CHAPTER 1 INTRODUCTION

THE
EARTH-
ATMOSPHERE
SYSTEM

The waters of the ocean are continually moving. This motion ranges from powerful currents like the Gulf Stream, down to small swirls and eddies (Figure 1.1)

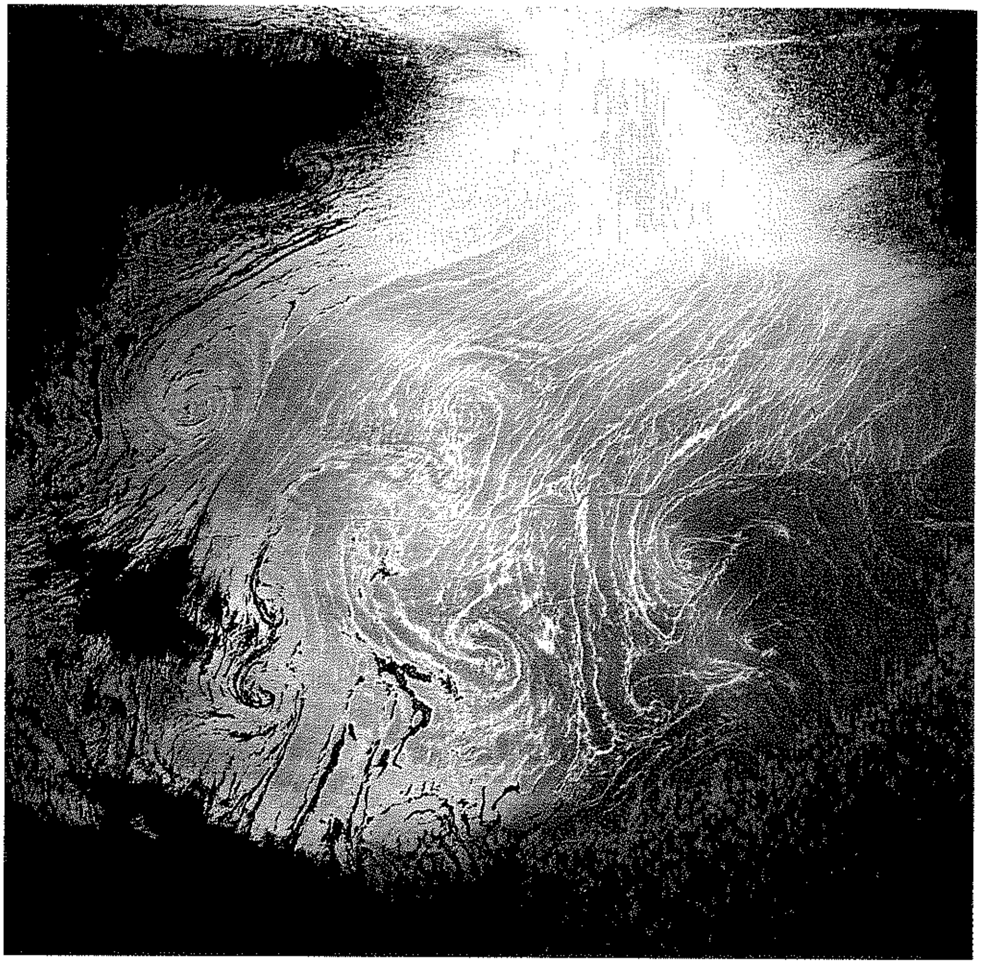

Figure 1.1 These spiral eddies in the central Mediterranean Sea were photographed from the Space Shuttle *Challenger*. Measuring some 12–15 km across, they are only one example of the wide range of gyral motions occurring in the oceans.

What drives all this motion?

The short answer is: energy from the Sun, and the rotation of the Earth.

The most obvious way in which the Sun drives the oceanic circulation is through the circulation of the atmosphere—that is, winds. Energy is transferred from winds to the upper layers of the ocean through frictional coupling between the ocean and the atmosphere at the sea-surface.

The Sun also drives ocean circulation by causing variations in the temperature and salinity of seawater which in turn control its *density*. Changes in temperature are caused by fluxes of heat across the air–sea boundary; changes in salinity are brought about by the addition or removal of freshwater, mainly through evaporation and precipitation, but also, in polar regions, by the freezing and melting of ice. All of these processes are linked directly or indirectly to the effect of solar radiation.

If surface water becomes denser than the underlying water, the situation is unstable and the denser surface water sinks. The vertical, density-driven circulation that results from cooling and/or increase in salinity—i.e. changes in the content of heat and/or salt—is known as **thermohaline circulation**. The large-scale thermohaline circulation of the ocean will be discussed in Chapter 6.

How does the rotation of the Earth contribute to ocean circulation patterns?

Except for a relatively thin layer close to the solid Earth, frictional coupling between moving water and the Earth is weak, and the same is true for air masses. In the extreme case of a projectile moving above the surface of the Earth, the frictional coupling is effectively zero. Consider, for instance, a missile fired northwards from a rocket launcher positioned on the Equator (Figure 1.2(a)). When it leaves the launcher, the missile is moving eastwards at the same velocity as the Earth's surface as well as moving northwards at its firing velocity. As the missile travels north, the Earth is turning eastwards beneath it. Initially, because it has the same eastwards velocity as the surface of the Earth, the missile appears to travel in a straight line. However, the eastwards velocity at the surface of the Earth is greatest at the Equator and decreases towards the poles, so as the missile travels progressively northwards, the eastwards velocity of the Earth beneath it becomes less and less. As a result, *in relation to the Earth*, the missile is moving not only northwards but also *eastwards*, at a progressively greater rate (Figure 1.2(b)). This apparent deflection of objects that are moving over the surface of the Earth without being frictionally bound to it—be they missiles, parcels of water or parcels of air—is explained in terms of an apparent force known as the **Coriolis force**.

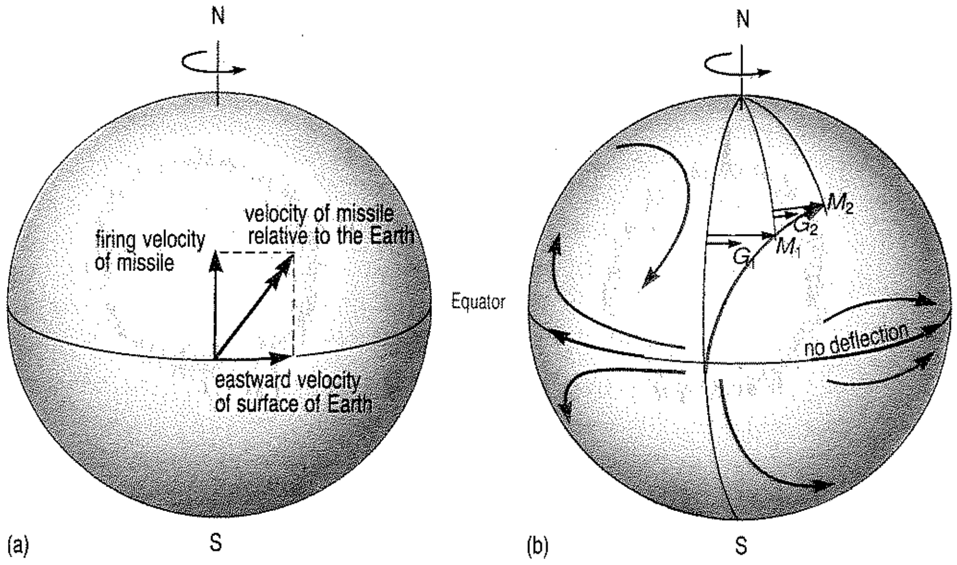

Figure 1.2 (a) A missile launched from the Equator has not only its northward firing velocity but also the same eastward velocity as the surface of the Earth at the Equator. The resultant velocity of the missile is therefore a combination of these two, as shown by the double arrow.

(b) The path taken by the missile in relation to the surface of the Earth. In time interval T_1, the missile has moved eastwards to M_1 and the Earth to G_1; in time interval T_2, the missile has moved to M_2 and the Earth to G_2. Note that the apparent deflection attributed to the Coriolis force (the difference between M_1 and G_1 and M_2 and G_2) increases with increasing latitude. The other blue curves show likely paths for missiles or any other bodies moving over the surface of the Earth without being strongly bound to it by friction.

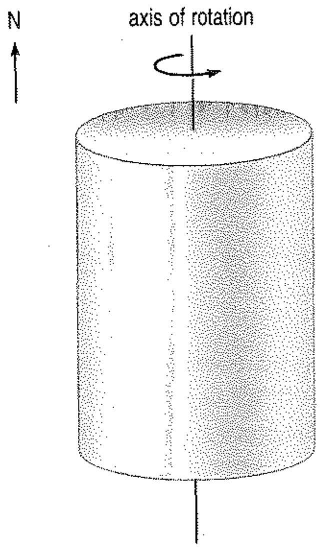

Figure 1.3 Diagram of a hypothetical cylindrical Earth, for use with Question 1.1.

QUESTION 1.1 Bearing in mind what you have just read, especially in connection with Figure 1.2, what can you say about the Coriolis force for a hypothetical *cylindrical* Earth rotating about its axis, as shown in Figure 1.3?

The example given above, of a missile fired northwards from the Equator, was chosen because of its simplicity. In fact, the rotation of the (spherical) Earth about its axis causes deflection of currents, winds, and projectiles, *irrespective of their initial direction* (Figure 1.2(b)). The reasons for this will be discussed more fully in Chapter 4, but for now you need only be aware of the following important points:

1 The magnitude of the Coriolis force increases from zero at the Equator to a maximum at the poles.

2 The Coriolis force acts at right angles to the direction of motion, so as to cause deflection to the *right* in the Northern Hemisphere and to the *left* in the Southern Hemisphere.

How these factors affect the direction of current flow in the oceans, and of winds in the atmosphere, is illustrated by the blue curves in Figure 1.2(b).

When missile trajectories are determined, the effect of the Coriolis force is included in the calculations, but the allowance that has to be made for it is fairly small. This is because a missile travels at high speed and the amount that the Earth has 'turned beneath' it during its relatively short period of travel is small. Winds and ocean currents, on the other hand, are relatively slow moving, and so are significantly affected by the Coriolis force. Consider, for example, a current flowing with a speed of $0.5\,\mathrm{m\,s^{-1}}$ (about 1 knot) at about 45° of latitude. Water in the current will travel about 1800 metres in an hour, and during that hour the Coriolis force will have deflected it about 300 m from its original path (assuming that no other forces are acting to oppose it).

Deflection by the Coriolis force is sometimes said to be *cum sole* (pronounced 'cum so-lay'), or 'with the Sun'. This is because of the direction in which the Sun appears to move across the sky—towards the right in the Northern Hemisphere and towards the left in the Southern Hemisphere.

The Coriolis force thus has the visible effect of deflecting ocean currents. It must also be considered in any study of ocean circulation for another, but less obvious, reason. Although it is not a real force in the fixed framework of space, it *is* real enough from the point of view of anything moving in relation to the Earth. This means that, like any other force, it must always be balanced by an equal and opposite force if acceleration is not to occur. For this reason, we can study, and make predictions about, currents in which horizontal forces resulting from pressure gradients are balanced by the Coriolis force. These are known as geostrophic currents and will be discussed in Chapter 3.

Because solar heating, directly and indirectly, is a fundamental cause of atmospheric and oceanic circulation, the second half of this introductory Chapter will be devoted to the radiation balance of the planet Earth.

1.1 THE RADIATION BALANCE OF THE EARTH–ATMOSPHERE SYSTEM

The solid red curve on Figure 1.4(a) shows the average daily amount of solar radiation reaching the Earth and atmosphere, as a function of latitude. The average daily amount of incoming radiation decreases from Equator to poles because low latitudes receive relatively large amounts of radiation all year, while at high latitudes the increasingly oblique angle of the Sun's rays, combined with the long periods of winter darkness, result in the average 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 atmosphere, particularly by carbon dioxide, water vapour and cloud droplets. Thus, the atmosphere is heated from beneath 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; this can be seen from the dashed curve on Figure 1.4(a).

The variation with latitude of the net amount of radiation energy supplied to the Earth–atmosphere system—i.e. the difference between the solid curve and the dashed curve in Figure 1.4(a)—is shown in Figure 1.4(b). There is clearly a net gain of radiation energy at low latitudes and a net loss at high latitudes.

QUESTION 1.2 (a) At what latitude does the radiation balance change from a net surplus to a net loss?

(b) The radiation budget for the Earth–atmosphere system as a whole must balance, i.e. the system cannot be continually gaining more radiation energy than it loses (or vice versa). How does Figure 1.4(b) illustrate this balance?

Despite the positive radiation balance at low latitudes, and the negative one at high latitudes, there is no evidence that low-latitude regions are steadily warming or that high-latitude regions are steadily cooling. There must therefore be a transfer of heat energy between low and high latitudes, and this is brought about 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 polewards transport of heat, but it is believed that the ocean contributes more in the tropics and the atmosphere contributes more at higher latitudes (Figure 1.5).

QUESTION 1.3 (a) How does the total polewards transport of heat in the ocean compare with that in the atmosphere, according to Figure 1.5?

(b) What do you think is the significance of the negative values shown on Figure 1.5?

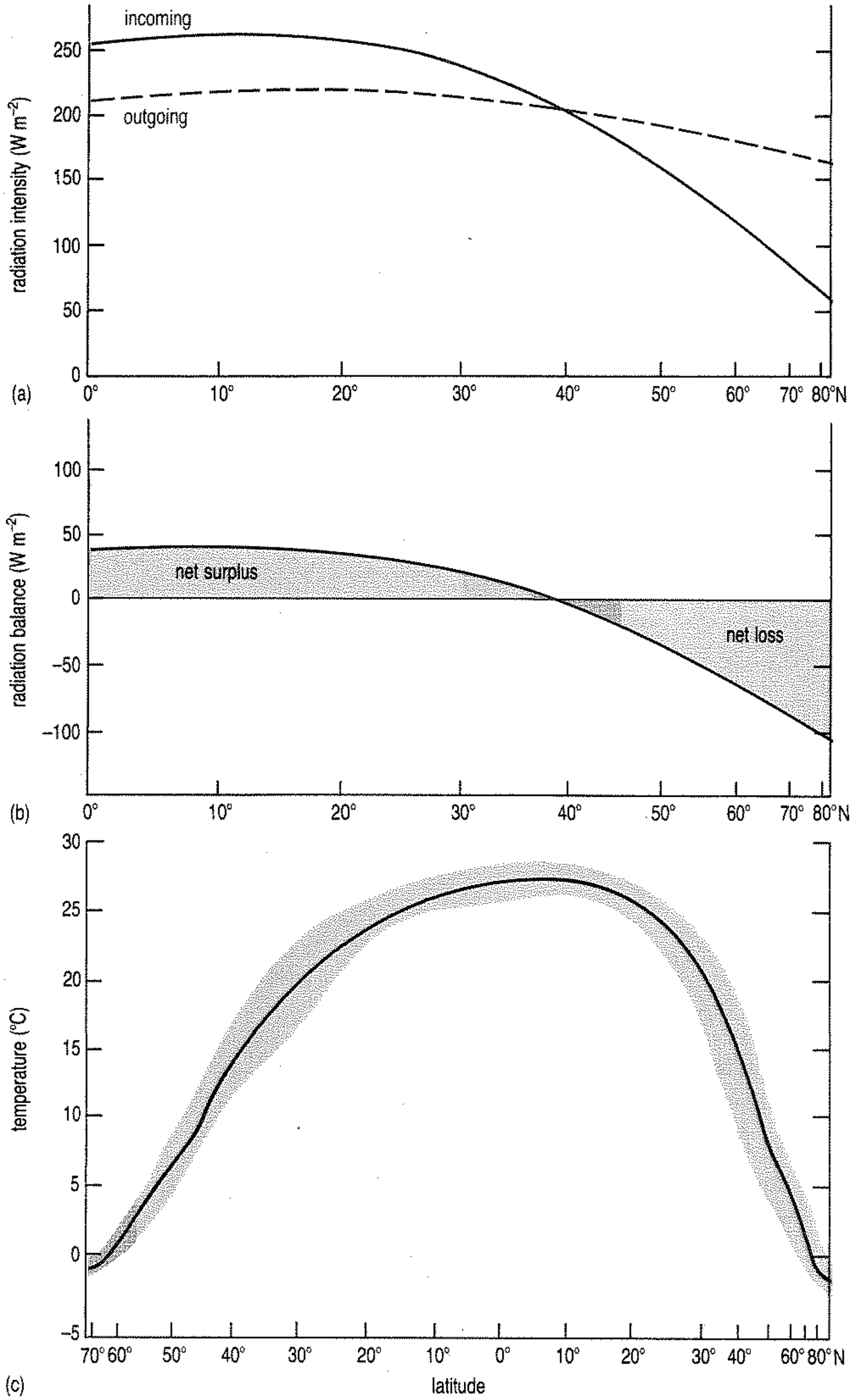

Figure 1.4 (a) Incoming solar radiation (red solid line) and the radiation lost to space (red dashed line) in relation to latitude, scaled according to the Earth's surface area. This diagram is based on data for the Northern Hemisphere only.

(b) The radiation balance for the Earth–atmosphere system (i.e. the difference between the solid and dashed curves in (a)).

(c) The mean annual temperature of surface waters at different latitudes; at a given latitude, there will be surface waters whose mean temperatures are higher or lower than shown by the curve. Mean annual ranges are represented by the thickness of the envelope. (This curve has been included for comparison with that in (a); however, as will be discussed later, sea-surface temperatures largely are determined by the *radiation balance at the sea-surface* rather than that at the top of the atmosphere.)

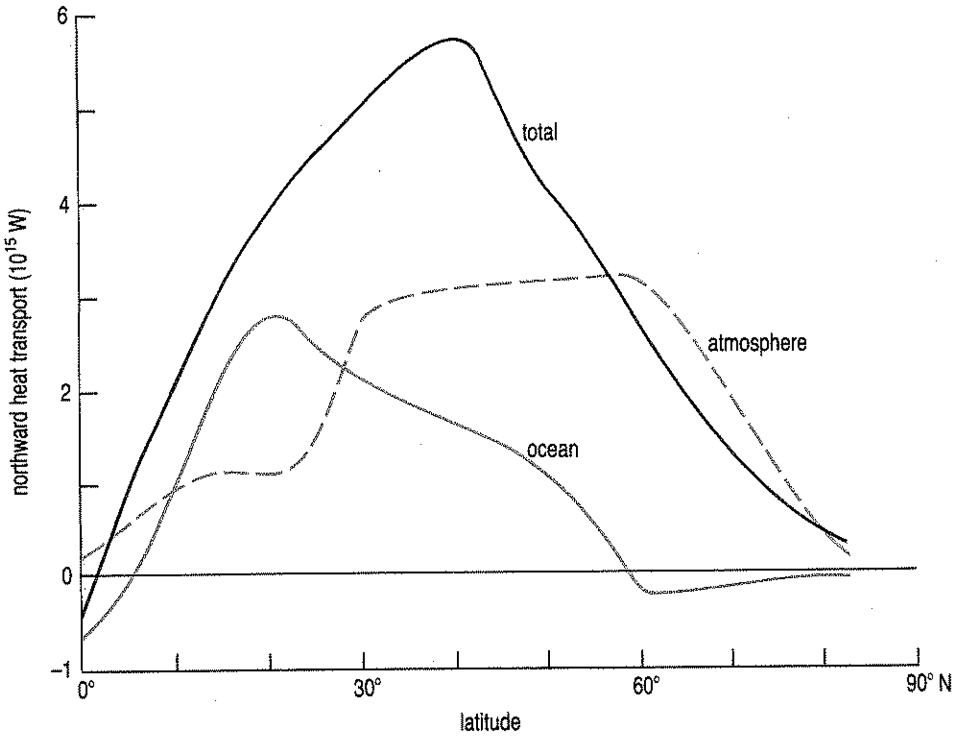

Figure 1.5 Estimates of the contributions to poleward heat transport by the ocean (solid blue curve) and the atmosphere (dashed blue curve), for the Northern Hemisphere. The curve for total heat transfer (red) is the sum of the two blue curves. The estimates were made by considering the difference between the radiation budget at the top of the atmosphere and the heat fluxes thought to be carried by the atmosphere.

While attempting Question 1.3, you may have been surprised to see that there are significant transports of heat across the Equator. The oceans are responsible for a *southward* transport of heat across the Equator; this is greater than the *northward* transport in the atmosphere, and so there is a *net* transport of heat from the Northern to the Southern Hemisphere.

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 thought to transport significant amounts of heat away from the tropical oceans in the form of latent heat. The generation of cyclones and their role in transporting heat will be described in Chapter 2.

1.2 SUMMARY OF CHAPTER 1

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

2 The radiation balance of the Earth–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 would a current be deflected by the Coriolis force if it flowed initially (i) eastwards at 45° N, (ii) westwards on the Equator?

QUESTION 1.5 The *average* amount of solar radiation received at the Equator is large because of the long daylength there. True or false?

QUESTION 1.6 In Figure 1.4(a) and (b), 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(c), showing the mean annual temperature of surface waters, is more compressed at northern than southern high latitudes?