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.

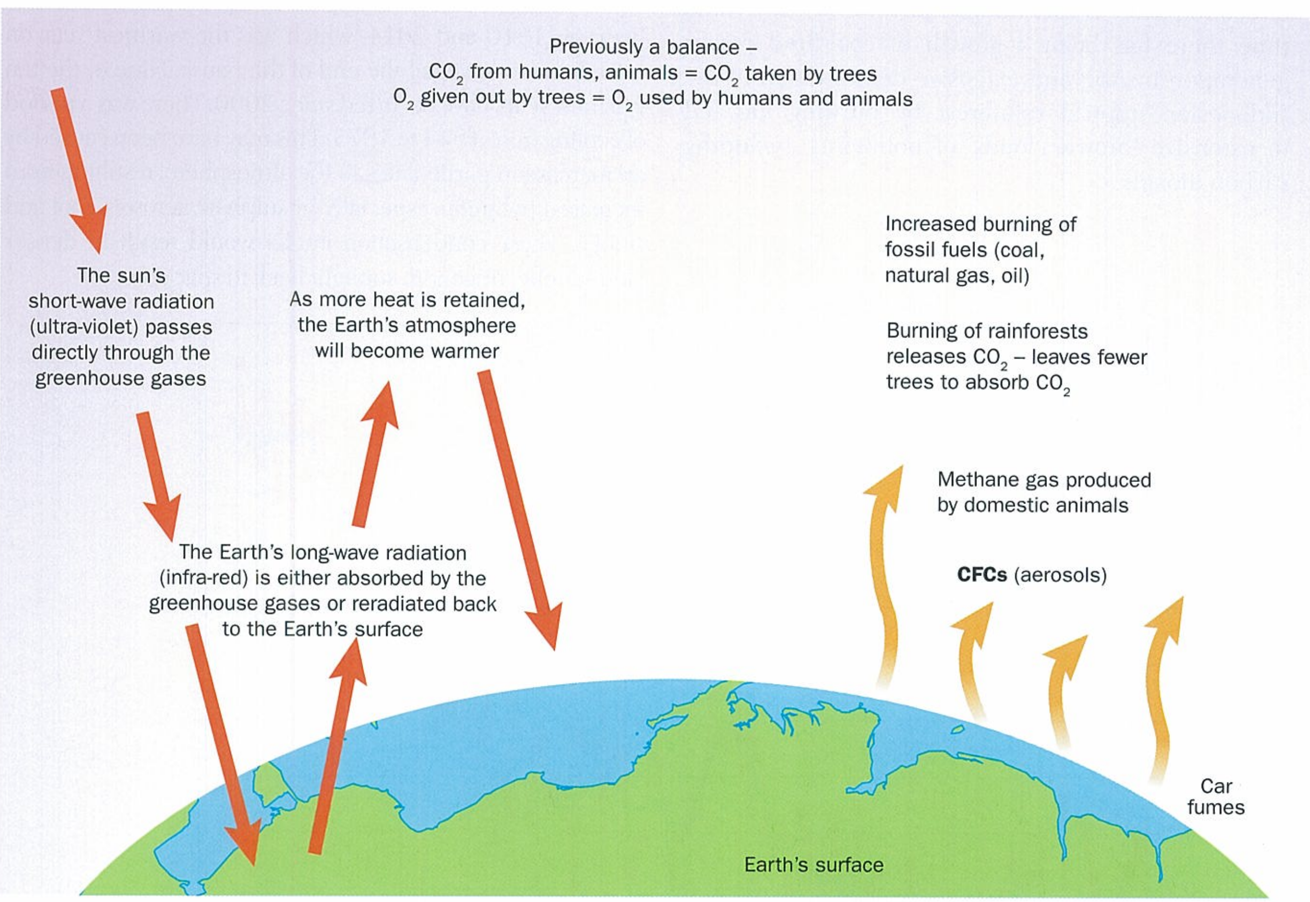

Fig. 2.57 The enhanced greenhouse effect

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.

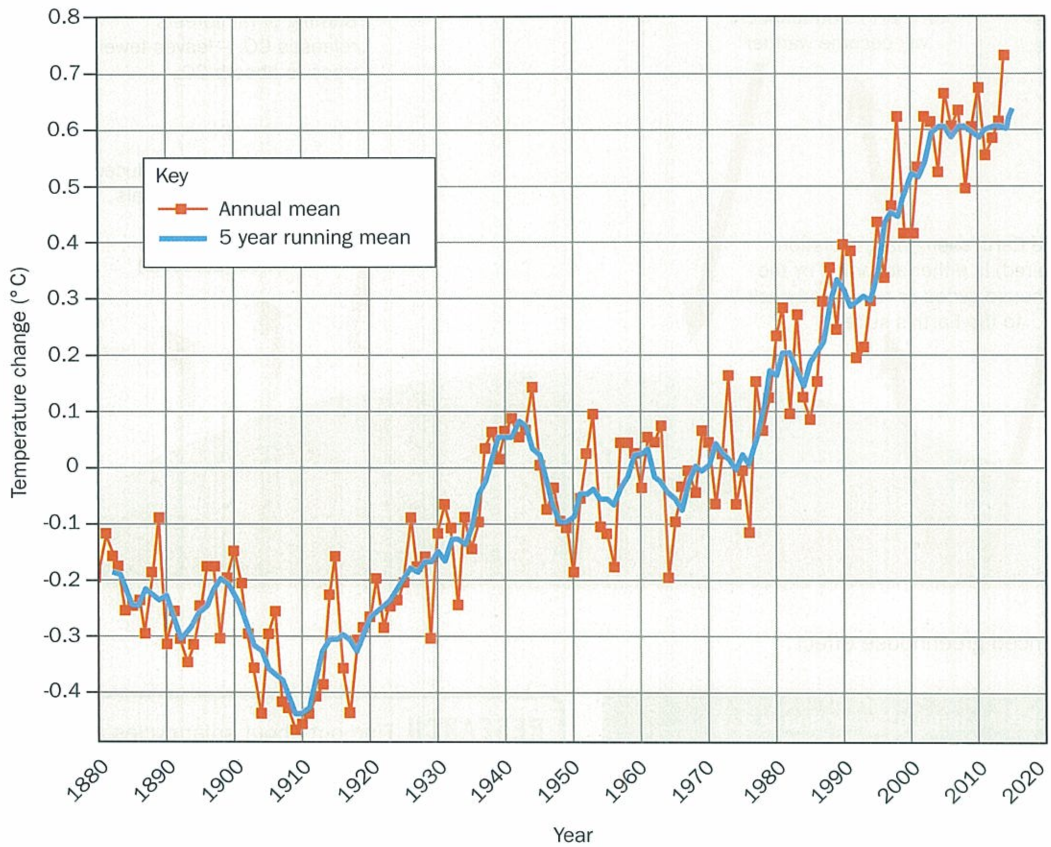

Fig. 2.58 Line graph showing how global annual temperature (in °C) and the 5 year running mean 1880–2014, varied from the mean temperature of the period 1951–1980, shown as 0 °C

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.

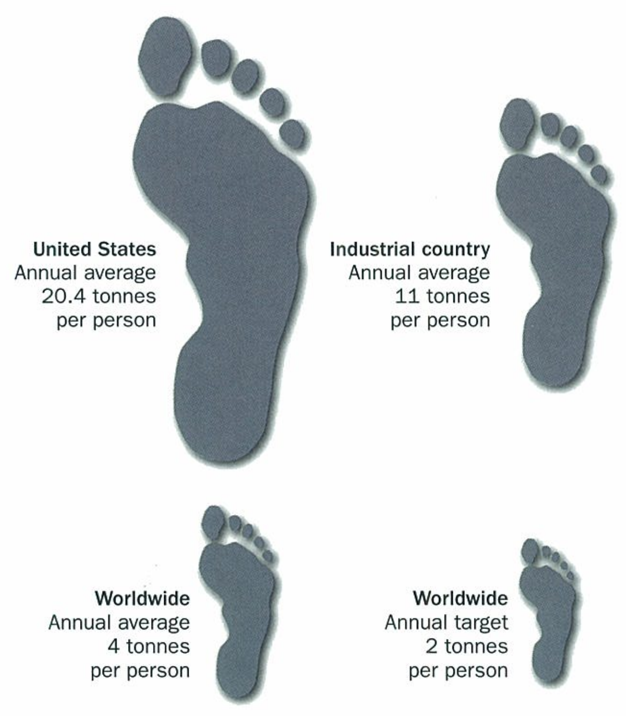

Fig. 2.60 Carbon footprint awareness can be raised by using easy to interpret diagrams. The target is what is thought necessary to limit global warming to 2 degrees C this century.

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.

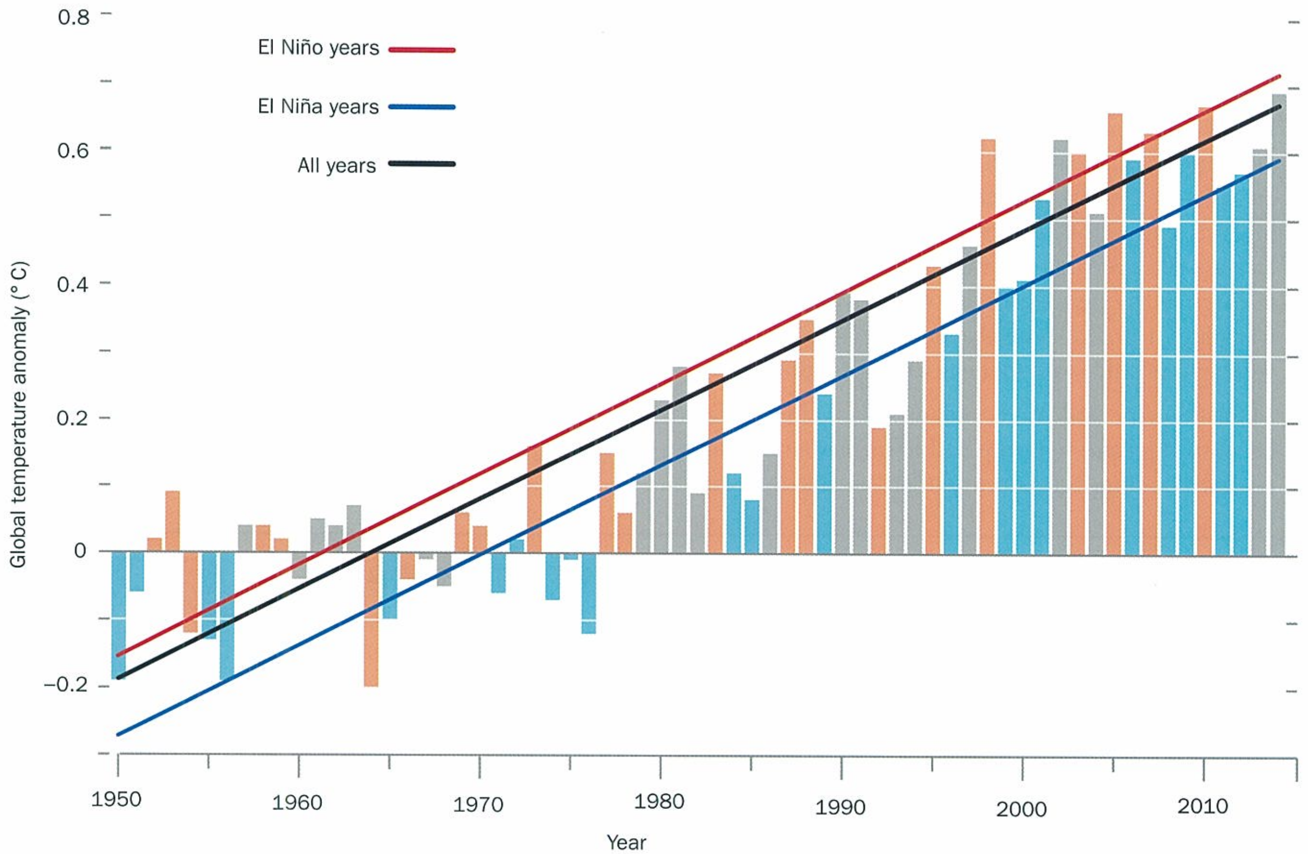

Fig. 2.61 Bar graph showing the relationship between global temperature anomalies calculated from the 1951 to 1980 mean temperature, shown as °C, and El Niño and La Niña events

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

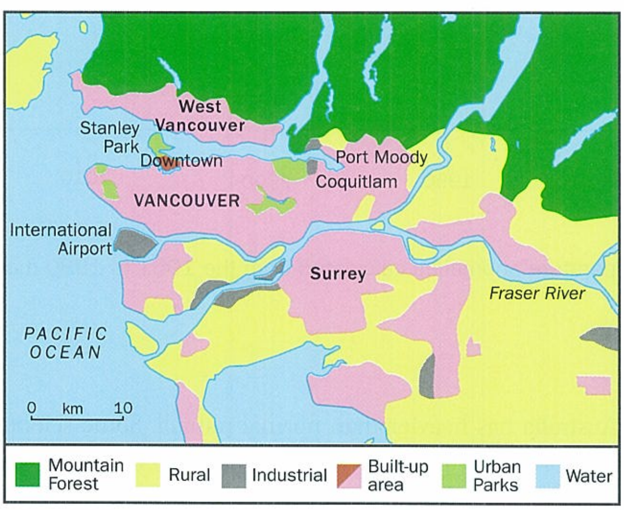

Fig. 2.62 Vancouver's land use zones and locations in the case study

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

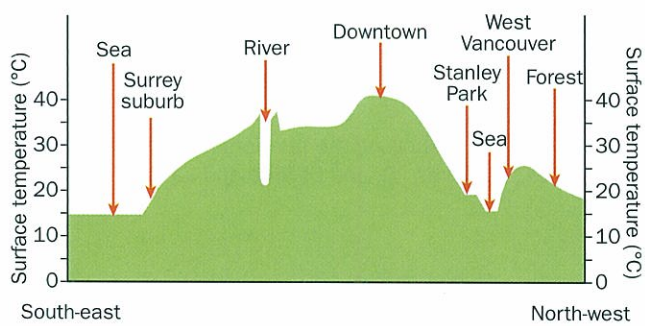

Fig. 2.63 Temperature transect across Vancouver's heat island on a very hot day in July

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

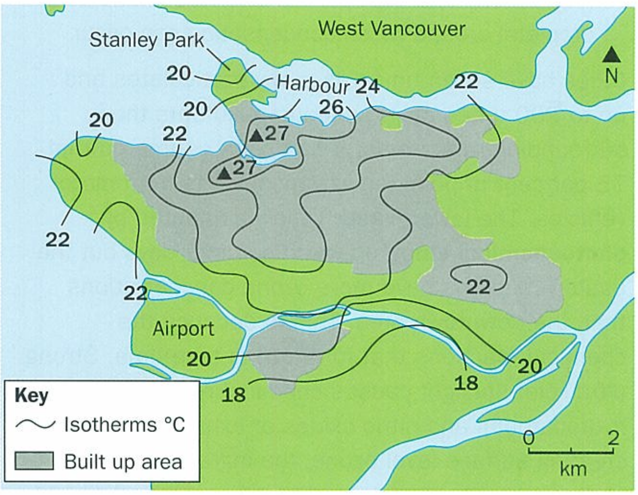

Fig. 2.65 An isotherm map of air temperatures in the Vancouver area

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.

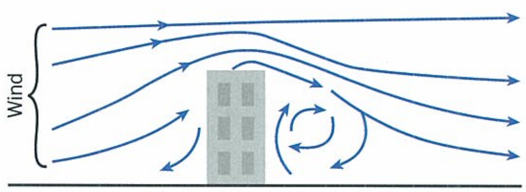

Fig. 2.66 The effects of a building on airflow

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.

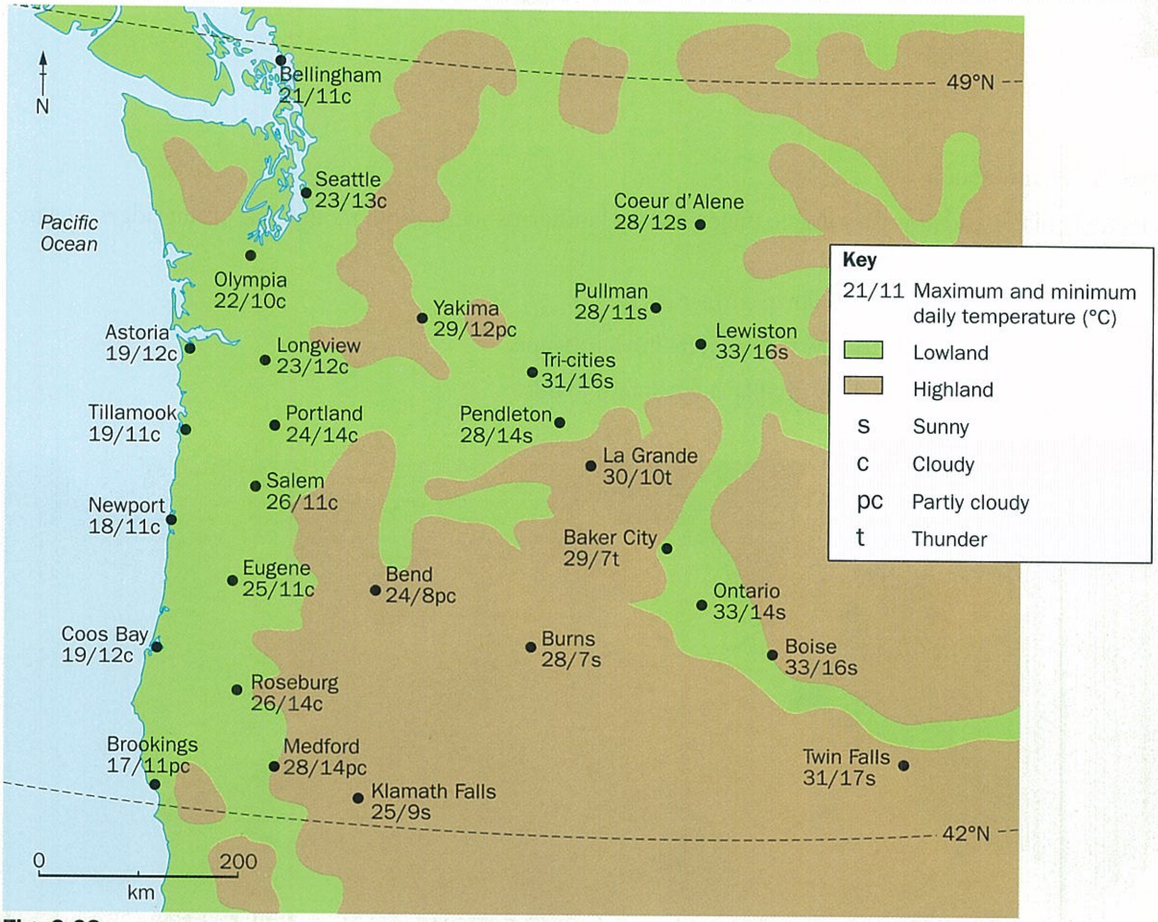

Fig. 2.68

(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]