

Anyone who has seen pictures of the Earth from space, like that in Figure 2.1, will have been struck by how much of our planet is ocean, and will have wondered about the swirling cloud patterns. In fact, the atmosphere and the ocean form one system and, if either is to be understood properly, must be considered together. What occurs in one affects the other, and the two are linked by complex feedback loops.

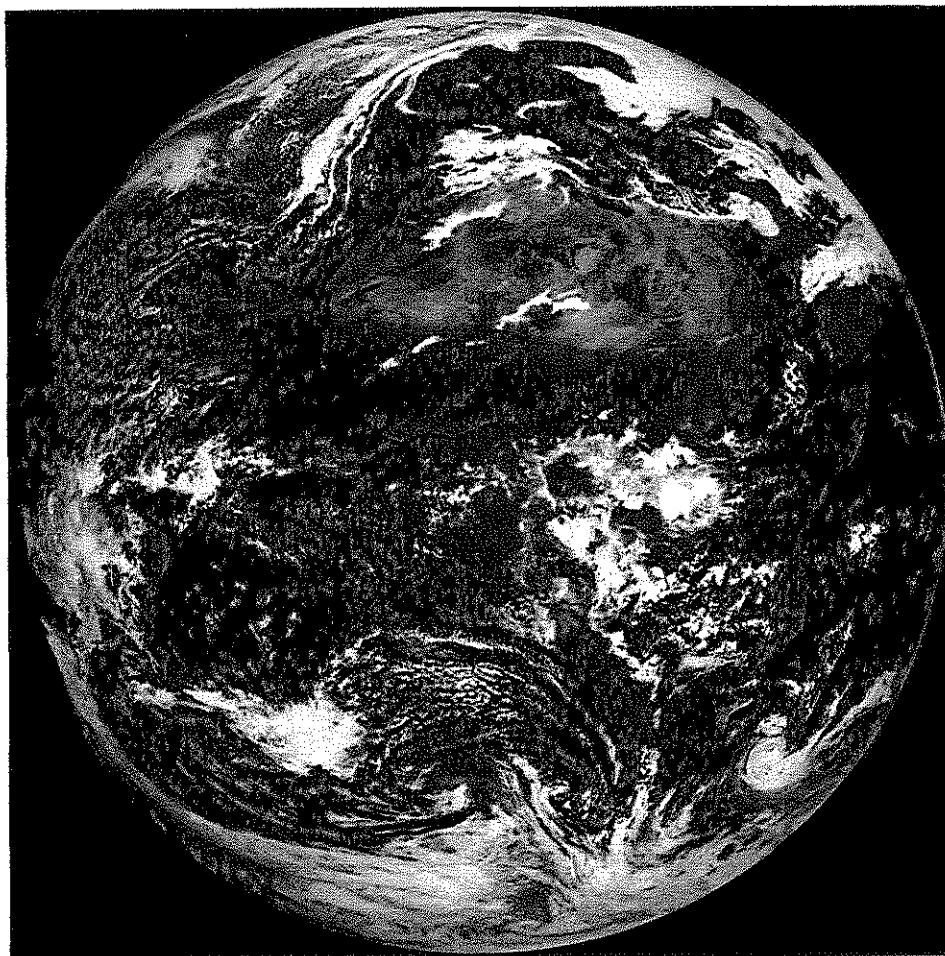


Figure 2.1 The Earth as seen from a geostationary satellite positioned over the Equator. The height of the satellite (about 35 800 km) is such that almost half of the Earth's surface may be seen at once. The outermost part of the image is extremely foreshortened, as can be seen from the apparent position of the British Isles. Colours have been constructed using digital image-processing to simulate natural colours.

The underlying theme of this Chapter is the redistribution of heat by, and within, the atmosphere. We first consider the large-scale circulation of the atmosphere, and then move on to consider smaller-scale phenomena that characterize the moist atmosphere over the oceans.

2.1 THE GLOBAL WIND SYSTEM

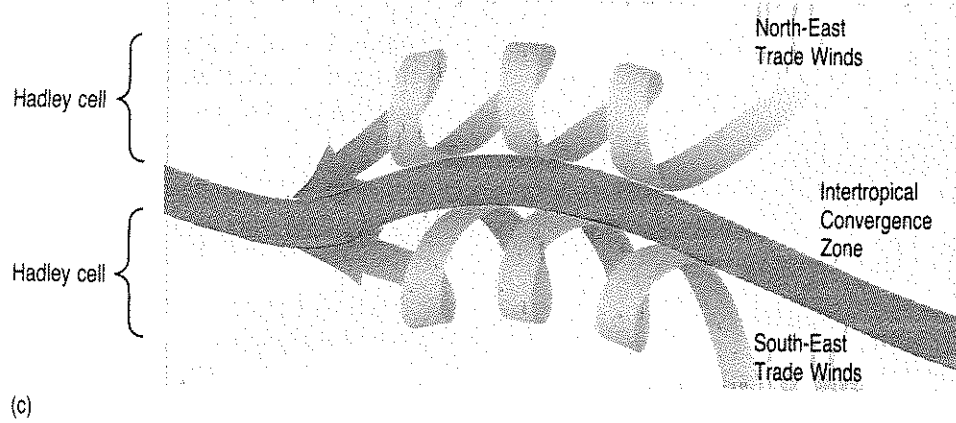
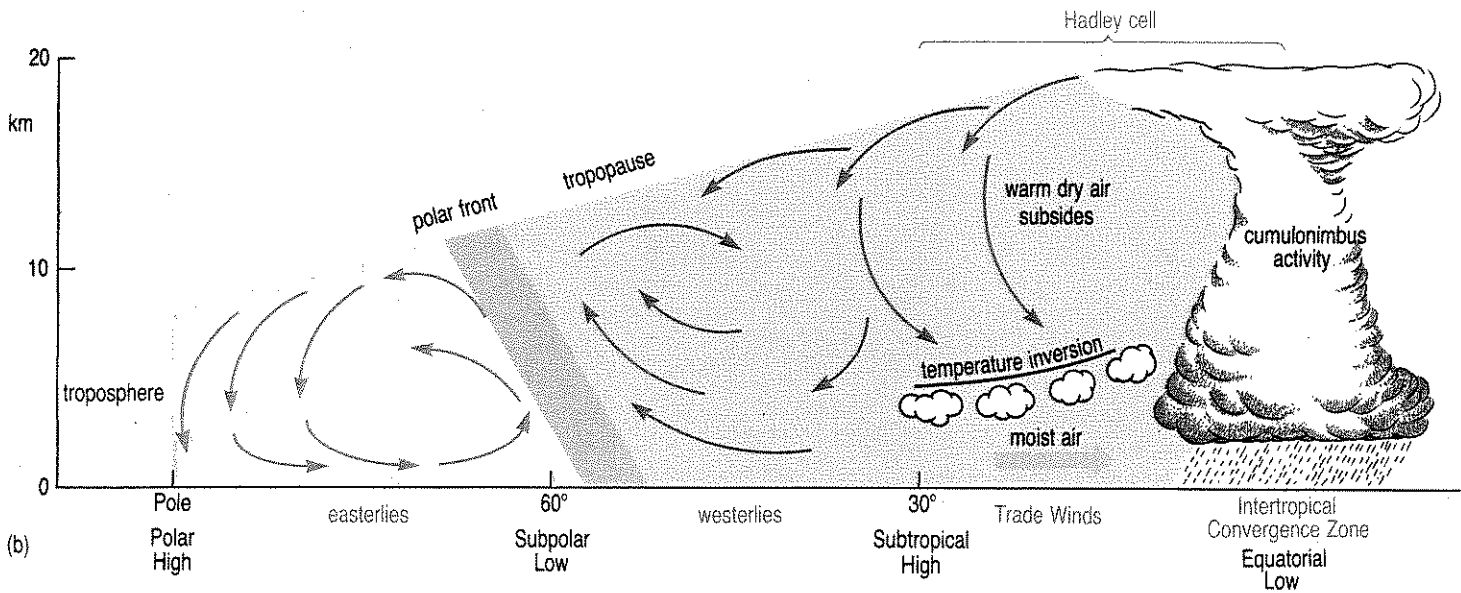
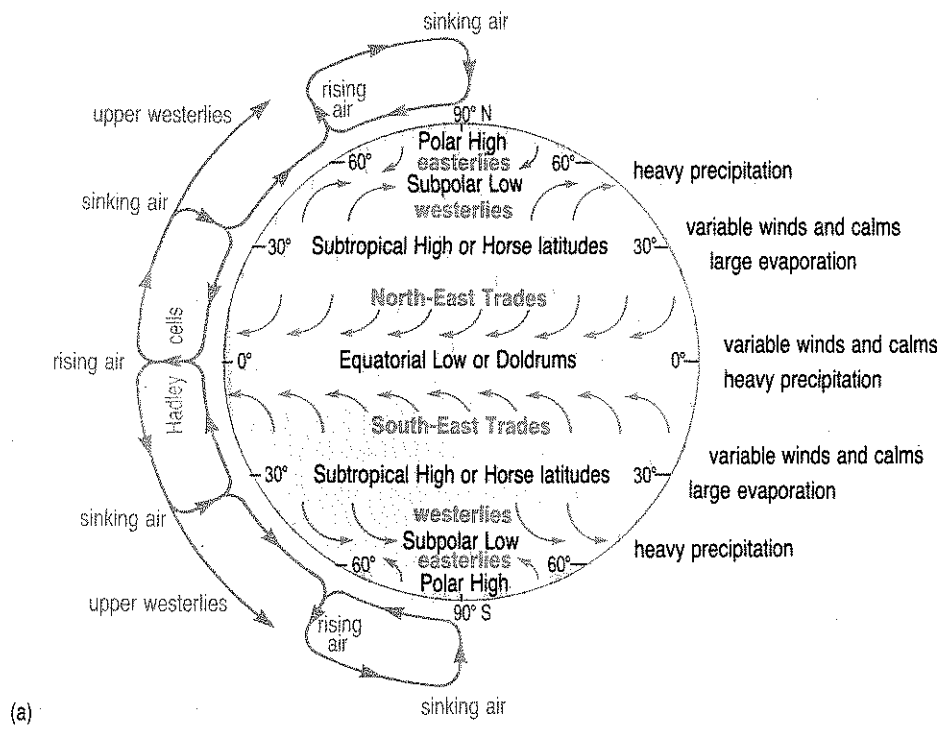
Figure 2.2(a) shows what the global wind system would be if the Earth were completely covered with water. As you will see later, the existence of large land masses significantly disturbs this theoretical pattern.

In the lower atmosphere, pressure is low along the Equator, and air converges here and rises. At about 30°N and S air descends, and there is high atmospheric pressure at the Earth's surface. There is therefore a

Figure 2.2 (a) Wind system for a hypothetical water-covered Earth, showing major winds and zones of low and high pressure. Vertical air movements and circulation cells are shown in exaggerated profile on the left of the diagram; characteristic surface conditions are given on the right of the diagram. The two north-south cells on either side of the Equator make up the Hadley circulation.

(b) Section through the atmosphere, from polar regions to the Equator, showing the general circulation and regions of tropical cloud formation. Note that the return flow in the atmosphere takes place in the upper part of the troposphere (the part of the atmosphere in which temperature decreases with distance above the Earth); the tropopause is the top of the troposphere. The Intertropical Convergence Zone is the zone along which the wind systems of the Northern and Southern Hemispheres meet. (This and other details are discussed further in the text.)

(c) The spiral circulation patterns of which the Trade Winds form the surface expression, seen from above.



pressure gradient from the subtropical highs towards the equatorial low (Figure 2.2(a)) and, as winds blow from areas of high pressure to areas of low pressure, equatorward winds result. These are the Trade Winds.

As Figure 2.2(a) shows, the Trade Winds blow from the north-east and the south-east, and do *not* blow directly from the north and south. Why is this?

The answer, of course, is because of the Coriolis force. Away from the Equator, the Coriolis force acts to deflect winds and currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

Note that the Trade Winds are named the South-East and North-East Trades because they come *from* the south-east and the north-east. However, you should bear in mind that although winds are always described in terms of where they are blowing *from*, currents are described in terms of where they are flowing *towards*. Thus, a southerly current flows *towards* the south and a southerly wind blows *from* the south. To avoid confusion, we have generally used *southward* rather than *southerly* (for example) when describing current direction.

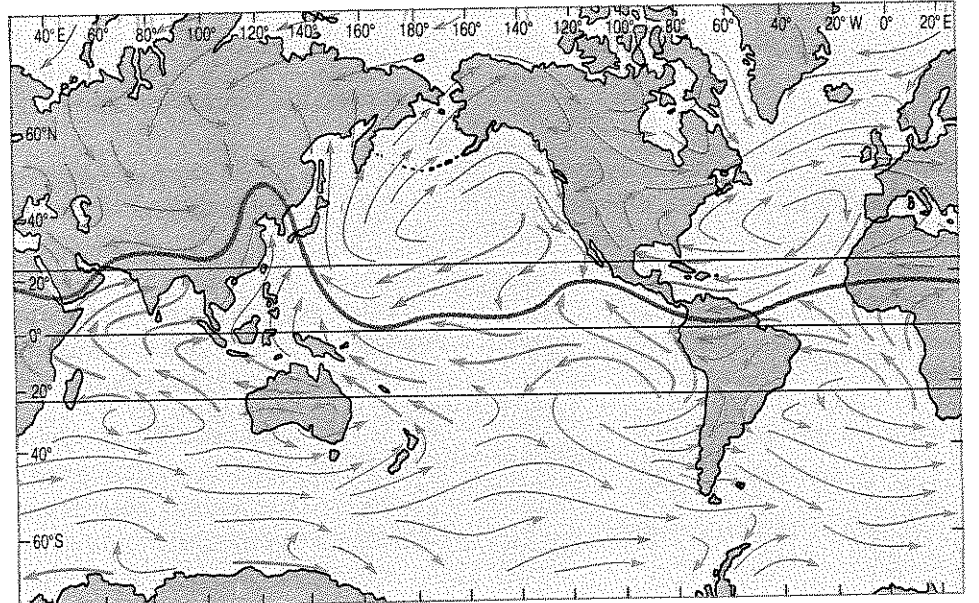
The Trade Winds form part of the atmospheric circulation known as the Hadley circulation, or **Hadley cells**, which can be seen on Figure 2.2(a) and, in more detail, on Figure 2.2(b) and (c). Strictly speaking, the term 'Hadley cell' refers only to the north-south component of the circulation (as shown on the left-hand side of Figure 2.2(a) and in Figure 2.2(b)). Because the flow is deflected by the Coriolis force, in three dimensions the circulation follows an approximately spiral pattern, as shown schematically in Figure 2.2(c).

Figure 2.3 shows the prevailing winds at the Earth's surface in (a) July and (b) January.




How closely do the actual winds over the Earth (Figure 2.3) correspond with the hypothetical wind system shown in Figure 2.2(a)?

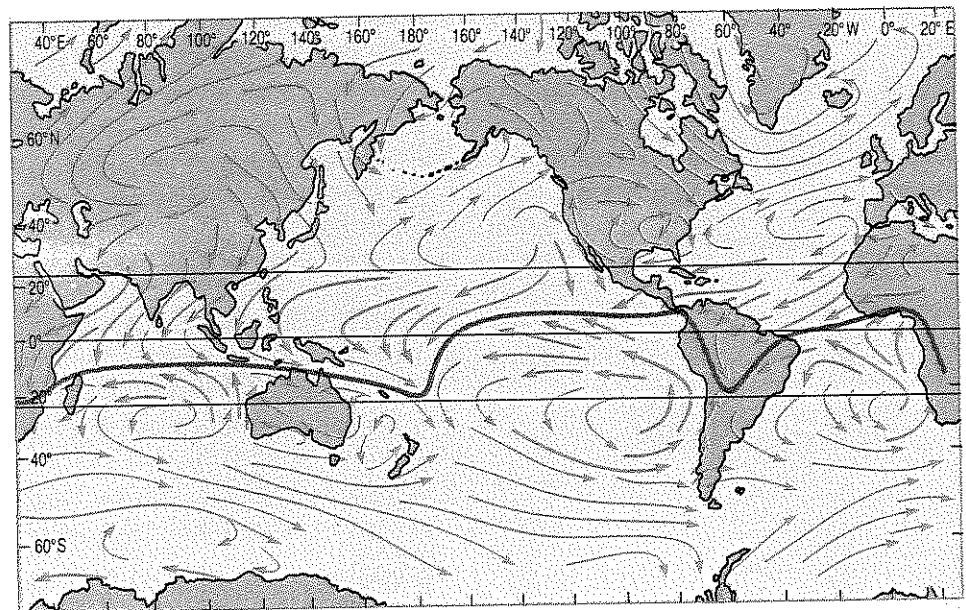
In general, not that closely, although the actual and hypothetical winds *are* very similar over large areas of ocean, away from the land.

If you compare Figure 2.3(a) and (b) you will see that the greatest seasonal change occurs in the region of the Eurasian land mass. During the northern winter, the direction of prevailing winds is outwards from the Eurasian land mass; by the summer, the winds have reversed and are generally blowing in towards the land mass. This is because continental masses cool down and heat up faster than the oceans (their thermal capacity is lower than that of the oceans) and so in winter they are colder than the oceans, and in summer they are warmer. Thus, in winter the air above the Eurasian land mass is cooled, becomes denser and sinks, so that a high pressure area develops. Winds blow out *from* this to regions of lower pressure. In the summer, the situation is reversed: air over the Eurasian land mass heats up and becomes less dense, so that there is a region of low pressure which winds blow *towards*. The oceanic regions most affected by these seasonal changes are the Indian Ocean and the western tropical Pacific, where the seasonally reversing winds are known as the monsoons.



(a)

 mean position of ITCZ
  most frequent wind direction
  prevailing wind direction (≥ 50% of observations)



(b)

Figure 2.3 The prevailing winds at the Earth's surface, and the position of the Intertropical Convergence Zone in (a) July (northern summer/southern winter) and (b) January (southern summer/northern winter).

The distribution of ocean and continent also influences the position of the zone along which the wind systems of the two hemispheres converge. This zone of convergence—known as the **Intertropical Convergence Zone** or **ITCZ**—is generally associated with the zone of highest surface temperature. Because the continental masses heat up faster than the ocean in summer and cool faster in winter, the ITCZ tends to be distorted southwards over land in the southern summer and northwards over land in the northern summer (Figure 2.3).

2.2 POLEWARD TRANSPORT OF HEAT BY THE ATMOSPHERE

Heat is transported to polar regions by the atmosphere both directly and indirectly. If you look at Figure 2.2(a) and (b) you will see that motion in the upper troposphere is generally polewards. Air moving equatorwards over the surface of the Earth takes up heat from the oceans and continents so that when, after rising at low pressure regions such as the Equator, it moves polewards, heat is also transported polewards. Thus, any mechanism that transfers heat from the surface of the Earth to the atmosphere also contributes to the poleward transport of heat. The most spectacular example of heat transfer from ocean to atmosphere is the generation of tropical cyclones, which will be discussed in Section 2.3.1.

The Hadley cells, of which the Trade Winds are the surface expressions, may be seen as simple convection cells, in the upper limbs of which heat is transported polewards. The situation at higher latitudes, to which we now turn, is not so straightforward.

2.2.1 LARGE-SCALE CIRCULATION IN MID-LATITUDES

It may have occurred to you that whereas the polar high pressure regions and the equatorial low pressure zone (Figure 2.2 (a)) may be seen as direct results of the uneven heating of the Earth's surface, the subtropical zones of high pressure and the subpolar lows shown on Figure 2.2(a) and (b) cannot be explained in this way. However, like the Hadley cells, the low and high pressure centres characteristic of mid-latitudes are a manifestation of the need for heat to be moved polewards, to compensate for the radiation imbalance between low and high latitudes (Figure 1.4).

If, in the long term, no given latitude zone is to heat up, heat must be transported polewards at *all* latitudes. One model of the atmospheric circulation that could be proposed to achieve this would be a simple wind system in which surface winds blew from the polar high to the equatorial low, and the warmed air rose at the Equator and returned to the poles at the top of the troposphere to complete the convection cell (see Figure 2.4).

However, when we take into account the fact that the Earth is rotating, complications arise. Because of the rotation of the Earth and the resulting Coriolis force, the equatorward winds would be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, and hence would acquire an easterly component in both hemispheres—as we have seen, the Trade Winds blow towards the Equator from the south-east and north-east. But the Coriolis force increases with latitude from zero at the Equator to a maximum at the poles. At low latitudes, therefore, winds are deflected relatively little and form Hadley cells, while at higher latitudes the degree of deflection is much greater and atmospheric vortices tend to form. These are the depressions and anticyclones familiar to those who live in temperate regions. Their predominantly near-horizontal, or slantwise, circulatory patterns contrast with the near-vertical circulatory cells of low latitudes.

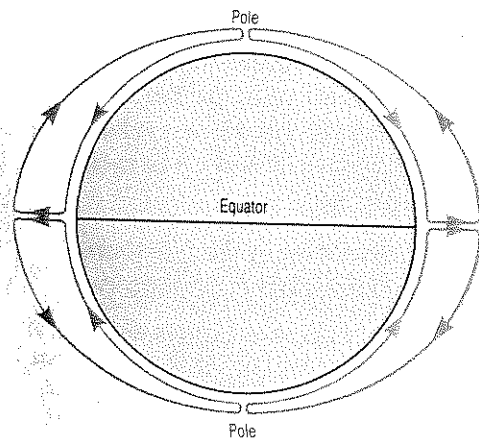


Figure 2.4 Simple atmospheric convection system for a hypothetical non-rotating Earth.

Before proceeding further, we should briefly summarize the conventions used in describing atmospheric vortices.

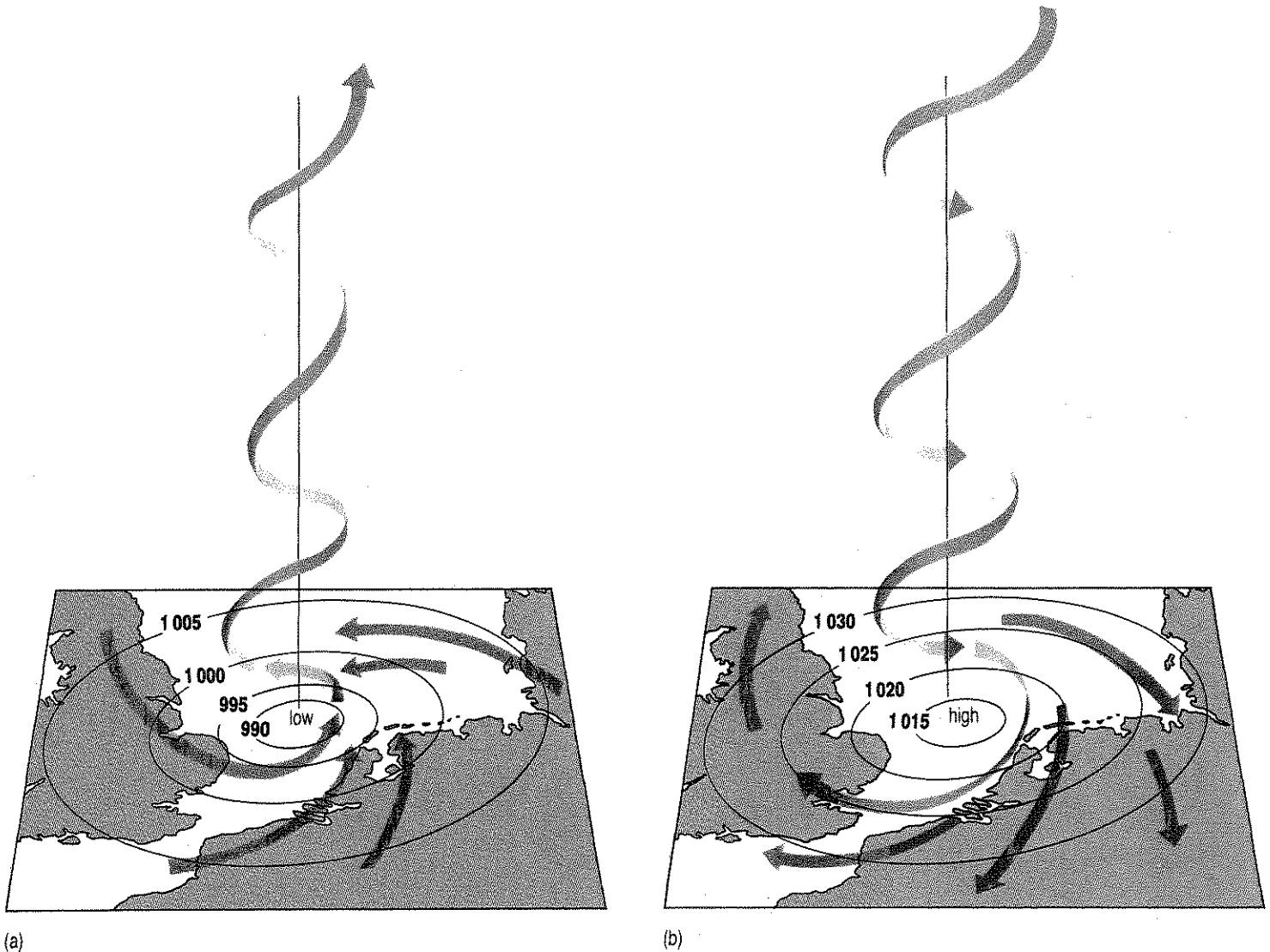


Figure 2.5 Diagrams to illustrate (a) how air spirals inwards and upwards in low pressure areas (cyclones) and (b) downwards and outwards in high pressure areas (anticyclones). These diagrams show the situation in the Northern Hemisphere. The contours are **isobars** (lines joining points of equal atmospheric pressure) and the numbers give typical pressures at ground level, in millibars.

Circulations around *low* pressure centres, whether in the Northern Hemisphere (in which case they are anticlockwise) or in the Southern Hemisphere (in which case they are clockwise) are known as **cyclones** (or lows, or depressions). The way in which air spirals in and up in cyclonic circulations is shown schematically in Figure 2.5(a).

Circulations around *high* pressure centres (clockwise in the Northern Hemisphere, anticlockwise in the Southern Hemisphere) are known as **anticyclones** (Figure 2.5(b)).

How can mid-latitude cyclones and anticyclones contribute to the poleward transport of heat?

Moving air masses mix with adjacent air masses and heat is exchanged between them. For example, air moving northwards in a Northern

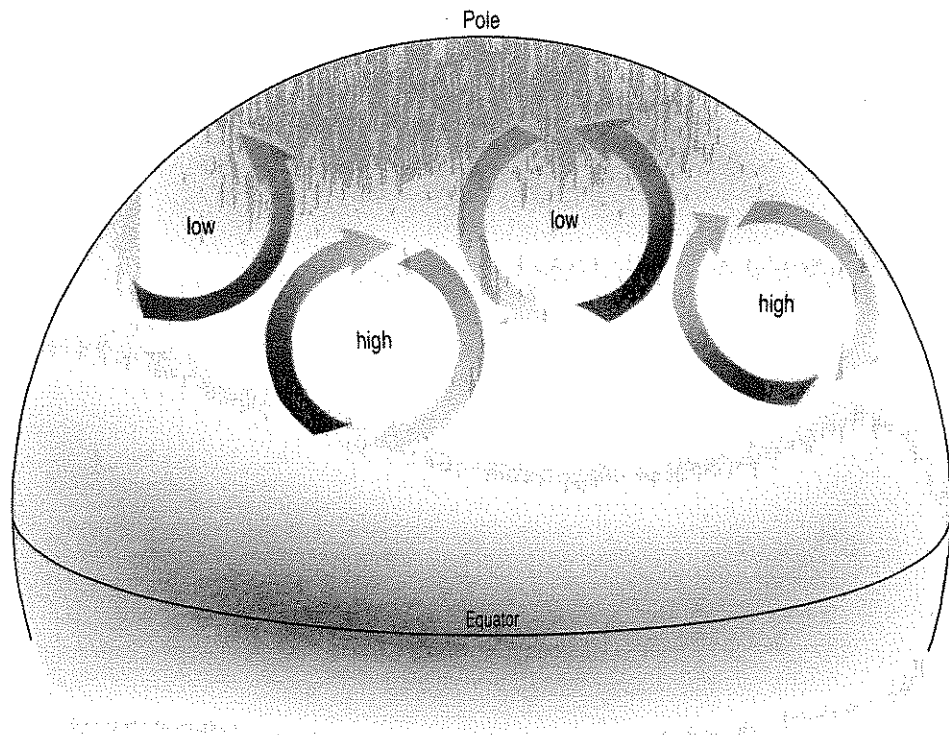


Figure 2.6 Highly schematic diagram to show the poleward transport of heat in the atmosphere by means of mid-latitude vortices (cyclones and anticyclones).

Hemisphere cyclone or anticyclone will be transporting relatively warm air polewards, while the air that returns equatorwards has been cooled. This may be likened to the stirring of bath water to encourage the effect of hot water from the tap to reach the far end of the bath, and is shown schematically in Figure 2.6. How it works in practice is perhaps easiest to see in the case of mid-latitude cyclones or depressions, which correspond to the zone labelled 'Subpolar Low' on Figure 2.2(a). Between the warm westerlies and the polar easterlies, there is a more or less permanent boundary region known as the polar front (Figure 2.2(b)). Undulations in the polar front may develop into depressions, and Figure 2.7(a) shows how formation of these depressions enables heat to be transported polewards. The paths taken by mid-latitude depressions and anticyclones

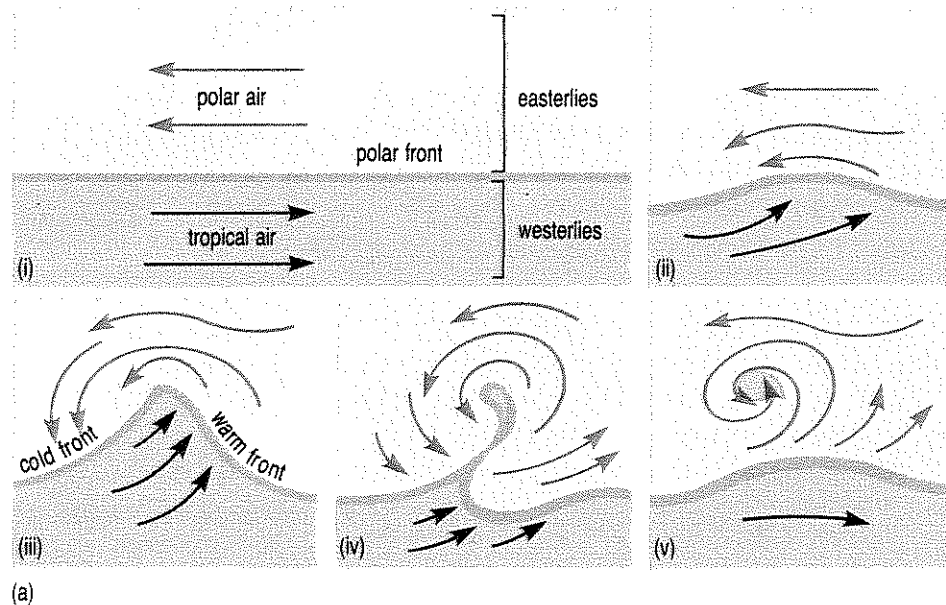
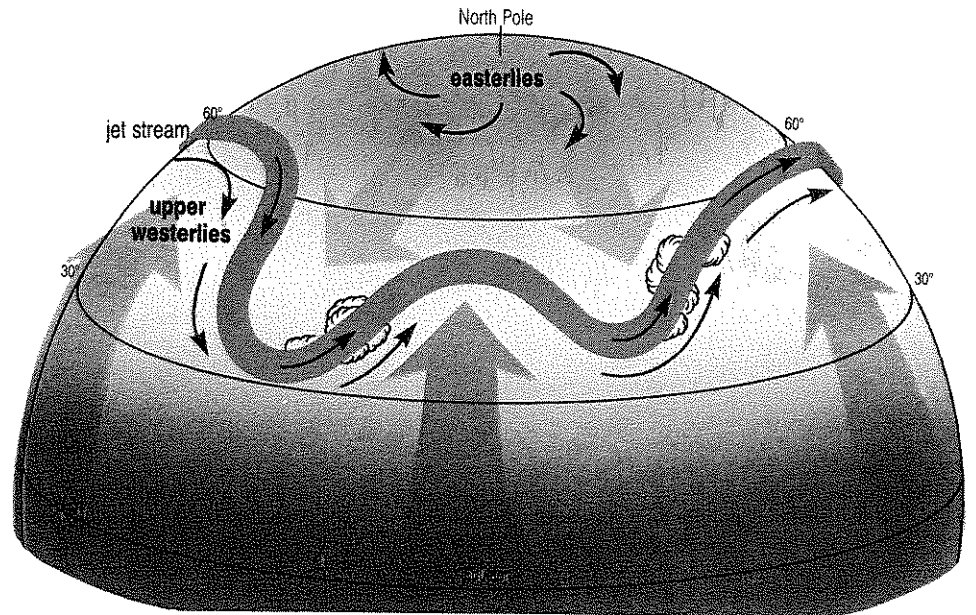
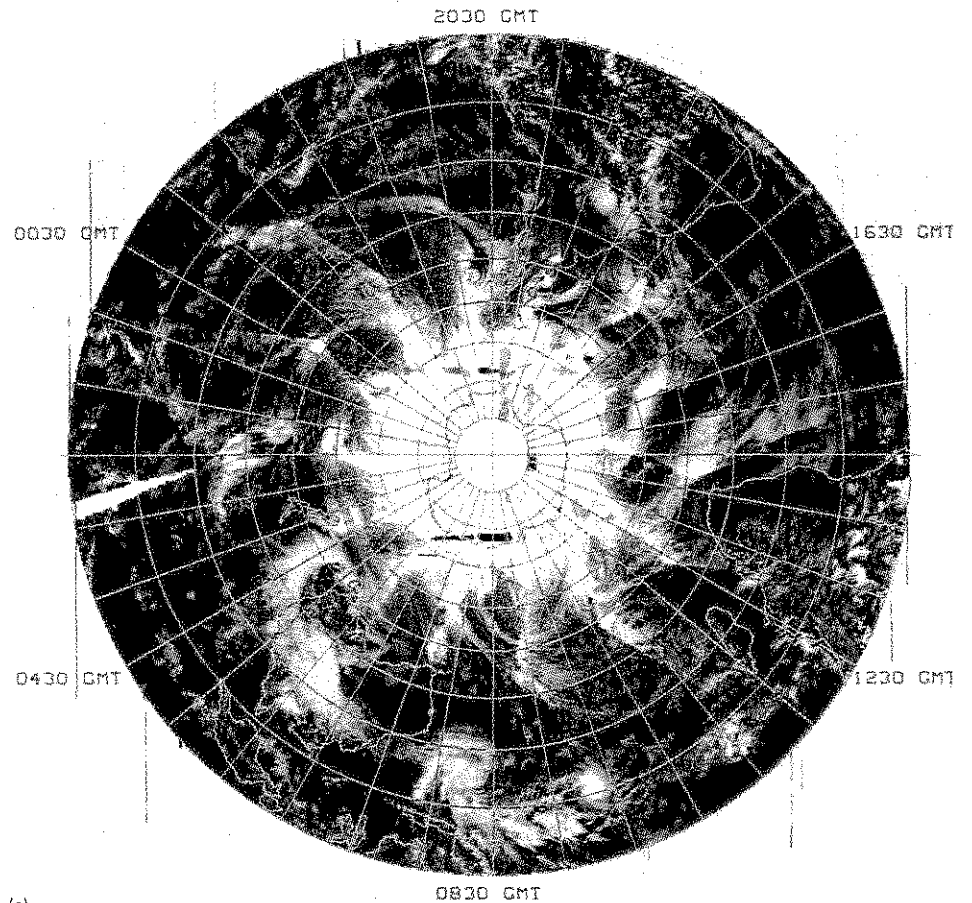


Figure 2.7 (a) Stages in the development of a mid-latitude cyclone (depression) in the Northern Hemisphere, showing how it contributes to the poleward transport of heat. Note that the frontal boundary slopes (warm air overlying cold air) as shown in Figure 2.2(b), and may be anything from 2–3 to 50 km across. That part of the front where cold air is advancing is known as a cold front, and that part where warm air is advancing, as a warm front.



(b)



(c)

Figure 2.7 (b) Schematic diagram showing typical undulations in the northern jet stream, its relation to the flow of warm air (red) and cold air (blue), and the paths taken by depressions. Note that the jet stream flows near the tropopause at heights of 8–15 km. For clarity, we have omitted the subtropical high pressure regions in mid-latitudes and the Hadley circulation in low latitudes.

(c) Satellite photomosaic of the Southern Hemisphere showing cloud cover for one day in April 1983 (i.e. during the southern winter). Cyclonic storms develop in association with the poleward-trending sections of the jet stream and so its undulating path is shown up by the cloud pattern.

are determined by the path taken by the jet stream, the high-level, fast air current that flows around the Earth along the polar limit of the westerlies. The jet stream is characterized by large undulations, typically three to six in number, as shown in Figure 2.7(b).

We now move on to consider how heat is redistributed *within* the atmosphere, by means of predominantly vertical motions.

2.2.2 VERTICAL CONVECTION IN THE ATMOSPHERE

Processes occurring at the air–sea interface are greatly affected by the degree of turbulent convection that can occur in the atmosphere above the sea-surface. This in turn is dependent on the degree of *stability* of the air, i.e. on the extent to which, once displaced upwards, it tends to continue rising.

Two ways in which density may vary with height in the atmosphere (or any other fluid) are illustrated in Figure 2.8. Situation (a), in which density increases with height, is unstable, and upper air will tend to sink and lower air to rise. Situation (b), in which density decreases with height, is stable: a parcel of air (at, say, position O) that is displaced upwards will be denser than its surroundings and will sink back to its original position.

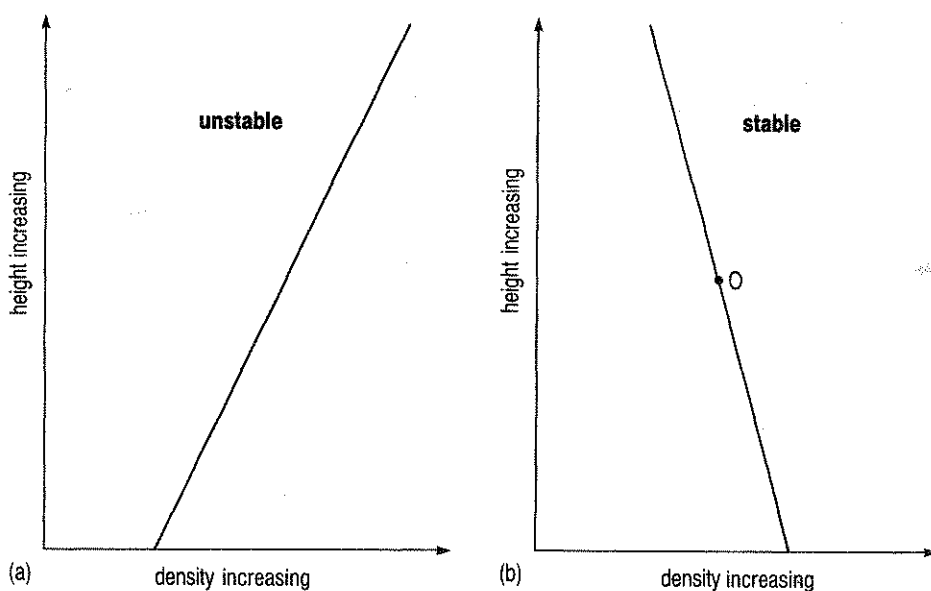


Figure 2.8 Possible variations of air density with height in the atmosphere, leading to (a) unstable and (b) stable conditions.

The density of air depends on its pressure and its temperature. It also depends on the amount of water vapour it contains—water vapour is less dense than air—but for most practical purposes water vapour content has a negligible effect on density. Thus, the variation of density with height in a column of air is determined by the variation in *temperature* with height.

However, the situation is complicated by two factors. The first is that air, like all fluids, is compressible. When a fluid is compressed, the internal energy it possesses by virtue of the motions of its constituent atoms, *and which determines its temperature*, is increased. Conversely, when a fluid expands, its internal energy decreases. Thus, a fluid heats up when compressed (a well-known example of this is the air in a bicycle pump), and cools when it expands. If these changes in temperature occur without gain or loss of heat from or to the surroundings, they are described as **adiabatic**.

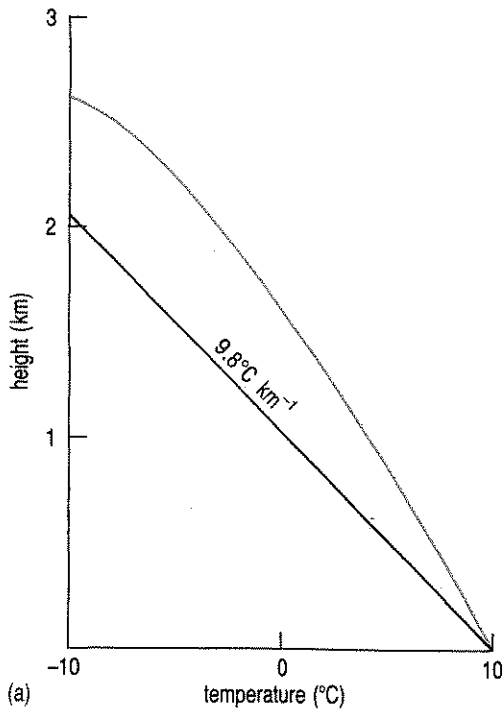


Figure 2.9 (a) Graph to illustrate that the rate at which dry air cools adiabatically (black line) is greater than the rate at which saturated air cools adiabatically (blue curve). (In the example shown, the air in question has a temperature of 10°C at ground level; in practice, it is atmospheric pressure rather than height as such that is important.)

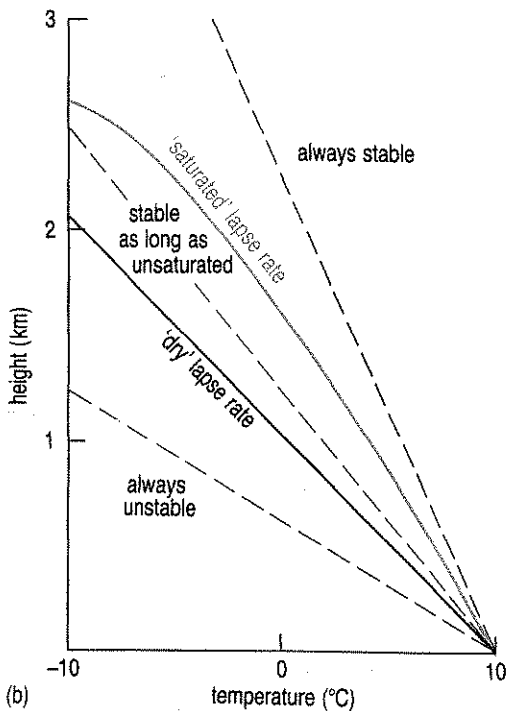


Figure 2.9 (b) The implications of the 'dry' and 'saturated' adiabatic lapse rates for columns of air with various temperature–height profiles.

When air rises, it is subjected to decreasing atmospheric pressure and so expands and becomes less dense. At the same time, it is experiencing an adiabatic decrease in temperature, which tends to increase its density. Air above the sea-surface may move upwards in random, turbulent eddying motions; whether it continues to rise depends on the relative sizes of these two effects. If the adiabatic decrease in temperature of a rising parcel of air is *less* than the decrease of temperature with height in the atmosphere, the rising parcel of air will be warmer than the surrounding air and will continue to rise. The situation will therefore be unstable and conducive to upward convection of air. If, on the other hand, the adiabatic cooling of the rising parcel of air is sufficient to reduce its temperature to a value below that of the surrounding air, it will sink back to its original level and the situation will be stable.

The other complicating factor is the effect of the water vapour in the air, not because of its lower density but because of its latent heat content. The rate at which rising *dry* air cools adiabatically is a constant 9.8°C per km (see the black curve on Figure 2.9(a); over the oceans in particular this 'dry' adiabatic lapse rate is of limited relevance. If rising air is saturated with water vapour—or becomes saturated as a result of adiabatic cooling—continued rise and associated adiabatic cooling results in the condensation of water vapour onto atmospheric nuclei, such as salt or dust particles, to form water droplets. Condensation releases latent heat of evaporation, which partly offsets the adiabatic cooling, so the rate at which air containing water vapour cools on rising is less than the rate for dry air.

This reduced adiabatic lapse rate for saturated air varies with temperature (see the blue curve in Figure 2.9(a)), because a small decrease in temperature at high temperatures results in more condensation than a similar decrease at low temperatures.

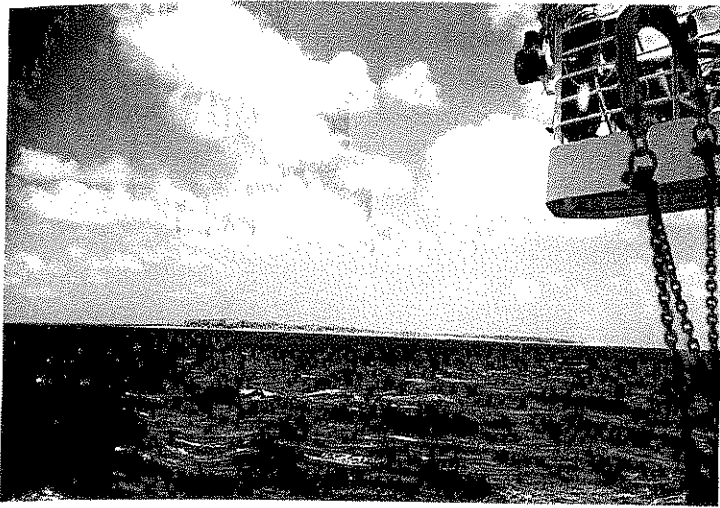
QUESTION 2.1 (a) The temperature of a column of dry air decreases from 10°C at ground level to -10°C at a height of 2.5 km. Use Figure 2.9(a) to explain why a parcel of air displaced upwards will *not* continue to rise, so that the situation is stable.

(b) What happens to the stability of this air if it becomes saturated as a result of increase in water vapour content or through adiabatic cooling?

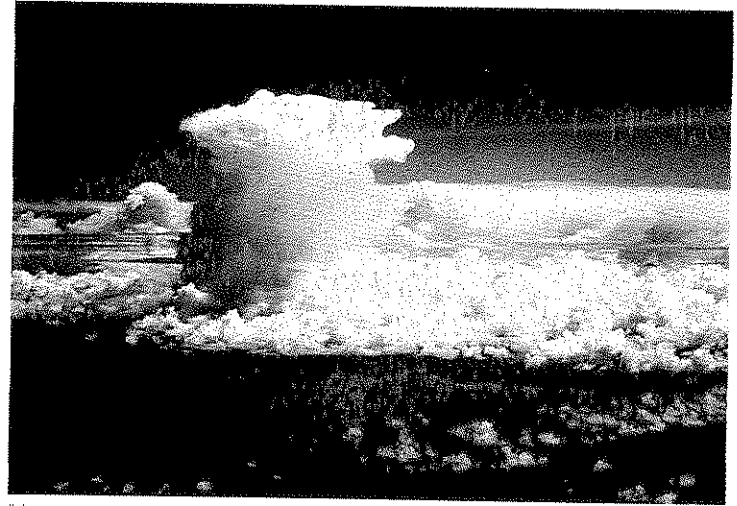
The implications of the 'dry' and 'saturated' lapse rates for the stability of various atmospheric temperature profiles are summarized in Figure 2.9(b).

Over most of the oceans, particularly in winter, the variation of temperature with height in the atmosphere, and the water content of the air, are such that conditions are unstable, air rises, and convection occurs. This is further promoted by turbulence resulting from strong winds blowing over the sea-surface; when turbulence is a more effective cause of upward movement of air than the buoyancy forces causing instability, convection is said to be *forced*. The cumulus clouds that are characteristic of oceanic regions within the Trade Wind belts are a result of such forced convection (Figure 2.10(a)).

As illustrated in Figure 2.2(b), upward development of the Trade Wind cumulus clouds is inhibited by the subsidence of warm air from above. This leads to an *increase* of temperature with height, or a temperature



(a)



(b)

Figure 2.10 (a) Cumulus clouds over the ocean in the Trade Wind belt.

(b) Cumulonimbus clouds and, at lower levels, cumulus clouds, in the Intertropical Convergence Zone over the Java Sea. Like cumulus clouds, cumulonimbus clouds form where moist air rises and cools, so that the water vapour it contains condenses to form droplets. However, cumulonimbus clouds generally extend to much greater heights than cumulus clouds (see (a)) and their upper parts consist of ice crystals.

inversion (Figure 2.11). Rising air encountering a temperature inversion is no longer warmer than its surroundings and ceases its ascent. The warmer air therefore acts as a 'ceiling' so far as upward convection is concerned.

Extremely vigorous upward movement of moist air occurs along the Intertropical Convergence Zone (Figure 2.2(b)). This gives rise to towering cumulonimbus clouds (Figure 2.10(b)), which enable the ITCZ to be easily seen on images obtained via satellites (Figure 2.12). Convection in the ITCZ extends much higher than that associated with cumulus formation, and is the principal way in which heat is distributed throughout the troposphere in low latitudes.

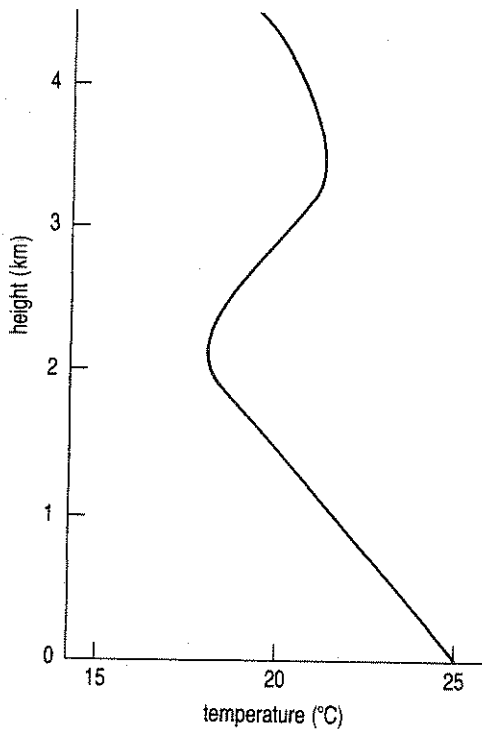


Figure 2.11 Variation of temperature with height in the Trade Wind zone, at about 5° of latitude, showing the temperature inversion.

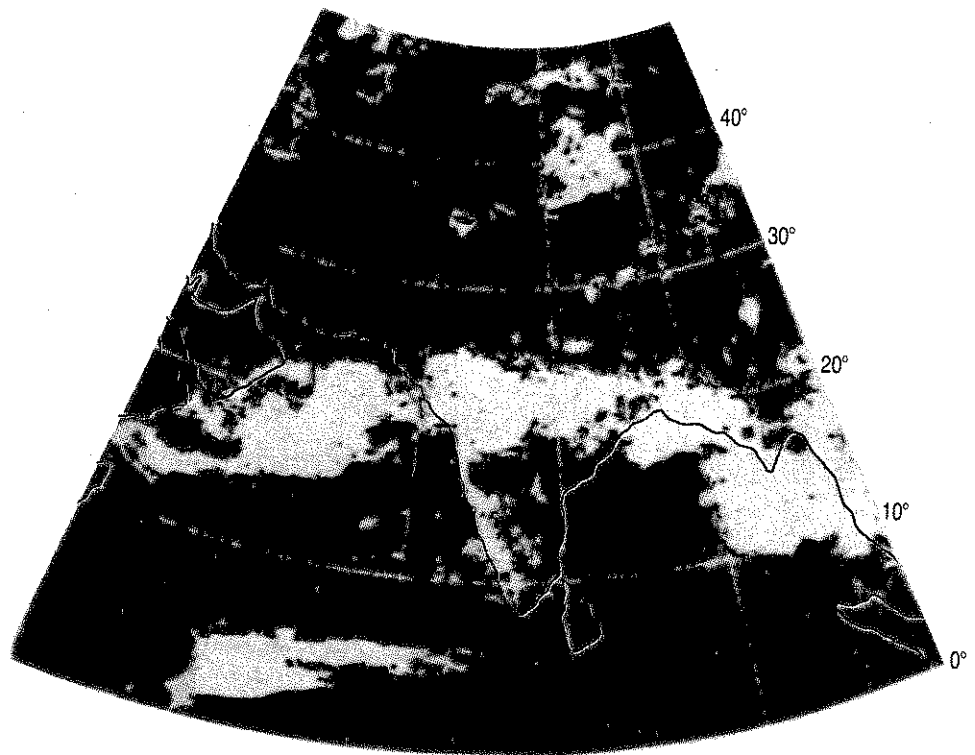


Figure 2.12 The position of the ITCZ over India and the Indian Ocean, as indicated by cloud cover. This satellite image was taken in July 1973.

2.3 ATMOSPHERE-OCEAN INTERACTION

The discussion in the previous Section illustrated how the ocean influences the atmosphere by affecting its moisture content and hence its stability. This is just one aspect of the complex interaction between the atmosphere and the ocean.

Another aspect of this interaction is the way in which the distribution of sea-surface temperature influences atmospheric circulation. For example, the intensity of the Hadley circulation is influenced by sea-surface temperature; and, as mentioned earlier, the position of the ITCZ generally corresponds to the zone of highest sea-surface temperature.

Why might this be?

It is common for the surface of the sea to be warmer than the overlying air; the higher the temperature of the sea-surface, the more heat may be transferred from the upper ocean to the lower atmosphere. Warmer air is less dense and rises, causing a low pressure region, towards which winds blow. Thus, for example, a region of exceptionally high surface temperature in the region of the Equator could lead to an increase in the intensity of the Trade Winds and the Hadley circulation. The position of the ITCZ will also be related to the low pressure zones associated with high sea-surface temperature; in addition, the warmer the sea-surface, the more buoyancy is supplied to the lower atmosphere and the more vigorous the vertical convection that will result.

In the next Section, you will see a striking example of the influence of sea-surface temperature on the atmosphere.

2.3.1 EASTERLY WAVES AND TROPICAL CYCLONES

A large amount of heat is transported away from low latitudes by strong tropical cyclones—also known as hurricanes and typhoons. Tropical cyclones only develop over oceans and so it is difficult to study the atmospheric conditions associated with their formation. It is known, however, that they are triggered by small low pressure centres, such as may occur in small vortices associated with the ITCZ. Cyclones may also be triggered by linear low pressure areas that form at right angles to the direction of the Trade Winds and travel with them (Figure 2.13). These linear low pressure regions produce wave-like disturbances in the isobaric patterns; because they move with the easterly Trade Winds they are known as easterly waves.

Easterly waves are most common in the western parts of the large ocean basins, between about 5° and 20°N. They occur most frequently during the late summer, and this is thought to be connected with the fact that the Trade Wind temperature inversion (Figures 2.2 (b) and 2.11) is weakest at that time. The temperature of the air in the lower Trade Winds is largely determined by the sea-surface temperature. This is at its highest during late summer, and so that is when the temperature increase across the temperature inversion is least.

Although only a small proportion of easterly waves give rise to cyclones, they are important because they bring large amounts of rainfall to areas

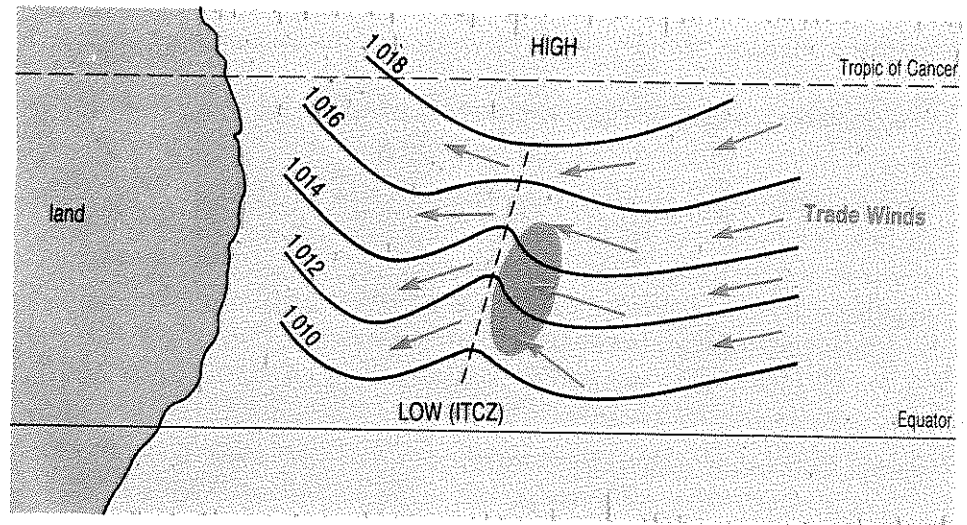
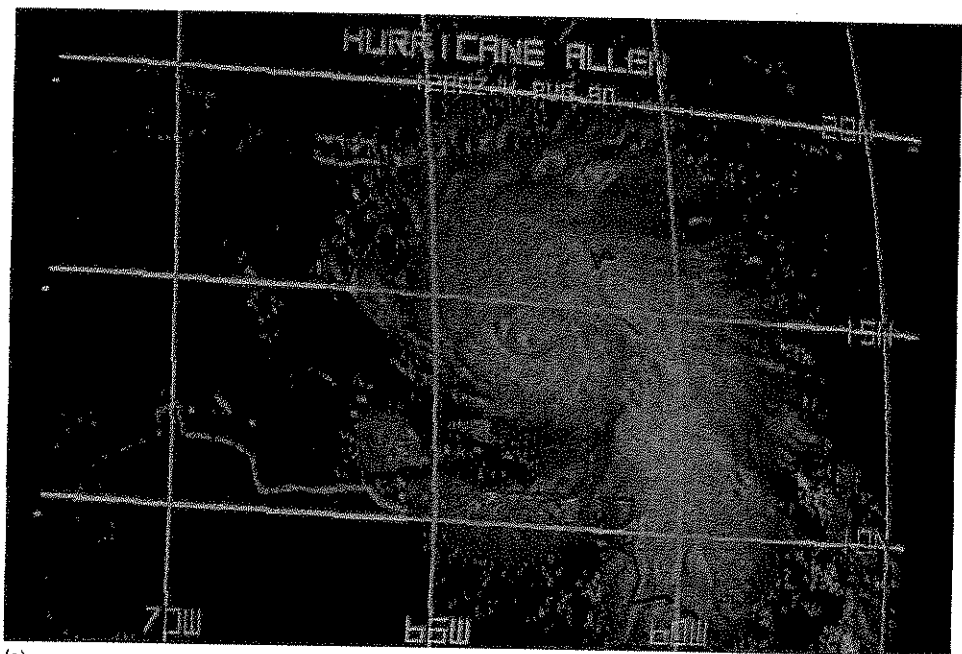


Figure 2.13 Schematic diagram of an easterly wave in the Northern Hemisphere. The black lines are isobars and the values are atmospheric pressure at ground level in millibars. The blue arrows show the wind direction. Ahead of the wave's 'axis', the Trade Wind inversion is strengthened and lowered, leading to articularly fine weather; behind it, the inversion is temporarily destroyed, causing rainfall. The main rainfall area is shown in greyish-blue.

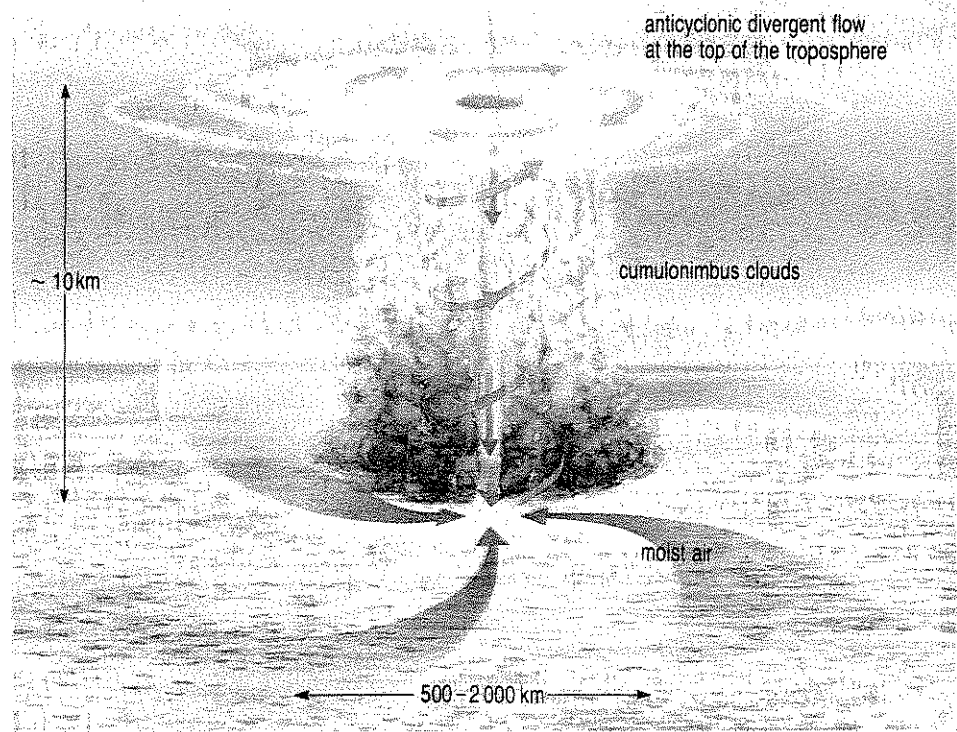
that remain generally dry as long as the Trade Winds are unperturbed (see Figure 2.13).

Once formed, the tropical cyclone is characterized by almost circular isobars closely packed around a centre of very low pressure (typically about 950mbar). Large pressure gradients near the centre of the cyclone cause air to spiral rapidly in towards the low pressure region (anticlockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere), and wind speeds commonly reach $100\text{--}200\text{km hour}^{-1}$. The core or 'eye' of the cyclone is an area of light winds and little cloud, but around it is a region where there is violent upward convection of warm humid air (see Figure 2.14(a) and (b)).



(a)

Figure 2.14 (a) Satellite image of Hurricane *Allen* passing from the Atlantic into the Caribbean. The image was obtained using the visible part of the spectrum, and the outlines of the land masses have been superimposed for clarity.



(b)

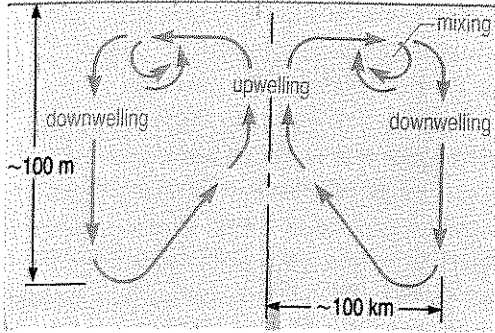
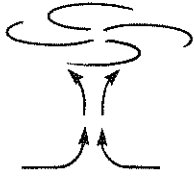
Figure 2.14 (b) Schematic diagram of a tropical cyclone showing air movements and areas of cloud formation and heavy precipitation. The cumulonimbus clouds are arranged in bands which form a spiral pattern around the core region (or eye) of the storm. Subsidence of air, and adiabatic warming, occurs in this core region, which is a region of light winds and little cloud.

The energy that drives the cyclone comes from the release of latent heat as the water vapour in the rising air condenses into clouds and rain; the resultant warming of the air around the central region of the cyclone causes it to become less dense and to rise yet more, intensifying divergent anticyclonic flow of air in the upper troposphere that is necessary for the cyclone to be maintained (Figure 2.14 (b)). Given their source of energy, it is not surprising that tropical cyclones occur only over relatively large areas of ocean where the surface water temperature is high.

In practice, the critical sea-surface temperature needed to generate the increased vertical convection which leads to extensive cumulonimbus cloud development and rain and/or cyclone formation is about 27–29°C. Why should this value be critical? One factor seems to be that the higher the temperature of air the more moisture it can hold, and the greater the upward transfer of latent heat that can occur. Given the positive feedback of the system, a rise in temperature from 27 to 29°C has a much greater effect on the overlying atmosphere than a rise from, say, 19 to 21°C. The full answer to this question is, however, as yet unknown.

QUESTION 2.2 (a) With the help of Figure 2.3 and bearing in mind what you have been reading about the conditions that favour the initiation and development of easterly waves and cyclones, can you explain why they occur more often in the Northern Hemisphere than the Southern Hemisphere?

(b) Can you also explain why cyclones do not develop within about 5° of the Equator?



(c)

Figure 2.14 (c) The effect of a cyclone on the surface ocean. Near the centre of the storm, surface water diverges and upwelling of deeper, cooler water occurs; some distance from the centre, the surface water that has travelled outwards from the centre converges with the surrounding ocean surface water and downwelling, or sinking, occurs. In between the zones of upwelling and downwelling, the displaced surface water mixes with cooler subsurface water. (Note that the way in which cyclonic winds lead to upwelling of subsurface water will be explained in Chapter 3.)

Tropical cyclones also occur more often in the western than the eastern parts of the Atlantic and Pacific oceans. This is because sea-surface temperatures are higher there, for reasons that will become clear in later Chapters.

The violent winds of tropical cyclones generate very large waves on the sea-surface. These waves travel outwards from the central region and as the cyclone progresses the sea becomes very confused. The region where the winds are blowing in the *same* direction as the cyclone is travelling is particularly dangerous because here the waves have effectively been blowing over a greater distance (i.e. they have a greater **fetch**). In addition, ships in this region may be blown into the cyclone's path.

Cyclones also affect the deeper structure of the ocean over which they pass. Near the centre of the storm the action of the wind causes the surface waters to diverge so that deeper, cooler water upwells to replace it. Thus, not only are cyclones *affected* by sea-surface temperature, but they also *modify* it, so that their tracks are marked out by surface water with anomalously low temperatures, perhaps as much as 5°C below that of the surrounding water. Figure 2.14(c) shows in more detail the changes in the water column that have been observed to accompany tropical cyclones.

Characteristic tracks followed by cyclones as they move away from their sites of generation are shown in Figure 2.15. Note that they nearly always move polewards, which is why they form such a powerful mechanism for the transport of heat to higher latitudes. If they move over land areas they begin to die away, as the energy conversion system needed to drive them can no longer operate. Their decay over land may be hastened by increased surface friction and the resulting increased variation of wind velocity with height (vertical **wind shear**) which inhibits the maintenance of atmospheric vortices. The lower temperatures of land masses (especially at night) may also play a part in their decay. The average lifespan of a tropical cyclone is about a week.

There is a great variation in the frequency of tropical cyclones. Over the past few decades there seems to have been an increase in their

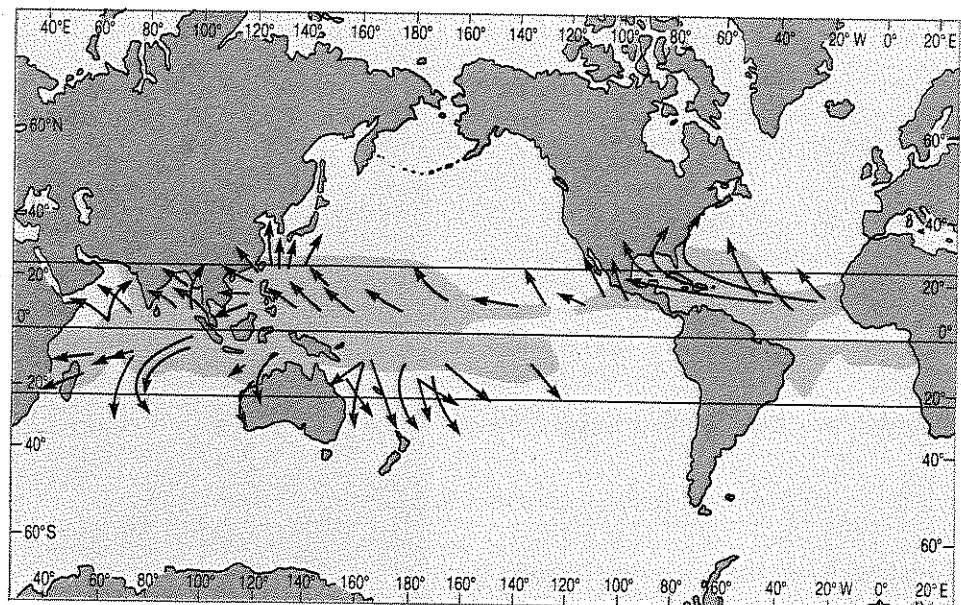


Figure 2.15 Characteristic tracks followed by tropical cyclones. Initially they move westwards, but then generally curve polewards and eastwards around the subtropical high pressure centres. The red shaded regions are those areas where the sea-surface temperature exceeds 27°C in summer (mean values for September and March, in the Northern and Southern hemispheres, respectively).

Table 2.1 Mean number of cyclones occurring over a ten-year period.

North Pacific (western part)	208
North Atlantic, Caribbean	85
Bay of Bengal	75
South-west Indian Ocean	41
North-east of Australia	31
North-west of Australia	23
Arabian Sea	19
North Pacific (eastern part)	10

occurrence, but it is not clear whether this is a genuine increase or part of a cyclical variation. The mean frequency in various regions is given in Table 2.1.

Cyclones have a great impact on life in the tropics. They are largely responsible for late summer or autumn rainfall maxima in many tropical areas. The strong winds and large waves associated with them may cause severe damage to natural environments such as reefs; indeed, these catastrophic events play a major role in determining the patterns of distribution of species and life forms within such communities. They may lead to great loss of human life, particularly where there are large populations living near to sea-level, on the flood plains of major rivers or on islands. The low atmospheric pressures associated with cyclones may cause a rise in the sea-level, quite apart from the high seas caused by the winds, and widespread flooding of low-lying areas can result. The cyclone disaster which devastated the delta region of the Bay of Bengal in May 1985 was largely the result of such a **storm surge**, further amplified by the occurrence of high tides.

Water spouts

Water spouts are similar to cyclones in that they are also associated with cyclonic air movements, vigorous atmospheric convection, and cumulus and cumulonimbus cloud formation (see Figure 2.16). They are funnel-shaped vortices of air with very low pressures at their centres, so that air and water spiral rapidly inwards and upwards. The funnels extend from the sea-surface to the 'parent' clouds that travel with them; they whip up a certain amount of spray from the sea-surface but are visible mainly because the reduction of pressure within them leads to adiabatic expansion and cooling which causes atmospheric water vapour to condense.

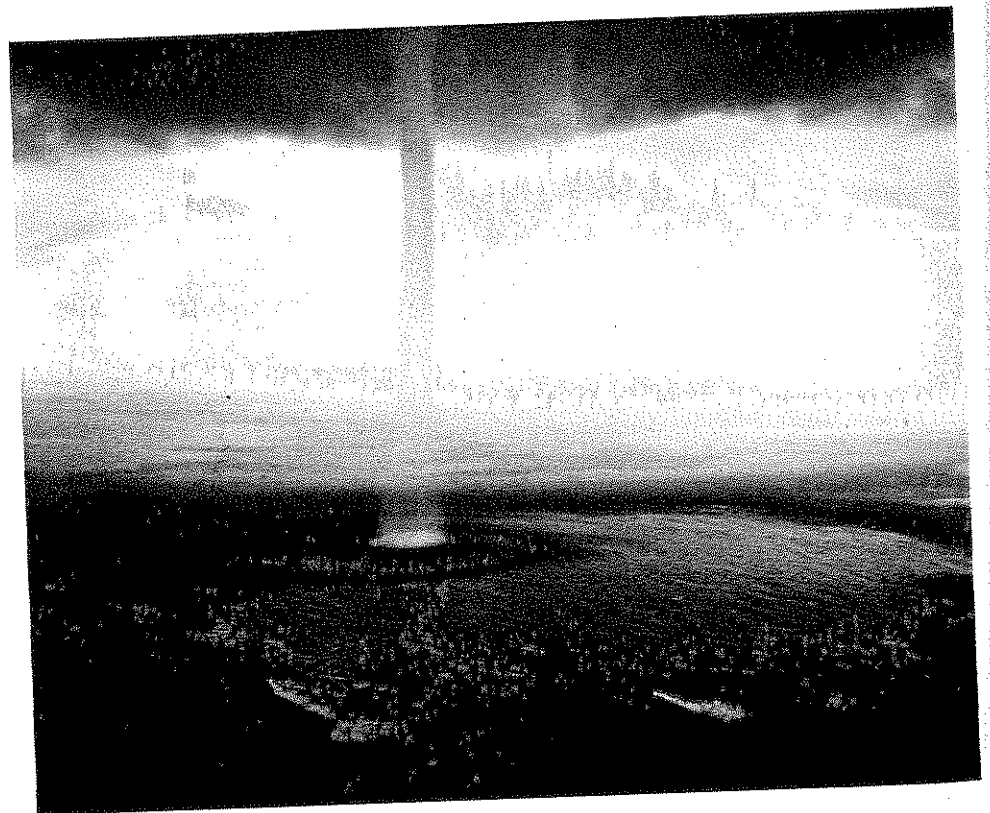


Figure 2.16 A water spout near Lower Malecumbe Key, Florida.

Water spouts are a much smaller-scale phenomenon than cyclones. They range from a few metres to a few hundred metres in diameter, and they rarely last more than fifteen minutes. They occur most often in the spring and early summer. Unlike cyclones they are not confined to the tropics, although they occur most frequently there, usually in the spring and early summer. They are particularly common over the Bay of Bengal and the Gulf of Mexico, and also occur frequently in the Mediterranean.

2.4 SUMMARY OF CHAPTER 2

- 1 The global wind system acts to redistribute heat between low and high latitudes.
- 2 Winds blow from regions of high pressure to regions of low pressure. Because of the differing thermal capacities of continental masses and oceans, wind patterns are greatly influenced by the distribution of land and sea.
- 3 Winds are deflected by the Coriolis force, to an extent that increases with increasing latitude. In mid-latitudes, the predominant wind systems are cyclones, which blow around low pressure centres or depressions, and anticyclones, which blow around high pressure centres. At low latitudes, the atmospheric circulation consists essentially of the spiral Hadley cells, of which the Trade Winds form the lowermost limb. The Intertropical Convergence Zone is the region where the wind systems of the two hemispheres meet; it is generally associated with the zone of maximum sea-surface temperature.
- 4 Heat is transported polewards in the atmosphere as a result of warm air moving into cooler latitudes. It is also transported as *latent* heat: heat used to convert water to water vapour is released when the water vapour condenses (e.g. in cloud formation). Over the tropical oceans, turbulent convection of the overlying air transports large amounts of heat from the sea-surface high into the atmosphere, leading to the formation of cumulus and, especially, cumulonimbus clouds. An extreme expression of this convection is the generation of tropical cyclones.

Now try the following questions to consolidate your understanding of this Chapter.

QUESTION 2.3 Which of statements (a)–(f) concerned with the global wind system are true and which are false?

- (a) Regions with high surface atmospheric pressure are regions where air is rising.
- (b) Heavy precipitation is characteristic of regions where air is sinking.
- (c) In both seasons of the year, the atmospheric circulation over the North Atlantic is predominantly anticyclonic.
- (d) In both seasons of the year, the atmospheric circulation over Eurasia is predominantly cyclonic.
- (e) The Trade Wind systems of the two hemispheres meet along a zone of high pressure.
- (f) In polar regions, the tropopause is about 12–15 km above the Earth.

QUESTION 2.4 (a) Draw a plan-view sketch of a tropical cyclone in the Northern Hemisphere, showing isobars and wind direction. Indicate on your diagram the regions that are particularly dangerous for navigation.
 (b) What is the 'fuel' that drives a tropical cyclone?

QUESTION 2.5 Figure 2.17 is a satellite image of the Earth made at the same time as the image in Figure 2.1 but using the electromagnetic wavelengths to which water vapour is opaque. The warmest areas are black and the coldest white. Thus, dark areas represent regions in which the upper troposphere is dry so that radiation from lower, warmer layers is able to reach the satellite; white areas correspond to radiation from the upper troposphere, which is cold. By comparing this image with that in Figure 2.1, use information from this Chapter to identify the following features:

- cumulonimbus cloud formation in association with the ITCZ;
- the northern and southern polar fronts;
- the subtropical high pressure regions.

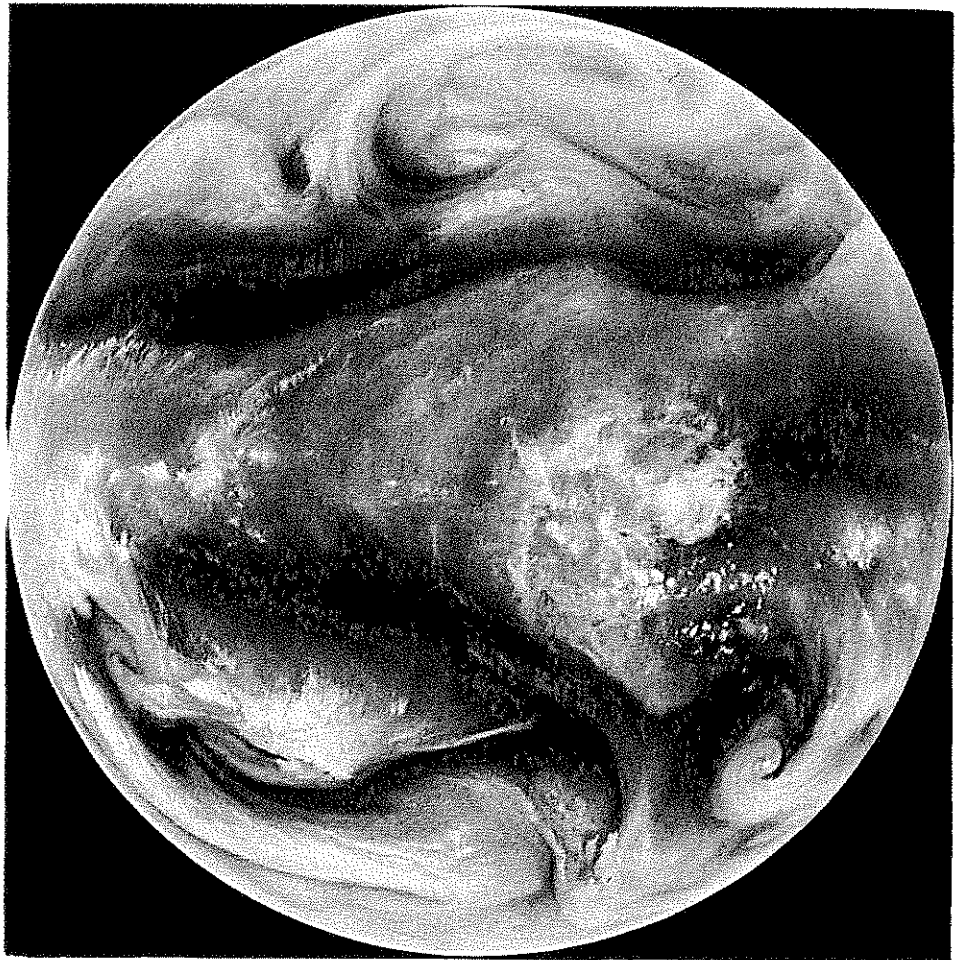


Figure 2.17 Satellite image of the Earth, constructed using the 'water vapour' channel (wavelength 3 000 nm); the colour is artificial. This image and that in Figure 2.1 show the same view of the Earth and are for 26 March 1982.

QUESTION 2.6 In Chapter 5, we will be discussing how disturbances may be transmitted from one part of the ocean to another by means of large-scale wave motions. From your reading of Chapter 2, give *two* examples of *atmospheric* disturbances that propagate as waves.