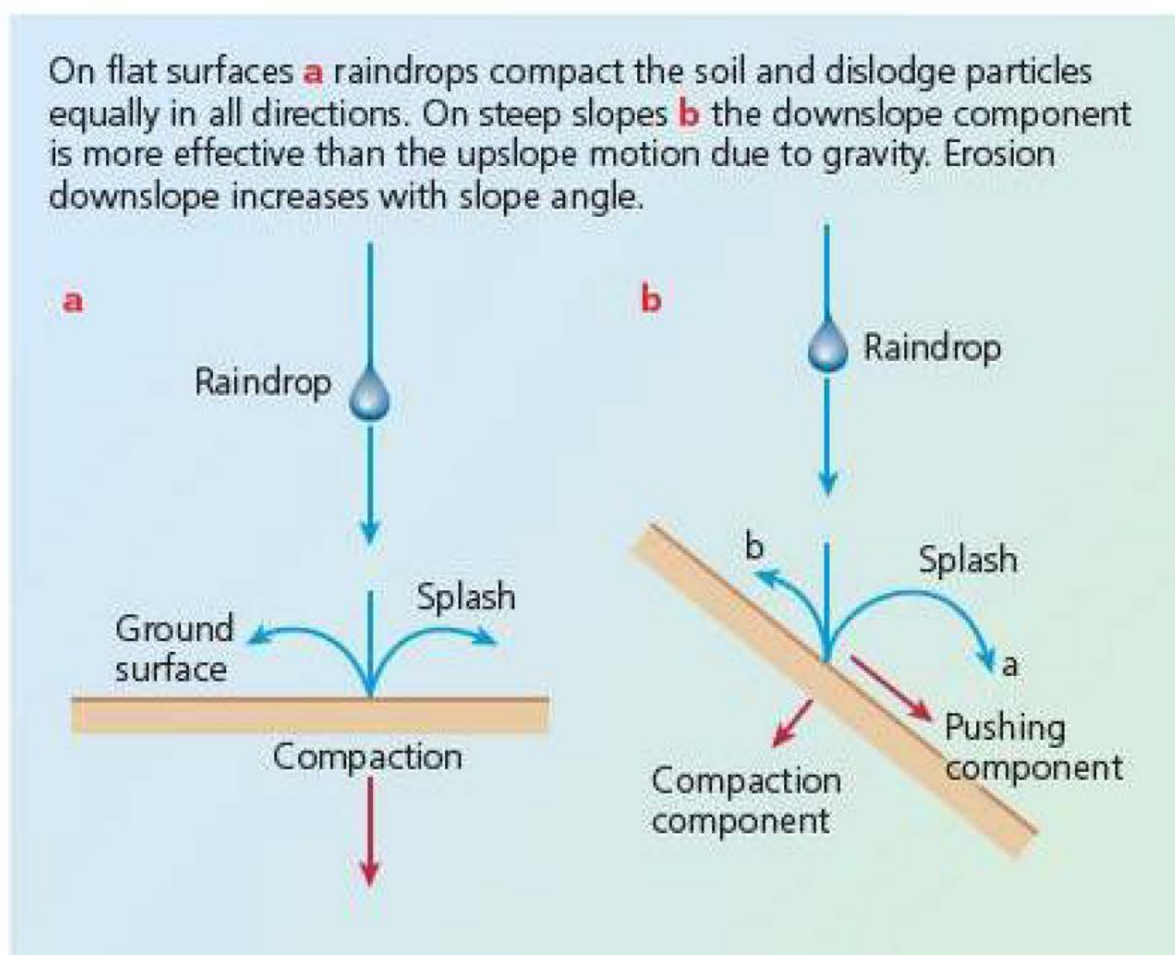


Figure 3.26 Rainsplash erosion

Section 3.3 Activities

1 Briefly explain how rainsplash erosion occurs.
2 Define the term *sheetwash*.
3 Under what conditions do rills occur?

3.4 The human impact

Stability of slopes

Rates of mass movement can be altered by human activities, such as building or excavation, drainage or agriculture. Mass movements can be accelerated by destabilising slopes. Local erosion can be intensified by footpath trampling in recreational areas. Some mass movements are created by humans piling up waste soil and rock into unstable accumulations that move without warning. Landslides can be created by undercutting or overloading. Most changes to slopes caused by human activities have been very minor in relation to the scale of the natural land surface. Human interference with slopes tends to have been most effective in speeding up naturally occurring processes rather than creating new features.

In urban areas, the intensity of slope modification is often very high, given the need for buildings and roads to be constructed safely, using sound engineering principles. Almost all buildings with foundations cause some modification to the natural slope of the land, and even on flat sites, large modern buildings generally involve the removal of material to allow for proper foundations. Slope modification tends to increase as a construction moves on to steeper slopes. In these conditions, in order to provide a horizontal base plus reasonable access, a cut-and-fill technique is often used (Figure 3.27), thereby creating a small level terrace with an over-steepened slope at both ends. The steep slopes, devoid of soil and vegetation, are potentially much less stable than the former natural slope and are, in times of intense rainfall, susceptible to small but quite damaging landslips.

Strategies to reduce mass movement

As well as causing mass movements, human activities can reduce them (Table 3.6).

Table 3.6 Examples of methods of controlling mass movement

Type of movement	Method of control
Falls	Flattening the slope Benching the slope Drainage Reinforcement of rock walls by grouting with cement, anchor bolts Covering of wall with steel mesh
Slides and flows	Grading or benching to flatten the slope Drainage of surface water with ditches Sealing surface cracks to prevent infiltration Subsurface drainage Rock or earth buttresses at foot Retaining walls at foot Pilings through the potential slide mass

Source: Goudie, 1993

Pinning is used to attach wire nets (or sometimes concrete blocks) to a rock face or slope so that the risk of rock falls is reduced or the risk of erosion is reduced. **Netting** may help collect fragments of scree, which can be safely removed at a later date. This is often used in areas where tourism is important, and where the risk of rock fall is high.

Grading refers to the re-profiling of slopes (see Figure 3.27) so that they become more stable. Afforestation is the planting of new forest in upper parts of a catchment to increase interception and reduce overland flow. They may take many years to be effective as the young, immature trees intercept relatively small amounts of water.

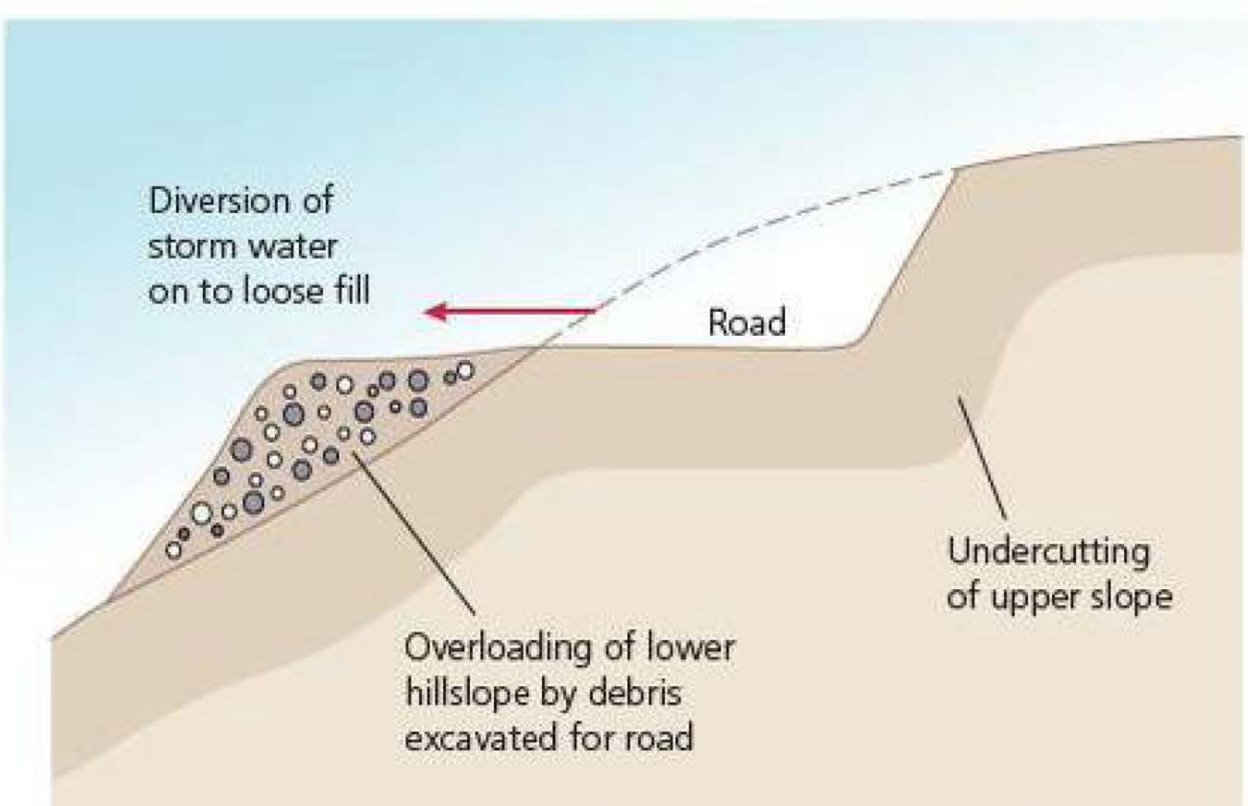


Figure 3.27 Slope instability caused by road building

Case Study: Landslides in Hong Kong

Hong Kong has a long history of landslides – largely due to a combination of high rainfall (the wet season is from May to September), steep slopes and dense human developments on the islands (Figure 3.28). Between 1947 and 1997, more than 470 people died as a result of landslides.

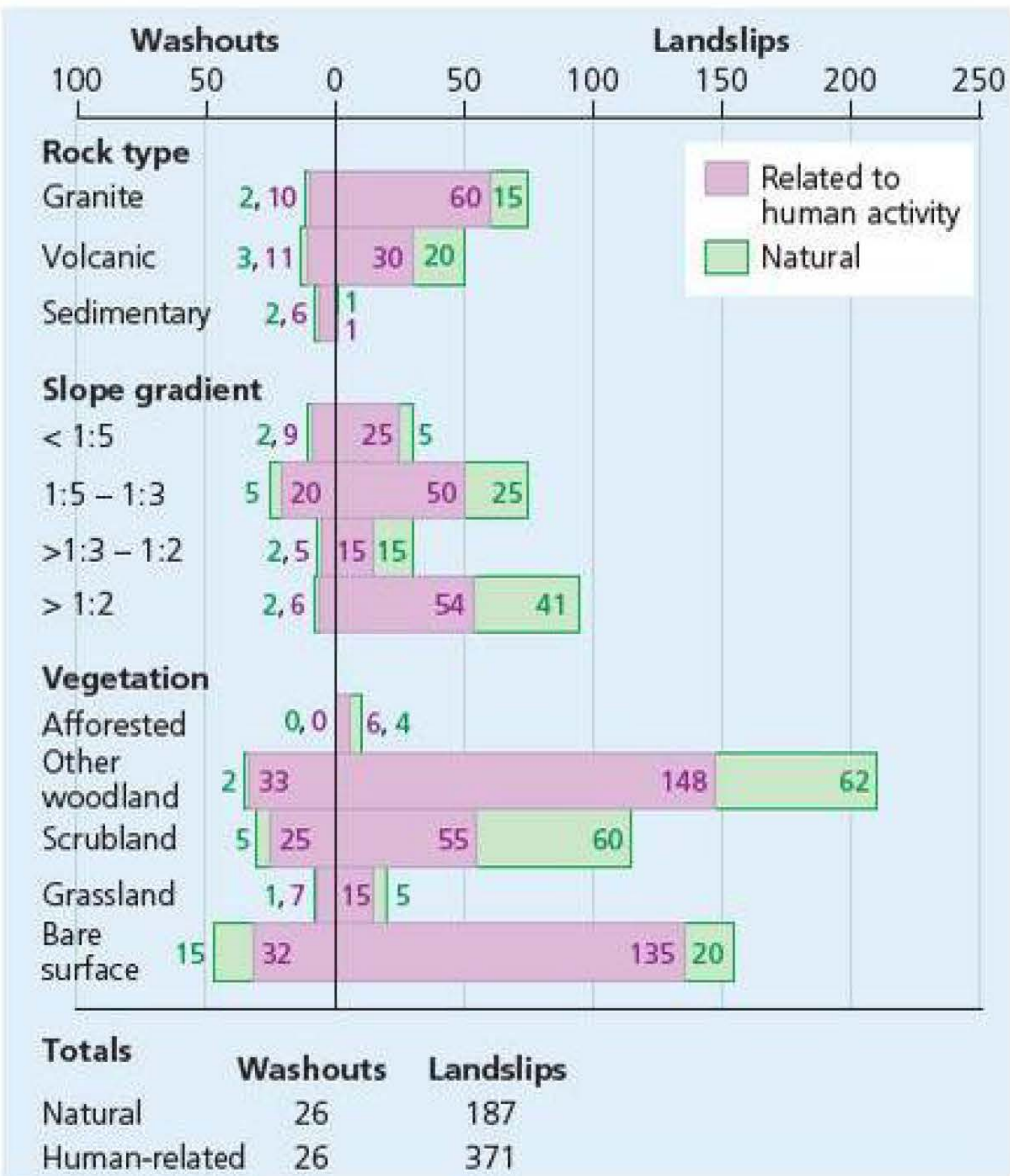


Figure 3.28 Number of mass movements per 100 km² in Hong Kong in the 1960s and 1970s

In June 1966, rainstorms triggered massive landslides that killed 64 people. Over 2500 people were made homeless and a further 8000 were evacuated. Rainfall had been high for the first ten days in June. Over 300 millimetres had fallen, compared with 130 millimetres in a normal year. On 11 and 12 June, over 400 millimetres fell – nearly a third of this occurred in just one hour! By 15 June, the area had received over 1650 millimetres of rain. Over 700 landslides were recorded in Hong Kong that month.

Some geographers believe that vegetation increased the problem. The trees held back many of the smaller landslides and allowed the larger ones, **washout**, to occur. Other forms of landslides included debris avalanches and rockslides.

At 1075 km², Hong Kong is one of the most densely populated urban areas worldwide, with a population of over 7 million (2015). It consists of the main island of Hong Kong, the peninsula of Kowloon, the New Territories and more than 230 islands with natural steep terrain and hills. The upper slopes are steeper than 30°. Most of the population is concentrated along the less steep urban areas on both sides of Victoria Harbour (Figure 3.30). With urban development, landslides are triggered by excavation and building works (Figures 3.31 and 3.32).

Figure 3.29 Hong Kong landscape

Figure 3.30 Map of Hong Kong showing Victoria Harbour

⇨

Figure 3.31 Landslide warning sign

Figure 3.32 Steep slopes and dense urban development combine to create a landslide risk

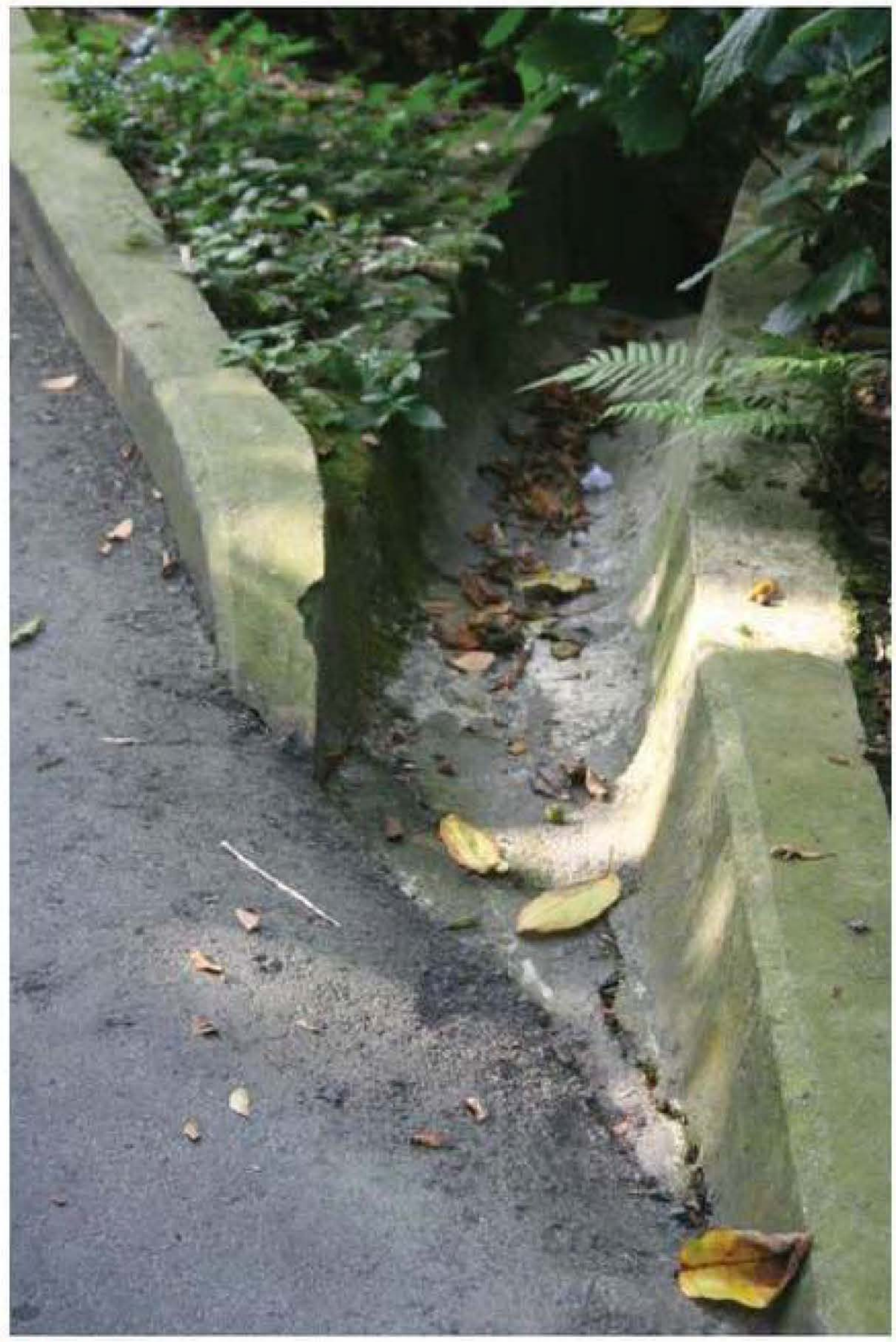


Figure 3.33 Drainage channel

Geology

The geology of Hong Kong is constructed mainly from three rock types: sedimentary rocks, granites and volcanic rocks. The sedimentary rocks generally form the lowlands. The granites and volcanic rocks, however, are situated on higher ground and are prone to failure. Both are seriously weathered, although granite rocks tend to be weathered more deeply than volcanic rocks. Volcanic rocks are more resilient and less prone to weathering and therefore less prone to slope failure.

Managing landslides in Hong Kong

The Hong Kong government has a responsibility to manage landslides. The Slope Safety System is managed by the Geotechnical Engineering Office (GEO) of the Civil Engineering Development Department (CEDD). The GEO has a staff establishment of over 700 for its wide range of activities. The GEO maintains its slope safety through investigating and researching the causes of significant and serious landslides to improve the Slope Safety Systems. The GEO is continuously updating, maintaining and disclosing the Catalogue of Slopes, which contains information of some 57 000 sizeable man-made slopes in Hong Kong.

One of Hong Kong's government interventions is to ensure that the private owners of slopes take responsibility for slope safety. If a slope owner does not comply with the regulation, prosecution will lead to a HK$50 000 fine, and to imprisonment for up to one year.

The government intervention in Hong Kong has had successful results. The risk from landslides has been reduced by 50 per cent since 1977. However, as a result of continued population growth, developers increasingly build further up the slopes. The risk from landslides, therefore, increases and the damages from a potential slide become greater.

Maintenance of slopes

Since heavy rainfall and surface runoffs are contributing to slope failure in Hong Kong, it is vital to remove excess water from slopes. Surface draining systems and protective covers are two methods used to protect slopes.

Surface drains are very vulnerable to blockage. Without proper drain maintenance, landslides are more common than on slopes without drains. Unfortunately, due to confusion over the responsibility, many drains are not properly maintained.

Man-made slopes are one of the main methods of slope stabilisation used in Hong Kong. These contain drains to intercept and direct water away from the slopes. The slope is usually protected from infiltration and the erosive effects of water by impermeable hard covers.

Greening techniques refer to the use of natural vegetation to reduce the risk of mass movements. There are three main types of greening techniques that are used in Hong Kong:

- The mulching system provides a protective cover that makes it possible for natural vegetation to grow on the slope; a natural vegetative cover is able to grow through the mat, securing it in place.
- The use of **long-rooting grass** is a fast and cost-effective system to cover man-made slopes. This system is applied by drilling planter holes into a hard cover. The drilled hole is then filled with soil mix and fertilisers, and finally the long-rooting grass is planted within.
- The **fibre reinforced soil system** is constructed by mixing polyester fibre into sandy soils. This mixture is capable of resisting tension.

Some of the advantages of greening techniques are outlined in Table 3.7.

Table 3.7 The advantages of greening techniques

Greening techniques	Advantages
Mulching system	Higher adhesive capacity on steep slopes High resistance to rain erosion High water-retaining capacity Long-lasting fertilisers Adaptable to rough surfaces
Planting long-rooting grass	Natural and environmentally friendly Cost-effective Fast and easy installation Can be applied on steep slopes Low maintenance
Fibre reinforced soil system	Self-sustained vegetation system with low maintenance Fibre strengthens soil particles to prevent erosion Visual improvement of the slope with various plant species Restoration of natural habitats on the slope

Section 3.4 Activities

1 Using the data in Table 3.8, draw a climate graph for Hong Kong. Describe the main characteristics of Hong Kong's climate.

Table 3.8 Climate data for Hong Kong

Month	Average temperature (°C)	Rainfall (mm)
January	16	30
February	15	60
March	18	70
April	22	133
May	25	332
June	28	479
July	28	286
August	28	415
September	27	364
October	25	33
November	21	46
December	17	17
Average/total	**23**	**2265**

2 Study Figure 3.28, which provides details of landslides in Hong Kong.
  a Using the data, describe and explain the relationship between mass movements and i rock type, ii gradient and iii vegetation.
  b What type of mass movement was most common in Hong Kong?
  c What do you think is the difference between a washout and a landslip? Give reasons for your answer.
  d Which type of rock was most affected by a washouts and b landslips?
  e What type of mass movement most affected a granite and b volcanic rocks? How do you explain these differences?
  f What is the relationship between gradient and mass movement? Give reasons for your answer.
  g What impact does vegetation have on the type and number of mass movements? Briefly explain your answer.
  h Briefly discuss the impact of human activity on mass movements. Use the evidence in Figure 3.28 to support your answer.

3 Study Figure 3.30, a map of Hong Kong. Using map evidence, suggest why landslides are a hazard in Hong Kong.

4 Suggest how population growth in Hong Kong contributes to the landslide hazard.

5 Describe the methods of landslide management that are used in Hong Kong.