8.2 Thermal energy transfer

Understanding

- Conduction, convection, and thermal radiation
- Black-body radiation
- Albedo and emissivity
- Solar constant
- Greenhouse effect
- Energy balance in the surface–atmosphere system

Nature of science

The study of the Earth's climate illustrates the importance of modelling in science. The kinetic theory for an ideal gas is a good model for the way that real gases actually behave. Scientists model the Earth's climate in an attempt to understand the implications of the release of greenhouse gases for global warming.

The climate is a much more complex system than a simple gas. Issues for scientists include: the availability of data for the planet as a whole, and greater computing power means that more sophisticated models can be tested. Collaboration between research groups means that debate about the accuracy of the models can take place.

Applications and skills

- Sketching and interpreting graphs showing the variation of intensity with wavelength for bodies emitting thermal radiation at different temperatures
- Solving problems involving Stefan–Boltzmann and Wien's laws
- Describing the effects of the Earth's atmosphere on the mean surface temperature
- Solving albedo, emissivity, solar constant, and the average temperature of the Earth problems

Equations

- Stefan-Boltzmann equation: $P = e\sigma AT^4$
- Wien's Law: $\lambda_{max}\,(\text{metres}) = \dfrac{2.90 \times 10^{-3}}{T(\text{kelvin})}$
- intensity equation: $I = \dfrac{\text{power}}{A}$
- albedo $= \dfrac{\text{total scattered power}}{\text{total incident power}}$

Introduction

We considered some of the energy resources in use today in Sub-topic 8.1. In the course of that sub-topic some of the pollution and atmospheric effects of the resources were mentioned. In this sub-topic we look in more detail at the physics of the Earth's atmosphere and the demands that our present need for energy are making on it. After a review of the ways in which energy is transferred due to differences in temperature, we discuss the Sun's radiation and its effect on the atmosphere. Finally, we look at how changes in the atmosphere modify the climate.

Thermal energy transfer

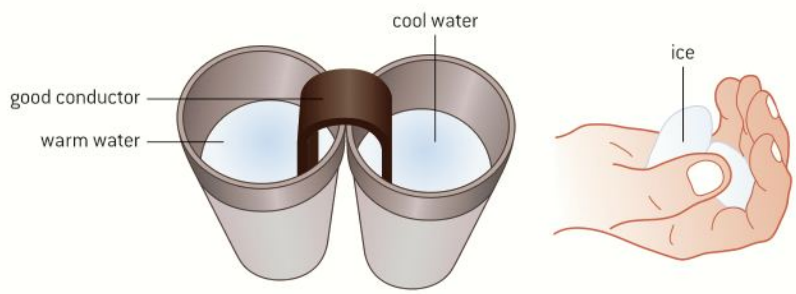
Any object with a temperature above absolute zero possesses internal energy due to the motion of its atoms and molecules. The higher the temperature of the object, the greater the internal energy associated with the molecules. Topic 3 showed that in a gas the macroscopic quantity that we call absolute temperature is equivalent to the average of the kinetic energy of the molecules. Given the opportunity, energy will spontaneously transfer from a region at a high temperature to a region at a low temperature. "Heat", we say rather loosely, "flows from hot to cold".

In this sub-topic we look at the ways in which energy can flow due to differences in temperature. There are three principal methods: conduction, convection, and thermal radiation. All are important to us both on an individual level and in global terms.

Thermal conduction

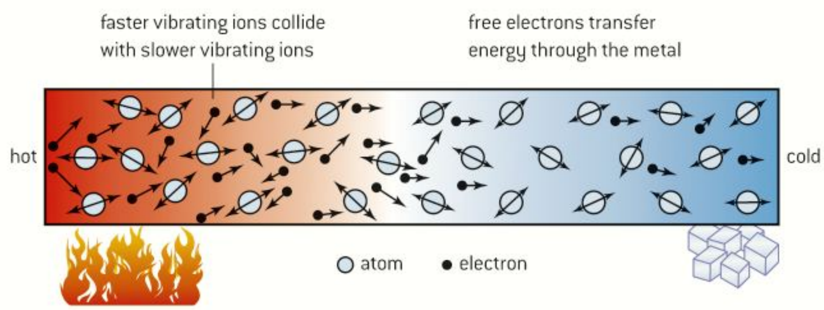
There are similarities between electrical conduction and thermal conduction to the extent that this section is labelled thermal conduction for correctness. However, for the rest of our discussion we will use the term "conduction", taking the word to mean thermal conduction.

We all know something of practical conduction from everyday experience. Burning a hand on a camping stove, plunging a very hot metal into cold water which then boils, or melting ice in the hand all give experience of energy moving by conduction from a hot source to a cold sink.



▲ Figure 1 Laboratory conduction demonstrations.

Metals are good thermal conductors, just as they are also good electrical conductors. Poor thermal conductors such as glass or some plastics also conduct electricity poorly. This suggests that there are similarities between the mechanisms at work in both types of conduction. However, it should be noted that there are still considerable differences in scale between the very best metal conductors (copper, gold) and the worst metals (brass, aluminium). There are many lab experiments that you may have seen designed to help students recognize the different thermal properties of good and poor conductors.



▲ Figure 2 How conduction occurs at an atomic level.

In conduction processes, energy flows through the bulk of the material without any large-scale relative movement of the atoms that make up the solid. Conduction (electrical and thermal) is known as a transport phenomenon. Two mechanisms contribute to thermal conduction:

- **Atomic vibration** occurs in all solids, metal and non-metal alike. At all temperatures above 0 K, the ions in the solid have an internal energy. So they are vibrating about their average fixed position in the solid. The higher the temperature, the greater is the average energy, and therefore the higher their mean speed. Imagine a bar heated at one end and cooled at the other (see figure 2). At the hot end, the ions vibrate at a large amplitude and with a large average speed. At the cold end the amplitude is lower and the speed is smaller. At the position where the bar is heated the ions vibrate with increasing amplitude and collide with their nearest neighbours. This transfers internal energy and the amplitude of the neighbours will increase; this process continues until the bar reaches thermal equilibrium. In this case the energy supplied to each ion is equal to that transferred by the ion to its neighbours in the bar or the surroundings. Each region of the bar will now be at the same uniform temperature.
- Conduction can occur in gases and liquids as well as solids, but, because the inter-atomic connections are weaker and the atoms (particularly in the gases) are farther apart in fluids, conduction is much less important in many gases and liquids than is convection.
- Although thermal conduction by atomic vibration is universal in solids, there are other conduction processes that vary in importance depending on the type of solid under discussion. As we saw in Topic 5, electrical conductors have a covalent (or metallic) bonding that releases **free electrons** into what is essentially an electron gas filling the whole of the interior of the solid. These free electrons are in thermal equilibrium with the positive ions that make up the atomic lattice of the solid. The electrons can interact with each other and the energy from the high-temperature end of the solid "diffuses" along the solid by interactions between these electrons. When an electron interacts with an atom, then energy is transferred back into the atomic lattice to change the vibrational state of the atom. This free-electron mechanism for conduction depends critically on the numbers of free electrons available to the solid. Good electrical conductors, where there are many charge carriers (free electrons) available per unit volume, are likely also to be good thermal conductors. For example, in copper there is one free electron per atom. You should be able to use Avogadro's number, the density of copper and its relative atomic mass, to show that there are 8.4×10^{28} electrons in every cubic metre of copper.

Nature of science

Thermal and electrical resistivity

Analogies are often used in science to aid our understanding of phenomena. Electrical and thermal conduction are closely linked and so it ought to be possible to transfer some ideas from one to the other. There is an analogy between thermal and electrical effects when thermal conduction is compared with electrical conduction for a wire of cross-section area A and length Δl:

Thermal

The rate of transfer of internal energy Q is proportional to temperature gradient:

$$\frac{\Delta Q}{\Delta t} = -\frac{A}{k}\left(\frac{\Delta T}{\Delta l}\right)$$

where k is the thermal resistivity of the material.

Electrical

The rate of transfer of charge q (the current) is proportional to potential gradient:

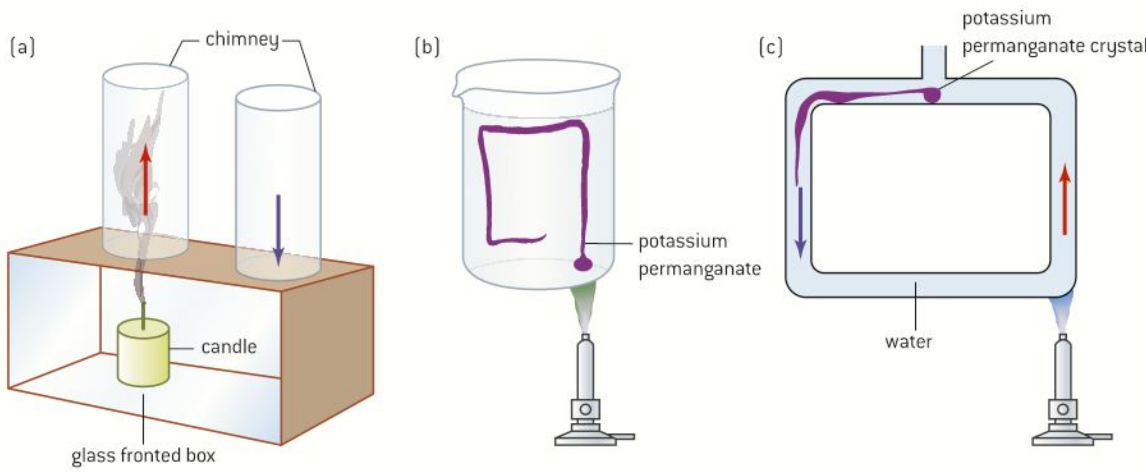
$$\frac{\Delta Q}{\Delta t} = -\frac{A}{\rho}\left(\frac{\Delta V}{\Delta l}\right)$$

where ρ is the electrical resistivity of the material.

The thermal resistivity k of a material corresponds to the electrical resistivity ρ and the temperature gradient corresponds to the electric potential gradient. The rate at which both internal energy and charge are carried through the wire is related to the presence of free electrons in the metal. It is more than a coincidence of equations, physics at the atomic scale is involved. Are good electrical conductors also good thermal conductors? Compare the values of ρ and k for different metals.

Convection

Convection is the movement of groups of atoms or molecules within fluids (liquids and gases) that arises through variations in density. Unlike conduction, which involves the microscopic transfer of energy, convection is a bulk property. Convection cannot take place in solids. An understanding of convection is important in many areas of physics, astrophysics and geology. In some hot countries, houses are designed to take advantage of natural convection to cool down the house in hot weather.



▲ Figure 3 Convection currents.

Figure 3 shows three lab experiments that involve convection. In all three cases, energy is supplied to a fluid. Look at the glass-fronted box (a) first. A candle heats the air underneath a tube (a chimney) that leads out of the box. The air molecules immediately above the flame move further apart decreasing the air density in this region. With a smaller density these molecules experience an upthrust and move up through the chimney.

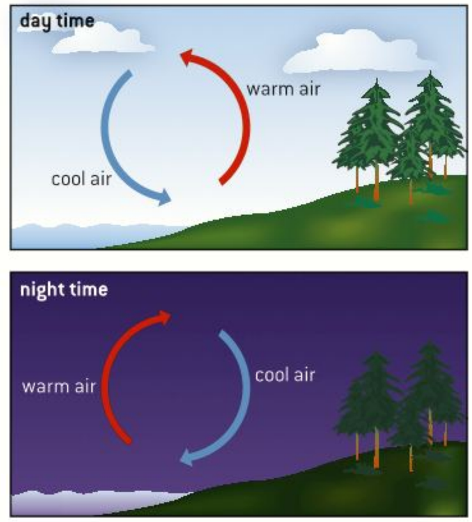
This movement of air reduces the pressure slightly which pulls cooler air down the other chimney. Further heating of the air above the flame leads to a continuous current of cold air down the right-hand chimney and hot air up the left-hand tube. This is a **convection current**.

Similar currents can be demonstrated in liquids. Figure 3(b) shows a small crystal of a soluble dye (potassium permanganate) placed at the bottom of a beaker of water. When the base of the beaker is heated gently near to the crystal, water at the base heats, expands, becomes less dense, and rises. This also leads to a convection current as in figure 3(c) where a glass tube, in the shape of a rectangle, again with a small soluble coloured crystal, can sustain a convection current that moves all around the tube.

This is the mechanism by which all the water heated in a saucepan on a stove eventually reaches a uniform temperature.

Examples of convection

There are many examples of convection in action. Figures 4 and 5 show examples from the natural world; there are many others.



▲ Figure 4 Sea breezes.

Sea breezes

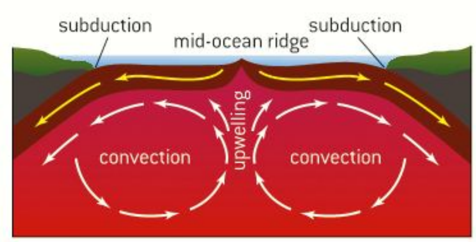
If you live by an ocean you will have noticed that the direction of the breeze changes during a 24-hour period. During the day, breezes blow on-shore from the ocean, at night the direction is reversed and the breeze blows off-shore from the land to the sea.

Convection effects explain this. During the day the land is warmer than the sea and warm air rises over the land mass, pulling in cooler air from above the ocean. At night the land cools down much more quickly than the sea (which has a temperature that varies much less) and now the warmer air rises from the sea so the wind blows off-shore. (You might like to use your knowledge of specific heat capacity to explain why the sea temperature varies much less than that of the land.)

A similar effect occurs in the front range of the Rocky Mountains in the USA. The east-facing hills warm up first and the high-pressure region on the plains means that the wind blows towards the mountains. Later in the day, the east-facing slopes cool down first and the effect is reversed.

Convection in the Earth

At the bottom of the Atlantic Ocean, and elsewhere on the planet, new crust is being created. This is due to convection effects that are occurring below the surface. The Earth's core is at a high temperature and this drives convection effects in the part of the planet known as the upper mantle. Two convection currents operate and drive material in the same direction. Material is upwelling at the top of these currents to reach the surface of the Earth at the bottom of the ocean. This creates new land that is forcing the Americas, Europe, and Africa apart at the rate of a few centimetres every year. In other parts of the world convection currents are pulling material back down below the surface (subduction). These convection currents have, over time, given rise to the continental drift that has shaped the continents that we know today.



▲ Figure 5 Convection currents in the Earth's mantle.

Why the winds blow

The complete theory of why and how the winds blow would occupy a large part of this book, but essentially the winds are driven by uneven heating of the Earth's surface by the Sun. This differential heating can be due to many causes including geographical factors and the presence of cloud. However, where the land or the sea heat up, the air just above them rises and creates an area of low pressure. Conversely, where the air is falling a high-pressure zone is set up. The air moves from the high- to the low-pressure area and this is what we call a wind. There is a further interaction of the wind velocity with the rotation of the Earth (through an effect known as the Coriolis force). This leads to rotation of the air masses such that air circulates clockwise around a high-pressure region in the northern hemisphere but anti-clockwise around a high-pressure area in the southern hemisphere.

Nature of science

Modelling convection – using a scientific analogy

Faced with a hot cup of morning coffee and little time to drink it, most of us blow across the liquid surface to cool it more quickly. This causes a more rapid loss of energy than doing nothing and therefore the temperature of the liquid drops more quickly too. This is an example of **forced convection** – when the convection cooling is aided by a draught of air. Doing nothing and allowing the convection currents to set up by themselves is **natural convection**.

Newton stated an empirical law for cooling under conditions of forced convection. He suggested that the rate of change of the temperature of the cooling body $\frac{d\theta}{dt}$ was proportional to the temperature difference between the temperature of the cooling body θ and the temperature of the surroundings θ_s.

In symbols,

$$\frac{d\theta}{dt} \propto (\theta - \theta_s)$$

The key to understanding this equation is to realize that it is about the temperature *difference* between the hot object and its surroundings; we call this the temperature excess. Newton's law of cooling leads to a half-life behaviour in just the same way that radioactive half-life follows from the radioactive equation

$$\frac{dN}{dt} \propto N$$

where N is the number of radioactive atoms in a sample.

Using radioactivity as an analogy, there is a cooling half-life so that the time for the temperature excess over the surroundings to halve is always the same for a particular situation of hot object and surroundings.

This is another analogy that helps us to understand science by linking apparently different phenomena.

Worked examples

1 Explain the role played by convection in the flight of a hot-air balloon.

Solution

The air in the gas canopy is heated from below and as a result its temperature increases. The hot air in the balloon expands and its density decreases below that of the cold air outside the gas envelope. There is therefore an upward force on the balloon. If this exceeds the weight of the balloon (plus basket and occupants) then the balloon will accelerate upwards.

2 Suggest two reasons why covering the liquid surface of a cup of hot chocolate with marshmallows will slow down the loss of energy from the chocolate.

Solution

The marshmallows, having air trapped in them, are poor conductors so they allow only a small flow of energy through them. The upper surface of marshmallow will be at a lower temperature than the lower surface. This reduces the amount of convection occurring at the surface as the convection currents that are set up will not be so strongly driven as the differential densities will not be so great.

Thermal radiation

Basics

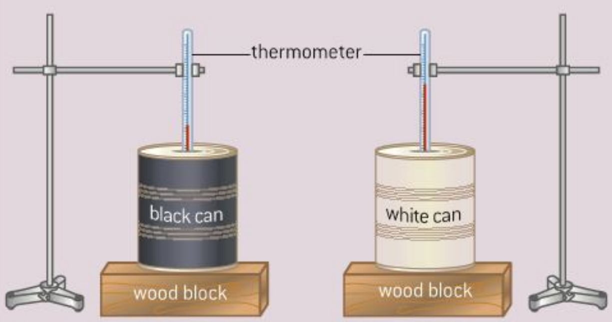
Thermal radiation is the transfer of energy by means of electromagnetic radiation. Electromagnetic radiation is unique as a wave in that it does not need a medium in order to move (propagate). We receive energy from the Sun even though it has passed through about 150 million km of vacuum in order to reach us. Radiation therefore differs from conduction and convection, both of which require a bulk material to carry the energy from place to place.

Thermal radiation has its origins in the thermal motion of particles of matter. All atoms and molecules at a temperature greater than absolute zero are in motion. Atoms contain charged particles and when these charges are accelerated they emit photons. It is these photons that are the thermal radiation.

Investigate!

Black and white surfaces

- Take two identical tin cans and cut out a lid for each one from polystyrene. Have a hole in each lid for a thermometer. Paint one can completely with matt black paint, paint the other shiny white.



▲ Figure 6 Comparing emission of radiation from two surfaces.

- Fill both cans with the same volume of hot water at the same temperature, replace the lids and place the thermometers in the water.

  Keep the cans apart so that radiation from one is not incident on the other.
- Collect data to enable you to plot a graph to show how the temperature of the water in each can varies with time. This is called a cooling curve.
- You could also consider doing the experiment in reverse, beginning with cold water and using a radiant heater to provide energy for the cans. In this case, you must make sure that the heater is the same distance from the surface of each can and that the shiny can is unable to reflect radiation to the black one.

Experiments such as the one in *Investigate!* suggest that black surfaces are very good at radiating and absorbing energy. The opposite is true for white or shiny surfaces; they reflect energy rather than absorb it and are poor at radiating energy. This is why dispensers of hot drinks are often shiny – it helps them to retain the energy.

Nature of science

Radiator or not?

In many parts of the world, houses need to be heated during part or all of the year. One way to achieve this is to circulate hot water from a boiler through a thin hollow panel often known as a "radiator". But is this the appropriate term?

The outside metal surface of the panel becomes hot because energy is conducted from the hot water through the metal.

The air near the surface of the panel becomes hotter and less dense; it rises, setting up a convection current in the room.

There is some thermal radiation from the surface but as its temperature is not very different from that of the room, the net radiation is quite low – certainly lower than the contributions from convection.

Should the radiator be called a radiator?

Making a saucepan

We all need pans to cook our food. What is the best strategy for designing a saucepan?

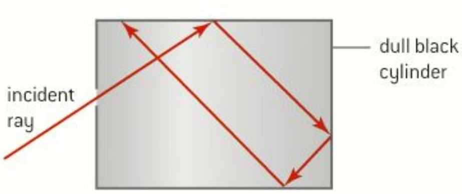
The pan will be placed on a flat hot surface heated either by flame or radiant energy from an electrically heated filament or plate. The energy conducts through the base and heats the contents of the saucepan. The base of the pan needs to be a good conductor to allow a large energy flux into the pan. The walls of the saucepan need to withstand the maximum temperature at which the pan will be used but should not lose energy if possible. Giving them a shiny silver finish helps this.

The handle of the pan needs to be a poor conductor so that the pan can be lifted easily and harmlessly. Don't make it solid, make it strong and easy to hold but as thin as possible (think how electrical resistance varies with the shape and thickness of a conductor).

Conclusion: a good pan will have a thick copper base (a good conductor), sides, and handle of stainless steel (a poor conductor) and the overall finish will be polished and silvery.

Black-body radiation

The simple experiments showed that black surfaces are good radiators and absorbers but poor reflectors of thermal energy. These poor reflectors lead to a concept that is important in the theory of thermal radiation: the **black-body radiator**. A black body is one that absorbs all the wavelengths of electromagnetic radiation that fall on it. Like the ideal gas that we use in gas theory, the black body is an idealization that cannot be realized in practice – although there are objects that are very close approximations to it.

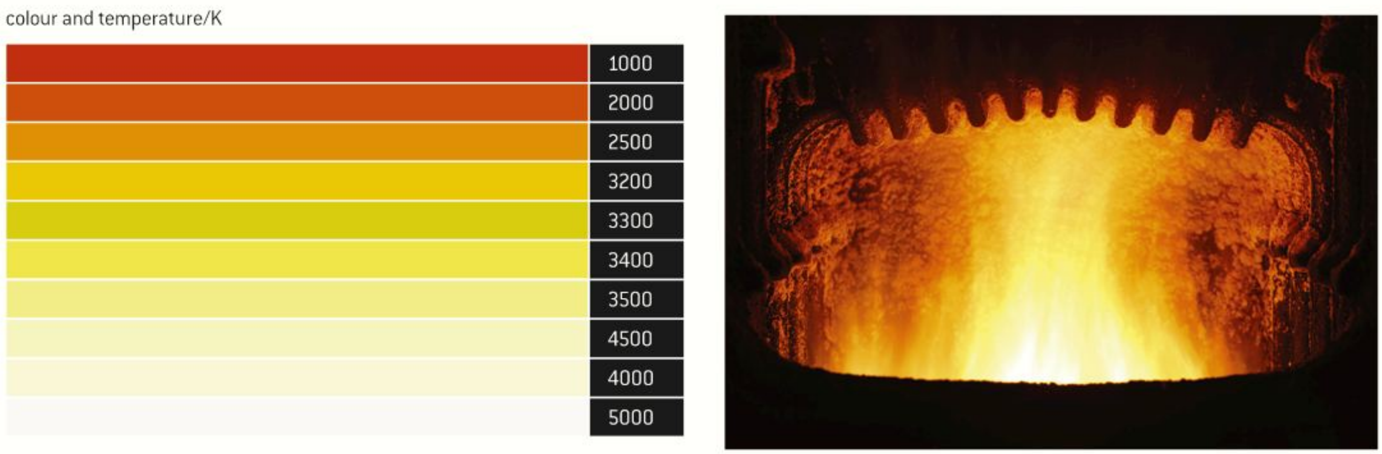


▲ Figure 7 A black-body enclosure.

One way to produce a very good approximation to a black body is to make a small hole in the wall of an enclosed container (a cavity) and to paint the interior of the container matt black. The container viewed through the hole will look very black inside.

Some of the first experiments into the physics of the black body were made by Lummer and Pringsheim in 1899 using a porcelain enclosure made from fired clay. When such enclosures are heated to high temperatures, radiation emerges from the cavity. The radiation appears coloured depending on the temperature of the enclosure. At low temperatures the radiation is in the infra-red region, but as the temperature rises, the colour emitted is first red, then yellow, eventually becoming white if the temperature is high enough. The intensity of the radiation coming from the hole or cavity is higher when the cavity is at a higher temperature. The emission from the hole is not dependent on the material from which the cavity is made unlike the emission from the surface of a container.

This can be seen in the picture of the interior of a steel furnace (see figure 8). In the centre of the furnace at its very hottest point, the colour appears white, at the edges the colour is yellow. At the entrance to the furnace where the temperature is very much lower, the colour is a dull red.



▲ Figure 8 Interior of furnace.

The emission spectrum from a black body

Although there is a predominant colour to the radiation emitted from a black-body radiator, this does not mean that only one wavelength emerges. To study the whole of the radiation that the black body emits, an instrument called a spectrometer is used. It measures the intensity of the radiation at a particular wavelength. Intensity is the power emitted per square metre.

As an equation this is written:

$$I = \frac{P}{A}$$

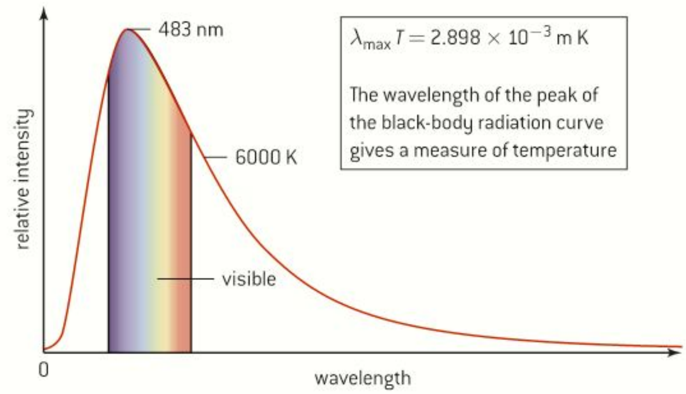
where I is the intensity, P is the power emitted, and A is the area on which the power is incident. The units of intensity are $\mathrm{W\,m^{-2}}$ or $\mathrm{J\,s^{-1}\,m^{-2}}$.

A typical intensity–wavelength graph is shown in figure 9 for a black body at the temperature of the visible surface of the Sun, about 6000 K. The Sun can be considered as a near-perfect black-body radiator. The

Nature of science

The potter's kiln

A potter needs to know the temperature of the inside of a kiln while the clay is being "fired" to transform it into porcelain. Some potters simply look into the kiln through a small hole. They can tell by experience what the temperature is by seeing the radiating colour of the pots inside. Other potters use an instrument called a pyrometer. A tungsten filament is placed at the entrance to the kiln between the kiln interior and the potter's eye. An electric current is supplied to the filament and this is increased until the filament disappears by merging into the background. At this point it is at the same temperature as the interior of the kiln. The filament system will have previously been calibrated so that the current required for the filament to disappear can be equated to the filament temperature.



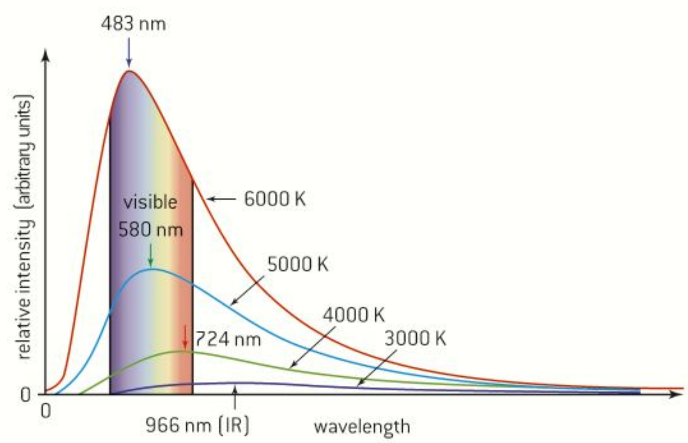
▲ Figure 9 Intensity against wavelength for a black body at the temperature of the Sun.

graph shows how the relative intensity of the radiation varies with the wavelength of the radiation at which the intensity is measured.

There are a number of important features to this graph:

- There is a peak value at about 500 nm (somewhere between green and blue light to our eyes). (Is it a coincidence that the human eye has a maximum sensitivity in this region?)
- There are significant radiations at all visible wavelengths.
- There is a steep rise from zero intensity–notice that the line does not go through the origin.
- At large wavelengths, beyond the peak of the curve, the intensity falls to low levels and approaches zero asymptotically.

Figure 10 shows the graph when curves at other temperatures are added and this gives further perspectives on the emission curves.



▲ Figure 10 Intensity against wavelength for black bodies at four temperatures.

This diagram shows four curves all at different temperatures. As before the units are *arbitrary*, meaning that the graph shows relative and not absolute changes between the curves at the four temperatures.

This family of curves tells us that, as temperature increases:

- the overall intensity at each wavelength increases (because the curve is higher)
- the total power emitted per square metre increases (because the total area under the curve is greater)
- the curves skew towards shorter wavelengths (higher frequencies)
- the peak of the curve moves to shorter wavelengths.

The next step is to focus on the exact changes between these curves.

Wien's displacement law

In 1893 Wilhelm Wien was able to deduce the way in which the shape of the graph depends on temperature. He showed that the height of the curve and the overall width depends on temperature alone. His full law allows predictions about the height of any point on the curve but we will only use it to predict the peak of the intensity curve.

Wien's displacement law states that the wavelength at which the intensity is a maximum λ_{max} in metres is related to the absolute temperature of the black body T by

$$\lambda_{max} = bT$$

where b is known as Wien's displacement constant. It has the value $2.9 \times 10^{-3}\,\mathrm{m\,K}$.

> **Tip**
>
> Notice that the unit for *b* is metre kelvin and must be written with a space between the symbols, take care not to write it as mK which means millikelvin and is something quite different!

Stefan–Boltzmann law

The scientists Stefan and Boltzmann independently derived an equation that predicts the total power radiated from a black body at a particular temperature. The law applies across all the wavelengths that are radiated by the body. Stefan derived the law empirically in 1879 and Boltzmann produced the same law theoretically five years later.

The **Stefan–Boltzmann law** states that the total power P radiated by a black body is given by

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

where A is the total surface area of the black body and T is its absolute temperature. The constant, σ, is known as the Stefan–Boltzmann constant and has the value $5.7 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$.

The law refers to the power radiated by the object, but this is the same as the energy radiated per second. It is easy to show that the energy radiated each second by one square metre of a black body is σT^4. This variant of the full law is known as Stefan's law.

Grey bodies and emissivity

In practice objects can be very close to a black body in behaviour but not quite 100% perfect in the way they behave. They are often called **grey** objects to account for this. A grey object at a particular temperature will emit less energy per second than a perfect black body of the same dimensions at the same temperature. The quantity known as **emissivity**, e, is the measure of the ratio between these two powers:

$$e = \frac{\text{power emitted by a radiating object}}{\text{power emitted by a black body of the same dimensions at the same temperature}}$$

Being a ratio, emissivity has no units.

For a real material, the power emitted can be written as

$$P = e\sigma AT^4$$

using the same symbols as before. A perfect black body has an emissivity value of 1. An object that completely reflects radiation without any absorption at all has an emissivity of 0. All real objects have an emissivity somewhere these two values. Typical values of emissivity for some substances are shown in the table. Emissivity values are a function of the wavelength of the radiation. It is surprising that snow and ice, although apparently white and reflective, are such effective emitters (and absorbers) in the infra-red.

Material	Emissivity
water	0.6–0.7
snow	0.9
ice	0.98
soil	0.4–0.95
coal	0.95

Nature of science

Building a theory

By the end of the 19th century, the graph of radiation intensity emitted by a black body as a function of wavelength was well known. Wien's equation fitted the experiments but only at short wavelengths. Rayleigh attempted to develop a new theory on the basis of classical physics. He suggested that charges oscillating inside the cavity produce standing electromagnetic waves as they bounce backwards and forwards between the cavity walls. Standing waves that escape from the cavity produce the observed black-body spectrum. Rayleigh's model fits the observations at long wavelengths but predicts an "ultraviolet catastrophe" of an infinitely large intensity at short wavelengths. Max Planck varied Rayleigh's theory slightly. He proposed that the standing waves could not carry all *possible* energies but only certain quantities of energy E given by nhf where n is an integer, h is a constant (Planck's constant) and f is the frequency of the allowed energy. Planck's model fitted the experimental results at all wavelengths and thus, in 1900, a new branch of physics was born: *quantum physics*. Planck limited his theory to the space inside the cavity, he believed that the radiation was continuous outside.

Later, Einstein proposed that the photons outside the cavity also had discrete amounts of energy. Planck was the scientific referee for Einstein's paper and it is to Planck's credit that he recognised the value of Einstein's work and accepted the paper for publication even though it overturned some of this own ideas.

Worked examples

1 The Sun has a surface temperature of 5800 K and a radius of 7.0×10^8 m. Calculate the total energy radiated from the Sun in one hour.

Solution

$P = \sigma AT^4$

Surface area of Sun $= 4\pi r^2 = 4 \times 3.14 \times (7\times10^8)^2$

$= 6.2 \times 10^{18}$

So power $= 5.7 \times 10^{-8} \times 6.2 \times 10^{18} \times 5800^4$

$= 4.0 \times 10^{26}$ W

In one hour there are 3600 s, so the energy radiated in one hour is 1.4×10^{30} J.

2 A metal filament used as a pyrometer in a kiln has a length of 0.050 m and a radius of 1.2×10^{-3} m. Determine the temperature of the filament at which it radiates a power of 48 W.

Solution

The surface area of the filament is $2\pi rh = (2\pi \times 1.2 \times 10^{-3}) \times 0.050 = 3.8 \times 10^{-4}\ \text{m}^2$

So the power determines the temperature as

$$48 = 5.7 \times 10^{-8} \times 3.8 \times 10^{-4} \times T^4$$

$$T = \sqrt[4]{\frac{48}{5.7 \times 10^{-8} \times 3.8 \times 10^{-4}}} = 1200\ \text{K}.$$

3 A spherical black body has an absolute temperature T_1 and surface area A. Its surroundings are kept at a lower temperature T_2.

Determine the net power lost by the body.

Solution

The power emitted by the body is; $\sigma A T_1^4$

the power absorbed from the surroundings is $\sigma A T_2^4$.

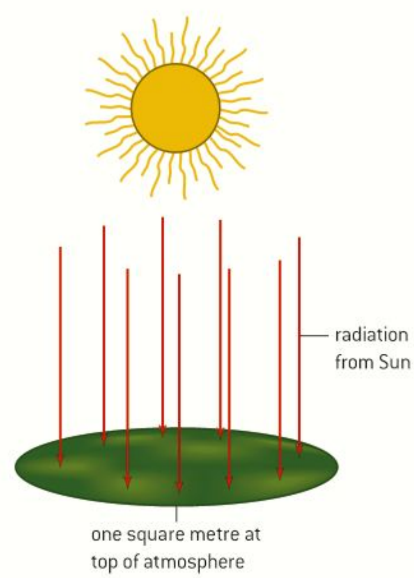
So the net power lost is $\sigma A(T_1^4 - T_2^4)$.

Note that this is not the same as $\sigma A(T_1 - T_2)^4$.

Sun and the solar constant

The Sun emits very large amounts of energy as a result of its nuclear fusion reactions. Because the Earth is small and a long way from the Sun, only a small fraction of this arrives at the top of the Earth's atmosphere. A black body at the temperature of the Sun has just under half of its radiation in our visible region, roughly the same amount in the infra-red, and 10% in the ultraviolet. It is the overall difference between this incoming radiation and the radiation that is subsequently emitted from the Earth that determines the energy gained by the Earth from the Sun. This energy is used by plants in photosynthesis and it drives the changes in the world's oceans and atmospheres; it is crucial to life on this planet.

The amount of energy that arrives at the top of the atmosphere is known as the **solar constant**. A precise definition is that *the solar constant is the amount of solar radiation across all wavelengths that is incident in one second on one square metre at the mean distance of the Earth from the Sun on a plane perpendicular to the line joining the centre of the Sun and the centre of the Earth.*



▲ Figure 11 Defining the solar constant.

The energy from the Sun is spread over an imaginary sphere that has a radius equal to the Earth–Sun distance. The Earth is roughly 1.5×10^{11} m from the Sun and so the surface area of this sphere is $2.8 \times 10^{23}\ \text{m}^2$.

The Sun emits 4×10^{26} J in one second. The energy incident in one second on one square metre at the distance of the Earth from the Sun is $\frac{4.0 \times 10^{26}}{2.8 \times 10^{23}} = 1400$ J. The answer is quoted to 2 s.f., a reasonable precision for this estimate and represents about 5×10^{-10} of the entire output of the Sun.

The value of the solar constant varies periodically for a number of reasons:

- The output of the Sun varies by about 0.1% during its principal 11-year sunspot cycle.
- The Earth's orbit is elliptical with the Earth slightly closer to the Sun in January compared to July; this accounts for a difference of about

7% in the solar constant. (Note that this difference is *not* the reason for summer in the Southern Hemisphere – the seasons occur because the axis of rotation of the Earth is not perpendicular to the plane of its orbit around the Sun.)

- Other longer-period cycles are believed to occur in the Sun with periods ranging from roughly hundreds to thousands of years.

Energy balance in the Earth surface–atmosphere system

The solar constant is the power incident on the top of the atmosphere. It is not the power that arrives at ground level. As the radiation from the Sun enters and travels through the atmosphere, it is subject to losses that reduce the energy arriving at the Earth's surface. Radiation is absorbed and also scattered by the atmosphere. The degree to which this absorption and scattering occurs depends on the position of the Sun in the sky at a particular place. When the Sun is lower in the sky (as at dawn and sunset), its radiation has to pass through a greater thickness of atmosphere and thus more scattering and absorption takes place. This gives rise to the colours in the sky at dawn and dusk.

Even when the energy arrives at ground level, it is not necessarily going to remain there. The surface of the Earth is not a black body and therefore it will reflect some of the energy back up towards the atmosphere. The extent to which a particular surface can reflect energy is known as its **albedo** (from the Latin word for "whiteness"). It is given the symbol a:

$$a = \frac{\text{energy reflected by a given surface in a given time}}{\text{total energy incident on the surface in the same time}}$$

Like emissivity, albedo has no units, it varies from 0 for a surface that does not reflect any energy (a black body) to 1 for a surface that absorbs no radiation at all. Unless stated otherwise, the albedo in the Earth system is normally quoted for visible light (which as we saw earlier accounts for nearly a half of all radiation at the surface).

The average annual albedo for the whole Earth is about 0.35, meaning that on average about 35% of the Sun's rays that reach the ground are reflected back into the atmosphere.

This figure of 0.35 is, however, very much an average because albedo varies depending on a number of factors:

- It varies daily and with the seasons, depending on the amount and type of cloud cover (thin clouds have albedo values of 0.3–0.4, thick cumulo-nimbus cloud can approach values of 0.9).
- It depends on the terrain and the material of the surface. The table gives typical albedo values for some common land and water surfaces.

Surface	Albedo
Ocean	0.06
Fresh snow	0.85
Sea ice	0.60
Ice	0.90
Urban areas	0.15
Desert soils	0.40
Pine forest	0.15
Deciduous forest	0.25

The importance of albedo will be familiar to anyone who lives where snow is common in winter. Fresh snow has a high albedo and reflects most of the radiation that is incident on it – the snow will stay in place for a long time without melting if the temperature remains cold. However, sprinkle some earth or soot on the snow and, when the sun shines, the snow will soon disappear because the dark material on its

surface absorbs energy. The radiation provides the latent heat needed to melt the snow. Albedo effects help to explain why satellites (including the International Space Station) in orbit around the Earth can take pictures of the Earth's cloud cover and surface in the visible spectrum.

Worked examples

1 Four habitats on the Earth are: forest, grassland (savannah), the sea, an ice cap.

Discuss which of these have the greatest and least albedo.

Solution

A material with a high albedo reflects the incident visible radiation. Ice is a good reflector and consequently has a high albedo. On the other hand, the sea is a good absorber and has a low albedo.

2 The data give details of a model of the energy balance of the Earth. Use the data to calculate the albedo of the Earth that is predicted by this model.

Data

Incident intensity from the Sun	= 340 W m^{-2}
Reflected intensity at surface	= 100 W m^{-2}
Radiated intensity from surface	= 240 W m^{-2}
Re-radiated intensity from atmosphere back to surface	= 2 W m^{-2}

Solution

The definition of albedo is clear.

It is $\frac{\text{power reflected by a given surface}}{\text{total power incident on the surface}}$

So in this case the value is $\frac{100}{340} = 0.29$

The greenhouse effect and temperature balance

The Earth and the Moon are the same average distance from the Sun, yet the average temperature of the Moon is 255 K, while that of the Earth is about 290 K. The discrepancy is due to the Earth having an atmosphere while the Moon has none.

The difference is due to a phenomenon known as the **greenhouse effect** in which certain gases in the Earth's atmosphere trap energy within the Earth system and produce a consequent rise in the average temperature of the Earth. The most important gases that cause the effect include carbon dioxide (CO_2), water vapour (H_2O), methane (CH_4), and nitrous oxide (dinitrogen monoxide; N_2O), all of which occur naturally in the atmosphere. Ozone (O_3), which has natural and man-made sources, makes a contribution to the greenhouse effect.

It is important to distinguish between:

- the "natural" greenhouse effect that is due to the naturally occurring levels of the gases responsible, and
- the enhanced greenhouse effect in which increased concentrations of the gases, possibly occurring as a result of human-derived processes, lead to further increases in the Earth's average temperature and therefore to climate change.

The principal gases in the atmosphere are nitrogen, N_2, and oxygen, O_2, (respectively, 70% and 20% by weight). Both of these gases are made up of tightly bound molecules and, because of this, do not absorb energy from sunlight. They make little contribution to the natural greenhouse effect. The 1% of the atmosphere that is made up of the CO_2, H_2O, CH_4 and N_2O has a much greater effect.

The molecular structure of greenhouse-gas molecules means that they absorb ultraviolet and infra-red radiation from the Sun as it travels through the atmosphere. Visible light on the other hand is not so readily absorbed by these gases and passes through the atmosphere to be absorbed by the land and water at the surface. As a result the temperature of the surface rises. The Earth then re-radiates just like any other hot object. The temperature of the Earth's surface is far lower than that of the Sun, so the wavelengths radiated from the Earth will peak in the long-wavelength infra-red. The absorbed radiation had, of course, mostly been in the visible region of the electromagnetic spectrum. So, just as gases in the atmosphere absorbed the Sun's infra-red on the way in, now they absorb energy in the infra-red from the Earth on the way out. The atmosphere then re-radiates the energy yet again, this time in all directions meaning that some returns to Earth. This energy has been trapped in the system that consists of the surface of the Earth and the atmosphere.

The whole system is a dynamic equilibrium reaching a state where the total energy incident on the system from the Sun equals the energy total being radiated away by the Earth. In order to reach this state, the temperature of the Earth has to rise and, as it does so, the amount of energy it radiates must also rise by the Stefan–Boltzmann law. Eventually, the Earth's temperature will be such that the balance of incoming and outgoing energies is attained. Of course, this balance was established over billions of years and was steadily changing as the composition of the atmosphere and the albedo changed with changes in vegetation, continental drift, and geological processes.

Nature of science

Other worlds, other atmospheres

The dynamic equilibrium in our climate has been very important for the evolution of life on Earth. Venus and Mars evolved very differently from Earth.

Venus has similar dimensions to the Earth but is closer to the Sun with a very high albedo at about 0.76. It's atmosphere is almost entirely carbon dioxide. In consequence, the surface temperature reaches a 730 K and a runaway greenhouse effect acts. Venus and Mars are clear reminders to us of the fragility of a planetary climate.

Why greenhouse gases absorb energy

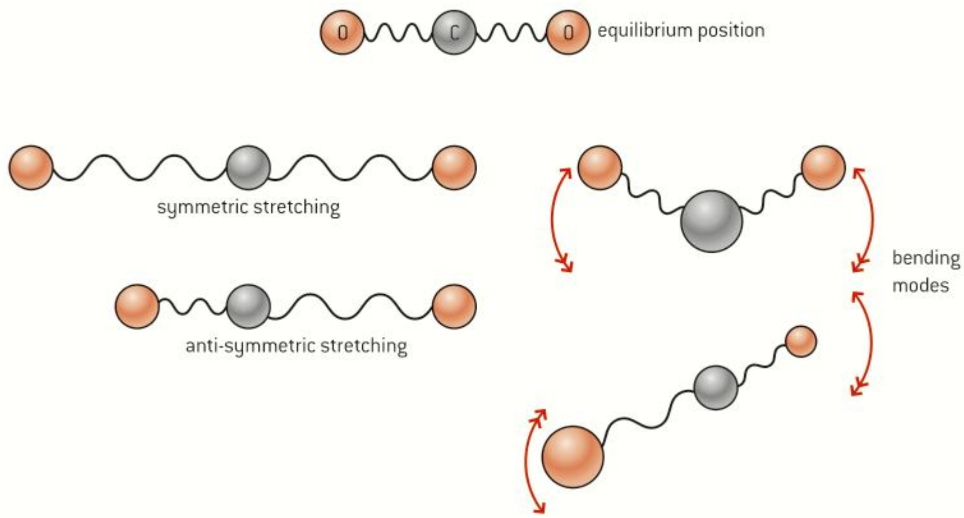
Ultraviolet and long-wavelength infra-red radiations are absorbed by the atmosphere.

Photons in the ultraviolet region of the electromagnetic spectrum are energetic and have enough energy to break the bonds within the gas molecules. This leads to the production of ionic materials in the atmosphere. A good example is the reaction that leads to the production of ozone from the oxygen atoms formed when oxygen molecules are split apart by ultraviolet photons.

The energies of infra-red photons are much smaller than those of ultraviolet and are not sufficient to break molecules apart. When the frequency of a photon matches a vibrational state in a greenhouse gas molecule then an effect called **resonance** occurs. We will look in detail at the vibrational states and resonance in carbon dioxide, but similar effects occur in all the greenhouse gas molecules.

In a carbon dioxide molecule, the oxygen atoms at each end are attached by double bonds to the carbon in a linear arrangement. The bonds resemble springs in their behaviour.

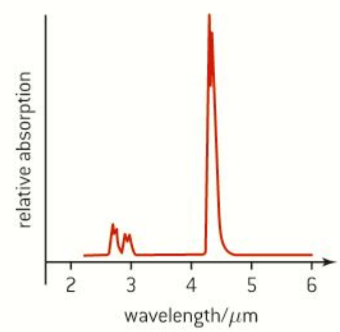
The molecule has four vibrational modes as shown in figure 12. The first of these modes – a linear symmetric stretching does not cause infrared absorption, but the remaining three motions do. Each one has



▲ Figure 12 Vibrational states in the carbon dioxide molecule.

a characteristic frequency. If the frequency of the radiation matches this, then the molecule will be stimulated into vibrating with the appropriate mode and the energy of the vibration will come from the incident radiation. This leads to vibrational absorption at wavelengths of 2.7 μm, 4.3 μm and 15 μm.

These effects of these absorptions can be clearly seen in figure 13 which shows part of the absorption spectrum of carbon dioxide. In this diagram a peak indicates a wavelength at which significant absorption occurs.



▲ Figure 13 Part of the absorption spectrum for carbon dioxide.

Modelling the climate balance

We said earlier that about 1400 J falls on each square metre of the upper atmosphere each second: the solar constant. We use the physics introduced in this topic to see what the consequences of this are for the Earth's surface–atmospheric system.

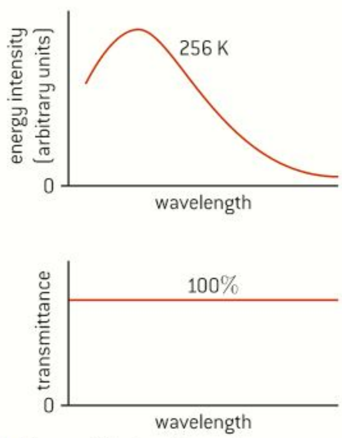
The full 1400 J does not of course reach the surface. Of the total, about 25% of the incident energy is reflected by the clouds and by particles in the atmosphere, about 25% is absorbed by the atmosphere, and about 6% is reflected at the surface.

The incoming radiation falls on the portion of the Earth's surface which is normal to the Sun's radiation – i.e. a circle of area equal to $\pi \times$ (*radius of Earth*)^2, as only one side of the Earth faces the Sun at any one time. However this radiation has to be averaged over the whole of the surface which is $4\pi \times$ (*radius of Earth*)^2. So the mean power arriving at each square metre is $\frac{1400}{4} = 350$ W.

The albedo now has to be taken into account to give an effective mean power at one square metre of the surface of

$$(1 - a) \times 350$$

For the average Earth value for a of about 0.3, the mean power absorbed by the surface per square metre is 245 W.



▲ Figure 14 Intensity and transmittance for a completely transparent atmosphere.

The knowledge of this emitted power allows a prediction of the temperature of a black body T that will emit 245 W m^{-2}. Using the Stefan–Boltzmann law:

$$245 = \sigma T^4$$

$$\text{So } T = \sqrt[4]{\frac{245}{5.67 \times 10^{-8}}} = 256\text{ K}$$

This is very close to the value for the Moon, which has no atmosphere. We need to investigate why the mean temperature of the Earth is about 35 K higher than this.

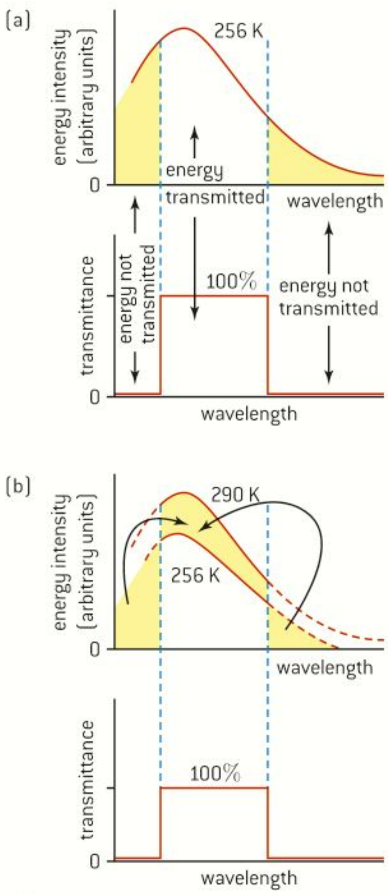
We made the assumption that the Earth emits 245 W m^{-2} and that this energy leaves the surface and the atmosphere completely. This would be true for an atmosphere that is completely transparent at all wavelengths, but Earth's atmosphere is not transparent in this way.

Figure 14 shows the relative intensity–wavelength graph for a black body at 256 K. As expected, the area under this curve is 245 W m^{-2} and represents the predicted emission from the Earth. It shows the response of an atmosphere modelled as perfectly transparent at all wavelengths. (Technically, this graph shows the transmittance of the atmosphere as a function of wavelength, a value of 100% means that the particular wavelength is completely transmitted, 0 means that no energy is transmitted at this wavelength.) Not surprisingly all the black-body radiation leaves the Earth because the transmittance is 1 for all wavelengths in this model.

In fact the atmosphere absorbs energy in the infra-red and ultraviolet regions. A simple, but slightly more realistic model for this absorption will leave the transmittance at 100% for the visible wavelengths and change the transmittance to 0 for the absorbed wavelengths. Figure 15 shows how this leads to an increased surface temperature.

When the transmittance graph is merged with the graph for black-body radiation to give the overall emission from the Earth into space, the area under the overall emission curve will be less than 245 W m^{-2} because the infra-red and ultraviolet wavelengths are now absorbed in the atmosphere and these energies are not lost (Figure 15(a)). This deficit will be re-radiated in all directions; so some returns to the surface.

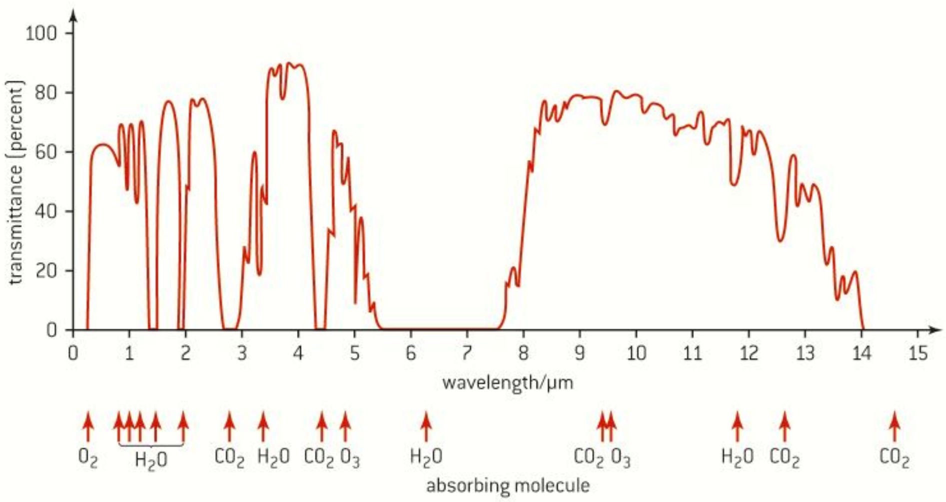
In order to get the energy balance correct again, the temperature of the emission curve must be raised so that the area under the curve returns to 245 W m^{-2}. As the curve changes with the increase in temperature, the area under the curve increases too. The calculation of the temperature change required is difficult and not given here. However, for the emission from the surface to equal the incoming energy from the Sun, allowing for the absorption, the surface temperature must rise to about 290 K. The net effect is shown in Figure 15(b) with a shifted and raised emission curve compensating for the energy that cannot be transmitted through the atmosphere.



▲ Figure 15 Intensity and transmittance for an atmosphere opaque to infra-red and ultraviolet radiation.

The suggestion that the atmosphere completely removes wavelengths above and below certain wavelengths is an over-simplification.

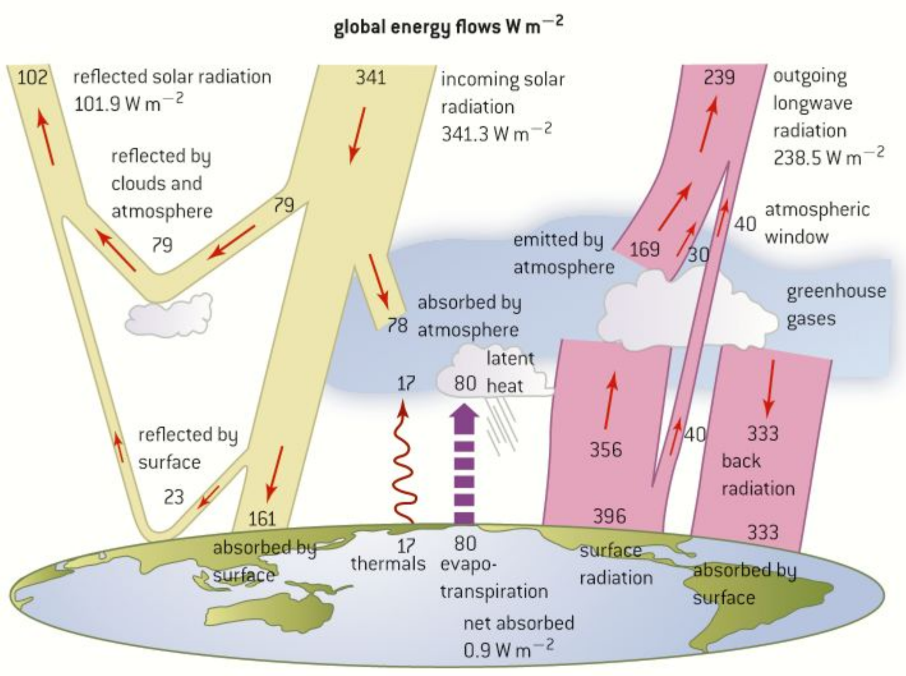
Figure 16 shows the complicated transmittance pattern in the infrared and indicates which absorbing molecules are responsible for which regions of absorption.



▲ Figure 16 Transmittance of the atmosphere in the infra-red.

The energy balance of the Earth

The surface–atmosphere energy balance system is very complex; figure 17 is a recent diagram showing the basic interactions and you should study it carefully.



▲ Figure 17 Factors that make up the energy balance of the Earth (after Stephens and others. 2012. ***An update on earth's energy balance in light of the latest global observations***. Nature Geoscience.).

Global warming

There is little doubt that climate change is occurring on the planet. We are seeing a significant warming that may lead to many changes to the sea level and in the climate in many parts of the world. The fact that there is change should not surprise us. We have recently (in geological terms) been through several Ice Ages and we are thought to be in an interstadial phase at the moment (interstadial means "between Ice Ages"). In the seventeenth century a "Little Ice Age" covered much of northern Europe and North America. The River Thames regularly froze and the citizens held fairs on the ice. In 1608, the Dutch painter Hendrick Avercamp painted a winter landscape showing the typical extent and thickness of the ice in Holland (figure 18).

▲ Figure 18 Winter landscape with skaters (1608), Hendrick Avercamp.

Many models have been suggested to explain global warming, they include:

- changes in the composition of the atmosphere (and specifically the greenhouse gases) leading to an enhanced greenhouse effect
- increased solar flare activity
- cyclic changes in the Earth's orbit
- volcanic activity.

Most scientists now accept that this warming is due to the burning of fossil fuels, which has gone on at increasing levels since the industrial revolution in the eighteenth century. There is evidence for this. The table below shows some of the changes in the principal greenhouse gases over the past 250 years.

Gas	Pre-1750 concentration	Recent concentration	% increase since 1750
Carbon dioxide	280 ppm	390 ppm	40
Methane	700 ppb	1800 ppb	160
Nitrous oxide	270 ppb	320 ppb	20
Ozone	25 ppb	34 ppb	40

ppm = parts per million; ppb = parts per billion

The recent values in this table have been collected directly in a number of parts of the world (there is a well-respected long-term study of the variation of carbon dioxide in Hawaii where recently the carbon dioxide levels exceeded 400 ppm for the first time for many thousands of years). The values quoted for pre-1750 are determined from a number of sources:

- Analysis of Antarctic ice cores. Cores are extracted from the ice in the Antarctic and these yield data for the composition of the atmosphere during the era when the snow originally fell on the continent. Cores can give data for times up to 400 000 years ago.
- Analysis of tree rings. Tree rings yield data for the temperature and length of the seasons and the rainfall going back sometimes hundreds of years.
- Analysis of water levels in sedimentary records from lake beds can be used to identify historical changes in water levels.

An enhanced greenhouse effect results from changes to the concentration of the greenhouse gases: as the amounts of these gases increase, more absorption occurs both when energy enters the system and also when the surface re-radiates. For example, in the transmittance–wavelength graph for a particular gas, when the concentration of the gas rises, the absorption peaks will increase too. The surface will need to increase its temperature in order to emit sufficient energy at sea level so that emission of energy by Earth from the top of the atmosphere will equal the incoming energy from the Sun.

Global warming is likely to lead to other mechanisms that will themselves make global warming increase at a greater rate:

- the ice and snow cover at the poles will melt, this will decrease the average albedo of Earth and increase the rate at which heat is absorbed by the surface.
- a higher water temperature in the oceans will reduce the extent to which CO_2 is dissolved in seawater leading to a further increase in atmospheric concentration of the gas.

Other human-related mechanisms such as deforestation can also drive global warming as the amount of carbon fixed in the plants is reduced.

This is a problem that has to be addressed at both an international and an individual level. The world needs greater efficiency in power production and a major review of fuel usage. We should encourage the use of non-fossil-fuel methods. As individuals we need to be aware of our personal impact on the planet, we should be conscious of our carbon footprint. Nations can capture and store carbon dioxide, and agree to increase the use of combined heating and power systems. What everyone agrees is that doing nothing is not an option.

Nature of science

An international perspective

There have been a number of international attempts to reach agreements over the ways forward for the planet. These have included:

- The Kyoto Protocol was originally adopted by many (but not all) countries in 1997 and later extended in 2012.
- The Intergovernmental Panel on Climate Change.
- Asia–Pacific Partnership on Clean Development and Climate.
- The various other United Nations Conventions on Climate Change, e.g. Cancùn, 2010.

Do some research on the Internet to find what is presently agreed between governments.

Questions

1 *(IB)*

a) A reactor produces 24 MW of power. The efficiency of the reactor is 32%. In the fission of one uranium-235 nucleus 3.2×10^{-11} J of energy is released.

Determine the mass of uranium-235 that undergoes fission in one year in this reactor.

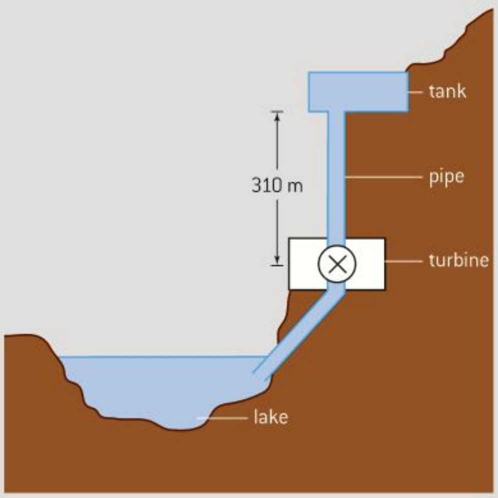
b) During its normal operation, the following set of reactions takes place in the reactor.

$$^{1}_{0}n + ^{238}_{92}U \rightarrow ^{239}_{92}U$$
$$^{239}_{92}U \rightarrow ^{239}_{93}Np + ^{0}_{-1}e + \overline{\nu}$$
$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e + \overline{\nu}$$

Comment on the international implications of the product of these reactions.

2 *(IB)*

The diagram shows a pumped storage power station used for the generation of electrical energy.



Water stored in the tank falls through a pipe to a lake through a turbine that is connected to an electricity generator.

The tank is 50 m deep and has a uniform area of 5.0×10^4 m^2. The height from the bottom of the tank to the turbine is 310 m.

The density of water is 1.0×10^3 kg m^{-3}.

a) Show that the maximum energy that can be delivered to the turbine by the falling water is about 8×10^{12} J.

b) The flow rate of water in the pipe is 400 m^3 s^{-1}. Calculate the power delivered by the falling water.

3 *(IB)*

The energy losses in a pumped storage power station are shown in the following table.

Source of energy loss	Percentage loss of energy
friction and turbulence of water in pipe	27
friction in turbine and ac generator	15
electrical heating losses	5

a) Calculate the overall efficiency of the conversion of the gravitational potential energy of water in the tank into electrical energy.

b) Sketch a Sankey diagram to represent the energy conversion in the power station.

4 *(IB)*

A nuclear power station uses uranium-235 (U-235) as fuel.

a) Outline:

(i) the processes and energy changes that occur through which the internal energy of the working fluid is increased

(ii) the role of the heat exchanger of the reactor and the turbine in the generation of electrical energy.

b) Identify **one** process in the power station where energy is degraded.

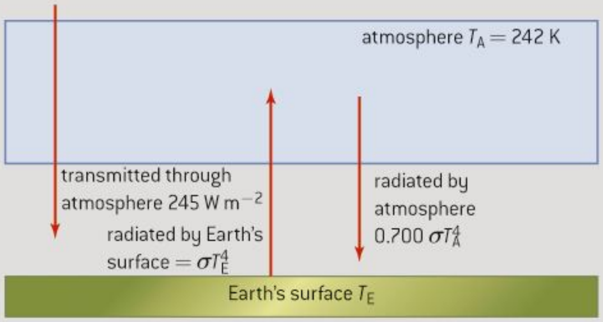
5 *(IB)*

The intensity of the Sun's radiation at the position of the Earth is approximately 1400 W m^{-2}.

Suggest why the average power received per unit area of the Earth is 350 W m^{-2}.

6 *(IB)*

The diagram shows a radiation entering or leaving the Earth's surface for a simplified model of the energy balance at the Earth's surface.



a) State the emissivity of the atmosphere.

b) Determine the intensity of the radiation radiated by the atmosphere towards the Earth's surface.

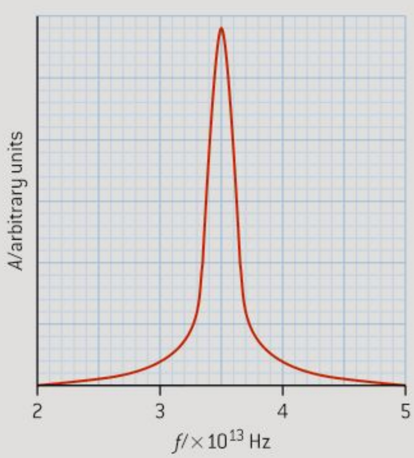
c) Calculate T_E.

7 a) Outline a mechanism by which part of the radiation radiated by the Earth's surface is absorbed by greenhouse gases in the atmosphere. Go on to suggest why the incoming solar radiation is not affected by the mechanism you outlined.

b) Carbon dioxide (CO_2) is a greenhouse gas. State **one** source and **one** sink (that removes CO_2) of this gas.

8 *(IB)*

The graph shows part of the absorption spectrum of nitrogen oxide (N_2O) in which the intensity of absorbed radiation A is plotted against frequency f.

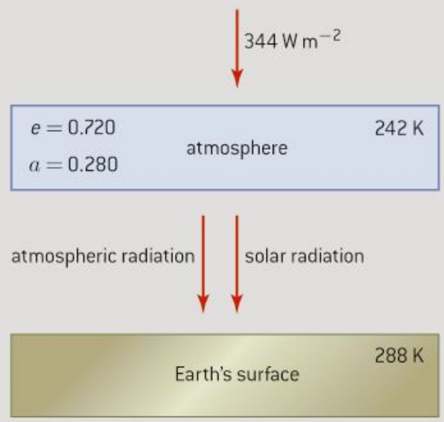


a) State the region of the electromagnetic spectrum to which the resonant frequency of nitrogen oxide belongs.

b) Using your answer to (a), explain why nitrogen oxide is classified as a greenhouse gas.

9 *(IB)*

The diagram shows a simple energy balance climate model in which the atmosphere and the surface of Earth are treated as two bodies each at constant temperature. The surface of the Earth receives both solar radiation and radiation emitted from the atmosphere. Assume that the Earth's surface and the atmosphere behave as black bodies.



Data for this model:

average temperature of the atmosphere of Earth = 242 K

emissivity e of the atmosphere of Earth = 0.720

average albedo a of the atmosphere of Earth = 0.280

solar intensity at top of atmosphere = 344 W m^{-2}

average temperature of the surface of Earth = 288 K

a) Use the data to determine:

(i) the power radiated per unit area of the atmosphere

(ii) the solar power absorbed per unit area at the surface of the Earth.

b) It is suggested that, if the production of greenhouse gases were to stay at its present level, then the temperature of the Earth's atmosphere would eventually rise by 6 K.

Calculate the power per unit area that would then be

(i) radiated by the atmosphere

(ii) absorbed by the Earth's surface.

c) Estimate the increase in temperature of the Earth's surface.

10 *(IB)*

It has been estimated that doubling the amount of carbon dioxide in the Earth's atmosphere changes the albedo of the Earth by 0.01. Estimate the change in the intensity being reflected by the Earth into space that will result from this doubling. State why your answer is an estimate.

Average intensity received at Earth from the Sun = $340\,\mathrm{W\,m^{-2}}$
Average albedo = 0.30