[redacted]

The solid red curves in Figure 1.4(a)(i) and (ii) show the incoming solar radiation reaching the Earth and atmosphere, as a function of latitude, for the northern summer and the southern summer, respectively. The intensity of incoming solar radiation is greatest for mid-latitudes in the hemisphere experiencing summer, while for high latitudes in the winter hemisphere, the oblique angle of the Sun's rays, combined with the long periods of winter darkness, results in amounts of radiation received being low.

However, the Earth not only receives short-wave radiation from the Sun, it also *re*-emits radiation, of a longer wavelength. Little of this long-wave radiation is radiated directly into space; most of it is absorbed by the

70%

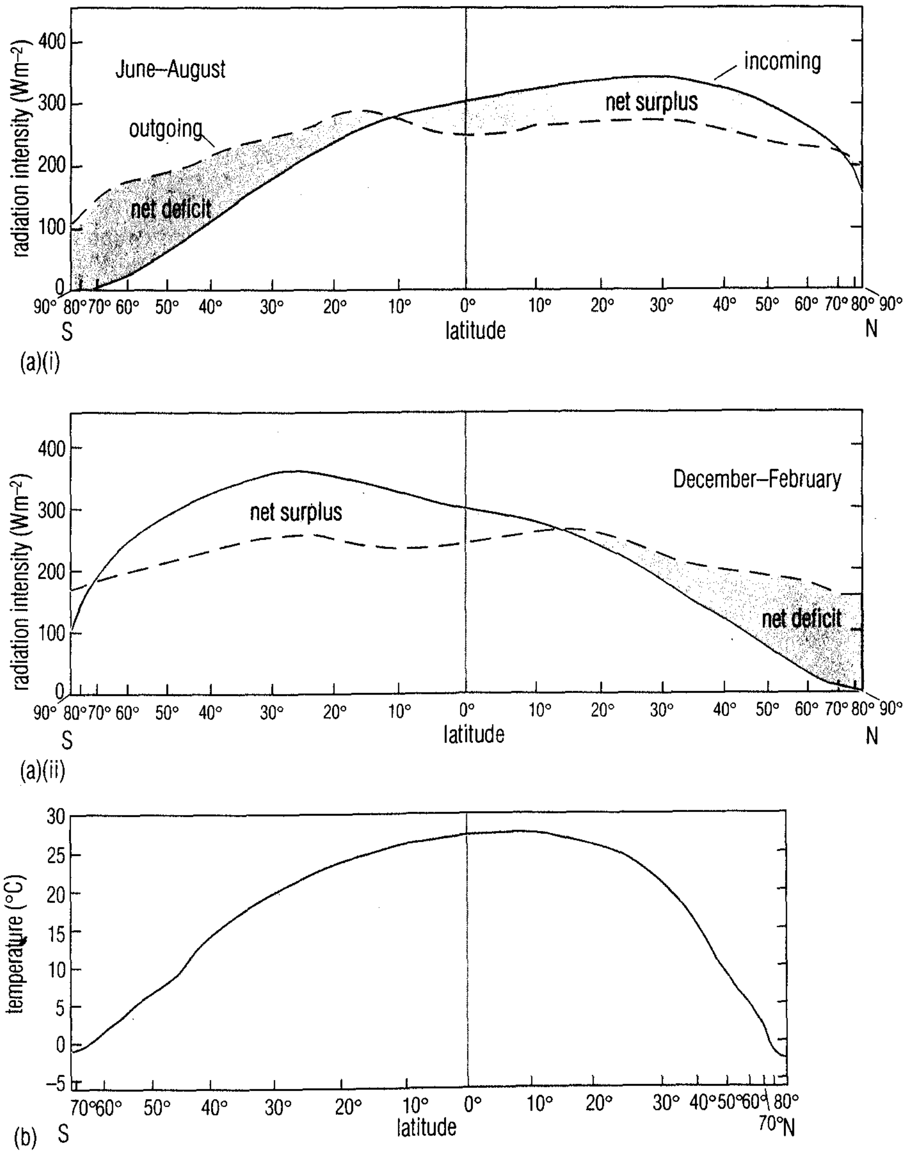

Figure 1.4 (a) The radiation balance at the top of the atmosphere plotted against latitude (scaled according to the Earth's surface area) for (i) the northern summer and (ii) the southern summer. The red solid line is the intensity of incoming solar radiation and the red dashed line is the intensity of radiation lost to space (both determined using satellite-borne radiometer).

(b) The average temperature of surface waters at different latitudes. At a given latitude, there will be surface waters whose annual mean temperatures are higher or lower than shown by the curve; this range is represented by the thickness of the pink envelope.

atmosphere, particularly by carbon dioxide, water vapour and cloud droplets. Thus, the atmosphere is heated from beneath by the Earth and itself re-emits long-wave radiation into space. This generally occurs from the top of the cloud cover where temperatures are surprisingly similar at all latitudes. The intensity of the radiation emitted into space therefore does not vary greatly with latitude, although as can be seen from the dashed curves in Figure 1.4(a), it is highest for the subtropics and lowest for high latitudes in the hemisphere experiencing winter.

QUESTION 1.2

(a) According to Figure 1.4(a), for what latitude band is there always a net surplus of radiation? At what latitudes is there always a deficit?

(b) (i) Approximately how much warmer than surface waters poleward of 70° are surface ocean waters within 10° of the Equator?

(ii) 'Sea-surface temperatures are highest in the vicinity of the Equator because of the long day-length there.' True or false?

In Figure 1.4(a), the two areas labelled 'net surplus' are together about equal to those labelled 'net loss'. This suggests that the radiation budget for the Earth–ocean–atmosphere system as a whole is in balance, i.e. that over the course of a year the system is not gaining more radiation energy than it is losing (or *vice versa*). Note that this use of areas under curves only works here because the horizontal axis is increasingly compressed towards higher latitudes to compensate for the decreasing area of the globe within given latitude bands. Note also that the temperature at the top of the atmosphere is not directly related to the global temperature in general so plots such as those in Figure 1.4(a) do not allow us to determine whether the 'enhanced greenhouse effect' resulting from increasing concentrations of atmospheric CO_2 is leading to global warming.

The positive radiation balance at low latitudes, and the negative one at high latitudes, results in a net transfer of heat energy from low to high latitudes, by means of wind systems in the atmosphere and current systems in the ocean. There has been much debate about the relative importance of the atmosphere and ocean in the poleward transport of heat. Figure 1.5 shows estimates of poleward heat transport, based on satellite observations of the upper atmosphere, and measurements within the atmosphere, published in 1985. Positive values correspond to northward transport and negative values to southward transport.

QUESTION 1.3

(a) How does the total poleward transport of heat in the ocean compare with that in the atmosphere, according to Figure 1.5?

(b) Over which parts of the globe does the ocean contribute significantly more to poleward heat transport, and over which parts does the atmosphere contribute significantly more?

Wind systems redistribute heat partly by the **advection** of warm air masses into cooler regions (and *vice versa*), and partly by the transfer of latent heat which is taken up when water is converted into water vapour, and released when the water vapour condenses in a cooler environment. The tropical storms known as cyclones or hurricanes are dramatic manifestations of the transfer of energy from ocean to atmosphere in the form of latent heat. The generation of cyclones, and their role in carrying heat away from the tropical oceans, will be described in Chapter 2.

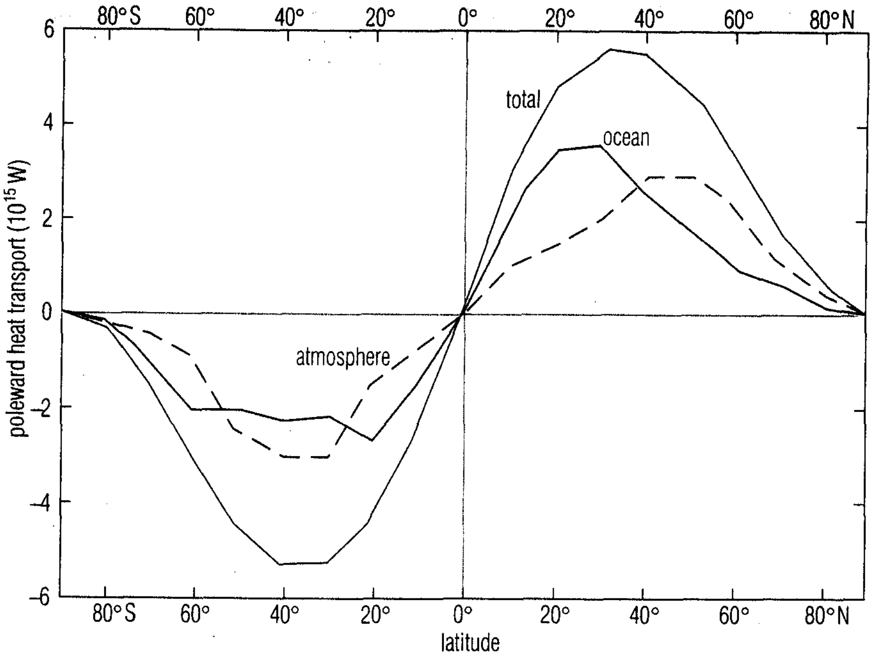

Figure 1.5 Estimates of the contributions to poleward heat transport (red curve) by the ocean (solid blue curve) and the atmosphere (dashed blue curve). Positive values are northward heat transport, negative values are southward heat transport. The total heat transport was derived from satellite measurements at the top of the atmosphere, heat transported by the atmosphere was estimated using measurements of atmospheric heat fluxes, and the heat transported by the ocean was calculated as the difference between the two.

1.2 SUMMARY OF CHAPTER 1

1 Circulation in both the oceans and the atmosphere is driven by energy from the Sun and modified by the Earth's rotation.

2 The radiation balance of the Earth–ocean–atmosphere system is positive at low latitudes and negative at high latitudes. Heat is redistributed from low to high latitudes by means of wind systems in the atmosphere and current systems in the ocean. There are two principal components of the ocean circulation: wind-driven surface currents and the density-driven (thermohaline) deep circulation.

3 Air and water masses moving over the surface of the Earth are only weakly bound to it by friction and so are subject to the Coriolis force. The Coriolis force acts at right angles to the direction of motion, so as to deflect winds and currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere; the deflections are significant because winds and currents travel relatively slowly. The Coriolis force is zero at the Equator and increases to a maximum at the poles.

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

QUESTION 1.4

(a) A missile is fired southwards from the Equator. Explain what will happen to the direction of its path in relation to the Earth.

(b) In which direction will a current be deflected by the Coriolis force if it is initially flowing (i) eastwards at 45° N, (ii) westwards on the Equator?

QUESTION 1.5 In Figure 1.4(a), the horizontal axis is scaled according to the surface area of the Earth in different latitude bands. Why do you think the horizontal axis of Figure 1.4(b), showing the annual mean temperature of surface ocean waters, is more compressed at northern than southern high latitudes?

CHAPTER 2

THE ATMOSPHERE AND THE OCEAN

Anyone who has seen images 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.

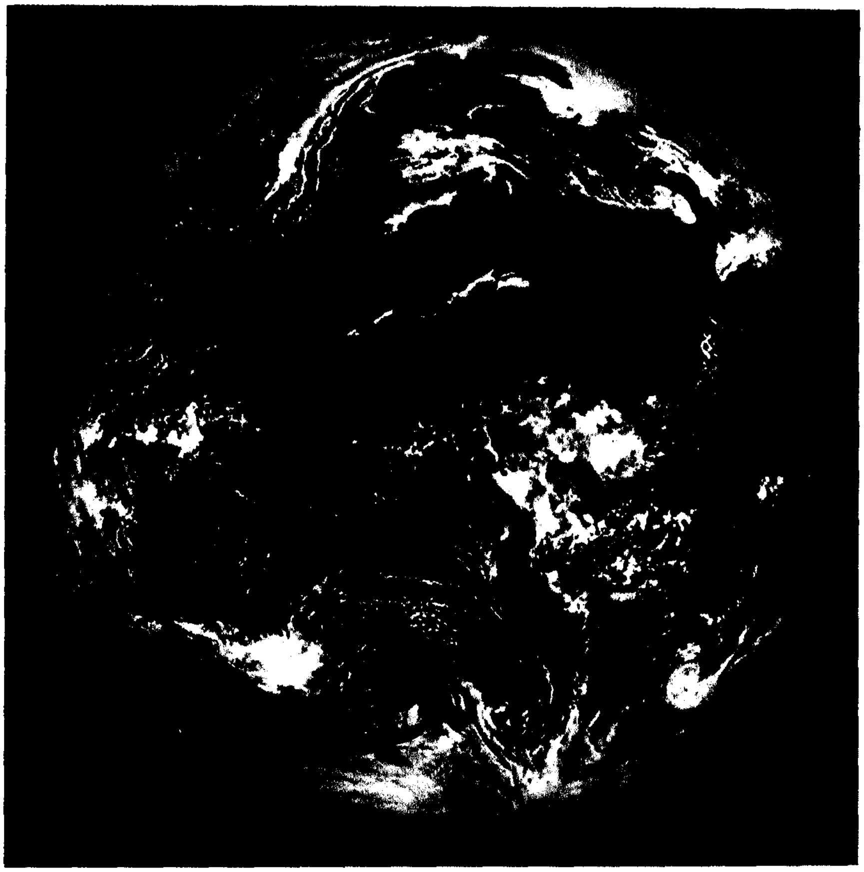

Figure 2.1 The Earth as seen from a geostationary satellite positioned over the Equator. The height of the satellite (about 35 800 km) is such that almost half of the Earth's surface may be seen at once. The outermost part of the image is extremely foreshortened, as can be seen from the apparent position 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 atmospheric circulation of the atmosphere, and then move on to consider the smaller-scale phenomena that characterize the moist atmosphere over the oceans.

[redacted]

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, but the features shown may all be found in the real atmosphere to greater or lesser extents.

In the lower atmosphere, pressure is low along the Equator, and warm air converges here, rises, and moves polewards. Because the Earth is spherical, air moving polewards in the upper part of the troposphere is forced to converge, as lines of longitude converge. As a result, at about 30° N and S there is a 'piling up' of air aloft, which results in raised atmospheric pressure at the Earth's surface below.* There is therefore a pressure gradient from the subtropical highs (where air is subsiding) 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) and (c) show, 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 north-east. However, whereas 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 will generally use south*ward* rather than south*erly* (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 in Figure 2.2(a) and (b). Strictly speaking, the term 'Hadley cell' refers only to the north–south component of the circulation. Because the flow is deflected by the Coriolis force, in three dimensions the circulation follows an approximately spiral pattern (Figure 2.2(c)).

Figure 2.3(a) and (b) (p. 20) show the prevailing winds at the Earth's surface for July and January, along with the average positions of the main regions of high and low pressure for these months of the year. Figure 2.3(c) shows the surface winds over the Pacific and Atlantic for one particular day in 1999.

How closely do the actual winds and pressure systems over the Earth (Figure 2.3(a),(b)) correspond with the hypothetical wind system and pressure pattern shown in Figure 2.2(a)?

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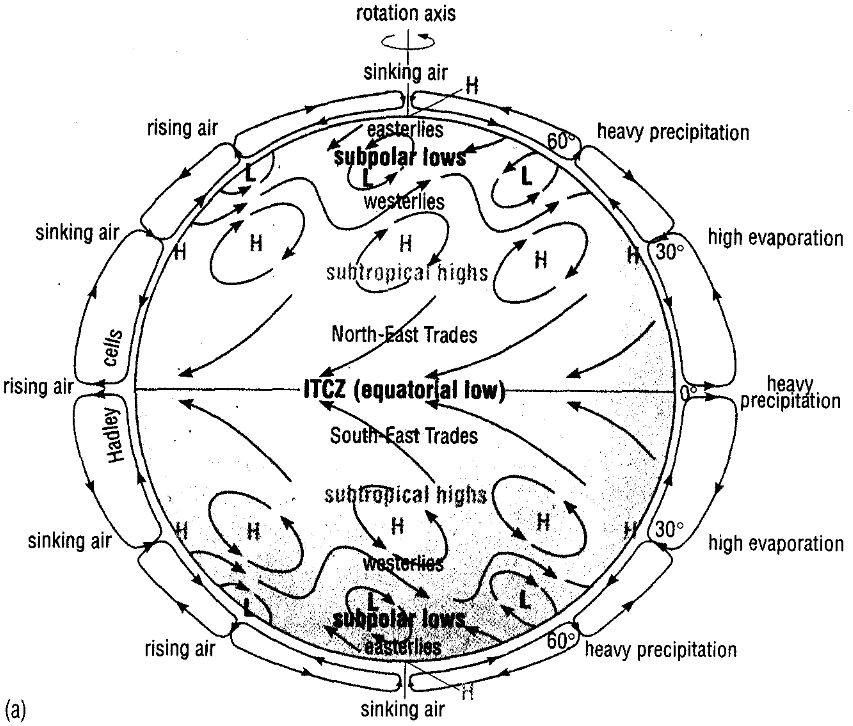
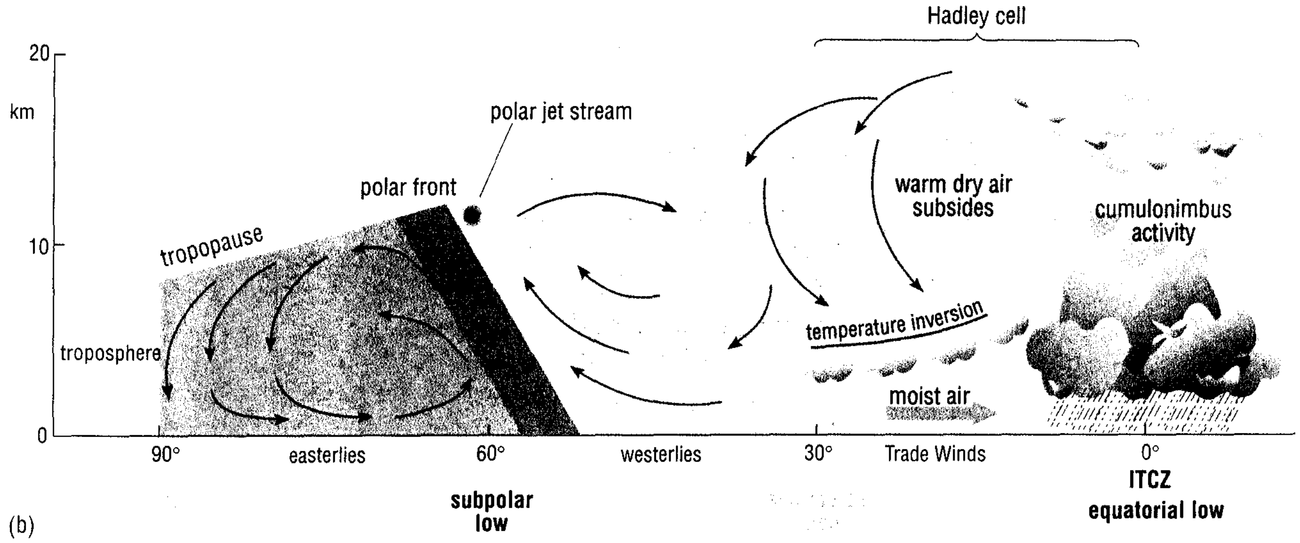
*Generally, atmospheric pressure at sea-level is determined by the weight of the column of air above, even if that air is gently rising or subsiding in regions of low or high pressure. Only in intense thunderstorms, cyclones and tornadoes, where the air has an appreciable upward acceleration, is atmospheric pressure directly affected by the vertical motion of the air.

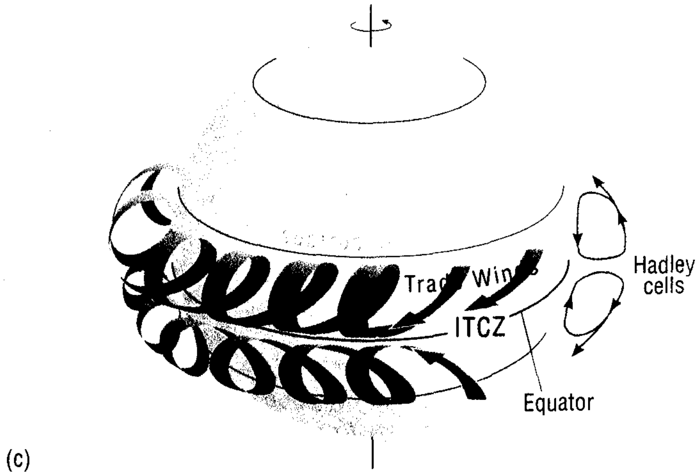
Figure 2.2 (a) Wind system for a hypothetical water-covered Earth, showing major winds and zones of low and high pressure systems. Vertical air movements and circulation cells are shown in exaggerated profile either side, with characteristic surface conditions given on the right. Note that convergence of air at low levels and divergence at high levels results in air rising, while the converse results in air sinking. The two north–south cells on either side of the Equator make up the Hadley circulation. ITCZ = Intertropical Convergence Zone, the zone along which the wind systems of the Northern and Southern Hemispheres meet. (This and other details are discussed further in the text.)

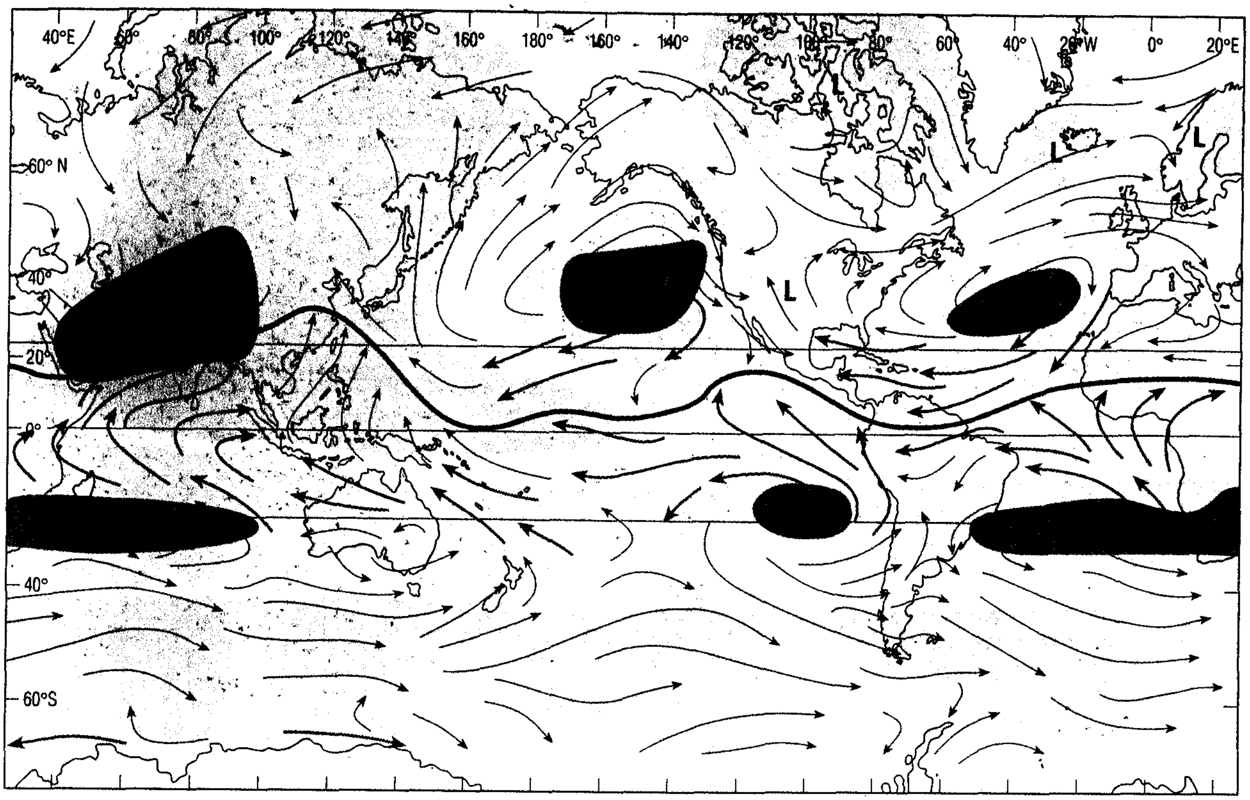
(b) Section through the atmosphere, from polar regions to the Equator, showing the general circulation, the relationship of the polar jet stream to the polar front, and regions of tropical cloud formation. Note that much of the poleward return flow takes place in the upper part of the troposphere (the part of the atmosphere in which the temperature decreases with distance above the Earth); the tropopause is the top of the troposphere and the base of the stratosphere.





(c) Schematic diagram to show the spiral circulation patterns of which the Trade Winds form the surface expression; the north–south component of this spiral circulation (see right-hand side) is known as the Hadley circulation or 'Hadley cells' (also shown on Figure 2.2(a)).





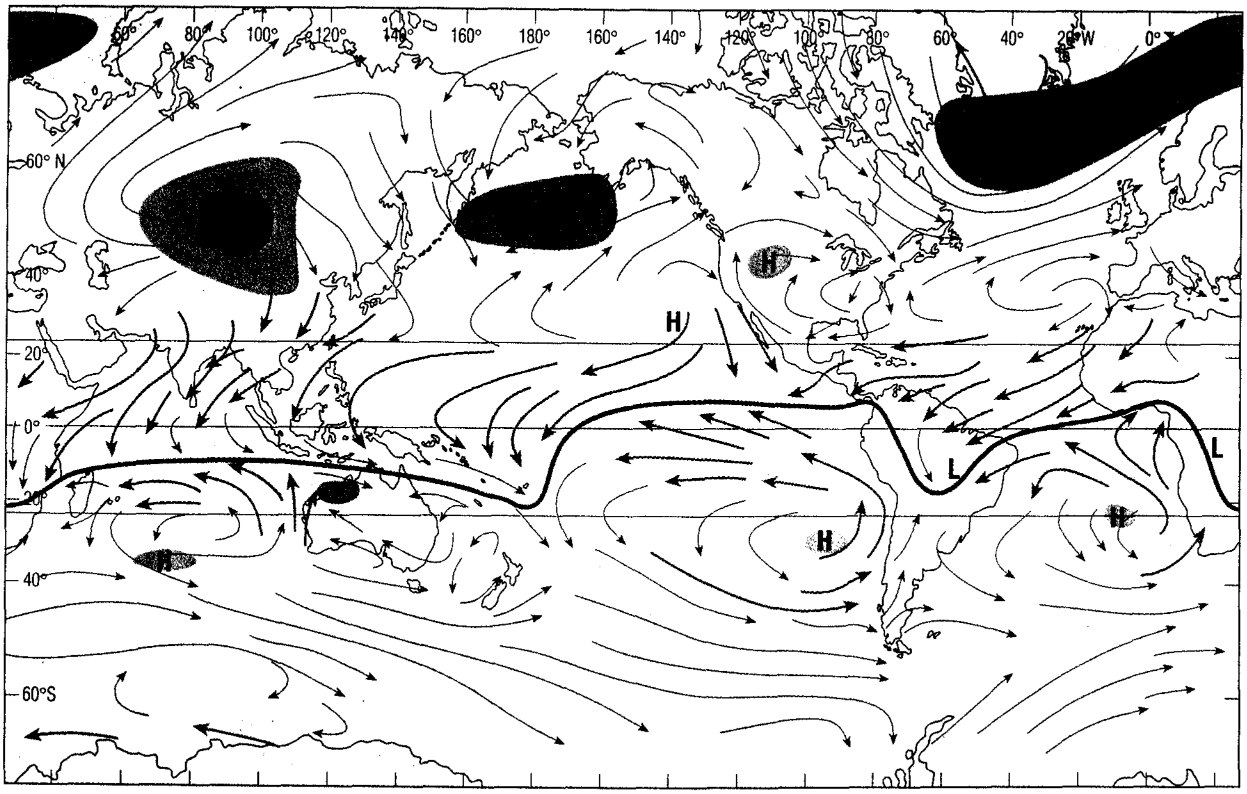
(a) JULY

KEY

mean position of ITCZ

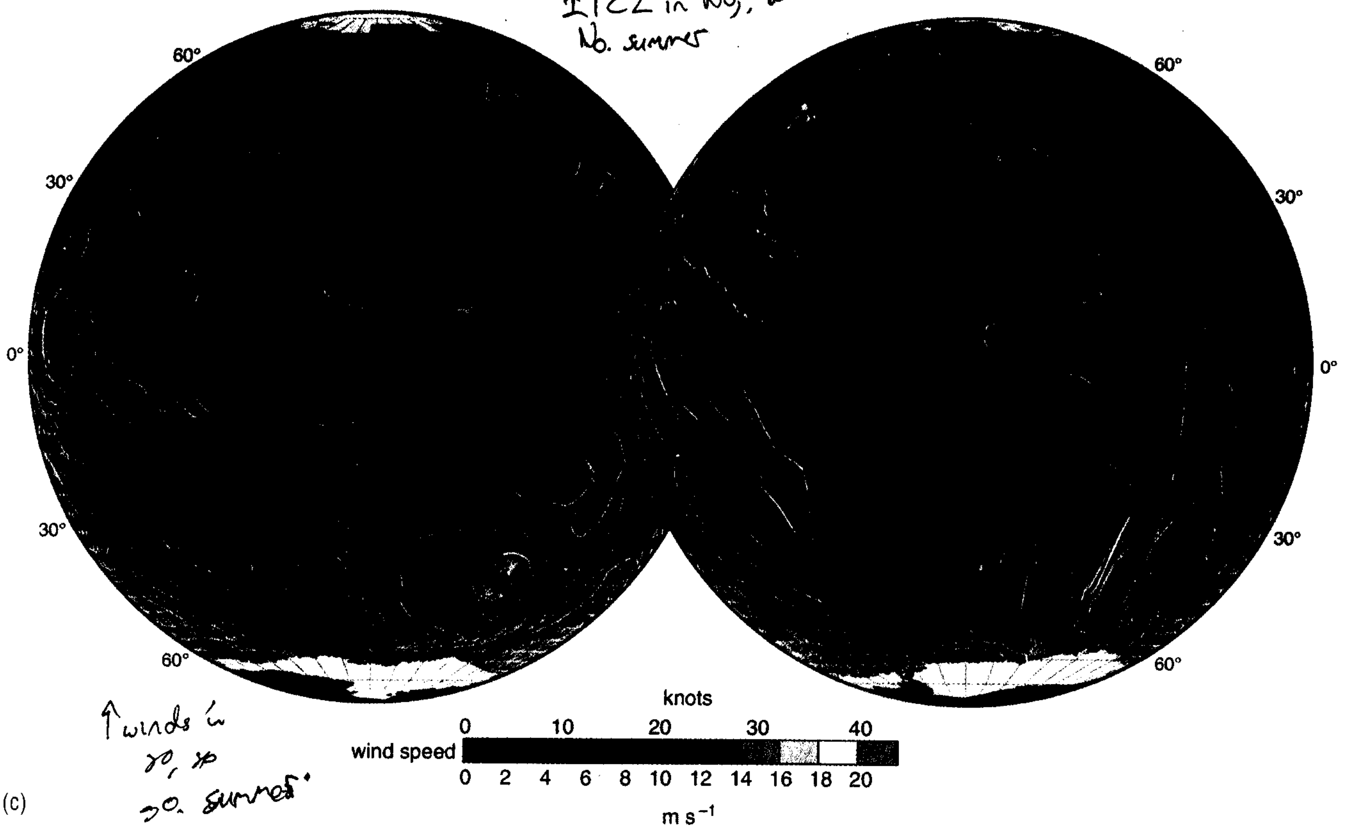
most frequent wind direction

prevailing wind direction (≥50 % of observations)



(b) JANUARY

ITCZ in No, so
No. summer



↑ winds in
So, so
So. summer.

(c)

Figure 2.3 The prevailing winds at the Earth's surface, and the average position of the Intertropical Convergence Zone for (a) July (northern summer/southern winter) and (b) January (southern summer/northern winter). Also shown are the positions of the main regions of high and low atmospheric pressure (red/pink for high pressure, blue for low). Note that as these maps represent conditions averaged over a long period, they show simpler patterns of highs and lows, and of wind flow, than would be observed on any one day (cf. the more complicated patterns in (c)). Extreme conditions are not represented, as they have been 'averaged out' (which is not the case in (c), above).

(c) Surface winds over the Pacific and Atlantic Oceans for one day in 1999 (to be used later, in Question 2.6). Green/pale blue = lowest wind speeds, yellow = highest wind speeds. The maps have been obtained using a satellite-borne 'scatterometer' which measures microwave radar back-scattered from the sea-surface (wind speed is calculated from the estimated roughness of the sea-surface, and wind direction determined from the inferred orientation of wave crests). Note the complexity of the flow pattern, and localized extreme conditions, which do not show up in the maps of averaged data in Figure 2.3(a) and (b).

In general, not that closely, although the actual and hypothetical winds *are* very similar over large areas of ocean, away from the land. You may also have noticed that the simple arrangement of high pressure systems in the subtropics and low pressure in subpolar regions is more clearly seen in the Southern Hemisphere, which is largely ocean.

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 and becomes denser, so that a large shallow high pressure area develops, from which winds blow out towards regions of lower pressure. In the summer, the situation is reversed: air over the Eurasian land mass heats up, and becomes less dense. There is a region of warm rising air and 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.

The distribution of ocean and continent also influences the position of the zone along which the wind systems of the two hemispheres converge. The 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).