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Edited by Charles Cockell
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Chapter 1

A habitable planet

No one knows whether life flourishes on planets orbiting stars more distant than our own Sun. Despite the excitement in 1996 about possible fossils in Martian meteorites, it is still not known whether life exists, or has ever existed, on Mars. It is known, however, that within the Solar System, the profusion of life in the forms that are recognised and understood on Earth could not be supported on any of the other planets. Why is this? In this introductory chapter you will explore some of the conditions that make the Earth habitable to life.

1.1 How does the Earth differ from other planets?

If you could observe the Solar System from far off, you would see the Sun and its orbiting planets, all virtually in the same plane. This is a legacy of their common origin from the same spinning nebular disc. If you were to look more closely at the four planets nearest to the Sun, you would see a small planet, Mercury, then a very bright one, Venus, then our own blue Earth with its swirls of white cloud, and finally the reddish globe of Mars. These four planets have very different surface environments, yet formed in more or less the same part of the solar nebula, and so are likely to be made up of the same elements in very similar proportions. Looking closer still at the blue planet, it has a thin envelope of hazy atmosphere. Through this, below the clouds, not only the blue of oceans and seas and the bright white of the ice caps can be seen, but also the greens, greys and browns of land. Even the night hemisphere is illuminated by billions of tiny light sources grouped into cities, by flashes of bluish lightning, and by the occasional red glow of fire or erupting magma.

The habitability of this mysterious and beautiful environment is the result of the complex interplay of many processes – physical, chemical, biological and geological – acting over a vast range of temporal and spatial scales. Looked at simply, however, the Earth is hospitable principally as a result of its position in relation to the Sun. Earth is half as far again from the Sun as Venus, where the average surface temperature is 460 °C. The Earth is about two-thirds of the distance of Mars, where the average surface temperature is –50 °C. By contrast, the average temperature at the surface of the Earth is a moderate 15 °C. Averages can, of course, conceal enormous ranges. On the Earth, at the present time, surface temperatures rarely rise above 50 °C, and rarely fall below –50 °C, although there are geographical variations, such as with latitude. However, some microorganisms on Earth can grow at temperature extremes much greater than even these (see Box 1.1 overleaf). Most life on Earth, particularly multicellular life, is confined to a much narrower range. The relatively small temperature range of most of the Earth's surface is a result of the form and content of the Earth's atmosphere and ocean. As you will see, the full story is very complicated (and by no means completely understood) but, in terms of regulating the Earth's surface temperature, the two most important atmospheric constituents are carbon dioxide (CO_2) and water.

Box 1.1 The diversity of microbial life in Earth's environments

The habitability of the Earth can be defined by the boundaries of environmental conditions in which life can grow. Many environments, once thought to be too extreme for life, are now known to support microbial life.

1 Currently, the highest temperature limit for life is set by the microorganism known as Strain 121, which was isolated from hot fluid emanating from a hydrothermal vent on the floor of the northeast Pacific Ocean. The previous record holder was *Pyrolobus fumarii*, which can grow at 114 °C. Strain 121 can grow at a temperature of 121 °C (the temperature used for sterilising objects). It could survive at 130 °C, but it needs to be at the lower temperature of 121 °C to grow. Although organisms with higher growth temperatures might eventually be found, it is likely that, at much higher temperatures, the energy imparted to molecules makes the energetic cost of repairing or synthesising them prohibitive to growth.

   Many of the microorganisms that can grow at high temperatures (known as **hyperthermophiles**) belong to the domain **Archaea**. Some of these organisms have been recovered from the deep subsurface, for example at 3 km depth in African mines, showing that life is not limited to the surface of the Earth and the oceans. It has been postulated that the characteristics of many of these groups of microorganisms reflect the conditions on the early Earth, when both volcanism and asteroid and comet impacts, and thus hot environments, were more common.

2 At the other end of the scale, frozen permafrost can provide an environment for metabolising bacteria. At temperatures below 0 °C, saline liquid water can exist because salt depresses the freezing point of water and at temperatures of –10 °C, bacteria that can metabolise and grow, albeit slowly, have been recovered from Siberian permafrost.

3 Microorganisms have also been found growing at extremes of pH. *Ferroplasma acidarmanus* can grow at a pH of 0, living in acidic waters at Iron Mountain in California, USA. Similarly, organisms have been found growing at high pH in alkaline soda lakes.

4 Some microorganisms, such as *Deinococcus radiodurans*, also have high radiation resistance, using highly efficient DNA repair processes to reverse radiation damage caused to their DNA. This organism can tolerate a radiation dose at least three orders of magnitude higher than that which is lethal to a human.

These **extremophiles** help define the envelope of life on Earth, and thus the extremes beyond which the planet becomes uninhabitable.

On the Earth, surface temperatures are such that most of the planet's surface water is in liquid form, with the remainder in the ice caps and in the atmosphere. The atmosphere contains a small amount of CO_2, the oceans a good deal more, and large amounts are effectively 'locked up' in crustal rocks. By contrast, on Venus the atmosphere is largely CO_2, there is a minute amount of atmospheric water vapour (i.e. H_2O gas) and, at the prevailing temperatures, none of it can condense on the planet's surface. The Martian atmosphere, like the Venusian one, largely consists of CO_2, but some CO_2 and most of the planet's water is in the form of ice. Were it not for the presence of liquid water on the surface of the Earth, life – at least in its familiar forms – could not exist here.

Look at Figure 1.1. The cloud cover, which obscures much of the Earth's surface, has been removed. Immediately obvious are bright areas of ice cover, the enormous area of ocean in the Southern Hemisphere, and the green of forests and crops.

- To what extent does this map tell you about life on Earth?

- It indicates where life is concentrated because much of the biologically productive life on Earth, and on land in particular, is based on plants and other **phototrophs** – organisms that can build their own organic material by harnessing the energy of sunlight by **photosynthesis**.

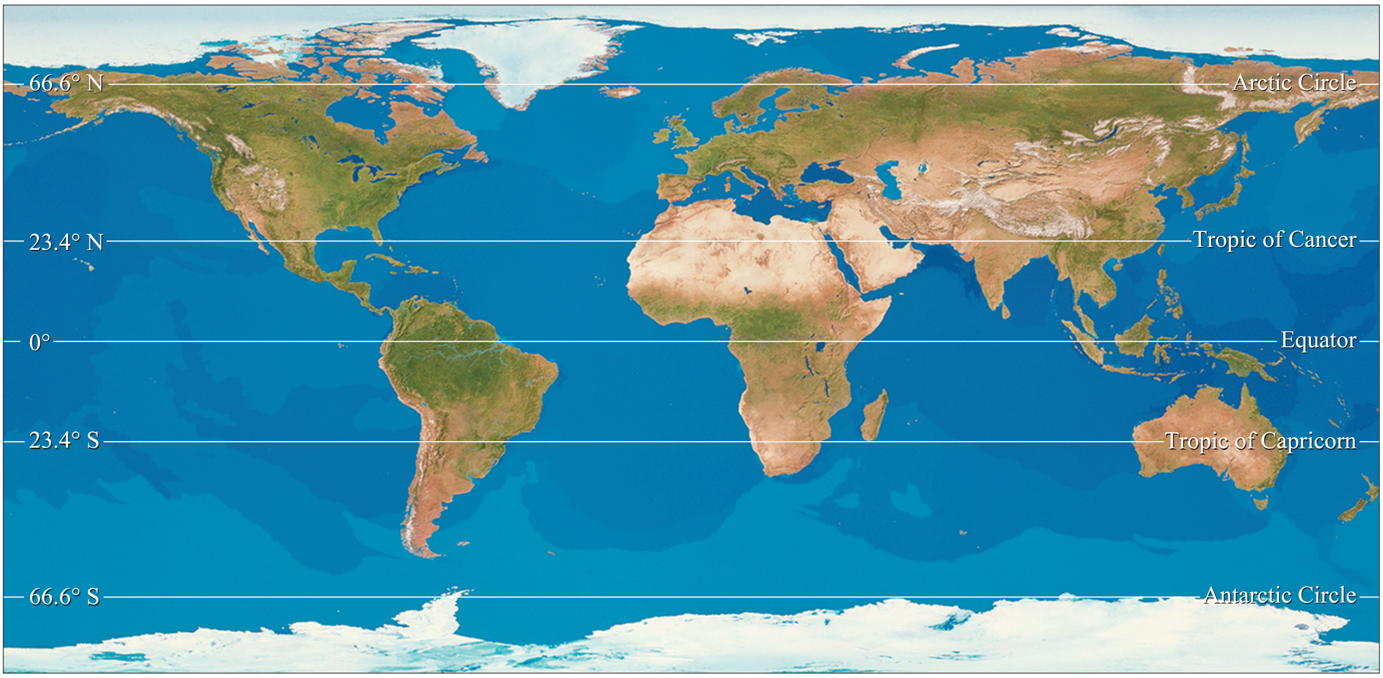

Figure 1.1 Composite satellite image of the Earth's surface. The green areas (e.g. Central Brazil and Western Europe) are forests and crops; the light-coloured areas in the tropics are mostly savannah, semi-arid scrub and desert; and the brown areas at high northern latitudes are tundra. At high latitudes, and at lower latitudes where there are mountains (e.g. the Rockies, Andes and Himalaya), white corresponds to ice and snow. *Note*: the area of ice at high latitudes is grossly exaggerated by this type of projection. (NASA)

Expressed simply, the chemical equation for photosynthesis can be written as follows:

$$\underset{\text{carbon dioxide from atmosphere}}{nCO_2(g)} + nH_2O \xrightarrow{\text{light energy}} \underset{\text{organic matter}}{(CH_2O)_n} + \underset{\text{oxygen}}{nO_2(g)} \qquad (1.1)$$

where n can have various values, $(CH_2O)_n$ represents a range of carbohydrate materials of which glucose ($C_6H_{12}O_6$) is the simplest, and (g) is gas. You could rewrite Equation 1.1, for instance, with glucose, $C_6H_{12}O_6$, representing organic matter in the form:

$$\underset{\text{carbon dioxide from atmosphere}}{6CO_2(g)} + 6H_2O \longrightarrow \underset{\text{organic matter}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2(g)} \qquad (1.2)$$

This process of taking free carbon from the atmosphere and combining it into living organic material is referred to as '**fixing**' **carbon**, and the process of building living material by fixing carbon is known as **primary production**. You will look at this in much more detail in Chapter 2. Animals cannot fix carbon and so can live only by consuming **primary producers**, either directly or indirectly.

But Figure 1.1 tells only a small part of the story; for one thing, the oceans like the land also support abundant phototrophs. Figure 1.2 shows not only the geographical variation of the potential for primary production on land (i.e. the potential for carbon to be incorporated into terrestrial living material), but also the average concentration of chlorophyll in algae living in surface waters. Chlorophylls are the light-collecting pigments found in photosynthesising organisms which give them their green colouration. Although both Figures 1.1 and 1.2 are composites of many satellite images, they are akin to snapshots in time. They provide information about the standing stock of plant material, but by themselves they do not reveal anything about the *rates* at which plant material is being made – the primary *productivity* – in different environments. Nor do they indicate anything about the rates at which the plant material is being eaten by animals, decomposing or being recycled. As you will see, because organic material is essentially carbon, almost all of which can eventually find its way back into the atmosphere as gaseous CO_2, all these processes are important influences on the Earth's climate and thus its habitability.

■ Returning to Figure 1.1 for a moment, suggest why the vegetation patterns shown are not wholly reliable as indicators of local climatic conditions.

■ (i) Humans have direct effects on vegetation through for example the removal of forests (particularly in temperate latitudes) and irrigation of land in arid regions; their domesticated animals graze the vegetation. (ii) Seasonal changes in local climatic conditions are not reflected in the figure.

Nevertheless, the patterns of primary production seen in Figures 1.1 and 1.2 are to a large extent determined by the movement of air and water over the surface of the Earth – including the swirling clouds. You will see *how* shortly, but first one of the primary influences on the continual motion of the Earth's atmosphere and oceans, i.e. energy from the Sun, is discussed.

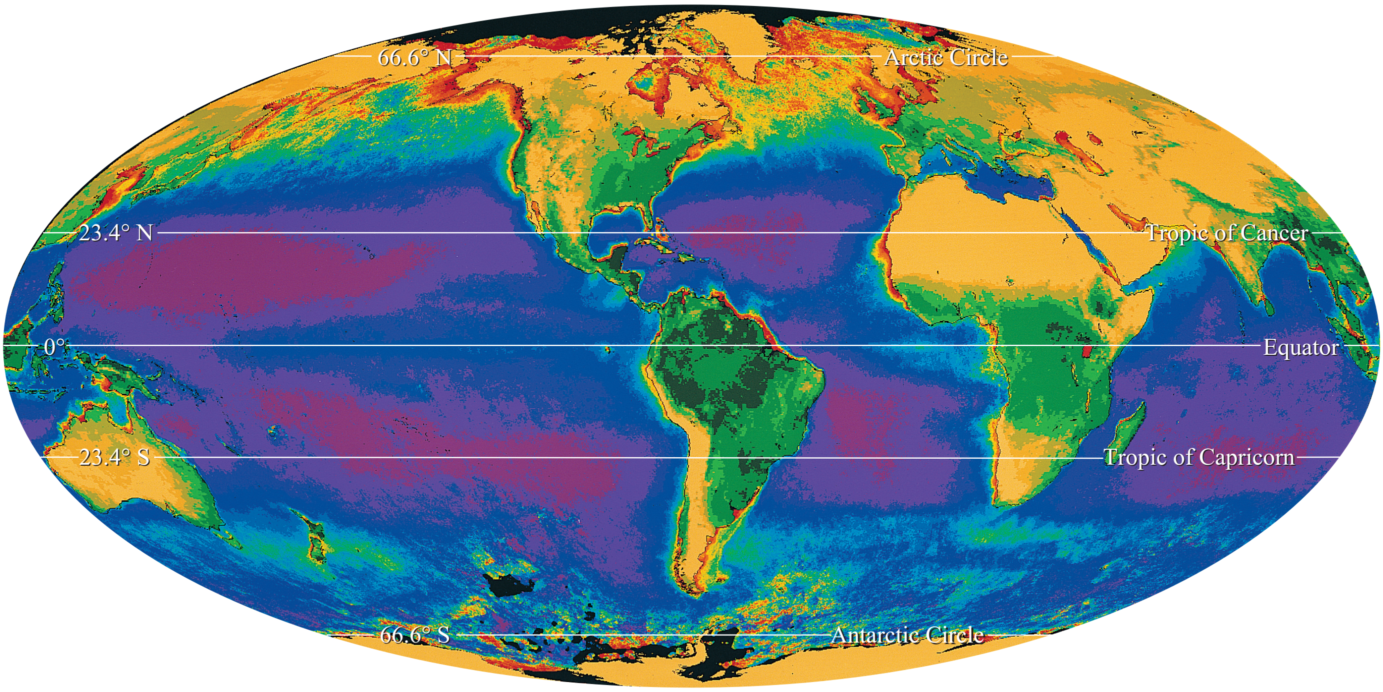

Figure 1.2 Global distribution of the potential for primary production on land and in surface waters, as indicated by chlorophyll concentration (determined using satellite-borne sensors). On land, the darkest green areas (e.g. Brazil) correspond to the greatest potential for production of new plant material; decreasing production potential is indicated by increasingly paler greens. Least productive of all are the paler deserts, high mountains and arctic regions shown in yellow. In surface waters, regions of highest productivity (bright red, e.g. Canadian coast) are mostly around the coasts, followed by yellow, green and blue. Least productive oceanic regions (e.g. large areas in the tropics) are shown in purplish-red. (NSF/NASA)

1.2 Energy from the Sun

The Earth is, on average, about 150×10^6 km from the Sun. From this, the average amount of solar energy reaching the top of the atmosphere can be calculated. The amount of solar energy that would fall on a surface at right angles to the Sun's rays, known as the **solar flux** (or solar irradiance, or solar constant), is ~1370 W m^{-2}. This means that the amount of solar radiation that the Earth intercepts is ~1370 W m$^{-2} \times \pi r^2$ W, where πr^2 is the area of a disc with the same radius as the Earth. However, the Earth is roughly *spherical*, so the area presented to the incoming solar radiation by the rotating Earth (over any period longer than a day) is $4\pi r^2$, i.e. four times as great. The average flux of solar energy is therefore effectively only a quarter of the solar flux:

1 W = 1 J s^{-1}

Surface area of a sphere $A = 4\pi r^2$, where r is the radius.

$$\frac{1370 \text{ W m}^{-2}}{4} \approx 343 \text{ W m}^{-2}.$$

So the average amount of solar energy reaching the top of the atmosphere, i.e. the *effective solar flux*, is ~343 W m^{-2} (Figure 1.3 overleaf).

Not all of this incoming solar energy is available to heat the Earth–atmosphere system: about 30% of it is reflected back into space, mainly from the tops of clouds. In other words, the **albedo** of the Earth as a whole (i.e. the fraction of

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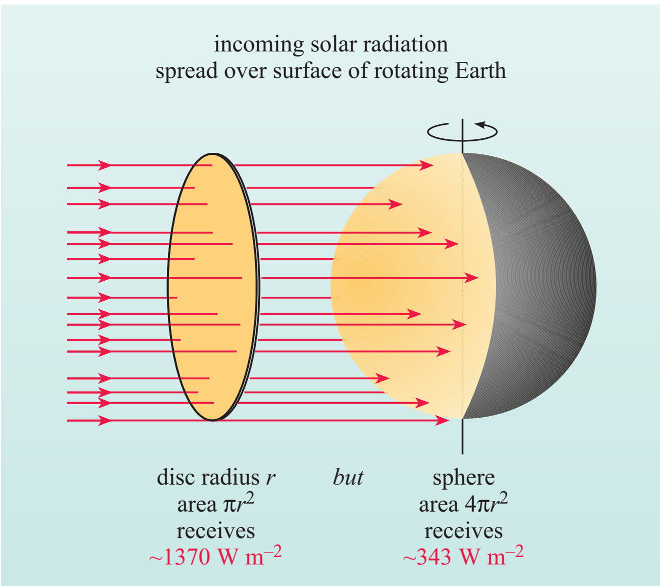

Figure 1.3 Diagram of the average flux of solar energy reaching a disc and the Earth (with the same radii).

incoming solar radiation that is reflected from it) is about 30%. This means that the Earth–atmosphere system receives ~70% of the solar flux, i.e. 240 watts of solar energy per square metre (240 W m^{-2}). But this number of 240 W m^{-2} is an average, and it is the uneven distribution of this heating that drives the Earth's climate engine.

■ Look at Figure 1.4 below. Bearing in mind that the atmosphere absorbs a proportion of incoming solar energy, suggest two reasons why the intensity of solar radiation at the Earth's surface, and hence the surface temperature, is generally lower at high latitudes than at low latitudes.

■ The intensity of solar radiation at the Earth's surface (on the diagram, the number of rays per unit area) depends on the angle of the rays with respect to the surface: the more oblique the angle, the larger the area over which the solar energy will be spread. Furthermore, the more oblique the rays, the greater the thickness of atmosphere through which the rays will have to travel.

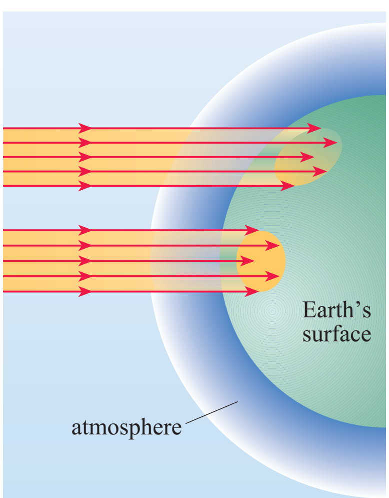

Figure 1.4 Schematic diagram to show why there is a difference in the intensity of solar radiation reaching the Earth's surface at different latitudes (the atmosphere is not to scale).

The relationship between the angles the Sun's rays make with the ground and their ability to warm it is, in fact, the origin of the word 'climate' (from the Greek *klima*, meaning slope). Slopes that face equatorwards (i.e. southwards in the Northern Hemisphere) – where the Sun's rays meet the ground at a steeper angle – are warmer.

If the Earth's axis of rotation were at right angles to the plane of its orbit, for any given latitude, the angle at which the rays of the noonday Sun fell upon the surface would remain constant, with higher latitudes in both hemispheres always receiving less solar radiation than lower latitudes. In other words, the Earth's surface at, for example, 10° N and 10° S would always receive the same amount of solar radiation, with this always being more than that received at, for example, 40° N and 40° S. The Sun would be overhead at noon only at the Equator, the poles would have perpetual twilight, and night and day would always be the same length (i.e. each 12 hours long) everywhere around the globe.

But the Earth's axis of rotation is *tilted* with respect to the plane of its orbit, currently at an angle of 23.4°. As a result, the latitude at which the noonday Sun is overhead migrates between 23.4° N (the Tropic of Cancer) and 23.4° S (the Tropic of Capricorn), passing the Equator only twice a year, at the equinoxes (when the lengths of night and day are equal). This change in the position of the noonday Sun throughout the year is the cause of the seasons (Box 1.2).

Box 1.2 The cause of seasons

Figure 1.5a shows the passage of the seasons for the Northern Hemisphere.

- Along the Tropic of Cancer (23.4° N), the noonday Sun is overhead, and maximum solar radiation is received during the summer solstice (the longest day), which is 21 June.

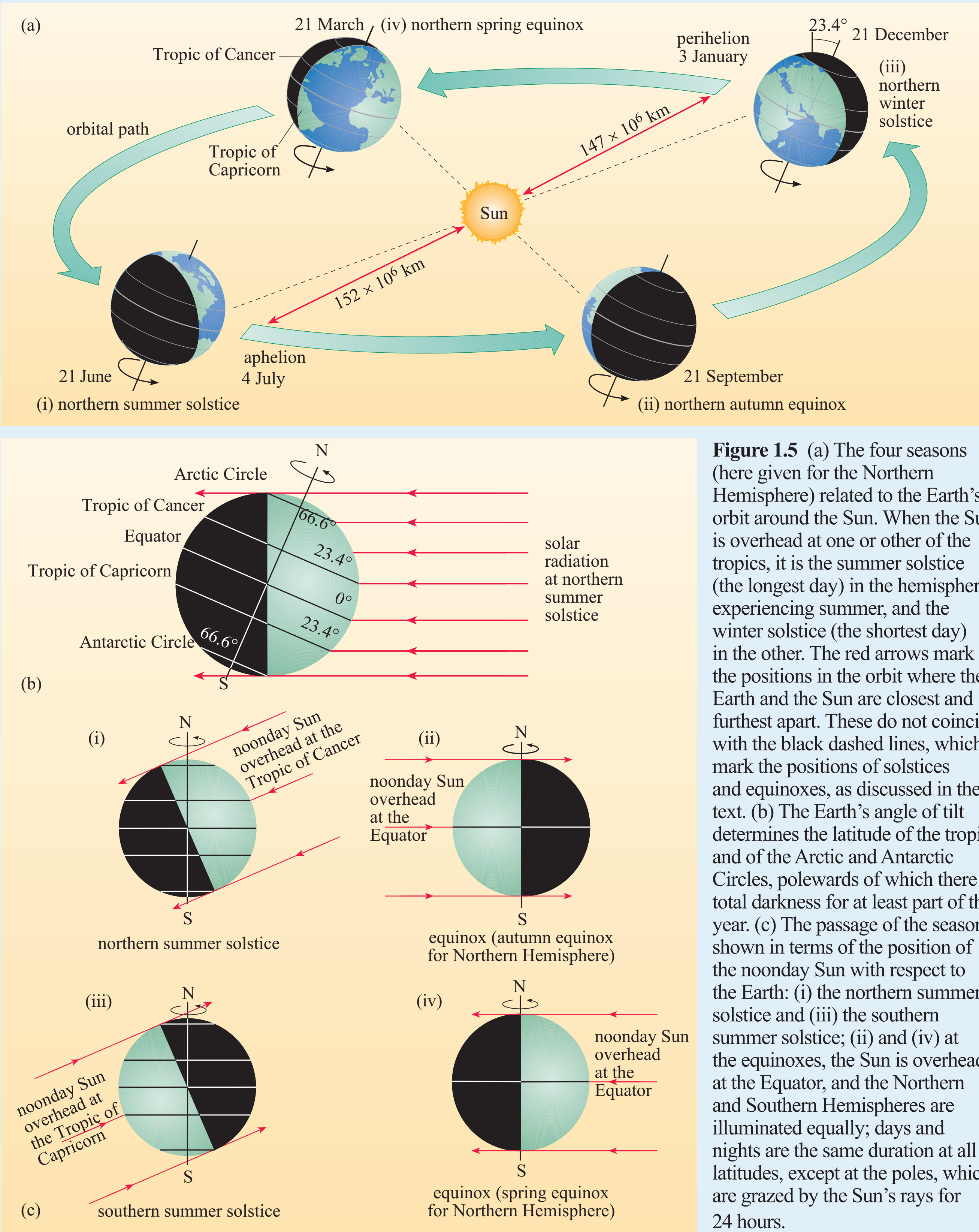

Figure 1.5 (a) The four seasons (here given for the Northern Hemisphere) related to the Earth's orbit around the Sun. When the Sun is overhead at one or other of the tropics, it is the summer solstice (the longest day) in the hemisphere experiencing summer, and the winter solstice (the shortest day) in the other. The red arrows mark the positions in the orbit where the Earth and the Sun are closest and furthest apart. These do not coincide with the black dashed lines, which mark the positions of solstices and equinoxes, as discussed in the text. (b) The Earth's angle of tilt determines the latitude of the tropics and of the Arctic and Antarctic Circles, polewards of which there is total darkness for at least part of the year. (c) The passage of the seasons shown in terms of the position of the noonday Sun with respect to the Earth: (i) the northern summer solstice and (iii) the southern summer solstice; (ii) and (iv) at the equinoxes, the Sun is overhead at the Equator, and the Northern and Southern Hemispheres are illuminated equally; days and nights are the same duration at all latitudes, except at the poles, which are grazed by the Sun's rays for 24 hours.

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- After 21 June, the days begin to shorten, until at the autumn equinox, on 21 September, day and night are of equal length.
- After 21 September, day lengths continue to shorten, until the shortest day (the winter solstice, on 21 December), after which the days begin to lengthen again.
- At the Equator, maximum solar radiation is received at the March and September equinoxes, when the noonday Sun is overhead, and day and night are of equal length. Polewards of the tropics, the Sun is *never* overhead, although it is at its highest at the summer solstice. The poles themselves are wholly illuminated in summer and wholly dark in winter.

The Earth's angle of tilt (presently 23.4°) determines the latitude of the tropics (where the Sun is overhead at one of the solstices) and of the Arctic and Antarctic Circles at 66.6° N and 66.6° S respectively (90° – 23.4°), polewards of which there is total darkness for at least part of the year (Figure 1.5b). The seasons in terms of the position of the noonday Sun with respect to the Earth are shown in Figure 1.5c.

Figure 1.6 shows the seasonal variation in the amount of solar radiation received daily at the Earth's surface (i.e. taking into account the amount absorbed in the atmosphere). The zero contour corresponds to 24-hour darkness. At the North Pole (90° N), it encompasses the period between 21 September and 21 March, and at the South Pole it encompasses the period between 21 March and 21 September. In each case, the first of these dates is the autumn equinox and the second is the spring equinox (compare with Figure 1.5). Don't worry if this type of diagram seems strange – you should be able to see how it works when you have tried Question 1.1.

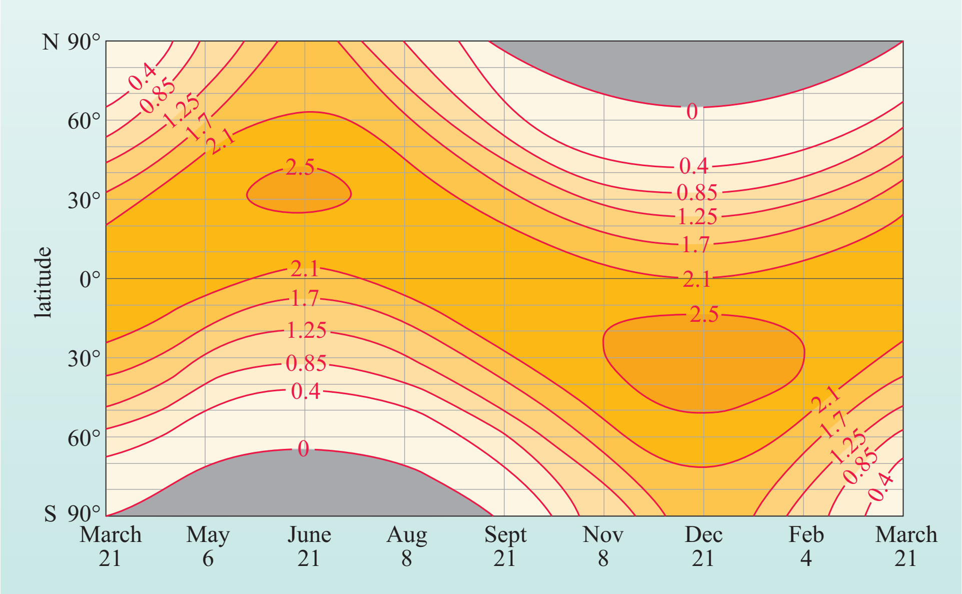

Figure 1.6 Seasonal variation of daily incoming solar radiation (in 10^7 J m^{-2}) at the Earth's surface, taking account of absorption by the atmosphere but ignoring the effect of topography. Note that this is not an ordinary spatial map, but a map, or plot, of incoming solar energy against latitude on the one axis and time of year on the other.

Question 1.1

(a) (i) With reference to Figure 1.6, describe briefly how the incoming solar radiation changes over the course of the year at 50° N.

(ii) The units used in Figure 1.6 are J m^{-2} because it shows values of incoming solar radiation *per day*. Convert the contour values so that they are for *average* incoming solar radiation in W m^{-2}.

(b) Over the year as a whole Figure 1.6 shows that, on average, the Equator receives the most solar radiation. Which latitudes receive the most solar radiation at any one time? Why is this?

One aspect of Figure 1.6 that may be initially puzzling is that the maximum amount of solar energy received by southern mid-latitudes in the southern summer is *greater* than the maximum amount received by northern mid-latitudes in the northern summer (e.g. the areas enclosed by the 2.5×10^7 J m^{-2} contour). Furthermore, careful study of Figure 1.6 indicates that in the southern summer *all* latitudes receive more energy than the corresponding latitudes in the other hemisphere in the northern summer. This is because the Earth's orbit is elliptical, and at the present time the Earth comes closest to the Sun (i.e. is at **perihelion**) during the southern summer (on 3 January), and is furthest from the Sun (i.e. is at **aphelion**) during the northern summer (on 4 July). It is because the Sun is at one of the two foci of the ellipse, rather than at its geometric centre, that perihelion and aphelion occur only once a year rather than twice a year.

Because of the varying gravitational attraction of the Sun and of the other planets (notably Jupiter and Saturn), the degree of ellipticity (*eccentricity*, or off-centredness) of the Earth's orbit varies with time and, over a period of about 110 000 years, changes from its most elliptical (maximum eccentricity) to nearly circular and back again (Figure 1.7a). This 110 000-year cycle is the longest of three astronomical cycles that affect the amount and distribution of solar radiation reaching the Earth's surface, and it is the only one that affects the *total* amount of solar radiation reaching the Earth. The two shorter cycles (tilt and precession: Figure 1.7b) involve the orientation of the Earth's spin axis, and so affect the *distribution* of solar radiation over the Earth's surface.

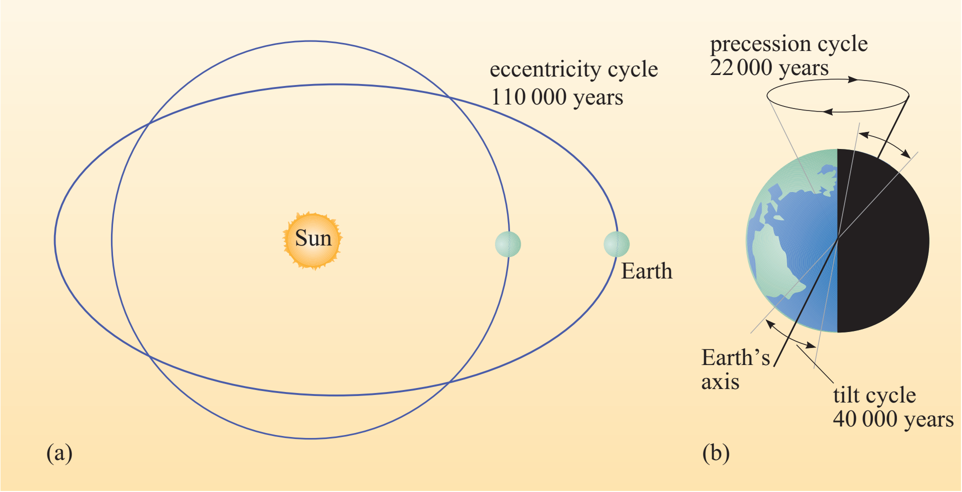

Figure 1.7 The component Milankovich cycles. (a) Plan view of the Earth's orbit to show how it changes shape from circular to almost elliptical and back again, over the course of the 110 000-year eccentricity cycle. (b) The Earth showing the 40 000-year tilt cycle and the 22 000-year precession cycle.

These three astronomical cycles (eccentricity, tilt and precession) are usually known as **Milankovich cycles**, after Milutin Milankovich, a Serbian astronomer. Milankovich's work in the 1930s and 1940s was an improvement and refinement of the work of Scotsman James Croll, for this reason the cycles are sometimes referred to as Milankovich–Croll cycles.

Over the course of about 22 000 years, the direction in which the Earth's spin axis points traces out a circle. Therefore, from about 11 000 years from now, the positions in the orbit of the northern and southern summer will be reversed as the seasons (i.e. the solstices and the equinoxes) will have moved clockwise around the orbit. In another 11 000 years, they will be back in their current positions. This phenomenon is often referred to as the *precession of the equinoxes*. (Of course, calendars will continually have to be adjusted to take account of this so that, for example, the northern summer solstice will remain in June and not gradually drift towards December.) Eccentricity will be roughly as it is now, thus the Earth will be at perihelion in the northern, rather than the southern, summer.

At the same time that the Earth's spin axis traces out a circle, the angle it makes with the normal to the orbital plane varies between about 21.8° and 24.4°, and back again, with a periodicity of about 40 000 years; at the moment, the angle of *tilt* is about 23.4°.

■ Bearing in mind Figure 1.5, what do you think the latitude of the tropics would be if the angle of tilt increased so that it was 24.4°, rather than 23.4°? What effect would this have on Figure 1.6?

■ If the angle of tilt increased to 24.4°, the tropics (over which the Sun would be directly overhead during the summer solstice) would be at 24.4° N and 24.4° S. This would mean that on a diagram like Figure 1.6, the areas of maximum incoming solar radiation corresponding to summer months would be shifted polewards slightly and, for the winter hemisphere, the zero contour (for example) would extend a little further towards the Equator.

So the greater the angle of tilt, the greater is the difference between winter and summer. At present the angle of tilt is in fact *decreasing*, so summers should be very gradually becoming cooler and winters should be very gradually becoming warmer.

The form of the three cycles over the past 800 000 years can be seen in Figure 1.8.

- The 110 000-year eccentricity cycle (Figure 1.8a) is actually a combination of a 100 000-year cycle with a much weaker 413 000-year cycle, and is sometimes referred to collectively as the 100 000-year cycle.
- The tilt cycle (Figure 1.8b) is sometimes referred to as the 40 000-year or 41 000-year cycle.
- The 22 000-year precession cycle (Figure 1.8c) can be broken down into a 19 000-year cycle and a stronger 23 000-year cycle.

At present the eccentricity of the Earth's orbit is such that the Earth–Sun distance is about 147×10^6 km at perihelion and about 152×10^6 km at aphelion (Figure 1.5a).