9 Solar radiation and the greenhouse effect

Radiation from the Sun is called **solar radiation**. This chapter considers how its energy is trapped by the Earth's atmosphere, and how certain human activities are adding to this effect. Before starting any of the sections in this chapter it would be useful to:

- know that the combustion of fossil fuels releases carbon dioxide into the atmosphere
- know that our demands for energy are projected to increase, leading to increased carbon dioxide production
- explain how conduction, convection, and radiation transfer thermal energy
- understand that there is evidence of a link between atmospheric carbon dioxide concentrations and global temperatures
- appreciate how scientists use data to support their arguments, but remember that there may be different possible interpretations of the same set of data.

Tim Kirk
Neil Hodgson:
"Physics
– Course Companion"
IB Diploma prog.
Oxford Uni. Press.
2007

The greenhouse effect

Some of the gases in the atmosphere (notably water vapour, carbon dioxide, and methane) effectively form an insulating blanket around the Earth. Without this, the Earth would be a rather cold and miserable place, with an average temperature of about −20 °C. The extra warming is called the **greenhouse effect**, because greenhouses also trap the Sun's heat. The gases that cause it are called **greenhouse gases**.

The greenhouse effect is necessary for life on Earth. It keeps global temperatures high enough for biodiversity to flourish. However there is evidence to suggest that human activity, mainly burning fossil fuels for energy production, has put significant amounts of extra carbon dioxide into the atmosphere over the last century or so. At present global temperatures are rising and there are predictions that this may cause dramatic climate changes and rising sea levels. Most (but not all) climate scientists believe that this **global warming** is being caused by the human, or **anthropogenic**, addition of greenhouse gases to the atmosphere. They call it the **enhanced greenhouse effect**.

Greenhouses

These buildings, made of glass or clear plastic, are used in many parts of the world to grow plants and food crops where the outside temperature is too low. For example, mangoes, a tropical fruit, can be grown successfully in Japan inside greenhouses.

So how does a greenhouse work? A common explanation suggests that the glass allows shorter wavelength radiation from the Sun to pass through to heat the ground, but reflects back the longer wavelength infrared from the warmed ground. However, if polythene is used for a greenhouse, it performs just as well as glass, even though it is almost as transparent to longer wavelengths as it is to shorter ones. A more likely explanation is that the temperature increase occurs because the warmed air inside a greenhouse is trapped and cannot rise and flow away. In other words, convection is prevented.

The atmospheric greenhouse effect does not work like a greenhouse. So a different model is needed. By the end of this chapter, you should be able to explain the greenhouse effect using the correct physics.

1 Briefly outline how thermal energy is transferred by conduction, convection, and radiation.
2 State which of the three mechanisms is normally responsible for transferring thermal energy from soil, plants, etc.
(i) to the air, and
(ii) within the air.
3 A small 50 W electrical immersion heater is used to heat some water for 10 minutes (specific heat capacity of water = 4200 J kg^{-1} K^{-1}). Calculate the temperature rise in
(i) 250 cm^3 of water (a beaker), and in
(ii) 3.75×10^5 cm^3 (a bath). You may assume that the mass of 1 cm^3 of water = 1 g.
4 Use the ideas in question 3 to suggest why a greenhouse is warmer inside than outside. To do this it might be useful to consider two identical sets of tropical plants and soil, one set inside a greenhouse and the other outside.

Black body radiation

The concept of a black body is covered in detail on pages 208–9. Stars are considered to be black bodies, but many cooler objects also approximate to black body radiators. The Earth is not a perfect black body, and this must be considered when developing a climate model to explain its observed average temperature.

Figure 1 shows some features of the radiation emitted by a black body. All wavelengths are radiated, but at different intensities, depending on the surface temperature of the object. The wavelength of the peak radiation is given by the **Wien displacement law**:

$$\lambda_{max} T = \text{constant}$$

The constant has a value of 2.90×10^{-3} m K.

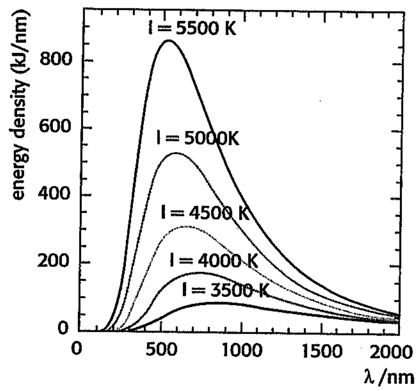

Figure 1 Black body radiation spectrum for a range of temperatures

By analysing the radiation curve of a hot, distant object, such as a star, its surface temperature can be estimated using the equation $\lambda_{max} T$ = constant. Doing the calculation for the Sun, for example, gives a surface temperature of just under 6000 K (see question 2 on next page.)

1 Use the graph in Figure 1 to find the wavelength of peak radiation for
(i) T = 5500 K
(ii) T = 3500 K.
2 Calculate the peak wavelength radiated by the Sun assuming the surface temperature is 5800 K. State which part of the electromagnetic spectrum this is found in.
3 Compare the curve for 3500 K, shown in Figure 1, with a curve for 280 K, which is similar to the Earth's mean temperature. State how the maximum energy density and peak wavelength positions differ.
4 Suggest a meaning for the physical quantity represented by the area under the black body curve.

It is very difficult to determine the Earth's mean temperature, averaged over one year. Temperatures vary significantly at different latitudes and altitudes, and from season to season. For the next question assume a value of 15 °C.

5 Write down the Earth's average temperature in kelvin (K) and calculate the peak wavelength radiated, assuming black body behaviour. In which part of the electromagnetic spectrum is this?

Solar radiation

To investigate this more closely, one needs to start with some definitions:

Power is the rate at which energy is transferred. A power of one watt (1 W) means a rate of energy transfer of one joule per second (1 J s^{-1}).

The **solar constant**, S, is the average solar power per m^2 arriving at the top of the Earth's atmosphere. Its value is 1.37 kW m^{-2}. In other words, 1.37 kilojoules of solar energy reach each square metre of the top of the Earth's atmosphere every second.

The Sun's **luminosity** is the *total* power radiated by the Sun. Although it fluctuates very slightly, the solar constant is normally assumed to be reasonably stable at 1.37 kW m^{-2}. A knowledge of the solar constant enables one to estimate the luminosity of the Sun and hence its surface temperature.

The Sun is approximately 149×10^6 km from the Earth. Astrophysicists call this distance one **astronomical unit** (1 AU). At the distance of the Earth, all the power emitted by the Sun is spread out over a sphere of radius 1 AU.

The solar power flux at the Earth's surface is significantly less than the solar constant.

There is a significant amount of absorption and reflection by the atmosphere. Also, the actual value of the solar power flux in any one region varies depending on the latitude, the season, and the time of day (at night it is, of course, zero). Typically, the average solar power flux at the Earth's surface at mid-European latitudes ≈ 150 W m^{-2}.

Compare your value with this estimate and list some reasons why your value is different. Consider how you might improve the experiment to get a more accurate result. If time allows, redesign your experiment and try again.

?

1 Use the value of the solar constant S, given above, to calculate the Sun's luminosity.

To estimate the temperature at the Sun's surface, you first need to estimate the Sun's surface area.

2 The angular diameter of the Sun measured from the Earth is 0.52°. Calculate
   (i) the angular diameter in radians,
   (ii) the Sun's radius in metres,
   (iii) the surface area of the Sun, assuming that it is a sphere.

The **Stefan-Boltzmann** law gives the relationship between the luminosity L of a star, the surface area A, and the surface temperature T:

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

where σ is the **Stefan-Boltzmann constant**: 5.67×10^{-8} W m^{-2} K^{-4}

3 Calculate the total power and the power per m^2 radiated by the Earth at a temperature of 228 K. You can assume the Earth is a sphere of radius 6400 km.

Mathematical physics: a simple energy balance model

If the Earth is at thermal equilibrium, this means that it is emitting energy at the same rate as it is absorbing it. So:

power radiated by the Earth = power received from the Sun

Assuming that the Earth is equivalent to a disc of radius r, normal to the incoming solar radiation:

total incoming power = $S \times \pi r^2$
(S is the solar constant)

Some of this radiation is reflected straight back into space. This fraction is called the **albedo**, α.

So: total power absorbed by the Earth = $S(1 - \alpha)\pi r^2$ (1)

The next stage is to calculate the power radiated by the Earth, assuming that this is emitted over a sphere of area $4\pi r^2$, and that this behaves as a black body radiator. For this, we apply the Stefan-Boltzmann law for an object at temperature T:

So: power radiated by the Earth = $\sigma \times 4\pi r^2 \times T^4$ (2)

So: $4\sigma\pi r^2 T^4 = S(1 - \alpha)\pi r^2$ (3)

So:

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

Using S = 1370 W m^{-2}, α = 0.3, and $\sigma = 5.67 \times 10^{-8}$ Wb m^{-2} K^{-4} gives

$$T = \sqrt[4]{\frac{1370 \times (1-0.3)}{4 \times 5.67 \times 10^{-8}}}$$

So: T = 255 K

This simple analysis predicts the temperature of the Earth to be lower than it actually is. So the model needs to be modified. The atmosphere (and the greenhouse gases in it) have an important role in keeping the planet at the much more acceptable global annual mean temperature of ≈288 K.

The Earth with its atmosphere is not a perfect black body. **Emissivity**, ε, is defined as the ratio of power radiated by an object to the power radiated by a black body at the same temperature. Allowing for this modifies equation 2 to this:

power radiated by the Earth = $4\varepsilon\sigma\pi r^2 T^4$

You should be able to show that the Earth's temperature will be given by:

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

1. Calculate the emissivity of the Earth assuming the mean temperature is 288 K.
2. Assuming that the Earth is a perfect black body, radiating at 288 K, calculate the power flux radiated.
3. Compare your answer to the previous question with the lower flux value radiated for a black body at 255 K.

Modelling energy absorption

In this section, the aim is to develop a model to explain how the atmosphere helps to keep the Earth warm. Before studying this section, make sure that you have read Chapter 7, dealing with the mathematical models used for simple harmonic oscillations.

Certain molecules in the atmosphere absorb particular wavelengths radiated by the Earth and the Sun. However, the Earth is significantly cooler than the Sun, so its black body radiation spectrum is shifted to regions of longer wavelength compared to that of the incoming solar radiation. Because of the shift in peak wavelength, molecules in the atmosphere absorb more of the outgoing (terrestrial) radiation than they do incoming (solar) radiation.

Several gases in the atmosphere absorb energy in these wavelengths but the most important ones are water vapour, carbon dioxide, and methane. All occur naturally, although human activities have significantly increased the concentrations of the first two.

To see how energy is absorbed, carbon dioxide will be used as an example (Figure 2).

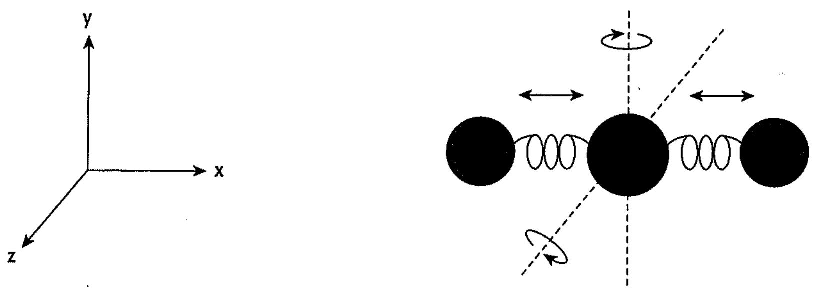

Figure 2 Carbon dioxide molecule and possible modes of translation, vibration, and rotation

Inquiry: temperatures throughout the Solar System

The surface temperature of a planet depend on several factors, including:

- the distance from the Sun
- the composition of the atmosphere
- the albedo (the proportion of incoming solar energy reflected back into space)
- the emissivity.

Choose a planet or moon in the Solar System and carry out some research to find out about the temperature range you would expect to find there. Present your findings to your group in a suitable way.

You should include the following:

- An estimate of the average solar power flux for your chosen planet or moon. Show how you calculated this.
- Details of the atmosphere, including its composition.

A good approach would be to research the key data for your object then use a spreadsheet or graphical calculator to develop your model.

Carbon dioxide has a linear molecule with a shape as shown in Figure 2. Each oxygen atom (purple) is joined to the carbon atom (black) by a double bond. Essentially, this bond is formed by clouds of electrons: see the chemistry course companion for further details. In the model in Figure 2, it is convenient to think of the bonds as a spring. When this spring is stretched or compressed, forces try to return the atoms to their equilibrium position.

The above molecule has kinetic energy which may be considered in separate modes:

(i) three linear modes due to movements in the *x*, *y*, and *z* directions;

(ii) two rotational modes due to rotation around the two dotted axes illustrated;

(iii) four vibrational modes (Figure 3), each one excited by a different wavelength.

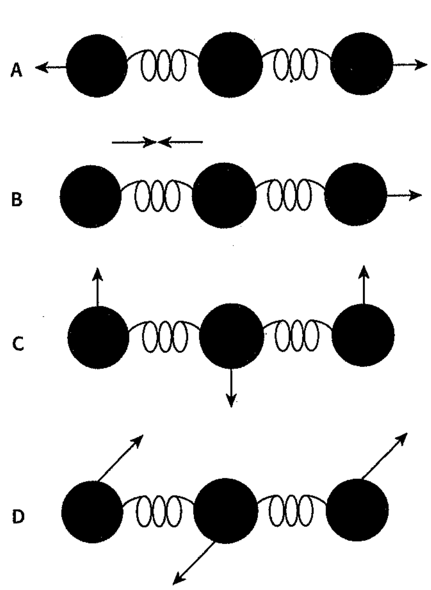

Figure 3 The four vibrational modes of carbon dioxide

1 Describe carefully the movement of each atom in the four modes of vibration shown in Figure 3.

In a linear molecule such as carbon dioxide, the number of vibrational modes is given by $3N - 5$, where N is the number of atoms in the molecule. In a non-linear molecule such as water or methane, the number of modes is given by $3N - 6$.

2 Calculate the number of vibrational modes in
 (i) a water molecule (non-linear)
 (ii) a methane molecule (also non-linear).

3 Draw a simple diagram to illustrate these modes in a water molecule.

From Chapter 7, you will know that the frequency of vibration of a spring is given by this equation:

$$f=\frac{1}{2\pi}\sqrt{\frac{k}{m}}$$ where k is the spring constant.

4 Compare modes A and C in Figure 3. Explain whether it is the stretching mode or the bending mode that
 (i) requires more energy
 (ii) has a higher frequency. (Hint: compare the value of k in each case.)

The rotational and vibrational modes have a **natural frequency** which corresponds to some of the wavelengths radiated by the Earth, particularly those in the infrared part of the spectrum. The carbon dioxide molecules absorb energy from precise wavelengths, and the oscillatory modes are excited. This is an example of **resonance** (see page 76). The internal energy of the molecules increases and they re-radiate this energy in random directions: this is called **scattering**. The net flux of outward energy is therefore reduced, as some of this scattered energy is re-absorbed by the Earth. In this way, the planet warms up until a new equilibrium temperature is reached.

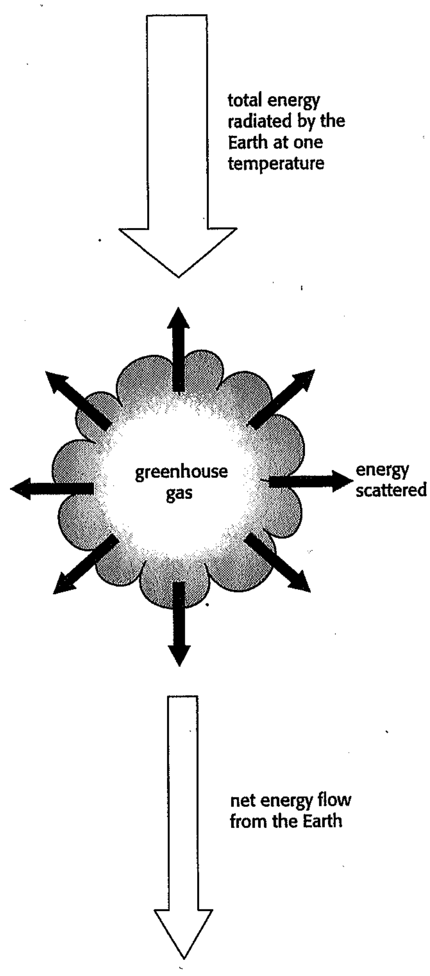

Figure 4 Absorption of energy by greenhouse gases leads to scattering

Data-based question: greenhouse gas absorption spectrum

The graph below shows the transmission of different wavelengths from a particular waveband through carbon dioxide gas.

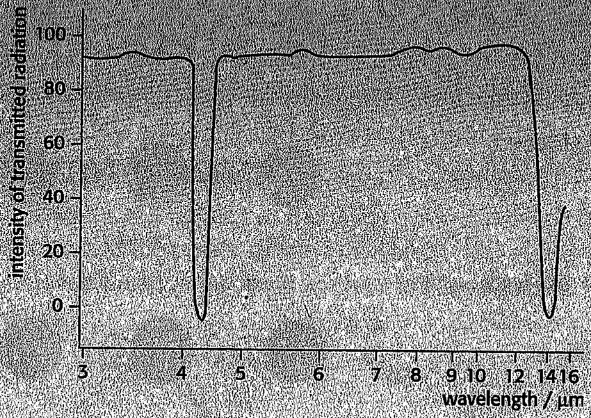

Figure 5 Carbon dioxide absorption spectrum

1 Write down how many µm there are in 1 m.
2 State the range of wavelengths illustrated in the graph and to which waveband in the electromagnetic spectrum they belong.
3 Write down the wavelengths of radiation that are absorbed most efficiently by carbon dioxide gas.
4 Outline the different molecular mechanisms possibly responsible for absorption in each wavelength.
5 Before going any further, refer back to the rather simplistic explanation of the greenhouse effect at the start of this chapter. You should now be able to write a much more detailed and physically accurate description of the process.

Evidence for an enhanced greenhouse effect

The enhanced greenhouse effect is another name for the global warming caused by the activities of humans.

The Inter-Governmental Panel on Climate Change (IPCC), a body within the UN, published its fourth assessment report in February 2007. It stated the following:

"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level".

The report backed up this statement with evidence from temperature records going back over nearly 200 years. Some of this data is included below. The range of uncertainty in any value is estimated and included in square brackets – [ ].

1 *Eleven of the last twelve years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850).*
2 *The updated 100-year linear trend (1906–2005) of 0.74 [0.56 to 0.92] °C is therefore larger than the corresponding trend for 1901–2000 given in the TAR (Third Assessment Report) of 0.6 [0.4 to 0.8] °C.*
3 *The linear warming trend over the last 50 years (0.13 [0.10 to 0.16] °C per decade) is nearly twice that for the last 100 years.*
4 *The total temperature increase from 1850–1899 to 2001–2005 is 0.76 [0.57 to 0.95] °C.*
5 *Urban heat island effects are real but local, and have a negligible influence (less than 0.006 °C per decade over land and zero over the oceans) on these values." (IPCC, 2007, p4)*

?

1 State three of the observed consequences of the enhanced greenhouse effect reported in the IPCC assessment on this page.
2 Use the data in point 2 to calculate the mean temperature increase per decade from 1906 to 2005.
3 Use the data in points 2 and 3 to plot
(i) the global mean temperature deviation from the 1956 value on a graph over the period 1906–2005
(ii) on the same axes, plot the global mean temperature deviation from the 1956 value averaged from 1956 to 2005.
4 Use your graph from question 3 to outline any changes in the rate of temperature rise in recent decades.
5 Explain
(i) the meaning of the term "urban heat island effect" used in point 5, and
(ii) why this point was included with the other data.

Modelling an enhanced greenhouse effect

Developing an accurate model to predict the consequences of the enhanced greenhouse effect is very difficult. Many of the models produced so far have led to different conclusions. A sensible approach is to look at the predictions of as many of the models as possible, then try to reach a consensus. However, this is not quite the same as reaching an average, because the scientific community may judge some models to be more accurate than others.

In the simple model discussed earlier in the chapter, this formula was used to predict the average global temperature:

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

S, α, and ε are all variables which can change over time.

The value predicted by this equation is too low by about 35 K. We now know that the atmosphere and its composition have a significant effect on the temperature. Also, climate is influenced by other mechanisms, such as the fluid dynamics of the atmosphere and oceans, combined with the effects of the Earth's spin. There is another process that is in action: positive feedback.

Positive feedback

To understand this, consider the following examples:

- Snow and ice reflect significant amounts of solar radiation straight back into space. Global warming has led to melting of the polar ice caps, which reduces the Earth's albedo. This in turn increases the absorption of solar radiation, which increases global warming.
- The oceans store huge quantities of dissolved carbon dioxide. Oceanic warming reduces the solubility of carbon dioxide, so gas is released into the atmosphere. This in turn causes more global warming.

In both cases, a change in one factor causes a change in another which, in turn, "feeds back" to magnify the original change.

?

Global warming may well lead to desertification (the formation of deserts) in certain parts of the planet. Outline an argument of how this may lead to:
(a) positive feedback, increasing the effects of global warming, or
(b) negative feedback, reducing the effects.

Assumptions for a simple model

This model is based on an idea from the climateprediction.net website. A spreadsheet or graphical calculator is used to model changes in the Earth's temperature over time.

The model assumes the following:

1 The initial power flux of incoming solar radiation at the Earth's surface is 390 W m^{-2}.
2 The outgoing power flux depends only on the temperature of the Earth, initially 288 K (the 2007 value), and is given by the Stefan-Boltzmann law:

outgoing power flux = σT^4

3 The change in temperature of the Earth over time depends on:
- the energy difference between the incoming and outgoing radiation
- the surface heat capacity, C, of the Earth. (C is the thermal energy needed to raise the temperature of 1 m^2 of the Earth's surface by 1 K. In the model, $C = 4.0 \times 10^8$ J m^{-2} K^{-1}.)

Over a period of time, Δt, the Earth absorbs energy which causes a temperature rise ΔT.

The energy absorbed = incoming energy – outgoing energy

But: energy = power × time

So: temperature rise = (incoming power – outgoing power) × time/heat capacity

The new temperature is calculated like this:

new temperature = old temperature + temperature change

The idea is to model what would happen if the effective incoming solar radiation changes. This could happen if:
- the solar luminosity changes due to solar flares or sunspot activity
- the Earth's albedo changes
- the Earth's emissivity changes due to increased greenhouse gas concentrations in the atmosphere.

?

This question is about the enhanced greenhouse effect and climate change.

Here is some data:
solar constant = 1.37 kW m^{-2}
Earth's radius = 6.4×10^3 km
Stefan-Boltzmann constant = 5.67×10^{-8} W m^{-2} K^{-4}
Surface heat capacity of Earth = 4.0×10^8 J m^{-2} K^{-1}

(a) (i) Show that, using a simple energy balance model, the Earth re-radiates about 340 W m^{-2} of power per unit area. [3]
(ii) State two assumptions you have made. [2]

(b) (i) Use the Stefan-Boltzmann law to estimate the mean temperature of the Earth using this data. [2]
(ii) Briefly explain why the Earth is warmer than your answer above suggests. [2]

A change in the atmosphere causes the effective power flux absorbed by the Earth to increase by 10%, causing the planet to become hotter.

(c) Calculate:
(i) the new power flux absorbed by the Earth. [1]
(ii) the total energy gained per m^2 in 1 year. [1]
(iii) the total energy radiated per m^2 in 1 year, assuming that the Earth continues to radiate at 340 W m^{-2} during this time. [1]

(d) (i) Determine the temperature rise of the planet over 1 year. [2]
(ii) State one additional assumption of this model. [1]

[Total 15 marks]

Setting up the spreadsheet

If designed well, a spreadsheet will quickly re-calculate all your dependent variables when you change just one of your independent variables. It is worth taking a little time to plan your spreadsheet design before inputting your variables. An Excel spreadsheet for this simple climate model is illustrated:

	A	B	C	D	E	F
1	Modelingclimate change.					
2						
3	σ	c	Δt (years)	Δt (s)	T_0	% change in energy
4	5.67E-08	400000000	0.5	15768000	288	5
5						
6						
7	time (years)	Incoming radiation	Outgoing radiation	ΔT	T	
8	0	390.07939	390.07939	0	288	
9	0.5	409.58336	390.07939	0.7688465	288.769	
10	1	409.58336	394.26154	0.6039864	289.373	
11	1.5	409.58336	397.57044	0.4735496	289.846	
12	2	409.58336	400.17928	0.3707091	290.217	
13	2.5	409.58336	402.2305	0.2898498	290.507	
14	3	409.58336	403.8398	0.2264114	290.733	
15	3.5	409.58336	405.10023	0.1767253	290.91	
16	4	409.58336	406.0861	0.1378621	291.048	
17	4.5	409.58336	406.85643	0.1074959	291.155	
18	5	409.58336	407.45783	0.0837884	291.239	
19	5.5	409.58336	407.92707	0.0652912	291.305	
20	6	409.58336	408.29299	0.0508664	291.355	
21	6.5	409.58336	408.57825	0.0396218	291.395	
22	7	409.58336	408.80054	0.0308588	291.426	
23	7.5	409.58336	408.97374	0.0240314	291.45	
24	8	409.58336	409.10865	0.0187131	291.469	
25	8.5	409.58336	409.21373	0.0145708	291.483	
26	9	409.58336	409.29557	0.0113449	291.495	
27	9.5	409.58336	409.35929	0.0088329	291.503	
28	10	409.58336	409.40891	0.0068768	291.51	
29						

Figure 6 Spreadsheet to model climate change

1 The constants, σ and *C*, are entered in cells A4 and B4. Note the format for the value of σ.
2 The time increment, Δ*t*, is entered in cell C4 in years for ease of use. As calculations use seconds, a formula is entered in cell D4 to covert years to seconds = C4*365*3600. The term C4 refers to the number in cell C4. The "$" s are used in Excel to "fix" the reference – see below.
3 The initial temperature is entered into cell E4.
4 The number in cell F4 is the % increase or decrease in the incoming solar radiation.
5 Row 8 is used to set up the initial conditions.
6 The formula = E4 is used in cell E8.
7 Cell C8 is calculated using the Stefan-Boltzmann law; = A4* E8^4.
8 As the incoming radiation must initially be equal to the outgoing radiation, the formula = C4 is entered into cell B4.
9 Row 9 makes the first set of calculations following the increase (or decrease) in the incoming solar radiation.

?

1 State the formula used in cells D9 and E9.
2 Use the graph to determine
  (i) the new steady state temperature
  (ii) the time to reach this new steady state

Change the time interval to (i) 0.25 years and (ii) 1 year.

3 Describe any similarities and differences between your new graphs and the one illustrated in Figure 7.
4 State, for each new time interval
  (i) the final steady state temperature
  (ii) the time to reach this steady state.

The formula in cell C9 is = A4*E8^4

5 Explain what would happen when filling down if the formula = A4*E8^4 was used. (You can test this out by trying it).
6 Explain the use of the "$" notation throughout the spreadsheet – it is very important to understand this when designing spreadsheets.
7 Explain whether you think this kind of model is useful for scientists to attempt predictions of future climate change.

10 The time interval chosen in cell C4 is generated in cell A9 using the formula = A8 + C4.
11 The increased solar power in cell B9 is generated using the formula = B8*(1 + F4/100)
12 The outgoing radiation in cell C9 is assumed to be constant in the model over the selected time interval. It is calculated using the formula = A4*E8^4. The temperature in cell E8 is the previous temperature.
13 The temperature change and new temperature are generated in cells D9 and E9.
14 Highlight the cells A9 to E9, grab the small black square in the bottom right-hand corner of cell E9 and fill down for 20 rows.
15 Plot a graph of temperature (y-axis) against time (x-axis). To do this highlight the cells A7 to A28, press and hold the CTRL key and highlight cells E7 to E28. Click the chart wizard button, and select the various options to complete the graph.

The graph for this model is shown below.

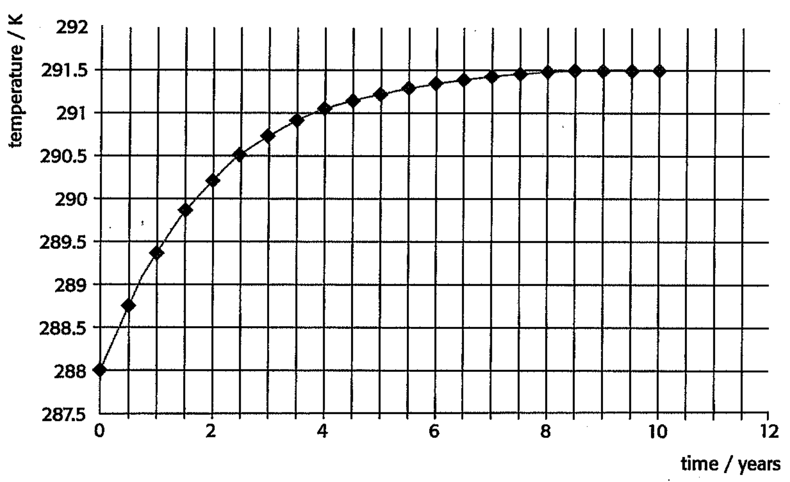

Figure 7 Graph of temperature against time for a simple climate model

This model is very flexible. Try different scenarios and find out what the model predicts. For example:

- Change the % change in solar energy to +8% and –5%.
- Change the initial temperature.
- Change the time interval.
- Try to improve the sophistication of the model by including albedo and emissivity in the calculations.
- Try to find out if there is a relationship between atmospheric carbon dioxide concentration and emissivity. If so, this could be included in the model.

An interesting feature of this model can be explored if you use a large time interval. For example, a time interval of 5 years gives the graph below.

This suggests an unstable model, with an oscillating temperature. Think about why the model predicts this result. Does temperature change in discrete time steps, or is it a continuous change? You might want to investigate this feature of the model further.

?

This question is about black body radiation and the greenhouse effect.

The power absorbed from the Sun at the surface of the Earth is 240 W m^{-2}.

(a) Calculate the mean temperature of the Earth. [4]
(b) State any assumptions you made in your calculation. [2]

The solar constant is measured to be 1.37 kW m^{-2}.

(c) Estimate the mean albedo of the Earth and state any assumptions you have made. [6]
(d) Describe the *greenhouse effect* and compare it with the *enhanced greenhouse effect*. [6]

[Total 18 marks]

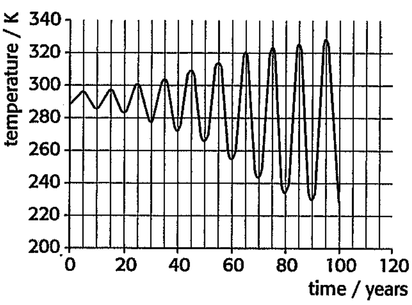

Figure 8 An unstable model of climate change