The greenhouse effect and global warming

This chapter deals with the physical mechanisms that control the energy balance of the earth. The important phenomenon of black-body radiation is introduced along with the associated Stefan–Boltzmann and Wien displacement laws. The 'greenhouse effect' is introduced as the trapping by gases in the atmosphere of radiation emitted by the earth. The enhanced greenhouse effect is also discussed. As much as possible, the chapter stays close to the physics of the problem, and does not enter into judgements based on political or moral grounds.

Objectives

By the end of this chapter you should be able to:

- understand and apply the *black-body radiation law*;
- understand the meaning of the terms *emissivity* and *albedo*;
- work with a simple *energy balance equation*;
- understand the meaning of the term *greenhouse effect* and distinguish this effect from the *enhanced greenhouse effect*;
- name the main *greenhouse gases* and their natural and anthropogenic sources and sinks;
- understand the molecular mechanism for *infrared radiation absorption*;
- state the evidence linking *global warming* to the increased concentrations of greenhouse gases in the atmosphere;
- understand the definition of *surface heat capacity* and apply it in simple situations;
- discuss the *expected trends on climate* caused by changes in various factors and appreciate that these are interrelated;
- state *possible solutions* to the enhanced greenhouse effect and *international efforts* to counter global warming.

The black-body law

One of the great advances in physics of the nineteenth century was the realization that all bodies that are kept at some *absolute* (kelvin) temperature T radiate energy in the form of electromagnetic waves. For example, the energy from the sun that warms the earth, thereby sustaining life on earth, is the energy radiated by the hot surface of the sun that arrives on earth through the vacuum of space. The power radiated by a body is governed by the **Stefan–Boltzmann law**.

▶ The amount of energy per second (i.e. the power) radiated by a body depends on its surface area A, absolute temperature T, and the properties of the surface:

$$P = e\sigma A T^4$$

This is known as the *Stefan–Boltzmann law.* The constant σ is known as the *Stefan–Boltzmann constant* and equals $\sigma = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$.

The constant e appearing in this formula is called the **emissivity** of the surface. It is a dimensionless number that varies from 0 to 1. The special case $e = 1$ corresponds to what is called a **black body**, a theoretical body that is a 'perfect' emitter. A real body is a good approximation to the theoretical black body if its surface is black and dull. For example, a piece of charcoal is a better approximation to a black body than a shiny silver surface. In other words, surfaces differ in the value of the emissivity e. Dark and dull surfaces have e close to 1, whereas light and shiny surfaces have e close to 0. Table 2.1 gives values for the emissivity of various surfaces.

Surface	Emissivity
Black body	1
Ocean water	0.8
Ice	0.1
Dry land	0.7
Land with vegetation	0.6

Table 2.1 Emissivity of various surfaces.

A body of emissivity e that is kept at some temperature T_1 will *radiate* power at a rate $P_{\text{out}} = e\sigma A T_1^4$ but will also *absorb* power at a rate $P_{\text{in}} = e\sigma A T_2^4$ if its surroundings are kept at a temperature T_1. Hence the net power *lost* by the body is

$$P_{\text{net}} = P_{\text{out}} - P_{\text{in}} = e\sigma A\left(T_1^4 - T_2^4\right)$$

At equilibrium, $P_{\text{net}} = 0$, i.e. the body loses as much energy as it gains, and so the body's temperature stays constant and equals that of the surroundings, $T_1 = T_2$.

Surfaces that are black and dull, as opposed to light and shiny, are also good *absorbers* of radiation. Thus we wear dark clothes in the winter to absorb the radiation from the sun. Light-coloured surfaces are good *reflectors* of radiation, which is why we wear light-coloured clothes in the summer.

The energy radiated by a body is electromagnetic radiation and is distributed over an infinite range of wavelengths. However, most of the energy is radiated at a specific wavelength that is determined by the temperature of the body – the higher the temperature, the shorter the wavelength. For a body at ordinary room temperature (20 °C, 293K) the wavelength at which most of the energy is radiated is an infrared wavelength. This is why we associate infrared radiation with 'heat'.

Figure 2.1 shows how the power is radiated from 1 m^2 of the same surface as the temperature of the surface is varied ($T = 350$ K, 300 K and 273 K).

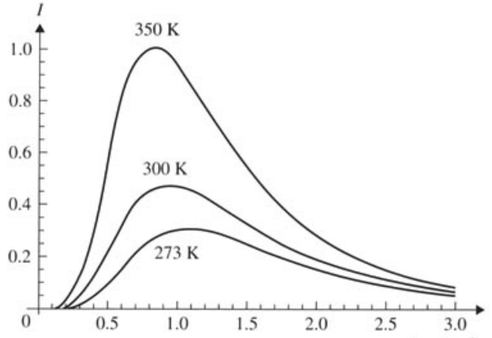

Figure 2.1 Black-body spectra for a body at the three temperatures shown. The units on the vertical axis are arbitrary. (The curves appear to start from a finite value of wavelength. This is not the case. The curves start at zero wavelength but are too small to appear on the graphs.)

We see that, with increasing temperature, the peak of the curve occurs at lower wavelengths and the height of the peak increases. The relation between the temperature and the peak wavelength, the wavelength at which most of the energy is emitted, is given by **Wien's law**:

$$\lambda T = 2.90 \times 10^{-3} \text{ m K}$$

(Note that the unit here is metre kelvin, not millikelvin.)

The earth's surface emits infrared radiation because the earth's surface is at a temperature of 288 K (global day and night average):

$$\lambda = \frac{2.90 \times 10^{-3}}{288} = 1.0 \times 10^{-5} \text{ m}$$

which is a typical infrared wavelength. The sun, by contrast, with a surface temperature of 5800 K emits at

$$\lambda = \frac{2.90 \times 10^{-3}}{5800} = 5.0 \times 10^{-7} \text{ m}$$

which is in the wavelength range of visible light.

Figure 2.2 shows the power emitted from 1 m^2 of various different surfaces kept at the same temperature (300 K). The difference in the curves is due to the different emissivities ($e = 1.0, 0.8$ and 0.2). The curves are identical apart from an overall factor that shrinks the height of the curve as the emissivity decreases.

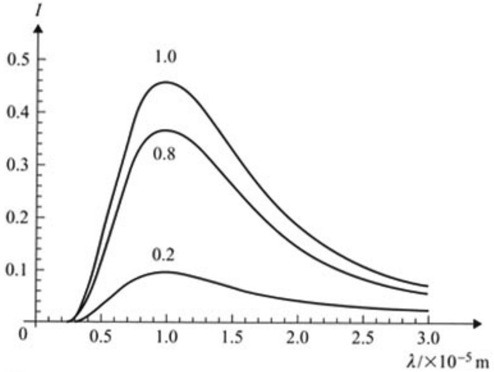

Figure 2.2 The spectrum of three bodies with different emissivities at the same temperature (300 K). The units on the vertical axis are arbitrary.

Example questions

Q1

By what factor does the power emitted by a body increase when the temperature is increased from 100 °C to 200 °C?

Answer

The temperature increases (on the kelvin scale) from 373 K to 473 K, and so the emitted power, being proportional to the fourth power of the temperature, will increase by a factor

$$\left(\frac{473}{373}\right)^4 = 2.59$$

Q2

The emissivity of the naked human body may be taken to be $e = 0.90$. Assuming a body temperature of 37 °C and a body surface area of 1.60 m^2, calculate the total amount of energy lost by the body when exposed to a temperature of 0.0 °C for 30 minutes.

Answer

From $P_{net} = P_{out} - P_{in} = e\sigma A(T_1^4 - T_2^4)$ we find that the net power lost by the body is (notice that we must use kelvins)

$$\begin{aligned} P_{net} &= 0.90 \times 5.67 \times 10^{-8} \times 1.60 \times (310^4 - 273^4) \\ &= 301 \text{ W} \end{aligned}$$

Hence the energy lost is

$$\begin{aligned} E &= P_{net}t \\ &= 301 \times 30 \times 60 \\ &= 5.4 \times 10^5 \text{ J} \end{aligned}$$

(For the purposes of an estimate, assume that the body has mass 60 kg and is made out of water, so that the specific heat capacity is $c = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$. This would result in a drop in body temperature of $\Delta T = \frac{5.4\times10^5}{60\times4200} = 2.1$ K. This would be serious! However, it ignores the fact that respiration provides a source of energy.)

Solar radiation

The sun may be considered to radiate as a perfect emitter (i.e. as a black body). The sun emits a total power of $P = 3.9 \times 10^{26}$ W. The average earth–sun distance is $d = 1.5 \times 10^{11}$ m. So, at the distance of the earth, we may imagine that the power radiated by the sun is distributed uniformly on the surface of a sphere centred at the sun of radius d (see Figure 1.11 on page 424). The earth receives only a very small fraction of this power, equal to $\frac{a}{4\pi d^2}$, where a is the area used to collect the power. Thus the *power per unit area* (i.e. the **intensity**) received by earth is

$$I = \frac{P}{4\pi d^2}$$

▶ *Intensity* is the power of radiation received per unit area of the receiver.

Substituting the numerical values gives

$$I = \frac{3.9 \times 10^{26}}{4\pi(1.5 \times 10^{11})^2} \approx 1400 \text{ W m}^{-2}$$

This is the intensity of the solar radiation at the top of the earth's atmosphere. It is called the **solar constant** and is denoted by S.

If we know that radiation of intensity I is incident on a surface of area A, we can calculate the **power** delivered to that area from:

$$P = IA$$

Albedo

The **albedo** (from the Latin for 'white'), α, of a body is defined as the ratio of the power of radiation reflected or scattered from the body to the total power incident on the body:

$$\alpha = \frac{\text{total scattered/reflected power}}{\text{total incident power}}$$

The albedo is a dimensionless number. Snow has a high albedo (0.85), indicating that snow reflects most of the radiation incident on it, whereas charcoal has an albedo of only 0.04, meaning that it reflects very little of the light incident on it. The earth as a whole has an average global albedo that is about 0.3. The albedo of the earth varies. The variations depend on the time of the year (many or few clouds), latitude (a lot of snow and ice or very little), on whether one is over desert land (high albedo, 0.3–0.4), forests (low albedo, 0.1), or water (low albedo, 0.1), etc.

The calculation of the solar constant as $S = 1400 \text{ W m}^{-2}$ is the value at a particular point in the upper atmosphere. At any one moment in time, the earth offers a 'target' area of πR^2, where R is the radius of the earth (see Figure 2.3). As the target area is only a quarter of the total surface area of the earth ($4\pi R^2$), the power of the radiation received per square metre of the earth's surface is $\frac{S}{4} = 350 \text{ W m}^{-2}$. Since 30% is reflected, this means that the earth receives a net radiation intensity of $350 \times 0.7 = 245 \text{ W m}^{-2}$.

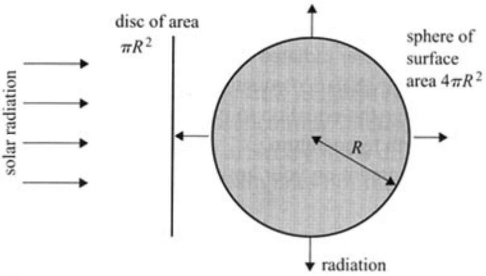

Figure 2.3 The radiation reaching the earth falls on a disc of area πR^2, where R is the radius of the earth.

Energy balance

The earth has a constant average temperature and behaves as a black body. So the energy input to the earth must equal (balance) the energy output by the earth. Taking account of albedo, the power delivered to surface area A (Figure 2.4) is

$$P = (1 - \alpha)IA$$

The next example introduces a first example of an **energy balance equation**.

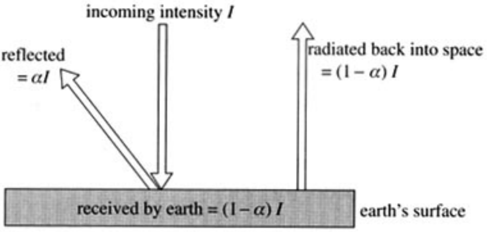

Figure 2.4 Energy diagram showing energy transfers in a model without an atmosphere. Note that the energy in equals the energy out.

Example question

Q3

Assume that the earth has a fixed temperature T and that it radiates as a black body. The average incoming solar radiation has intensity $I = \frac{S}{4} = 350\ \text{W m}^{-2}$. Take the albedo of the earth to be $\alpha = 0.30$. Ignore the effect of the atmosphere.

(a) Write down an equation expressing the fact that the power received by the earth equals the power radiated by the earth into space (an energy balance equation).

(b) Solve the equation to calculate the constant earth temperature.

(c) Comment on your answer.

Answer

(a) The power *received* by an area A of the earth's surface is

$$P_{\text{in}} = (1-\alpha)IA = (1-\alpha)\frac{S}{4}A$$

This is because a power $\alpha\frac{S}{4}A$ has been reflected back into space. The earth radiates power from the entire surface area of its spherical shape, and so the power *radiated* from 1 m^2 (by the Stefan–Boltzmann law) is

$$P_{\text{out}} = \sigma A T^4$$

(Here we are assuming that the earth is a black body, so $e = 1$; and the surrounding space is taken to have a temperature of 0 K.) Equating the above two equations gives

$$(1-\alpha)\frac{S}{4}A = \sigma A T^4$$
$$(1-\alpha)S = 4\sigma T^4$$

(b) Hence we find

$$T = \sqrt[4]{\frac{(1-\alpha)S}{4\sigma}}$$

This evaluates to

$$T = \sqrt[4]{\frac{(1-0.30)\times 1400}{4(5.67\times 10^{-8})}} \approx 256\ \text{K}$$

This temperature is −17 °C.

(c) It is perhaps surprising that this extremely simple model has given an answer that is not off by orders of magnitude! But a temperature of 256 K is 32 K lower than the earth's average temperature of 288 K, and so obviously the model is just too simplistic. One reason this model is too simple is precisely because we have not taken into account the fact that not all the power radiated by the earth actually escapes. Some of the power is absorbed by the gases in the atmosphere and is re-radiated back down to the earth's surface, causing further warming that we have neglected to take into account. In other words, this model neglects the *greenhouse effect*. This simple model also points to the general fact that increasing the albedo (more energy reflected) results in lower temperatures.

Another drawback of the simple model presented above is that the model is essentially a zero-dimensional model. The earth is treated as a point without interactions between the surface and the atmosphere. (Latent heat flows, thermal energy flow in oceans through currents, thermal energy transfer between the surface and the atmosphere due to temperature differences between the two, are all ignored.) Realistic models must take all these factors (and many others) into account, and so are very complex.

The greenhouse effect

This effect applies to any planet with an atmosphere, but in this discussion the planet will be assumed to be the earth.

The solar radiation reaching the earth is mainly radiation in the visible region of the electromagnetic spectrum (with small amounts in the ultraviolet and infrared). About 30% of this radiation is reflected back into space, and the rest arrives at the earth's atmosphere and the surface, warming both. The earth's surface radiates back as all warm bodies do. But the earth's surface is at an average temperature of 288 K and, using Wien's law, we see that the wavelengths at which this energy is radiated are infrared wavelengths. Unlike visible light wavelengths, which pass through the atmosphere unobstructed, infrared radiation is strongly absorbed by various gases in the atmosphere, the so-called *greenhouse gases*. This radiation is in turn re-radiated by these gases in all directions. This means that some of this radiation is received by the earth's surface again, causing additional warming (Figure 2.5). This is radiation that would be lost in space were it not for the greenhouse gases. Without this **greenhouse effect**, the earth's temperature would be 32 K lower than what it is now. This effect would be absent if there was no atmosphere.

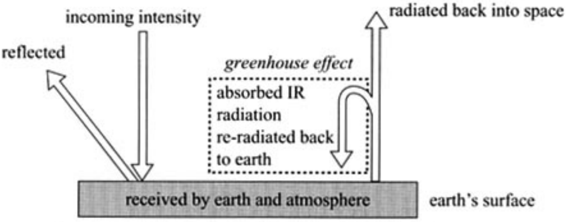

Figure 2.5 A simplified energy flow diagram to illustrate the greenhouse effect.

▶ The *greenhouse effect* may be described as the warming of the earth caused by infrared radiation, emitted by the earth's surface, which is absorbed by various gases in the earth's atmosphere and is then partly re-radiated towards the surface. The gases primarily responsible for this absorption (the *greenhouse gases*) are water vapour, carbon dioxide, methane and nitrous oxide.

A more detailed energy flow diagram is shown in Figure 2.6. The total incoming intensity is represented by 100 in arbitrary units or percentages. (The diagram does not include

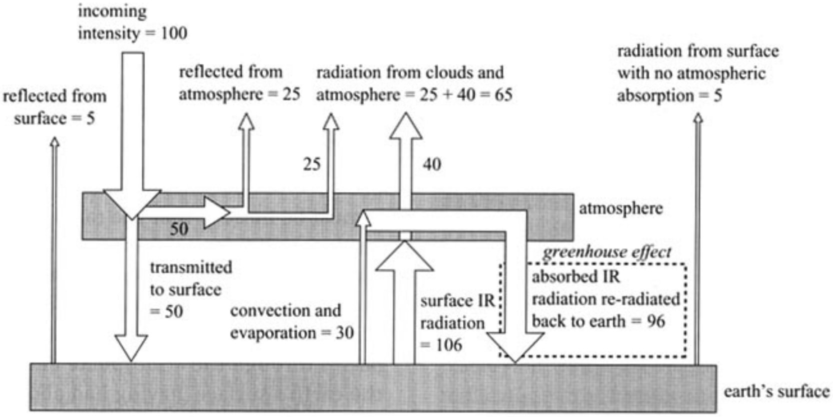

Figure 2.6 A more detailed energy flow diagram for the earth–atmosphere system.

energy associated with winds, ocean waves and currents and transfers of energy across the earth's surface. These are important but are too complicated for our purposes here.) Notice that the energy in and the energy out balance separately, as indicated in Tables 2.2 and 2.3 for the entire earth system and the surface. It is left as an exercise to check that the energy also balances for the atmosphere.

Mechanism	**Intensity in (arbitrary units)**
Radiation from sun	100
Total for entire earth system	100
Mechanism	**Intensity out (arbitrary units)**
Reflected from surface	5
Reflected from atmosphere	25
Radiation from clouds and atmosphere	65
Radiation from surface with no atmospheric absorption (the IR 'window')	5
Total for entire earth system	100

Table 2.2 Energy balance for the entire total earth system.

Mechanism	**Intensity in (arbitrary units)**
Transmitted to surface from sun	50
Absorbed IR radiation re-radiated back to earth (greenhouse effect)	96
Total for earth's surface	146
Mechanism	**Intensity out (arbitrary units)**
Reflected from surface	5
Convection and evaporation	30
IR radiation from surface	106
Radiation from surface with no atmospheric absorption (the IR 'window')	5
Total for earth's surface	146

Table 2.3 Energy balance for the earth's surface.

For the earth as a whole, the total reflected radiation is thus $5 + 25 = 30$, consistent with an albedo of 0.3. The total outgoing radiation is 100, consistent with energy conservation.

Notice that, for the surface, the amount of radiation emitted is $106 + 5 = 111$, compared to the incoming amount of 100. This represents 111% of the average incoming intensity $I = \frac{S}{4} = 350\ \text{W m}^{-2}$, so is

$$111\% \times 350 = \frac{111}{100} \times 350 = 390\ \text{W m}^{-2}$$

This must be consistent with the earth's surface temperature of 288 K. Indeed, the radiation per unit area from a surface at this temperature is

$$\sigma T^4 = 5.67 \times 10^{-8} \times (288)^4 \approx 390\ \text{W m}^{-2}$$

The greenhouse effect is thus a *natural* consequence of the presence of the atmosphere. There is, however, also the *enhanced* greenhouse effect, which refers to additional warming due to *increased* quantities of the greenhouse gases in the atmosphere. The increases in the gas concentrations are due to human activity.

The greenhouse gases in the atmosphere have natural as well as man-made (anthropogenic) origins (Table 2.4). Along with these sources of the greenhouse gases, we have 'sinks' as well, that is to say, mechanisms that reduce these concentrations. For example, carbon dioxide is absorbed by plants during photosynthesis and is dissolved in oceans. Methane is destroyed in the lower atmosphere by chemical reactions involving free hydroxyl radicals (·OH). Nitrous oxide is also destroyed in the atmosphere by photochemical reactions.

It must be noticed that the radiation incident on the earth is mainly visible light. Photons of visible light, unlike photons of infrared radiation, are *not* absorbed by the gases of the atmosphere. Therefore, the incident radiation passes through the atmosphere and arrives at the earth's surface (having had about 25% of the radiation *reflected* back into space from the upper atmosphere).

Greenhouse gas	Natural sources	Anthropogenic sources
H_2O (water vapour)	evaporation of water from oceans, rivers and lakes	
CO_2 (carbon dioxide)	forest fires, volcanic eruptions, evaporation of water from oceans	burning fossil fuels in power plants and cars, burning forests
CH_4 (methane)	wetlands, oceans, lakes and rivers	flooded rice fields, farm animals, termites, processing of coal, natural gas and oil, and burning biomass
N_2O (dinitrogen oxide, nitrous oxide)	forests, oceans, soil and grasslands	burning fossil fuels, manufacture of cement, fertilizers, deforestation (reduction of nitrogen fixation in plants)

Table 2.4 Sources of greenhouse gases.

Mechanism of photon absorption

Consider a molecule of carbon dioxide (one of the many gases that are capable of absorbing infrared photons). We already know from atomic physics that the energy of electrons within atoms is quantized (i.e. it assumes discrete values). The same effect (i.e. the existence of discrete energy values) applies to the energy of molecules due to their vibrational and rotational motion. This energy is also quantized, and there are vibrational and rotational energy levels (Figure 2.7) just as there are atomic energy levels. The big difference between the two kinds of energy level (vibrational/rotational versus atomic) is that the difference in energy between the vibrational/rotational energy levels is approximately the same as the energies of infrared photons. (Atomic energy levels, in general, differ in energy by amounts far greater than the energy of infrared photons.)

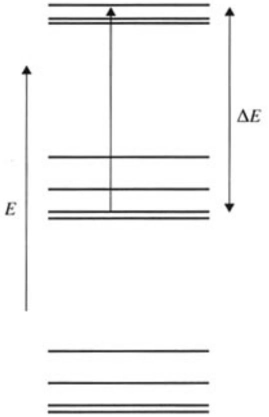

Figure 2.7 Combined vibrational and rotational energy levels of a diatomic molecule. The absorption of a photon of energy ΔE results in the transition indicated.

This means that infrared photons travelling through these gases will be absorbed. Absorbing photons means that the gas molecules will now be excited to higher energy levels. But the molecules prefer to be in low-energy states, and so they will immediately make a transition to a lower-energy state by emitting the photons they absorbed. But these photons are *not all* emitted outwards into space. Some are emitted *back towards the earth*, thereby warming the earth's surface.

The precise mechanism for photon absorption by the greenhouse gases is complex and requires quantum mechanics. Here we will try to understand the absorption by making use of the concept of resonance that we met in our study of simple harmonic motion (Chapter 4.1).

Consider two atoms forming a diatomic molecule (we concentrate on diatomic molecules – this discussion would get very complicated for molecules with three or more atoms). The force between the atoms may be very loosely modelled as a mass–spring system (Figure 2.8). The atoms

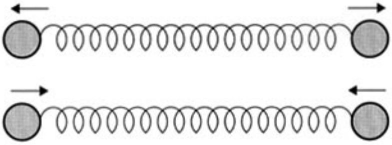

Figure 2.8 The atoms of a diatomic molecule vibrate. The energy associated with the vibration is quantized.

may be thought to be connected by a spring, and simple harmonic oscillations take place when the atoms are disturbed from their equilibrium positions.

The frequency of oscillation is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where m is related to the masses of the two atoms, m_1 and m_2, through

$$m = \frac{m_1 m_2}{m_1 + m_2}$$

For carbon monoxide (CO), the 'spring' constant has a value $k = 1900\ \text{N m}^{-1}$ and $m = 1.14 \times 10^{-26}$ kg. Therefore the frequency is

$$f = \frac{1}{2\pi}\sqrt{\frac{1900}{1.14 \times 10^{-26}}}$$

$$= 6.5 \times 10^{13}\ \text{Hz}$$

This frequency is the *natural frequency* of the molecule. Photons travelling through the gas will be in resonance with the molecule if they have a frequency equal to the natural frequency. A typical infrared photon has an energy of 0.25 eV and so its frequency is

$$f = \frac{E}{h}$$

$$= \frac{0.25 \times 1.6 \times 10^{-19}}{6.6 \times 10^{-34}}$$

$$= 6.1 \times 10^{13}\ \text{Hz}$$

This is approximately the same as the natural frequency of the molecule. This means that the photons will be absorbed by the molecule.

Transmittance curves

Consider infrared radiation passing through the atmosphere. The intensity of radiation after passing through the atmosphere will be less than the incident intensity because some of the radiation will be absorbed. We may then make a transmittance curve that shows the variation with wavelength of the percentage of radiation that actually gets through the gas. The transmittance curve of Figure 2.9 indicates that all photons of wavelength less than about $\lambda = 4 \times 10^{-6}$ m and larger than $\lambda = 8 \times 10^{-6}$ m are transmitted through the gas, whereas photons of wavelengths between $\lambda = 4 \times 10^{-6}$ m and $\lambda = 8 \times 10^{-6}$ m are absorbed to varying degrees. The curve implies that *all* the photons of wavelength $\lambda = 6 \times 10^{-6}$ m are absorbed. The amount of absorption depends on the concentration of the absorbing gas.

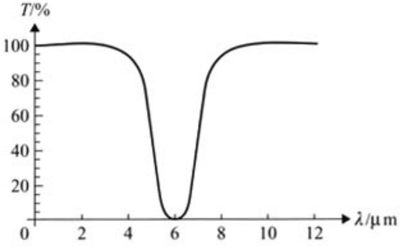

Figure 2.9 A typical transmittance curve for a gas, showing absorption at wavelengths around 6 μm.

Figure 2.10 shows the theoretical black-body spectrum of the sun and the actual spectrum due to absorption by gases in the atmosphere. A realistic transmittance curve is shown in Figure 2.11. It shows the transmittance, through the earth's atmosphere at sea level, for infrared radiation in the wavelength range 1×10^{-6} m to 15×10^{-6} m. There are very strong absorption bands at wavelengths of 1.1×10^{-6} m, 2.8×10^{-6} m and 4.1×10^{-6} m, and between 5.5×10^{-6} m and 7.5×10^{-6} m.

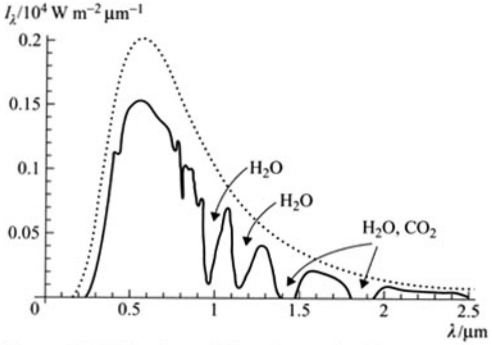

Figure 2.10 The dotted line shows the black-body spectrum of the sun. The solid line is the actual spectrum observed at the surface of the earth due to absorption of the incoming radiation by gases in the atmosphere.

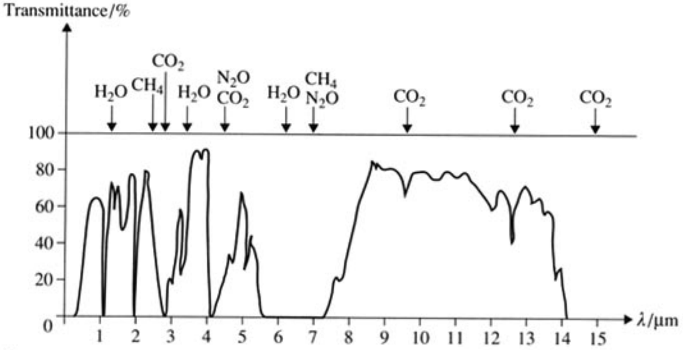

Figure 2.11 Transmittance curve showing absorption from various gases.

Surface heat capacity

We define C_S, the surface heat capacity of the body, to be the energy required to increase the temperature of 1 m^2 of the surface by 1 K. The concept is useful in the context of bodies radiating and absorbing energy, since it is the surface that is responsible for the energy lost and gained. The units of C_S are J m^{-2} K^{-1}. Thus, for a surface of surface heat capacity C_S and area A, the amount of thermal energy needed to increase its temperature by ΔT is given by

$$Q = AC_S\Delta T$$

Example question

Q4

Show that the surface heat capacity is related to the ordinary specific heat capacity c, through $C_S = \rho hc$, where ρ is the density of the material and h is the depth of the surface.

Answer

We have $Q = AC_S\Delta T$ and $Q = mc\Delta T$, and so $AC_S\Delta T = mc\Delta T$. But $m = \rho V = \rho Ah$, and hence

$$AC_S\Delta T = \rho Ahc\Delta T$$

$$C_S = \rho hc$$

This example shows that, in order to calculate the surface heat capacity, one must make estimates of the relevant depth h that will go into the expression. In addition, one has to take an average over various surface heat capacities corresponding to different materials on the surface, for example water, ice, dry land, etc. Thus, if we consider a surface of water of depth 100 m we would have

$$C_S = \rho hc = 10^3 \times 100 \times 4200 = 4.2 \times 10^8 \text{ J m}^{-2}\text{ K}^{-1}$$

The surface heat capacity of dry land is smaller by a factor of about 10.

Example question

Q5

Radiation of intensity 340 W m^{-2} is incident on the surface of a lake of surface heat capacity $C_S = 4.2 \times 10^8$ J m^{-2} K^{-1}. Calculate the time t required to increase the temperature by 2.0 K. Comment on your answer.

Answer

The thermal energy needed to increase the temperature by ΔT is given by $Q = AC_S\Delta T$.

This happens in time t and so

$$\frac{Q}{t} = AC_S \frac{\Delta T}{t}$$

$$\frac{Q/A}{t} = C_S \frac{\Delta T}{t}$$

$$I = C_S \frac{\Delta T}{t}$$

$$340 = 4.2 \times 10^8 \times \frac{2.0}{t}$$

$$t = \frac{4.2 \times 10^8 \times 2.0}{340} \text{ s}$$

$$= 29 \text{ days}$$

We are assuming (unrealistically) that the lake receives the radiation for the entire duration of a day. The answer would be twice as long if the lake received the radiation for only 12 hours per day.

We can make use of the concept of surface heat capacity to make a very simple model of energy balance for a planet. Assume that a planet has surface heat capacity C_S. The planet receives a solar intensity of I_{in} and loses energy into space at a rate I_{out}. The net influx of power on the planet is then $I_{in} - I_{out}$. Over a time t the energy received by an area A of the planet's surface is then $(I_{in} - I_{out})At$, and so $(I_{in} - I_{out})At = AC_S\Delta T$. The increase of the planet's surface temperature after a time t is then

$$\Delta T = \frac{(I_{in} - I_{out})t}{C_S}$$

If $I_{in} > I_{out}$ then the temperature of the planet will increase.

This model is very unrealistic, of course, since even the smallest imbalance between I_{in} and I_{out} would result, over time, in an enormous temperature increase. The model assumes, for example, that the rate of temperature change is constant. A more realistic model would involve a variable rate and so would read

$$\frac{dT}{dt} = \frac{(I_{in} - I_{out})}{C_S}$$

Clearly, if $I_{in} = I_{out}$, the temperature stays constant. Because I_{out} certainly depends on the planet's temperature, this becomes a differential equation, which usually requires a computer to solve it.

Global warming

We have seen that the natural greenhouse effect works in order to keep the earth's temperature at 288 K. This makes life, as we know it, possible on earth. Due to human activities, the concentration of the greenhouse gases in the atmosphere is increasing, and this will lead to additional warming due to the enhanced greenhouse effect. Figure 2.12 shows the variation of the deviations of the earth's average temperature from the expected long-term average since 1880. The deviations are positive and increasing over the last 25 years.

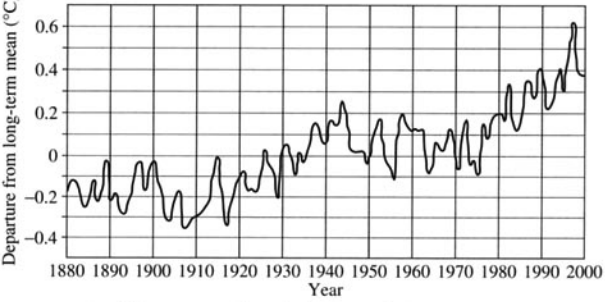

Figure 2.12 The deviation of the earth's global average surface temperature from the expected long-term average since 1880. (Source: US National Climatic Data Center, 2001.)

Figure 2.13 shows the variation with time of the concentrations of the main greenhouse gases over geological, recent and present time periods. The concentrations are all increasing. For carbon dioxide, in particular, the present concentrations are almost double those in pre-industrial times (before approximately the nineteenth century).

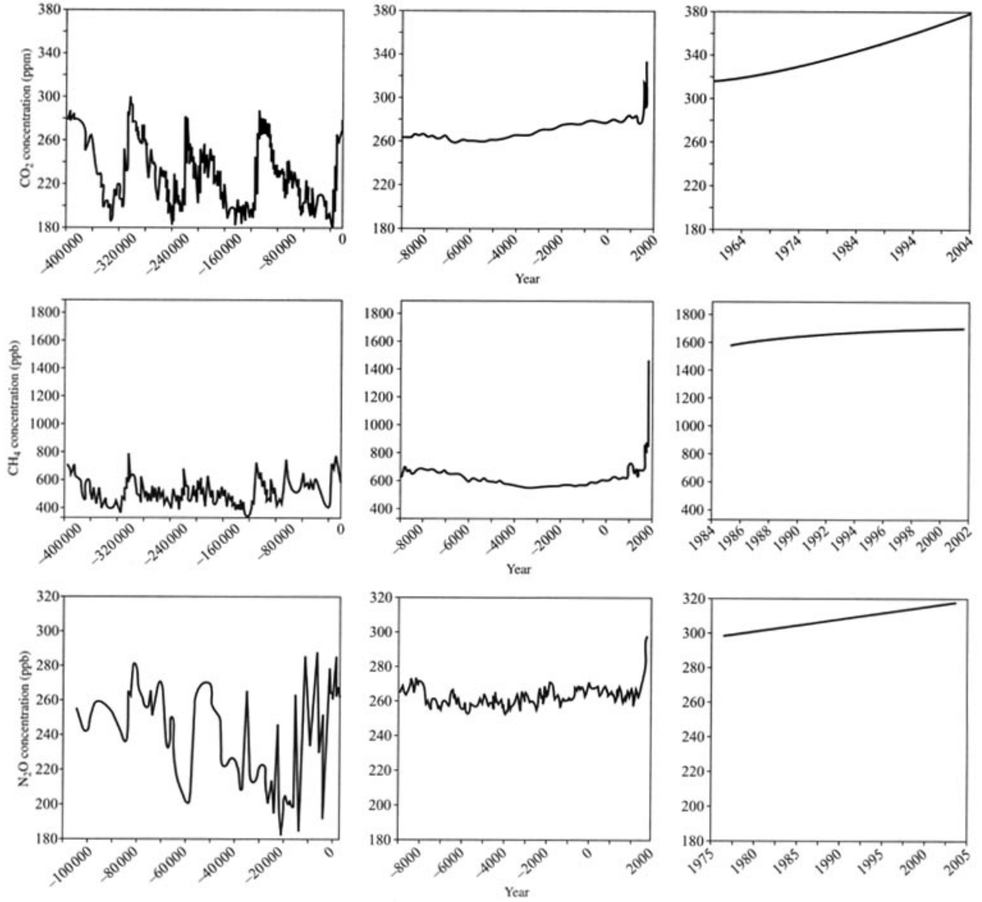

Figure 2.13 The concentrations of carbon dioxide, methane and nitrous oxide in the atmosphere. (Source: US Environmental Protection Agency.)

The graph of temperature in Figure 2.12 and the gas concentration graphs in Figure 2.13 are strong evidence of the connection between global warming and greenhouse gases. A criticism of the conclusion linking the two has been that the data do not cover a large enough time span. Countering this argument is the very impressive body of evidence collected from ice cores in Antarctica and Greenland. Analysing very old ice core samples gives, among many other things, information about gas concentrations and atmospheric temperature at the time of freezing. The results of this analysis are that there is a very close link between global warming and increased greenhouse gas concentrations.

The Antarctic ice cores, in particular, extracted from a depth of about 3600 m over (frozen) lake Vostok in East Antarctica in 1998, have been thoroughly analysed to reveal a connection between temperature changes and changes in carbon dioxide and methane concentrations. The ice cores give a detailed account of global climatic conditions over a time period spanning some 420 000 years.

Figure 2.14 shows the variation with time of the change in average world temperature relative to the present temperature. The curve indicates that the earth has been cooler for most of the last 400 000 years. The graph also shows that the earth was warmest whenever the levels of carbon dioxide in the atmosphere increased. Therefore, it is certain that the average global temperature of the earth will increase. What is uncertain is the *detailed* effect of this temperature increase on the global climate – in magnitude (How big will these effects be?) and in time scale (How soon will they happen?). Predicting these effects is a central problem for both scientists and policy-makers around the world.

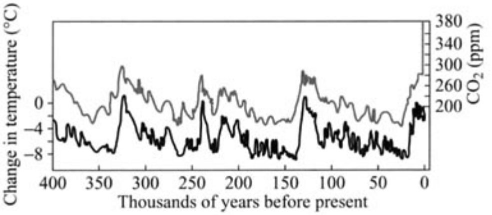

Figure 2.14 Changes in atmospheric carbon dioxide concentration (upper curve) and average temperature (lower curve) over the past 400 000 years show a strong correlation. Source: A. V. Fedorov et al., *Science*, **312**, 1485 (2006).

The questions that need answers are many. They include the following:

- What is the best estimate for the temperature increase, over a given time period?
- What will be the effects of a higher temperature on the amount of rainfall?
- How much ice will melt?
- What will be the rise in sea level?
- Will there be areas of extra dryness and drought and, if so, where will these areas be?
- Will the temperature of the oceans be affected and, if so, by how much?
- Will ocean currents be affected and, if so, how?
- Will there be periods of extreme climate variability?
- Will the frequency and intensity of tropical storms increase?
- What is the effect of sulphate aerosols in the atmosphere? Do they offset global warming?
- What are the feedback mechanisms affecting global climate?
- Can the observed temperature increase be blamed on greenhouse gases exclusively?
- Given the long lifetime of carbon dioxide in the atmosphere, can the process of global warming be reversed even if present emissions are drastically reduced?
- What are the ecological implications of the expected changes in the habitat of many species?
- What will be the effects on agriculture?
- Will there be more diseases?
- What are the social and economic effects of all of the above?

The majority of experts tend to agree that the enhanced greenhouse effect is behind global warming. Others have looked for different causes. One theory is that global warming may be due to increased solar activity, which results in an increased solar power output. It is known that the sun undergoes periodic changes in its total emitted power. These changes are complex phenomena and not very well understood. The general opinion is that the pattern of global warming is not consistent with the changes in solar activity. Other theories include increased concentrations of the greenhouse gases due to volcanic activity and changes in the earth's orbit around the sun (see end-of-chapter question 4 for a simple example). The changes involve variations in the *eccentricity* of the orbit as well as the 'tilt' of the orbit with respect to the sun. These are used to introduce variations in the received energy from the sun in order to account for changes in the temperature. These orbital phenomena occur over time scales ranging from 20 000 to 100 000 years. So, while they are relevant at these time scales, they are perhaps not so relevant for the climate changes of, say, the last 200 years.

Sea level

The level of water in the sea is always varying. Many reasons contribute to this, for example varying atmospheric pressure, plate tectonic movements, wind, tides, flow of large rivers into the sea, changes in water salinity and others.

What concerns us here are changes in sea level due to climate changes. The relation between climate and sea level is a complicated one. It is known that climate changes affect sea level through the fact that the temperature determines how much ice melts or how much water freezes. For example, it is known that, during the last ice age of 18 000 years ago, the sea level was lower than its present value by as much as 100 m.

▶ Changes in sea level affect the amount of water that can evaporate and the amount of thermal energy that can be exchanged with the atmosphere. In addition, changes in sea level affect ocean currents. The presence of these currents is vital in transferring thermal energy from the warm tropics to colder regions.

The melting of ice

To melt a mass m of ice at 0 °C requires an amount of thermal energy $Q = mL$, where L is the **specific latent heat of fusion** of ice. Thus, to melt ice, energy must be provided, and therefore cooling results at the place from where this energy is removed. For the purposes of discussing changes in sea level, we must distinguish between land ice (ice supported on land) and sea ice (ice floating in sea water). Sea ice, when melted, will not result in a change of sea level. This is a consequence of a principle of fluid mechanics known as Archimedes' principle. The weight of the ice is equal to the weight of the *displaced water* and so when the ice melts it will occupy a volume equal to the volume of the displaced water (i.e. no change in sea level will come about). By contrast, land ice, when melted, will result in an increased sea level.

Estimating changes in sea level

Overall, warming will, in general, result in a rise in sea level, not only because more land ice will melt but also because warmer water occupies a larger volume. The expansion of water is anomalous, however. Water will actually contract in volume as it is heated from 0 °C to 4 °C, and then will expand as the temperature is increased further from 4 °C. This means that the density of water is highest at 4 °C, a fact that is of considerable importance for life in lakes, rivers and oceans.

Given a volume V_0 at a temperature θ_0, the volume after a temperature increase of $\Delta\theta$ will increase by ΔV given by

$$\Delta V = \gamma V_0 \Delta\theta$$

where γ is a coefficient known as the **coefficient of volume expansion**.

▶ The *coefficient of volume expansion* is defined as the fractional change in volume per unit temperature change.

For water, the coefficient γ actually depends on temperature, and so a given volume of water will change by different amounts even for the same temperature changes $\Delta\theta$ depending on the initial temperature of the water.

The following example is a typical, rough estimate of the expected rise in sea level as a result of an increase in temperature.

Example question

Q6

The area of the oceans of the earth is about 3.6×10^8 km^2 and the average depth of water is about 3.7 km. Using a coefficient of volume expansion of water of 2×10^{-4} K^{-1}, estimate the expected rise in sea level after a temperature increase of 2 K. Comment on your answer.

Answer

The total volume of water in the oceans is approximately $V_0 = A \times d$, where A is the area and d is the average depth. So

$$V_0 = 3.6 \times 10^8 \times 3.7 = 1.33 \times 10^9 \text{ km}^3$$
$$= 1.33 \times 10^{18} \text{ m}^3$$

The increase in volume is then:

$$\Delta V = \gamma V_0 \Delta\theta$$
$$= 2 \times 10^{-4} \times 1.33 \times 10^{18} \times 2$$
$$= 5.3 \times 10^{14} \text{ m}^3$$

Sea level will increase by an amount h such that (converting A to m^2)

$$h = \frac{\Delta V}{A}$$
$$= \frac{5.3 \times 10^{14}}{3.6 \times 10^{14}}$$
$$= 1.5 \text{ m}$$

This estimate assumes a constant coefficient of expansion, uniform heating of all the water and does not take into account the initial water temperature. It also does not take into account the fact that, with a higher water temperature, more evaporation would take place, hence cooling the water. This estimate calculates the rise in sea level of the *existing* area of water. A rising sea would cover dry land and so the area of water would increase. This would *decrease* the height found in the estimate.

Effects of global warming on climate

A higher average earth temperature implies a rising sea level. One effect on climate of a rising sea level is the change in the albedo of the surface (more water as opposed to dry land). This effect is considered in the next example.

Example question

Q7

About 50% of the area of a certain large region of the earth's surface was covered by water. As a result of ice melting, 60% of this region is now covered by water. Estimate the change in the albedo of the region. Take the albedo of sea water to be $\alpha_S = 0.20$ and that of land to be $\alpha_L = 0.40$.

Answer

Let radiation of intensity I fall on the region. Then the total amount of radiation originally reflected was

$$\alpha_S \times 0.5I + \alpha_L \times 0.5I = (\alpha_S \times 0.5 + \alpha_L \times 0.5)I$$

The average albedo of the region was thus $\alpha_S \times 0.5 + \alpha_L \times 0.5$. With more water the albedo similarly becomes $\alpha_S \times 0.6 + \alpha_L \times 0.4$. The change in albedo is thus

$$\Delta\alpha = (\alpha_S \times 0.6 + \alpha_L \times 0.4) - (\alpha_S \times 0.5 + \alpha_L \times 0.5)$$
$$= 0.1 \times \alpha_S - 0.1 \times \alpha_L$$
$$= 0.1 \times (\alpha_S - \alpha_L)$$
$$= -0.1 \times 0.20$$
$$= -0.020$$

The albedo thus decreases, which means that a small additional warming can perhaps be expected. (This is an example of positive feedback – warming causes ice to melt, which in turn decreases the albedo, which results in additional warming.)

The expected changes in temperature due to a change in albedo, because of more water covering land, are actually small. A more significant effect of ice melting and the sea level rising is expected to be the fact that, with more water, and at a higher temperature, the evaporation rate will increase and therefore more water vapour will be released into the atmosphere. This means:

- cooling of the earth's surface (because latent heat is given to the water in order to evaporate);
- more cloud cover (and therefore more reflected radiation);
- more precipitation (i.e. rain, but not necessarily in the region of interest).

An additional effect of higher temperatures on climate is the fact that carbon dioxide solubility in the oceans decreases. This means that more carbon dioxide is left in the atmosphere.

The next example discusses another factor affecting global climate, deforestation.

Example question

Q8

Large areas of rainforests are being destroyed by cutting down (and burning) trees. Discuss the possible effects of this on the energy balance of the region.

Answer

Changing forests to dry land has three immediate consequences. The first is that the low albedo of the dark, moist forests is replaced by a higher albedo – this tends to reduce temperatures since more radiation is reflected rather than absorbed. The second is that the evaporation rate is decreased – this tends to increase temperatures since the surface no longer has to supply the latent heat for evaporation. The two are thus opposing effects. Models show that, regionally, there are no significant changes in temperature as a result of deforestation. The local precipitation rate, though, generally drops. The third factor is that by removing the forests and burning the trees a carbon dioxide sink is removed (the trees) and more carbon dioxide is produced (by burning the trees). It is estimated that two billion tonnes of carbon dioxide has been released into the atmosphere as a result of deforestation. This, as we have seen, enhances the greenhouse effect.

The issue of deforestation is still a bit controversial. Rainforests must, of course, be preserved in order to maintain the existing habitat and thus prevent the extinction of very many animal and plant species. However, the effect of deforestation on climate is uncertain because rainforests do produce methane and thus contribute to the increased concentrations of greenhouse gases. Forests do absorb carbon dioxide but that is returned to the atmosphere when the trees die and decompose.

Measures to reduce global warming

There is clearly an urgent need to stop the increase in all the greenhouse gases, and carbon dioxide in particular. Measures to achieve this include the following:

- using fuel-efficient cars and developing hybrid cars further;
- increasing the efficiency of coal-burning power plants;
- replacing coal-burning power plants with natural gas-fired plants;
- considering methods of capturing and storing the carbon dioxide produced in power plants (carbon capture and storage, CCS);
- increasing the amounts of power produced by wind and solar generators;
- considering nuclear power;
- being energy conscious, with buildings, appliances, transportation, industrial processes and entertainment;
- stopping deforestation.

The Kyoto protocol and the IPCC

An extremely important agreement towards cutting greenhouse gas emissions was reached in 1997, in Kyoto, Japan. The industrial nations agreed to reduce their emissions of greenhouse gases by 5.2% from the 1990 levels over the period from 2008 to 2012. The protocol allowed mechanisms for developed nations to use projects aimed at reducing emissions in developing nations as part of their own reduction targets. Endorsed by 160 countries, the protocol would become legally binding if at least 55 countries signed it. The non-ratification of the protocol by the USA and Australia has weakened the impact of the agreement.

Unlike the Kyoto protocol, which imposed mandatory limits for greenhouse gas emissions, the Asia–Pacific Partnership on Clean Development and Climate (APPCDC, or AP6) asked for voluntary reductions of these emissions. It was signed by the USA, Australia, India, the People's Republic of China, Japan and South Korea in 2005. It is an agreement in which the signatory nations agree to cooperate in reducing emissions. It has been criticized as worthless because the reductions are voluntary.

It has been defended because it includes China and India, major greenhouse gas producers, who are not bound by the Kyoto protocol.

A major, comprehensive, detailed and scientifically impartial analysis of global climate has been undertaken by the Intergovernmental Panel on Climate Change (IPCC). The IPCC was created by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988. While conducting no research of its own, the IPCC reports on technical, scientific and socio-economic aspects of climate change using assessments of existing published scientific material. Its four reports in 1990, 1997, 2001 and 2007 have been instrumental in providing an accurate analysis of the global situation.

Questions

1 (a) State what you understand by the term *black body*.

(b) Give an example of a body that is a good approximation to a black body.

(c) By what factor does the rate of radiation from a body increase when the temperature is increased from 50 °C to 100 °C?

2 The graphs in Figure 2.15 show the variation with wavelength of the intensity of radiation emitted by two bodies of identical shape.

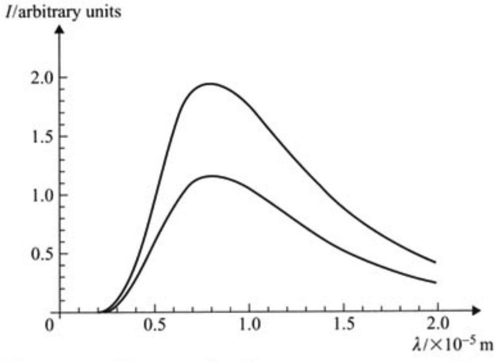

Figure 2.15 For question 2.

(a) Explain why the temperature of the two bodies is the same.

(b) The upper graph actually corresponds to a black body. Calculate the emissivity of the other body.

3 The total power radiated by a body of area 5.00 km^2 and emissivity 0.800 is 1.35×10^9 W. Assume that the body radiates into vacuum at temperature 0 K. Calculate the temperature of the body.

4 If the distance d between the sun and the earth decreases, the earth's average temperature T will go up. The fraction of the power radiated by the sun that is received on earth is proportional to $\frac{1}{d^2}$; the power radiated by the earth is proportional to T^4.

(a) Deduce the dependence of the temperature T of the earth on the distance d.

(b) Hence estimate the expected rise in temperature if the distance decreases by 1.0%. Take the average temperature of the earth to be 288 K.

5 (a) Define the term *intensity* in the context of radiation.

(b) *Estimate* the intensity of radiation emitted by a naked human body of surface area 1.60 m^2, temperature 37 °C and emissivity 0.90, a distance of 5.0 m from the body.

6 A body radiates energy at a rate (power) P.

(a) Deduce that the intensity of this radiation at distance d from the body is given by

$$I = \frac{P}{4\pi d^2}$$

(b) State one assumption made in deriving this result.

7 The graph in Figure 2.16 shows the variation with wavelength of the intensity of the radiation emitted by a black body.

(a) Determine the temperature of the black body.

(b) Copy the diagram, and, on the same axes, draw a graph to show the variation with wavelength of the intensity of radiation emitted by a black body of temperature 600 K.

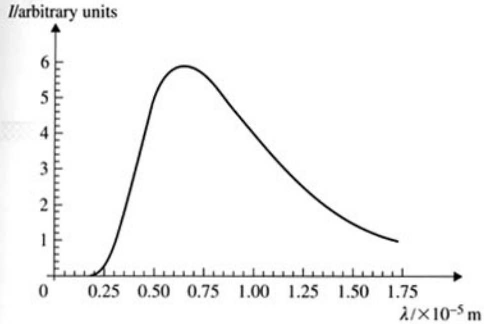

Figure 2.16 For question 7.

8 (a) Define the term *albedo*.

(b) State three factors that the albedo of a surface depends on.

9 A researcher uses the following data for a simple climatic model of an earth without an atmosphere (see Example question 3 in the text): incident solar radiation = 350 W m^{-2}, absorbed solar radiation = 250 W m^{-2}.

(a) Make an energy flow diagram for this data.

(b) Determine the average albedo for the earth that is to be used in the modelling.

(c) Determine the intensity of the outgoing long-wave radiation.

(d) Estimate the temperature of the earth according to this model, assuming a constant earth temperature.

10 Radiation of intensity 340 W m^{-2} is incident on a lake of depth 50 m.

(a) How much time is needed to increase the water temperature by 1 K?

(b) Estimate the heat capacity of the entire body of water on earth. (Use an average depth of 300 m if you cannot find a better estimate.)

(c) Then estimate the time needed to increase the water temperature by 1 K if solar radiation of intensity 340 W m^{-2} were incident on the water.

11 (a) Repeat the calculations of the simple model presented in Example question 3 for the planets Venus and Mars in order to predict their surface temperatures. Take the distances to the sun to be 1.08×10^{11} m (Venus) and 2.28×10^{11} m (Mars), and use a solar power output of 3.9×10^{26} W. Assume that the albedo α for Venus is 0.59 and that for Mars is 0.15.

(b) The actual surface temperatures are 740 K (Venus) and 213 K (Mars). What do your answers in (a) suggest about the atmospheres of Venus and Mars?

12 Make a simple model of the greenhouse effect as in Figure 2.17. Assume that only a fraction t of the energy radiated by the earth actually leaves the earth.

(a) Copy the diagram and complete the three boxes (i)–(iii) to show the intensities involved.

(b) Write the energy balance equation and calculate t so that the temperature is $T \approx 288$ K. Take $\frac{S}{4} = 350$ W m^{-2} and the earth albedo to be 0.30.

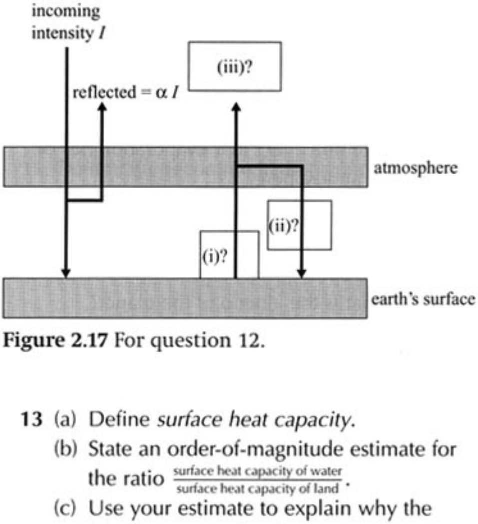

Figure 2.17 For question 12.

13 (a) Define *surface heat capacity*.

(b) State an order-of-magnitude estimate for the ratio $\frac{\text{surface heat capacity of water}}{\text{surface heat capacity of land}}$.

(c) Use your estimate to explain why the climate over water changes much more slowly than the climate over land.

14 Outline the main ways in which the surface of the earth loses thermal energy to the atmosphere and to space.

15 A researcher making climate simulations wants to investigate the effects of deforestation by changing the value of the albedo in her calculations. Should she increase or decrease the albedo?

16 (a) How does the albedo of a subtropical, warm, dry land compare to that of a tropical ocean?

(b) Suggest mechanisms through which the subtropical land and the tropical ocean lose thermal energy to the atmosphere.

(c) If the sea level were to increase, sea water would cover dry land. Suggest one change in the regional climate that might come about as a result.

17 Suggest a reason why covering dry land near the equator by water would have a smaller effect on climate than covering subtropical land with water. (*Hint*: Consider the fact that equatorial land is probably better covered by vegetation than subtropical land, and concentrate on the fact that the albedo of vegetation and water are almost the same.)

18 Evaporation is a method of thermal energy loss. Do you expect this method to be more significant for a tropical ocean or an arctic ocean? Explain your answer.

19 (a) State one effect that evaporation has on the earth's surface.

(b) State one effect that evaporation has on the atmosphere.

20 Radiation is incident on a planet with an atmosphere. Figure 2.18 shows the energy balance of the planet.

(a) What is the albedo of the planet?

(b) How can it be deduced that the planet's temperature is constant?

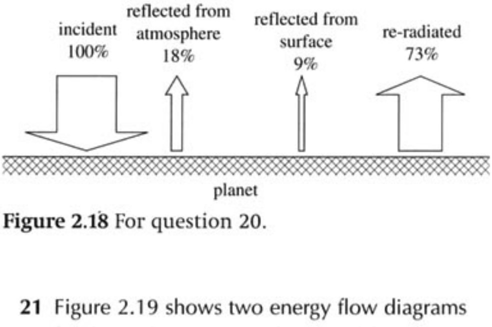

Figure 2.18 For question 20.

21 Figure 2.19 shows two energy flow diagrams for thermal energy transfer to and from specific areas of the surface of the earth.

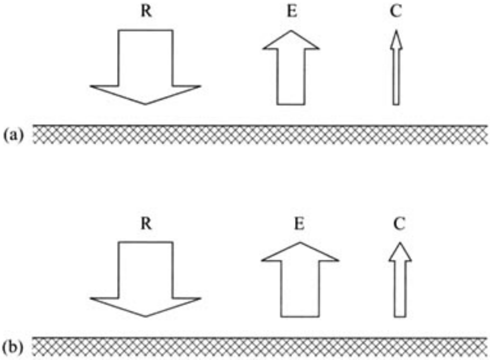

Figure 2.19 For question 21.

R represents the net energy incident on the surface in the form of radiation; E is the thermal energy lost from the earth due to evaporation; and C is the thermal energy conducted to the atmosphere because of the temperature difference between the surface and the atmosphere. Suggest, giving a reason, whether the earth area in each diagram is most likely dry and cool or moist and warm.

22 Draw a sketch graph to show how the latent heat flux from the earth's surface depends on latitude.

23 It is estimated that a change of albedo by 0.01 will result in a 1 °C temperature change. A large area of the earth consists of 60% water and 40% land. Calculate the expected change in temperature if melting ice causes a change in the proportion of the area covered by water from 60% to 70%. Take the albedo of dry land to be 0.30 and that of water to be 0.10.

24 (a) State what is meant by the *greenhouse effect*.

(b) State the main greenhouse gases in the earth's atmosphere, and for each give three natural and three man-made sources.

25 Distinguish between the *natural* greenhouse effect and the *enhanced* greenhouse effect.

26 Outline the evidence that links increased concentrations of carbon dioxide with global warming over a long period of time.

27 (a) Describe what is meant by a transmittance curve.

(b) Figure 2.20 shows a transmittance curve for IR radiation through the atmosphere. Discuss the changes you would expect to the general shape of this curve if the concentrations of carbon dioxide were to be reduced drastically.

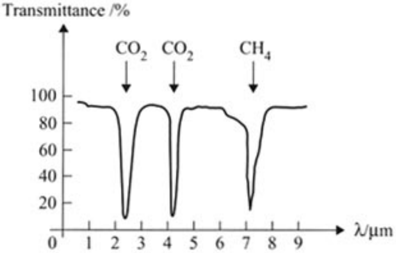

Figure 2.20 For question 27.

28 (a) State and explain two ways in which a rising sea level affects the global climate.

(b) State two physical mechanisms that may contribute to increased sea levels.

29 An iceberg of total mass 10^5 kg floats in water.

(a) Assuming a constant temperature of 0 °C for the iceberg, calculate the amount of energy required to melt it. Take the specific latent heat of fusion of ice to be 330 kJ kg^{-1}.

(b) State whether or not this will result in an increased sea level.

30 The area of the Mediterranean Sea is approximately 2.5×10^6 km^2 and the average depth of water is about 1.5 km. Using a coefficient of volume expansion of water of 2×10^{-4} K^{-1}, estimate the expected rise in sea level after a temperature increase of 3 K. State any assumptions made in your estimate.

31 The West Antarctic ice sheet, if it melts, will result in a 6 m sea level rise. Estimate the volume of this ice sheet. List any assumptions you make.

32 Suggest effects of deforestation on the global climate.

33 State two mechanisms, other than the enhanced greenhouse effect, which have been postulated to account for global warming.

34 List measures that might help to reduce global warming.

35 Outline the recommendations of the Kyoto protocol.

36 What is the IPCC and what does it do?