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.

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.

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

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.)

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.

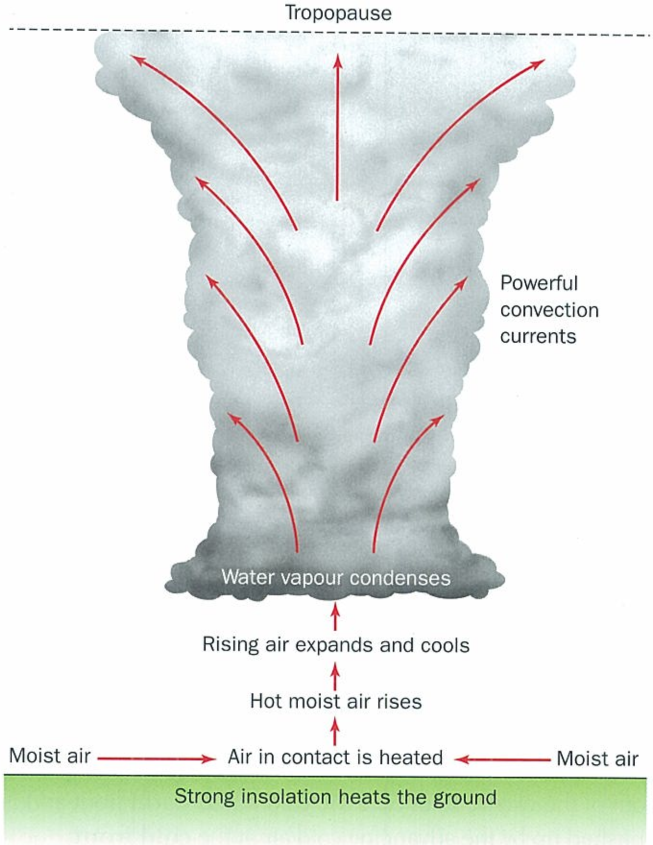

Fig. 2.38 Cumulonimbus cloud and rainfall

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

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.

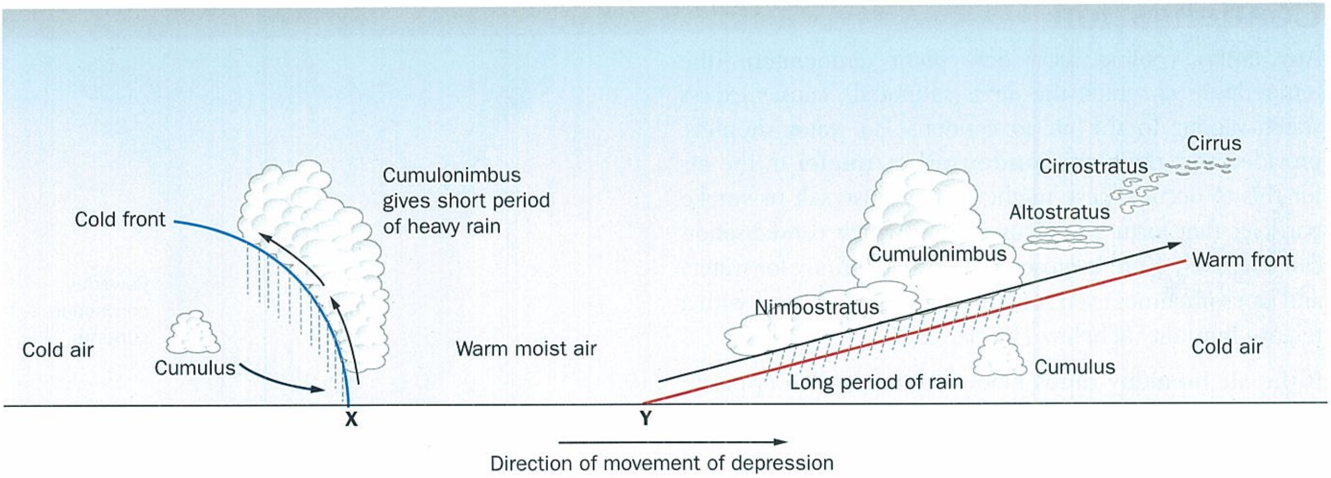

Fig. 2.40 Section through a mature depression showing warm air rising over cold air along the warm and cold fronts

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**.

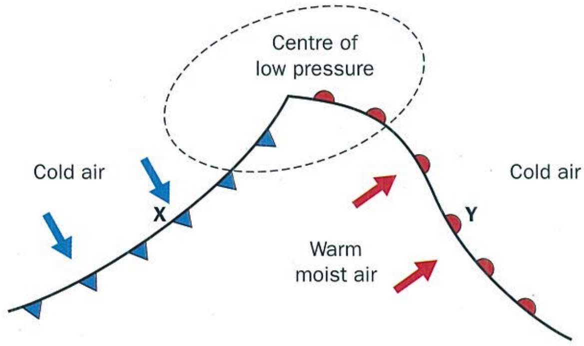

Fig. 2.41 Plan of a mature depression

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.

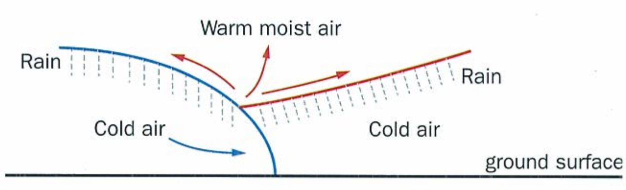

Fig. 2.42 Section through an occluded front

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.

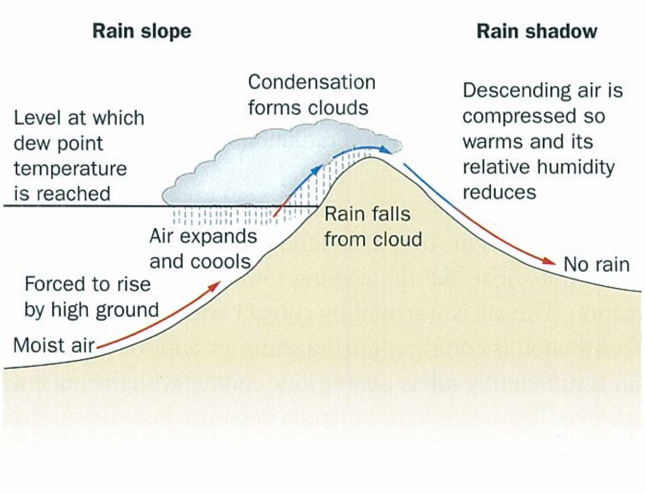

Fig. 2.43 Forced ascent of air over a hill or mountain

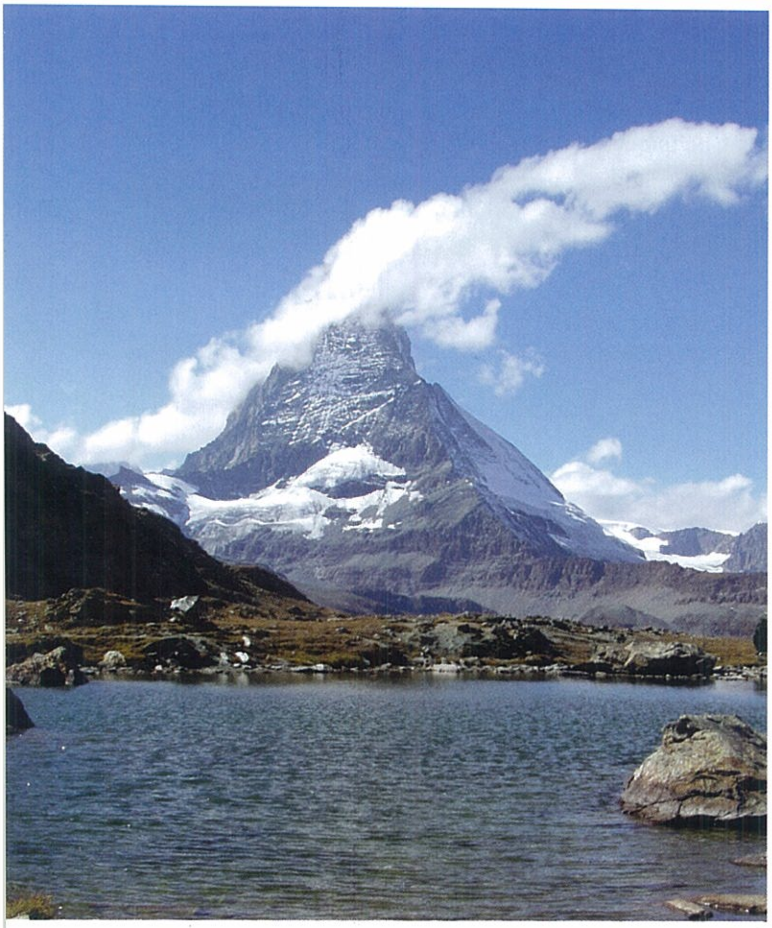

Fig. 2.44 Orographic uplift over the Matterhorn

Radiation cooling

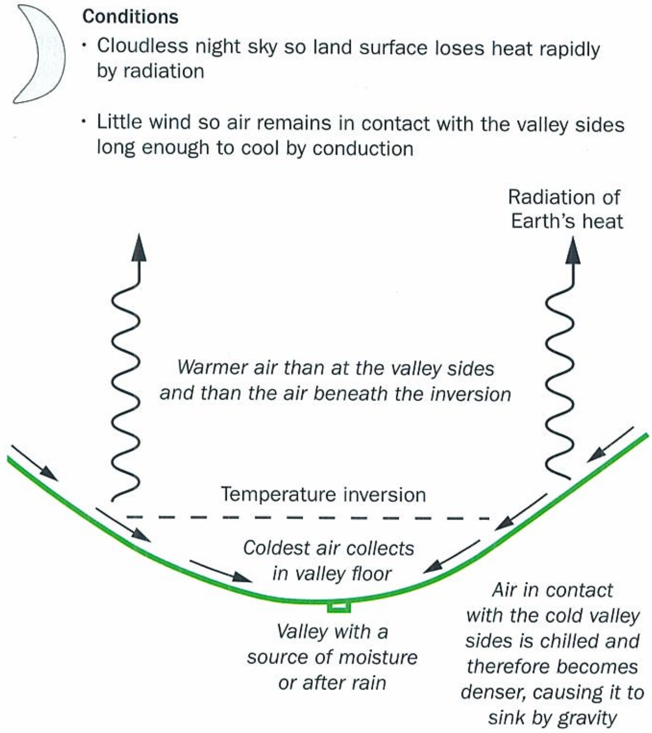

Fig. 2.45 Radiation cooling in a mid-latitude valley in winter

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.

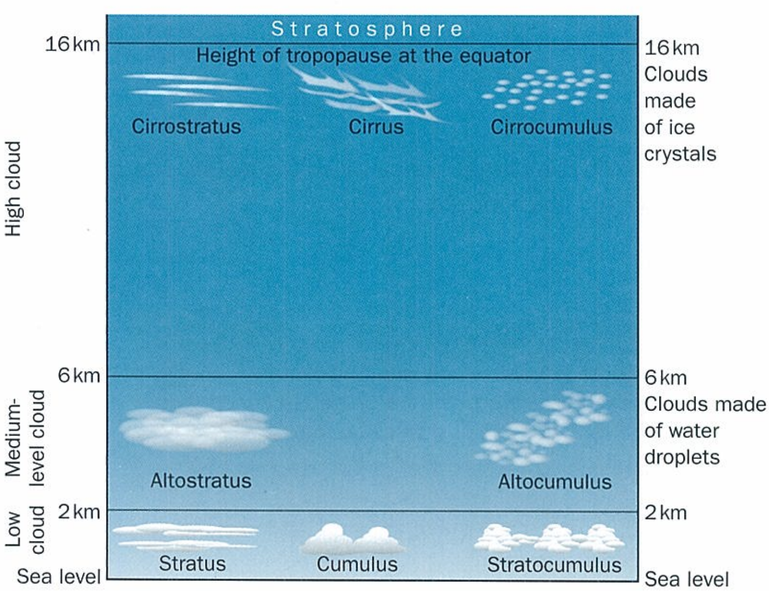

Fig. 2.46 Fair weather clouds, showing their heights in the tropics

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.

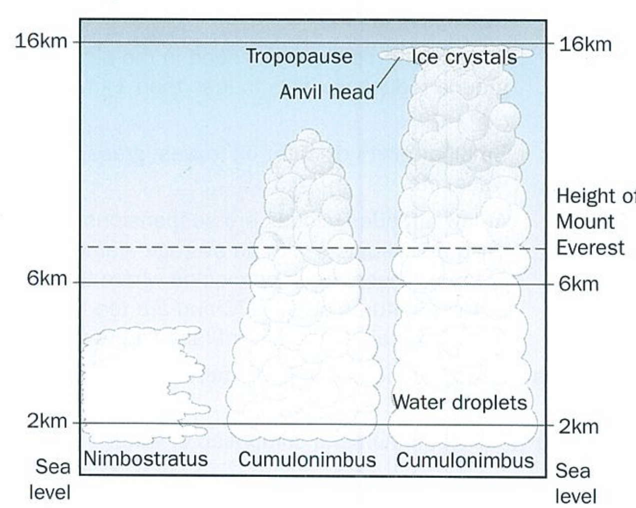

Fig. 2.48 Rain-bearing cloud, showing their heights in the tropics

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.