GEOGRAPHY for Cambridge International AS & A Level

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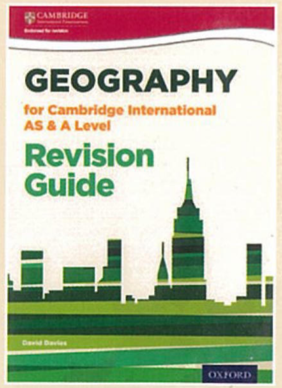

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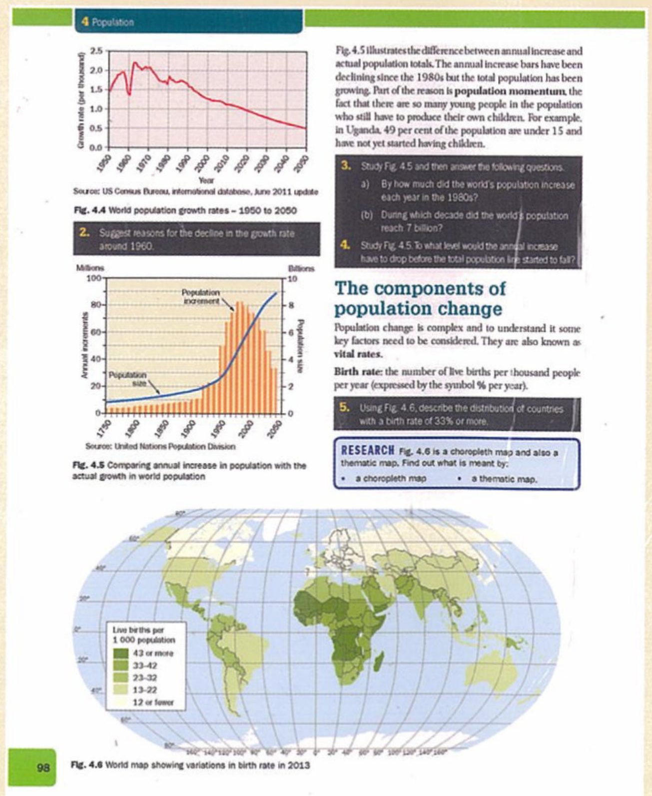

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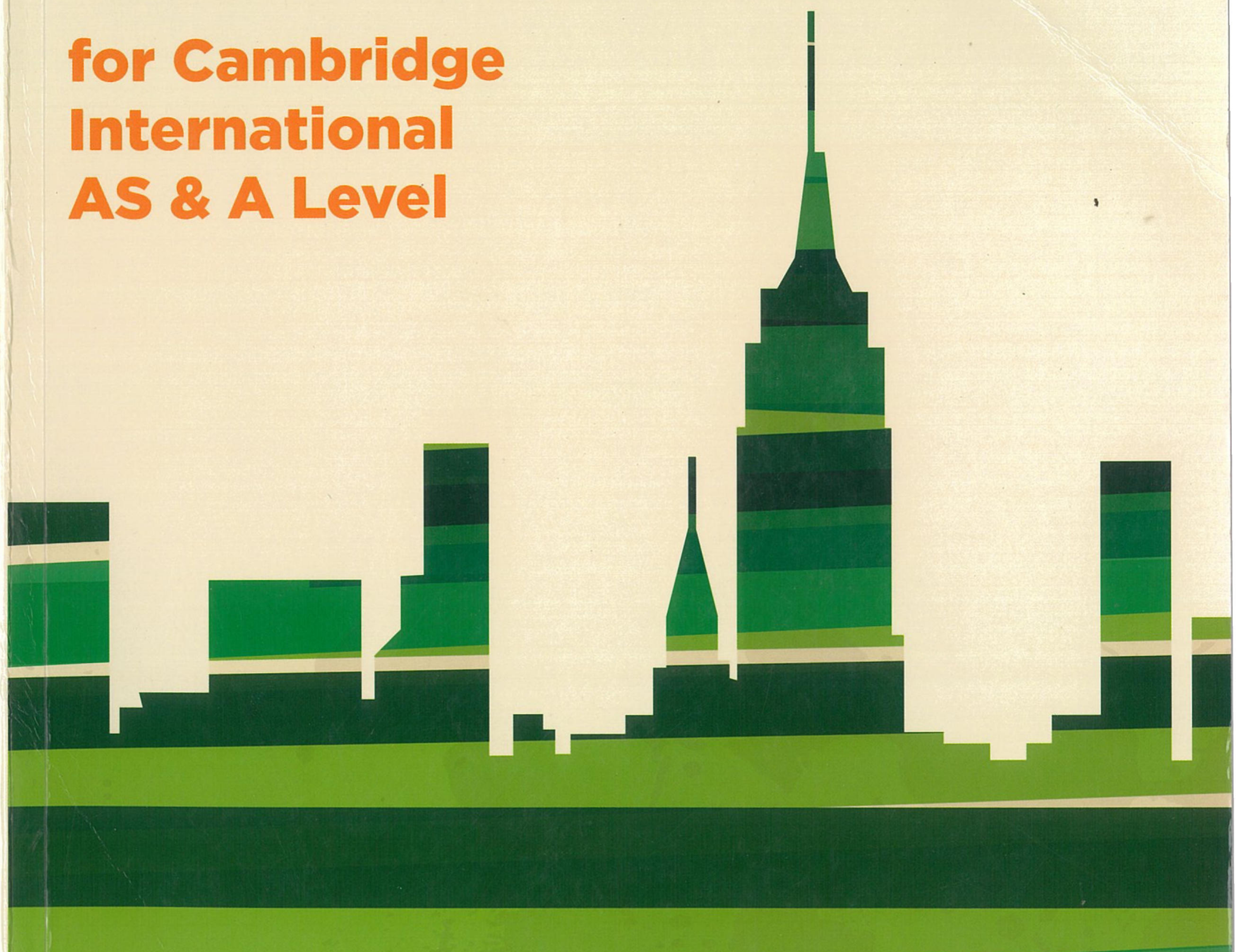

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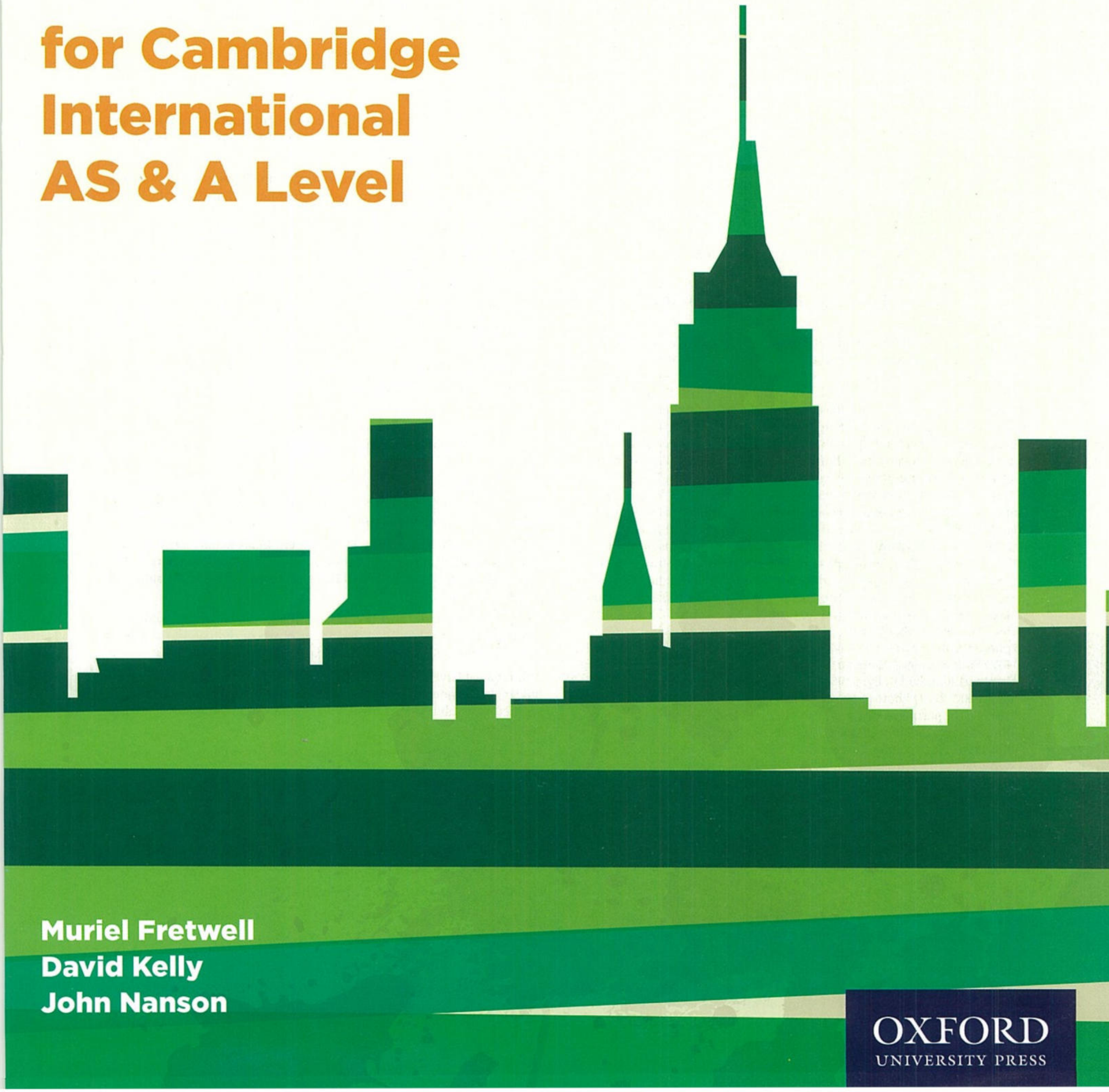

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Contents

AS Level

A Level

Introduction

The purpose of this book is to help you get the most out of your Geography for Cambridge International AS & A Level course. Written to support progression from IGCSE to AS & A Level and then all the way into higher education, this student book provides the knowledge to understand the key issues facing the world today.

The book follows the latest Cambridge International AS & A Level Geography syllabus (for examination from 2018) and is divided in two parts:

AS Level	Chapters 1-3	Core Physical Geography
	Chapters 4-6	Core Human Geography
A Level	Chapters 7-10	Advanced Physical Geography Options
	Chapters 11-14	Advanced Human Geography Options

The AS Level part will guide you through all the core topics you need to study, while the A Level part will guide you through the four options, out of the eight available, you have chosen to study.

Taking a structured approach and guiding you through the course in a logical, clear way, this textbook has a number of features that allow you to explore and discover the subject:

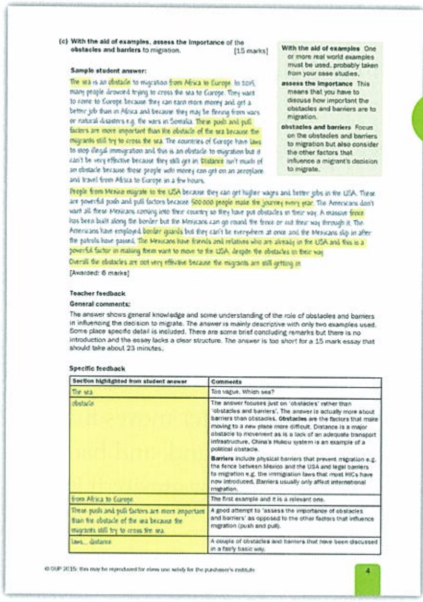
- **Subject-specific terms** (highlighted in bold type) to support you develop your vocabulary
- **In-chapter questions** to improve your map, data interpretation and essay-writing skills
- **Research tasks** to support your analytical and critical thinking skills
- Real-world **case studies** to provide context for your learning
- **Key concept** summaries at the end of each chapter to help you integrate knowledge and make links between the topics studied
- **Exam-style questions** at the end of each chapter to help you prepare for the examination.

Answers to all the in-chapter questions in this book are provided on the accompanying CD.

All questions and answers in this book have been written by the authors. In the examination, the way marks would be awarded to answers like the ones included here might be different.

What's on the CD?

On the CD accompanying this book, you will find material specifically written to support your learning, help you prepare for the examination and achieve your best.

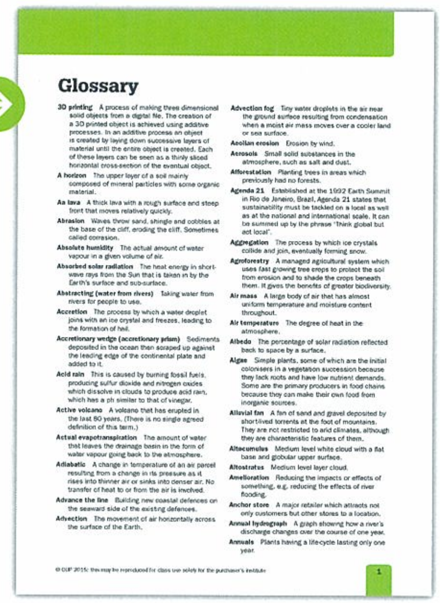


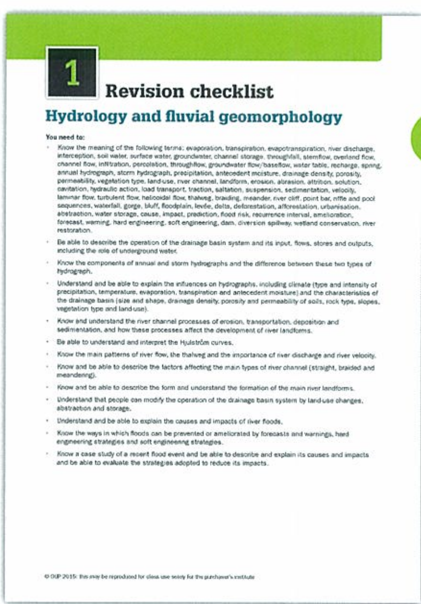
On Your Marks

Structured in the same way as the exam, these activities consist of questions with sample answers and specific teacher feedback. All the questions requiring interpretation of a geographical resource are presented as an interactive activity, allowing you to take a step-by-step approach. Structured and extended writing questions are presented as PDFs, which you can print and work through.

Glossary

A comprehensive revision tool, the glossary contains definitions for all the subject-specific terms highlighted in the student book.



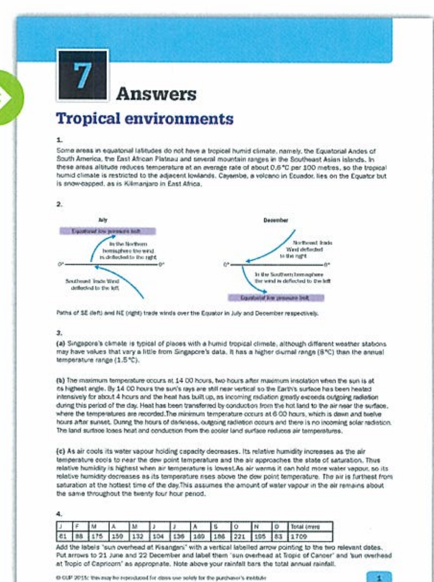


Revision checklists

One for each chapter, these checklists allow you to structure your revision and tick off those topics you are confident about.

Answers

These are the answers to the in-chapter questions in the student book.



1 Hydrology and fluvial geomorphology

In this chapter you will learn about:

- How the hydrological cycle operates in general terms and the more specific ways in which water moves through a drainage basin.
- How storm and annual hydrographs are influenced by the climate and by the characteristics of the drainage basin.
- How the processes of erosion, transportation, deposition and sedimentation shape the river channel and help to produce the landforms found along the river's course.
- How people use rivers and how people contribute to the causes and effects of floods. The prediction, prevention and **amelioration** of river floods.

The drainage basin system

The hydrological cycle

The **hydrological cycle** is an example of a model (or theory). Geographers use models to help them describe and explain reality. The real world is complex and is often difficult to understand so geographers use models to simplify it. Models are useful because they help us understand the important processes and cycles that occur on the Earth's surface. However, because they are simplifications, they don't always tell the full story and they should be used with care. The hydrological cycle is a useful and versatile model because it can be applied at a range of scales, so the model applies to any land area on Earth.

The hydrological cycle is the way that water moves from the sea, through the air, onto (and into) the land, and back into the sea. It is driven by the sun's heat and by gravity. It is often known simply as the water cycle.

At any one time, the Earth's water is distributed as follows:

- 97 per cent is in the sea
- 2.1 per cent is frozen as snow and ice (mostly Greenland and Antarctica)
- 0.8 per cent is fresh water in rivers, lakes and the ground
- 0.1 per cent is in the atmosphere.

People use *fresh* water and fresh water accounts for less than 1 per cent of all the water on the planet. It is this 0.9 per cent of the Earth's water that is involved in the hydrological cycle at any one time. This is why we need to fully understand the hydrological cycle in order to use the available fresh water as efficiently and effectively as possible.

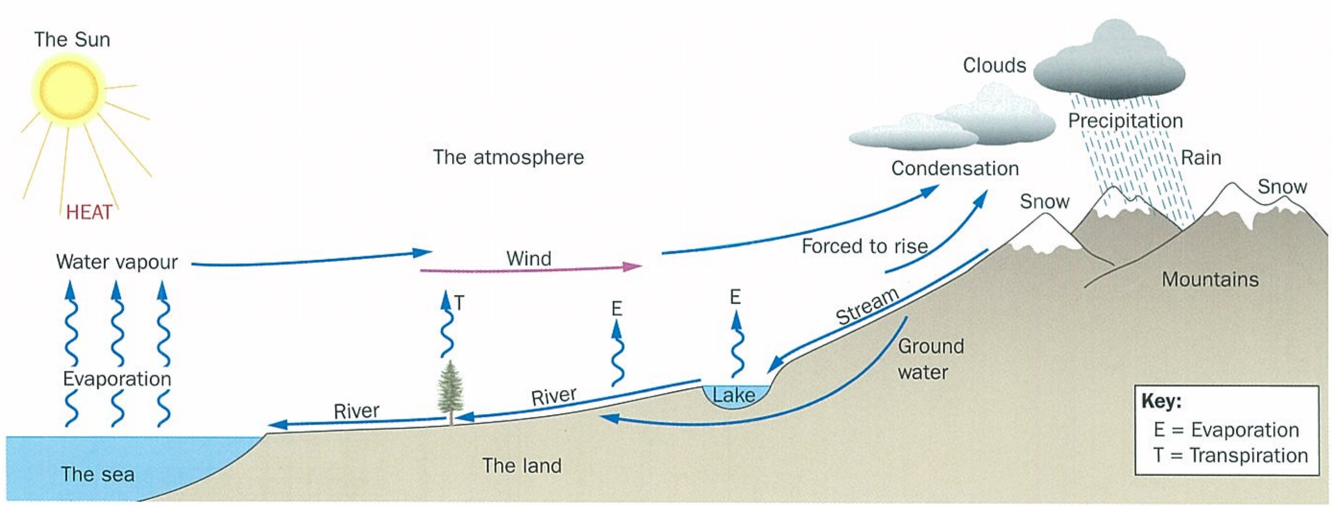


Fig. 1.1 The hydrological cycle

1. Study Fig. 1.1 and then write a short paragraph to describe and explain the movement of water around the hydrological cycle. It should begin 'The sun shines down on the sea and...'.

The drainage basin as a system

This is the part of the hydrological cycle which operates once rain has fallen onto a **drainage basin**. It is known as the drainage basin system because it has inputs, stores, flows and outputs. Geographers often use a *systems approach* in their studies. As with models, the systems approach allows geographers to simplify reality in order to understand it.

The drainage basin system is an open, dynamic system: *open* because water and energy flow into, through and out of the drainage basin; *dynamic* because the system responds to changes in its inputs: e.g. river **discharge** varies in response to changing inputs of precipitation.

We have to understand the drainage basin system in order to be able to understand how rivers behave, especially if we want to explain changes in river discharge and river flooding.

The drainage basin

A drainage basin is the area of land drained by a river and its tributaries. A drainage basin supplies a river with its water.

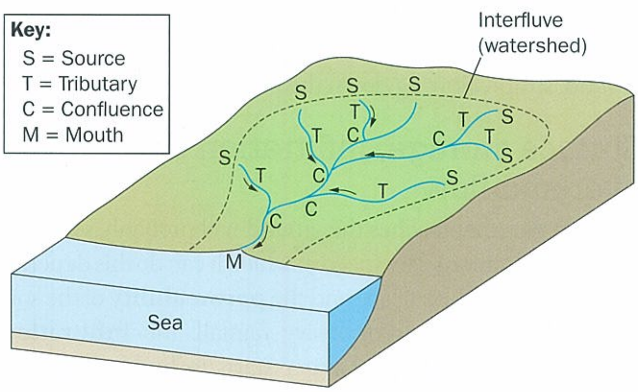


Fig. 1.2 A diagram of a typical drainage basin

Geographers in different parts of the world often use different words for the same thing. This is the case here. In the UK, 'drainage basin' is the phrase used to describe the area of land drained by a river and its tributaries. Some UK geographers also use the phrase 'river catchment'. This phrase is also used in the USA, as is the word 'watershed'. Confusion arises here because in the UK the word 'watershed' is used for the boundary of a drainage basin, not for the drainage basin itself. It is probably best to avoid the word 'watershed' and stick to 'drainage basin' and 'interfluve'.

Fig. 1.3 The source of a river. This photograph shows a stream rising from a series of springs. The water simply rises from the ground and flows off downhill as a new stream

2. Write definitions of the following terms:

- Interfluve
- Source
- Tributary
- Confluence
- Mouth.

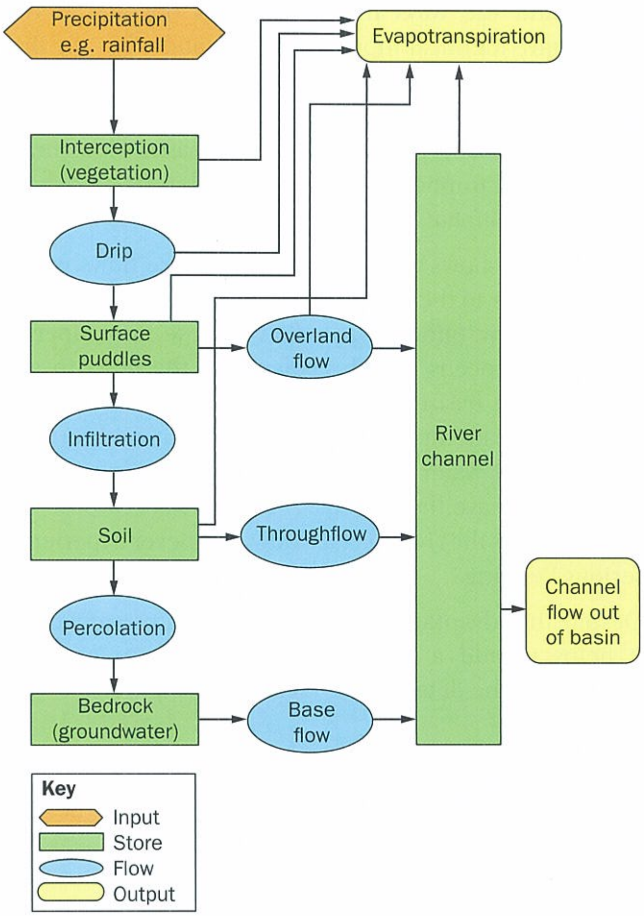


Fig. 1.4 The drainage basin system – a flow diagram

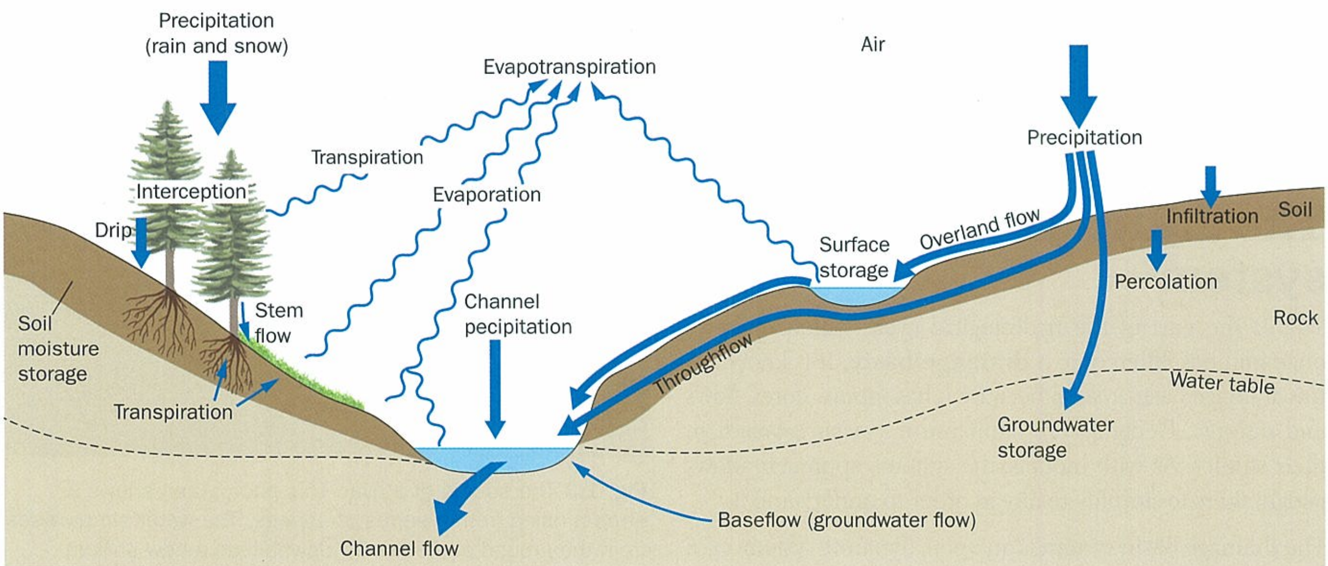


Fig. 1.5 The drainage basin system – a pictographic representation. This shows a cross-section of a river valley. The stream is flowing 'out of the page', towards the reader

Fig. 1.4 shows the drainage basin system reduced to its basic components. This is a combination of a model with the systems approach.

The drainage basin system only has one input (precipitation) but has two outputs: **evapotranspiration** and **channel flow** (river discharge). This helps us understand the ways in which rivers operate. If two basins have identical inputs of precipitation, but the first basin has much more evapotranspiration than the second basin, the first basin will have much less water in the main river (discharge) than the second basin. This simple fact has huge implications for the way that rivers behave in different climate zones and from season to season.

Fig. 1.4 also shows that there are only three flows which provide water to the river: **overland flow**, **throughflow** and **baseflow** (groundwater flow). These flows operate at different speeds and the balance of the flows in any one drainage basin will determine how quickly a river responds to an input of rainfall. A basin with a high proportion of water reaching the river via overland flow will tend to have flash floods. A basin where most of the water reaches the river via baseflow may never experience serious flooding.

Despite the advantages of simplified diagrams, sometimes it helps to add a little more complexity in order to understand the details more clearly (see Fig. 1.5).

The components of the drainage basin system

Precipitation

Water falling from the sky. Rain is the most important form of precipitation.

Interception

This is rain which is intercepted before it reaches the surface of the ground. It is usually intercepted by vegetation, especially by the leaves of trees. During a short summer shower it is possible to stay dry by standing under a tree because the tree's leaves 'intercept' and 'store' the raindrops before they reach the ground.

Throughfall (drip) and stemflow

In a prolonged rainstorm, the leaves become saturated and water will begin to drip to the ground. Stemflow is another important way in which water moves from the tree to the ground, simply flowing down the outside of the tree trunk.

Surface storage, infiltration and overland flow

The first rain that reaches the ground will probably soak into the soil (infiltration). The speed at which it can do this depends on the nature of the surface and the **permeability** of the soil. During prolonged and/or heavy rainfall, the **infiltration capacity** is exceeded and water starts to build up on the surface. This is surface storage and produces puddles. On a slope, this surface water will flow downhill towards the river, producing overland flow (surface runoff). Overland flow is a relatively quick process. When the soil is saturated and rain continues to fall, the rainfall will then produce surface runoff. This runoff is called saturated overland flow.

Urban surfaces such as concrete are designed to be flat and impermeable. They rapidly produce Hortonian overland flow, which is shallow, laminar, and fast-moving. Hortonian overland flow is most commonly encountered on city streets, construction sites and dirt roads in the countryside. This process poses a significant problem in steep, recently ploughed rural areas, where the water flowing over the surface can build up great speed and contribute to serious soil erosion.

Soil storage, percolation, and throughflow

In the soil, water is held in pores, so soil often feels quite damp.

- Clay soil has very small pores and does not let water pass through it easily - it is an impermeable soil, but holds water well. Infiltration rates of 0-4 mm/hour are typical.
- Sandy soil has many large pores and allows water to pass through it easily. The pores are gaps between the sand grains and they make the sand **porous**. It is this **porosity** which makes the sandy soil permeable, but losing its water very quickly. Infiltration rates of 6-12 mm/hour are typical.

A permeable soil allows water to pass through it in two ways. Water that flows down into the bedrock is called **percolation**. Water that flows downhill through the soil, parallel to the surface, is called throughflow. Throughflow gets water to the river more slowly than overland flow, but faster than baseflow.

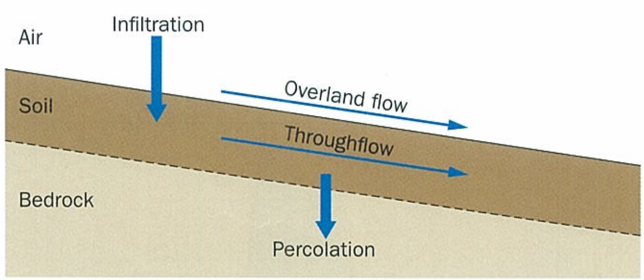


Fig. 1.6 Water in the soil

Groundwater and baseflow

Water that percolates into the bedrock is called **groundwater**. This water flows down through the rocks until it reaches the level of saturation or **water table**. Most groundwater eventually flows down through the rocks towards the nearest river. We call this baseflow or groundwater flow and it is normally a very slow process indeed. The water table moves up and down, depending on the amount of rainfall percolating downwards and the amount of baseflow flowing out of the rocks into the river. Where the water table reaches the surface other than at a river bed, groundwater reappears as a spring (see Fig. 1.3 on page 3). Where the rock structure is favourable, groundwater can remain in the rocks for a very long time. In the Sahara, there are underground stores of groundwater (**aquifers**) which fell as rain thousands of years ago.

Groundwater is an important source of fresh water. Wells can be dug and **boreholes** can be drilled down to the water table and the groundwater can be extracted. Because it has been filtered through the rocks, this water is normally very pure. Because of the continuous operation of the hydrological cycle, water is a renewable resource, but if groundwater is extracted faster than it is replaced, the water table will fall and the well will dry up. For example, the Saharan aquifers are being used unsustainably and they will eventually dry up. This is because the rate of **recharge** (water moving from the surface into the rocks) is much slower than the rate of **abstraction**.

Evapotranspiration

- Water evaporates from leaves, puddles and streams. The rate depends on the temperature of the water, the warmth and humidity of the air, and the speed of the wind.
- Plants draw water from the soil through their roots and allow it to evaporate into the air through their leaves. The water vapour exits the leaves through the stomata, pores which are found on the underside of the leaf. We call this **transpiration**.
- Together, we refer to this water loss from the basin as evapotranspiration. It is an important output of water from the basin and in an equatorial rainforest area it can amount to 80 per cent of the total output of water from the basin.

Channel flow

Rainfall reaches the river via overland flow, throughflow and baseflow. Once it is in the river it flows downhill towards the sea as river discharge. This is another output from the drainage basin.

3. (a) Copy and complete the following table using the words listed below:

Inputs	Flows	Stores	Outputs

Evapotranspiration	Infiltration	Soil
Vegetation	Baseflow	Drip (throughfall)
Overland flow	Bedrock	Ground water
Rainfall	Percolation	Stem flow
Throughflow	Puddles	

(b) Name the output not listed in the table.

The drainage basin system and human activity

People need water for many purposes including agriculture. Farmers need to have water in the soil in order to grow their crops. The amount of water in the soil depends on the balance between precipitation and **potential evapotranspiration**. **Actual evapotranspiration** is the amount of water that leaves the drainage basin in the form of water vapour going back to the atmosphere. Potential evapotranspiration is the amount of water that could go back to the atmosphere if an unlimited supply of soil moisture was available. For example, in a desert area such as Egypt, rainfall is about 45 mm per year. The actual evapotranspiration is also 45 mm per year because that is all the water that is available. However, the climate of Egypt is so hot and dry that the potential evapotranspiration is over 2000 mm per year. The balance between the precipitation and potential evapotranspiration is known as the **water budget**.

The water budget (or water balance) is an 'accounting' of the inputs and outputs of water. It can be determined by calculating the inputs, outputs and storage changes of water in the drainage basin. The input of water is from precipitation and outputs are evapotranspiration and channel flow.

It is usually stated in the form of an equation:

$$S = P - Q - E$$

where S = soil storage

P = precipitation

Q = channel flow out of the basin

E = evapotranspiration.

This water balance equation is used by hydrologists to plan and manage water supply within a drainage basin. It can be used to suggest possible water supply shortages for which special measures like hosepipe bans can be introduced to preserve water stocks. It has implications for irrigation, pollution control and flooding, too. The water balance changes from season to season.

Case study: Malaga in southern Spain

Fig. 1.7 Location of Malaga

Malaga is on the Costa del Sol in southern Spain. The Costa del Sol is an important tourist area and there are many small farms producing fruit and vegetables for the tourist hotels and for export. Farmers need enough water in the soil for their crops to grow during the summer tourist season when the crops are in great demand. The annual rainfall is 526 mm but very little falls during the summer. The important question for farmers is how much of this water is available in the soil for their crops. Southern Spain has high summer temperatures and the potential evapotranspiration is high at the time when rainfall is low. The water budget graph shows this information.

The graph for Malaga shows the problems that local farmers face. Evaporation exceeds precipitation from April to October and the soil moisture is used up by the end of May. From June to October there is a soil moisture deficit and crops will not be able to grow unless irrigation water is available from reservoirs or deep wells.

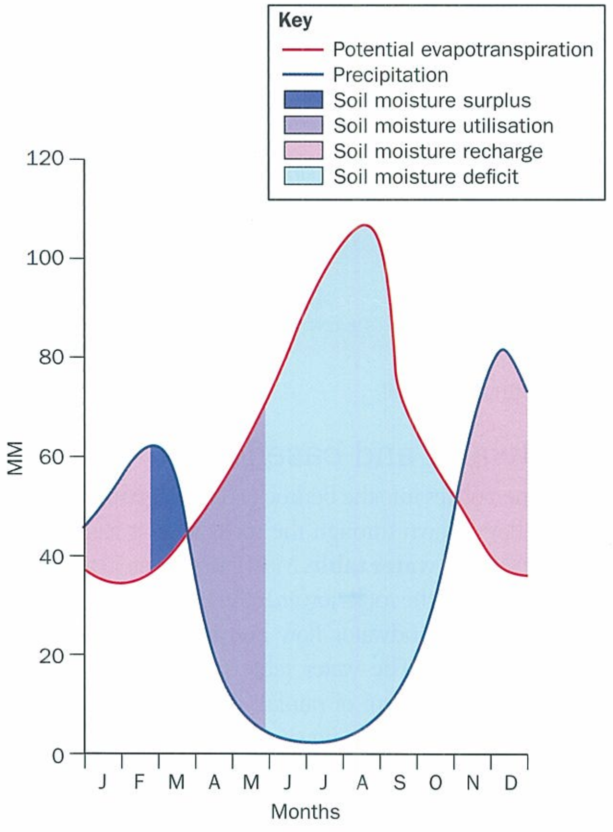


Fig. 1.8 Water budget graph for Malaga, Spain

Streams dry up at this time. Water supply for local people and tourists becomes a problem too – this is why there are so many reservoirs in the hills behind Malaga, storing winter rainfall for use in the summer. Soil moisture is recharged between November and March, but there is only a surplus for one month. Non-irrigated crops can only be grown during the winter months which are warm, as well as wet.

4. Use Fig. 1.8 to compare potential evapotranspiration with precipitation in southern Spain. You should quote figures in your answer. Remember that when you are asked for a comparison you should not write two separate accounts.

RESEARCH Find out what the water budget graph looks like for a tropical rainforest area. Suggest how this water budget might influence the nature of the natural vegetation in the rainforest.

Discharge relationships within drainage basins

River discharge

The amount of water flowing down a river at any one time is called the discharge of the river. Discharge is measured in cubic meters of water per second (cumecs). Most large rivers have several gauging stations along their length, where a continuous record is kept of the river's discharge at that point.

The discharge of a river changes over time, depending on the amount of precipitation, the amount of evapotranspiration and the nature of the drainage basin itself. Drainage basins are open, dynamic systems and changes of discharge over time illustrate the *dynamic* nature of drainage basins.

→ *Key fact 1:* Any factor that increases evapotranspiration will reduce river discharge because water is going back to the atmosphere rather than into the river.

→ *Key fact 2:* Any factor that increases overland flow at the expense of throughflow and baseflow or groundwater flow will increase river discharge because overland flow gets water to the river much more quickly than the other two flows.

The factors affecting river discharge

Climatic factors

The climate has a major impact on the operation of the drainage basin system. River discharge responds to changes in the input of precipitation and to changes in the outputs of evaporation and transpiration.

Precipitation

Precipitation is the major factor affecting river discharge because it is the only input into the system. Large amounts of rainfall will cause river levels to rise while a period of dry weather will lead to falling river levels. The *type* and *intensity* of rainfall are also important. Heavy rainfall from a thunderstorm arrives at the surface quickly, exceeding the infiltration capacity of the soil and causing rapid surface run-off which increases discharge. Steady, drizzly rain arrives on the surface slowly and has more chance of infiltrating into the soil. This slows the rate at which water reaches the river, producing a smaller rise in discharge. Snowfall arrives on the surface as a solid and can't drain away. Sudden rapid melting can lead to a lot of overland flow (especially if the soil is frozen) and this increases the discharge. If the warm weather that melts the snow is accompanied by heavy rainfall, the discharge can be very high - the river, in effect, receives two inputs of precipitation at the same time.

Antecedent moisture

If the ground is already saturated from previous rainfall, a new input of rain will not be able to infiltrate into the soil, causing large amounts of overland flow and increasing discharge rapidly.

Temperature and evaporation

When temperatures drop below freezing point, the soil becomes frozen and impermeable. Rain which falls on frozen soil runs across the surface rapidly, increasing discharge quickly. Temperature also affects evaporation rates. When temperatures are high, evaporation is also high, resulting in less water reaching the river.

Transpiration and evapotranspiration

Forests in a river basin tend to reduce the discharge of the river. Increased interception and increased transpiration mean that evapotranspiration could be a more important output from the drainage basin than river discharge. In the Amazon basin in Brazil, 80 per cent of the rain that falls goes back to the atmosphere, reducing the discharge of the rivers. Vegetation also encourages infiltration and throughflow rather than overland flow. This reduces the speed at which rainfall reaches the river, reducing river levels.

Seasonality

In **temperate** areas of the world, such as Ireland, the season of the year has an important influence on river discharge. In Ireland, rainfall is spread fairly evenly throughout the year, but trees tend to be dormant in winter and have little effect on discharge at this time of year. The colder weather also reduces evaporation rates. This reduction in evapotranspiration is a major reason why Irish river levels are higher in winter. In tropical monsoon areas and in areas with a savanna climate, seasonality is also important. Rainfall occurs during the summer, increasing river discharge during this season. In areas with a Mediterranean climate, the opposite is true. Rainfall is mostly in the winter and streams tend to dry up during the summer.

Drainage basin characteristics

The nature of the drainage basin affects the way water moves through it. Interception, infiltration and percolation all impact on the amounts of overland flow, throughflow and baseflow. These, in turn, determine the speed at which water moves through the drainage basin to the river. The rate at which water arrives at the river affects river discharge.

Size and shape of the drainage basin

Basin size is important. Smaller drainage basins collect less rainfall than larger basins and the discharge of their rivers is smaller as a result. Smaller basins also respond more rapidly to inputs of rainfall. In 2004, heavy rain fell on the small drainage basin that includes Boscastle in the UK. The basin responded so rapidly that the flash floods gave people no warning and no time to prepare. Basin shape also affects flooding. Circular basins respond more promptly to rainfall inputs and have a higher discharge than long, narrow basins of a similar area.

Drainage density

This is the total length of surface streams per square km. It is related to the infiltration rate. Basins with low infiltration have more overland flow and a higher **drainage density** than basins with high infiltration. As a result, drainage basins with a high drainage density respond more quickly to inputs of rainfall so they have rapid surface run-off and a rapidly rising, high discharge.

Soil and rock type

A drainage basin with impermeable soil and bedrock will have a great deal of overland flow but less throughflow and baseflow. Because overland flow is a much faster process than the other two flows, this sort of basin will have higher discharge. A drainage basin with permeable (or porous) soil and bedrock will have much more infiltration and percolation, so throughflow and baseflow (groundwater flow) will be more important than overland flow. This will result in lower river discharge because throughflow and baseflow are much slower than overland flow. Baseflow from the large groundwater store in a basin with permeable rock will also keep the summer discharge relatively high, reducing seasonal variations in discharge.

Permeable rocks allow water to pass through them for different reasons. Granite and limestone contain tiny cracks, mostly vertical joints and horizontal bedding planes. Water can percolate down through these rocks along the cracks and we call these rocks *pervious* as a result. Chalk and Sandstone are made up of particles with pore spaces between the particles. Water can soak down through the pore spaces so these rocks are porous. Pervious limestone and porous sandstone are both permeable, in that they let water percolate down through them, but for different reasons.

Slopes

A drainage basin with steep slopes will have more overland flow and higher river levels than a basin with more gentle slopes where there is more time for water to infiltrate.

Vegetation type and land-use

Forests growing in a river basin tend to reduce the discharge of the river because forests increase interception, leading to greater evaporation. Forests also lead to increased transpiration, which also removes water from the basin before it can reach the river. Any land-use that creates impermeable surfaces or reduces vegetation cover tends to increase overland flow and river discharge. Pasture land allows rainfall to soak into the ground, but has less evapotranspiration than the forest it may have replaced, increasing river discharge. Floodplains tend to be fertile and are often used for arable farming which can involve the use of heavy machinery. These machines squash the soil, reducing infiltration, increasing overland flow and river discharge.

5. Explain how evapotranspiration influences river discharge.
6. Explain how overland flow, throughflow and baseflow affect river discharge.
7. 'Climatic factors are more important than drainage basin characteristics when explaining variations in river discharge'. To what extent do you agree with this statement?

Hydrographs – graphing the changes in river discharge

A graph showing how the river's discharge changes over time is called a **hydrograph**.

- A graph showing how a river's discharge changes over the course of one year is called an **annual hydrograph**.
- A graph showing how a river's discharge changes over a short period of time, responding to a single input of rainfall is called a **storm hydrograph**.

Each of these graphs can be used by hydrologists to help them understand the nature of a drainage basin and the factors that affect the discharge of its river. Water is a valuable resource so it is important to understand the river if its water is to be used sustainably. River flooding is an important hazard and if people are to manage flooding effectively, it is important to understand the way a river behaves and the factors that affect the changes in its discharge.

Annual hydrographs

Annual hydrographs are useful when hydrologists study the responses of a river to its environment. The following examples are all taken from the British Isles.

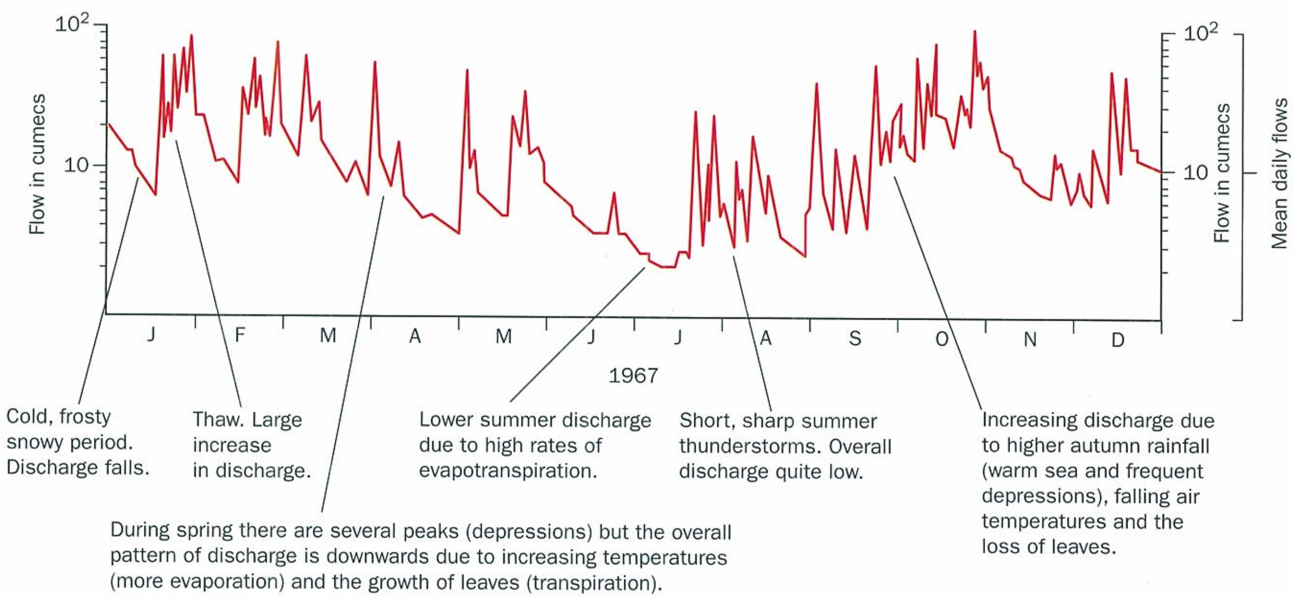


Fig. 1.9 River Dart annual hydrograph at Austin's Bridge, Devon, UK

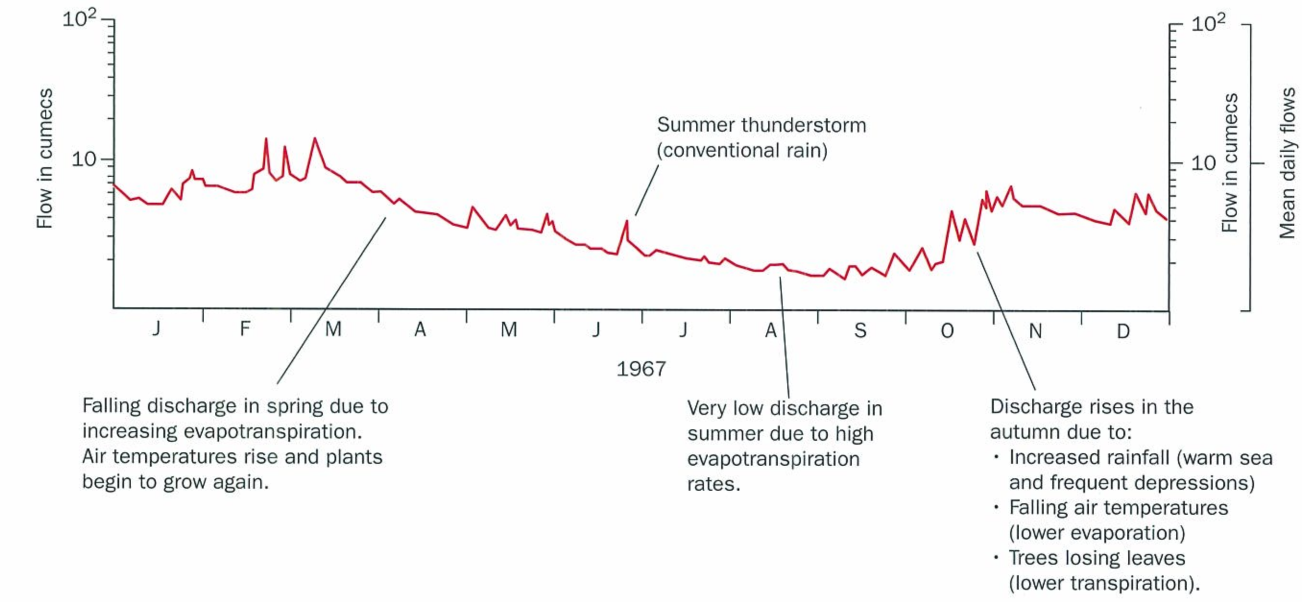


Fig. 1.10 River Avon annual hydrograph near Salisbury, Wiltshire, UK

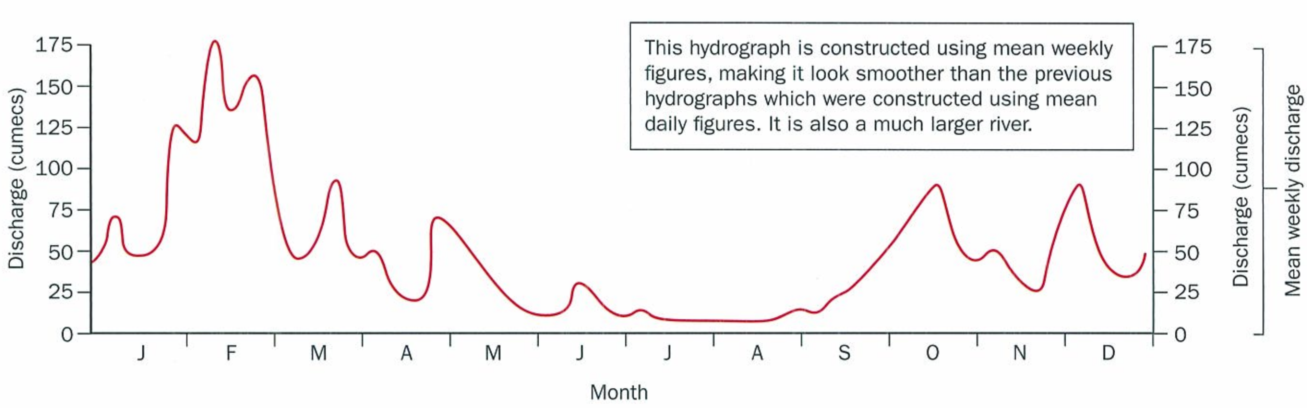


Fig. 1.11 River Severn annual hydrograph at Montford Bridge, Shropshire, UK

The River Dart is a short river that flows from Dartmoor in Devon. This is a very 'peaky' hydrograph, typical of rivers in western Britain. There is clearly a great deal of overland flow because the river responds quickly to the frequent inputs of rainfall. This river is likely to experience flash floods. The underlying reasons for the way that the River Dart behaves are as follows:

- high rainfall and frequent rainstorms, typical of hilly areas in western Britain
- impermeable soil and bedrock; Dartmoor is made of granite which encourages surface runoff at the expense of throughflow and baseflow
- a grass-covered drainage basin with very little forest to slow down and absorb rainwater.

The River Avon flows across Salisbury Plain, a chalk upland in southern Britain. This is a relatively smooth annual hydrograph with low and infrequent flood peaks. There is very little overland flow but a lot of baseflow. The river is responding to seasonal changes in rainfall and evaporation rates, rather than to individual rainstorms. Flooding is unlikely on this river. The underlying reasons for the way that the River Avon behaves are as follows:

- rainfall is relatively low in southern England
- permeable soil and bedrock; the bedrock is chalk, which is very porous and absorbs rainfall very easily. Throughflow and baseflow are much more important than overland flow because of the high infiltration rates. It might be supposed that this is a forested basin, but Salisbury Plain is actually mostly arable land or short grassland. It is the effect of the chalk bedrock which is the dominant factor affecting the discharge of this river.

8. Study Fig. 1.11.

(a) Describe the changes that take place in the discharge of the River Severn between January and August.

(b) Suggest reasons for these changes. You should consider precipitation, temperature, rock type, land-use and other possible factors. (The River Severn rises in the mountains of central Wales. Snowfall is common in the winter months.)

Storm hydrographs

How a drainage basin reacts to a large input of rainfall tells us about the nature of that drainage basin. We can then predict how it will react in future to similar rainstorms and make plans to cope with the perceived flood risk. The storm hydrograph is crucial here; it is the drainage basin's 'fingerprint'.

Definitions of some of the key words and phrases:

- *Discharge*: the amount of water in the river channel. It varies over time and it is the result of rainwater flowing into the channel via overland flow, throughflow and baseflow. In Fig. 1.12, the discharge responds to a large input of rainfall.

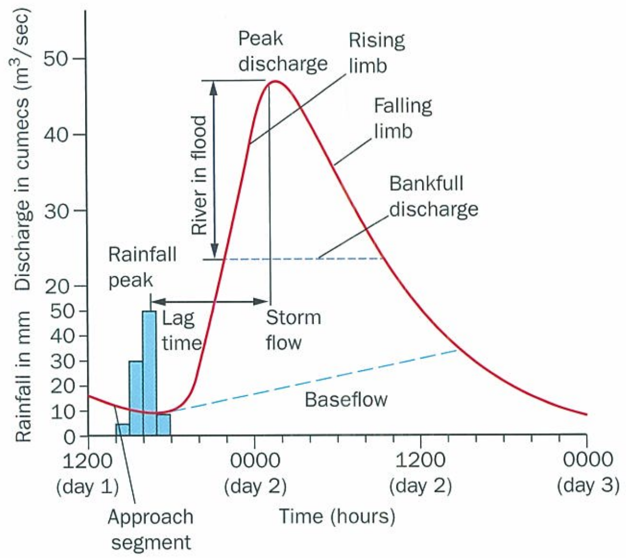


Fig. 1.12 A typical storm hydrograph

- *Cumecs*: cubic metres of water per second. The unit of measurement for river discharge.
- *Approach segment*: the discharge before the rainstorm.
- *Rising limb*: the discharge rises steeply after the storm, mostly due to overland flow.
- *Bankfull discharge*: when the river channel is completely full. If the river rises further there will be a flood.
- *Peak discharge*: the highest level that a river reaches during a flood.
- *Lag time*: the time between the maximum rainfall and the peak discharge. Drainage basins with a lot of overland flow have a short lag time.
- *Falling limb* (or *receding limb*): this is when river levels fall, after the peak discharge. It is less steep than the rising limb because throughflow is now reaching the river.
- *Stormflow*: stream discharge after a rainstorm, produced by a combination of overland flow and then throughflow. It is overland flow that makes the greatest contribution to the flood peak.
- *Baseflow (groundwater flow)*: Stream discharge produced by water seeping from the bedrock. It is a very slow process.

Influences on the shape of the storm hydrograph

The factors affecting the storm hydrograph are the same as the factors affecting river discharge. The speed at which the input of rainfall arrives in the river channel is the key influence. It is the balance of overland flow (relatively quick), throughflow (medium speed) and baseflow (relatively slow) that determines the shape and size of the storm hydrograph.

Precipitation

Three aspects of precipitation influence the shape and size of the storm hydrograph:

- Prolonged rainfall leads to saturated ground and a lot of overland flow.
- Intense rainfall usually means that the infiltration capacity is exceeded, even in a permeable basin. This produces overland flow.
- Snowfall. Snow can't flow into the river because it is frozen. Snow often melts when a depression brings more precipitation in the form of rain. The warm air and the rain melt the snow, so two lots of precipitation reach the river together. The ground under the snow is often frozen and impermeable; therefore all the rainfall and the snowmelt run over the surface, producing a rapid and massive input of water into the river.

Temperature

In summer it is warm so evaporation is high. In winter it is cold so evaporation is low and more precipitation goes into the river. Frozen ground leads to a lot of overland flow.

Vegetation

Forests encourage interception, evapotranspiration and infiltration. Forested areas have smaller flood peaks.

Seasonality

The three factors mentioned above show that similar inputs of rainfall can have different effects on the storm hydrograph at different times of the year.

Soil and rock type

Permeable soil and rock reduce overland flow and enhance throughflow and baseflow. Impermeable soil and rock enhance surface runoff.

Basin relief

Steep slopes and high relief in the drainage basin tend to get water to the river quickly and create high flood peaks.

Urbanisation

Tarmac and concrete increase overland flow, so water gets to the river faster. Gutters and drains speed up throughflow.

Comparing storm hydrographs

Different drainage basin factors produce differing storm hydrographs. We need to consider the contribution that overland flow, throughflow and baseflow make to the typical storm hydrograph.

- Rain falls on the drainage basin.
- The overland flow arrives first and builds up the flood peak.

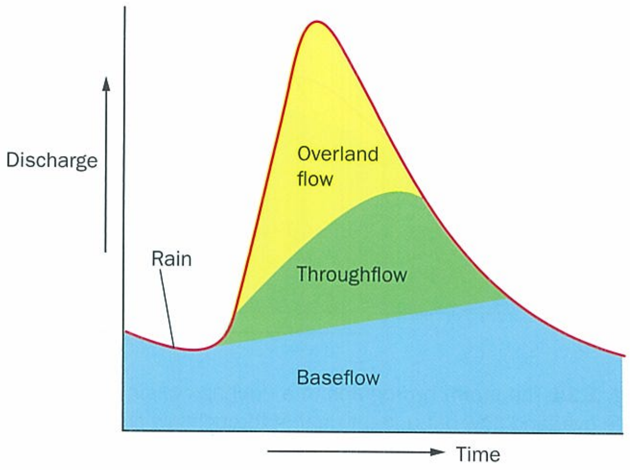


Fig. 1.13 The makeup of a typical storm hydrograph

- After several hours or days (depending on the size of the drainage basin) the overland flow reduces and eventually stops. By this point, throughflow is contributing to the river's discharge and this stops the floodwaters going down as quickly as they rose. As a result, the falling limb is not as steep as the rising limb.
- Eventually, baseflow takes over. Baseflow takes much longer to reach the river than the other two flows, but because the groundwater store is vast, it keeps on supplying water to the river well after the rainfall has stopped. This is why most rivers don't dry up during a period of dry weather.

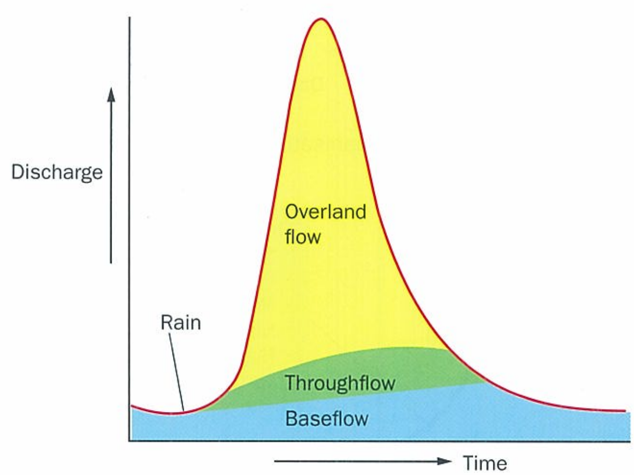


Fig. 1.14 The storm hydrograph of a drainage basin with a lot of overland flow but not much throughflow and baseflow

Fig. 1.14 is typical of a deforested drainage basin or a drainage basin with impermeable soil and bedrock. It is also typical of an urbanised drainage basin. Notice that even in an impermeable or deforested drainage basin there is always some infiltration and percolation.

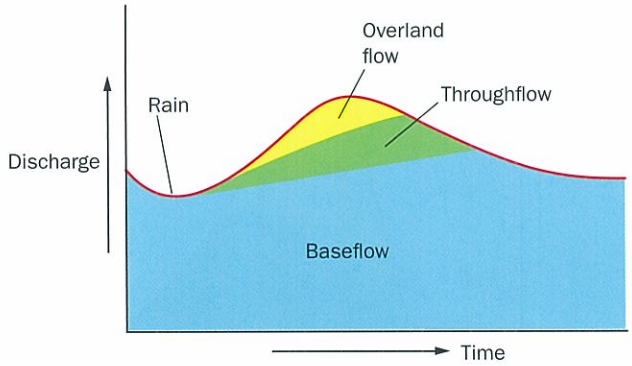


Fig. 1.15 The storm hydrograph of a drainage basin with very little overland flow but a great deal of throughflow and baseflow

Fig. 1.15 is typical of a well-forested drainage basin or a drainage basin with permeable soil and bedrock. The lag time is long and peak discharge is low. Baseflow is controlling the discharge of this river.

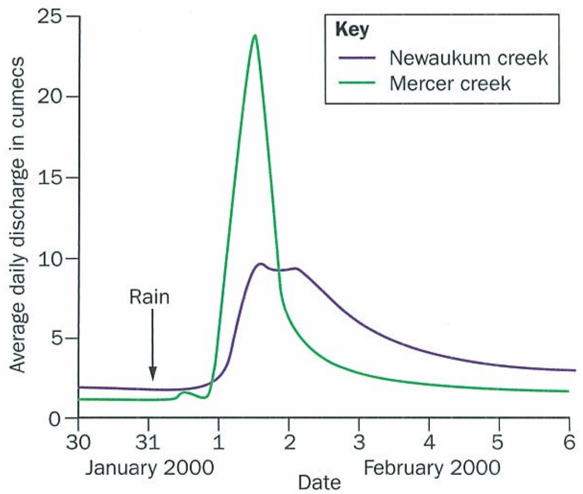


Fig. 1.16 The impact of urbanisation on the storm hydrograph

Fig. 1.16 shows the storm hydrographs for two, very similar and neighbouring drainage basins in western Washington, USA. Both drainage basins received equal inputs of rainfall from the same storm on 31 January 2000. Discharge in Mercer Creek, an urbanised drainage basin, increased more quickly and reached a higher peak than discharge in Newaukum Creek, a neighbouring rural drainage basin of equivalent size.

9. Study Fig. 1.16. Suggest reasons for the differences in the two storm hydrographs.

River channel processes and landforms

Channel processes

The **river channel** is the 'trench' in which the river flows. It is defined by the river bed and the river banks.

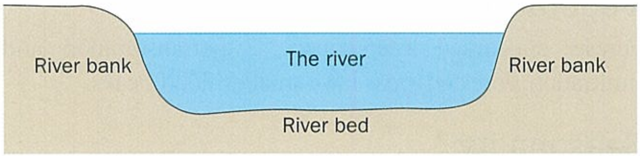


Fig. 1.17 A cross-section of a river channel

Water flows downhill through the river channel. Because the flowing water has mass and velocity, it also has energy and it uses this energy to do work, changing the shape and nature of the river channel. Considerable changes to the river channel occur as the river flows from its source to its mouth. These

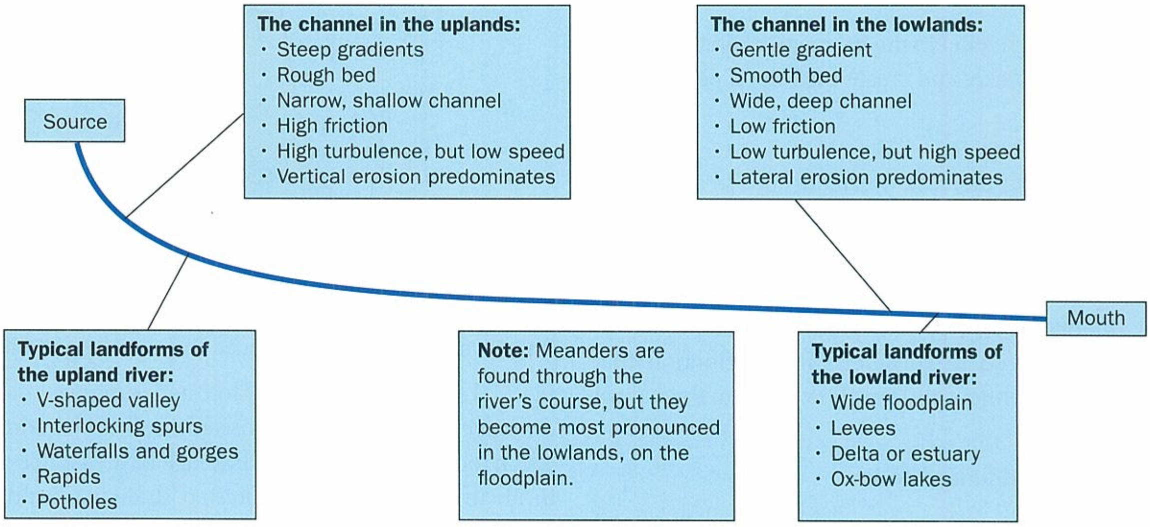


Fig. 1.18 The long profile of a river channel

changes are illustrated by the **long profile** of a river channel. The long profile of a river channel is a line drawn from the source of the river (where it starts) to the mouth of the river (where it meets the sea). It shows how the gradient of the river channel changes as it flows downhill. The typical long profile is concave – steeper in the hills and gentler in the lowlands.

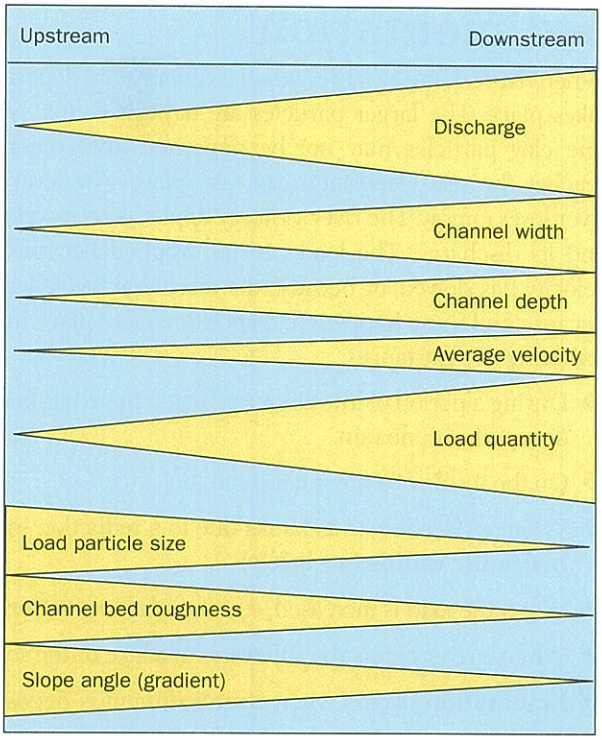


Fig. 1.19 Bradshaw's model of downstream changes on a river

This diagram summarises many of the changes that take place in the river channel as you move downstream, from the source to the mouth. The river is an open, dynamic natural system and Bradshaw's model is important because it shows that the river can respond to changes in its inputs of discharge and **sediment** by changing any one of the variables shown.

10. (a) What is 'discharge'? Describe and attempt to explain how it changes as the river flows downstream.

(b) What is 'load quantity'? Describe and attempt to explain how it changes as the river flows downstream.

(c) What is 'load particle size'? Describe and attempt to explain how it changes as the river flows downstream.

River channel processes – erosion

Erosion is the *wearing away* of the surface of the Earth. It is an active process, involving movement. Rivers erode their channels as they flow downhill towards the sea. Rivers have energy because the river water has mass and velocity and some of this energy is used to erode the river channel in four main ways.

Abrasion – sometimes called corrasion. A river uses its load of sediment to wear away its bed and banks. In the uplands, pebbles get caught in hollows in the river bed. As they swirl around, the process of abrasion produces a pothole.

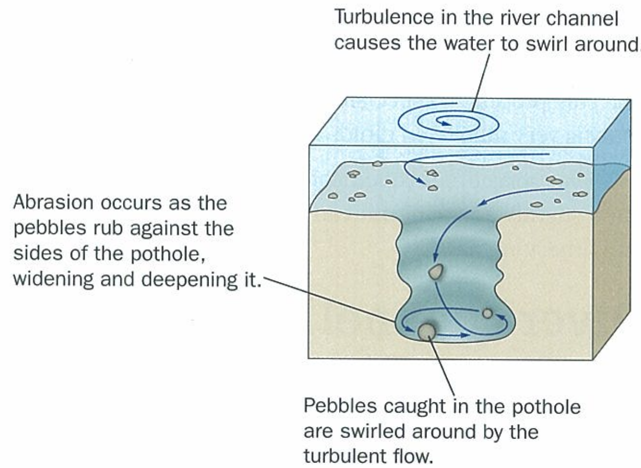
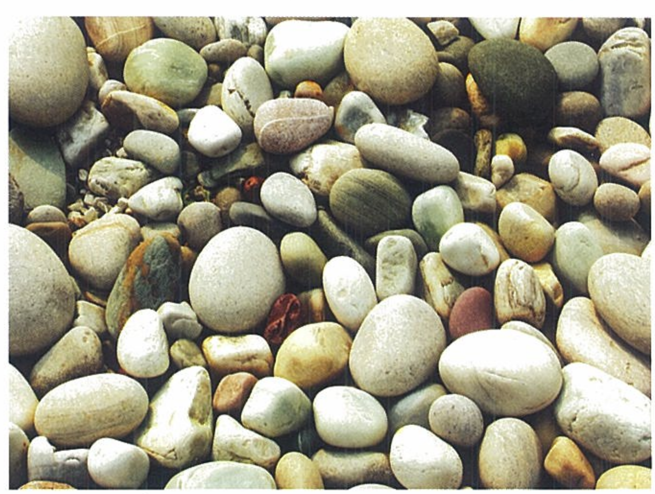


Fig. 1.20 The effect of abrasion on a rocky river bed

Attrition – particles of sediment in the load of the river (especially the **bedload**) bump into each other and wear each other away. As a result, river sediment becomes smaller and more rounded as it is carried downstream.

Upstream, the bedload is mostly angular



Further downstream, attrition has made the bedload much rounder, smaller and smoother

Fig. 1.21 The effect of attrition on a river's bedload

Hydraulic action – the direct force of the flowing river water can break material from the bed and banks. Even more powerful is the related process of **cavitation**, the force of exploding air. Powerful **eddies** in the flowing river water compress and decompress water in cracks in the river bank. This can lead to the formation of air bubbles in the water, which explode outwards, weakening the crack and leading to pieces breaking off. This process is especially important where the water is moving very quickly, in rapids and waterfalls.

Solution – sometimes called corrosion. Natural river water is often slightly acidic and it can dissolve rocks such as chalk and limestone.

River channel processes – transportation

Rivers transport the load that is supplied to them in four main ways. The sediment is produced by river erosion and by other landscape processes such as weathering and mass movement on the valley sides.

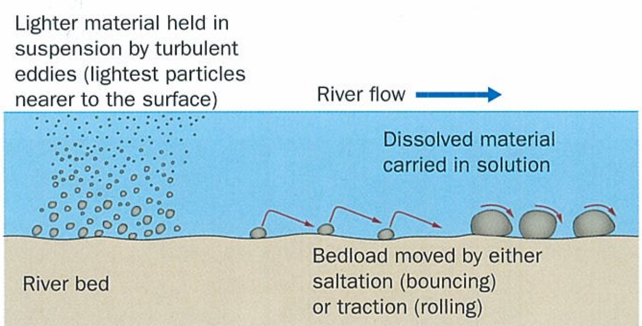


Fig. 1.22 How the river transports its load of sediment

Traction – the larger particles of the bedload are rolled along by the force of the flowing water. (The bedload is the load that spends all or some of its time on the river bed.)

Saltation – the smaller particles of bedload tend to hop along the bed of the river. A faster eddy picks them up and they move along in the body of the water until the current slows and they fall back to the river bed.

Suspension – this accounts for most of the load, especially in a lowland river. Lowland rivers nearly always look muddy and brown because of the large amounts of sand, silt and clay suspended in the water.

Solution – the dissolved load is derived from soluble rock such as limestone and chalk. Chalk streams are often clear because the dissolved load is not visible.

The load of the river varies as the energy of the river (discharge and velocity) changes. At times of high discharge, the river can carry a large amount of sediment – even small streams look muddy at times of flood. The load of a river is usually calculated at the **bankfull** stage, at the point when the river is flowing most efficiently, just before it spills out onto its floodplain. The **capacity** of the river is the total amount of load that it is carrying. The **competence** of the river is the maximum size of particle that the river is capable of transporting at the bankfull stage.

River channel processes – deposition and sedimentation

When rivers slow down they have less energy and deposition takes place. The larger particles are deposited first, while fine clay particles may not be deposited until the river reaches the sea. Deposition can take place whenever the river loses energy. The river's energy depends on its velocity and its discharge. The load can be dropped because the velocity has slowed, or because the discharge has fallen, or because both have happened. Deposition takes place in the following circumstances:

- → During a period of low discharge when there has been a dry spell with no rain.
- → On the inside of a meander bend.
- → When a river bursts its banks due to a reduction in the **hydraulic radius** (see below).
- → When the load is increased, e.g. after **deforestation**.
- → When a river enters the still water of a lake or the sea.

Sedimentation occurs when river sediment is deposited from still water. This process is common on floodplains and on the sea bed. On the sea bed it is aided by the process of **flocculation**, the way that charged ions in sea water allow clay particles to coagulate together and settle out of suspension. The bottomset, foreset and topset beds in a **delta** (Fig. 1.36 on page 20) are produced by sedimentation. Material deposited as sediments may become sedimentary rock, linking river processes with the rock cycle.

River channel processes – the Hjulström curves

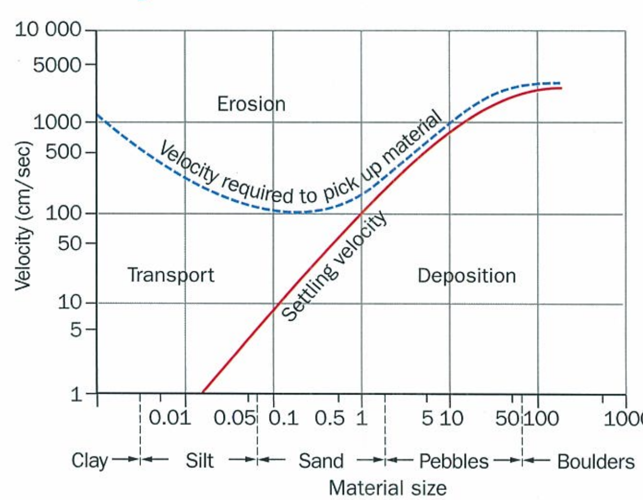


Fig. 1.23 The Hjulström curves

This diagram is a complex graph which uses logarithmic scales on both the horizontal and vertical axes. This is known as a **log/log graph**. This technique allows a wide range of data to be shown on a relatively small graph. The diagram shows the relationship between particle size and velocity. The top curve is sometimes known as the *critical erosion velocity curve* and shows the river velocity required to pick up sediment particles of different sizes. The lower curve is the *mean settling velocity curve* and shows the speed that the river has to slow to, before particles of different sizes will be dropped (deposited). The main points to note are:

- The velocity needed to keep particles moving is always lower than the velocity needed to start them moving. This means that if a swift eddy starts to move a particle, the river water will have to slow down significantly before the particle is dropped.
- Sand is the easiest material to erode. Sand can be picked up at lower velocities than either smaller or larger particles. Clay is cohesive (sticky) and pebbles are heavy - both need more energy to be eroded than sand particles do.
- Fine clays, once picked up, will stay in suspension even if the water stops moving. This is another reason why lowland rivers always look muddy.
- When a river slows down, the coarse material is dropped first, the finest last. This why **levées** form close to the river during a flood.

11. Study Fig. 1.23.

(a) How fast has the river to be moving before an average-sized pebble (10 mm) is picked up?

(b) At what velocity will a sand particle of 1 mm be dropped by the river?

(c) The velocity of water in the river channel increases after heavy rain. As the velocity reaches 1000 cm/sec, what is the status of: a tiny clay particle on the river bed, a sand grain and a boulder on the river bed?

River flow – factors affecting the energy of a river

Rivers have *kinetic* energy because they have mass (discharge) and velocity.

Discharge is affected by precipitation and the characteristics of the drainage basin system. Discharge generally increases as a river flows downstream because more and more tributaries bring their water to the main river.

Velocity is affected by a range of factors but friction and gradient are the most important. Although we would expect rivers with a steep gradient to flow very quickly, research has shown that friction is more important than gradient. This is why rivers in the lowlands with a gentle gradient, but a very smooth bed, flow faster than rivers in the uplands with a steep gradient, but a very rough bed. Upland rivers look as if they are flowing quickly but the extreme **turbulence** caused by the very rough river bed means that the downstream velocity is quite low. Friction is measured in two ways: bed roughness and hydraulic radius.

Bed roughness

A rough channel produces more friction and provides more resistance to river flow than a smooth channel. Roughness is measured by *Manning's N*. There are different ways of calculating Manning's N, but the simplest formula is as follows:

$$N = \frac{R^{0.67} \times S^{0.5}}{V}$$

where:

N = Manning's N - the roughness coefficient

R = hydraulic radius (see below)

S = channel gradient (as a fraction)

V = mean velocity of flow

The gradient, hydraulic radius and the velocity can all be measured using fieldwork instruments, but the calculation of Manning's N is usually carried out using a computer. The higher the value of N, the rougher the bed. Small mountain streams typically have values of around 0.05, while lowland rivers have values closer to 0.015.

Hydraulic radius

This is a measure of the *efficiency* of the river. It compares the friction caused by the bed and banks with the amount of discharge flowing down the river. In an efficient river, the water moves relatively easily, with minimum resistance to flow from friction. The formula for hydraulic radius is as follows:

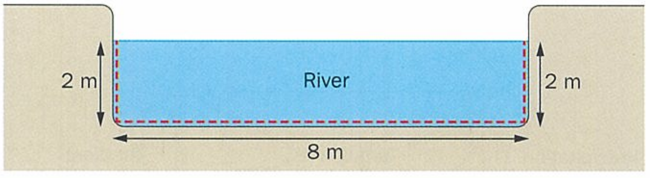
$$\text{Hydraulic radius} = \frac{\text{channel cross-sectional area (CSA)}}{\textbf{wetted perimeter (WP)}}$$

where:

CSA = channel depth × channel width

WP = length of the bed and banks in direct contact with the water in the river channel.

This is best shown in a diagram:



cross-sectional area (CSA)	$= 2\,m \times 8\,m = 16\,m^2$
wetted perimeter (WP)	$= 2\,m + 8\,m + 2\,m = 12\,m$
hydraulic radius = CSA/WP	$= \frac{16\,m^2}{12\,m} = 1.34\,m$

Fig. 1.24 How to calculate the hydraulic radius

Hydraulic radius increases downstream. The hydraulic radius also changes as the discharge changes at any one point along a river.

12. Study Fig. 1.25. Calculate the hydraulic radius for:

(a) low water

(b) normal flow

(c) the bankfull stage

(d) the overbank flood.

When is the river at its most efficient? Explain your answer.

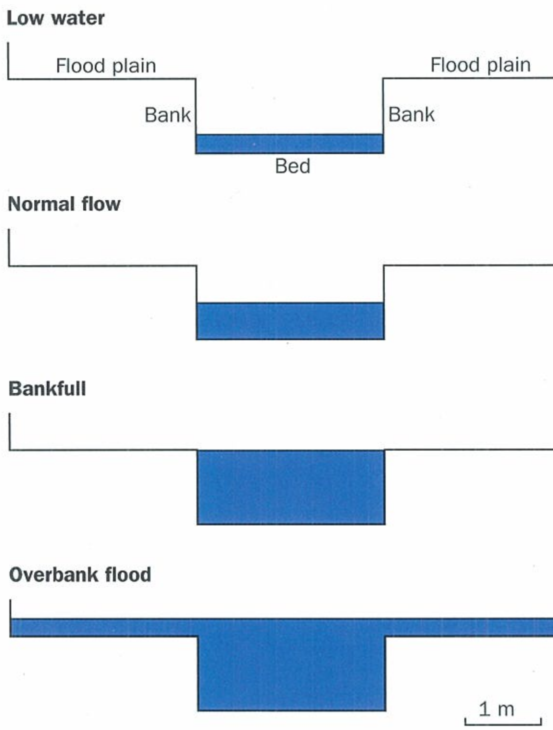


Fig. 1.25 Changing hydraulic radius

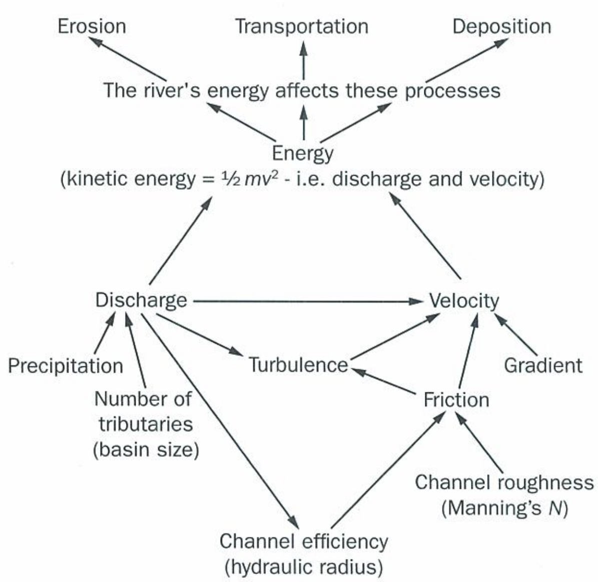


Fig. 1.26 River channel processes – a summary diagram

13. Bradshaw's model (Fig. 1.19 on page 13) does not consider all the river variables. How would you expect the following factors to change as you move downstream:

(a) channel efficiency (hydraulic radius)

(b) friction

(c) turbulence

(d) channel cross-sectional area?

Figure 1.26 summarises the complex relationships between the various processes that operate within the river channel. Don't forget that the processes change with time, often depending on changes in the river's discharge.

Patterns of flow

Water flows downhill in three main ways:

→ **laminar flow**

→ **turbulent flow**

→ **helicoidal flow**.

Laminar flow

Water flowing downwards over a smooth surface can flow in a simple sheet, with no eddies or meanders. This is known as laminar flow. Laminar flow can be observed on a smooth road surface or paved area during heavy rainfall, but it is very rare in nature because most surfaces exert enough friction for turbulence to disrupt the flowing sheet.

Turbulent flow

Water flowing in a river channel is subject to friction, both with the river bed and the banks. This friction slows the water closest to the bed and banks and the water nearer the centre of the river overtakes the slow water. Because water is a liquid, this results in turbulence. Water at the sides of the river begins to eddy towards the banks and water close to the bed of the river begins to eddy downwards. Both types of eddy operate at the same time and this leads to chaotic, turbulent flow.

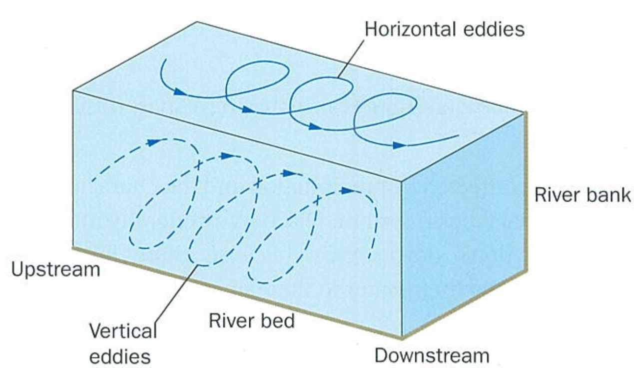


Fig. 1.27 Turbulent flow

Helicoidal flow

Water flowing down a plughole often starts to spiral as it flows downwards. This spiralling motion is typical of fluids moving at or close to the surface of a rotating planet. It is no surprise that water flowing down a river channel is subject to the same forces. The line of fastest flow (**thalweg**) follows a corkscrew or spiralling path as the river moves downstream. This is closely related to the development of meanders but even in a straight, artificial channel, helicoidal flow can be observed.

The spiralling movement of the thalweg is constrained by the river channel. Not only does the thalweg spiral from the surface to the river bed and back to the surface, but it also moves from one bank to another in a downstream direction. The vertical movement of the thalweg produces pools and riffles while the bank-to-bank motion concentrates erosion first on one bank and then on the other. This contributes greatly to the formation of regularly spaced meanders along the river's course (see Fig. 1.38 on page 21).

Channel types

There are three main types of river channel:

- straight channels
- meandering channels
- braided channels.

The **sinuosity** of a river channel is a measure of how 'bendy' it is. It is calculated by dividing the length of the river channel by the length of the valley in which it flows. This can be done for a whole river but more usually it is done for sections of a river. A perfectly straight river will have a sinuosity of 1.0 but natural river channels are rarely perfectly straight. Any river with a sinuosity less than 1.5 is considered 'straight', while a river with a sinuosity of over 1.5 is considered to be 'meandering'.

Straight river channels

These are quite rare because helicoidal flow dominates in most rivers and makes them meander. Even on a straight river, the thalweg (line of maximum flow velocity) moves from side to side because of helicoidal flow.

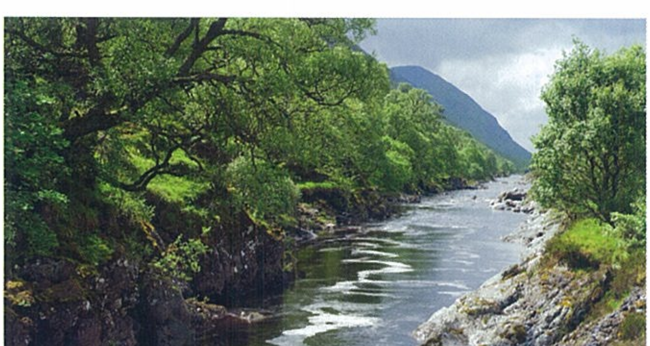


Fig. 1.28 A straight river channel. This is the river in Glen Tilt, Scotland, UK. The reason it is so straight is that it is guided by a straight fault (weakness) in the rocks

Meandering river channels

Most rivers meander to some extent. Upland streams meander but the most pronounced meanders are found on floodplains where **lateral erosion** is facilitated by the soft nature of the river banks. Meanders are so common because spiralling is the normal behaviour of moving fluids on the surface of a rotating planet. Rivers are confined to their channels so the tendency to spiral downwards produces helicoidal flow. This is the main reason why rivers meander (see Fig. 1.29). Meanders are *not* produced by large obstacles in the river's course.

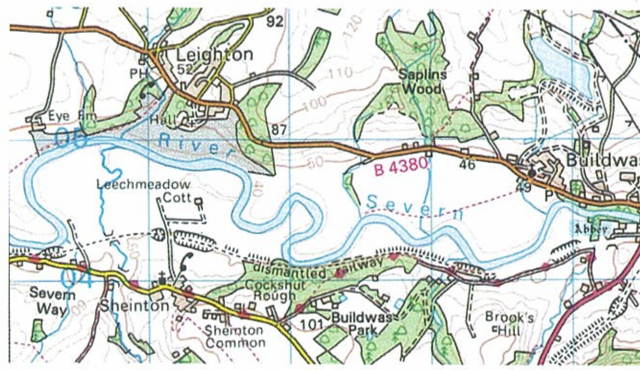


Fig. 1.29 A meandering river channel. This map extract shows the River Severn near Ironbridge in Shropshire, UK

Braided river channels

These are river channels that contain a large number of islands and bars made of sediment. They are found in areas where discharge varies a lot during the year and where a large amount of fairly coarse sediment is being carried by the river, for example glacial **outwash** streams and seasonal rivers in semi-arid areas. The braiding results from the deposition of sediment on the riverbed during a time of falling discharge. The river then splits as it flows around these deposits. A braided river channel can be extremely wide and constantly changing.

Fig. 1.30 A braided river channel. This is a river on the Skeidararsandur glacial outwash plain in southern Iceland

River landforms

Flowing water has energy which allows rivers to do work through the processes of erosion, transportation and deposition. These processes produce a whole range of distinctive *landforms* such as waterfalls, floodplains and deltas. Together, these river landforms make up what we recognise as a river *landscape*.

Landforms of the upper course

Potholes

Fig. 1.31 Potholes on a rocky river bed in South Africa

Potholes are formed by turbulence which swirls pebbles around in a depression on the river bed. The swirling pebbles enlarge the pothole by the process of abrasion. The process is explained in more detail in Fig. 1.20 on page 13. They are usually quite small features and they are evidence that vertical erosion predominates in upland rivers.

Rapids

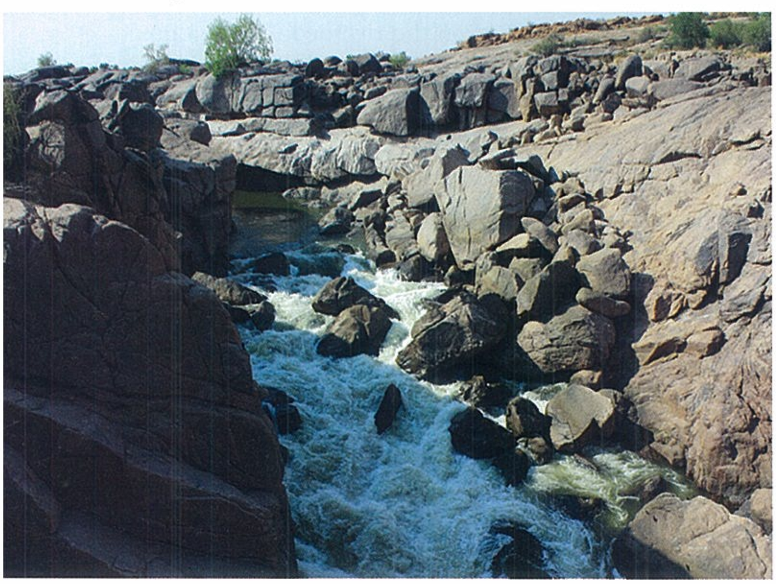


Fig. 1.32 Rapids on the Orange River in South Africa

Rapids are common in the upper course of a river. They form at places where the gradient is steep and the river bed is rocky, resistant to erosion, and irregular. They are usually caused by a band, or bands, of hard rock in the river bed.

Waterfalls and gorges

Waterfalls form where a horizontal layer of hard rock lies on top of a layer of softer rock in a river valley. The soft rock underneath is eroded more quickly by the river and gradually a **plunge pool** develops. The splashing water and eddy currents in the plunge pool undercut the hard rock layer above. This eventually creates an unsupported overhang of hard rock. The overhang then collapses into the plunge pool. If the processes of undercutting and collapse are repeated over a long period of time, the waterfall will retreat upstream - forming a deep, steep-sided valley called a **gorge**.

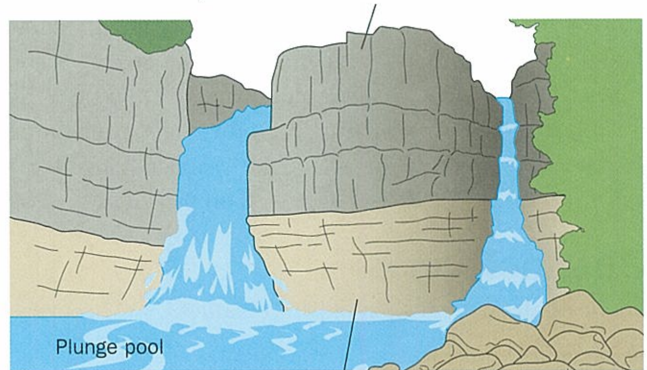


Fig. 1.33 The High Force waterfall on the River Tees is one of the largest waterfalls in England

14. (a) Make a copy of diagram A in Fig. 1.34. Add labels to the diagram to identify the main features. Write a short paragraph to explain what the diagram shows. Try to use subject specific vocabulary e.g. the names of the different types of erosion that are operating.

(b) Repeat the exercise for the other three diagrams: B, C and D.

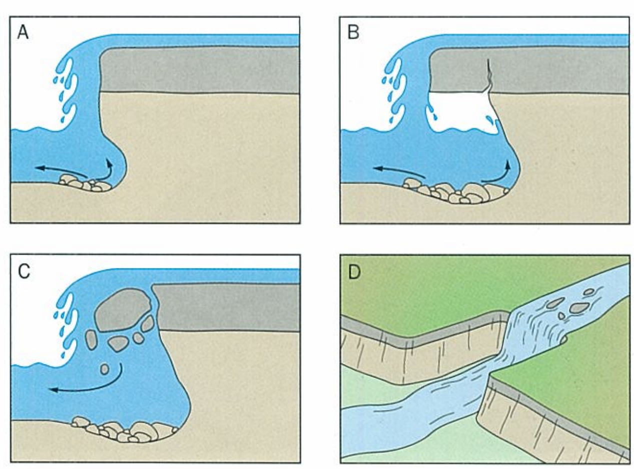


Fig. 1.34 Four diagrams showing the development of a waterfall and a gorge over time

Gorges form best when the hard rock is especially resistant to weathering but succumbs to river erosion. As well as being formed by the retreat of a waterfall, gorges can form in other circumstances:

- In semi-arid areas, where there is a short wet season leading to vertical erosion of the river bed when the river is flowing, but no water for weathering at other times of the year.
- Where a mountain range has been formed across the path of a river, but the vertical erosion of the river has been able to keep up with the growth of the mountain range. The gorge of the Brahmaputra River where it flows from Tibet, through the Himalayas, is an excellent example. This is known as **antecedent drainage**.

Landforms of the lower course

Floodplains, levées and bluffs

A floodplain is the flat land next to the river which is liable to flood when the river rises after heavy rainfall. Floodplains are often badly drained, with marshes and **ox-bow lakes**. In their natural state they are unhealthy areas to live on because diseases are common. Sometimes the river actually flows above the level of the surrounding floodplain, but it is enclosed by natural embankments called levées.

Lateral erosion predominates on a floodplain. The river is close to sea level (**base level**) so it can't cut down much further. However, the floodplain is made of soft alluvium so lateral erosion is facilitated and the **meander belt** migrates constantly across the floodplain. Where a meander reaches the edge of the floodplain, it may erode back the low valley side, helping to maintain the low **bluffs** found at the side of most large floodplains.

The floodplain is made of alluvium (river silt) because it is formed by deposition of material from the river. There are three main forms of deposition which contribute to the formation of the floodplain:

- The deposition of fine silt and mud (part of the suspended load) on the floodplain itself, during times of flood. As the floodwater spreads across the floodplain, the hydraulic radius decreases, friction becomes more important, the river slows, and deposition takes place. Most deposition takes place closest to the river. This means that areas further from the river receive thinner layers of sediment and don't grow upwards quite so fast. This leads to lower areas, further from the river channel, known as backswamps.
- The deposition of **point bars** in the slow water on the inside of meanders. These deposits spread across the floodplain as the meanders migrate.
- The deposition of sediment on the river bed at times of low water when the velocity of the river slows. This is why big rivers often raise themselves above the level of the floodplain.

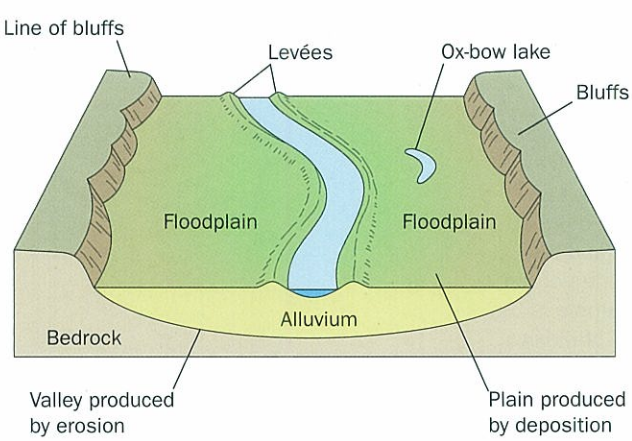


Fig. 1.35 Block diagram showing the main features of a floodplain

Like the floodplain, levées are depositional features. When rivers reach bankfull stage and then burst their banks, the current slows and deposition takes place. The biggest particles are deposited first and when the river level falls after a flood, these coarse deposits form embankments at each side of the river. They are natural features but people often raise them and strengthen them to prevent flooding. Sometimes completely artificial embankments are built for the same purpose, and in the USA these embankments are also called levées.

Landforms produced by sedimentation

Deltas

These are depositional features which form when the river meets the sea or runs into a lake. When a river meets the still water of the sea or lake, the loss of velocity leads to a loss of energy and the river's load of sediment is deposited. Sea water contains charged ions of the salts dissolved in it and these charged ions lead to the flocculation of clay particles - tiny particles cluster together, becoming bigger and so are more able to settle to the bottom. Deposition of sediment blocks the river's main channel which splits into smaller channels called **distributaries**. Continued deposition over time means that the delta grows outwards into the sea, forming a flat, marshy extension of the land. There are often lakes and **lagoons** within the delta. Because deltas are formed of fertile alluvium they are attractive areas for human settlement. They are dangerous places to live, however, because they are susceptible to flooding, both by the river and by the sea. An example of a densely populated delta is the Ganges delta in India and Bangladesh.

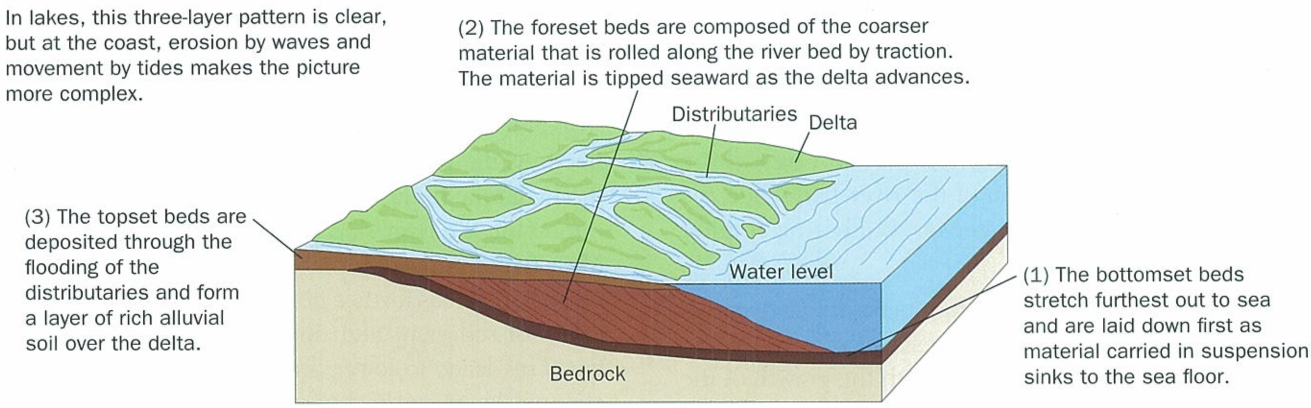


Fig. 1.36 The formation of a delta. The structure produced by the deposition of bottomset, foreset and topset beds

There are many types of delta but there are three classic types.

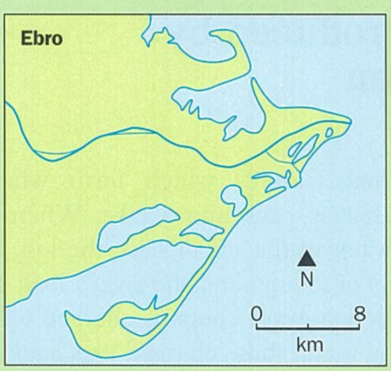
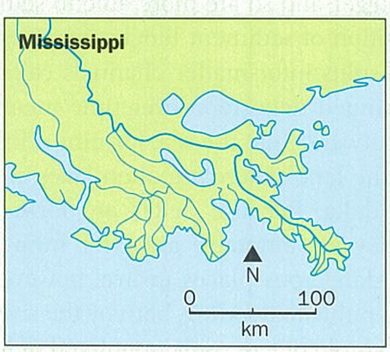
Map of delta	**Description**
The Niger delta  	**Arcuate deltas** are fan-shaped and they form when the **tidal range** is quite low and there is a strong movement of sediment in one direction along the coast, e.g. by longshore drift or an offshore current. This keeps the seaward edge of the delta smooth in shape. A good example is the Niger delta in West Africa.
The Ebro delta  	**Cuspate deltas** are shaped like an arrowhead or a worn tooth. There is a low tidal range and two offshore currents shape this sort of delta, operating in opposite directions at different times of the year. A good example is the Ebro delta to the south of Barcelona in Spain.
The Mississippi delta  	**Bird's foot deltas** are formed where the tidal range is low and where the river currents are strong. There is no clear offshore current to shape the delta so each distributary builds the land out into the sea, acting like a series of thin conveyor belts. The best example is the Mississippi delta in the Gulf of Mexico.

Fig. 1.37 Types of delta

Meanders and ox-bow lakes – river landforms produced both by erosion and deposition

Meanders are the most typical of all river landforms. They can be found at any point along a river's course and their associated landforms are relatively easily explained. However, the reasons why meanders form in the first place are complex and difficult to understand.

It used to be thought that meanders were caused by an obstacle along the course of the river, causing it to deflect from a straight course. Once initiated, the different rates of erosion and deposition in the inside and outside of meander bends ensured that meanders remained and developed. However this idea was thrown into doubt in the mid-20th century when it was noticed that there were certain regularities and relationships that applied to meanders wherever they were found. The most obvious was that whatever the size of the river, the wavelength of its meanders was roughly 8-10 times the width of the river. This sort of regular mathematical relationship implied that meandering was a fundamental part of a river's nature and that a universal principle was involved in their formation. This led geomorphologists to look at the way in which water flowed in rivers and to look for other regular relationships in the form of river channels.

Pools and riffles

Straight rivers develop deeper sections where erosion predominates (pools) and shallower sections where sediment has been deposited (riffles). The process that causes this is complex and not fully understood but the regular spacing of pools and riffles (the distance from pool to pool is 4-5 times the width of the river) suggests it is related to helicoidal flow. Close study of the thalweg showed that the thalweg did indeed move in a corkscrew fashion (helicoidal) and that the rising and falling of the zone of maximum velocity within the river channel corresponded to the position of pools and riffles.

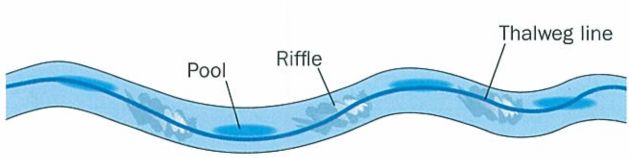


Fig. 1.38 Pools and riffles on a relatively straight river channel

Meanders

Meanders are related to pools and riffles because the meander wavelength is usually 8-10 times the river width, with a pool on the outside of each bend. In other words the distance pool to pool to pool equates to a meander wavelength.

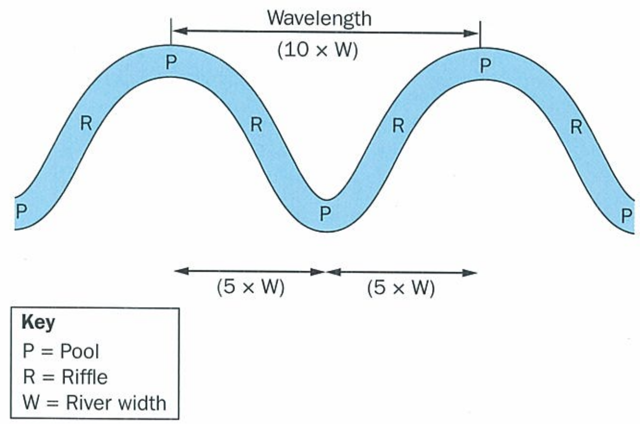


Fig. 1.39 Pools and riffles on a meandering river channel

Meanders have an asymmetric cross section and the flow of water in three dimensions is complex.

The form of a meander is the same wherever it is found. Deep water and a **river cliff** are found on the outside of the bend while shallow water and depositional features (slip-off slope or point bar) are found on the inside of the bend. This is related to the nature of the river flow, especially the different amounts of energy that the river has on the outside and inside of the bend.

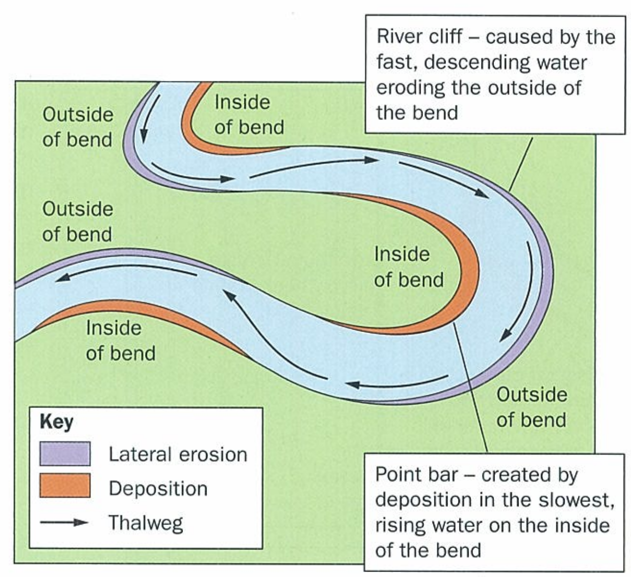
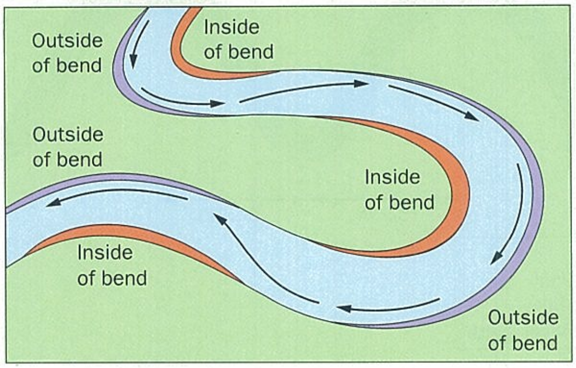
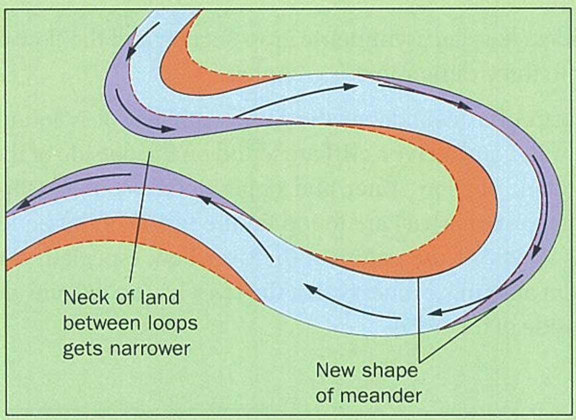
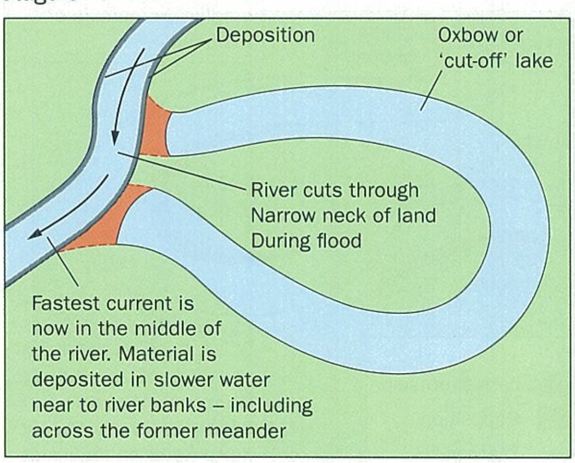


Fig. 1.40 A map of a typical meander

Ox-bow lakes

Meanders become more sinuous (bendy) over time as erosion and deposition continue to change their shape. In the soft alluvium of a floodplain, lateral erosion can be so effective that the neck of the meander becomes narrower and narrower. Eventually (usually during the high energy conditions of a flood) the neck is breached and the meander cuts itself off. An ox-bow lake is the result.

Map	Description
Stage 1 	*A meander on a floodplain.* Because the alluvium of the floodplain is soft and because the river is close to sea level (base level), lateral erosion predominates. Erosion is focused on the outside of the meander bend and deposition on the inside of the bend.
Stage 2 	*The meander becomes more sinuous.* Continued erosion on the outside of the bend undercuts the river cliff, which retreats. Deposition of material on the point bar on the inside of the bend continues. Together, these processes move the whole meander sideways. The neck of the meander becomes narrower as the two river cliffs move closer together.
Stage 3 	*An ox-bow lake is formed.* During a large flood, when the water is moving rapidly, erosion of the two river cliffs finally removes the neck of land between them. The river adopts a more direct line of flow because this increases the gradient of the river bed and makes the river flow more efficient. Deposition in the still water of the old meander cuts the meander off from the new course of the river. The ox-bow lake is a temporary feature because the growth of vegetation eventually fills it up and turns it into an area of marshy ground – very much like the rest of the natural floodplain.

Key

Land lost to the river (eroded)

Land gained from the river (deposited)

Fastest current

Earlier course of the river

Fig. 1.41 The stages in the formation of an ox-bow lake

RESEARCH Use old maps to see how much the meanders on a river near you have changed over time.

The human impact

How human activity can modify the natural hydrological cycle

By changing the operation of the natural system (inputs, stores, flows and outputs) in a drainage basin, human activity can have a significant impact on the way that the drainage basin operates.

By affecting the nature and amount of precipitation, evapotranspiration and river discharge, people can increase or decrease the impacts of river floods.

Direct human modification of the drainage basin system usually involves:

- changing the amount of precipitation entering the river's drainage basin
- storing water within the drainage basin by building dams or by groundwater recharge
- changing the channel characteristics of the river so that the speed of flow is affected
- transferring water between drainage basins
- **abstracting** water from the river for industrial, domestic and agricultural use.

Indirect human modification of the drainage basin system usually involves changing the nature of the drainage basin itself through:

- deforestation or afforestation
- changing the agricultural land use
- urbanisation - building towns and cities.

Precipitation

Cloud seeding involves adding artificial particles to clouds so that large water droplets form around these **condensation nuclei** and raindrops then fall. Silver iodide and dry ice are commonly used and this cloud seeding has led to local increases in rainfall in Australia and the USA of between 10–30 per cent. There is only a limited amount of water in the atmosphere, so increasing rainfall in one place can lead to less rainfall elsewhere.

Cities produce air pollution, which includes particles of soot from vehicle exhausts, domestic fires and industrial chimneys. These extra condensation nuclei, together with the heat island effect (which produces warm, rising air and atmospheric turbulence), can produce up to 10 per cent more rainfall in cities than in nearby rural areas.

Human-induced climate change (global warming) also has an effect. Warmer seas produce more evaporation. More water vapour in the atmosphere leads to more rainfall. Heat is energy, so a warmer atmosphere moves faster. Weather systems that produce rainfall, e.g. temperate depressions and tropical cyclones, could become more frequent as a result.

Water storage

Dams have been built on rivers throughout the world. A large dam is defined as a dam over 15 metres high. Worldwide there are over 48 000 of these large dams. Dams store water and have a major impact on river discharge. They are built to:

- provide water for irrigation, for homes and for factories
- produce hydro-electric power (HEP)
- control flooding.

15. (a) What is meant by 'irrigation' and why do many farmers use this technique?

(b) Make a list of all the ways that water can be used in the home.

(c) How is water used in factories?

Large dams can even out the flow of water in a river, ensuring that river levels remain high enough for water abstraction but stopping river levels rising above the bankfull stage, thereby reducing flooding. Significant amounts of water evaporate from large reservoirs. The Aswan dam in Egypt has reduced the annual flooding on the River Nile in Egypt but up to 30 per cent of the Nile's water is lost by evaporation from Lake Nasser, the reservoir created by the building of the dam. Because water abstraction from the River Nile downstream of the dam has increased, hardly any Nile water now reaches the Mediterranean Sea.

RESEARCH Make a list of the advantages and disadvantages of the building of the Aswan Dam for the people and economy of Egypt.

Artificial groundwater recharge is used to store water in underground aquifers. At times of high discharge, water is pumped from rivers into the ground via boreholes. This maintains or increases the height of the water table and boosts the discharge in streams fed by springs flowing from the aquifer. This stops the streams drying up during a dry spell. Water can also be extracted for human use, using the same boreholes used for the recharge. Artificial groundwater recharge is a strategy used in southern England, for example, where water is often in short supply during the summer months.

Changing the nature of the river channel

Large rivers are often straightened and deepened in order to make them easier to navigate by barges. This is called

canalisation and it tends to increase the hydraulic radius of the river channel. These straight, deep channels move water more efficiently and this can lead to shorter lag times and increased flood peaks. The River Rhine has been extensively canalised and the flood surge, which used to take five days to move from Switzerland to the Netherlands, now takes only three days.

In urban areas, rivers are often confined to concrete channels or underground drains. This can lead to increased levels of flooding in nearby buildings.

Transferring water between drainage basins

In north-east England there are three large industrial cities: Newcastle-upon-Tyne, Sunderland and Middlesbrough. They each have a high demand for water. A huge reservoir has been built on the **headwaters** of the River Tyne at Kielder and this supplies water, via the River Tyne, to Newcastle. Kielder can hold far more water than is needed by Newcastle, so a series of pipelines have been built to transfer water from the River Tyne into the River Wear (for Sunderland) and into the River Tees (for Middlesbrough). One large reservoir in a very sparsely-populated area is therefore supplying water to three large urban/industrial areas, allowing all three cities to develop their economy. The natural discharge of all three rivers has been changed as a result.

Abstracting water from the river

River water is in demand for three main uses:

- Agriculture: in many parts of the world, rainfall is low and farmers need to irrigate their fields so that crops can grow.
- Industrial use: industry can use huge amounts of water for manufacturing (e.g. papermaking) or for cooling (e.g. power stations).
- Domestic use: in HICs people use large amounts of water each day for drinking, washing, flushing toilets, watering gardens and even washing cars. In LICs people use much less water, mostly for drinking.

16. Suggest why people in LICs use less water than people in HICs.

It is important that the use of water is sustainable - water use should not exceed water supply. If too much water is used, river levels fall and wetland areas dry out. This can have an impact on wildlife because habitats are reduced or destroyed.

Centre-pivot irrigation

Centre-pivot irrigation is a modern technology that has the potential to use water in a very unsustainable way. A borehole is drilled down to groundwater held in an aquifer. Water is pumped from the aquifer and sprayed onto crops via a long, wheeled boom that slowly rotates around the central borehole. This produces circular areas of cultivation in what might otherwise be a dry, brown landscape.

Near Lubbock, Texas, this technique has lowered the water table by about a metre a year since its introduction in the 1960s. This suggests that the use of groundwater in this way is unsustainable because water is being used up faster than it is being replaced. In Libya, there are many aquifers that filled with water when the Sahara desert was a rainy place. The Sahara became a desert around 7000 years ago and very little rain now falls there. Centre-pivot irrigation in Libya is also an unsustainable use of groundwater because here the groundwater is, in effect, a non-renewable resource. The same is true of centre-pivot irrigation schemes in other dry parts of the world.

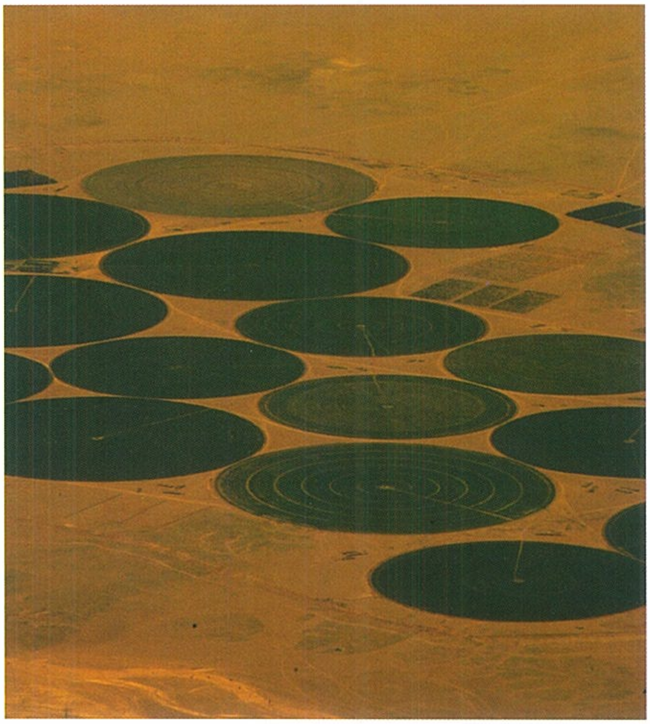


Fig. 1.42 Centre pivot irrigation circles in the Jordanian desert

Although water use per person is much greater in HICs than in LICs, water shortages can occur anywhere. Water is a renewable resource but when water use exceeds supply, long-term water shortages can result. This can have an impact on local people and on the potential for economic development. This leads to competition for the use of the available water resources and water has to be carefully managed. This can be an issue within one country or between countries.

Case study: Water management issues within one country: south-west USA

In Nevada, USA, there is a large lake called Pyramid Lake. It is an important source of water in this semi-arid area. There is intense competition for the water from Pyramid Lake:

- The farmers around Fallon, Nevada, need water to irrigate their crops of alfalfa.
- The residents of Reno, a tourist city similar to Las Vegas, need water for domestic use. The city is growing and demand for water is increasing rapidly.
- Pyramid Lake is a nature reserve, much valued by the local Native Americans who believe they are spiritually connected to a rare fish species that lives in the lake. Water is needed to allow the fish spawning runs each year. Without the spawning runs the fish will become extinct.

Competition between the different **stakeholders** was so intense that legal action was taken. The federal authorities ruled that the Native Americans and the residents of Reno should have priority and the Fallon farmers lost their water supply, resulting in their fields drying out.

Case study: International water management issues: the River Euphrates

The River Euphrates rises in Turkey, flows through Syria and Iraq and empties into the Gulf. Between 1983 and 1990, Turkey built the Ataturk Dam on the river in order to generate electricity and irrigate crops in Turkey. Despite previous agreements on the use of water, Turkey stopped the flow of the river for a month in 1990 to allow the reservoir behind the dam to fill. Syria and Iraq both protested because their water supplies had been disrupted. Turkey allowed the flow of water to resume but water use in Turkey means that the flow of the Euphrates below the dam is one-third less than it used to be. The reduction in water supply has had a bad effect on Syria and Iraq, reducing their potential for economic development.

17. (a) What is meant by a 'stakeholder'?

(b) Did the federal authorities make the right decision about the use of water from Pyramid Lake? Justify your answer.

18. Water wars are predicted in several parts of the world during the 21st century. Why might a country feel that it has to go to war to protect its water supplies?

Deforestation and afforestation

Forests growing in a river basin tend to reduce the discharge of the river. Increased interception and increased transpiration mean that evapotranspiration can become a more important output from the drainage basin than river discharge. Forests also encourage infiltration and throughflow rather than overland flow, reducing the speed at which rainfall reaches the river. **Flood peaks** are lower in a basin that is forested. If the forest is removed, much more water goes into the river, increasing the discharge and the flood risk.

Population growth in Nepal, in the Himalayas, has led to pressure to cut the trees down to provide fuelwood and terraced fields on the steep hillsides. Over-grazing of the deforested land has led to soil erosion. The local rivers are tributaries of the Ganges which has received more discharge and more sediment as a result. The sediment clogs up the river channels and leaves less room for the water. Increased levels of river flooding in Bangladesh, where the Ganges reaches the sea, have been blamed on deforestation in Nepal.

Devastating floods on the River Chang Jiang (Yangtze) in China in 1998 (see page 29) prompted the authorities to institute an afforestation programme in the upper reaches of the river. The province of Yunnan used to be heavily forested but many of the forests were removed in the 1960s because of the need for land to produce food for the growing population. As on the Ganges, this led to increased flooding on the Chang Jiang. The afforestation programme has met resistance from some local people in Yunnan but it is going ahead. It will be several years before the growing trees have a significant effect on reducing river discharge and flood peaks.

Changing agricultural land use

Land uses that create impermeable surfaces or reduce vegetation cover tend to increase overland flow and river discharge. Pasture land allows rainfall to soak into the ground but has less evapotranspiration than the forest it may have replaced. Floodplains tend to be fertile and are often used for arable farming. Ploughing increases infiltration because it loosens the surface soil but in HICs, arable farming can also reduce infiltration because the use of heavy machinery for cultivation and harvesting squashes the soil, so there is more overland flow and flood peaks increase. This was a significant factor in the flooding on the River Rhine in 1995.

Urbanisation

Covering large areas in concrete, tile and tarmac leads to an increase in overland flow, therefore floods are more likely, especially in places downstream of the urban area. The concrete drains and sewers of urban areas allow water to reach the river quickly, replacing natural throughflow with a much more rapid process. This reduces lag times and increases flood peaks. Building on a floodplain means that there is less room for the water when the river floods. The floodwaters will rise higher as a result.

River flooding – recurrence intervals and the prediction of flood risk

River flooding occurs when a river's discharge exceeds the capacity of the river channel. The river overflows its banks. River flooding is a significant hazard that affects many parts of the world. It is important that people are aware of the risk of flooding in the place where they live and work. It is also important to be able to give them accurate and reliable flood warnings.

Flood risk analysis

In the UK the Environment Agency is responsible for flood risk analysis and for issuing flood warnings. Flood risk analysis is important because it tells homeowners and tenants what flood risk their property faces. Owners of high-risk properties need to be especially alert for flood warnings.

The Environment Agency works out the flood risk at a place by using 'magnitude and frequency analysis'. A scatter graph is produced using historical flood data from that place. The **magnitude** (size) of the flood is plotted against the **recurrence interval** of the flood, i.e. how often, on average, that size of flood is likely to occur. This is done on special semi-log graph paper and a straight best-fit line can be drawn. Using the **best-fit line** the size of the 5-year flood, 50-year flood, 100-year flood, 500-year flood, etc., can be calculated. An example is shown Fig. 1.43. The vertical scale is arithmetic but the horizontal scale is logarithmic, making this a semi-log graph.

As can be seen from Fig. 1.43, the magnitude and frequency analysis deals in probabilities. The '10-year flood' is the size of flood that can be expected every 10 years on average and there is a 10 per cent chance of a flood of this size happening in any one year. This means that once the 10-year flood has happened, there is no guarantee that it will be 10 years before it happens again. However, the use of recurrence intervals is useful when planning flood defences and when drawing flood risk maps.

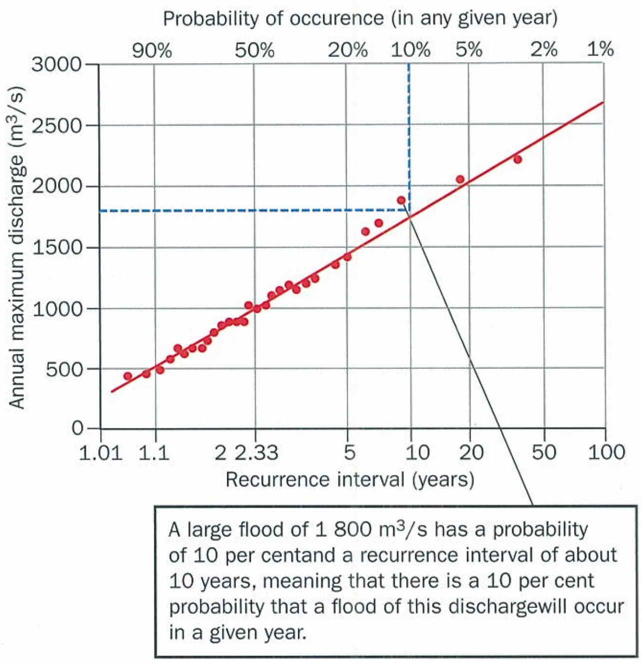


Fig. 1.43 Magnitude and frequency analysis of flood risk

Current advice in the UK is that densely-populated urban areas should be protected against floods up to the height of the 100-year flood. The 'magnitude and frequency analysis' graphs can show the Environment Agency how high to build the walls and embankments in order to do this. This means that there will occasionally be floods that will come over the top of the defences. The Dutch have recently rebuilt the flood defences on the River Rhine to cope with the 1000-year flood, but this has cost a lot of money. Politicians in the UK have decided to pay for the damage caused by very rare floods rather than pay for very expensive flood defences to protect people from them. It's a question of what is cheapest over the long term. However, climate change could be making big floods more frequent. What is currently the 100-year flood might soon become the 20-year flood. This adds another level of uncertainty to flood risk analysis and planning.

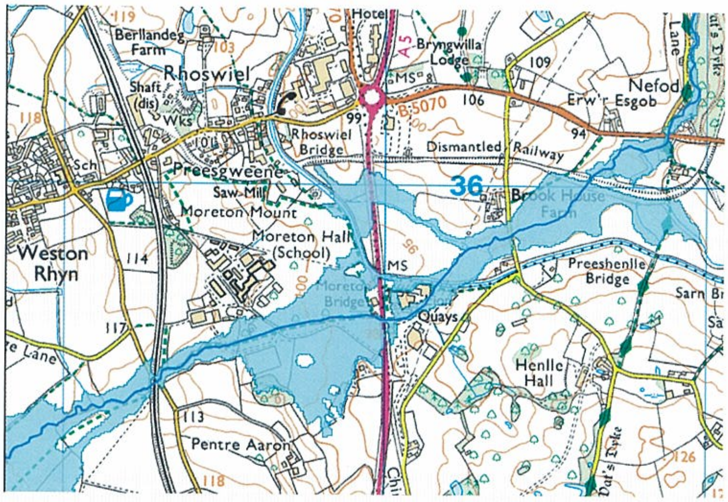
Flood risk maps

On the Environment Agency's website it is possible to obtain flood risk maps for most places in the UK.

This flood risk map is very reassuring for most of the people who live in the area shown. Very few buildings are at risk. Some low-value agricultural land could be flooded but if the farmer gets sufficient warning, any grazing animals can be moved to higher ground and safety.

Flood predictions and warnings

In the UK, the Environment Agency monitors rainfall and river levels and is able to produce flood warnings as a result.



A Key:
■ = significant flood risk (1–75 year flood)
■ = moderate flood risk (76–200 year flood)

Fig. 1.44 Flood risk at Moreton Hall, Shropshire, UK

The details are as follows:

→ Rainfall radar can plot the approach of depressions and other rain-bearing weather systems. These data are fed into the Agency's computer system.

→ Tipping rain gauges throughout the drainage basin monitor the actual amount of rain falling and feed this information into the system.

→ Along the river, automatic river discharge gauges monitor the rising river levels and this is added to the system data.

→ The system's database includes a model of the way the drainage basin behaves at different times of the year and with different inputs of rainfall. This is based on past flood events, i.e. a whole series of past storm hydrographs.

→ As a result the computer system can continuously compare the incoming data with past events and produce predictions of river levels at different points along the river. It can predict how high the flood peak will be and when it will reach different places.

→ On the basis of these predictions the Environment Agency issues detailed flood warnings. People are then given time to prepare for the flooding.

River flooding – the causes, impacts and management of river flooding

River flooding causes death, damage and disruption (both economic and social). Because of this, people try to manage the flood hazard. Management involves a combination of prediction, prevention and amelioration. For management to be successful we have to fully understand the causes of flooding.

The causes of river flooding

River floods are caused when rates of overland flow exceed the river's capacity to hold the water it is supplied with. The natural factors affecting overland flow have been dealt with earlier in this chapter but can be summarised as:

→ heavy, persistent and/or intense rainfall

→ rapid snowmelt

→ impermeable soil and bedrock

→ a lack of vegetation in the drainage basin

→ cold temperatures which reduce evapotranspiration.

In addition, human activities can make flooding worse. These activities include:

→ deforestation

→ urbanisation

→ mechanised farming

→ **acid rain** (which destroys forests)

→ global climate change.

The impacts of river flooding

As with all natural hazards, the impacts of river flooding are:

→ death – of people and animals

→ damage – to buildings, infrastructure and farmland

→ disruption – to people's lives. Disruption can be social (e.g. people are made homeless), or it can be economic (e.g. damage to businesses or factories which means that people are unable to continue making a living).

The impacts of river floods vary from country to country. As a general rule, in HICs the *economic cost* of the flooding is higher than in LICs but the *death toll* is usually higher in LICs than in HICs.

19. Suggest why the cost of flooding is greater in HICs but the death toll is higher in LICs.

The management of river flooding

How well the flood hazard is dealt with depends on:

→ The level of economic development of the place. This influences factors such as emergency service provision, infrastructure and the ability to recover from the flood.

→ The willingness of the local people and their governments to spend money on flood preparation and alleviation.

- The accuracy and length of any warnings that are given.

Flood management strategies can be grouped into three main categories:

- *Forecasts and warnings which allow the adoption of behavioural strategies* - people adjusting their lifestyles and taking personal responsibility for the hazard risk.
- *Hard engineering solutions* - these usually involve building something.
- *Soft engineering strategies* - working with nature rather than trying to dominate it.

Forecasts and warnings which allow the adoption of behavioural strategies

- Make sure people understand the flood forecasting and warning service. This gives them time to move animals, move furniture and carpets, and evacuate people.
- Have an emergency plan, so that people know what to do once the warnings are given and once the flooding takes place. Each household needs to have its own plan and the whole town needs an overall plan.
- Organise at-risk houses so that they have tiled floors, moveable mats, drains in the floor, cupboards above flood level, plug sockets above flood level, wide stairs and space for storage upstairs.
- Take out insurance. A householder pays a set amount per year to the insurance company. If there is no flood, the insurance company keeps the money. If there is a flood, the insurance company pays the householder to repair the damage. The amount that has to be paid by the householder will depend on the level of the flood risk.

Hard engineering strategies

- Dams and reservoirs can be built upstream. As long as they are not already full, the reservoirs can store some of the floodwaters.
- Platforms can be built on the floodplain before any buildings are constructed. This raises the buildings above flood level (but still reduces the room for water on the floodplain).
- Build embankments along the river. They are effective but they are expensive and don't always look very nice. Temporary flood barriers are an alternative solution but the preparatory work is permanent.
- Dredge the river. This lowers the bed and makes more room for water in the river channel. It is very expensive and cannot be a permanent solution as the river deposits fresh silt over time.
- Straighten the river. This allows the water to flow faster and so prevents the build-up of flood waters. It does cause bigger floods further downstream, however.
- Retention basins can be built. These are areas surrounded by an embankment into which floodwaters are diverted at times of crisis. The land-use within the retention basin is severely restricted as a result. These have been built beside the River Rhine near Strasbourg in an attempt to reduce flood levels downstream.
- Flood relief channels. Artificial channels can be built around a town to take away excess water and prevent the town flooding. Once again, it causes worse flooding downstream.

Fig. 1.45 A hard engineering solution to flood risk. This is an artificial river channel in Nerja, southern Spain. The photo was taken during the summer dry season. The small inner channel is designed to cope with the normal winter flow of the river. The larger outer channel is designed to cope with extreme rainfall events which could cause flash floods, for which very little warning can be provided. The vegetation growing in the flood channel could be a problem as it takes up space and makes less room for the floodwaters

Soft engineering strategies

- Floodplain zoning. Only use the floodplain land for things that will not be affected too much by floods, e.g. sports pitches. Don't build houses in high-risk floodplain areas.

- → Rely on 'washlands'. The land upstream is allowed to flood. This acts as a safety valve and protects the town. On the River Chang Jiang, Dongting and Poyang lakes serve this purpose.
- → Plant trees in the upper part of the drainage basin. Trees encourage interception, evapotranspiration and infiltration. Forested areas have fewer floods.
- → Wetland and riverbank conservation schemes. This involves protecting the natural floodplain areas which still remain. It gives the floodwaters a place to go and protects disappearing wildlife habitats, enhancing species diversity.
- → River restoration schemes. This returns the river and its floodplain to its natural state providing sustainable environmental gain – but there is often an economic cost. In the Netherlands, some river floodplains have been returned to their original state and nature reserves have replaced farmland. Flood protection has been enhanced. The Netherlands is a rich country that can afford to do this and the farmers have been compensated.

Case study: River flooding on the River Chang Jiang, China

China is one of the largest countries in the world, both in terms of population size, land area and economic power. Its economic growth since 1980 has been phenomenal but the country is threatened by a variety of natural hazards which include earthquakes, typhoons and flooding.

China has many large rivers with the Chang Jiang (Yangtze) being the third longest in the world at 6380 km. Every year the summer monsoon rains, combined with snowmelt from the Himalayas, cause the river to rise to very high levels. Despite embankments, flooding is common.

Fig. 1.46 The location of the Chang Jiang River in China

Flooding on the Chang Jiang has caused many problems. Its valley is home to 400 million people. It floods annually but in 1931, 1934, 1954 and 1998 the floods were particularly catastrophic. 300 000 people died from its floods during the 20th century. The worrying trend is that the floods seem to be getting worse and the 1998 flood set new records.

Physical causes of flooding on the Chang Jiang

Flooding on the Chang Jiang is an annual event, caused by snowmelt in the Himalayas and the summer monsoon rains. In 1998 the rains lasted a month longer than usual and the 'El Niño' effect was blamed for this.

RESEARCH Find out what the El Niño effect is and how it can lead to increased rainfall in China and other areas on the west side of the Pacific Ocean.

Human causes of flooding on the Chang Jiang

As on most rivers, human activities have made the impact of the floods worse:

- China's urban population has been growing rapidly. Many of the cities are sited beside the river. More people and more property are at risk than in the past.
- To counteract the pressure for rural-to-urban migration, factories have been built in the village communes to provide jobs for the country folk. Many of these factories are on the floodplain and are not as well protected from floods as those in the cities. These factories and the workers' houses are at risk.

- More buildings on the floodplain mean less room for the floodwater so the flood levels rise higher.
- Deforestation in the headwaters of the river in the 1960s means that there is less interception, less evapotranspiration and less infiltration. This leads to more surface run-off and bigger flood peaks.
- Mismanagement of the deforested land, e.g. overgrazing, has led to soil erosion and more silt being washed into the river channel. There is, therefore, less room for the water.
- Canalisation of the river to improve river transport has straightened the river, speeding up the flow, reducing the lag time and increasing the flood peak.
- Flood protection embankments have constrained the river. This means that the river can hold more water but when the banks break the flooding is rapid and more deadly – people have less time to escape.
- In the old days, Dongting and Poyang Lakes near Wuhan acted as safety valves. Floodwater from the river was diverted into the lakes, reducing the potential flood peak. More recently, farmers have been reclaiming **polders** from the lakes to create new farmland. This means the lakes are much smaller and there is less room in the lakes for the floodwaters. Flood peak levels are increased.
- Global warming could have resulted in more rainfall in China.

The impacts of the 1998 Chang Jiang floods

The Chang Jiang floods of 1998 were some of the worst floods on this river in the last one hundred years. The monsoon rains were not more intense than normal but lasted for a month longer. At one time the river was 45 metres high. What were the impacts of these devastating floods?

- 240 million people in seven of China's provinces were affected by the floods in some way.
- 4000 people were drowned.
- Thousands of farm animals died.
- Huge areas of crops were destroyed. These included food crops such as rice and industrial crops such as cotton.
- To protect Wuhan, the largest city in the area, many of the river's flood protection embankments had to be deliberately breached. Large areas of the countryside were flooded as a result, destroying houses and factories in the village communes.
- 14 million people were homeless for months until their houses could be repaired or replaced.
- People were out of work for months while factories were repaired.
- Great thicknesses of sticky clay were deposited onto the fertile fields. This clay had to be removed before farming could re-commence.
- The total cost to China's economy was enormous.

Management of flooding on the Chang Jiang

Several schemes have been developed to reduce flooding on the Chang Jiang. These include both 'hard' and 'soft' engineering projects.

The Three Gorges Dam: a hard engineering solution

Downstream of the city of Chongqing, the Chang Jiang flows through a deep, narrow section of its valley known as the 'Three Gorges'. This is an ideal site for a dam because the reservoir is very big but is contained in the narrow valley and does not spread out over a huge lowland area. The dam has been built at Sandouping and the reservoir is 660 km long and 1 km wide, extending upstream almost as far as Chongqing.

The Three Gorges dam is the largest hard engineering project ever undertaken on a river. Construction started in 1994 and the dam was completed in 2006. The project was finally completed in 2009 when the reservoir completely filled up. The dam is 2.3 km long and almost 200 metres high. A series of gigantic ship locks has been built at the north-east end of the dam and an 18 000 megawatt H.E.P. station has been built inside the southwest end of the dam. It has cost in excess of US$ 38 billion to build.

What are the benefits of the scheme?

- At least 50 million people have been protected from the sort of catastrophic flooding that occurred in 1998, including those living in the mega-cities of Wuhan and Shanghai.
- Millions of hectares of farmland have been protected from flooding *and* provided with guaranteed irrigation water. This will raise grain and oil-seed production.

- Water supplies to the 13 million people living in Shanghai are now secure.
- It is generating 10 per cent of China's electricity, equivalent to 15 nuclear power stations. This is clean HEP and its production will not contribute to air pollution or to climate change. The power produced will boost economic growth, especially in central and eastern China, including the cities of Wuhan and Shanghai.
- The Chang Jiang is now navigable by ships of up to 10 000 tonnes, as far upstream as Chongqing. There is expected to be a 500 per cent increase in river traffic and this will also boost economic growth.

What are the disadvantages of the scheme?

- The reservoir has flooded 150 towns and cities and 1300 villages. 1.2 million people have been resettled in new settlements close to their old homes but the compensation did not cover the cost of their new homes.
- The reservoir is heavily polluted by toxins from flooded mines and factories. This has damaged the river's fragile ecosystem and species such as the White Flag River Dolphin and the Siberian Crane are endangered.
- The landscape itself could be a problem. As the water seeps into the rocks of the steep valley sides, landslides are expected. This is also an earthquake region and if the dam were to break the resulting flood would be unbelievably devastating.
- The Chang Jiang is laden with silt. This will be deposited in the reservoir, reducing its capacity. It will have to be dredged or flushed out on a regular basis. In the past, farmland downstream was fertilised with a thin layer of silt each year. This has been lost and more chemical fertilisers are needed.
- Over 1000 cultural and archaeological sites have been flooded, including the Zhang Fei temple.

Afforestation: a soft engineering solution

Upstream of Chongqing, the Chang Jiang runs through a hilly area on the borders of Yunnan and Sichuan provinces. This used to be heavily forested but many of the trees were cut down in the 1960s for fuel, timber and farm land. The new fields are used to grow crops like buckwheat but the terraces are poor and soil erosion is a problem. Animals are grazed here too. There is a now a big programme to get the local people to replant the trees wherever possible. The advantages are:

- Trees encourage interception, evapotranspiration and infiltration. This will help to reduce flooding, both locally and downstream.
- Forested areas have less soil erosion. This will be good for the local area and will reduce the amount of silt further down the river. This also reduces flooding and will reduce the rate of sedimentation in the Three Gorges reservoir.
- Trees can be harvested for food, fodder, fuel and timber.

However, the disadvantages are that the local farmers are losing their arable and grazing fields. Many of the trees planted are fast growing conifers which are less useful than the natural forest and do not stimulate biodiversity.

20. 'The Three Gorges Dam has caused more problems than it has solved'. To what extent do you agree with this statement?

Key concepts

The key concepts listed in the syllabus are set out below. For each one a summary of how it applies to this chapter is included.

Space: the drainage basin is an excellent example of the concept of space. The inputs, flows and outputs of the drainage basin system all operate within and across the space provided by the drainage basin. The nature of the drainage basin space determines the way in which the system operates to influence the functioning of the streams and rivers in the drainage basin. The river landscape is another example of the concept of space. The different river landforms are arranged logically throughout this space, from the upper valley to the lower valley of the river.

Scale: spatial scale is an important concept when studying rivers and their landscapes. Individual landforms are found at the local scale while drainage basins occupy the regional scale and the hydrological cycle operates at the global scale. The timescale is important when considering how quickly water moves through a drainage basin, how changes that are made to the drainage basin can affect these timescales and how these changing timescales can modify the nature and magnitude of river floods.

Place: distinctive river landforms are found in similar places within drainage basins. The source of a river is usually in a hilly place while the mouth is often beside the sea. Floodplains are places which provide people who live on them with opportunities and challenges.

Environment: rivers are part of the natural environment and they interact with people in a variety of ways. Water abstraction needs to be managed sustainably to ensure that supplies do not run out. Flood risk is a challenge which needs to be managed sensibly, considering the whole drainage basin and not just one place.

Interdependence: the water cycle operates at a range of scales and its interaction with human systems at each of these scales is complex. People need to understand the processes and links that operate in each drainage basin system if they are to successfully exploit the opportunities that it provides to them and manage the threats that it presents.

Diversity: every drainage basin and river landscape has its own distinctive character but they all obey overarching physical laws. Despite this, the human response to the opportunities and challenges that rivers provide is variable. This variation is often to do with the level of economic development of the country or society concerned.

Change: river basins and the landforms in them are constantly changing. This change is not only a response to the physical processes operating there (e.g. erosion, transportation and deposition) but also to the human activities going on there (e.g. water abstraction and flood risk management). Geographers should aim to understand the physical processes, the human activities and the way that the interaction between them leads to change.

Exam-style questions

1 Study Fig. 1.47 which shows the annual hydrograph of the River Severn at Bewdley.

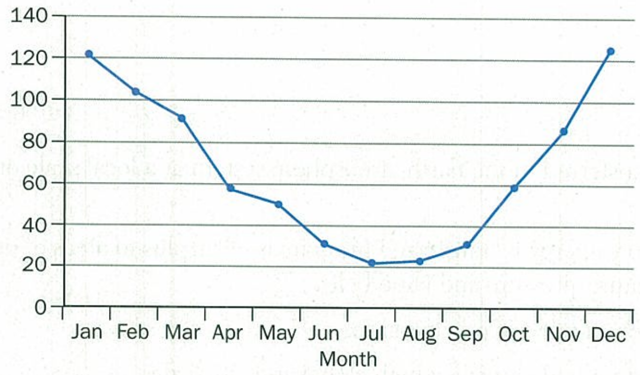


Fig. 1.47

(a) Using Fig. 1.47, identify the:

(i) Mean monthly discharge of the River Severn in October? [1]

(ii) The lowest mean monthly discharge of the River Severn and the month in which it occurs. [2]

(b) Briefly describe the pattern of the annual discharge of the River Severn. [3]

(c) Suggest how seasonal changes in evapotranspiration could cause the variations in river discharge shown in Fig. 1.47. [4]

2 (a) (i) Define the terms overland flow and throughflow as they apply to the movement of water in a drainage basin. [4]

(ii) Briefly explain how the shape of a storm hydrograph can be affected by overland flow. [3]

(b) Explain how vegetation type can affect the flows and stores of water in a drainage basin. [8]

(c) With the aid of examples, assess the extent to which human activities can increase the impact of river floods. [15]

2 Atmosphere and weather

In this chapter you will learn:

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

The atmosphere

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

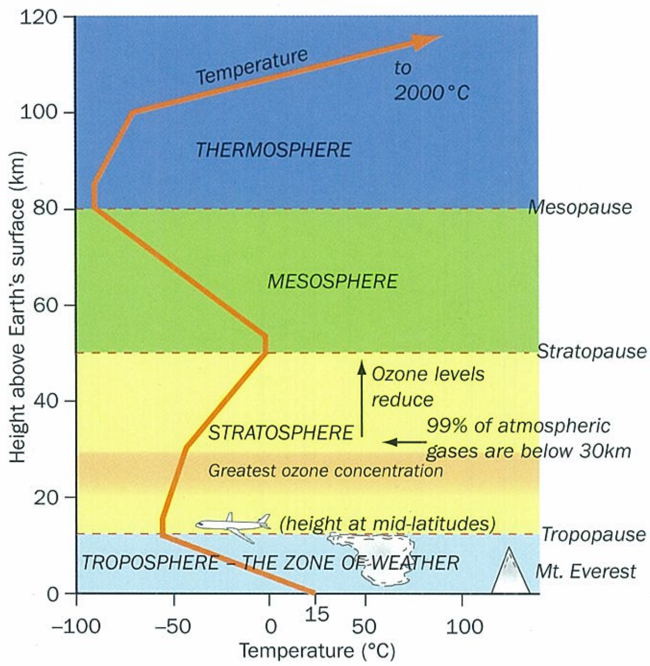


Fig. 2.1 The vertical structure of the atmosphere

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

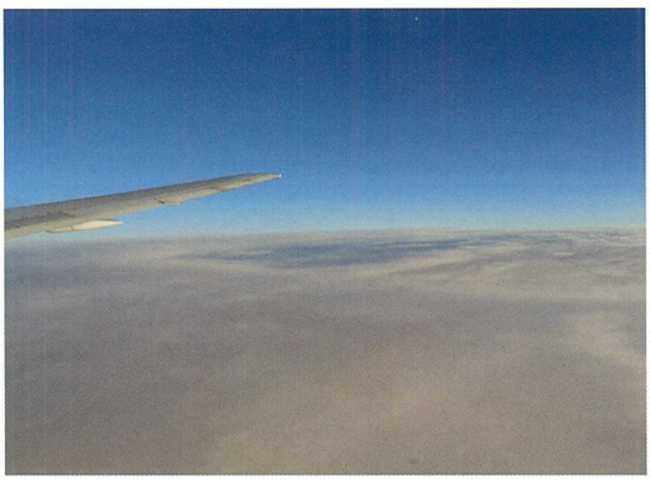


Fig. 2.2 Flat upper surfaces of cloud at the tropopause indicate the temperature inversion

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

Local diurnal energy budgets

Factors affecting the daytime energy budget

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

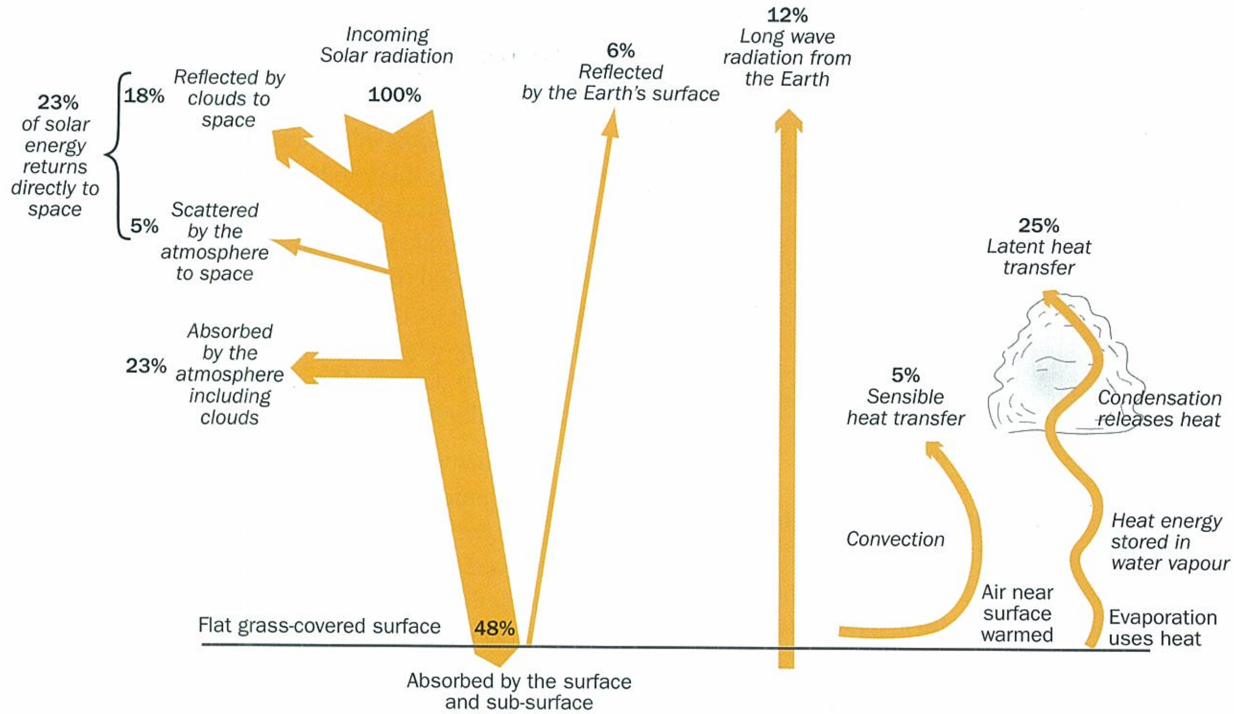


Fig. 2.3 The daytime energy budget

Incoming solar radiation (insolation)

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

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

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

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

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

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

Solar radiation reflected by the Earth's surface

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

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

Table 2.1 Average albedo values

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

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

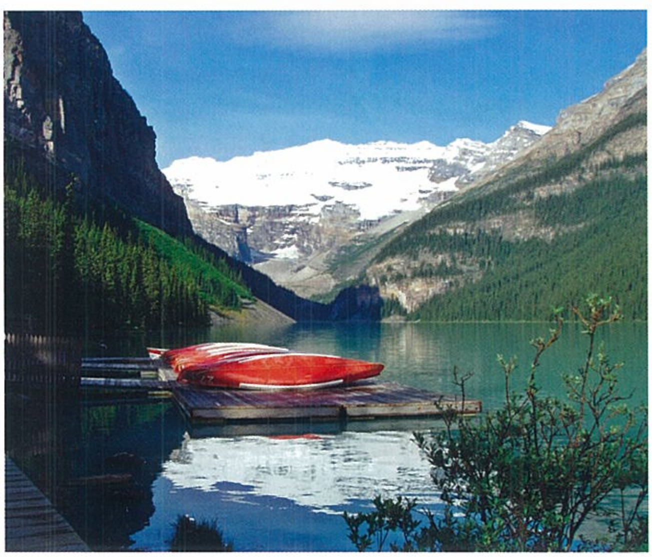


Fig. 2.5 Local variations in albedo in the Canadian Rocky Mountains

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

Energy absorbed into the surface and sub-surface

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

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

Long-wave Earth radiation

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

Sensible heat transfer

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

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

Latent heat transfer

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

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

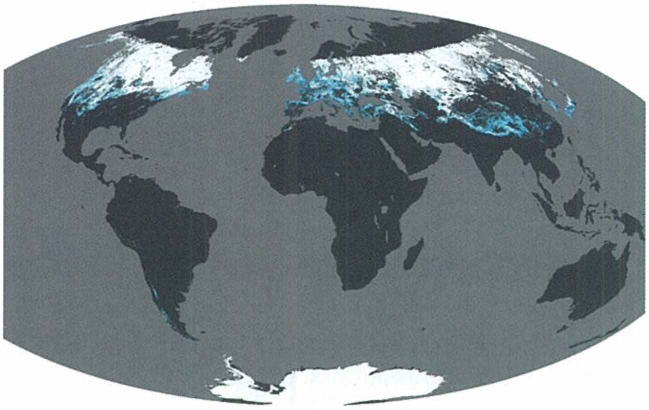


Fig. 2.6 Satellite image showing snow cover in December

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

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

> **3** (a) Describe two types of latent heat transfer that would be occurring when the photograph, Fig. 2.5, was taken.
>
> (b) Describe and explain the atmospheric process occurring in Fig. 2.7.

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

The influence of clouds on the daytime energy budget

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

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

> **4.** Using a different example for each, describe how, and explain why, a daytime energy budget will vary:
>
> (a) from time to time.
>
> (b) from place to place.

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

Table 2.2 The daytime energy budget

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

The night-time energy budget

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

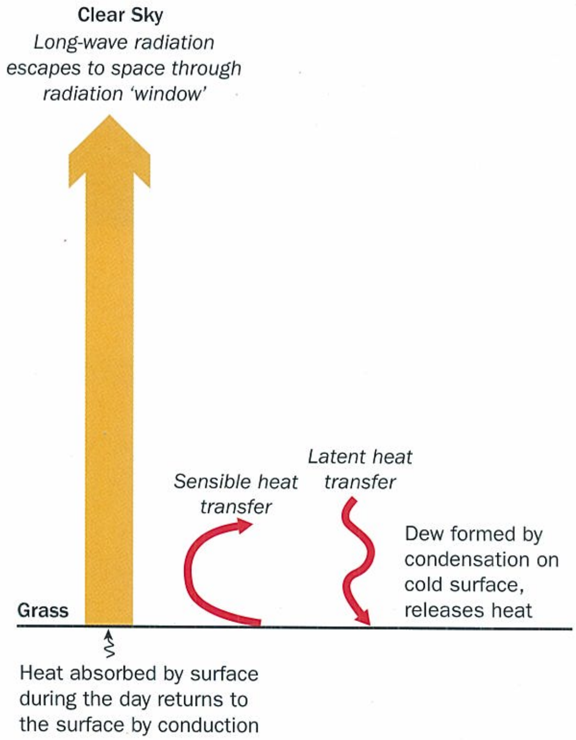


Fig. 2.9a The night-time energy budget

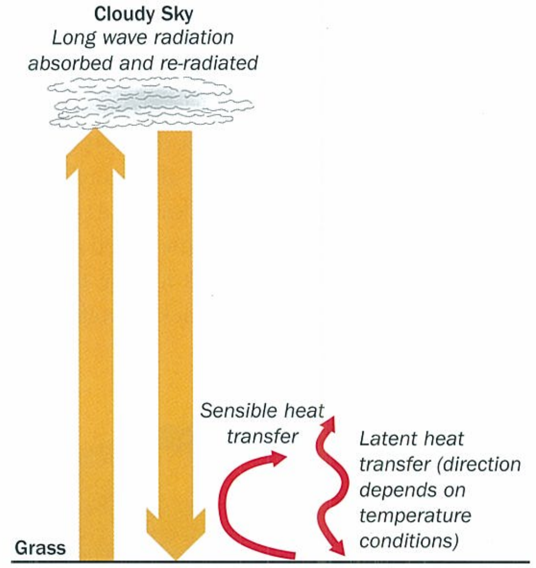


Fig. 2.9b How cloud changes the model

Conduction of heat to the surface

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

Long-wave Earth radiation

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

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

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

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

Sensible heat transfer

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

Latent heat transfer

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

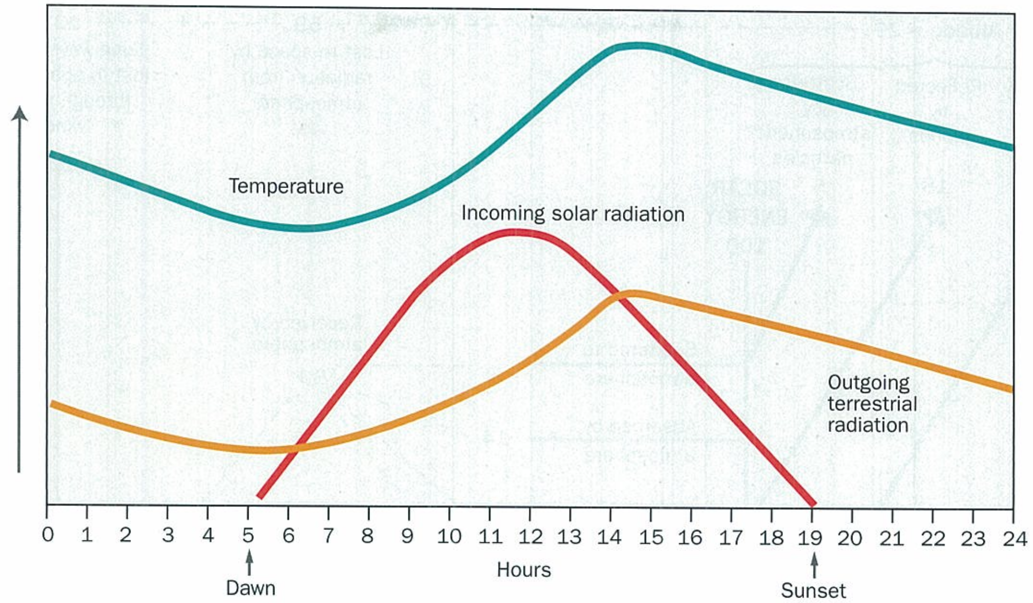


Fig. 2.10 Multiple line graph showing the influence of solar and terrestrial radiation on temperature during a day in mid-latitudes

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

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

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

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

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

The global energy budget

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

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

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

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

Table 2.4 The energy budget of the atmosphere

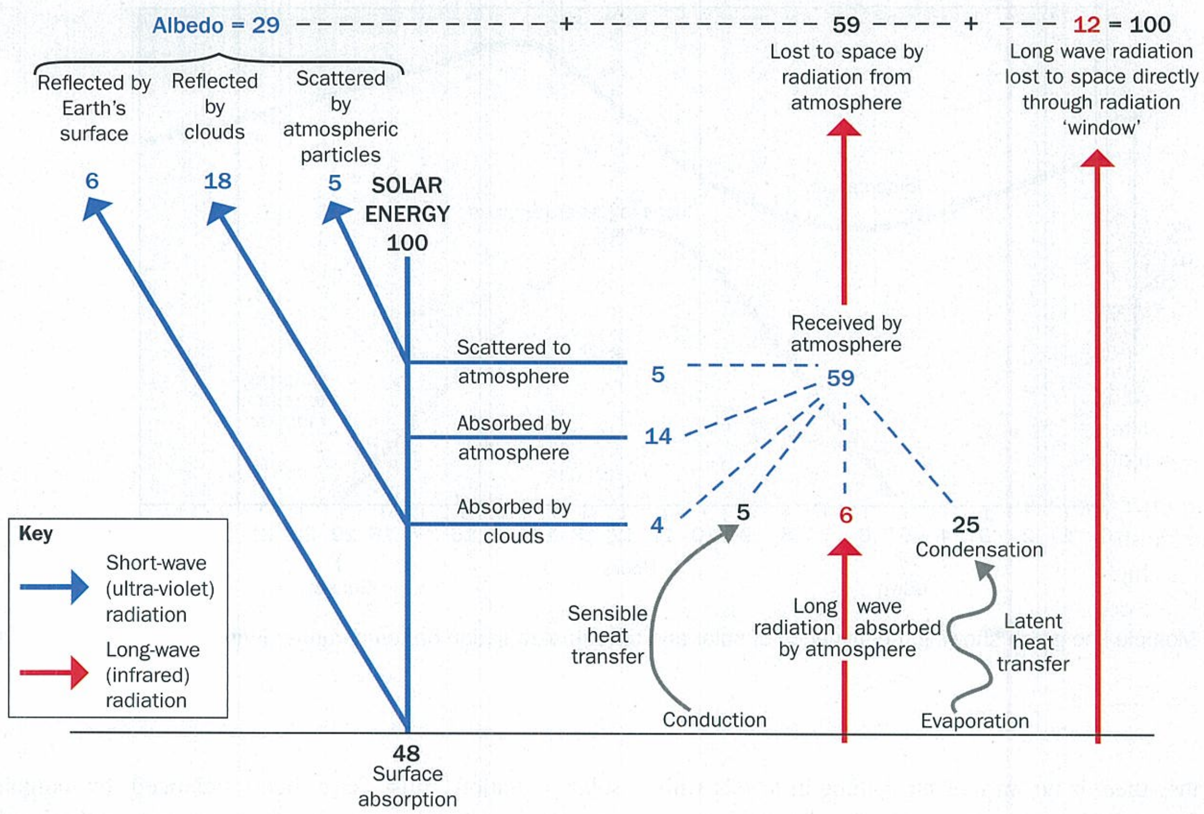


Fig. 2.11 The global energy budget (estimated figures)

As 59 per cent of the received solar radiation is radiated by the atmosphere to space while the surface of the Earth radiates only 12 per cent to space, most cooling by radiation occurs in the atmosphere and most radiative heating occurs at the Earth's surface. Energy is constantly being transferred around the Earth-atmosphere system for this to happen.

If the gases in the atmosphere did not absorb long-wave radiation, the surface temperature of the Earth would be up to 40 °C lower.

6. Produce a detailed key for Fig. 2.12 to explain the higher or lower albedo levels at (a) to (d).

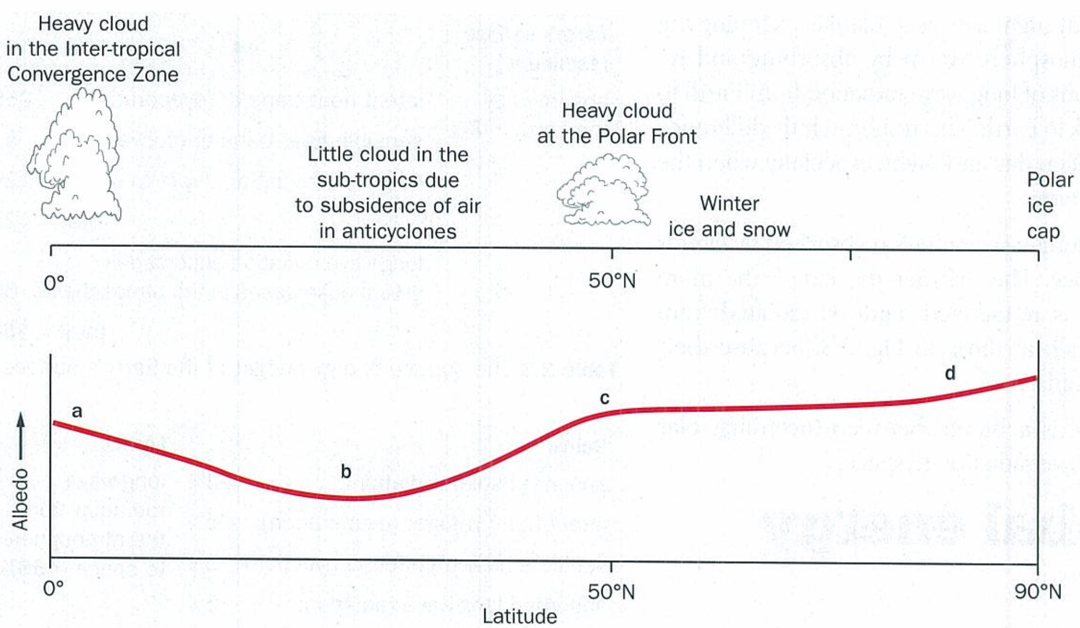


Fig. 2.12 The generalised pattern of albedo in the northern hemisphere

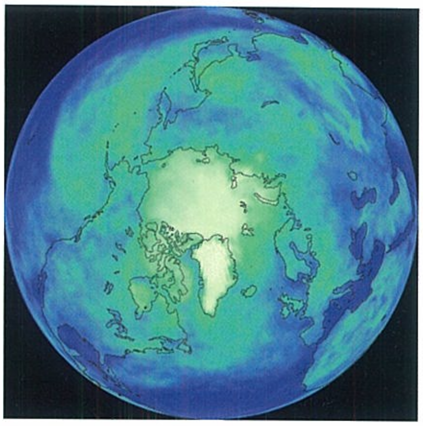


Fig. 2.13 Satellite image of reflected short-wave radiation in the polar region of the northern hemisphere in June 2009

On this summer image (Fig. 2.13), the white areas are the Greenland ice sheet and sea ice in the Arctic Ocean where reflectivity is highest (reaching 425 W/m²). Green areas have moderate reflectivity (about 212 W/m²), from snow on the ground in Eurasia and northern Canada. The darker land and ocean surfaces, shown in blue, have lower albedos so are absorbing more of the summer sun and warming.

The latitudinal pattern of radiation: excesses and deficits

7. Describe the variations in average annual solar radiation measured at the Earth's surface by detailing areas where it is highest at over 225 W/m² and areas where it is lower than 150 W/m². To what extent is the influence of latitude shown?

8. Suggest why total insolation received in the southern hemisphere at any latitude is lower than it is in the northern hemisphere.

Case study: Components of the energy budgets that influence the temperatures in Equatorial regions and hot deserts

	Equatorial regions	Hot deserts (latitude 15–30°)
Incoming solar radiation at the edge of the atmosphere	High (about 440 Watts/m² per year).	Less (about 340 Watts/m² per year).
Radiation at the Earth's surface	150–200 W/m²	250–300 W/m²
Absorption, scattering and radiation by cloud	Very high absorption and scattering by the cover of deep convective cloud in the afternoons and evenings. The high tops of the convective cloud are cold, so outgoing radiation to space is very little.	Low because it is cloudless, so the sun's rays are high intensity and outgoing long-wave radiation from the warm surface is very large.
Surface albedo	Low – tropical rain forest about 10 per cent (but shade from forest cover reduces surface temperatures).	High because soils are dry. Desert 28 per cent (rising to 40 per cent if there is sand cover).
Energy absorbed into the surface	Wet soils conduct energy down.	Little energy is transferred down into the rock or dry sand.
Sensible heat transfer	Strong uplift, especially in the daytime and early evening.	Strong uplift by day, strong conduction cooling at night and sinking of cold air from above in the high pressure zone.
Latent heat transfer	Very high because the air has a high moisture content supplied by evaporation from the many water bodies and transpiration from the forest cover.	Very low because the air is very dry.
Radiation balance	Positive, with a large difference between gains and losses.	Positive but with a smaller surplus.

Table 2.5 Energy budget differences between equatorial regions and hot deserts

The net effect of the energy budget in equatorial regions is hot temperatures all year, with daytime highs of about 30 °C dropping to 23 °C at night, giving a daily range of about 7 °C. The forest increases latent heat transfers but decreases sensible heat transfers.

By contrast, deserts have extreme diurnal (daily) temperatures all year. Daytime temperatures average about 38 °C but can reach 50 °C in summer, dropping down to about 15 °C at night and to 5 °C on winter nights.

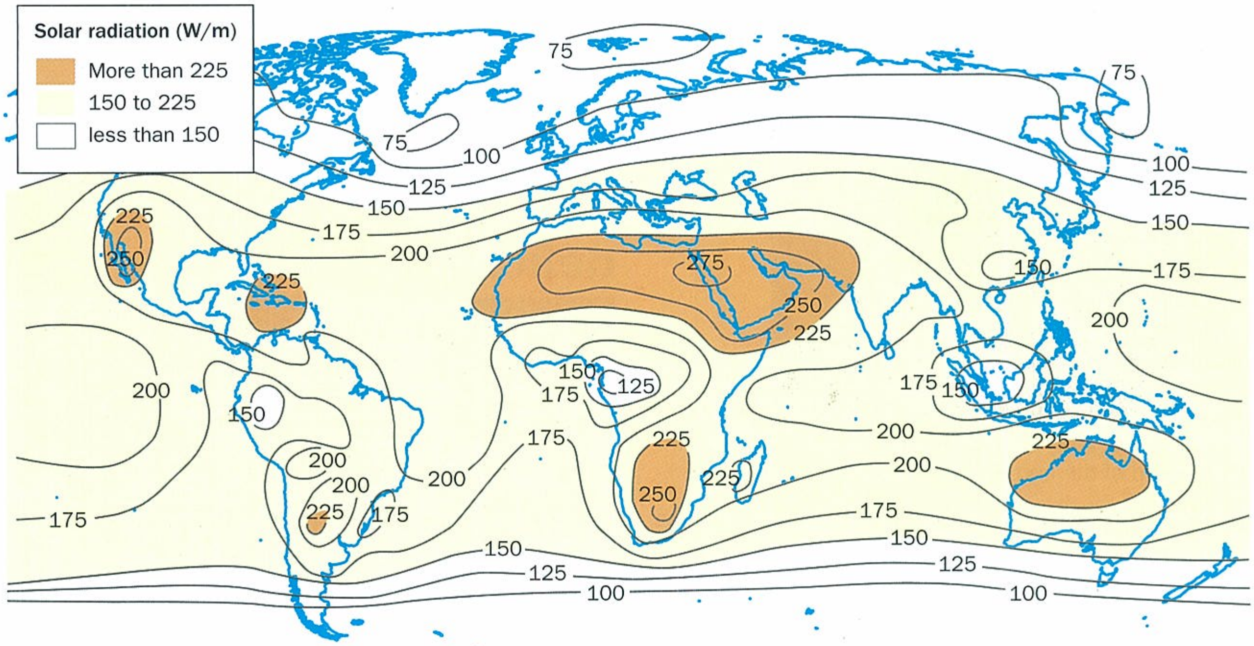


Fig. 2.14 Isoline map of the average annual distribution of solar radiation (W/m²) received at the Earth's surface

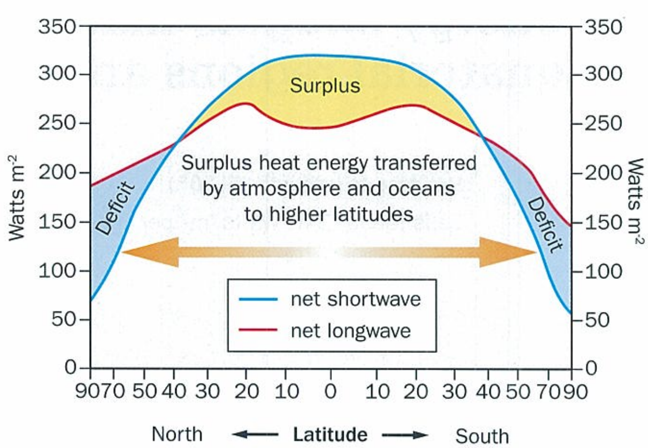


Fig. 2.15 The net radiation balance

The surplus and deficits shown in Fig. 2.15 would lead to the area between 40° and the Equator becoming increasingly warmer and the areas between 40° and the poles becoming increasingly colder if surplus heat energy from the Equator was not transferred to higher latitudes to inject warmth there. This transfer of heat is achieved by winds and ocean currents. They also move moisture.

Atmospheric transfers by wind belts

Winds are moving **air masses** - large bodies of air which are almost uniform horizontally in temperature and moisture characteristics. They are separated from adjacent different air masses by **frontal zones** along which there are usually large temperature and humidity gradients.

Air masses gain their characteristics in their source regions by prolonged contact with the ground or sea surface. Sub-tropical high pressure belts are the source regions for warm tropical air masses which undergo much heating. Heat energy is moved from these areas of surplus towards the poles by the south-westerly and north-westerly wind belts.

Source regions for polar air masses are high pressure systems over the continents. In winter the air becomes very cold by conduction cooling during contact with the cold land surface and in summer they are relatively cool. North-easterly winds in the northern hemisphere and south-easterly winds in the southern hemisphere move air towards the Equator to gain heat.

Air masses are further classified into continental or maritime according to where they formed, or were modified as they moved. A maritime track allows the lower layers of the air mass to become saturated with moisture, whereas a continental track leaves the air mass with low **humidity**. Thus, winds from the sea also transfer moisture from one place to another.

Further information about surface and upper wind transfers of heat energy is given later in the chapter.

Air mass	Temperature	Humidity
Equatorial maritime (mE)	warm	very moist
Tropical maritime (mT)	mild in winter warm in summer	moist
Tropical continental (cT)	very warm	dry
Polar maritime (mP)	cool	moist
Polar continental (cP)	cold	dry
Continental Arctic and Antarctic (cA and cAA)	very cold	very dry

Table 2.6 Characteristics of air masses

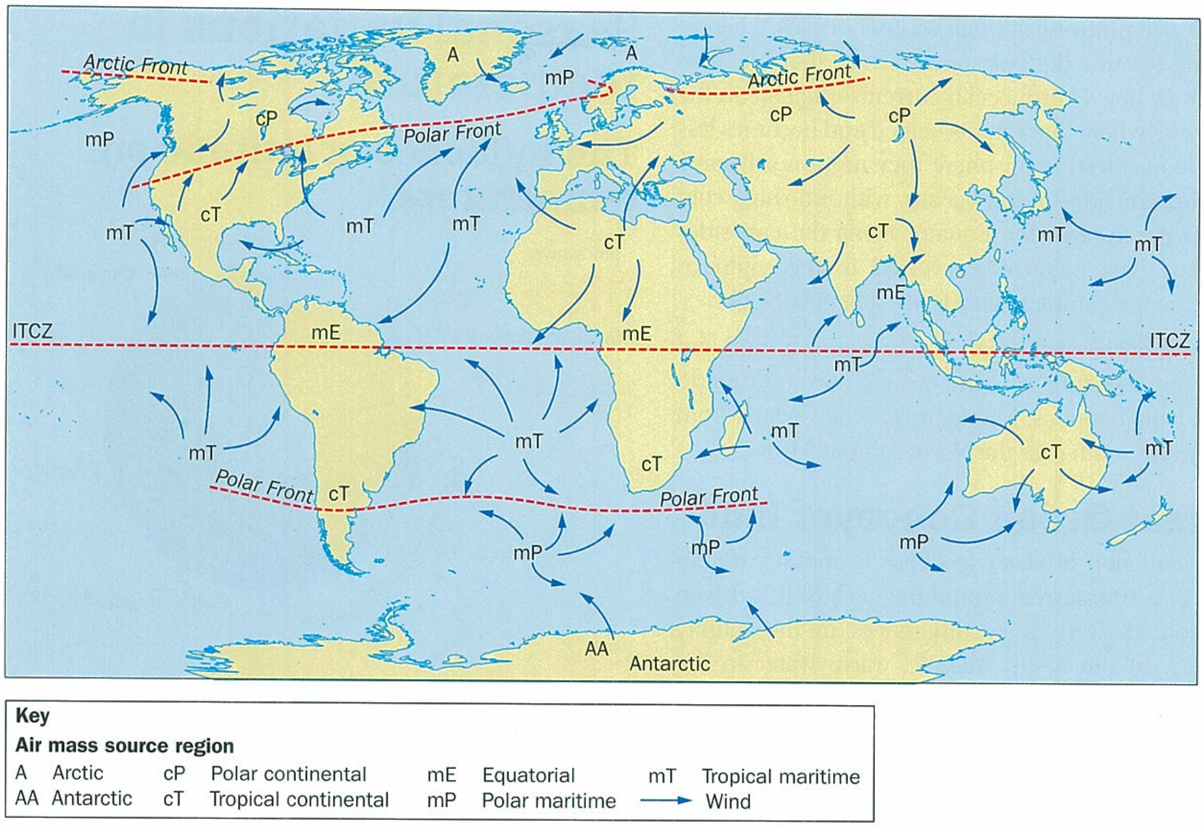


Fig. 2.16 Winds moving from air mass source regions

Atmospheric transfers by ocean current

Ocean currents are mainly driven by prevailing surface winds and are another mechanism by which surplus heat energy in the tropics is distributed to higher latitudes. Warm currents transfer 20 per cent of the energy compared with the 80 per cent transferred by winds.

The pattern of surface ocean currents in January and July are similar. Ocean currents moving towards the Equator are

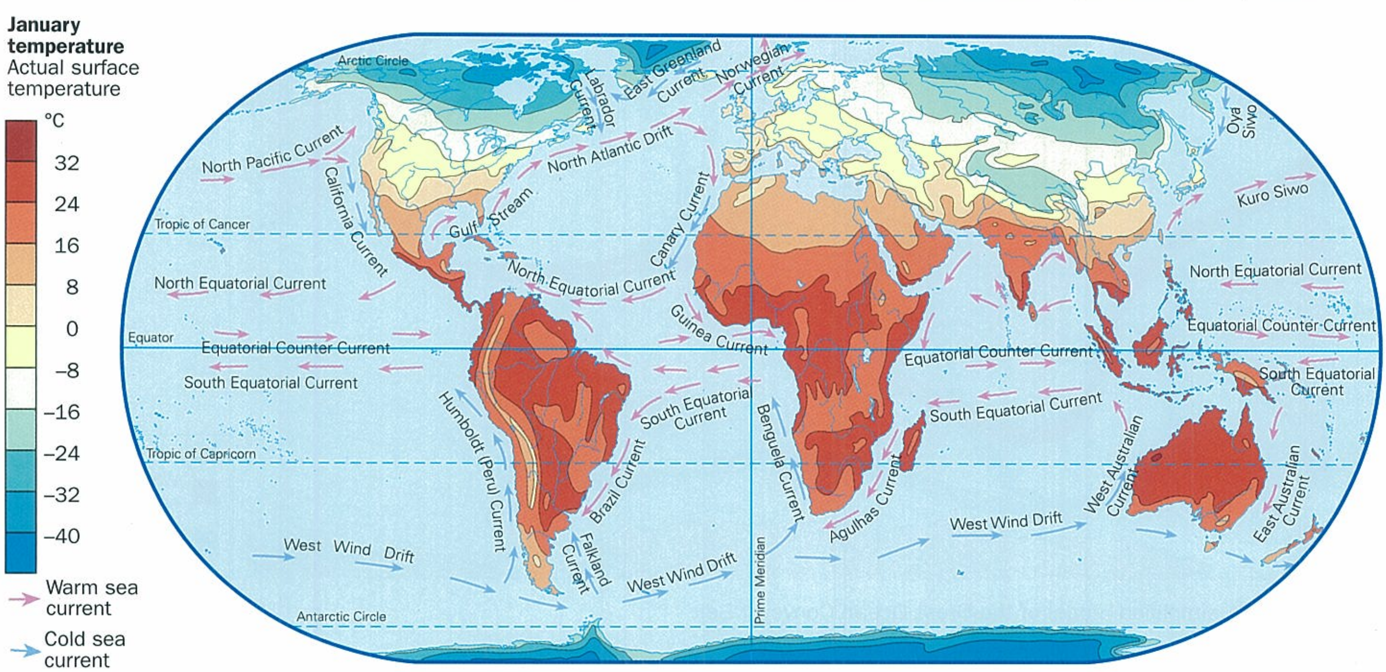


Fig. 2.17 Temperature and ocean currents in January

cold flows of water moving through warmer oceans, whereas those flowing towards the poles are warmer than the seas into which they flow. Warm ocean currents originate in the equatorial zone where the water is heated and becomes less dense. In the northern hemisphere they move northwards along the western sides of the oceans, with returning cold currents moving towards the Equator along the east sides of the oceans. The pattern is reversed in the southern hemisphere, so the complete flow is like a figure of eight.

Winds moving over warm ocean currents are warmed and gain increased moisture content, which they transfer to other areas. This happens, for example, when winds from Greenland move south over the North Atlantic Drift.

The Great Ocean Conveyor Belt

This slow circulation of water at depth is another way in which energy is transferred around the oceans. It is driven by convection, as well as by differences in the salinity of the waters. In the North Atlantic, warm water in the North Atlantic Drift heats the air. This loss of heat to the atmosphere makes the water colder and denser. Its density also increases because evaporation makes the water saltier. This cold, salty water sinks and moves towards the Equator. It flows at a depth of about 4 km to the Antarctic and then into the Pacific Ocean. By the time it reaches the north Pacific it has warmed enough to rise back to the surface. The warm water then moves into the Indian and Atlantic Oceans as a surface current, until it completes the conveyor belt and sinks again in the North Atlantic.

Seasonal variations in temperature

The influence of latitude on temperature

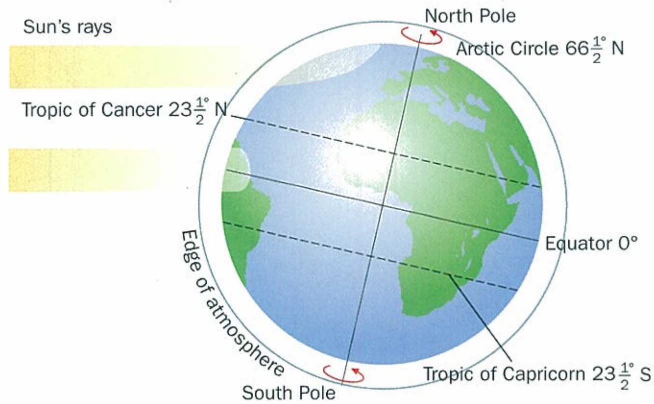


Fig. 2.19 The influence of latitude on temperature

Angle of the sun's rays

At the Equator the sun's rays are vertical, or nearly so, all year at noon. Insolation is intense because a given amount of solar radiation heats a relatively small part of the Earth's surface. Towards the poles the sun's rays strike the surface at increasingly lower angles, increasing the area heated by the same amount of solar radiation and reducing the intensity of the insolation and temperatures.

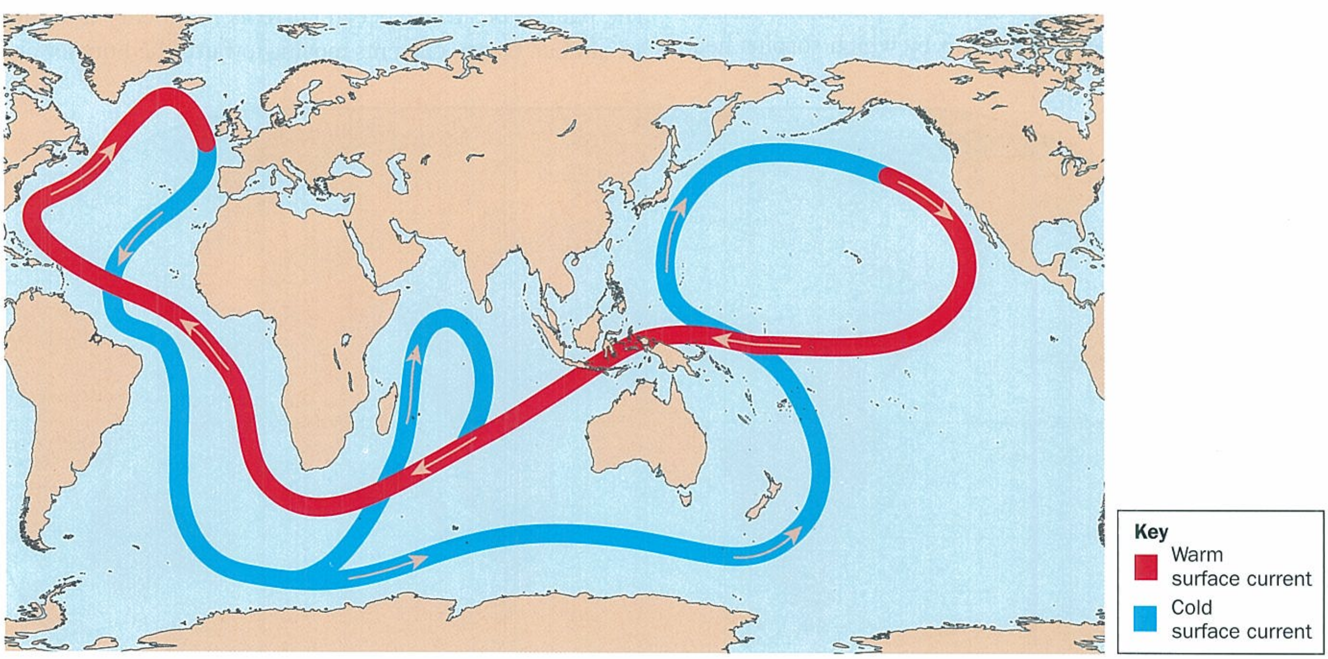


Fig. 2.18 A simplified model of the Great Ocean Conveyor Belt

Thickness of atmosphere

The higher the latitude, the greater the thickness of atmosphere though which the sun's rays have to pass. Consequently, absorption, scattering and reflection of solar radiation increase with increased latitude (except in the polar region where the air is clean and contains very little water vapour).

If latitude was the only influence on temperature, the world would be hottest at the Equator and become progressively colder towards the poles. This is not the case.

Mean Sea Level Temperatures (°C) – January

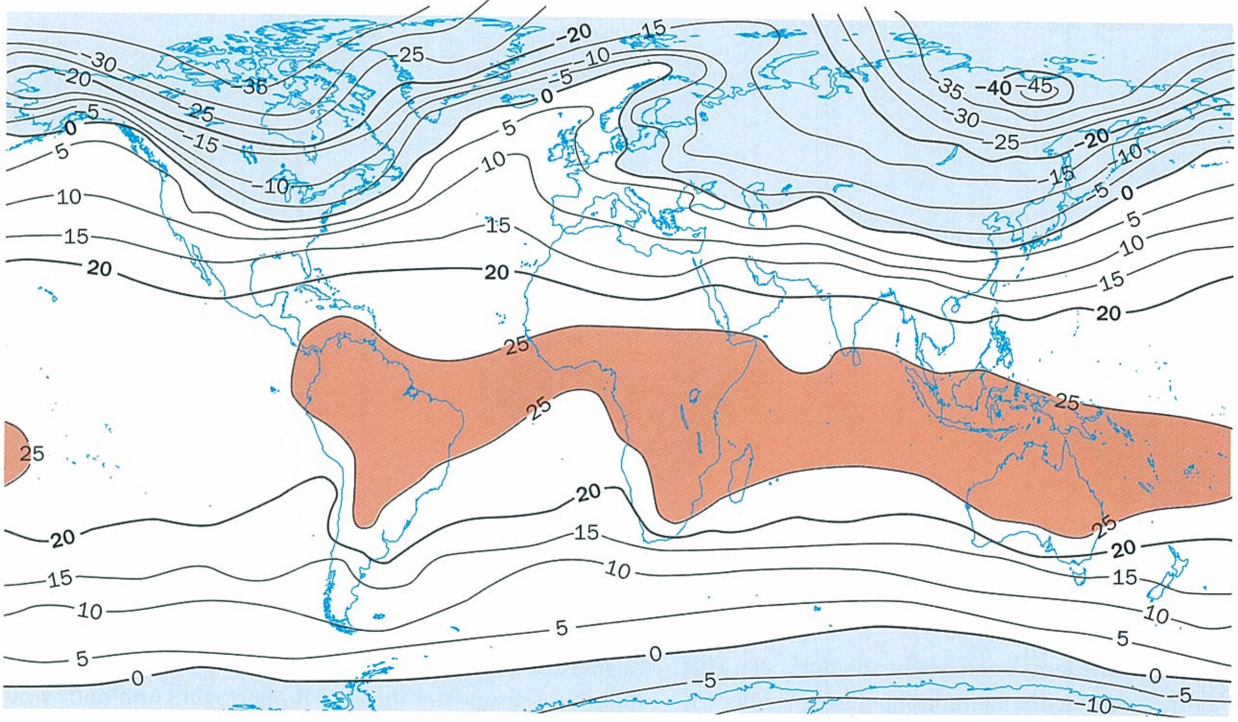


Fig. 2.20 Isotherm map showing the global pattern of temperatures in January

Key to Figs 2.20 and 2.21

- Above 25 °C
- 0–25 °C
- Below 0 °C

Mean Sea Level Temperatures (°C) – July

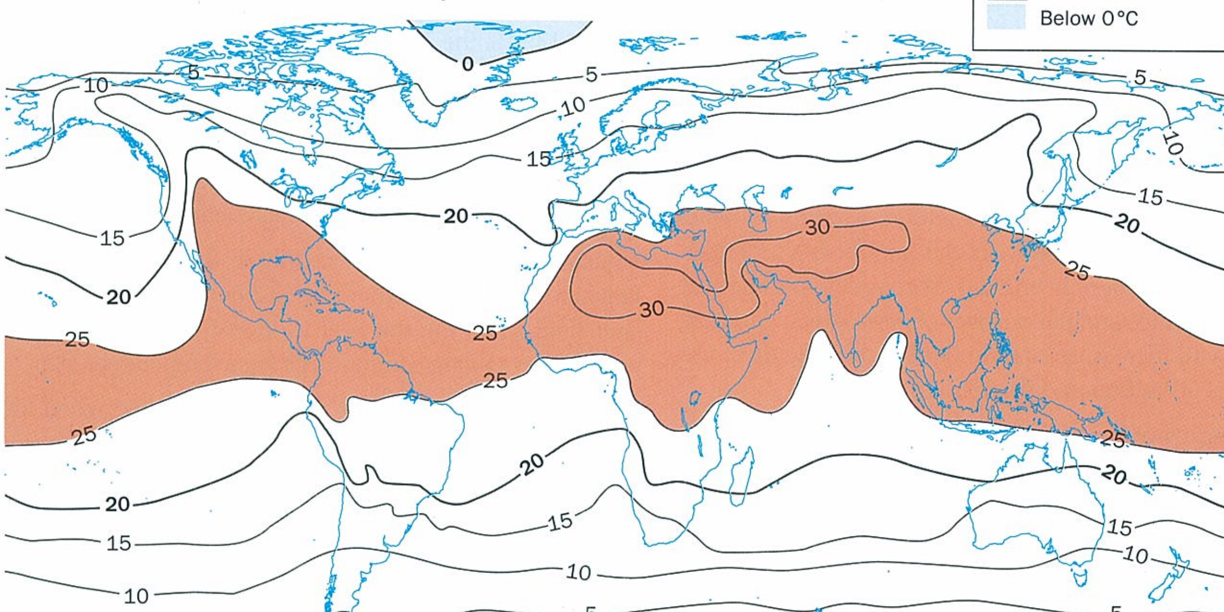
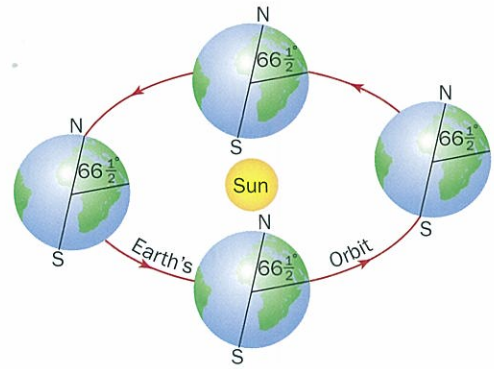


Fig. 2.21 Isotherm map showing the global pattern of temperatures in July

9. Describe how the temperature pattern in January (Fig. 2.20) shows the influence of latitude and comment on ways in which the pattern is distorted by the distribution of land and sea.

10 Describe, with reasons, how the July temperature pattern (Fig. 2.21) differs from that of January.



Lengths of daylight and darkness and seasons

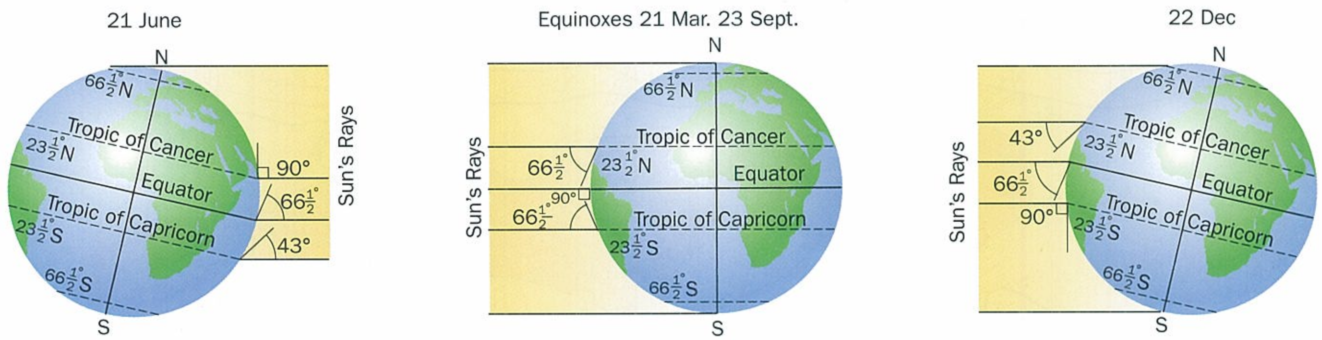


Fig. 2.22 The orbit of the Earth round the sun causes varying angles of the noonday sun on different dates in the year

Latitude influences the length of daylight and darkness. This alters the temperature in mid-latitudes but has little effect in equatorial regions where there are twelve hours daylight and twelve hours darkness all year. Lengths of daylight increase towards the pole in the summer hemisphere that is tilted towards the sun, until at latitude 66½° there is one day with 24 hours of daylight at the summer **solstice**. The number of days of total daylight continues to increase to the pole, which has six continuous months of daylight. However, the angle of the sun is so low there that it has little heating power.

Meanwhile, in the other hemisphere, the Earth is tilted away from the sun and it is the winter season. Towards the pole, the days become increasingly shorter and the nights longer. At latitude 66½° there is one day of complete darkness at the winter solstice and the number of days of total darkness increase with increasing latitude until at the pole there are six months of continuous darkness.

At the **equinoxes** (21 March and 23 September) all latitudes are bisected equally by the circle of solar illumination, so all have twelve hours daylight and twelve hours darkness. However, the mean annual **thermal Equator** (the zone of maximum heating) is at latitude 5°N, not the Equator, because of the greater heating of the northern hemisphere continents.

The position of the overhead sun changes with the seasons because the Earth orbits the sun with its axis at an angle of 23½° to the plane of orbit. The sun is never overhead further north than 23½°N or further south than 23½°S. In different seasons the thermal Equator, pressure and wind belts shift slightly in the direction of the position of the overhead sun.

The sun is overhead at 23½°N, the Tropic of Cancer, on 21 June (summer solstice for the northern hemisphere) and at 23½°S, the Tropic of Capricorn, on 22 December (summer solstice for the southern hemisphere), so it might be expected that these months would be the hottest for those hemispheres. They are not. The hottest months are July and January respectively, a month later, because there is a temperature lag as the ground heat builds up.

Similarly, in the northern hemisphere, the coolest month is January, and in the southern hemisphere it is July, a month later than when the sun is at its lowest in the sky at noon because net cooling continues, giving a temperature lag.

For any latitude, summer is the warmest period when the noonday sun is at its highest angle in the sky and winter is the coldest period when it is at its lowest angle. There are no seasons based on temperature in equatorial regions.

11. Use Figs 2.24a and 2.24b to compare the locations with the highest radiation gains in January and July. Explain why these locations have the greatest gains.

12. Compare the areas with the greatest loss in January and July. Explain their locations.

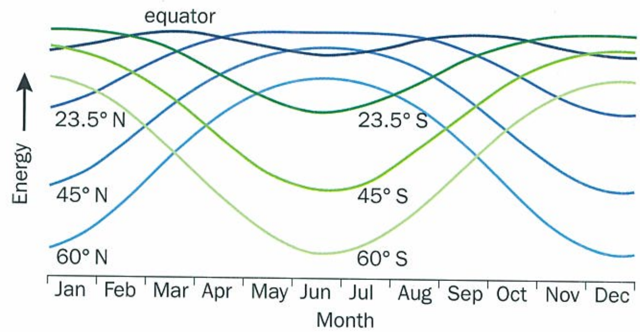


Fig. 2.23 Multiple line graph showing how solar energy received at noon varies with latitude during a year

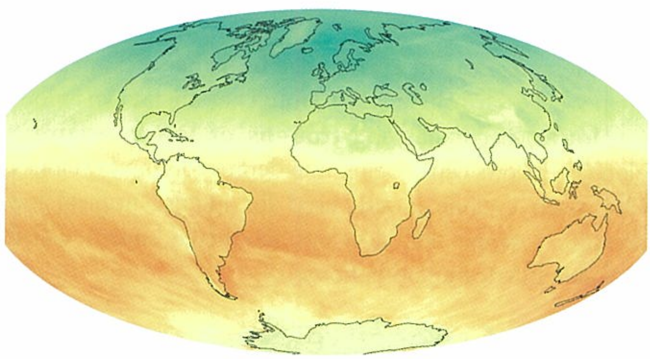
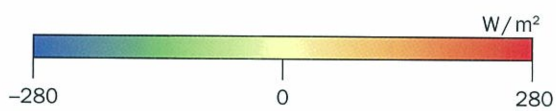


Fig. 2.24a Image of net radiation in January compiled from satellite data



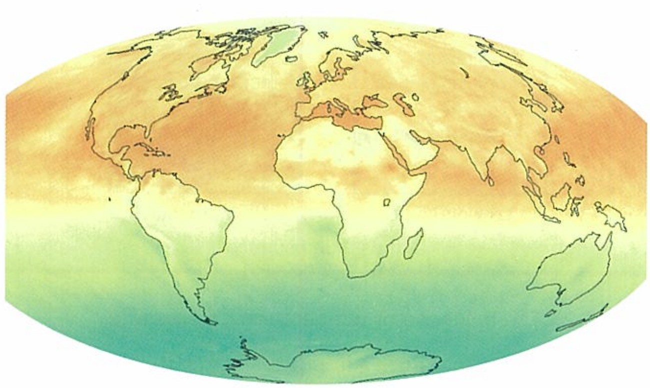


Fig. 2.24b Image of net radiation in July compiled from satellite data

In the tropics there is a net gain. In the middle and high latitudes of the southern hemisphere, lines of constant albedo and outgoing radiation are parallel to lines of latitude but this is not so in the northern hemisphere where differences between land and sea are clear. In middle to high northern latitudes in July there is greater outgoing long-wave radiation over the continents, which are warmer but albedo is greater over the oceans because of their greater cloud cover.

The influence of the distribution of land and sea

Land	Sea
Lower reflectivity (except when covered by ice and snow), so most radiation is absorbed.	Higher reflectivity, especially when the sun is low, so the sea absorbs less energy.
Heat is confined to near the surface because most surfaces are poor conductors of energy.	The sun's rays can penetrate deeper and convection currents in the sea also distribute the heat to greater depths.
Land has a low specific heat, so a certain amount of heating will raise the temperature of land much more.	The sea has a high specific heat, so the same amount of heating will raise the temperature of water less.
Little energy is used up in evaporation as there is less water.	Large amounts of energy are used in evaporation, especially in lower latitudes.

Table 2.7 Factors resulting in the differential cooling and heating of land and sea

Land heats and cools much more quickly than the sea which, like all water bodies, retains its heat for longer. Places near the sea have equable temperatures, with cooler summers and warmer winters than places inland. Small temperature ranges are typical of **maritime climates** where temperatures are moderated by proximity to the sea, while very large temperature ranges characterise **continental climates** with their seasonal temperature extremes.

The effects of continentality are especially marked in the northern hemisphere where large land masses stretch into high latitudes. In north-east Siberia annual temperature ranges are more than 60 °C. Verkoyansk, 67 °N, is the 'cold pole' of the Earth. It recorded a temperature of -68 °C in February 1982. Its long-term February mean is -45 °C and the July mean, its warmest month, is 14 °C, so its annual range is 59 °C. Fig. 2.25 shows the increase in annual temperature ranges eastwards from the Atlantic Ocean coast to the heart of Eurasia.

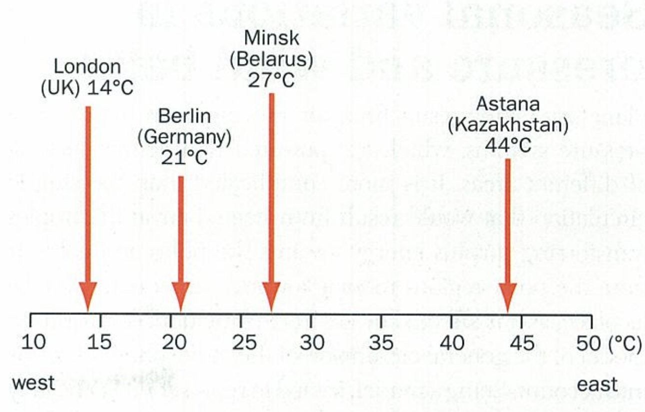


Fig. 2.25 Changes in annual temperature range along (or close to) 52½ °N

Winds are involved in sensible heat transfer. Warm winds move towards the poles, transferring heat to higher latitudes; cold winds move cooler air towards the Equator. The **prevailing wind** (most frequent wind) will influence the temperature of a place more than any other wind. The south-westerlies are Europe's prevailing winds and, as their source is the warmer ocean in winter, they bring warm air to make coastal western Europe's winter temperatures about 11 °C warmer than average for the latitude. By contrast, in the same latitudes, eastern Canada's prevailing winter winds are from the north-west and bring bitterly cold Arctic air over the area, resulting in January temperatures being at least 2 °C lower than average for the latitude.

The influence of ocean currents

Ocean currents change the sea temperatures and the temperatures of the air above them but can only affect temperatures on nearby land if an onshore wind blows over them.

13 How do the isotherms on Figs 2.20 and 2.21 indicate the influence of the Humboldt (Peruvian) and Benguela currents off the west coasts of South America and Africa?

14. Use information on Fig. 2.17 (influence of ocean currents) to explain the northwards curves in the isotherms over the northern hemisphere oceans in January, as shown on Fig. 2.20.

The influence of altitude

Air temperature decreases as altitude increases because the air becomes thinner and contains less water vapour to absorb the Earth's long-wave radiation, so at night there is very rapid heat loss. During the day, rock surfaces in the sun become very warm because almost all the insolation reaches the ground. The rate of decrease in temperature with altitude in *still* air varies but averages about 0.65°C for every 100 metres.

Seasonal variations in pressure and wind belts

Planetary winds result from air moving from high to low pressure systems, which are powered by unequal heating of different areas. It is more complicated than the simple circulation that would result from heated air at the tropics transferring surplus energy towards the poles and cold air from the polar regions moving towards the Equator to take its place, as it is affected by the Earth's rotation. A tri-cellular model of the general circulation of the atmosphere took this into account. Being a model, it tried to represent what usually happens, but there are areas where, and times when, it does not fit reality. In order to understand the model, knowledge of both the influences on pressure and on winds is necessary.

Seasonal variations in pressure

Pressure is the weight of the atmosphere and varies with height. Pressure maps usually show the pressure that is exerted at the Earth's surface reduced to sea level. Average pressure is 1013 millibars (mb) at sea level at latitude 45°. Pressure is always reduced to sea level because, if not, a pressure map would be like an inverted relief map - as there is less air in a column of air above a mountain than above the adjacent plain, so it would weigh less. Pressure on maps is shown by **isobars** (lines of equal pressure reduced to sea level). High pressure areas are surrounded by lower pressure and are not necessarily above 1013 mb. They are known as **anticyclones** if fairly circular or **ridges of high pressure** if they are elongated.

Low pressure areas are surrounded by higher pressures, and are not necessarily below 1013 mb. They are known as lows (**cyclones**) if circular and **troughs of low pressure** if elongated. Lows can develop into depressions and cyclones. (The term cyclone is also used for intense tropical low pressure systems that develop into fierce storms called cyclones, hurricanes or typhoons.)

Types of pressure change

Thermal pressure changes

When air is heated, it expands and becomes lighter than an equal column of cooler, heavier air because there is less air in the column.

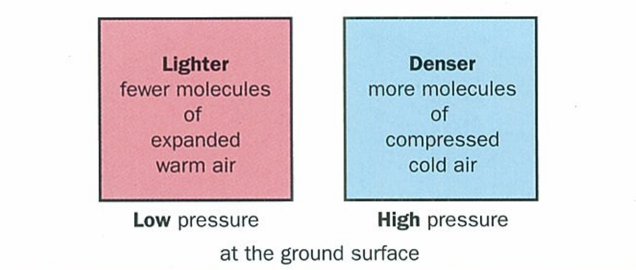


Fig. 2.26 The influence of temperature on pressure

Changes in temperature alter pressure at the surface; air pressure falls when its temperature rises and air pressure rises when its temperature falls.

Dynamic pressure change

If a glass of liquid is spun, **centrifugal force** sends the liquid to the sides and reduces the pressure in the centre. Pressure at the sides is increased and so is frictional drag. This type of pressure change affects winds because of the rotating earth. As the earth rotates, the atmosphere rotates with it but is also able to move freely. The shape of the Earth causes angular momentum to change with latitude. It depends on the distance from the axis of rotation of the Earth (a line between the two poles). Air moving towards the poles is getting closer to the axis of rotation so it speeds up (e.g. in the **jet streams**) while air moving towards the Equator slows down because it is getting further from the axis of rotation.

15. Explain why the permanent low pressure along the Equator and the permanent high pressure at the poles are thermally induced.

Seasonal variations in wind belts

Pressure and the pressure gradient force

High pressure areas have outflowing winds and low pressure areas have in-blowing winds. The speed of the air movement is determined by the pressure gradient - the difference between the high and low pressure systems. If the difference is great, the pressure gradient is high and the wind will be strong. Little difference results in weak winds. The pressure gradient is steep if isobars are close together and gentle if they are far apart.

The force of gravity

The wind will stay close to the ground if the pressure gradient force is balanced by gravity.

The Coriolis force

The rotation of the Earth causes an *apparent* deflection of wind direction. (The wind is actually blowing straight but its path when plotted on a map is a curve.)

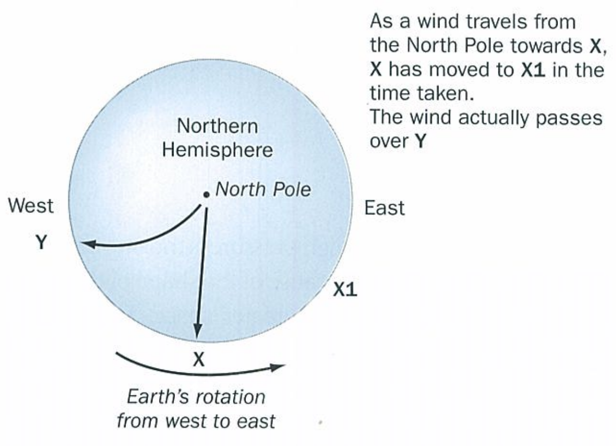


Fig. 2.27 The effect of the Coriolis force on wind direction

This effect is summarised by **Ferrel's Law,** which states that any moving body in the northern hemisphere will be deflected to its right and any moving body in the southern hemisphere will be deflected to its left, as shown on Fig. 2.27.

Fig. 2.28 shows the situation on an isobar map for the northern hemisphere. The wind cannot go on constantly curving because air can't flow from low to high pressure so, once it has started to flow parallel to the isobars, the effect of the pressure gradient force is balanced by the Coriolis force and the wind flows parallel to the isobars (provided there is no surface friction). It is then known as a **geostrophic wind**. Winds in the upper troposphere, such as the upper westerlies, are geostrophic.

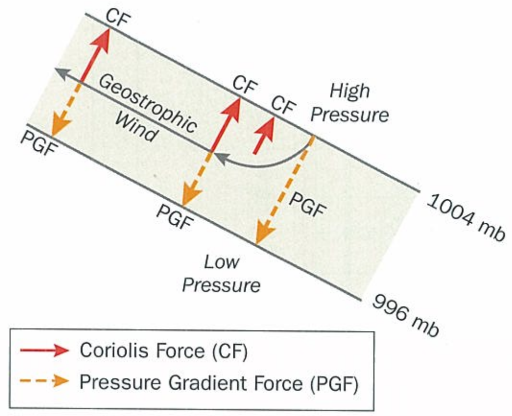


Fig. 2.28 Geostrophic wind

The force of friction

Winds near the surface lose energy and speed because of friction. This reduces the geostrophic force, so the pressure gradient force is no longer balanced by the Coriolis force. Friction causes the wind to blow across the isobars at an angle towards low pressure.

The global pattern of pressure and winds

The tri-cellular model shown in Fig. 2.29 demonstrates how warm air from the tropics could be transferred by an indirect route to add warmth to areas of insolation deficit, whilst these polar areas in turn send colder air back to replace the air from the tropics.

The Hadley cells

These low latitude circulations of air between the Equator and 30° of latitude in each hemisphere are the direct result of thermal differences. Insolation is intense at the warmest part of the Earth's surface (the thermal Equator). Air in contact with the hot land is warmed and rises, creating the permanent equatorial low pressure belt (doldrums). **Trade winds** are drawn into this low pressure belt and meet at the ITCZ (inter-tropical convergence zone). Beneath this zone of rising air, surface winds are light and variable.

Moist air, warmed in the ITCZ, rises in strong convection currents. As the air cools and the water vapour condenses, a lot of latent heat is released which is converted into potential energy and transferred in upper troposphere winds towards the poles. As the air travels towards the poles,

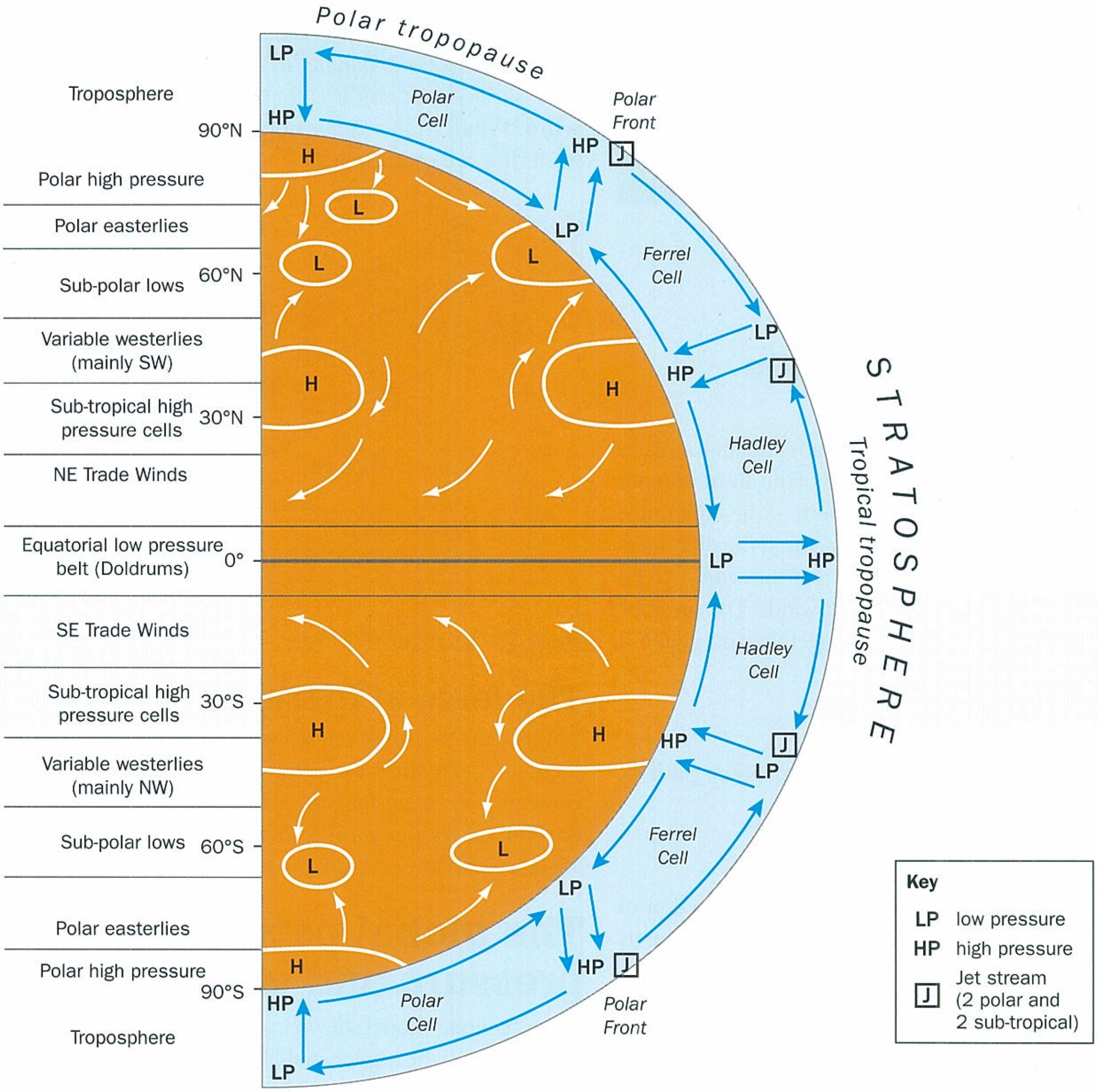


Fig. 2.29 The tri-cellular model of the Earth's atmospheric circulation

it is increasingly deflected to the right or left depending on which hemisphere it is in until, by the time it reaches 30 °N and S, it is strongly under the influence of the Coriolis force, and no longer travels towards the poles much. The air accumulates in the upper troposphere and moves eastwards as the sub-tropical jet streams. Air subsides at 30 °N and S beneath the sub-tropical jet streams, causing sub-tropical high pressure cells at the surface. The trade winds blow down the pressure gradient between these sub-tropical high pressure cells and the equatorial low pressure belt to complete the Hadley cell.

The polar cells

These are also directly thermally induced. Polar air, chilled over the ice caps, subsides to produce high pressure at the surface and then moves into temperate latitudes. The air moving away from the polar high pressure is moving into areas of increasingly wider space because of the shape of the Earth, so it spreads out to occupy the greater space. This reduces its pressure, causing low pressure belts at 50° to 60° north and south. In theory, some of the warmed air rises at these latitudes along the polar fronts and moves towards the poles to be chilled and sink over the polar ice caps to complete the cell. These theoretical upper-air south-easterlies do not occur; instead upper westerlies circulate in high latitudes.

The Ferrel cells

These cells are not directly thermally induced but are consequences of the adjacent thermally induced cells. Some of the air that sinks in the sub-tropical high pressure belts moves towards the sub-polar low pressure belts where it meets the colder air from the polar cell moving towards the equator. The surface between these two air masses is known as the **polar front** and is the boundary between the polar and Ferrel cells. Here the warmer air rises up the frontal surface to the tropopause where, according to the model, it moves back towards the Equator to complete the cell by sinking again in the sub-tropical high pressure zones.

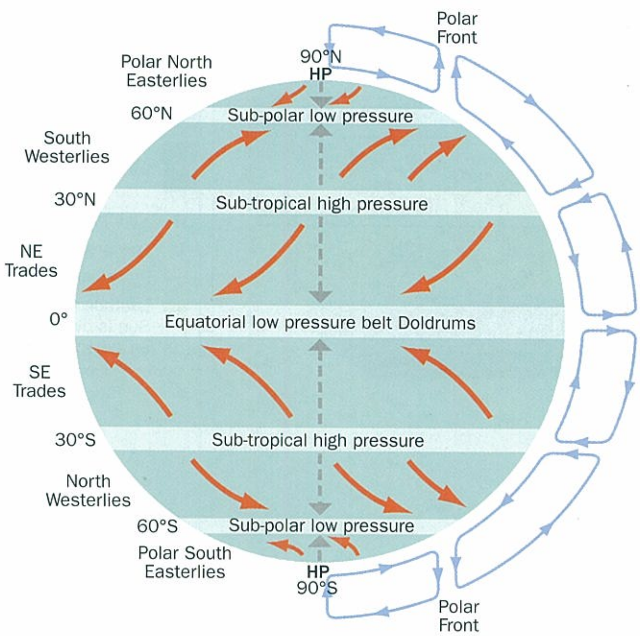


Fig. 2.30 Model of pressure belts and surface planetary winds at the Equinoxes

Fig. 2.30 shows the winds that would result from a tri-cellular model if the only other influences on them were the pressure gradient and Coriolis forces, with the winds moving from high to low pressure and being deflected to the right in the northern hemisphere and to the left in the southern hemisphere. It shows the situation at the Equinoxes when the sun is overhead at the Equator. Actual pressure and wind belts show several deviations from this model. They move further south in the southern hemisphere summer and further north in the northern hemisphere summer.

16. To what extent can you recognise the planetary wind belts, shown in the model on Fig. 2.30, on the map of the actual winds that blow over the Earth in Fig. 2.31?

17. Identify two major pressure systems in January that do not match the tri-cellular model, even after allowing for a slight southern shift expected then. How do they influence the actual wind pattern to make it differ from the model of planetary winds?

18. (a) Explain the thermal low pressure over northern India, shown on Fig. 2.32.

(b) Explain why there are no thermal high pressures over the southern hemisphere continents, although it is the winter season there in July.

Surface winds are only part of the general circulation of the atmosphere; upper air movements are also involved in the transfer of energy round the world.

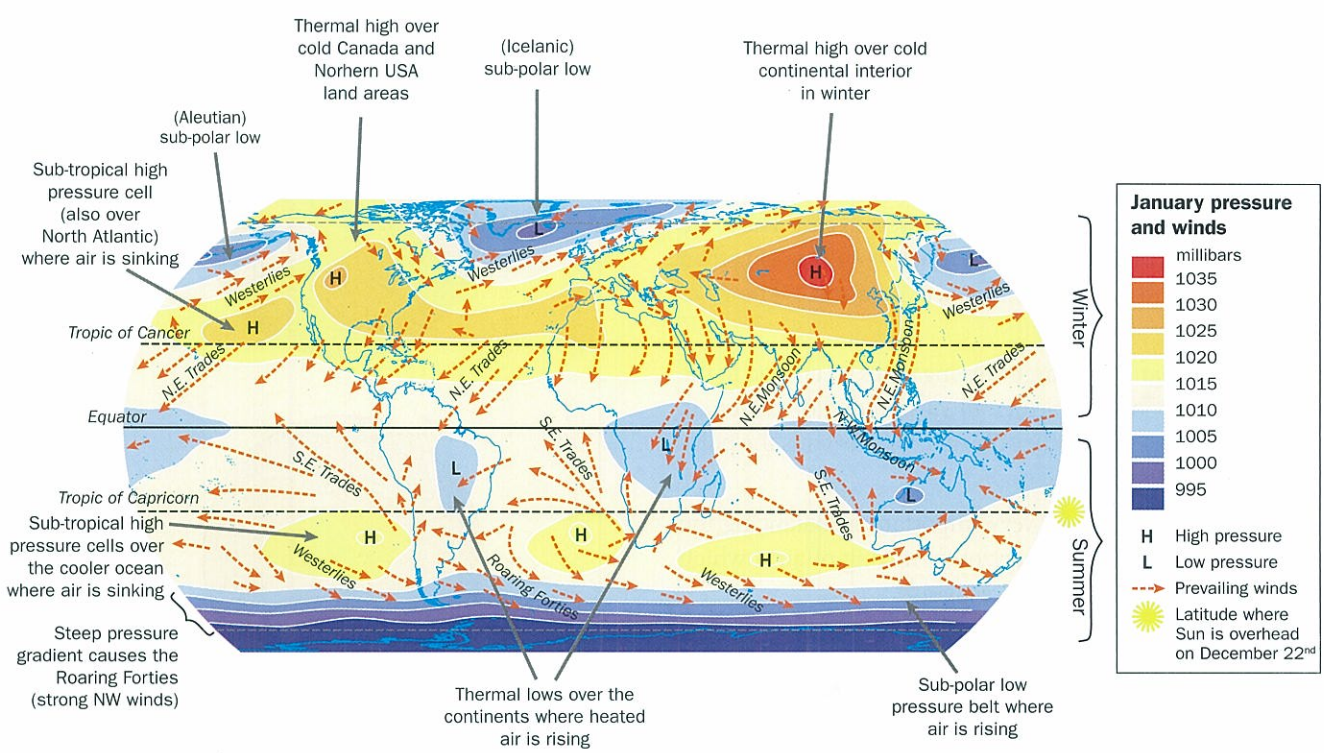


Fig. 2.31 Isobar map of surface pressure belts and their influence on winds in January

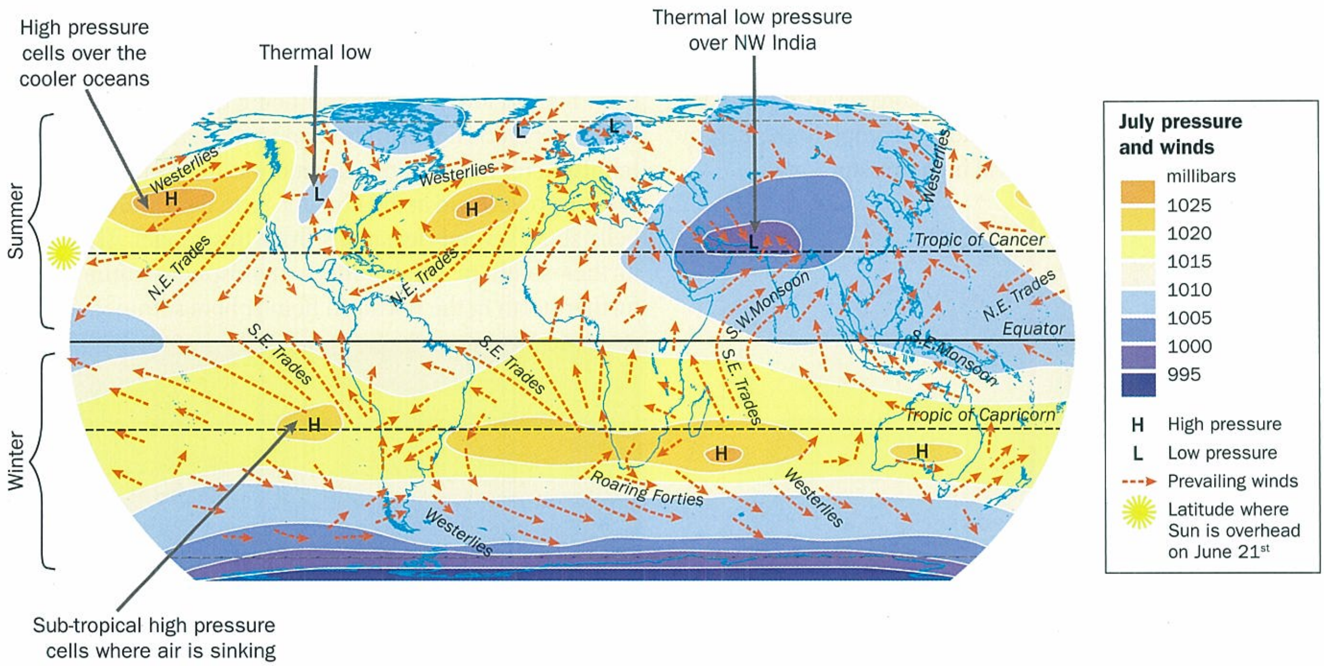


Fig. 2.32 Isobar map of surface pressure belts and their influence on winds in July

The upper westerlies and Rossby waves

These are fast moving westerly winds at a high level between latitudes 30° and 50° that result from:

- a very strong north to south temperature gradient which causes a very strong pressure gradient in temperate latitudes
- the Coriolis force increasing as the air flows towards the poles, causing the air to take a path towards the east and become geostrophic.

Sometimes the upper westerlies only deviate a little from a west to east path but they can have three to six waves in each hemisphere which move slowly from west to east. These are known as **Rossby waves** and are much slower-moving than the air flowing through them which, at its fastest, is known as a jet stream.

When they meander in large curving paths it can lead to the separation of 'pools' of warmer air surrounded by colder air, or vice versa. In this way they transfer heat towards the poles and cooler air towards the tropics.

The upper westerlies are very important in balancing the Earth's energy budget by horizontal mixing of air - which the tri-cellular model did not recognise.

Rossby waves may be caused by a disturbance in the airflow. When the upper westerlies cross a very high mountain range, such as the Rocky Mountains or the Tibetan Plateau, the vertical column of eastwards flowing air is compressed to cross the high ground. As a result it is thrown frequently into wave troughs over north-eastern North America and eastern

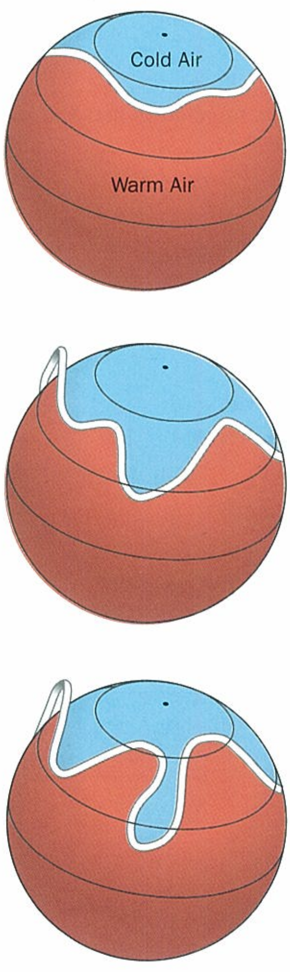


Fig. 2.33 The growth of a wave trough in the upper westerlies of the northern hemisphere until just before a pool of cold air is cut off to be mixed with warmer air. The growth of a ridge towards the north can cut off a pool of warm air in the same way

Siberia. This is especially so in winter when the cold of the continental interiors intensifies them, whereas ridges form over the warmer oceans.

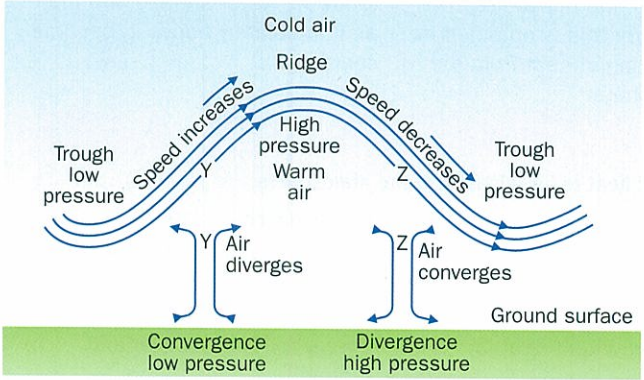


Fig. 2.34 The relationship between Rossby waves and pressure systems at the ground surface. The diagram combines a plan of a Rossby wave and vertical sections of airflow at points Y and Z

Ridges and troughs in the upper westerlies are closely linked to air movements and pressures at the surface. When there is a high pressure ridge in the upper airflow there is a low pressure trough at the surface and vice versa. This is because as the air flows towards the poles, it speeds up and divergence occurs. Then, as the air turns to move towards the Equator it slows, the air piles up, and convergence occurs. This leads to convergence and divergence at the Earth's surface which, in turn, results in low pressure and high pressure respectively at the surface.

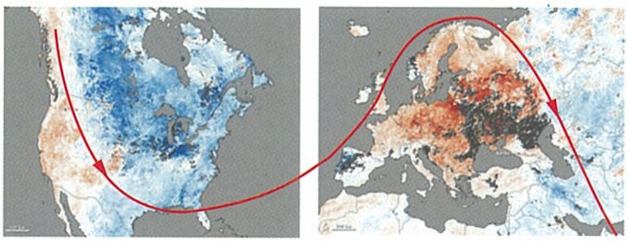


Fig. 2.35 Rossby waves superimposed on to satellite maps of resulting temperature anomalies for January 1–7 2014 in North America and Europe

The map images show how Rossby waves caused abnormal temperatures at the same time in different continents. Areas in blue had negative temperature anomalies (below the average temperatures), with the deepest blue-18 °C below average. Areas in red had positive anomalies, with the deepest red 18 °C above normal. A giant meander in the upper westerlies caused a trough to loop down over North America, allowing very cold air from the Arctic to reach much further south than usual. Temperatures were well below zero as a result. Meanwhile, the Rossby wave continued to form another giant meander creating a ridge over Europe. This brought a winter 'heat wave' with abnormally high temperatures of about 10 °C, as warm air from the south was able to move north. As a result, Russia had to provide artificial snow for the Sochi Winter Olympics, where it would normally have been well below zero in January.

Alaska experienced record-breaking warmth (some places were 22 °C above normal), as it was under the ridge of high pressure over the Pacific coast on the other side of the trough that brought the cold to continental USA. Between the trough over the USA and the ridge over Europe, the speeding limb of the ridge brought storms, heavy rain and intense flooding to western parts of the UK, which had its wettest January since records began.

Fig. 2.36 Rossby waves brought storms to the western UK in January 2014. The south-west airstream was so moist and unstable that only a small amount of orographic uplift was needed to trigger heavy cumulonimbus cloud and torrential rain

As there has not been a change in the amount of atmospheric energy circulating in the world, these weather extremes cannot be explained in that way. Research suggests that the unusual pattern of the Rossby waves in winter 2013-14 was driven by abnormally warm sea surface temperatures in the western tropical Pacific Ocean, extending along the west coast of North America into the north Pacific.

Jet streams

A jet stream is a narrow ribbon of very fast-moving air that runs through the centre of the Rossby waves. Whereas the upper westerlies travel at 50-100 km/h, the jet streams often reach speeds of 250 km/h. They are discontinuous but can be thousands of kilometres long and meander from west to east. There are two in the upper westerlies - one in each hemisphere. Jet streams are often seasonal.

Jet streams form at a high level at the polar front, at the meeting of very cold polar air with warm tropical air, where there are the greatest differences in temperature and pressure in a narrow horizontal distance. The jet stream is located in the warm air about one kilometre below the tropopause. The polar front jet streams are fastest and most frequent in winter when the temperature differences are most marked. They are very variable and can extend latitudinally from 35 °

Changes that result from an increase in temperature and cause absorption and storage of heat from the atmosphere			
Change	**Description**	**Reason**	**Consequence**
Melting	Solid to liquid (ice to water).	All involve an increase in the speed of the molecules. The energy for this is obtained by absorption of heat from the atmosphere.	The immediate surroundings (both the water surface and the air immediately above it) become cooler.
Evaporation	Liquid to gas (water to water vapour).		
Sublimation	Solid to gas (ice to water vapour).		

Table 2.8 Phase changes taking heat from the atmosphere

Changes that result from a decrease in temperature and cause latent heat to be released to the atmosphere			
Change	**Description**	**Reason**	**Consequence**
Condensation	Gas to liquid (water vapour to water).	All involve a decrease in the speed of the molecules, so less energy is required, therefore latent heat is released.	The released heat warms the surroundings. This release of heat is very important in providing energy for depressions and storms.
Freezing	Liquid to solid (water to ice crystals).		
Deposition	Gas to solid (water vapour to ice).		

Table 2.9 Phase changes adding heat to the atmosphere

to 70° in each hemisphere. They are at the lowest latitudes in the winter.

Sub-tropical jet streams occur at about 25°N and S where the Hadley cell and mid-latitude circulations meet. They are also westerly flows (moving from west to east) but do not meander as much as the sub-polar jet streams.

Weather processes and phenomena

Atmospheric moisture processes

Atmospheric moisture exists in three **phases** or states:

- *gas* – water vapour, an invisible gas, is the stable phase of moisture when temperatures are above 100°C, but it can exist at temperatures down to well below freezing point.
- *liquid* – water is the stable phase between 0°C and 100°C but exists as super-heated water above 100°C and as super-cooled water down to −40°C (it then freezes as soon as it touches ice).
- *solid* – ice is the stable phase of moisture at temperatures below 0°C.

Phase changes can occur in two ways: a change of temperature and a change in the amount of water vapour in the air.

19. Describe and explain the phase change occurring in Fig. 2.37 and the effect this has on the air temperature.

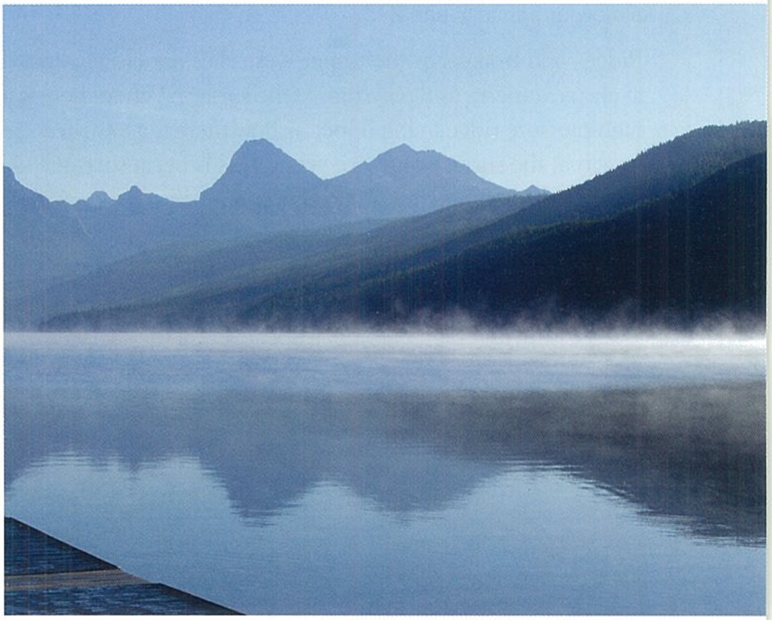


Fig. 2.37 A phase change occurring in early morning in Glacier National Park, USA

Humidity

Humidity refers to how moist the air is because of the water vapour it contains. **Absolute humidity** is the *actual* amount of water vapour in a given volume of air.

Relative humidity is more useful, as it measures how near the air is to saturation. It indicates how much water vapour the air is holding (i.e. the absolute humidity) compared with the *maximum* amount that it could hold *at that temperature and pressure.*

$$\text{Relative humidity } \% = \frac{\text{Actual moisture content} \times 100}{\text{The saturation moisture content at the same temperature and pressure}}$$

Air is saturated when it has 100 per cent relative humidity. Warm air can hold more moisture than cold air.

Evaporation

Water changes to gas when it is heated and the air is unsaturated. Rates of evaporation increase when temperatures rise and the air is very dry, conditions are calm and there is a water source available.

Condensation

Any *further* cooling *below* dew point temperature (the temperature at which the air is saturated), causes excess water vapour in the air to condense to water droplets, provided that there are **condensation nuclei** in the air for this to occur. These might be tiny dust, salt or smoke particles that form a nucleus around which condensation can begin. They are hygroscopic (have an affinity for water) and can sometimes even result in condensation in air with a relative humidity of below 100 per cent.

If the air humidity drops below saturation, the opposite will occur - the droplets will evaporate. Saturation can be attained either by the addition of water vapour into the air, as when the air moves over a warm, evaporating sea surface, or by cooling, which is the more important method.

Cooling of the air can be achieved in three ways:

1 Conduction (contact) cooling

Contact cooling leads to condensation when moist air comes into contact with a cold object whose temperature is below the dew point of the air. This may be a cold land surface which has lost heat rapidly by terrestrial radiation during a cloudless night, or a cold sea surface.

2 Radiation cooling

Air loses heat to space by long-wave radiation from clouds and gases in the atmosphere.

3 Expansion cooling

When air is forced to rise, it expands because it is rising into thinner air. When gases expand, their temperature falls, so the air cools. (Similarly, when air descends it is compressed because it is sinking into denser air, so it warms.)

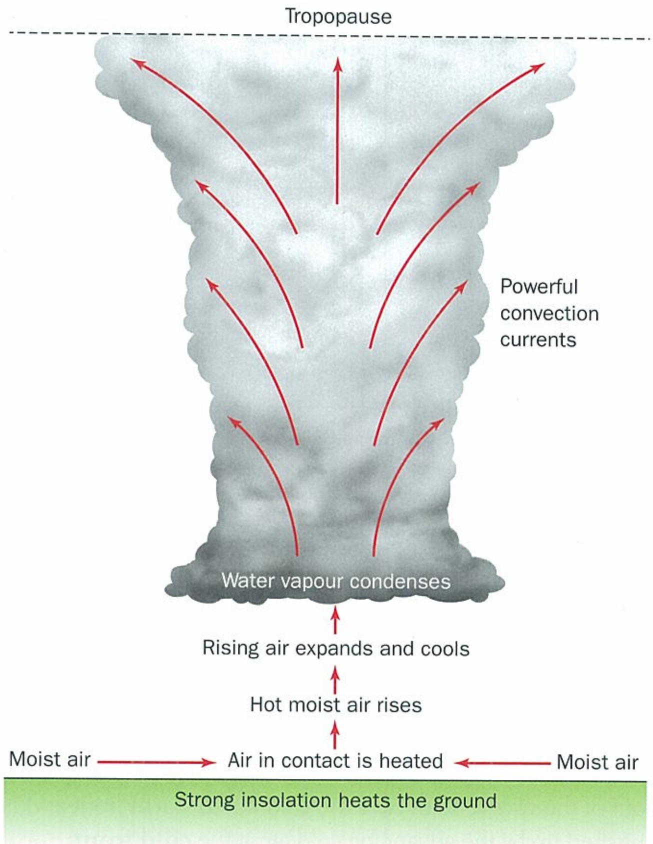


Fig. 2.38 Cumulonimbus cloud and rainfall

Fig. 2.39 Convection cells causing adjacent cumulonimbus clouds with horizontal spreading beneath the tropopause in the UK in summer

Causes of precipitation

Precipitation is moisture that is deposited on the Earth's surface in liquid or solid form from the atmosphere. For it to occur, air has to cool to below dew point temperature, either by being forced to rise or by conduction.

Vertical movement can be triggered by convection, frontal uplift, orographic uplift and radiation cooling.

Convection

Convection occurs over a hot land surface or over a structure that emits heat like the cooling tower of a thermal power station. The air is warmed by contact with the heat source. Convection is common during summer anticyclones when air is sufficiently still to enable long contact with the hot land surface. The heated air expands, becomes less dense, rises and cools. Clouds form as moisture in the air condenses and the latent heat released adds further warmth to speed the ascent, which can reach the tropopause, forming cumulonimbus cloud.

Frontal uplift

At the ITCZ moist tropical air masses of the same temperature meet and rise as a result of winds moving into the equatorial low pressure system, resulting in dense cumulonimbus cloud formation, especially in the afternoon and evenings.

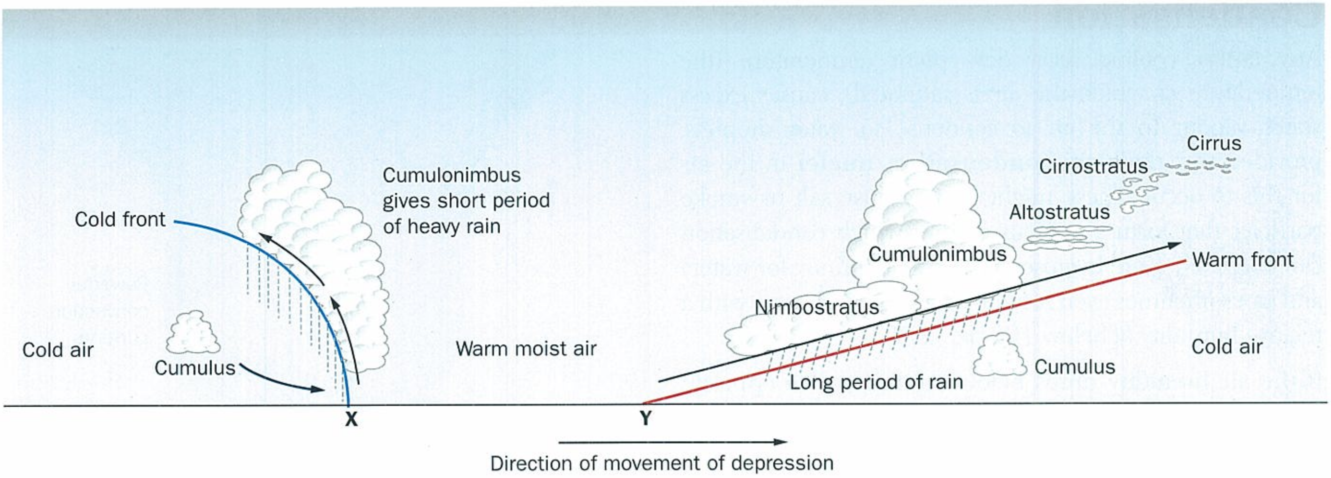


Fig. 2.40 Section through a mature depression showing warm air rising over cold air along the warm and cold fronts

Warm tropical air masses and cold polar air masses meet along the polar fronts in mid-latitudes. Low pressure systems called depressions form and, at their mature stage, have warm and cold fronts, the fronts of the advancing warm and cold air masses respectively. Being less dense, the warm moist air in the 'warm sector' of the depression can't push the cold air out of the way, so rises over the cold at the warm front and is pushed up by the advancing cold air at the **cold front**.

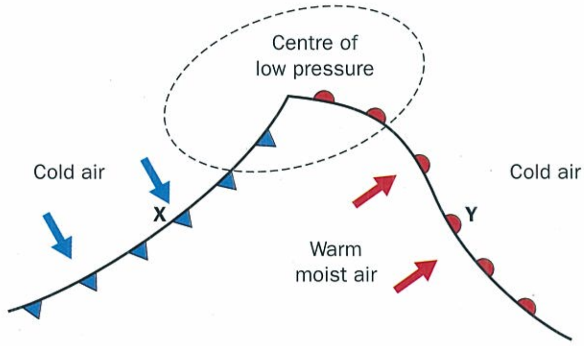


Fig. 2.41 Plan of a mature depression

A long period of precipitation occurs as the warm front passes over a place, followed by a shorter period of very heavy precipitation as the cold front moves through. Eventually, the cold front catches up with the warm front because the cold air in the rear moves faster. The warm air is completely lifted off the ground by the cold air, forming an occluded front with a long period of rain.

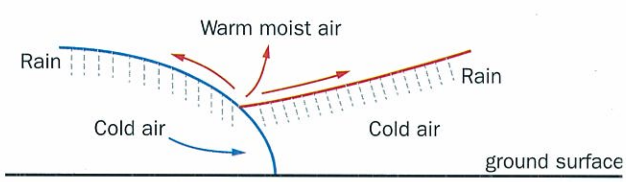


Fig. 2.42 Section through an occluded front

Orographic uplift

This occurs when the pressure force is strong enough to cause air to rise over a hill or mountain. As it rises up the windward slope, it cools and reaches dew point temperature at condensation level. Above this, condensation occurs, forming cloud from which precipitation falls if the cloud is thick. For this reason, the windward slope of a mountain is known as the rain slope while the lee slope is the rain shadow. The lee will be dry because the air is sinking and warming. Sometimes, conditions result in the cloud being too thin for rain or snow to fall from it.

Often orographic cloud gives heavy rain on the windward slope but, in certain conditions, forced ascent of air over a hill or mountain results in thin stratiform cloud, which is seen as hill fog. The situation in Fig. 2.43 occurs if the air at the top of the lee slope is cooler than the air around it at that level (a condition described as stable air), so it will be denser and sink. However, if the rising air is warmer than the air into which it is rising (a condition known as unstable air), the air continues to rise for a time instead of falling down the lee slope.

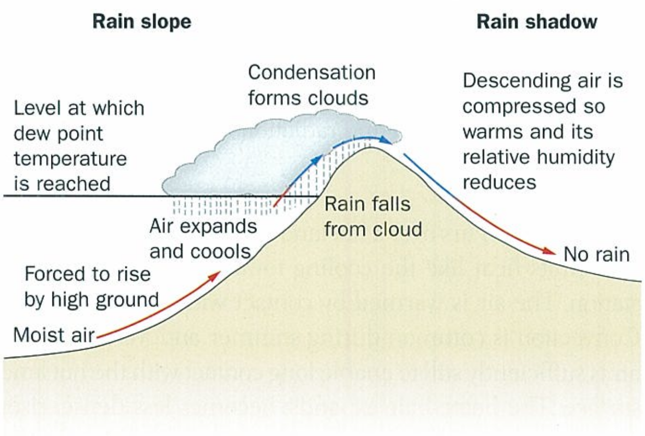


Fig. 2.43 Forced ascent of air over a hill or mountain

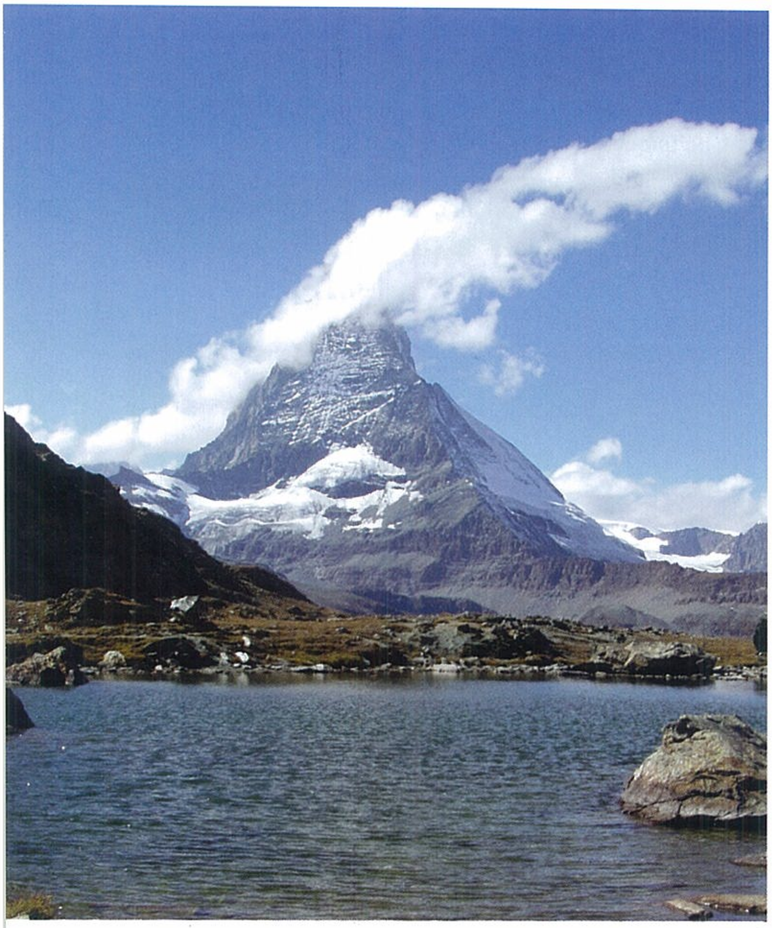


Fig. 2.44 Orographic uplift over the Matterhorn

Radiation cooling

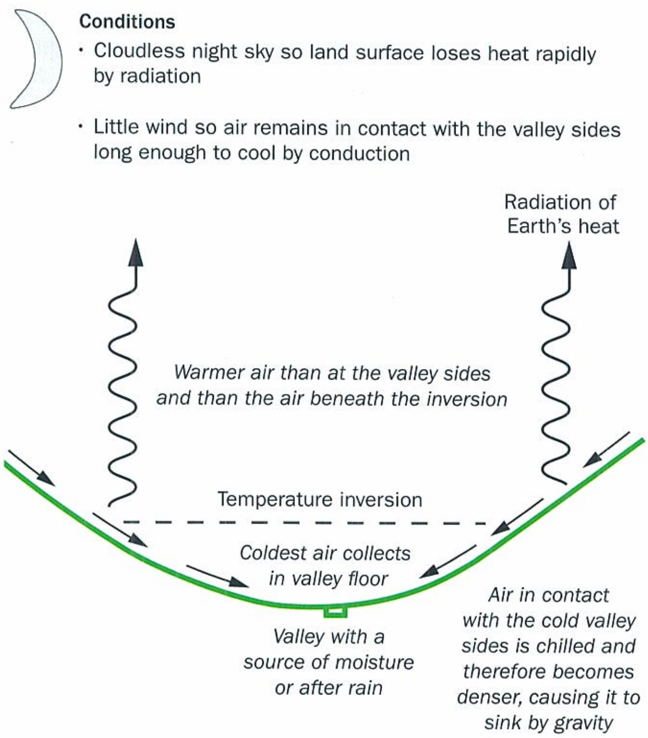


Fig. 2.45 Radiation cooling in a mid-latitude valley in winter

This is the reason why dew, **radiation fog** and ice form in valley bottoms. If the ground surface is cooler than freezing point, frost made of ice crystals occurs.

Types of precipitation

Cloud and fog are included here for convenience as weather phenomena formed of moisture, but they are not precipitation. Clouds *produce* precipitation and fog can add a little by fog-drip but most does not reach the ground.

Composed of water

Weather	Description of form	Origin
Fog	Tiny water droplets suspended in the air near the ground reduce visibility to less than 1 km.	Moist air is cooled to below dew point by contact with a cool land or sea surface and the water vapour condenses. Origin may be radiation fog or **advection fog**.
Dew	Small droplets of water on leaves, grass, spiders' webs, etc.	Water vapour condenses onto cold objects (e.g. grass). Still conditions allow prolonged contact with the object.
Clouds	At low altitudes, clouds are suspensions of tiny water droplets with an average diameter of 0.1 mm. These are super-cooled where they exist at temperatures below 0 °C and are too light to fall, so remain in the air until they are evaporated.	Formed above ground level when moist air rises, expands and cools adiabatically to below dew point temperature and the excess water vapour condenses around condensation nuclei.
Raindrops	Usually about 2 mm in diameter.	Formed when falling water droplets collide and coalesce. Some may be melted snowflakes or hailstones.

Table 2.10 Weather phenomena composed of water

Composed of ice

Weather	Description of form	Origin
Snowflakes	Aggregates of ice crystals arranged in hexagonal patterns.	Water vapour in cloud changes to ice and when the crystals fall, they collide and combine (process known as aggregation).
Hailstones	Roughly circular, made of alternate layers of opaque rime and clear ice glaze.	Formed when ice particles fall and rise in cumulonimbus clouds and super-cooled water droplets collide with and freeze around them (accretion).

Table 2.11 Weather phenomena composed of ice

Clouds

The main types of cloud

Clouds are classified into three main types according to their shapes:

- **stratus** are layer clouds that form when there is little vertical uplift but it is over a wide area
- **cumulus** occur where more vertical but localised uplift results in heaped clouds with flat bases and globular upper surfaces
- **cirrus** form where condensation occurs at very high levels, forming wispy clouds made of ice.

These are further sub-divided according to their altitude. Very high clouds are prefixed **cirro**, while middle-level clouds are prefixed **alto**. Low-level cloud is stratus or cumulus - or **stratocumulus** if it has the characteristics of both.

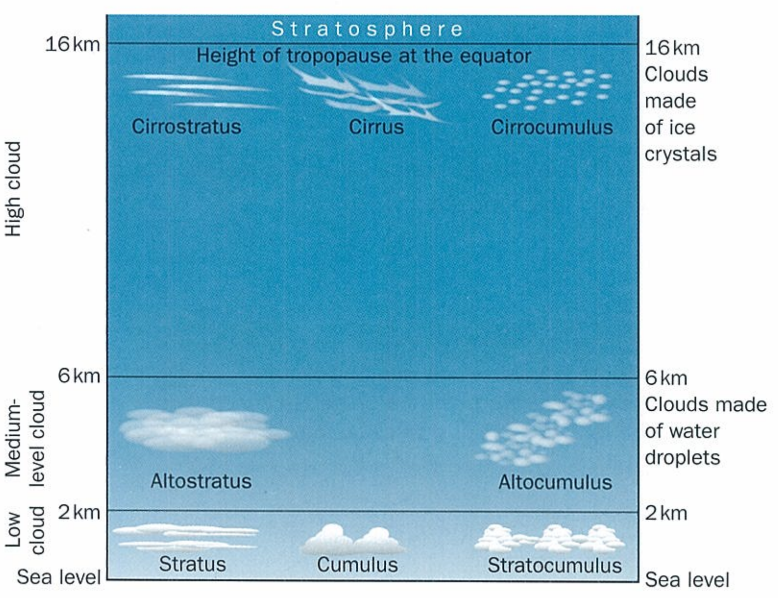


Fig. 2.46 Fair weather clouds, showing their heights in the tropics

If a cloud is sufficiently thin for sunlight to pass through, it is white and will not produce precipitation, although it could give fog if in contact with a valley side or mountain top, as the low-level layer cloud, stratus, in Fig. 2.47.

Fig. 2.47 Stratus filling a valley in the Rocky Mountains, resulting in hill fog

Clouds that produce precipitation

Rain cloud will have a large vertical extent which will prevent sunlight penetrating to its base and will appear to be black from below. **Nimbostratus** is a thick, dark grey layer cloud which can be 5000 metres deep, enough to produce steady rain. The biggest cloud by far is the towering **cumulonimbus.** It is a dense, dark grey cloud with a great vertical extent and can grow from near sea level to the tropopause, where it spreads out to form a distinctive flat anvil top because its cold air cannot rise through the warmer air above. If it does not reach the tropopause, its top is high and globular. It is composed of ice crystals at the top and water droplets lower down.

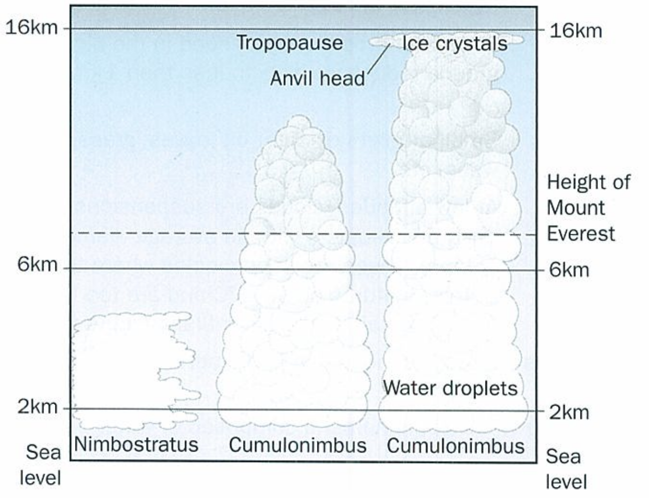


Fig. 2.48 Rain-bearing cloud, showing their heights in the tropics

Fig. 2.49 Cumulonimbus starting to develop on a sunny summer afternoon under high pressure conditions in the UK

Fig. 2.50 The base of this cumulonimbus cloud on Easter Island is at ground level because the warm air from the Pacific Ocean is very moist and cools to dew point temperature after a small uplift

Fig. 2.51 Nimbostratus is a dull grey, opaque cloud that covers the sky

Precipitation from cloud

Very few cloud droplets become raindrops. This can only happen in clouds with an abundance of moisture. For rain, hail and snow to reach the Earth's surface the droplets need to grow big and heavy enough to fall through the rising air currents that are responsible for the cloud's formation. There are two theories as to how this happens: collision theory and Bergeron-Findeisen theory.

Collision theory

Different sized water droplets have different falling rates and are carried in rising and falling air currents within cumulonimbus clouds. The droplets collide with others and join together to form a larger drop. Three processes occur:

- **coalescence** – two water droplets collide and join together. This is the main mechanism for the formation of rainfall
- **aggregation** – two ice crystals collide and join together to form snow
- **accretion** – an ice crystal collects a water droplet, leading to the formation of hail.

Bergeron-Findeisen theory

Air is saturated with respect to ice before it is saturated with respect to water. The Bergeron-Findeison process describes the growth of cloud droplets that occurs when the air is between ice and water saturation and has a temperature between -12° and -40°C. In these conditions, water droplets evaporate and the resulting water vapour is deposited onto ice crystals. This continues until all water droplets are evaporated or until the ice crystals have aggregated into a snowflake and are large enough to fall. If they fall into warmer levels of the atmosphere they melt to reach the surface as rain. Most summer rain in mid-latitudes forms in this way. Snow falls if the temperature of the atmosphere remains below freezing point.

Fig. 2.52 Thick snow in the UK

Case study: A cumulonimbus experience

A parachutist practising for the **Commonwealth** Games opening ceremony in Brisbane in 1982 experienced the mighty up-draughts that are fuelled by the release of large amounts of latent heat during condensation, building cumulonimbus clouds to great heights. When he jumped from the plane into an up-draught, he was swept up 2000 m while being hit by falling hailstones. Knowing that the type of cloud could be more than 8000 m high and that at that height he would pass out through lack of oxygen, he cut his main parachute and free fell to a safe altitude. As he dropped, he experienced more hail coming up at him in the up-draughts.

Hail

The top parts of cumulonimbus clouds are below freezing point, so more latent heat is released when the water droplets that formed from condensation lower in the cloud are carried up and freeze round a freezing nucleus. This may be an ice crystal, snow pellet or frozen raindrop. Freezing is rapid in the highest parts of the cloud, so a layer of opaque ice is added to the frozen droplets. They fall again and are covered with another film of water which freezes more slowly in the warmer part of the cloud to form clear ice. Once again, they are uplifted to above freezing level where another coating of opaque ice is added. This continues until the hailstone has so many layers of ice that it is heavy enough to fall through the powerful up currents. Hailstones can be the size of golf balls and can cause considerable damage, but many melt to rain at lower levels.

Fig. 2.53 Hail from a cumulonimbus cloud at a Spanish holiday resort in May

Dew and fog

On calm, cloudless nights, air chilled by contact with the cold land surface becomes colder and denser, so sinks by gravity down the valley sides and valley floor.

Dew forms in the totally calm conditions of anticyclones if the temperature of the ground surface is above 0 °C. When there is a light breeze to mix the air near the surface, condensation takes place in the air, rather than at ground level, forming radiation fog. This often forms on winter mornings when convection just after sunrise causes air to mix.

Fig. 2.54 Early evening fog in Namibia

Fig. 2.55 Early morning fog in the UK

20. Use evidence from the photographs to explain the processes occurring in Fig. 2.54 and the reverse processes starting to occur in Fig. 2.55. Describe the effects these processes are having on the air temperature.

Advection fog occurs when:

- winds move towards the pole over a colder sea surface. Widespread advection fog forms if the air is chilled to below its dew point
- winds blow over a cold ocean current, forming advection fog over the current
- air crosses from the sea onto a cold land surface in winter. This also results in advection fog or in hill fog and stratus cloud if the air is forced to rise by the relief. Sometimes the cloud may be thick enough for a little drizzle to fall.

Fig. 2.56 Advection fog formed where warmer air from the Pacific Ocean blows over cold, icy water near a glacier in Alaska. Orographic cumulus and stratocumulus lie above the ridge

The human impact

The enhanced greenhouse effect

The natural greenhouse effect that keeps our planet warm enough to live in results from greenhouse gases, such as water vapour and carbon dioxide, which occur naturally in the atmosphere. Water vapour accounts for up to 85 per cent of the greenhouse effect in very cloudy conditions and about 50 per cent when there are no clouds. Large amounts of carbon dioxide are naturally present and are released during volcanic eruptions but they are equal to less than 1 per cent of the added anthropogenic carbon dioxide.

The **enhanced greenhouse effect** refers to the addition of greenhouse gases to the atmosphere by human activity. This is thought to lead to global warming and various types of climate change.

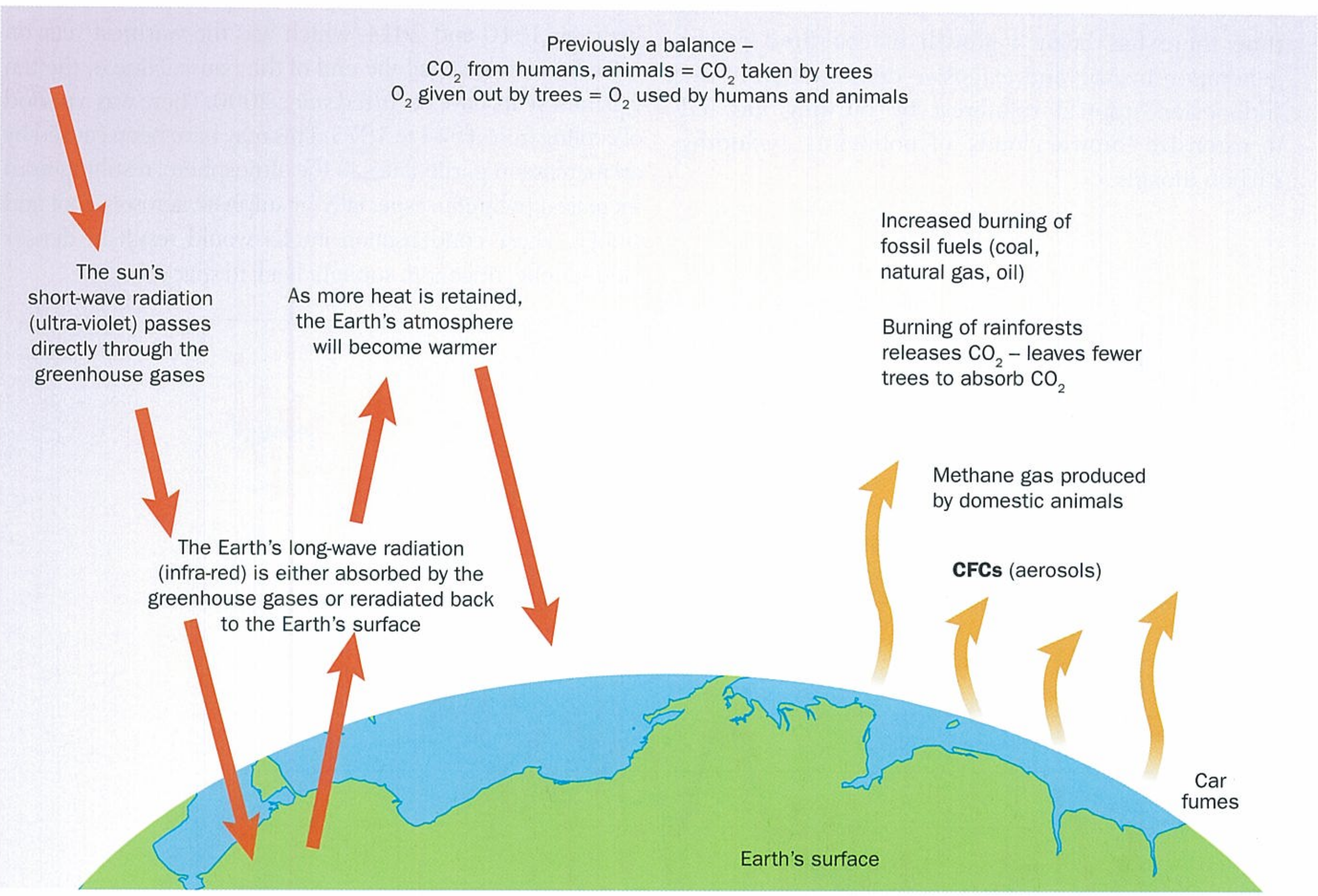


Fig. 2.57 The enhanced greenhouse effect

21. (a) Explain the meaning of 'greenhouse gas'.

(b) State which parts of Fig. 2.57 show the (natural) greenhouse effect.

(c) Explain why the effect of human activity is described as the *enhanced* greenhouse effect.

RESEARCH Find out about solar cycles and whether they can be responsible for the pattern of temperature increases in Fig. 2.58.

The warming effect of a gas is known as its **radiative forcing**. Although there is some disagreement about the degree of warming caused over a particular timescale, there is general agreement that:

→ Current temperatures are 0.7 °C above pre-industrial (1880s) levels.

→ Warming was less than expected during the 20th century.

→ Global temperature rise since 1998 has been so little (0.05 °C in the first decade of this century) that it is described as having 'paused'. Possible reasons include changes in solar activity and a ban on CFCs. Also important are increased sulphur and ash emissions to the atmosphere from volcanic eruptions (Pinatubo in the Philippines caused cooling by 0.4 °C in 1992 by emitting 20 million tonnes of sulphur dioxide in 1991). Another possibility is that the climate is less affected by carbon dioxide than previously thought.

→ There have been small-scale and large-scale periods of cooling since records began in 1880. At the same time there has been a growth of coal-fired power generation in Asia and extensive deforestation of the Indonesian tropical rainforest by burning has led to extensive 'brown clouds' of pollutants, including carbon dioxide.

Evidence for global warming

Increase in global temperatures

22. Use Fig. 2.58 to answer the following.

(a) Calculate the Earth's mean temperature change between 1910 and 2013. Is this a large amount per year? A graph should give a correct visual impression of the data it shows but there are good reasons why this is not always done. Justify the scale used for this graph.

(b) The 5-year running mean suggests that warming paused in 2002 but it is generally agreed that it paused in 1998. What is the evidence for this?

(c) Explain how the five-year running mean was calculated.

Fig. 2.58 shows that mean world temperatures rose overall between 1910 and 2014, which was the warmest year on record and may signal the end of the pause. Nine of the ten warmest years have occurred since 2000. There was a period of cooling from 1944 to 1975. This may have been caused by an increase in particulates in the atmosphere, resulting from increased pollution, especially by sulphate aerosols, soot and smoke. These condensation nuclei would result in denser clouds, reflecting more sunlight back to space.

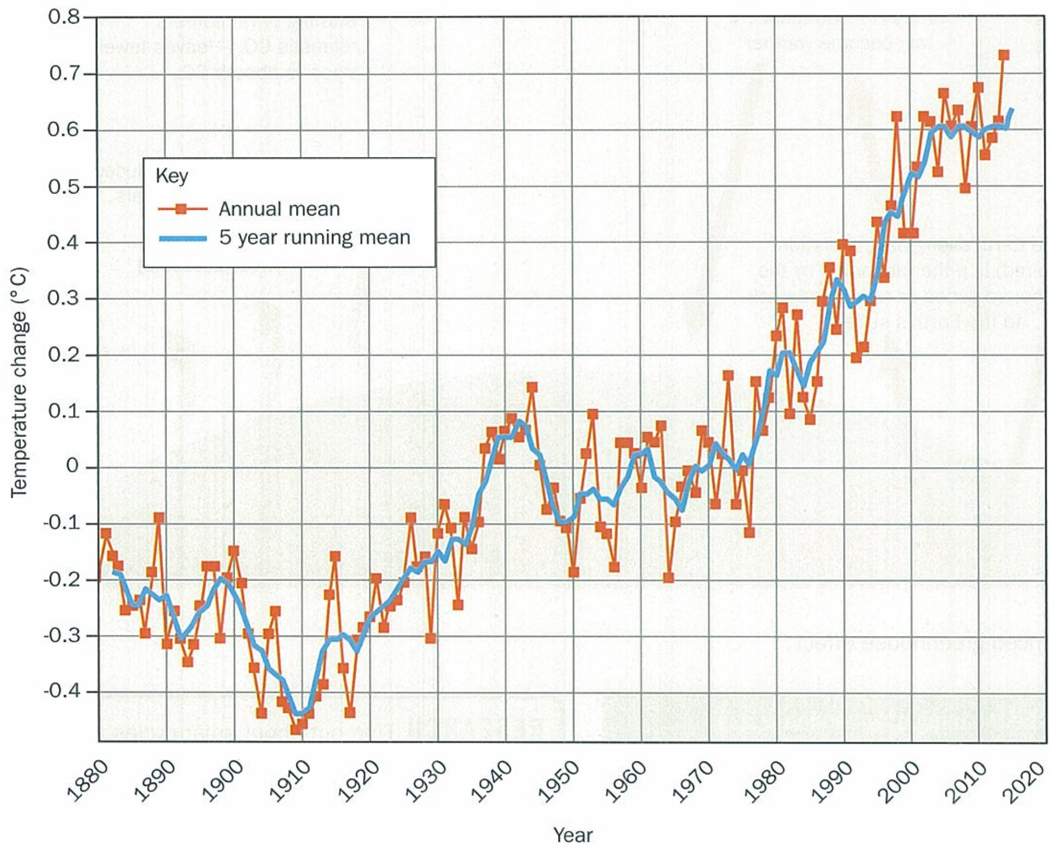


Fig. 2.58 Line graph showing how global annual temperature (in °C) and the 5 year running mean 1880–2014, varied from the mean temperature of the period 1951–1980, shown as 0 °C

Each decade since the 1970s has been a little warmer than the preceding one. This has been attributed to the increase of greenhouse gases in the atmosphere, whereas much of the increase between 1910 and 1940 was thought to be largely natural.

Upper ocean heat has increased steadily over the past 20 years as a result of the oceans storing an estimated 63 per cent of the heat added by enhanced global warming. Monitoring of the deep oceans suggests heat is accumulating there, rather than in the atmosphere.

Ocean salinity

Drier areas and areas of high evaporation, such as the western Indian Ocean, have become saltier whereas wetter areas, such as the North Atlantic, have fresher water. As the Arctic sea ice and glaciers melt and rainfall increases, more freshwater is entering the north Atlantic Ocean and diluting the salt water, making it less dense. This will cause it to remain on the surface and could prevent the sinking of north Atlantic surface waters which power the Great Ocean Conveyor Belt. Tropical water will then no longer move towards the poles because there will be no sinking water to replace. These ocean currents show signs of weakening, which would make Europe colder.

Melting sea ice

Arctic sea ice extent has declined since satellite observations began in the late 1970s. Its March maximum extent declined by about 2.4 per cent per decade since 1980 and was at a record low in 2012, but recovered considerably in 2013 only to fall to the third lowest June extent in the satellite record in 2015. The ice is also becoming much thinner but, according to the European Space Agency, thickened by up to a third in 2013.

By contrast, in June 2015 Antarctic sea ice reached its third highest June extent since satellite records began. It is believed to have increased by over 4 per cent per decade recently and has been well above the mean in 9 of the 13 years between 2001 and 2014, even though an active volcano is beneath it. To complicate matters, scientists have recently found two channels that may be allowing warm ocean water to move beneath the 75-mile-long Totten Glacier. If proved, it would contribute to rising sea levels by melting ice. Between 2010 and 2014 the extent of Antarctic ice increased from 19 million square kilometers to more than 20 million square kilometers.

Rising sea levels

Global sea level rose by an average of 3.1 mm a year between 1992 and 2010, twice the average rate for the last century. The record highest yearly average height was in 2014, when it reached 67 mm above the 1993 average. It is rising because melting glaciers send more water to the sea and also because of thermal expansion - water expands as it warms. As oceans store heat for longer periods than land and store it over a large body of water, a small increase in temperature could result in a significant rise in sea level.

RESEARCH Venice is regularly flooded to increasing depths. The rise in sea level there partly results from ice melting and partly from the Earth's crust sinking in that region. Find out about sea level changes caused by tectonic and isostatic movements.

Melting glaciers

With some exceptions, most mountain glaciers have been shrinking since the middle of the 19th century. In 2013, three Norwegian glaciers were advancing and all in Nepal were either stable or growing because snowfall was greater than average in 2013. Glaciers and ice sheets in Greenland and West Antarctica are melting rapidly at the highest speeds since satellite records began and increasing sea levels. Fortunately, the East Antarctic ice sheet is increasing.

Fig. 2.59 This glacier in Chile used to reach the sea

Increasing acidity of the oceans

Oceans are thought to have absorbed about 50 per cent of the carbon dioxide emissions released by human activity by dissolving carbon dioxide into them, forming carbonic acid. Since 1750, the pH of the ocean surface is thought to have fallen by 0.1, from 8.2 to 8.1. This is a logarithmic scale and is equivalent to a 26 per cent increase in acidity. The 1750 level was calculated by analysing the CO_2 content of air bubbles trapped in glaciers at that time and the knowledge that the ocean surface has the same concentrations of CO_2 as the atmosphere. As pH 7 is neutral, a more accurate description of the situation is that the ocean surface is a little less alkaline now.

Biological indicators of warming

Examples include:

- the bee-eater, a tropical bird, is now found in the UK every spring
- malaria, a tropical disease, is increasing in southern Europe where mosquitos have moved in with the increased warmth
- the blanching of some coral reefs is believed to result from increased acidity of the oceans.

Possible causes of global warming

Greenhouse gas	Atmospheric concentration	Sources resulting from human activity	Number of years the gas stays in the atmosphere	GWP*	Contribution to the enhanced greenhouse effect
Carbon dioxide	400 ppm (2014 at Hawaii and some other locations)	Burning fossil fuels and wood, deforestation; especially by burning.	Variable: up to 200 but averaging about 62	1	Thought to be the main greenhouse gas, it has increased from 280 ppm in 1850.
Methane	1800 ppb	Bacteria in wet padi fields, bogs, waste landfill sites and the guts of cattle and sheep.	12	25	In small quantities but 25 times more effective than CO2. Increasing by up to 2 per cent p.a.
CFCs	1863 ppt	Old aerosols and refrigerators (CFCs are no longer used)	Variable – up to 50 000	Variable – most more than 3500	Very efficient absorbers of long-wave radiation.
Nitrous oxides	323 ppb	Nitrate fertiliser, burning fossil fuels (especially diesel engines) and burning vegetation.	114	nearly 300	In small quantities but impact nearly 300 times that of carbon dioxide.

*GWP is the global warming potential of the gas compared with carbon dioxide (1) shown for a 100 year period

Table 2.12 Greenhouse gases

The radiative forcing of the greenhouse gases increased by nearly a third between 1990 and 2012, with carbon dioxide contributing 80 per cent of this increase in warming, according to the World Meteorological Association.

Carbon dioxide has been of most concern because it stays in the atmosphere for much longer and is much more abundant than methane. Measurements at the Mauna Loa Observatory in Hawaii show that CO_2 concentration in the atmosphere increased fairly steadily from 1960 to 2014 with a slightly increased rate from about 1995, which is about the time that warming appeared to have paused.

People are being made aware of their '**carbon footprint**', a measure illustrating the impact human activities have on the environment. The carbon footprint will be proportional to the amount of greenhouse gases (such as carbon dioxide) produced.

23. Use the information in Table 2.13 to construct a percentage divided bar chart to show country shares of the world total CO_2 emissions. Add 13 per cent from other MICs and 29 per cent from other LICs.

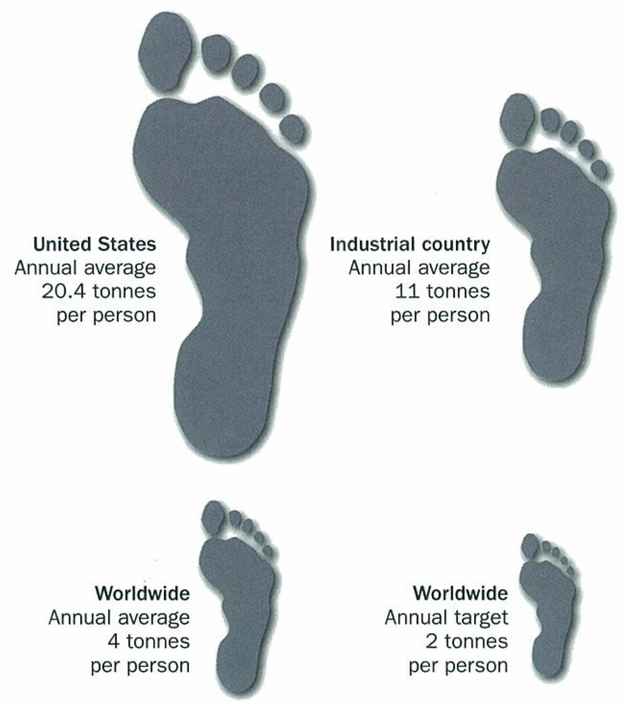


Fig. 2.60 Carbon footprint awareness can be raised by using easy to interpret diagrams. The target is what is thought necessary to limit global warming to 2 degrees C this century.

Country	2009 (million tonnes)	2011 (million tonnes)	Change from 2009	2011 emissions per person (tonnes)	2011 country share of world total (per cent)
China	7037	8715	increase	6.2	27
USA	5657	5490	decrease	17.2	17
Russian Federation	1716	1788	increase	12.2	5
India	1802	1725	decrease	1.4	5
Japan	1208	1180	decrease	9.2	4

Table 2.13 Emissions of carbon dioxide (Source: CDIAC, US Department of Energy)

RESEARCH Find out the main sources of carbon dioxide emissions for one of the countries in Table 2.13.

El Niño

Global temperature changes appear to be linked with natural events in the equatorial Pacific Ocean known as **El Niño** and La Niña. These are characterised by different pressure patterns and reversals of wind and ocean water movements. El Niño is also known as ENSO (El Niño Southern Oscillation).

There are discrepancies between data shown on Figs 2.58 and 2.61: for example, the anomaly for 2014 was +0.74 on Fig. 2.58, whereas on Fig. 2.61 it is +0.69. Both diagrams were obtained from NASA sources - the first from the Goddard Institute of Space Studies and the second from NOAA. These institutions use their own methods of research, leading to minor variations, but are in broad agreement, as are results from research by the Japanese Meteorological Agency and the UK Meteorological Office's Hadley Centre.

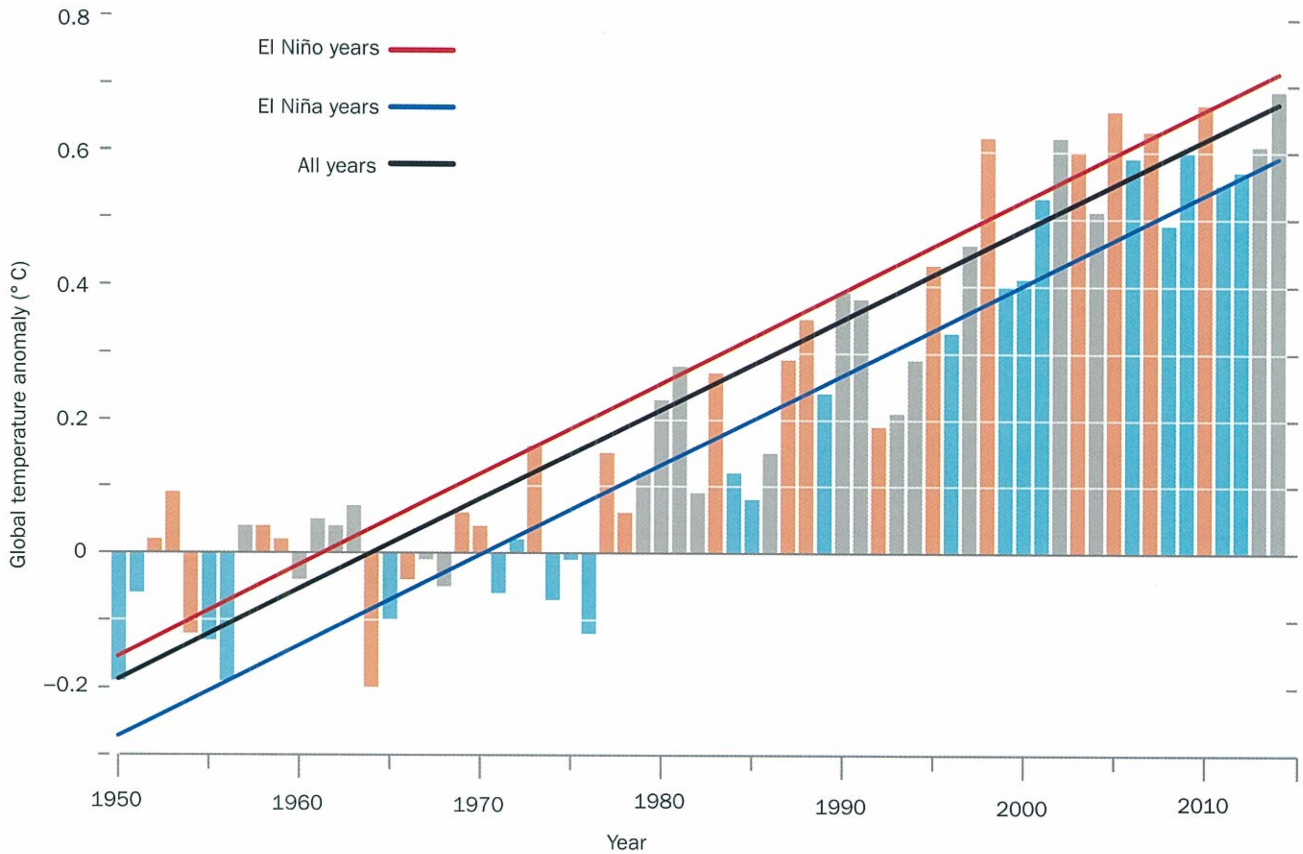


Fig. 2.61 Bar graph showing the relationship between global temperature anomalies calculated from the 1951 to 1980 mean temperature, shown as °C, and El Niño and La Niña events

During El Niño events, such as in 2010 (the second hottest year on record), but not 2014, the warmest, the world is warmed by heat from the Pacific Ocean. The Pacific warms because the normal westward surface flow of ocean currents reverses and warm water moves east across the Pacific from Indonesia. Large areas have sea surface temperatures in excess of 28 °C, causing low pressure over the eastern Pacific Ocean and heavy rain in Peru and northern Chile. Meanwhile, eastern Australia experiences high pressure, drought and extreme heat. In El Niño years, sea levels rise because there is more rainfall over the warmer oceans and warmer waters expand.

La Niña brings cooler years. Cold upwellings of water off the coast of Peru make the central and eastern part of the Pacific Ocean up to 2 °C cooler than average while eastern Australia has heavier than normal rainfall. Some scientists are linking the 'pause' in global warming to La Niña cooling the eastern Pacific.

Atmospheric impacts of global warming

- The melting of Arctic sea ice and loss of snow cover will reduce the albedo, resulting in less reflection of solar radiation and more heating of the Earth and atmosphere, so accelerating global warming.
- Warmer temperatures will lead to more evaporation from the oceans, increasing moisture in the atmosphere, giving the potential for increased cloud and rainfall in places, which would cause local cooling.

- Warmer temperatures in places with high pressures, such as south-west USA, South Africa, Australia and the Mediterranean, will cause less rainfall and more severe droughts.
- Heat waves will occur especially in cities because urban temperatures are always higher than those of surrounding rural areas. 30 000 people died in Europe in the hot summer of 2013.
- Western Siberia is warming quickly because, as the covering of snow and ice melts, the darker rock and soil surfaces absorb much more radiation. If all the permafrost melts, massive quantities of methane will be released into the atmosphere, accelerating global warming. Methane releases from the melting permafrost are already causing numerous wildfires in Alaska and Siberia. Permafrost also stores more than twice the amount of carbon that is in the atmosphere, which will be released as the permafrost decomposes and accelerates warming. If it accelerates beyond the 'tipping point', it will be impossible to stop the warming continuing.
- More frequent and more violent storms are expected because of greater moisture in the warmer air and more coastal flooding from storm surges are likely because of higher sea levels. However, no connection has been found between the number of tropical storms and warmer years. Despite being the fourth warmest year on record, 2013 was the quietest year for North American hurricanes with only one reaching category 1 status.

The amount of CO_2 in the atmosphere has not increased as much as expected. Carbon dioxide that is not absorbed by the atmosphere is stored in other carbon 'sinks', such as the oceans and vegetation.

The changes will not be uniform and are difficult to predict. Some areas will be hotter and others colder. Some will be wetter and others, such as the Amazon basin, drier. Areas of unequal pressure will still exist to drive the winds but they could be in different locations. The greatest changes will be to areas that are near climatic boundaries.

Difficulties of predicting climate change

Predictions of the degree of warming made by the IPCC, a panel of experts, were revised down a little in their 2014 report. They depended on computer models, so were only as good as the weightings attached to the various inputs.

Case Study: Vancouver's microclimates

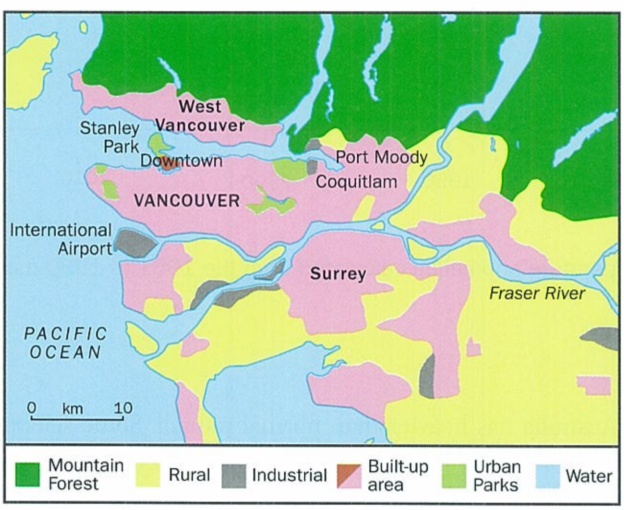


Fig. 2.62 Vancouver's land use zones and locations in the case study

Vancouver, Canada's third largest city, is open to the sea but backed by mountains broken by the valley of the Fraser River, which enters the coastal lowland to the east of the city.

Temperature

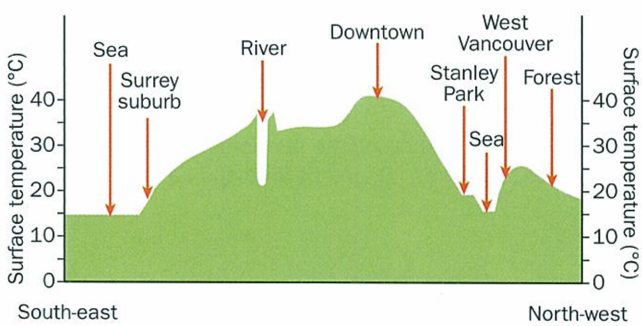


Fig. 2.63 Temperature transect across Vancouver's heat island on a very hot day in July

On sunny summer days a surface temperature traverse across the city shows a marked heat island. The sea has the lowest temperature, followed by the river. Stanley Park also has relatively cool temperatures, similar to those in the rural farmland of the Fraser Valley. The international airport is not shown on the diagram but would record a higher temperature than the well-vegetated Stanley Park because of the terminal buildings and runways. Temperatures are higher in the suburbs of West Vancouver and Surrey but the 'dome' of the heat island is centred on the downtown (CBD) area where there is a high density of skyscrapers.

When sea breezes blow on some summer afternoons, air temperatures near the coast can be 5–10 °C cooler than in the Fraser Valley beyond their influence, whereas in winter it is the inland areas that are cooler, by about 2 °C.

	Downtown	Airport
Daily mean temperature (°C)	11	10.4
mean annual precipitation (mm)	1587	1189
Mean annual sunshine hours	1818	1937

Table 2.14 Some climatic differences within Vancouver

Fig. 2.65 shows atmospheric daytime temperatures typical of the summer temperatures in the area. Again, the CBD is the warmest area at 27 °C and is 10 °C warmer than the rural area to the south of the city, where the temperature is only about 17 °C. There is a steep rise in temperature at the edge of the built-up area, then it increases more gradually to 25 °C before peaking in the CBD. There are two peaks of temperature, separated by cooler temperatures over a small inlet of water.

The difference in temperature between urban and rural areas is also high on summer nights under calm and cloudless anticyclonic conditions when there are no winds to remove the heat. In those conditions,

Fig. 2.64 The view north-west from downtown Vancouver, showing the forested mountain rim with the suburb, West Vancouver, in the background and part of Stanley Park on the left

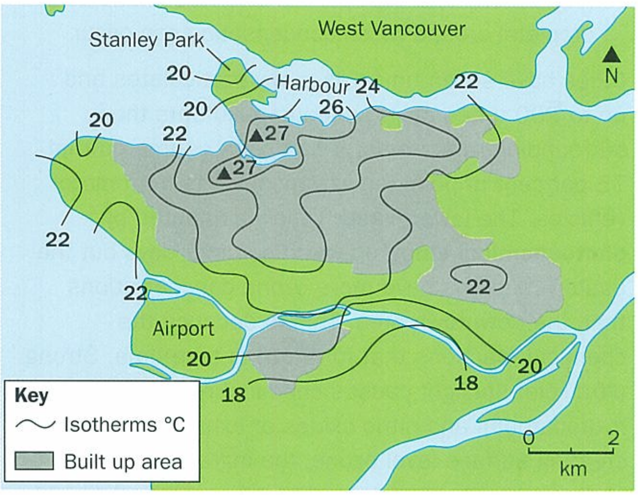


Fig. 2.65 An isotherm map of air temperatures in the Vancouver area

temperatures can decrease steadily outwards from 20 °C in central Vancouver to 15 °C at the international airport. All large urban areas have earlier springs, later autumns and fewer frosts than nearby rural areas. This heat island effect is caused by several factors:

- Brick, concrete and dark tarmac surfaces have a large specific heat capacity and low albedos. They rapidly absorb solar radiation by day, especially in summer. The heat is conducted away from the surface, stored and re-radiated steadily into the air at night as long-wave radiation.
- Tall buildings turn streets into 'canyons', giving a reduced sky view and a smaller angle of direct heat loss at night. Large urban parks, such as Stanley Park, and open countryside are cooler because the sky is much 'wider', so radiational heat losses are greater. The greater the building density, the greater the heating, so city centres have the highest minimum temperatures at night and temperatures gradually cool through the more spacious suburbs to the countryside.

- Central heating, gas and electric fires, together with heat from industrial sources, all warm the urban atmosphere.
- Although pollutant particles and gases (such as sulphur dioxide from the combustion of fossil fuels and carbon monoxide from vehicle exhausts) reduce the amount of short-wave radiation reaching the surface by day, their main effect is reducing the loss of re-radiated energy at night by absorbing and re-radiating long-wave radiation.
- Higher rates of evapotranspiration in rural areas lower their temperatures by absorbing heat.

Wind

Skyscrapers in the CBD can cause turbulence and vertical uplift with eddies in the lee of buildings, but winds are generally less strong in the city centre because the tall buildings obstruct and deflect airflow and increase friction. There are more calm days in the built-up area than in the surrounding countryside. However, canyon-like streets have the strongest gusts when winds are funnelled between their tall buildings.

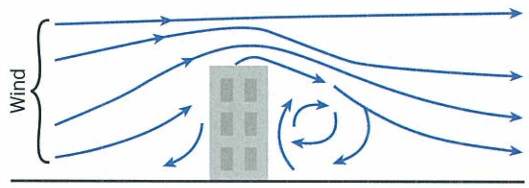


Fig. 2.66 The effects of a building on airflow

Humidity

Absolute and relative humidity are both lower during the day in the city than in the rural area because less surface water and vegetation is present for evaporation and transpiration to occur. Rainfall runs off rapidly down gutters and drains. However, humidity rises over the harbour, Burrard Inlet and the Fraser River where more evaporation is possible. Daytime humidity is also greater over Stanley Park where moisture is increased by transpiration.

At night, humidity tends to be slightly higher over the city because in rural areas more dew is deposited from the air, making it less humid.

Precipitation

An orographic effect is present as, for every increase in height of 100 metres within Vancouver, precipitation increases by about 100 mm. The mountain edge of West Vancouver receives double that of the main city. Snow falls there in winter but is rare in the lower areas, the parts of the city nearer the warmer ocean and in the central city, where the warmth melts most snow as it is falling.

Relief is the most important cause of variations in rainfall within the city but the greater amount of cloud and precipitation also results from:

- the development of convection currents on calm, clear nights when the urban-rural temperature differences are largest. Warm air rises over the central city and the airflow moves towards the rural area aloft and then sinks. Meanwhile, air moves from the rural area over the surface to the lower pressure in the city. These convection currents result in higher rainfall in the central city, with more thunderstorms. It can be 10 per cent cloudier than in the surrounding rural area
- storm cells intensifying by contact with the warm surface as they pass over
- buildings forcing moist air to rise, triggering convection
- the increased density of hygroscopic (condensation) nuclei strongly encourages condensation.

Fog and smog

Fogs are more frequent in the city, particularly in winter, because:

- lower wind speeds and more frequent calm periods allow the air to remain in contact with the ground and to cool by conduction
- there are a greater number of hygroscopic nuclei (e.g. smoke and dust particles and sulphuric acid droplets) around which condensation can occur.

Cities have seven times as many particulates and up to 200 times more gaseous pollutants than surrounding rural areas. It has been estimated that 75 per cent of pollution in Vancouver is from motor vehicles. The lower Fraser Valley is affected by **photochemical smog** on warm summer days but the eastern suburbs have more ozone concentrations than the downtown area. This is because the chemical reactions that form ozone take time. Strong ultraviolet sunlight causes chemical reactions in the hydrocarbons and nitric oxides of exhaust fumes, creating surface level ozone, the ingredient of photochemical smog. It is gradually produced as sea breezes move the pollutants inland. Mountains to the north and east trap the pollutants in the eastern suburbs of Port Moody and Coquitlam.

The worst pollution occurs during anticyclones because the subsiding air warms and causes a temperature inversion above the city, which acts as a lid on rising air and traps the pollutants below it. The light winds in anticyclones do not disperse the pollutants, so assist fog to form and mix with pollutants to form smog.

Fig. 2.67 Aerial photograph of photochemical smog. The level of the temperature inversion 'lid' and trapping effect of the mountain rim can be clearly seen

Key concepts

The key concepts listed in the syllabus are set out below. For each one a summary of how it applies to this chapter is included.

Space: throughout the chapter, space is evident in the global distributions of radiation energy, temperature, wind belts and ocean currents. Collectively, they use all the space the world has. The patterns of radiation energy, temperature and winds are evident in maps covering all land and sea surfaces, while ocean currents not only span ocean surfaces but also great depths down to and along the ocean floors. This space is dwarfed by the immensity of atmospheric space; radiation energy from the sun crosses 149.6 million kilometres to warm the Earth.

Scale: influences on temperature vary from those operating at the global scale which are controlled by latitude, to others which complicate the global model at a local scale, such as distance from the sea and cloud cover. Human impact is considered in this chapter at both the global and city scales in the studies of climate change and the microclimates of cities. Timescale is also important: for example, the speed of movement of a weather system determines whether it rains for a short or a long time, or the late arrival of the wet monsoon which has severe consequences for the people dependent on it for growing crops.

Place: location has a very important influence on the weather and climate a place experiences. Proximity to the ocean compared to an inland location results in differences in atmospheric pressures, temperatures and precipitation amounts. Similarly, planetary winds and pressure systems are complicated by local differences resulting from the unique physical characteristics of a locality. Very localised small-scale changes are illustrated in the study of microclimates where temperatures and humidity vary between riverside and downtown locations or urban parks and areas of high building density.

Environment: the interactions between people and their environment do create the need to manage the environment sustainably. This is well seen in studies of climate change; research strongly suggests that sustainability depends upon limiting the emissions of greenhouse gases into the atmosphere. The wide-ranging impacts of not doing so, such as the melting of polar ice caps resulting in substantial rises in sea level, will impact adversely on many people. A vicious cycle starts with humans interfering with atmospheric composition and ends with the atmosphere interfering with human activity. In addition, the study of microclimates in cities illustrates that variations result from differences in human use of the various physical environments within the city boundary. The problem of photochemical smog in Vancouver and many other cities is caused by humans using polluting vehicles and combustion. It needs managing sustainably to reduce this important cause of ill-health.

Interdependence: weather is the result of complex interacting systems and processes. Differences in radiation amounts lead to different pressure systems which, in turn, result in winds which bring particular moisture and temperature characteristics to their destination areas from their source regions. Human systems then modify the temperature and rainfall by interfering with the composition of the atmosphere, which has the effect of modifying the weather, causing increased storminess and rainfall in some places and drought in others.

Diversity and **change**: these are evident in the variation of weather from hour to hour, day to day or season to season and also from place to place, as the controlling energy inputs and pressure systems change.

Exam-style questions

1 Fig. 2.68 shows information about the weather in the northwest of the USA on a day in August when there was a westerly wind.

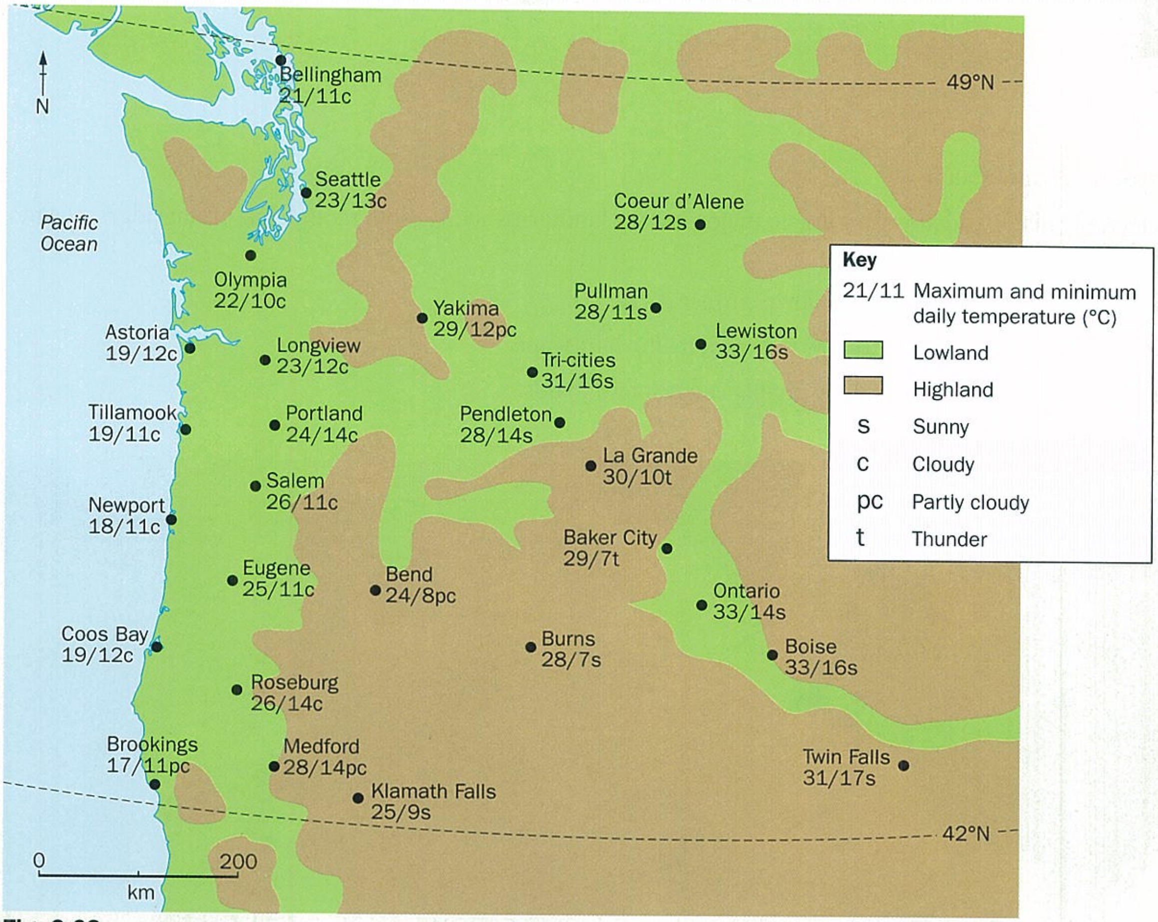


Fig. 2.68

(a) (i) Calculate the diurnal temperature range at Astoria on the coast. [1]

(ii) Using words only, compare the maximum temperatures at Astoria and Lewiston. [1]

(b) Using evidence from Fig. 2.68, describe the relationship between maximum temperature and distance from the sea. [4]

(c) Explain differences in cloudiness within the area that is south of Eugene, Bend and Ontario. [4]

2 (a) (i) Define the term enhanced greenhouse effect. [3]

(ii) Describe the differences between solar radiation and terrestrial radiation. [4]

(b) Describe and explain the air circulation in the Hadley cell of the northern hemisphere. [8]

(c) Assess the extent to which precipitation is dependent on air movement. [15]

3 Rocks and weathering

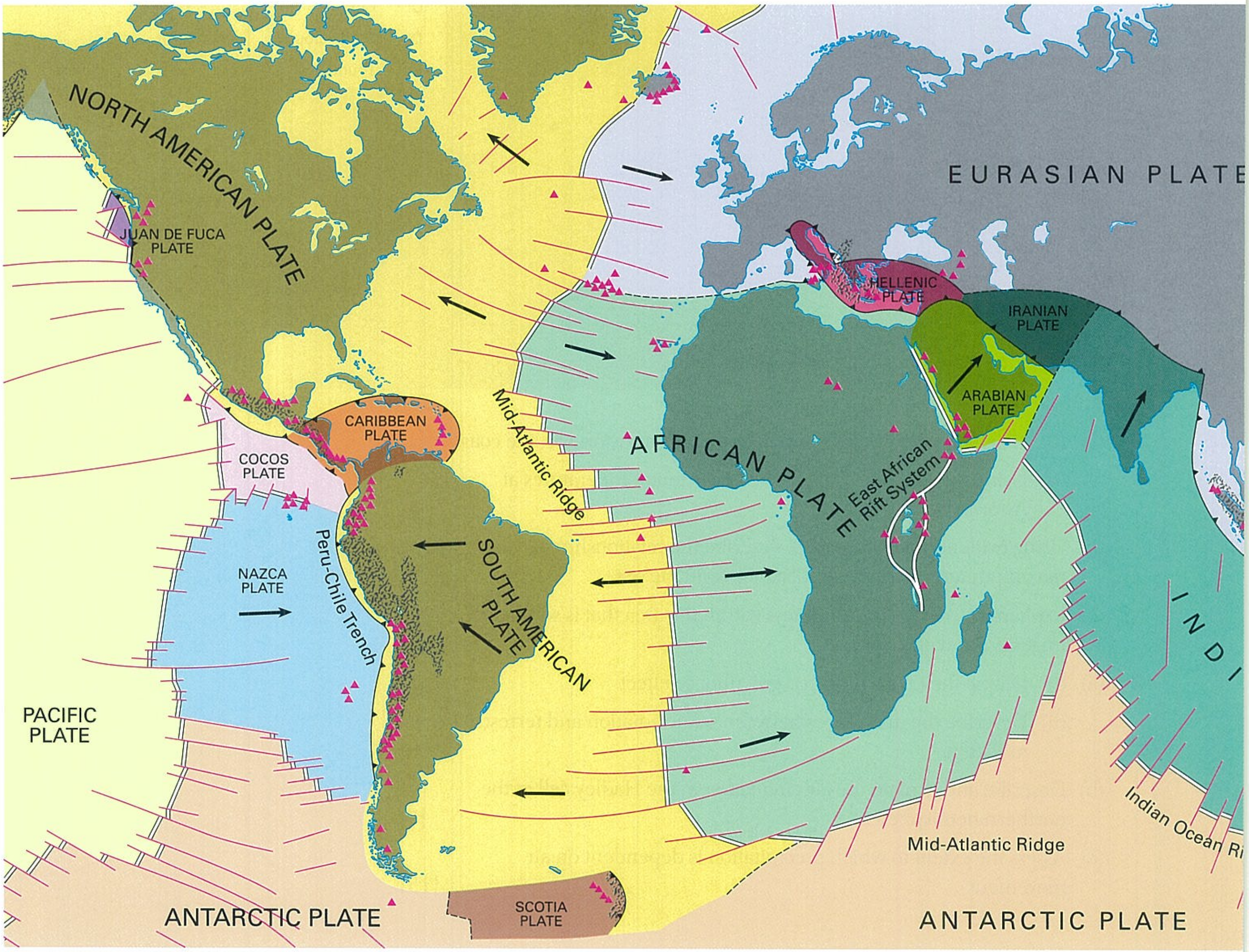
In this chapter you will learn about:

→ The Earth's tectonic plates and how they link to major surface landforms such as fold mountains, ocean ridges, ocean trenches and volcanic island arcs.

→ The processes of weathering which break down surface rocks.

→ The processes acting on hill slopes and how they modify the landscape.

→ How slopes can become unstable and how people can respond to this.



Figs. 3.1 The world's tectonic plates

Plate tectonics

Global patterns of plates

The upper part of planet Earth is known as the **lithosphere**. It is colder than the part of the Earth below it and therefore more rigid. The thickness of the lithosphere varies greatly, ranging from less than 15 kilometres for young oceanic lithosphere to about 200 kilometres or more for ancient continental lithosphere, e.g. the interior parts of North and South America. The average is 50-75 kilometres. The lithosphere includes the Earth's crust and part of the upper mantle. Below the lithosphere is the **asthenosphere**. The boundary between the two (the base of the lithosphere) is taken at the 1300 °C isotherm, dividing the colder, more rigid rocks above from the hotter, more plastic rocks below. There is no change in composition at this boundary.

The lithosphere is divided into a number of **plates** which move relative to one another. Some of the plates are large but there are also smaller plates.

The concept of **plate tectonics** - meaning that the lithospheric plates are in motion and that the movement is responsible for the formation of major landforms - was developed in the 1960s and 1970s. This was partly a result of the first surveys of the floors of the deep ocean basins. The idea of **continental drift** was proposed about 100 years ago but it was not completely accepted until the ocean floor evidence came to light and plate tectonic theory was developed.

1. Name the seven major plates and note whether they include part of an ocean, part of a continent, or both.

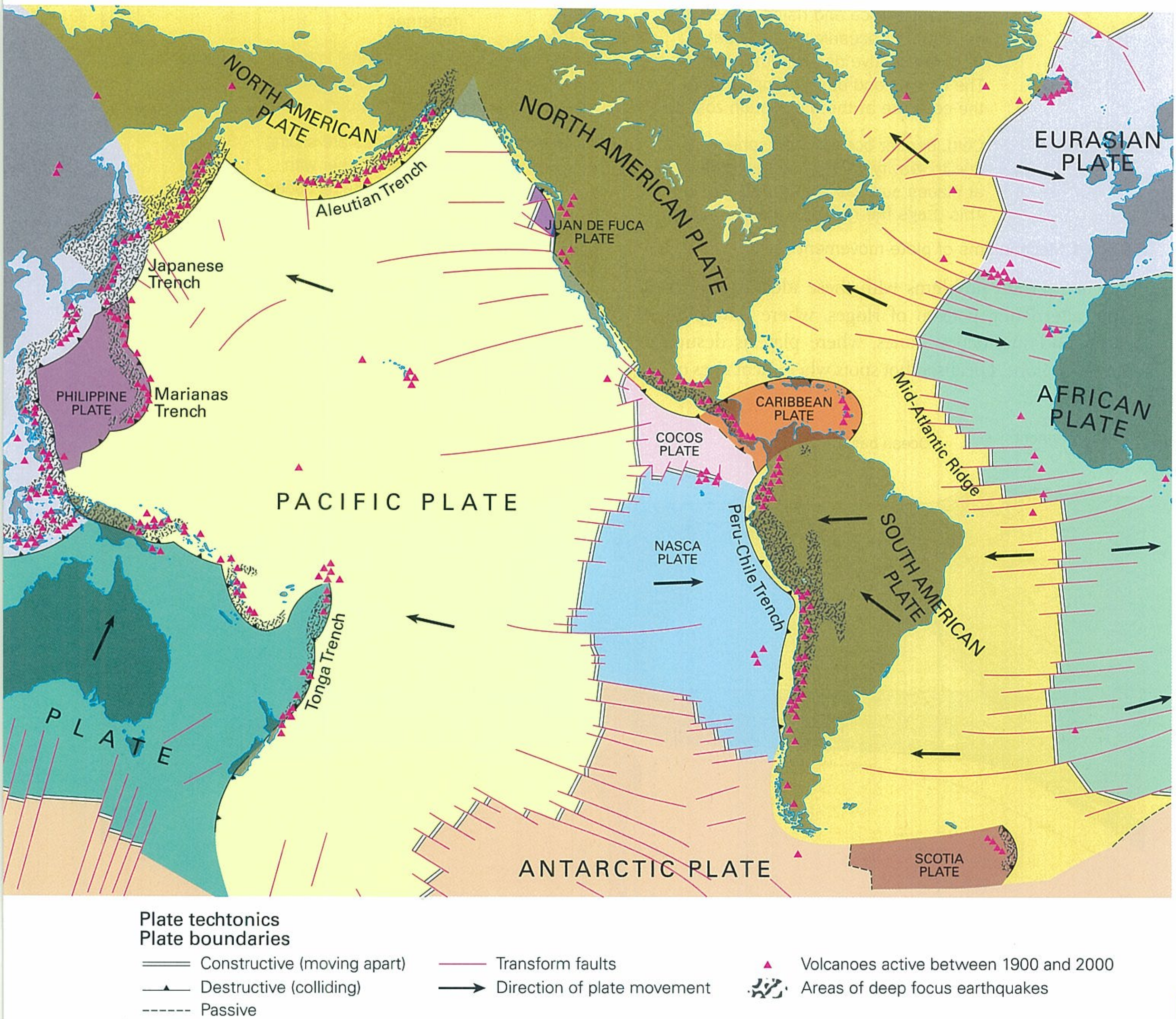


Plate movements

Measurements, taken using fixed stars as reference points, show that the plates are moving between 1 and 10 centimetres a year. Most of the ideas about these plate movements are related to convectional movements of material in the Earth's mantle. Deep within the Earth, heat is being produced by radioactivity. Some areas are hotter than others. At the hotter areas the plastic rocks in the Earth's mantle are thought to become lighter and rise, causing convection currents. This may involve the three mechanisms shown in Table 3.1.

Ridge push	Intrusion of magma into the spreading ocean ridges such as the Mid-Atlantic Ridge propels plates apart.
Convection drag	Convection currents in the plastic mantle drag the overlying lithosphere. The heat source and rising limbs are beneath the oceanic ridges. Heat is from radioactive decay in the mantle. The cooling and descending parts of the cells are at the subduction zones.
Slab pull	Cold, denser oceanic lithosphere sinks due to gravity into the subduction zones at places such as the Aleutian trench. This drags the rest of the plate with it.

Table 3.1 Mechanisms of plate movement

There are certain problems with these ideas. There is no simple alternating pattern of ridges, where new plate is created, and subduction zones, where plate is destroyed, around the globe. Localised hot spots where heat rises occur in places such as Hawaii, well away from the spreading ridges. The mantle may be too rigid to behave like a liquid and allow convection cells to develop.

Plate boundaries (plate margins)

The boundaries between the plates are belts of *major* earthquakes. There are three main types of plate margin, as shown in Table 3.2.

Type of boundary	Description	Type of stress affecting the area
Convergent (destructive)	Where material is being destroyed or subducted and the plates are moving together.	Compression → ←
Divergent (constructive)	Where material is being added and the plates are moving apart.	Tension ← →
Conservative	Where plates are sliding past one another with no material being added to or subducted from either side.	Shearing → ←
Collision	Where two continental plates meet and subduction has ceased	Compression → ←

Table 3.2 Types of plate margin

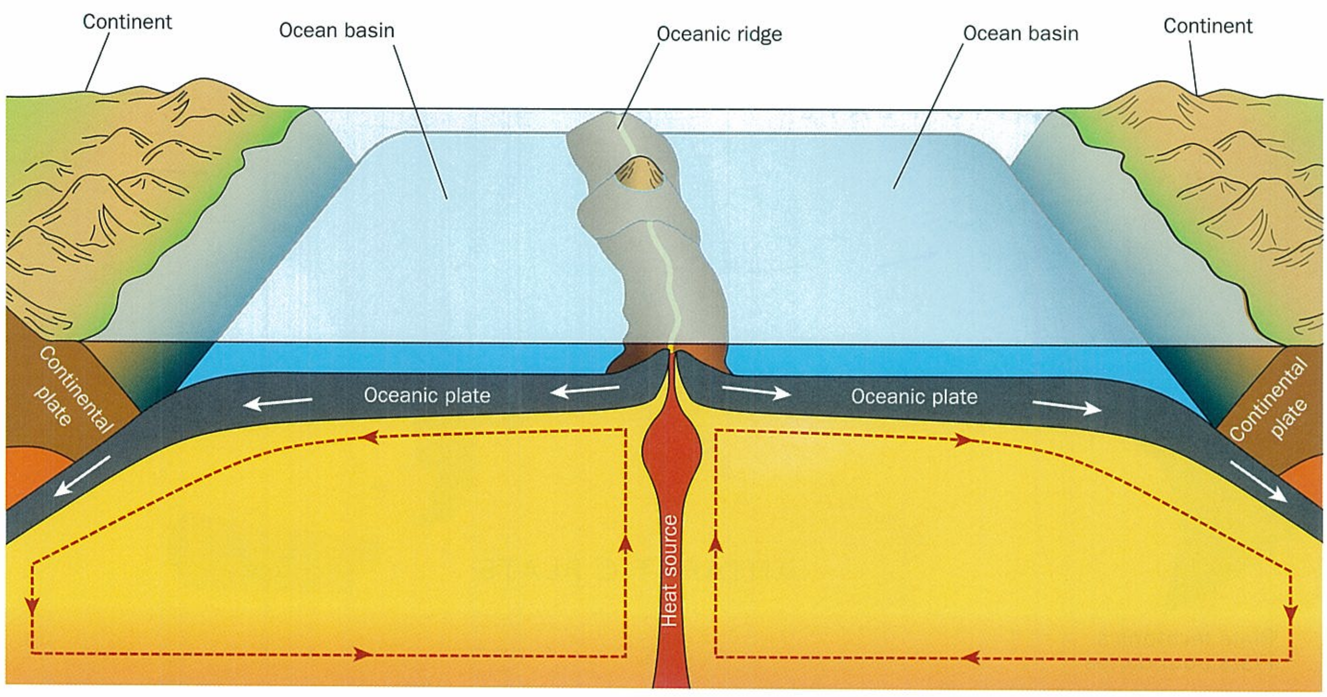


Fig. 3.2 Mechanisms of plate movement

2. Using Fig. 3.1, and Table 3.2, name examples of each type of boundary.

3. Using Fig. 3.1, explain why the Atlantic Ocean is growing by a few centimetres a year but the Pacific Ocean is shrinking.

Convergent plate boundaries

There are three different types of convergent plate margin, depending on the nature of the plates involved. The continental edge of a plate may meet the oceanic edge of a plate, the Andes being the classic example. However, two oceanic edges may meet, as in the Philippines, Japan or the Aleutian Islands, or two continental edges may meet, as in the Himalayas. In the first two of these, plate is destroyed and they are referred to as **destructive** plate boundaries.

Continental-oceanic convergent plate boundaries

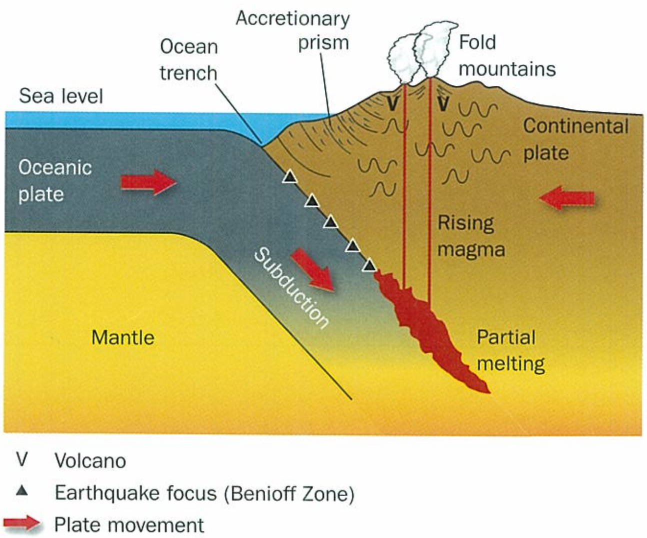


Fig. 3.3 A cross-section through a continental-oceanic convergent plate boundary

The important surface features produced here are **fold mountains**, volcanic cones and **ocean trenches**.

Fold mountains form the highest of the world's mountain ranges. They are long, relatively narrow belts of mountains. They have parallel ridges and valleys and the main range is made up of a series of ranges. Flatter areas form plateaux in the mountains.

4. Find a good atlas map of the physical geography of North America. The ranges of mountains in the west are collectively called the Western Cordillera (meaning western chains). List examples of the many sub-ranges, parallel valleys and inter-montane plateaux.

Fold mountains have been formed where compression caused by the plate collision has squeezed the layers of rock. When the upfolds or **anticlines** form the ridges and the downfolds or **synclines** form valleys this is referred to as **normal relief**. The folding takes place at great depths in the Earth, where the high temperatures and pressures make the rock behave as a plastic solid. As well as the mountains being uplifted, material at depth is forced downwards, leading to thickening of the Earth's crust in the mountain belt. Sediments deposited in the adjacent ocean and trench are scraped up against the leading edge of the continental plate and added to it. This is described as an **accretionary wedge** or **accretionary prism** (see Fig. 3.4).

Active volcanoes form high conical mountains in the ranges. These are usually strato-volcanoes (composite cones) made up of alternate layers of lava and ash and produced by explosive volcanic eruptions. The highest mountain in South America is Aconcagua, 6960 metres above sea level and an active strato-volcano. At these plate margins, the denser oceanic plate is forced beneath the less dense continental plate. This process is referred to as **subduction**. The oceanic plate is absorbed into the mantle and is destroyed. The subducted plate and the overlying mantle are partially melted (see Fig. 3.4.). The small pockets of magma gradually merge with each other and begin to rise to form volcanoes. Collectively, the mountain-building processes are referred to as **orogenesis**.

Offshore, there is no wide continental shelf and the ocean floor drops steeply into a long, narrow ocean trench which is parallel to the fold mountains. Here the water depth is about 10 kilometres, compared to a depth of 2–5 kilometres in the rest of the deep ocean floor. Trenches are a result of the surface being dragged down by subduction.

The sloping zone of earthquake foci shown in Fig. 3.4 is known as the **Benioff Zone**.

Oceanic-oceanic convergent plate boundaries

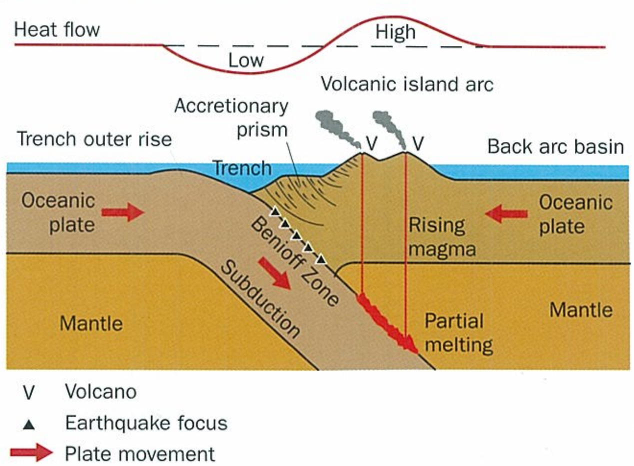


Fig. 3.4 A cross-section through a oceanic-oceanic convergent plate boundary

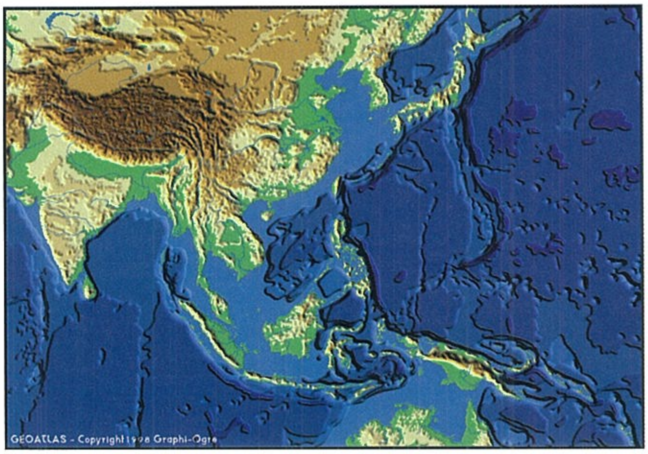


Fig. 3.5 The south-west Pacific Ocean showing island arcs and ocean trenches

The processes that occur at this type of margin are similar to those at the continental-oceanic convergent plate margins. Strato-volcanoes, ocean trenches, accretionary prisms and a Benioff Zone of earthquake foci all occur but there are no fold mountains like the Andes.

Instead the main features are **island arcs** and **ocean trenches**, best illustrated by the western part of the Pacific Ocean. An atlas map will show the Aleutian Islands and trench, the Kuril Islands and trench, Japan and the Japanese trench, the Philippines and the Philippine trench and the Mariana Islands and the Mariana trench. The latter includes the Challenger Deep, at 11 022 metres below sea level, the deepest point on the Earth's surface. The trenches are long, narrow crescents which present their convex sides to the Pacific Ocean and their concave sides towards the Asian continent. Fig. 3.5 shows these very well.

The island arcs are island chains with the same convexo-concave form. The island arcs are made principally of active strato-volcanoes but also by some sediments in an accretionary prism. The chemistry of the lavas is the same as those in the Andes and they form in the same way. As the two converging plates are both oceanic, the rocks at the edges of the plates have the same density. It is always the larger section of plate from the ocean side which is subducted, because of its greater mass. Heat flow (the heat flowing from depth to the Earth's surface) is less than normal over the trench with its cold descending slab, and higher than normal over the volcanic island arc.

Fig. 3.6 Mount Fujiama, Japan, a typical conical strato-volcano

Continental-continental collision boundaries

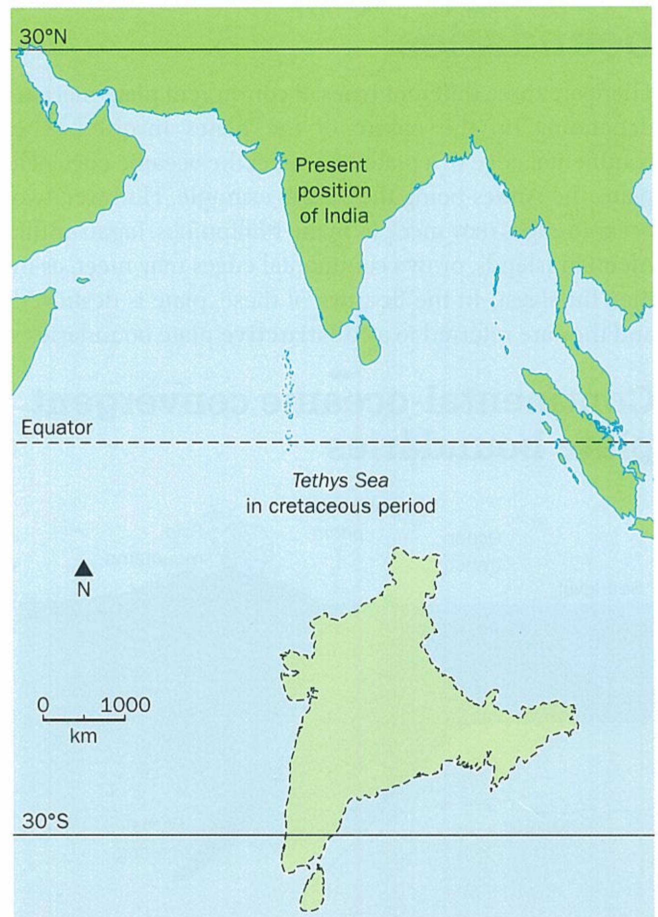


Fig. 3.7 The northward drift of India and the closure of the Tethys Sea

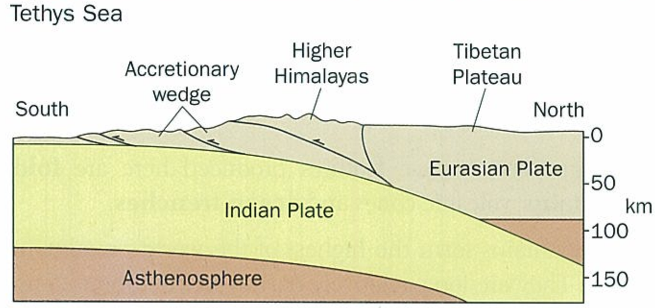


Fig. 3.8 Indian Plate is being forced beneath the Eurasian Plate. Sediments deposited in the Tethys Sea now form an accretionary wedge of folded sediments which is forced upwards to form the mountains.

Fold mountains are formed at these plate boundaries in the same way as at continental-oceanic convergent boundaries described above. Examples include the Himalayas, Tian Shan, Caucuses and Alps. As there is no subduction, there are no active volcanoes. The compressional stresses lead to the formation of earthquakes but these tend to have shallow and intermediate foci and not the deeper foci found in the Benioff Zones.

The fold mountains referred to so far are actively forming today at plate margins. However, there are examples of fold mountains that formed at ancient plate margins that are no longer active. These include the mountains of Scandinavia, Scotland and the Appalachians in North America. These areas do not have active volcanoes or major earthquakes.

Divergent plate boundaries

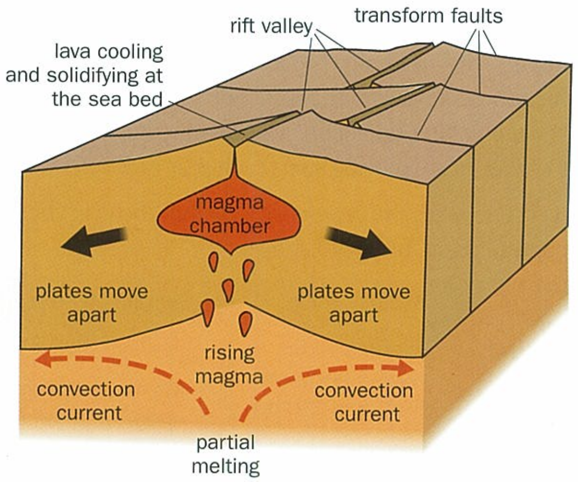


Fig. 3.9 A block diagram through a divergent plate boundary

Fig. 3.10 The deep ocean floor showing the form of ocean ridges

The divergent plate boundaries of the Earth are the sites of the great **oceanic ridges**. They are the most prominent topographic features on the surface of the planet and are well illustrated in Fig. 3.10. The ridges encircle the Earth; they are more than 50 000 kilometres long in places and more than 800 kilometres across. They rise an average of about 4500 metres above the sea floor. They are generally hidden beneath the ocean surface but exceptions are found, such as in Iceland. The Mid-Atlantic Ridge is one-third of the width of the ocean. Other examples include the East Pacific Rise and the Carlsberg Ridge in the Indian Ocean. The latter was named after the multinational brewing company which provided finance for research of the area.

The ridges' higher relief than the rest of the ocean floor is because the ridges consist of relatively hot, thermally expanded rock - an area of high heat flow. The ocean becomes deeper further away from the ridges; as the crustal material moves away from the ridge it cools, contracts and becomes lower. As Fig. 3.9 shows, the ridges are really a series of parallel ridges. There is a double central ridge separated by a **rift valley**. As a result of tension or stretching in the crust, a central block falls between parallel fault systems. The ridge is continuously offset by **transform faults**, sometimes referred to as **fracture zones** (see Fig. 3.9).

5. Explain the meaning of the terms 'lithosphere', 'asthenosphere', 'subduction', 'orogenesis' and 'island arc'.

Continental drift

The speculation that continents might have moved their positions was first put forward by Abraham Ortelius in 1596. The concept was developed by Alfred Wegener in 1912. The evidence was as follows:

Coastline fit

Wegener's theory was based in part on what appeared to him to be the remarkable fit of South America and Africa. The fit is best when the edges of continental slopes are used and features such as the Niger Delta are omitted.

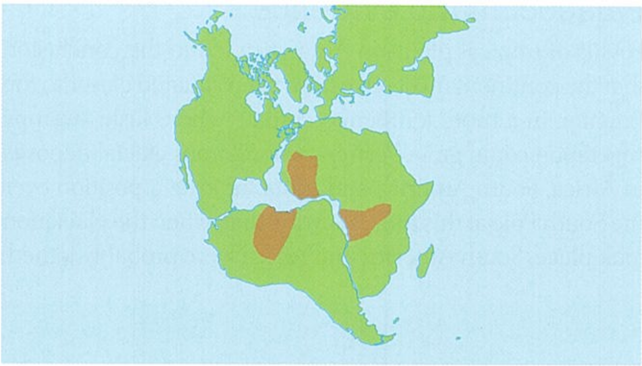


Fig. 3.11 The fit of the Atlantic continents. The shaded areas show rocks more than 2000 million years old

Fossils, flora and fauna

There are similarities between plant and animal fossils found on the matching coastlines of South America and Africa. It would be physically impossible for most of these organisms to have swum or been transported across the vast oceans. One of these fossils is Mesosaurus, a crocodile-like reptile which lived in lakes and could not have crossed wide seas. This suggests the continents were joined 270 million years ago. It was also suggested that the flightless birds of the southern hemisphere (ostrich in Africa, emu in Australia, kiwi in New Zealand and rhea in South America) evolved separately from a common ancestor on the ancient super-continent of Gondwanaland. Then the super-continent split and the birds evolved separately and developed different features.

Fit of orogenic belts

When Atlantic coastlines are fitted together, orogenic belts (fold mountain belts) of the same age join up, e.g. the orogenic belts of North Appalachians, Newfoundland, northern Britain and Norway.

Fig. 3.12 The fit of orogenic belts across the North Atlantic

Fit of rock types

Precambrian rocks more than 2000 million years on either side of Atlantic join up when the Atlantic coastlines are fitted together (see Fig. 3.11). The same is true of sedimentary sequences 140–100 million years old on the Atlantic margins of both continents, indicating that the rocks were deposited in lakes and narrow seas between the continents.

Palaeoclimatic evidence

Fossils of tropical plants in Antarctica led to the conclusion that the continent must once have been situated closer to the Equator, in a more temperate climate where lush, swampy vegetation could grow. Permo-carboniferous glacial deposits in Africa, South America and India indicate a position over the South Pole at this time, showing that, when the glaciation took place, South America and Africa were probably joined.

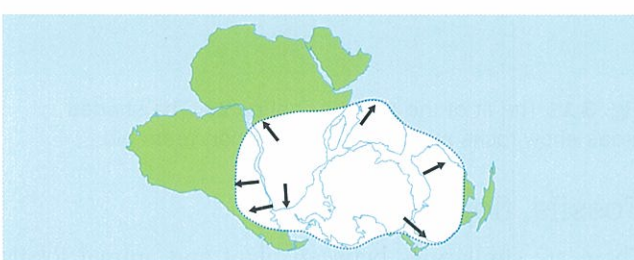


Fig. 3.13 The position of an ice sheet over the southern continents about 280 million years ago. The arrows show the ice movement directions indicated by features in the glacial deposits

6. Wegener noticed the remarkable fit of South America and Africa. The fit is best when the edges of continental slopes are used and features such as the Niger Delta are omitted. Why is this so?

Sea-floor spreading

Sea-floor spreading is the process of creation of new oceanic lithosphere at the ocean ridges and the divergence of the new lithosphere on either side of the ridge. The process begins with partial melting of rocks (a dark, dense rock called peridotite) in the upper mantle (the asthenosphere) beneath the ridge axis, in high temperature and low pressure conditions. The resulting magma forms pockets which collect together and rise to the surface. The magma is eventually extruded along the ridge as dark-coloured **basalt** lavas. The lava cools rapidly in contact with sea water and develops spherical structures known as pillows. Below this, some magma cools and solidifies below the surface to form the rock types dolerite and gabbro. The newly formed lithosphere cracks and diverges and the plates on either side of the ridge move slowly outwards from it, driven apart by mantle convection currents. Rates of divergence vary across the Earth but on either side of the Mid-Atlantic Ridge, Britain and North America are moving apart each year by 8 centimetres.

The crust beneath the oceans differs from the crust beneath the continents, as Table 3.3 shows.

	Oceanic crust	Continental crust
Thickness	Average 7 km (varies between 5 km and 10 km)	Average 35 km Maximum 90 km under mountain ranges such as the Himalayas
Structure	Layered structure: 1. Sediment 2. Basalt pillow lava 3. Dolerite 4. Gabbro	More complex structure: igneous, sedimentary and metamorphic rocks
Composition	Chemical composition of basalt	Overall chemical composition similar to granite
Chemistry	Rich in iron and magnesium	Rich in silicon and aluminium
Density	$2.9 g.cm^{-3}$	$2.7 g.cm^{-3}$
Age	Oldest rocks 200 million years	Oldest rocks 4000 million years
Physical state	Solid	Solid

Table 3.3 A comparison of the oceanic and continental crust

7. Study Table 3.3. Using information from Table 3.3 and what you have learned so far, explain the different ages of the oceanic and continental crusts.

Evidence for sea-floor spreading

The more recent evidence from ocean floor surveys confirmed that continental drift has occurred and led to the acceptance of plate tectonic theory:

- → Age of the rocks of the ocean floor – this can be determined by be a technique called radiometric dating (e.g. the K-Ar method). At the crest of the ridge the basalts and the sediments which lie above them are very young, and they become progressively older away from the ridge crest.
- → Thickness of sediment on the ocean floor – this increases with increasing distance away from the ridge – there has been more time for the sediment to accumulate. Older sediments are found on the sea bed at the margins of the oceans (see Fig. 3.14).

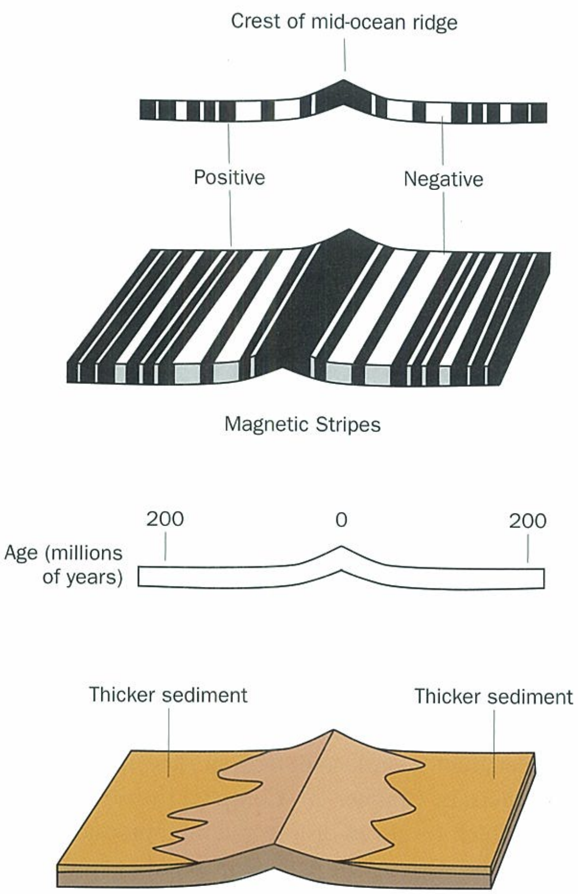


Fig. 3.14 Magnetic stripes, ocean floor sediments and the age of the ocean floor

- → Direct satellite measurements of the width of the oceans – very precise measurements over time, of fixed points on the land masses, show the rate of ocean opening and closure.
- → **Magnetic stripes** – iron minerals in the Earth's crust are magnetised by the Earth's magnetic field when the rock is forming, especially iron-rich basalt. These iron minerals tend to become aligned like tiny compass needles parallel to the magnetic field. The magnetism is weak but permanent, unless rocks are reheated. This is **palaeomagnetism** – fossil magnetism. It can be measured to give information about the Earth's magnetic field in the past.

The Earth acts as though it has a bar magnet through the centre. In the past there have been periodic geomagnetic reversals – reversals in the dipoles of the Earth's magnetic field – as though the bar magnet has 'flipped'. The youngest rocks at the ridge crest always have present-day (normal) polarity. Stripes of rock parallel to the ridge crest alternate in magnetic polarity (normal–reversed–normal, etc.), showing a symmetrical pattern on either side of the ridge. The stripes are of unequal width. This shows that the rate of spreading is the same on both sides of the ridge but that geomagnetic reversals do not take place at regular time intervals (see Fig. 3.14).

Hot spots

Although most volcanic activity takes place at plate margins, there are exceptions. A good example is Hawaii and the Emperor **seamounts** (a seamount is a submarine volcano). A hot spot is a volcano in a plate above a **mantle plume**. The plume is a stationary area of high heat flow in the mantle. It rises from great depths and generates magma. The age and distance apart of hot spot volcanoes are used to calculate the rate of sea-floor spreading. This is because the volcanoes form over the mantle plume then the plate movement carries them away.

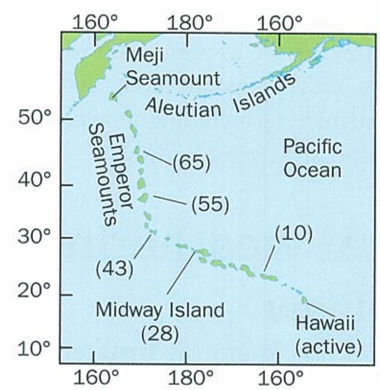


Fig. 3.15 The Hawaiian volcanic islands and the Emperor seamounts. The number in brackets is the age of the islands in millions of years

8. Using Fig. 3.15, describe the direction of plate movement

(a) between today and 43 million years ago

(b) between 43 and 65 million years ago.

9. The distance between Hawaii and Midway Island is about 320 kilometres. Calculate the rate of plate movement in centimetres per year during the movement of Midway Island.

10. How does it appear that the rate of plate movement has changed and what is the evidence?

Iceland is unusual because it is believed to be a hot spot on a plate boundary. One half of the island is on the North American Plate and the other half is part of the Eurasian Plate (see Fig. 3.16).

Fig. 3.16 The Mid-Atlantic Rift at Thingvellir, Iceland. The North American Plate is on one side of the rift and the Eurasian Plate is on the other

Weathering

Weathering is the decay and disintegration of rocks *in situ*, involving physical, chemical and biological processes. It excludes the erosional effects of running water, rivers, the sea, glaciers and the wind. The weathering processes do not transport the products away.

Rocks and minerals become adjusted to surface environments different from those in which they were formed. The products cover the Earth's surface as part of the **regolith** and go on to form new rocks. The regolith is the surface cover of loose, unconsolidated material including alluvium, glacial deposits, wind-blown sand, peat, scree and soil.

Physical weathering

Freeze–thaw

This process is also known as **frost shattering**. Water trickles into cracks such as joints during the day. At night this water freezes, expands by about 10 per cent and widens the crack. The stress produced by the expansion is greater than the resistance of the rock. Repeated freezing and thawing results in disintegration and the production of **scree** (**talus**) and **felsenmeer** (block fields). In temperate areas such as the highlands in the UK, these features are largely relics of the past periglacial climate rather than actively forming today. The critical feature for the process to be active is the number of freeze–thaw cycles rather than the intensity of the frost. This means that the processes is not active in winters in continental interiors where there is constant frost.

The shape and size of the particles produced by the process is controlled by the nature of the rock, especially lines of weakness such as joints, bedding planes and cleavage.

Scree is angular rock fragments. It falls from cliffs in areas of freeze–thaw action, falls down gulleys and is deposited as cone or fan shapes which may coalesce with one another. Such slopes are prominent features of many mountainous areas.

Fig. 3.17 Scree slopes in north-west Scotland

Heating and cooling (thermal fracture)

Large diurnal ranges of temperature in deserts cause rocks and minerals to expand during the day and contract during the night, resulting in disintegration.

Granular disintegration

This process is partly responsible for producing sand in deserts. Rates of expansion and contraction vary between:

- different minerals
- different axes of a crystal
- crystals of different sizes.

Also, different coloured minerals absorb and emit heat at different rates. A pale-coloured rock like granite will reflect more heat than a dark-coloured one like basalt (see the albedo effect in Chapter 2). Complex stresses are set up in rocks which results in disintegration to produce mineral grains and the great sand seas or **ergs** found in some deserts.

Fig. 3.18 A sandy desert surface in Namibia

Block disintegration

This produces rock fragments not mineral grains and results in the features of the stony deserts known as **reg**. Scree slopes at the foot of cliffs and boulder fields are produced.

Fig. 3.19 A rocky desert surface in Namibia

Salt crystal growth

This process happens when salt solutions in the pores or joints of a rock crystallise. The crystals then expand and force the rock apart. The most effective salts are sodium sulfate, magnesium sulfate, sodium carbonate and calcium chloride. The process is particularly effective in temperatures of around 27 °C where temperature fluctuations produce expansion rates of up to 300 per cent.

Pressure release (dilatation)

This process, also known as **unloading**, affects areas where the ground surface is lowered by erosion. This removes weight from previously deeply buried rocks, e.g. a granite pluton which formed at immense pressure, several kilometres below the Earth's surface. This removal of weight leads to the expansion of the upper parts of the granite and allows cracks to occur parallel to the ground surface, sometimes known as **pseudo-bedding planes**. A similar process may occur where horizontal pressure is released by rock falls on a cliff face, allowing the growth of vertical cracks which, in turn, leads to further rock falls. This mechanism is significant after glaciation has occurred and can be caused by quarrying (see pages 87-90 on mass movement).

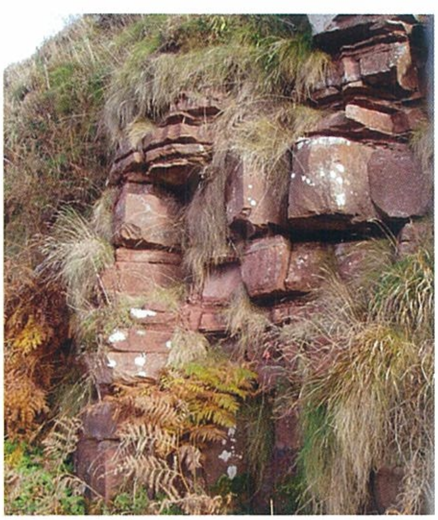


Fig. 3.20 In these alternating layers of sandstone and shales, the latter have been weathered more rapidly and have crumbled. The cliff surface is indented along the shale layers where vegetation is growing

Chemical weathering

Hydrolysis

This is when a mineral is broken down by a reaction with water. It is important in the silicate minerals that form most rocks, especially the mineral feldspar. The process usually occurs in acid conditions.

$$2KAlSi_3O_8 + 11H_2O + 2CO_2 \longrightarrow Al_2Si_2O_5(OH)_4$$

kaolinite (clay)

feldspar + $4H_4SiO_4$ silicic acid + $2K^+$ + $2HCO_3^-$ } ions in solution

The reaction shown above also includes some carbonation. The reaction produces a clay residue and various solutions which are removed in the groundwater and can be found in analysis of river water. You may see the variations in the formula written for hydrolysis.

Other clays are produced from other silicate minerals, e.g. montmorillonite.

Hydration and dehydration

Wetting and drying can cause the addition or removal of water from the molecules of some minerals, causing expansion or contraction which assist disintegration. The calcium sulfate minerals anhydrite and gypsum are affected.

$$\underset{\text{anhydrite}}{CaSO_4} + 2H_2O \longleftrightarrow \underset{\text{gypsum}}{CaSO_4.2H_2O}$$

Carbonation

This process affects the carbonate minerals that make up limestone, especially calcite, calcium carbonate. Rainwater contains the weak acid, carbonic acid, which forms as the rain absorbs atmospheric carbon dioxide. Carbonic acid then attacks the carbonate minerals.

$$\underset{\text{water}}{H_2O} + \underset{\text{carbon dioxide}}{CO_2} \rightarrow \underset{\text{carbonic acid}}{H_2CO_3}$$

$$\underset{\text{carbonic acid}}{H_2CO_3} + \underset{\text{calcite}}{CaCO_3} \rightarrow \underset{\text{calcium hydrogen carbonate}}{Ca(HCO_3)_2}$$

Calcium hydrogen carbonate is removed in solution (sometimes known as hard water) and is washed away down rivers. The muddy insoluble impurities in the limestone are left as a clay residue. The process is responsible for the characteristic limestone scenery known as karst. The chemical weathering of limestone is accelerated by pollutants such as sulfur dioxide and oxides of nitrogen.

Fig. 3.21 Spheroidal weathering of basalt. Water has penetrated the rectangular joints allowing chemical weathering to produce rounded blocks

11. Physical and chemical weathering are often considered separately; however, in nature the two are often linked. Explain how chemical processes can have a physical effect.

Organic action – vegetation roots

Biological weathering can have a physical effect on rocks as seen in the wedging effect of tree roots. Where the soil is shallow, the seeds and roots of trees find their way into natural cracks in the bedrock. As the seeds germinate and the roots get bigger, they make the cracks wider and deeper, eventually breaking up the bedrock. This effect can often be seen in road cuttings and quarries.

Other biological effects tend to assist chemical processes, for example as follows:

- The release of humic acids by decaying vegetation encourages hydrolysis.
- The release of carbon dioxide by plants encourages carbonation.
- A blanket of vegetation traps water and encourages a variety of chemical processes.

Fig. 3.22 The wedging effect of tree roots, Drakensberg Mountains, South Africa

Factors influencing weathering

Climate	Climate determines which weathering processes will occur and the rate at which they occur. This is considered in more detail below.
Rock structure	Weaknesses such as joints, bedding planes and cleavage allow water penetration and increase both physical and chemical effects (see Fig. 3.20). These weaknesses also control the size and shape of the weathered fragments. Good examples are the spheroidal weathering of dolerite, the formation of tors in granite and the formation of scree slopes.
Rock texture	In general, coarse-grained rocks weather faster than their fine-grained equivalents because the weathering of one mineral in the rock tends to weaken the fabric of the rock to a greater degree. Igneous rocks have a greater resistance to physical disintegration than sedimentary rocks because of the greater strength of interlocking crystalline textures in comparison with granular ones.
Rock composition	The minerals which form at the highest temperatures are the least stable at surface temperatures. This means that minerals in the dark-coloured rocks such as basalt weather faster than those in pale-coloured rocks such as granite.

	Minerals in basalt	**Minerals in granite**
Most susceptible	olivine plagioclase feldspar pyroxene	biotite
Least susceptible		orthoclase feldspar muscovite quartz

Slope processes

Mass movement

Mass movement (also known as mass wasting) is the term for the downslope movement of rock and weathered debris by gravity alone. It does not include the work of erosive agents such as running water or glaciers. Care is needed when reading accounts of mass movements because phrases such as 'landslide' may not be used in a technically correct way.

Mass movement	Creep and solifluction	
	Debris flows and lahars	
	Slope failures	Slides
		Falls

Table 3.5 Types of mass movement

Fig. 3.25 Terracettes caused by soil creep

Creep

This is the slow, downslope movement of unconsolidated material and soft rocks. This movement is rarely more than 1–2 centimetres a year. It is the result of several different processes:

→ Clay-rich material is liable to **plastic flow**. This is more likely to happen on saturated, thick, surface deposits on steeper slopes. It can also be affected by pressure from overlying cap rocks or human constructions.

→ Freezing and thawing of water in the surface layers of the clay or soil can produce **heave**. The expansion of water on freezing causes bulging of the surface parallel to the slope. On thawing, the material drops back vertically leading to a net downslope movement of the particles.

→ Wetting and drying causes clays to expand and contract, causing heave to occur in the same way as freezing and thawing.

In areas of permafrost, the waterlogged summer conditions lead to accelerated creep known as **solifluction**, although this may involve some viscous flow.

Creep may be responsible for the convexo-concave rolling landscapes found in temperate areas such as western Europe. The process is also thought to be responsible for the small ridges across hillsides known as **terracettes**.

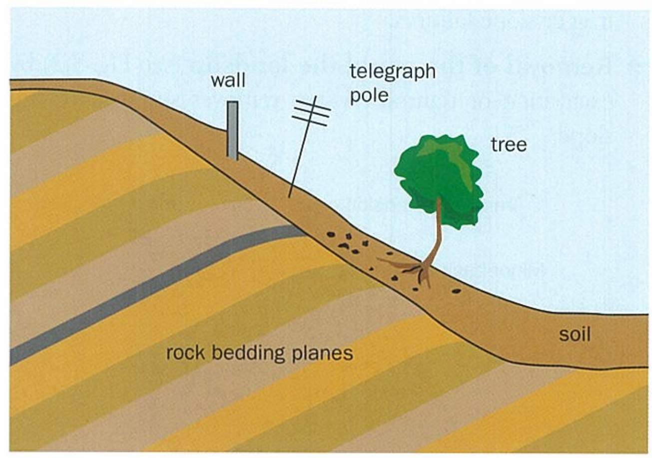


Fig. 3.26 Evidence for soil creep

13. Study Fig. 3.26. Describe the evidence for soil creep shown in the diagram.

Flows

Often referred to as mudflows (see Fig. 3.45), these involve the rapid movement of rock and weathered debris mixed with water down valleys. They do not involve shearing and are a turbulent, structureless mixture of sediment and water. Flows are linked to the following factors:

→ steep slopes

→ narrow valleys

→ removal of vegetation and construction projects

→ a thick regolith, therefore they are common in the tropics where deep chemical weathering occurs

→ heavy rainfall to saturate the ground

→ a slope failure or slide (see below) which may trigger the flow

→ earthquakes or traffic vibration; earthquakes can also cause liquefaction of saturated material.

These conditions may be found on the slopes of active volcanoes where the mudflows are termed **lahars**. In this case loose, volcanic ash combines with run-off from convectional rainstorms produced by eruptions.

Mudflows have devastating effects in less-economically developed countries, especially when the narrow valleys are densely populated. However, they affect affluent areas too.

Slides

Landslides are single dramatic events when a section of a hillside becomes unstable, shears away and moves downhill. The shear stresses in the slope exceed the shear strength of the soil or rock. The slopes in question could be natural or the result of human activity such as road cuttings, embankments and spoil heaps.

Factors leading to slope failure include the following:

- **Slope angle** – the steeper the slope the greater the potential for instability.
- **Geological structure** – fractures such as bedding planes dipping out of the slope increase the possibility of slippage.
- **Rock type** – vertical cliffs may be quite stable in some rocks whereas some clay slopes are unstable on slope angles of less than 10 degrees. Layers of impermeable rock trap water above them, leading to highly lubricated layers.
- **Amount of water present** – water increases the weight of soil or rock. Pore water pressure decreases the shear strength of the material, with saturated clays being particularly unstable. Heavy rain or snow melt can trigger slope failures.
- **Removal of the toe of the landslip** (see Fig. 3.2) by excavation or natural erosion removes support for the slope.

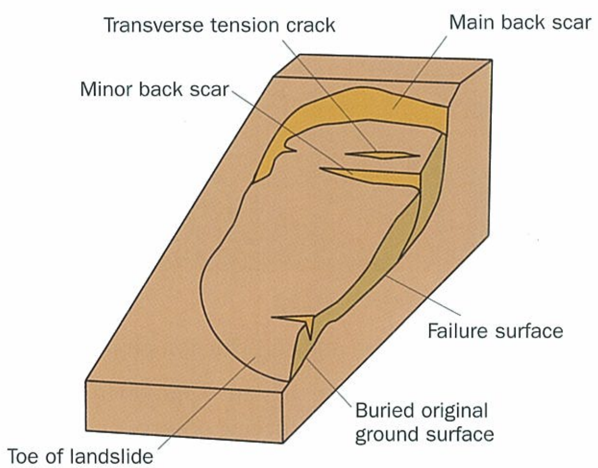


Fig. 3.27 The effect of a landslide on the surface. The failure surfaces can be planar as well as curvilinear. Notice the curved slip faces and the rotational movement which tilts the slope backwards. The toe of the slip is often an area of uneven, deformed ground

Fig. 3.28 An old landslide at Black Combe, Cumbria, UK. Notice the main back scar

- **Loading of the head of the slope** by construction projects can cause the slope to fail.
- **Vibrations** from explosions, earthquakes or heavy traffic temporarily increase stress.

These factors work by either increasing the shear stresses in the slope or reducing the shear strength of the soil or rock.

Case study: The Vaiont dam disaster, Italy, 1963

This landslide resulted in the loss of 2600 lives. A dam 266 metres high was constructed across the Vaiont River to produce hydro-electricity. The site was a deep, narrow valley chosen to store large volumes of water. Slippage started when the reservoir started to be filled, so the slope was reinforced. When the reservoir was filled completely, water seeped into the rock layer, increasing pore water pressure and reducing cohesion. On 9 October 1963 heavy rainfall resulted in 270 million cubic metres of rock sliding into the reservoir at a speed of 25 metres per second. This created a wave 100 metres high which flowed over the dam and into the valley below.

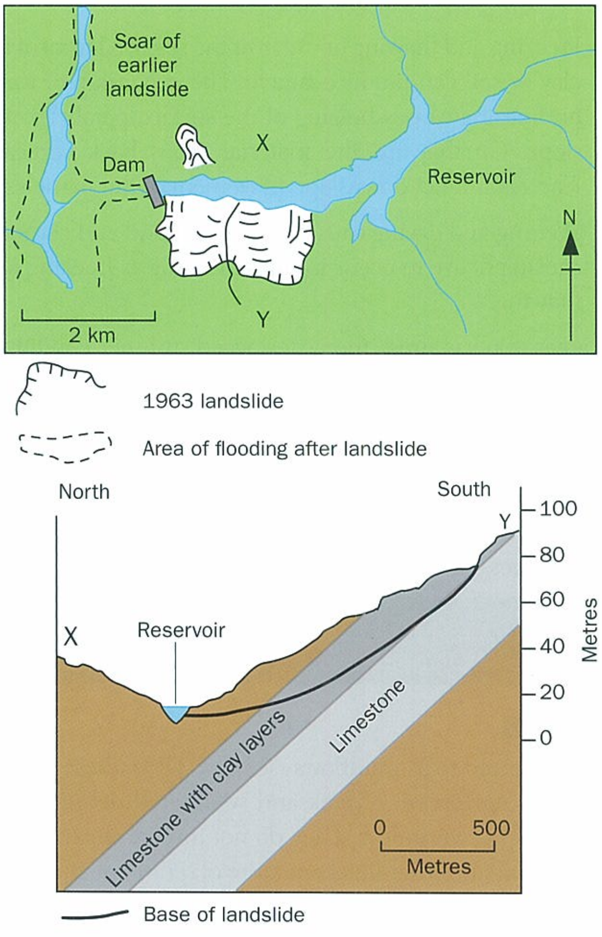


Fig. 3.29 The Vaiont dam landslide

Rock type	**Sandstone** The cement is generally attacked to produce granular disintegration. Resistance depends on the nature of the cement. For example, quartz cement is most resistant, while $CaCO_3$ cement is prone to carbonation. Joints and bedding planes may provide lines of weakness for physical or chemical attack. **Shale** The clay minerals in shale are weathered products of other rocks, therefore tend to be resistant to chemical weathering. Iron oxides and sulfides are commonly present and these tend to oxidise and hydrate, resulting in changes in volume and disintegration. Laminations (and porosity in clays) allow water penetration, increasing both physical and chemical attack. The softness of the rock also increases susceptibility to physical weathering. Shales and clays usually form lowlands as they are easily weathered (and eroded). **Slate** Chemical reactions occur similar to those in shale. Slate is chemically resistant to many reactions, but iron compounds, e.g. pyrite, are prone to oxidation, leaving brown stains; weathered cubes of pyrite often leave holes in slate. Cleavage may allow water penetration and allow freeze–thaw action to produce 'flat' scree fragments. **Basalt** Basalt is rich in minerals which are less resistant to decay by hydrolysis (see the list above). Basalt is often highly weathered, as seen in the rusty residues of iron oxides. The resulting soils are dark coloured and highly fertile due to the presence of a wide range of elements held in montmorillonite clay. Joints allow water penetration which encourages chemical decay and physical processes leading to block disintegration. **Dolerite** Chemical decay occurs in the same way as described for basalt. **Spheroidal weathering** (see Fig. 3.21) is controlled by the joint pattern and is often a sub-surface process. **Limestone** The carbonate minerals are weathered by carbonation and removed in solution. Insoluble clay minerals are left as a residue. Joints allow water penetration and deeper weathering. **Granite** The quartz and muscovite in granite resist chemical decay and are left as a residue of sand grains and mica flakes. Feldspar and other minerals break down by hydrolysis to produce clay minerals. Joints allow water penetration and deeper weathering.
Vegetation	In general, increased amounts of vegetation increase the rate of chemical action through the release of organic acids, important in processes such as chelation. The increased level of carbon dioxide from plant respiration forms carbonic acid when dissolved in water and increases rates of carbonation. Rates of physical weathering will decrease due to the thermal insulation of the vegetation which decreases frost action and thermal effects. Direct biological weathering, through the growth of plant roots into joints and along bedding planes and wedging rock apart, will increase.
Relief	The effect of relief is largely because of its indirect effect on climate. For example, in temperate areas where chemical weathering is usually dominant, freeze–thaw action may be important in mountainous areas. Rainfall totals tend to be higher in upland areas and temperatures colder, again increasing rates of physical weathering such as freeze–thaw action. Slope processes, such as landslides, can result in the exposure of previously unexposed, bare rock which then becomes susceptible to weathering. In lowland areas, unweathered rock may be protected by thick layers of soil and weathered material. The accumulation of water at the base of slopes may also provide more water for chemical processes to take place. Aspect of different slope faces may also affect rates of weathering. In the northern hemisphere, rates of physical weathering are greater on north-facing slopes, which experience more freeze–thaw cycles due to the lack of direct sunlight. The opposite is the case in the southern hemisphere.
Human activity	Humans have increased rates of weathering by increasing the concentrations of chemical pollutants in the atmosphere by industry, power stations and vehicle emissions. The increase in gases such as carbon dioxide, sulfur dioxide and nitrogen oxides has lead to increased acidity of rainfall. This acid rain increases rates of carbonation and hydrolysis. Removal of vegetation can result in a decrease in chemical and biological weathering, e.g. through a reduction in organic acids.

Table 3.4 Factors influencing weathering

Climate

Polar and sub-polar areas

These high latitude areas are affected mainly by freeze-thaw action. These conditions may also occur on mountains in temperate areas. The degree of activity depends on the number of freeze-thaw cycles rather than the degree of frost, therefore the rate of weathering in very cold areas is restricted.

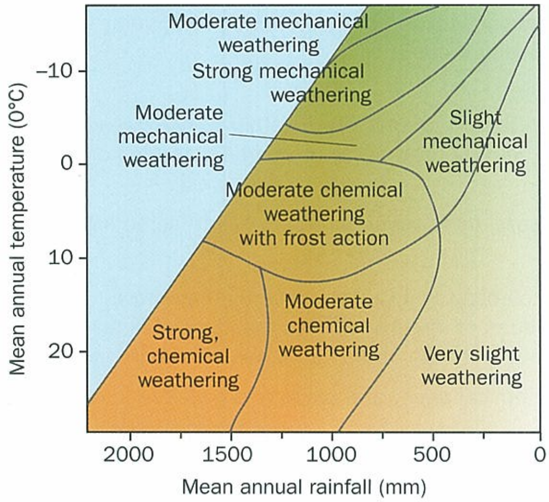


Fig. 3.23 The effect of climate on weathering, as described by Peltier in 1950

Chemical action is restricted by the cold temperatures which slow rates of chemical reactions. However, carbon dioxide is more soluble at low temperatures so carbonation can occur. Hydration may occur in waterlogged areas in summer.

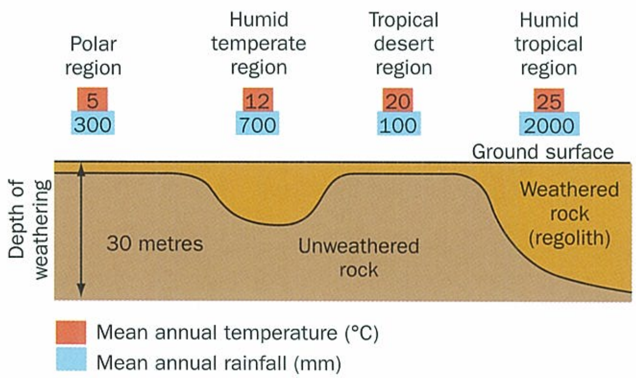


Fig. 3.24 Rates of weathering in different climates

Humid temperate areas

Physical weathering is minimal; the screes of upland areas may be relict features of periglacial conditions in the Quaternary period (the last 2 million years). Similarly, the tors of areas such as Dartmoor in south-west England may also have formed in past climates, although in this case possibly in warm conditions in the Tertiary period when rates of chemical weathering were greater.

All the chemical and biological weathering processes are significant due to the wet climate and the blanket of vegetation which causes the biological effects. Pollution effects are important, especially in urban areas.

Arid and semi-arid areas

Rates of weathering are the slowest on Earth in these areas. This is illustrated by well-preserved archaeological remains, e.g. Cleopatra's Needle weathered more in 10 years in the wet, polluted atmosphere of London than in 3500 years in the Egyptian desert.

Chemical action is probably very slow due to the lack of moisture. Salt crystal growth, and physical expansion and contraction, due to the large diurnal ranges of temperature, may lead to granular disintegration, block disintegration and exfoliation (see Chapter 10).

Humid tropical areas

These areas have the most rapid rates of weathering on Earth. The regolith is often up to 40 metres deep and rocks are observed to weather significantly in decades. Rates of chemical reaction are accelerated by the hot, wet conditions; in particular, the increased ionisation of water increases the rate of hydrolysis of silicates. The increase rate of weathering at higher temperatures is known as Van't Hoff's Law.

12. Study Fig. 3.23 and the information on weathering processes. Describe the rates of weathering and weathering processes that are likely to occur in each of the following conditions:

(a) mean annual temperature 25 °C and mean annual precipitation 2000 millimetres

(b) mean annual temperature 15 °C and mean annual precipitation 1000 millimetres

(c) mean annual temperature 20 °C and mean annual precipitation 250 millimetres

(d) mean annual temperature 5 °C and mean annual precipitation 1000 millimetres.

14. Study Fig. 3.29. Explain how the geology of the area led to the landslide.

Falls

Rock falls from vertical faces share many of the features of landslides and are caused by similar factors. In addition, undercutting of the base of the cliff by a river or the sea are common factors.

Rock falls reduce horizontal pressure on a cliff face, allowing the growth of vertical cracks which, in turn, lead to further rock falls. This mechanism is significant after glaciation has occurred. Glaciers excavate deep valleys and support steep valley sides. After the ice has melted the sides are less supported and liable to rock falls.

Rock falls produce scree (talus) which accumulates as cones or fans at the base. These may eventually join together to produce a continuous slope like those in Fig. 3.30 or huge boulders like those shown in Fig. 3.31. Some fragments may bounce significant distances. Scree slope angles rarely exceed 40°, despite their appearance.

The angle of the scree slope depends on:

- the size of the rock fragments
- the shape of the rock fragments
- the height of the cliff (or 'free face') through which the fragments have fallen.

15. Suggest the effect that each of the factors listed above is likely to have on the angle of a scree slope. Illustrate your answer with diagrams.

Fig. 3.30 Scree slopes on Arkle, a mountain in north-west Scotland

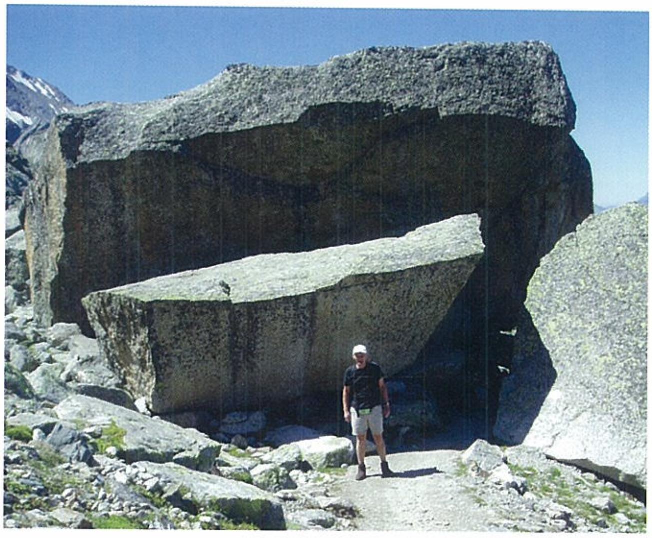


Fig. 3.31 Boulders produced by rock falls in the French Alps

Erosion processes on slopes

The slope processes described above are all types of mass movement in that they are all independent of running water. However, running water does play a part, particularly where **rainfall intensity** exceeds the **infiltration rate** and **overland flow** occurs. The effects are often increased by human activity such as deforestation, over-grazing, burning or cultivation which leaves the soil bare. On gentle slopes, water may run off the surface as a uniform sheet, causing **sheet erosion**. On steeper slopes the water becomes concentrated in channels leading to **gully erosion**. Ploughing down the slope rather than across it is also a factor. The intermediate stage between the two produces fine channel networks known as **rills**.

Fig. 3.32 Gullies on farmland in Kwazulu Natal, South Africa

Intense rainfall with large droplets can have a direct erosive effect on bare soil known as rainsplash erosion. The effect is greatest on steeper slopes because more of the energy of the impact is used in pushing soil down the slope.

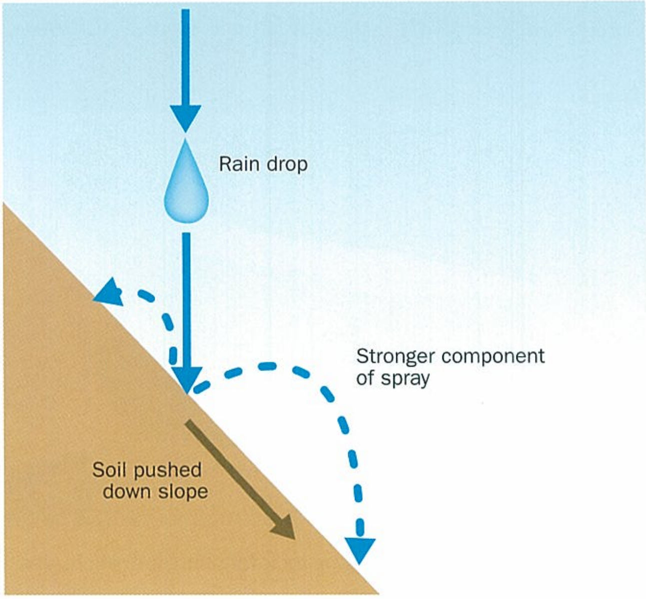


Fig. 3.33 Rainsplash erosion

The human impact

How human activity can result in mass movement on slopes

Excavations

Perhaps the most common way that human activity can result in mass movement is where the ground is removed, e.g. in road and railway cuttings, to make level ground for a building, or in quarries. In areas prone to mass movements (e.g. where there are soft or unconsolidated rocks, where the rock strata dip down the slope, or where there are alternating permeable and impermeable layers) this can create a slope which is too steep to be stable and therefore liable to failure.

Where an excavation removes the toe of an old landslip (see Fig. 3.27) this can re-activate the feature and lead to further movement. Other, smaller excavations are those for road and railway cuttings, and for the foundations of buildings. New slopes are being created and this must be done in a way that ensures that the new slopes are stable and not liable to catastrophic mass movements.

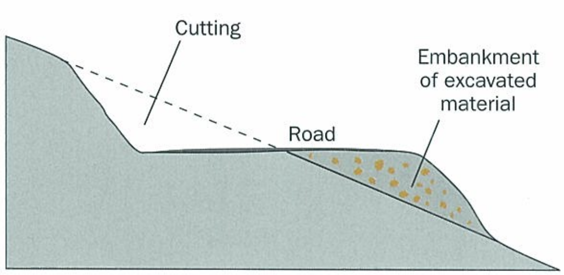


Fig. 3.34 A cross-section through a road constructed across a slope. This method raises various questions. Is the cutting sufficiently gentle to ensure that mass movement will not occur? If not the measures described in Fig. 3.37 should be employed. Is the embankment of excavated material stable? Is water drainage from the road adequate and will it cause mass movement or erosion? Will the material in the embankment settle over time and cause the road surface to be uneven?

Waste heaps

Often waste heaps from quarrying and mining have steep slopes and are made of material which is unconsolidated or highly porous.

Fig. 3.35 The spoil heaps of the quarry

The newly created steep slopes may be unstable and liable to slope failures. One example of this was the catastrophic slope failure of a coal mine spoil tip in the village of Aberfan, near Merthyr Tydfil, Wales, on 21 October 1966, which killed 116 children and 28 adults. It was caused by a build-up of water in the accumulated rock waste, which started to move downhill as a mudflow.

Loading by building

Building on the top of a slope liable to landslip can add sufficient mass to the ground that it will trigger the process described in Fig. 3.27.

Loading by water

When rock cuttings or building projects are carried out, drainage may be disturbed, diverting water into these areas. Water has a lubricating effect on unconsolidated material and saturated clays are unstable, all of which can lead to landslips. However the extra weight of water in the rock is also a factor. If the saturated sands or clays are shaken by an earthquake then liquefaction may occur. Before the earthquake, the water pressure in the sand is relatively low, but shaking causes the water pressure to increase, allowing the sand particles to move relative to each other, acting like a liquid.

Removal of vegetation

Deforestation, construction projects or even leaving land bare after cultivation can increase surface runoff leading to mudflows in susceptible areas.

Case study: The Merriespruit tailings dam disaster, Virginia, Free State, South Africa

Gold is extracted from the ground at very low purities and the processing produces large quantities of fine-grained waste mixed with water known as tailings or locally as 'slime'. This waste is deposited in 'slime dams' which are prominent features of the landscape, appearing as rectangular, steep-sided, flat-topped hills.

Fig. 3.36 Tailings from gold mining, Johannesburg, South Africa. The Central Business District (CBD) can be seen in the background

Like many others in South Africa, the Merriespruit tailings dam was made by constructing a 'daywall' perimeter which was allowed to settle and dry out. This activity was often done during the day under supervision. After this and often at night, the slurry was pumped into the 'nightpan' between the perimeter walls. A drainage system was installed in the dam to drain away the water plus any rain water.

There were 250 houses in Merriespruit, a suburb of the goldfields town of Virginia, when the dam was constructed in 1978.

Late in the afternoon on 22 February 1994 there was a thunderstorm and about 50 millimetres of rain fell in 30 minutes. That night the tailings dam failed and flooded Merriespruit when 600 000 m^3 of liquid slurry flowed 4 kilometres away from the dam. The nearest houses were located 300 metres downslope of the dam and when the wave of water and slime reached them it was 2.5 metres high. There was widespread devastation and environmental damage, 17 people were killed and 80 houses were destroyed. Inadequate systems for draining water from the dam were blamed for the disaster.

Traffic vibrations

Movement of heavy vehicles is not a sole cause of mass movement but it can be a trigger for movements.

How human activity can result in erosion on slopes

Removal of vegetation

This could be through:

- overgrazing,
- soil exposure during cultivation
- cultivating in areas of low rainfall
- construction projects.

All these activities can lead to bare surfaces liable to rainsplash erosion, sheet erosion, rill erosion and gullying. In extreme cases, after heavy rainfall, it may also lead to mudflows.

Ploughing up and down slopes

Ploughing up and down steep slopes creates pathways for surface runoff which can lead to the development of rills.

Destroying soil structure

Poor agricultural practices such as growing too many crops in an area (overcropping) or allowing the organic content of the soil to deteriorate can lead to the destruction of the crumb structure which helps to bind the soil together. This leaves the soil loose and prone to erosion both by wind and running water.

Case study: Railway landslide in Cumbria, UK, 1995

Landslides are surprisingly common on railway cuttings. The line from Settle to Carlisle, UK, runs through an area of Carboniferous shales and sandstones and the alternating impermeable and permeable rocks are prone to slippage. At 18:55 on 31 January 1995, a train was derailed by a landslide on this line at Aisgill. It was dark and raining heavily. The train was hit by a train travelling in the opposite direction. The conductor of the first train was fatally injured in the collision.

Strategies to reduce mass movement and its impact on slopes

The methods described below are generally used to prevent slides and falls, often on artificially-created slopes.

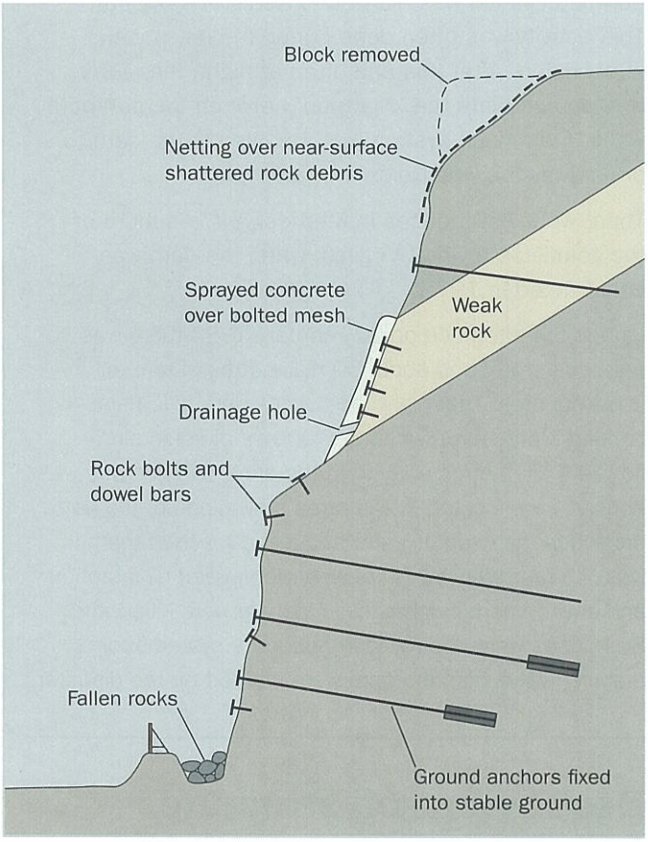


Fig. 3.37 Rock slope stabilisation

Pinning (including rock bolts, dowel bars and ground anchors)

Fig. 3.38 Rock bolts

These methods involve drilling a long hole through loose blocks into the stable rock beyond. A metal rod is inserted and fixed in place with a resin or an expansion bolt. A metal plate is then bolted onto the outside of the rod. Rock bolts and dowel bars are relatively short but ground anchors may be long cables used to stabilise whole landslide areas.

Netting

Fig. 3.39 Netting

Metal netting is fastened to road cuttings to prevent loose blocks falling on the road below.

Gabions

Fig. 3.40 Gabions

Gabions are boxes made of metal mesh. They fold flat for transport and are assembled on-site and filled with rocks. They do have other purposes but they may be used to stabilise the toe of a landslip.

Drainage

Fig. 3.41 Beneath the crash barrier on this road, a gravel-filled trench provides drainage

Excess water on slopes adds mass, provides lubrication and is often a key factor in the formation of flows and slides. Moving water away from vulnerable slopes is one of the most important ways of preventing these mass movements. The simplest and cheapest way of doing this is often to dig a trench, as shown in Fig. 3.41, and fill it with a highly permeable aggregate (gravel).

Grading

Fig. 3.42 A gently graded cutting. The slope here consists of strata dipping towards the road. Alternating layers of permeable limestone and impermeable shale make it unstable after heavy rain and liable to slip along the bedding planes. For this reason the cutting has been made with a gentle slope

Slope angle is a key feature in mass movements. The steeper the slope, the more potentially unstable it is. Where slopes are artificially created, they need to be made more gentle if there is a risk of movement. However, this requires more excavation and produces more waste rock to be transported away and disposed of, increasing costs. Similarly, the slope angle of natural slopes can be decreased to reduce risk. The process of making slopes more gentle is referred to as grading.

Fig. 3.43 The rocks in this cutting are stable as they dip at right angles to the slope (the same would be true if the rocks dipped away from the road and into the slope). It has been possible to make a steep cutting and save costs

Afforestation

Planting trees and other vegetation is often used to reduce soil erosion but it can also reduce the risk of mass movements. The trees have various effects. Trees increase interception and therefore evaporation losses are greater. Roots absorb water and therefore increase transpiration losses. This means that there is less surface runoff (which might otherwise result in mudflows) and less infiltration to add mass to the rocks. The roots themselves may have the effect of binding soil and loose rock.

Grouting

This involves injecting permeable rocks with cement to reduce pore water and increase strength.

Shotcrete

Loose rock surfaces can be sprayed with concrete which can help to prevent loose blocks falling from the slope.

Mapping hazards

Many landslides occur when old landslides, which have moved many times in the past, are re-activated as a result of heavy rainfall, excavations or earthquakes. The case study of California in this chapter illustrates this (see page 92). Detailed mapping of these features can help planners to decide which areas should be avoided by future house or road building or to decide what precautionary measures need to be taken. This mapping can make use of historical accounts but often looks for topographic features like those described in Fig. 3.27.

Strategies to reduce erosion on slopes

Method	Erosion prevented	
	Wind	Water
Terracing		✓
Contour ploughing		✓
Crop rotation	✓	✓
Fallow periods	✓	✓
Strip cultivation and inter-cropping	✓	✓
Cover cropping	✓	✓
Reducing stock density	✓	✓
Check dams		✓
Filling gullies		✓
Afforestation	✓	✓
Shelter belts (wind breaks)	✓	
Dry farming	✓	
Irrigation	✓	✓

Table 3.6 Strategies for reducing erosion on slopes

16. Explain how each of the strategies in Table 3.6 can reduce erosion on slopes.

Case Study: California and Los Angeles

Slides and flows are common in California, damaging roads, railways, pipelines, electricity cables, and other infrastructure. The suburbs of Los Angeles are particularly affected.

The causes are as follows.

Intense rainfall

Downtown Los Angeles has an annual precipitation of only 385 mm, which mainly occurs during the winter and spring, with heavy rainfall during winter storms. The coast gets slightly less but the hilly suburbs get slightly more. However, there is great variation from year to year. Heavy rainfall on dry ground can lead to mudflows and loading of the ground resulting in landslides.

Soft, poorly-consolidated rocks

The geology of the area consists of relatively young Neogene and Pleistocene marine sediments deposited between 15 million and 1 million years ago.

Steep relief

Los Angeles rises from sea level to 1547 m (Mount Lukens) in the form of a basin. The central parts of the city are flat but the outer suburbs are hilly, for example areas such as the San Fernando Valley, the Santa Monica Mountains, Mount Washington, Boyle Heights and San Pedro.

Road and housing construction

Los Angeles (population 3.88 million in 2013) has grown rapidly outwards into hilly districts prone to mass movements. Construction in these hilly districts can add load to unstable slopes and road cuttings in these areas may also be unstable.

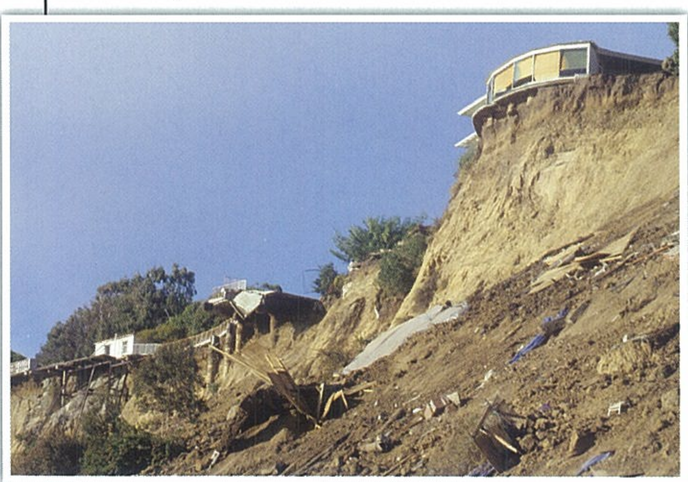


Fig. 3.44 Landslide damage in the Pacific Palisades area of Los Angeles

Oil and water extraction

Groundwater extraction for water supply and petroleum extraction have both caused ground subsidence. In 1963 in the Baldwin Hills a dam collapsed as a result of this.

Earthquakes

The San Andreas fault system and other active faults in the area can trigger landslides on slopes affected by the factors listed above. As mentioned earlier in the chapter (pages 85–86), earthquakes can also cause liquefaction of the ground.

Examples

Although slope failures are common in California, some of the most significant include:

- April 18, 1906. A major earthquake in San Francisco triggered numerous landslides, including the Devil's Slide in San Mateo County. The latter is still active today.
- January 3–5, 1982. Landslides in the San Francisco Bay area killed 25 people and caused at least 66 million USD in damage.
- January 10, 2005. A mudslide in La Conchita killed 10 people and destroyed 18 homes.

Mudflows in southern California, December 2010

In one week in December 2010 the area received half of its annual average rainfall and some streets flooded. California Governor, Arnold Schwarzenegger, declared a state of emergency for half a dozen communities and residents were evacuated and authorities put on alert for landslides and mudflows. Hundreds of people were evacuated in the suburbs of Los Angeles, with particular concerns for homes in steep-sided valleys previously affected by wildfires. 'The ground is so saturated it could move at any time', said Bob Spencer, spokesman for the Los Angeles County Department of Public Works.

Then heavy rains of up to 25 mm per hour caused a landslide on a heavily used section of Interstate 10 early on Wednesday, covering three lanes near the city of Pomona. In Highland District, 104 km east of Los Angeles, two rivers overflowed, swamping as many as 20 homes in mud. In Silverado Canyon, Orange County 25 to 30 people were evacuated from their mountain homes. 'This mudflow moved cars, picked them up, stood them up on their nose at 45-degree angles, buried them', said Bill Peters, a spokesman for the California Department of Forestry and Fire Protection.

Homes in the mountains were blocked by boulders and mud as rescue workers helped residents seek shelter. Officials ordered the evacuation of 232 homes at the bottom of large hillsides in La Canada Flintridge and La Crescenta, in the suburbs of Los Angeles.

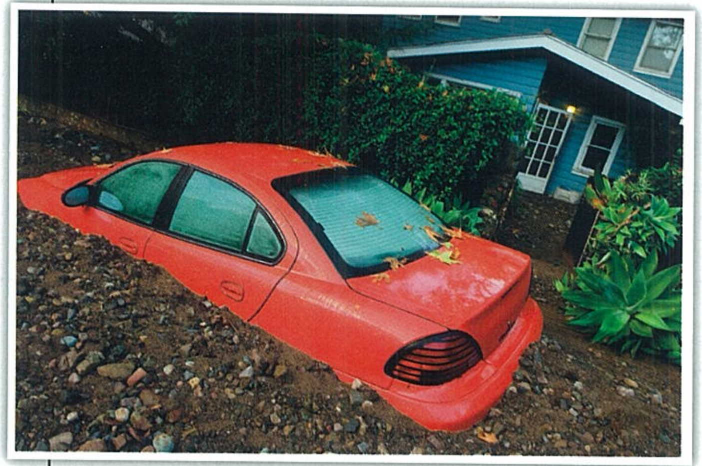


Fig. 3.45 A mudflow in Silverado Canyon, CA, December 2010

Attempts to reduce mass movement

The main method of reducing risk has been to produce maps that show past landslide features which are likely to be re-activated. This is done by the California Geological Survey. The maps indicate areas where the probability of liquefaction and earthquake-triggered landslides are significant enough to require a more detailed site evaluation prior to developments such as buildings or road construction. Before 1995 these site evaluations were voluntary but they are now a legal requirement.

A landslide inventory and related hazard zone maps are available on the California Geological Survey website. The new landslide inventory maps cover 62 square mile areas known as 'quadrangles', including parts of Burbank, Universal City, Beverly Hills, West Hollywood, Culver City and Glendale, as well as communities of Baldwin Hills and nearby View Park.

Systems such as rock bolts, netting and shotcrete are not appropriate for stabilising slopes in the soft, poorly-consolidated rocks which form many of the slopes.

Slope failures still happen frequently outside the built-up area but the system is focused on reducing the risk to property and human life where slope failures are the result of human activity.

It is difficult to produce hard statistics to evaluate the success of the system but there is little doubt that it will have had a significant effect.

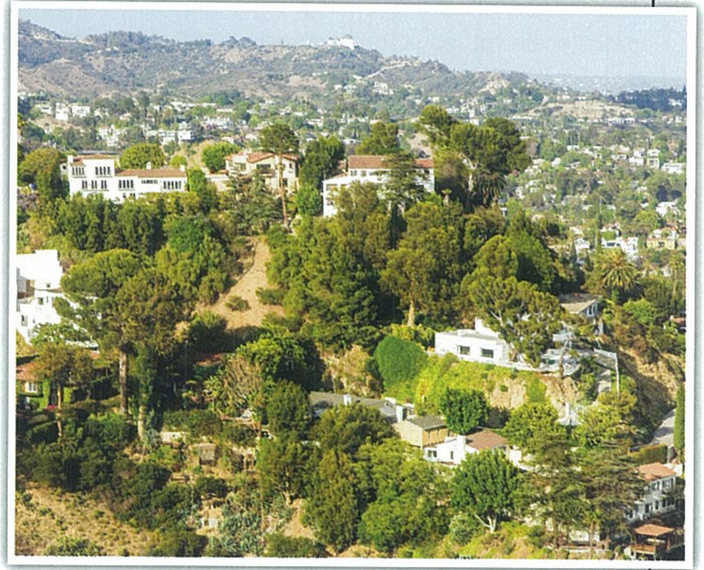


Fig. 3.46 Landslide damage in the Griffith Observatory area of Los Angeles

RESEARCH Examine mass movements in California through historical accounts such as those found at: http://articles.latimes.com/keyword/landslides-los-angeles.

Key concepts

The key concepts listed in the syllabus are set out below. For each one a summary of how it applies to this chapter is included.

Space: this chapter shows the concept of space in the way that weathering processes act differently in different global spaces as a result of different climatic factors. The global spatial patterns of phenomena associated with global plate tectonics are discussed. Plate tectonics provide a good illustration of the concept of changing spaces, as continents move their positions and oceans open, grow, shrink and disappear. Different global spaces have different landforms depending on the plate tectonic situation and the operating weathering processes.

Scale: this chapter shows the importance of the time scale in interpreting change from the geological past to future scenarios. Plate tectonics show how small changes over a long time scale result in the global landforms we see today. The California Geological Survey maps past slope failures which may be re-activated at some point in the future. This chapter also illustrates the importance of spatial scale. Slope processes can operate on very long time scales, e.g. creep, or very short time scales, e.g. flows, slides and falls. The chemical weathering processes operate at a molecular spatial scale yet result in large scale landform development.

Place: distinctive landforms resulting from the processes of weathering, or plate tectonics or on slopes occur in similar places in different continents. Island arcs form where oceanic plates converge wherever that place is on the globe. Granite weathers in a particular climate in the same way wherever that place happens to be on the globe. This chapter shows how widely separated places can have great similarities.

Environment: interactions between people and their environment create the need for environmental management, particularly of slope processes. Human activity is one of the key factors that can trigger slope failures which, in turn, can lead to loss of life. Building projects can lead to slope instability but measures can be taken to stabilise slopes. The last section of this chapter and the California case study demonstrate this.

Interdependence: understanding the interactions between humans and slope processes is important in knowing how particular building projects can be managed. The systems operating on slopes show how the complex nature of interacting physical processes and human activities can lead to slope failures but, once these interactions are understood, measures can be taken to prevent slope failures and to ensure human safety.

Diversity: the range of landscapes produced by plate tectonics is diverse: from fold mountains, to ocean basins, ocean trenches, island arcs and oceanic ridges. Weathering processes differ greatly in different climates and with different rock types. Slope processes differ on different slope angles and in different geological situations.

Change: the key point of plate tectonic theory is that the Earth's surface is in a state of constant change. Plates are generally moving at rates between 1 and 10 cm per year but these small movements produce the major features of the Earth's surface. Weathering and slope processes are similar in that they show how slow changes over long time periods can have major effects on the landscape. Weathering has a low magnitude and high frequency but a slope failure has high magnitude and lower frequency.

Exam-style questions

1 Study Fig. 3.47 which shows a cross-section through a road cutting.

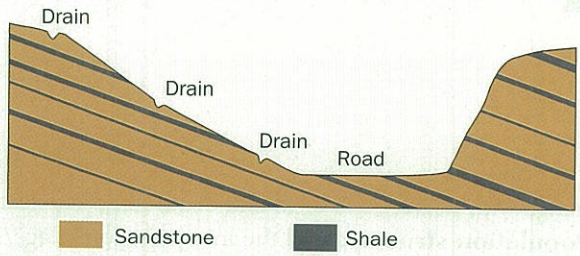


Fig. 3.47 A cross-section through a road cutting

(a) Explain why the left side of the cutting is more liable to slope failure than the right side. [3]

(b) Explain how the cutting has been designed to reduce the risk of slope failure. [3]

(c) Describe the process of soil creep and explain how it takes place on slopes. [4]

2 (a) Describe the process of sea floor spreading. [7]

(b) With the help of a diagram, explain the formation of landforms at the convergent plate margin formed by the meeting of an oceanic plate and a continental plate. [8]

(c) Why are some of the world's oceans shrinking but others are expanding? [15]