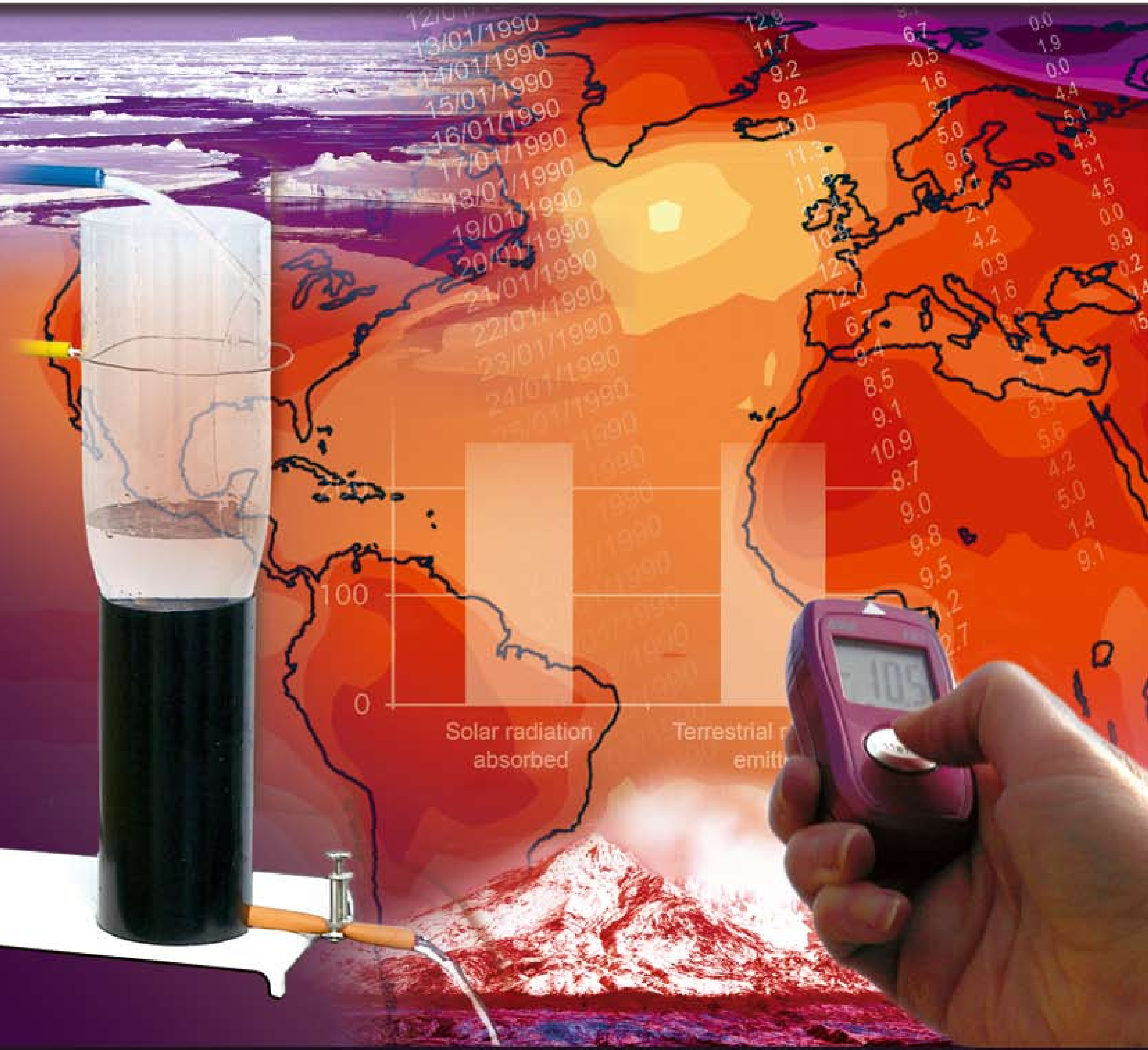
Science Enhancement Programme

MODELLING CLIMATE CHANGE



MODELLING CLIMATE CHANGE

Science Enhancement Programme

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The Gatsby Charitable Foundation

Walker INSTITUTE

The Science Enhancement Programme is a part of Gatsby Technical Education Projects. It is developing curriculum resources to support effective learning in science, and providing courses and professional development opportunities for science teachers. This booklet is part of the series 'Innovations in practical work', exploring ways in which low-cost and novel resources can be used in secondary science. The Gatsby Science Enhancement Programme has worked in partnership with the Walker Institute for Climate System Research in the production of this publication and the accompanying resources.

The University of Reading's Walker Institute for Climate System Research aims to improve understanding of future climate and its impacts. It covers a range of disciplines, including climate and weather processes and modelling, water resources and quality, biodiversity, agriculture, soils and the urban environment. The Institute also supports the provision of education and training in climate system science.

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Allington House (First Floor)
150 Victoria Street
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Author: Kathy Maskell
Series editor: Richard Boohan

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HEALTH AND SAFETY

For practical activities, the Science Enhancement Programme has tried to ensure that the experiments are healthy and safe to use in schools and colleges, and that any recognised hazards have been indicated together with appropriate control measures (safety precautions). It is assumed that these experiments will be undertaken in suitable laboratories or work areas and that good laboratory practices will be observed. Teachers should consult their employers' risk assessments for each practical before use, and consider whether any modification is necessary for the particular circumstances of their own class/school. If necessary, CLEAPSS members can obtain further advice by contacting the Helpline on 01895 251496 or e-mail science@cleapss.org.uk.

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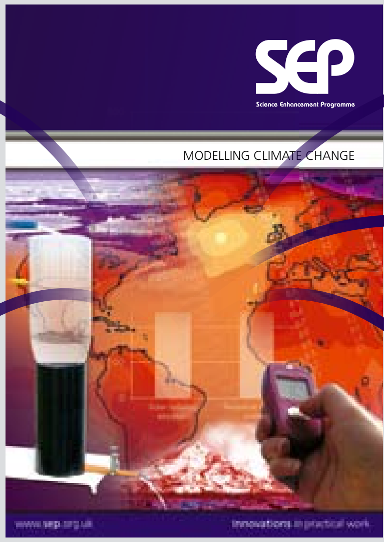
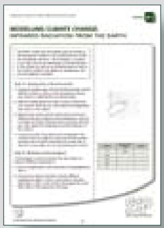


Modelling climate change in the classroom

An 'illustrated overview' of the topic with ideas for practical activities



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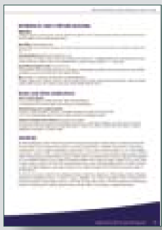

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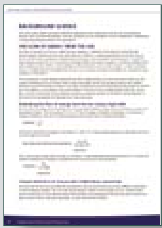


Background science

Further resources

DOWNLOADING* DIGITAL RESOURCES *FROM THE SEP WEBSITE

www.sep.org.uk

ORDERING* PRACTICAL RESOURCES *FROM MUTR

www.mutr.co.uk

See pages 50 - 51 for further details

INTRODUCTION

We have seen global temperature rise over the 20th century by around 0.7 °C and scientists now know that most of the warming since the mid-20th century is due to increasing greenhouse gases from human activities, like the burning of fossil fuels.

To understand climate and why it changes we need to understand the science of the climate system – the oceans, atmosphere and land and how these components interact. Climate scientists don't have a 'climate in a test tube' to try out their ideas, so they create computer models that they use to do 'experiments'.

This booklet provides an introduction to the way in which the climate can be modelled and the science behind the models. Its focus is on:

- the fundamental physical processes that influence climate
- practical activities that illustrate some key phenomena
- the principles of modelling any complex system
- examples of some simple climate models
- the importance of observed data.

The activities are intended for 14-16 year old students, but the work could also be adapted for post-16. A selection of the practical resources used in the activities are available for purchase from Middlesex University Teaching Resources (MUTR).

CURRICULUM LINKS

The following table shows the main relevant sections for each of the current GCSE science specifications.

GCSE specification	Sections particularly related to climate change
AQA	How do humans affect the environment? Carbon dioxide and methane in the atmosphere absorb most of the energy radiated by the Earth. Some of this energy is reradiated back to the Earth and so keeps the Earth warmer than it would otherwise be. Increasing levels of these gases may be causing global warming by increasing the 'greenhouse effect'. An increase in the Earth's temperature of only a few degrees Celsius: may cause quite big changes in the Earth's climate; may cause a rise in sea level. (11.8) What are the changes in the Earth and its atmosphere? Nowadays the release of carbon dioxide by burning fossil fuels increases the level of carbon dioxide in the atmosphere. (12.6) How is heat (thermal energy) transferred and what factors affect the rate at which heat is transferred? Thermal (infra red) radiation is the transfer of energy by electromagnetic waves. (13.1) What are the uses and hazards of the waves that form the electromagnetic spectrum? (13.5)
Edexcel 360 Science	Explain how burning fossil fuels may lead to global warming. (C1 b 7.3) Discuss how the composition of the Earth's atmosphere and its temperature have varied over time. (C1 b 7.4) Recognise that predictions about the amount of warming of the Earth are based on computer models, which carry uncertainties. (C1 b 7.5)
OCR 21st Century Science	What types of electromagnetic radiation are there? What happens when radiation hits an object? (P2.1) How does electromagnetic radiation make life on Earth possible? (P2.3) What is the evidence for global warming, why might it be occurring, and how serious a threat is it? (P2.4) Understand that computer climate models provide evidence that human activities are causing global warming. (P2.4, 5) Do all types of electromagnetic radiation behave in the same way? (P6.3)
OCR Gateway Science	Explain how human activity and natural phenomena both have effects on weather patterns. Dust from: volcanoes reflect radiation from the Sun causing cooling; factories reflect radiation from the city causing cooling. Interpret given information about climate change as a result of natural or human activity. (P1h) Find out about the evidence for global warming in the last 200 years. Discuss the possible consequences of global warming. (P2c)
WJEC Science	Know that there is debate in the scientific community on the issue of global warming and be aware that many scientists attribute the main cause of global warming to the increase in carbon dioxide in the atmosphere caused by the combustion of fossil fuels. (Chemistry 3 7d) Examine and evaluate given data on global warming. (Chemistry 3 7e) Appreciate some effects and consequences of global warming. (Chemistry 3 7f) Evaluate given data with regard to proposed solutions to the problem of global warming. (Chemistry 3 7g)

MODELLING CLIMATE CHANGE IN THE CLASSROOM: IDEAS AND SUGGESTIONS

What do we mean by climate and climate change? Climate is usually defined as the average weather (temperature, rainfall, sunshine hours, and so on) experienced by a particular location, region or over the globe as a whole. More strictly, climate is the statistical description of relevant variables (in terms of the mean and variability) over a period of time ranging from years to millennia. Climate scientists typically use a 30 year period to derive climate statistics.

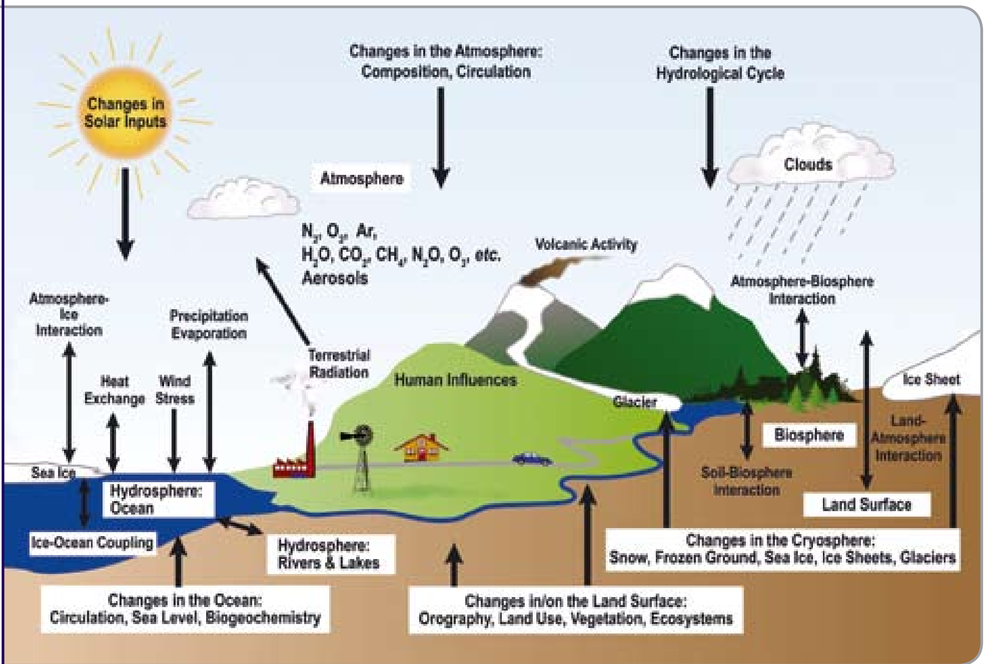
Climate can change for lots of reasons. Climate varies naturally on a whole range of timescales – from ice-age periods to year to year variability. However, there are now concerns that people are altering the global climate because of emissions of greenhouse gases from burning of fossil fuels and other human activities. We need models to investigate why climate has changed in the past and how it might change in the future.

This section gives an 'illustrated overview' of how work on modelling climate change can be undertaken in the classroom. In the margin, references are given to student activities – these resources and the accompanying teachers' notes can be found later in the booklet.

MODELLING THE CLIMATE

The climate system is made up of the atmosphere, oceans, land surface and living things (like vegetation and life in the oceans) and the interactions between these components. Many processes are at work within and between these components, making the climate an extremely complex system to model.

Complex models are required to represent the processes occurring in and between the atmosphere, oceans and land surface.

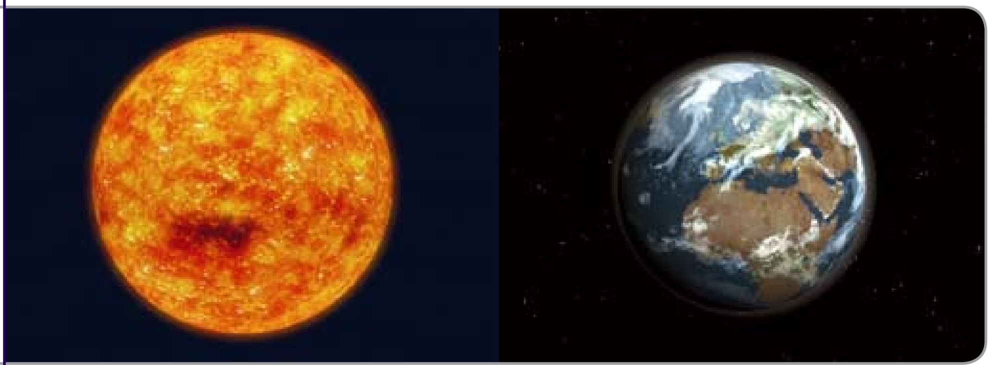


Scientists use a whole hierarchy of climate models to investigate the climate system. This booklet introduces two of the simplest models used. The most complex models used by scientists are general circulation models (GCMs) which divide the atmosphere and oceans into a three-dimensional grid, on which equations governing the movement of air, heat and moisture are solved. GCMs consist of hundreds of thousands of lines of computer code and are run on some of the most powerful computers in the world.

UNDERSTANDING SOLAR AND TERRESTRIAL RADIATION

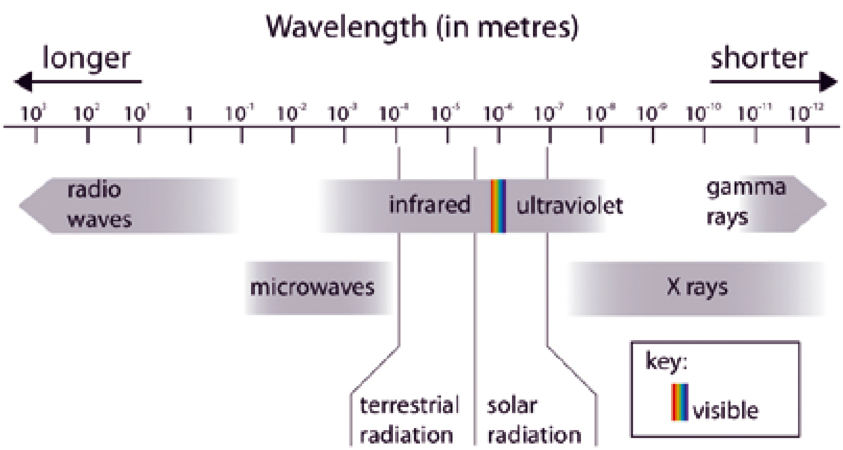
All of the energy which drives the climate system comes ultimately from the Sun in the form of electromagnetic radiation. The solar energy absorbed by the Earth causes the surface to warm, and energy is radiated from the Earth's surface and atmosphere. At any time our planet is simultaneously absorbing energy from the Sun and radiating energy back into space.

All of the Earth's weather and climate is driven ultimately by energy from the Sun.



Temperature largely controls the total energy emitted by a 'body' or surface, and it also governs the wavelengths of electromagnetic radiation emitted. Hotter objects emit more energy and at shorter wavelengths. The Sun is very hot with a surface temperature of over 5000 °C and so it emits electromagnetic radiation in visible, ultraviolet and near infrared wavelengths. The Earth is much cooler than the Sun so it emits electromagnetic radiation at much longer wavelengths in the far infrared part of the spectrum and which is invisible to the human eye (see *Background science* section page 44 for more details).

The radiation emitted from the Earth's surface (terrestrial radiation) has longer wavelengths than solar radiation.



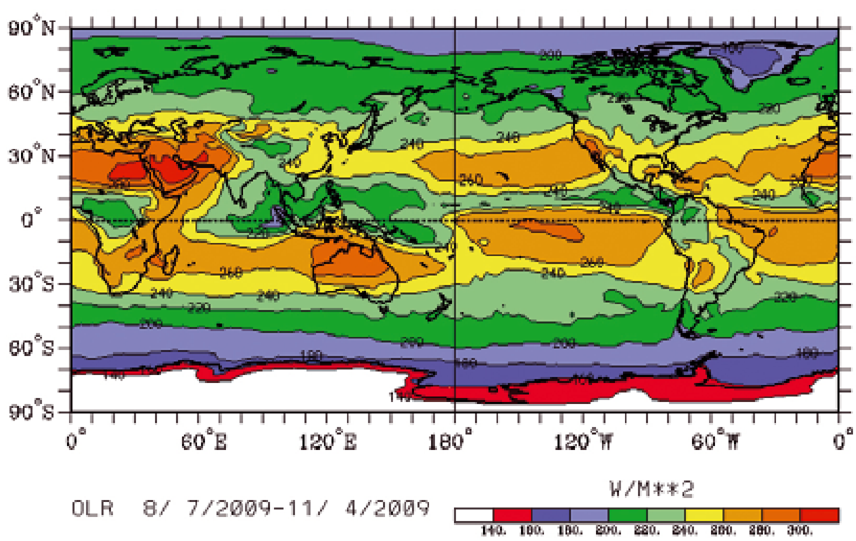
Classroom activities

While students may find it perfectly intuitive that the Sun provides the energy that warms the Earth's surface, it is far less obvious that the Earth's surface and atmosphere are themselves emitting electromagnetic radiation, but at wavelengths invisible to the human eye. An infrared thermometer works by detecting emitted infrared radiation and calculating a temperature. Students can use an infrared thermometer to take temperature readings outside (ground, walls, clouds, and so on) as a way of helping them to understand this idea.

See Activity A1
Infrared radiation from the Earth (page 29)

An infrared thermometer produces a temperature reading based on the infrared radiation emitted from an object.

Students could use their temperature readings to construct a 'thermogram' of an outside area using different colours to represent different temperatures. Thermograms are a useful way of seeing the variations in temperature and thus the energy emitted.



Satellites can measure outgoing terrestrial radiation at the top of the atmosphere. This picture is like a 'thermogram' taken from space.

See Extension X2
Radiation from the Sun and Earth (page 42)

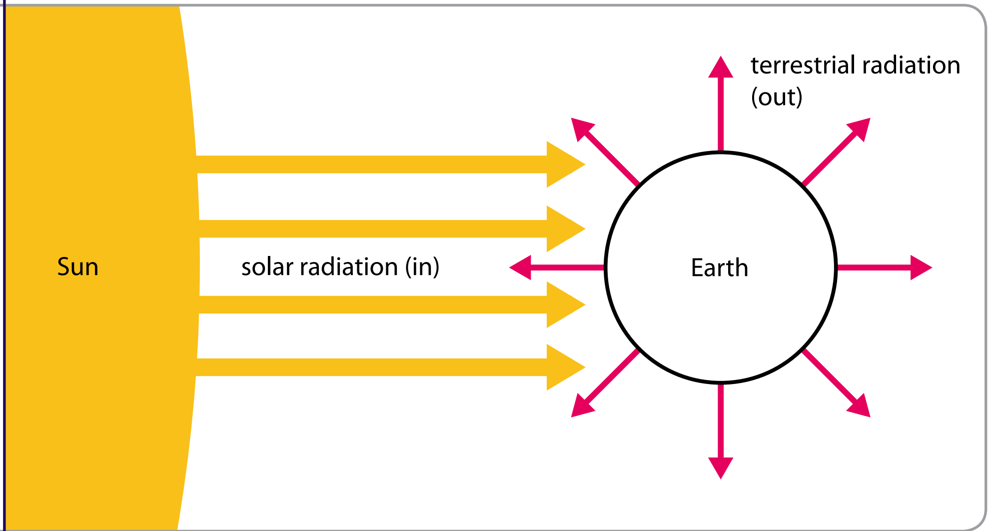
As an extension, students could use a computer simulation to look at the nature of the radiation emitted from objects at different temperatures, and at the differences between the radiation emitted by the Sun and the Earth.

A SIMPLE MODEL OF THE CLIMATE SYSTEM

Modelling any complex system typically involves simplifying that system. All of the complexity of the climate system can be condensed into a single variable – the globally averaged surface temperature. Now we can think about what controls the Earth's surface temperature.

The simplest model of the climate system assumes that globally averaged temperature is controlled by the balance between the solar radiation absorbed by the Earth and terrestrial radiation emitted by the Earth. In this model, the Earth is warmed by the flow of energy from the Sun and the Earth is cooled by radiating out to space. If the energy absorbed and energy emitted are in balance then, in this model, the global temperature of the Earth must be constant. A change in either the energy absorbed or the energy emitted will throw the system out of balance and the temperature must change to re-establish an equilibrium between energy absorbed and energy emitted.

The simplest model of the climate system assumes a balance between solar radiation absorbed and terrestrial radiation emitted.



Classroom activities

The fact that temperature is controlled by the flow of energy in and the flow of energy out is fundamental, not just to the climate system, but to the temperature of any system. The concept of energy flow, imbalance and a change in temperature to re-establish an equilibrium can be demonstrated to students by using a 'steady state bottle' – an inverted plastic bottle with the bottom cut off and a rubber tube attached to the neck. Water is used to represent energy and the level of water in the bottle represents temperature.

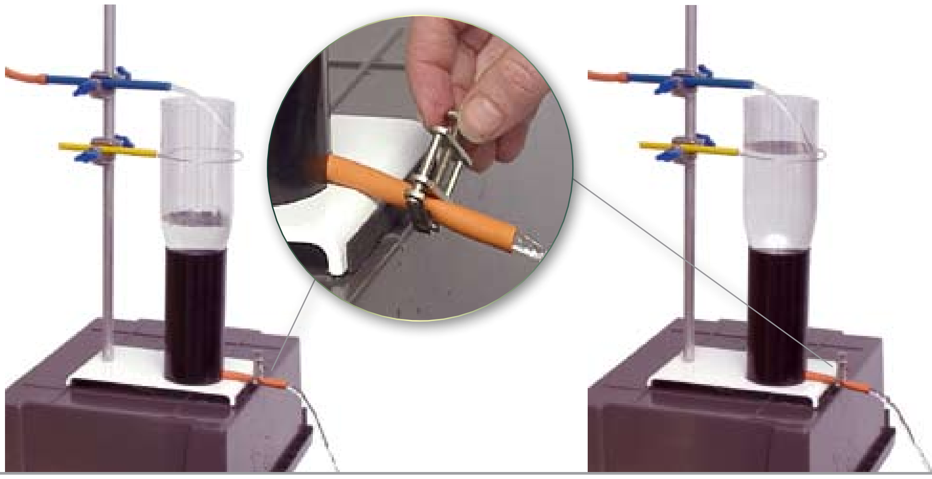
See Activity A2
Energy balance as a leaky bottle (page 30)

A simple starting point is to use this to model what happens, for example, when an object is heated and then left to cool. Adding water (energy) causes the water level (temperature) to rise. Outflow of water (energy) causes the water level to fall (cooling). What is important to notice here is that the flow of water *decreases* as the level of the water in the bottle *decreases*. This is a key idea in understanding the nature of feedback.

Using the steady state bottle model to represent heating and cooling.

If the bottle is now set up with a constant flow of water from a tap, an equilibrium will be established in which the rate of water (energy) inflow is the same as the outflow, and the water level (temperature) is steady. If the inflow to the bottle or outflow from the bottle is changed, then the level of water will change until a new equilibrium is re-established. In the case of the climate system, the inflow represents the flow of energy from the Sun which is absorbed by the Earth's surface and atmosphere. The outflow represents the emission of terrestrial radiation to space.

The steady state bottle is in equilibrium (left). A change to the water (energy) outflow results in a new equilibrium position (right).

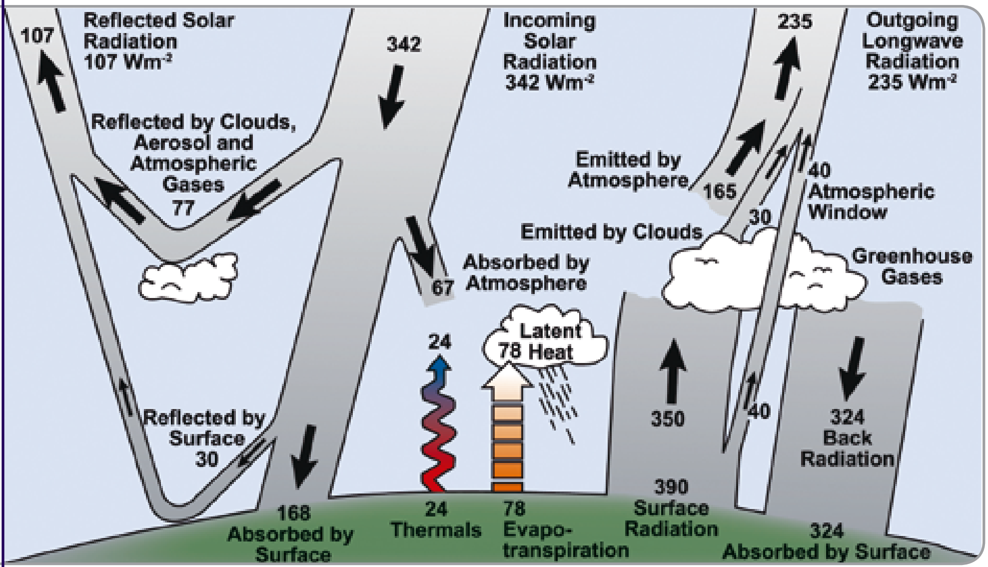


COMPONENTS OF THE EARTH'S ENERGY BALANCE

The Earth is warmed by electromagnetic radiation from the Sun and is cooled by emission of terrestrial radiation to space. The Earth's surface and atmosphere affect the absorption, transmission and reflection of solar and terrestrial radiation.

Around 30% of incoming solar radiation is reflected (by clouds, small particles in the atmosphere and by the Earth's surface); most of the rest passes through the atmosphere and warms the surface of the Earth. A small amount of solar radiation is absorbed – this is largely the absorption of ultraviolet (UV) light by ozone in the high atmosphere. Greenhouse gases, such as water vapour and carbon dioxide, which occur naturally in the atmosphere, absorb strongly at the far infrared wavelengths of terrestrial radiation. This absorbed infrared radiation is re-radiated and it warms the surface and lower atmosphere. This warming of the surface and lower atmosphere is the *natural greenhouse effect*. At the surface, convection and evaporation also transfer some energy up into the atmosphere.

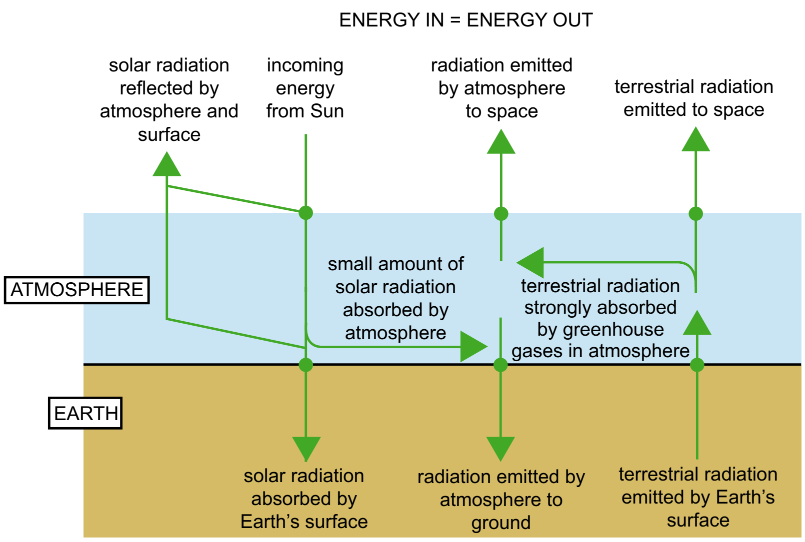
The Earth's energy balance. At the top of the atmosphere, incoming solar radiation is balanced by outgoing terrestrial radiation.



The concept of the Earth's energy balance can be used to develop a simple model of the climate system. This model has 4 variables:

- the flow of energy from the Sun
- the Earth's reflectivity or 'albedo' (proportion of solar radiation reflected)
- the transmission of terrestrial radiation (proportion of terrestrial radiation which passes through the atmosphere)
- the global surface temperature.

A simple energy balance model of the climate system.



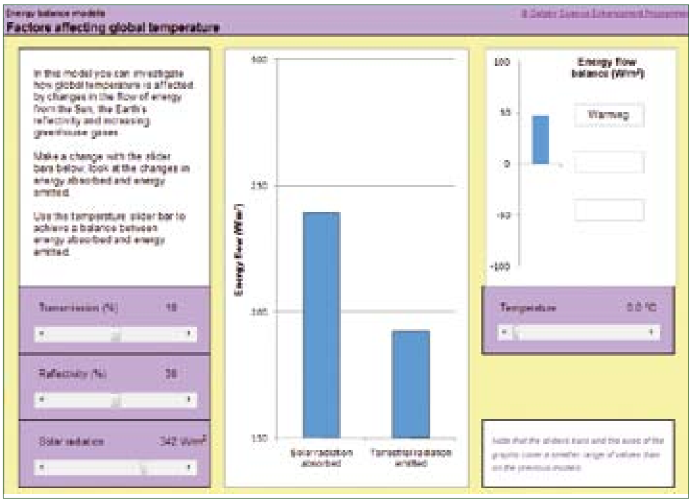
The 'energy in' at the top of the atmosphere is the incoming solar radiation minus the proportion of solar radiation that is reflected. The 'energy out' is the terrestrial radiation emitted from the top of the atmosphere to space – this depends on the surface temperature and the absorption by the atmosphere (see *Background science* section page 44 for more details).

Classroom activities

A computer spreadsheet based on the energy balance model described above can be downloaded from the SEP website. Students can use this spreadsheet model to look at the effects of changing the factors that affect the Earth's energy balance.

Within the spreadsheet file, there are different versions of the model that progressively make available more factors that students can alter. Each version has a central graph with two bars representing 'energy in' and 'energy out; the left-hand side has the various factors that can be changed, and the temperature can then be adjusted on the right-hand side to re-establish an energy balance.

One of the sheets from the computer spreadsheet based on a simple energy balance model.



See Activity A3
The natural greenhouse effect (page 31)

A good starting point is for students to look at the effect of adding an atmosphere to an Earth which does not have one. They will see that there is a decrease in the terrestrial radiation emitted into space, because some of it has been absorbed by greenhouse gases in the atmosphere. To re-establish an energy balance, students will see that they have to increase the surface temperature.

For this model, students will find that the absorption of terrestrial radiation by naturally occurring greenhouse gases keeps the Earth's surface at a comfortable temperature of around 15 °C (averaged over the globe). Without the atmosphere, the surface temperature of the Earth would be around -18 °C.

See Activity A4
Absorption by the atmosphere (page 32)

Students can carry out a practical activity that illustrates the absorption of infrared radiation using an infrared emitter and detector, and with water representing the atmosphere. Like the atmosphere, a beaker of water lets visible light pass through, but it absorbs infrared radiation.

Absorption of infrared radiation: when water is added to the beaker, more infrared is absorbed.

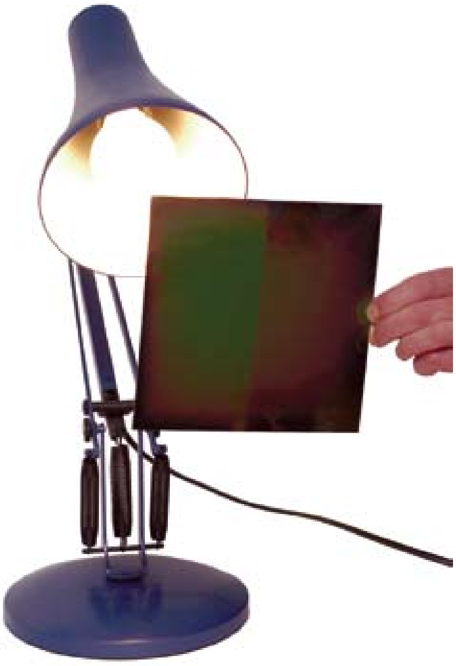
Students can relate this to the effect of increasing greenhouse gases in the atmosphere, and can return to the spreadsheet model to investigate what happens as they change the transmission of terrestrial radiation through the atmosphere. If greenhouse gases increase in the atmosphere, more terrestrial radiation is absorbed, and less is transmitted and emitted into space, so the surface temperature rises to re-establish an energy balance.

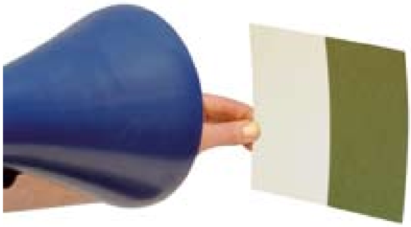
They can also carry out a practical activity that illustrates how the colour of a surface can affect the reflection of solar radiation.

See Activity A5
Ice and reflectivity
(page 33)

Half a sheet of thermocolour film is covered in white card (which represents snow and ice) and the other half with dark green card (which represents forests and open sea water revealed as ice and snow melt). The darker area of the thermocolour film warms most, as it absorbs more (reflects less) radiation, as shown by the change in colour of the thermocolour film.

The reflectivity of a surface can be investigated using thermocolour film.





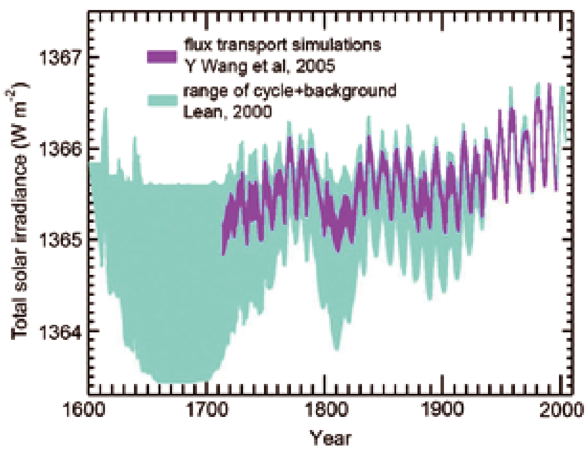
Students can then investigate the effect of reflectivity on the Earth's surface temperature using the spreadsheet model. They will find that as reflectivity decreases, less solar radiation is reflected and more is absorbed by the Earth. This leads to an increase in temperature.

WHAT CAUSES THE GLOBAL TEMPERATURE TO CHANGE?

Changes in the Earth's energy balance can affect the climate. The key factors that control global temperature in our simple energy balance model of the climate system are: the flow of energy from the Sun (solar radiation), the reflectivity of the Earth and the absorption of terrestrial radiation by greenhouse gases. In reality (and in more complex climate models) global temperature can change even if these factors remain unchanged because of 'internal climate variability'.

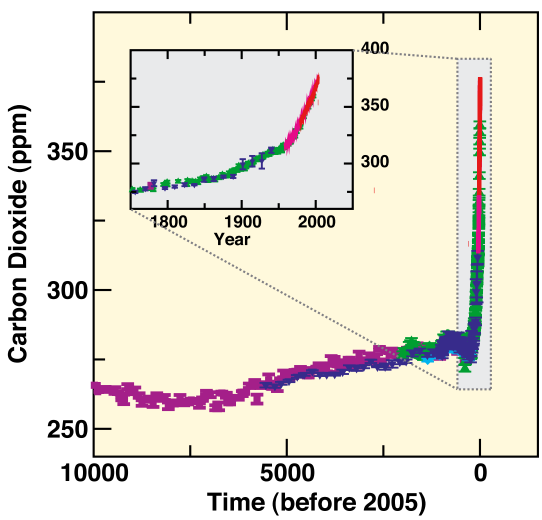
The flow of energy from the Sun changes over time. It varies over an 11-year cycle as well as over much longer timescales. For example, during the 15th and 16th centuries, there was a period known as the Maunder minimum, when the numbers of sunspots and solar radiation levels were lower than today. This period coincided with colder temperatures in Europe, known as the 'Little Ice Age'.

The energy flow from the Sun varies with an 11-year cycle and over longer timescales.



Human activity, such as the burning of fossil fuels and agriculture, are increasing the concentration of greenhouse gases in the atmosphere. Carbon dioxide and methane are the two most important greenhouse gases whose levels are being affected by people.

The concentration of carbon dioxide in the atmosphere has increased dramatically.



As greenhouse gases increase, more terrestrial radiation is absorbed by the atmosphere and so less is emitted to space. The temperatures of the surface and of the lower atmosphere increase, which in turn increases the emission of energy by the Earth to space. A new equilibrium is established (between energy absorbed and energy emitted), but at a higher global temperature. This phenomenon is known as the *enhanced greenhouse effect.*

The enhanced greenhouse effect – people are increasing the level of greenhouse gases in the atmosphere causing warming of the Earth's surface and lower atmosphere.

Natural phenomena can alter the Earth's reflectivity and change the amount of solar radiation that is absorbed by the Earth. When volcanoes erupt they throw dust and gas into the atmosphere which can reflect sunlight and cool the Earth's surface. You can actually see the effect of major volcanic eruptions in the global temperature record.

Human activity can also alter the Earth's reflectivity. Sulphur dioxide gas is produced when coal is burnt. This forms small droplets (aerosols) in the atmosphere, which reflect sunlight and cause cooling. Deforestation affects the amount of solar radiation reflected, since forests have a lower reflectivity than the agricultural crops that typically replace them.

The Earth's reflectivity is affected by natural phenomena (e.g. volcanic eruptions) and by human activity (e.g. burning coal, deforestation).

See Activity A2
Energy balance as a leaky bottle (page 30)

Classroom activities

By returning to the steady state bottle model, students can be asked to think about what might happen to the Earth's temperature if there is a change in energy inflow or energy outflow. Energy inflow is the solar radiation absorbed by the Earth at the top of the atmosphere and the outflow is the terrestrial radiation emitted to space.

Starting at equilibrium, with the water level steady, the outflow can be decreased. This represents a decrease in terrestrial radiation emitted to space due to an increase in greenhouse gases. Students will see the water level (Earth's surface temperature) rise until a new equilibrium is established. They could also look at changes to energy inflow that would represent, for example, a change in the flow of energy from the Sun.

See Activity A7
Factors affecting climate change (page 35)

Using the spreadsheet model, students can predict how much temperature might change as a result of a change in solar radiation, greenhouse gases or reflectivity.

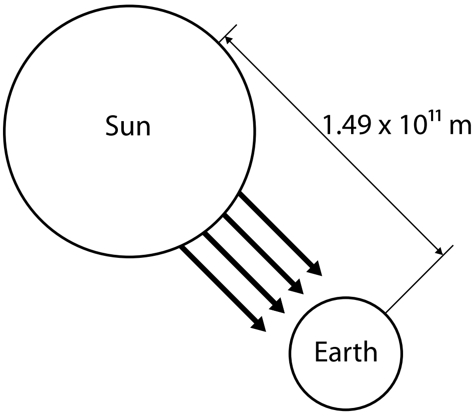
For example, particles thrown into the atmosphere by the eruption of Mt Pinatubo in 1991, caused the Earth's reflectivity to increase from approximately 30% to 31%. Students can alter reflectivity in the spreadsheet energy balance model to investigate the effect on surface temperature. They will find that the spreadsheet model predicts a decrease in temperature of around 1 °C. In reality temperatures fell by around 0.2 °C. Predicted and observed values differ because the energy balance model excludes many processes which influence the response of the climate system. For example, a change in temperature will lead to changes in rainfall patterns, humidity and clouds, all of which will in turn affect temperature.

Students can also try to predict what might happen to temperature if carbon dioxide concentrations double from their pre-industrial value (i.e., increase from 280 ppm to 560 ppm). This increase in carbon dioxide would reduce the transmission of terrestrial radiation through the atmosphere from 10% to 8%. Using the spreadsheet model, students will find the effect of this is that the temperature has to increase by 1.3 °C to achieve an energy balance. More complex models give an average global warming for a doubling of carbon dioxide of 2.5 °C, because they take account of other factors such as changes in humidity and clouds, which are neglected by the energy balance model.

The solar energy received at the top of the atmosphere that is directly facing the Sun is 1370 W/m^2. This energy is spread over the whole surface of the globe giving an average of 342 W/m^2 – this is the value that is used in the spreadsheet model (see *Background science* section page 44 for more details). As an extension, students can estimate a value of the energy flow received from the Sun using a light bulb. The energy received from a powerful energy source (such as the Sun) which is far away can be equivalent to a weaker power source (for example a desk lamp) which is nearer.

See Extension X1
Estimating energy flow from the Sun (page 41)

The energy flow from a 60 W bulb at close range is equivalent to the energy flow from the Sun (which emits 3.8×10^{26} W), but is very far away.



INTRODUCING COMPLEXITY

The response of the climate system to increasing greenhouse gases is much more complex than implied by the simple energy balance model discussed so far.

As the surface and lower atmosphere warm in response to increasing greenhouse gases, many other aspects of the climate system respond to the warming. For example, as the atmosphere warms, the amount of water vapour in the atmosphere increases. Water vapour is itself a greenhouse gas, and so this increase in water vapour produces further warming – an example of a *positive feedback*. Warming also causes snow and ice to melt, revealing open water and ground which are darker in colour and have a lower reflectivity (albedo). They reflect less solar radiation (and absorb more solar radiation), leading to further warming – again a positive feedback, known as the 'ice-albedo feedback'.

As the Earth gets warmer, sea ice and snow are melting revealing darker areas below. This decreases the Earth's reflectivity and leads to further warming.

Other positive feedbacks include a reduction in the oceans' ability to take up carbon dioxide as greenhouse gases rise, and a release of large amounts of methane as frozen ground thaws at high latitudes. An example of a *negative feedback* is the increase in emission of terrestrial radiation as temperature increases.

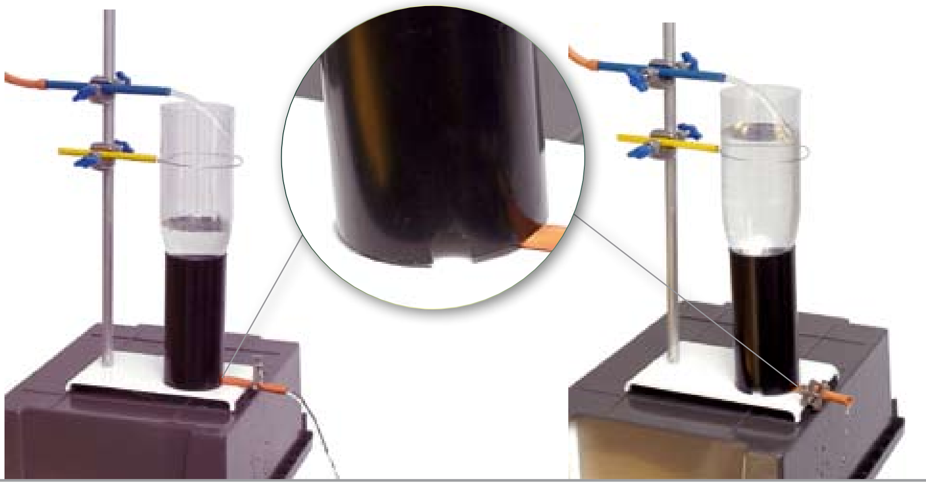
An increase in cloud cover can exert both a negative feedback (by reflecting more solar radiation back to space), and a positive feedback (by absorbing more terrestrial radiation). Scientists are uncertain which effect will dominate.

The combination of these positive and negative feedbacks in the climate system govern how sensitive the climate system is to change. Scientists don't know the sensitivity of the climate system precisely. Different scientists with different climate models get different results. This means that scientists are not certain about exactly how much the climate system will respond to increasing greenhouse gases.

Classroom activities

The idea of positive feedback can be investigated using the steady state bottle model. It can first be set up as before to remind students of how an equilibrium is maintained with an equal inflow and outflow of water. The base can then be turned, so that it presses on the outflow tube. Now, as the level of water (temperature) rises, the water outflow is *reduced* by the weight of the bottle, causing the water level to rise still further – a positive feedback. Students can discuss how the behaviour of this system relates to positive feedbacks such as increasing water vapour as the atmosphere warms or the release of methane as frozen ground thaws.

See Activity A6
Modelling positive feedbacks (page 34)



An illustration of positive feedback – as the level of water in the bottle (temperature) rises, the water outflow is reduced by the weight of the bottle, causing the water level to rise still further.

One of the greatest areas of uncertainty in predictions of future climate is how clouds will respond as the climate system warms. The processes that form clouds in the atmosphere are very complex and range from the very large scale to the microscopic. Clouds can warm the Earth by absorbing terrestrial radiation and can cool by reflecting solar radiation.

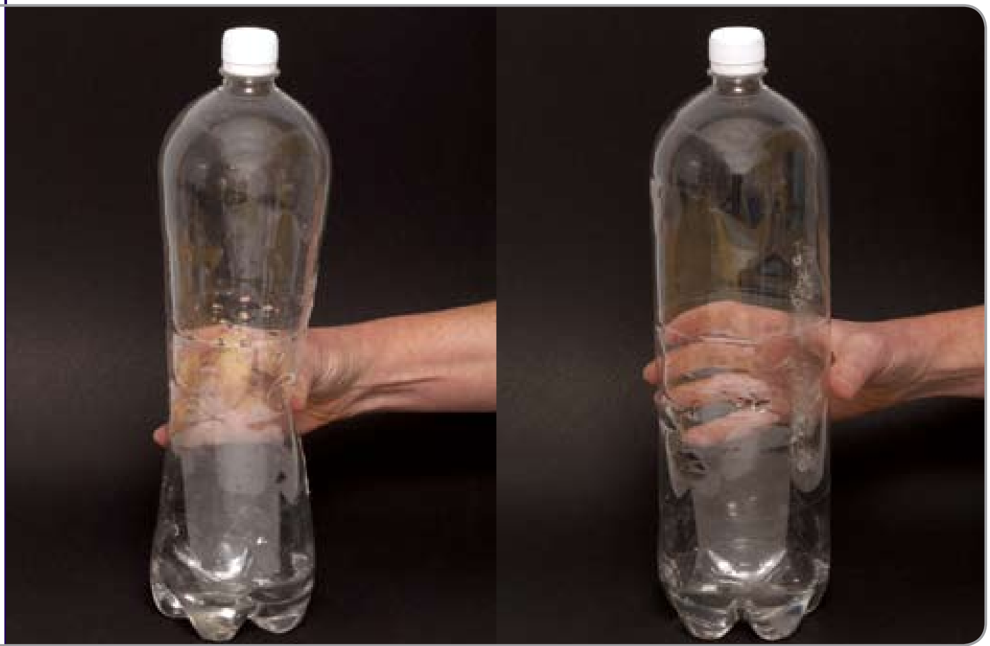
Clouds remain one of the largest areas of uncertainty in climate change – they are complicated to understand, observe and model.

See Activity A8
Making a cloud in a bottle
(page 36)

Students may think that clouds form simply when moist air is cooled, and they can investigate the complexity of cloud processes by creating a 'cloud in a bottle'. They can simulate the cooling of moist air by squeezing and releasing a plastic bottle which has a small amount of water in the bottom. Squeezing the bottle will increase the temperature inside and releasing the bottle will cool it. Students will find however, that when they squeeze and release the plastic bottle, no cloud appears.

They can then add tiny smoke particles to the bottle. When they repeat the procedure they will find that now a cloud does form. For condensation to occur, tiny particles are needed around which water vapour will condense.

When a plastic bottle filled with moist air is squeezed (to warm the air) and released (to cool the air), nothing appears to happen.



When tiny smoke particles are added to the bottle and the experiment repeated a cloud forms.

The formation of clouds in the atmosphere depends on the presence of tiny particles (cloud condensation nuclei) as well as other processes which operate at microscopic scales. This makes them very hard to model.

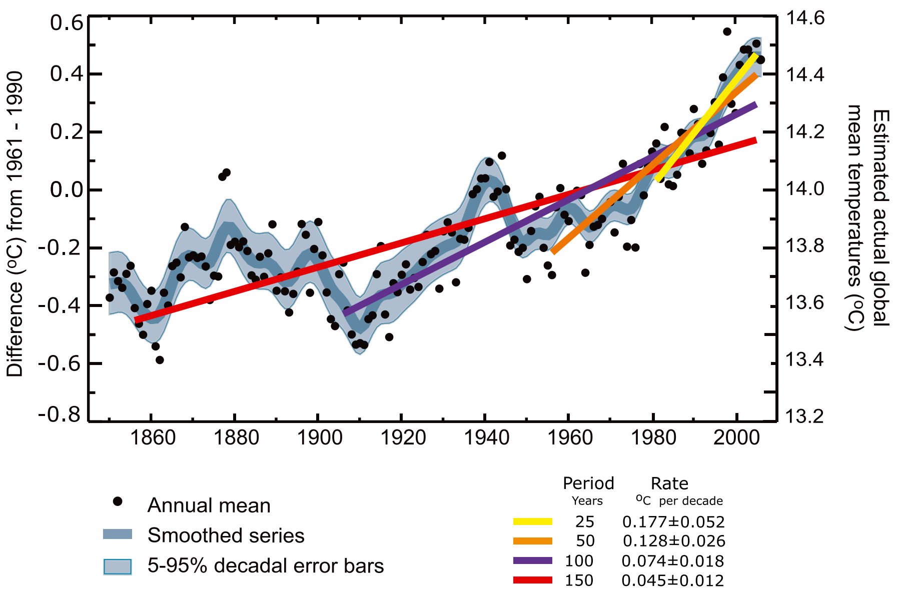
UNDERSTANDING PAST TEMPERATURE AND PREDICTING THE FUTURE

The simple energy balance model of the climate system discussed so far tells us nothing about how temperature changes over time. Nor does it incorporate the feedback processes like changes to clouds and atmospheric water vapour discussed in the previous section. So we need a more complex model.

Global surface temperature does not respond immediately to an increase in greenhouse gases; there is a lag in the system due to some thermal energy being absorbed by the oceans. So, a model which tells us about how temperature changes over time needs to include this effect. Using a more complicated model we can investigate the causes of past temperature change and try to predict how global temperature might change in the future.

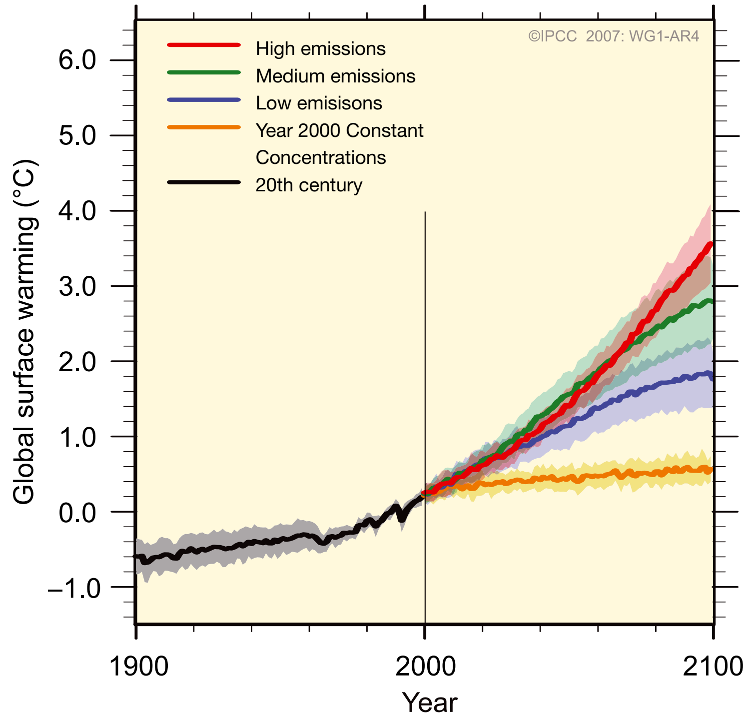
Over the 20th century global temperature has risen by around 0.7 °C, but the warming has not been steady. Using climate models and observations, scientists have concluded that most of the warming since the mid-20th century is very likely due to increasing greenhouse gases.

A graph of annual mean global temperature shows a rise of around 0.7 °C over the 20th century.



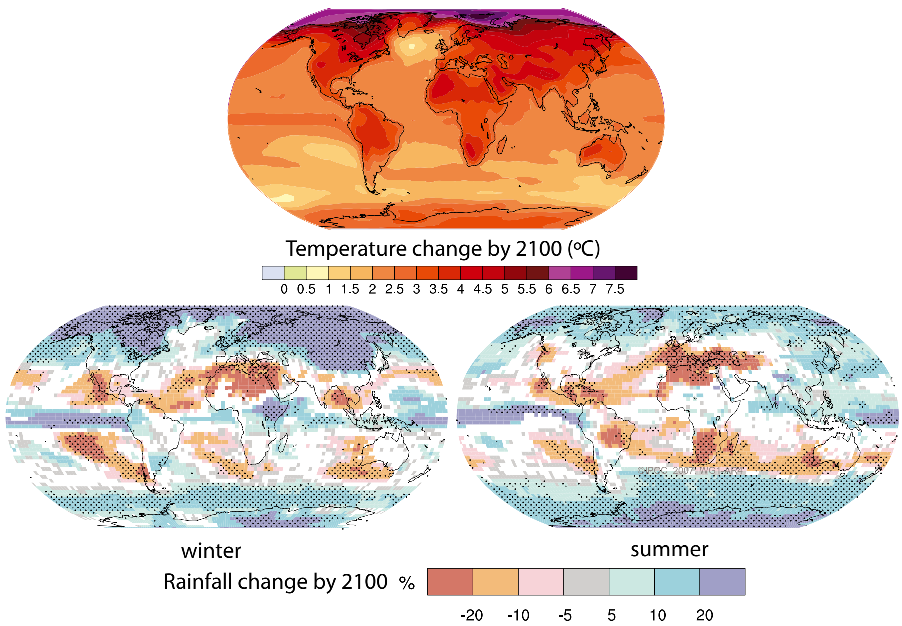
If greenhouse gas emissions from human activity continue to rise, then global temperature will also continue to rise through the 21st century and beyond. Scientists do not know exactly how much the temperature will rise, but the latest predictions suggest a warming of between 1.5 °C and 4 °C by 2100 (with some predictions suggesting as much as 6 °C).

Warming is very likely to increase through the 21st century, but there is uncertainty about exactly how much there will be.



Using highly complex models of the climate system, scientists predict that mid and high latitudes in the northern hemisphere are likely to warm the most. Dry areas are likely to get drier, wet areas to get wetter. Local details are uncertain.

Predictions made using complex computer models show which areas will warm the most and how patterns of rainfall will change as greenhouse gases continue to rise.



See Activity A9
Global temperature change model (page 37)

Classroom activities

To investigate causes of past temperature change and to look at future changes, a more complex climate model is introduced for the activities in this section. The model uses an atmosphere very similar to the energy balance model, but it also includes the effect of thermal energy being taken up by the surface and deep ocean. In this model the effect of climate feedbacks are incorporated by a variable called 'climate sensitivity', which governs the strength of climate system response. Students can use the more complex climate model through a web interface, to investigate the causes of changes in temperature.

Students can see how various factors (both natural and human-induced) have affected temperature over the 20th century by using the model to turn each of them on and off. Natural factors include the effect of volcanic eruptions and changes in the Sun's output; man-made factors include the increase in greenhouse gases and aerosols. Students will find that natural factors cannot explain the warming over the 20th century, and it is only when man-made factors are added that they will see a warming. This is evidence that human activity has caused much of the warming over the 20th century.

Students can also use the model to investigate how much global temperature might rise by 2100. We do not know exactly the amount of greenhouse gases that will be emitted in the future. This depends on population growth and many other social and economic factors, such as our dependence on fossil fuels. Scientists are also uncertain about exactly how sensitive the climate system is to changes in energy flow. The model enables students to specify a range of scenarios of future greenhouse gas emissions and a range of values for the climate sensitivity. The variation in the values for temperature change by 2100, depending on which assumptions are made, emphasises the issue of uncertainty in predictions of future climate.

It is useful to discuss with the class the limitations of the model used in this section. For example, it only predicts global temperature, does not predict anything about patterns of temperature change, and does not tells us anything about other changes in climate, such as effects on rainfall.

OBSERVING CLIMATE CHANGE

An understanding of the physics of the climate system clearly shows that increasing greenhouse gases have warmed the climate during the 20th century and, as their concentrations continue to rise, will continue to produce warming and other changes in climate. But can we actually observe climate change when we look at a particular place or region?

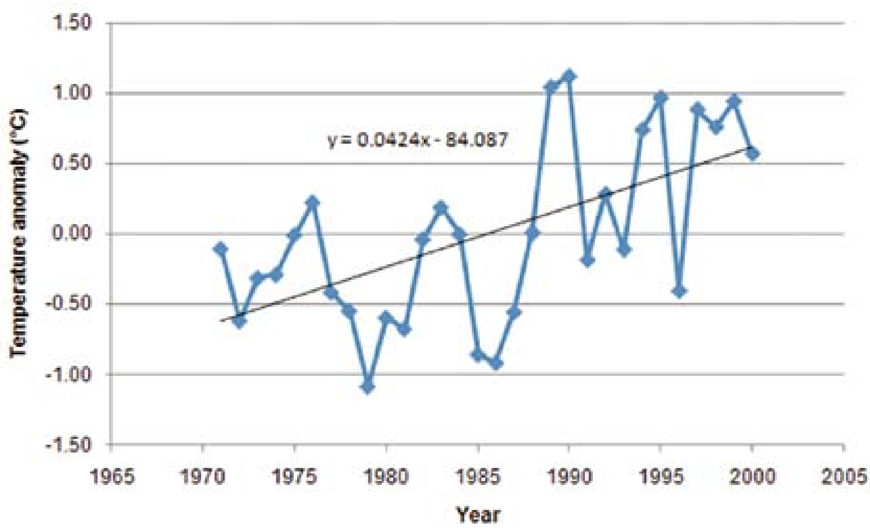
See Activity A10
Analysing observed climate change (page 39)

Classroom activities

Using temperature and rainfall data for Reading, for Central England and for the globe, students can compare the 'signal' of climate change at a single location, over a larger region and across the globe as a whole.

Reading and Central England have warmed by around 1 °C since 1971, while the globe has warmed by 0.3 °C. It is important for students to realise that scientists expect some regions to warm more than others as a result of increasing greenhouse gases. Temperature data for Reading and Central England are much more variable from year to year than the global data. Scientists call this 'noisy' data. The signal of climate change is harder to discern amongst the noisy data.

Annual mean temperature anomaly for Reading.



FUTURE DEVELOPMENTS IN CLIMATE MODELLING

The scientific evidence clearly shows that the climate system is warming and that the warming will increase through the 21st century. However, there is uncertainty about exactly how much it will warm and about the local and regional details of climate change.

Currently there are huge efforts by scientists across the world to improve climate models and to reduce the uncertainty in predictions of future climate. Increasing computer power is being used to improve climate models in three main ways:

- including more detailed processes, for example, including links between the atmosphere and vegetation, improving the representation of cloud processes
- increasing the resolution of climate models, which gives more detailed regional and local information
- running many more experiments, thus reducing uncertainty by using a greater number of samples.

Climate change research is not just about understanding changes in the physical climate system. It is also important to understand the impacts that these changes have on people and the natural environment. Human health, food security, water supply and biodiversity are all under threat from climate change. Studying these areas is another realm of modelling. We can perhaps envisage a future where modelling of the physical climate system is coupled with social and economic models that try to predict human impacts and responses, and in turn, the way that human behaviour influences the climate system.

STUDENT ACTIVITIES

MODELLING CLIMATE CHANGE

Teachers' notes

The student materials consist of a series of practical and computer-based activities that are intended for use at KS4. They focus on the underlying science that influences the climate system and on the principles of modelling. The key ideas are concerned with:

- the climate system and some of the main factors that affect global average temperature
- solar and terrestrial radiation and their impact on the greenhouse effect
- using a variety of models to make predictions about our climate system
- effects of natural and man-made influences on the climate system
- analysis of weather data.

To support the activities there are a number of practical resources that can be obtained from Middlesex University Teaching Resources.

Visit the SEP website www.sep.org.uk for supporting resources including images files and editable versions of the student sheets. See page 51 for information on obtaining the practical resources.

An overview of the activities

The activities are:

- **Activity A1** Infrared radiation from the Earth
- **Activity A2** Energy balance as a leaky bottle
- **Activity A3** The natural greenhouse effect
- **Activity A4** Absorption by the atmosphere
- **Activity A5** Ice and reflectivity
- **Activity A6** Modelling positive feedbacks
- **Activity A7** Factors affecting climate change
- **Activity A8** Making a cloud in a bottle
- **Activity A9** Global temperature change model
- **Activity A10** Analysing observed climate change

There are two extension activities:

- **Extension X1** Energy flow from the Sun
- **Extension X2** Radiation from the Sun and Earth

There is one resource sheet:

- **Resource R1** Glossary of technical terms

Notes on the activities

Activity A1: Infrared radiation from the Earth

Students use an infrared thermometer to measure the temperature and infrared emission of different surfaces, and use their data to make a simple thermogram (see also page 4 of this booklet 'Understanding solar and terrestrial radiation').

LEARNING OBJECTIVES
Students will:

- investigate the electromagnetic radiation emitted by the land surface and atmosphere
- draw conclusions consistent with their results
- construct a simple thermogram.

NOTES
In Task A students use an infrared (IR) thermometer to measure the electromagnetic radiation emitted by the Earth's surface and atmosphere. It is important to explain that the silicon based sensor in the thermometer can pick up electromagnetic radiation in a different range to that of our own eyes. In the range of temperatures being considered here, the higher the temperature the greater the emission of IR.

This activity can be used to re-iterate that the Sun warms the Earth's surface and atmosphere which then emits infrared radiation to balance the incoming flow of solar radiation.

You could extend this experiment by taking measurements at different times of the day and on different days (sunny days, cloudy days).

In Task B, students construct a simple thermogram and they could consider real life applications for thermal imaging. This activity gives an opportunity for students to consider how thermograms can be misleading depending on how the colours are assigned.

As an extension students could be shown IR images from satellites which are like a thermogram image taken from space (see the 'Useful links' section for this publication on the SEP website).

RESOURCES NEEDED

- Access to outside with different surfaces
- IR thermometer
- Compass
- Colouring pencils.

Activity A2: Energy balance as a leaky bottle

Students observe a teacher demonstration of a bottle with water inflow and outflow, which models energy flow, imbalance and equilibrium (see also page 6 of this booklet 'A simple model of the climate system' and page 11 'What causes the global temperature to change?').

LEARNING OBJECTIVES
Students will:

- use a physical model and relate it to the energy input and output of the Earth
- investigate negative feedback and equilibrium.

NOTES
Task A uses the steady state bottle to introduce students to the principles of heating, cooling and equilibrium; in Task B, they are asked to think about the steady state bottle in relation to energy balance in the climate system.

The parts of the steady state bottle represent the following:

- inflow = addition of energy (e.g. solar radiation absorbed by the Earth/atmosphere)
- outflow = loss of energy (e.g. terrestrial radiation emitted by the Earth)
- water level = temperature (e.g. Earth's global surface temperature).

Before setting the bottle up on its stand, it is helpful to start with the outflow tap closed and add water. This represents the addition of energy, i.e. heating. Open the outflow tap and let the bottle empty – this represents a loss of energy, i.e. cooling. An important point is that the rate of outflow decreases as the water level drops.

The steady state bottle can then be set up with the outflow tube passing through the notch at the base of the stand. As the bottle fills the outflow will increase until an equilibrium is reached and the water level stops rising (or at least rises only very slowly).

It is important to highlight that negative feedback occurs in this system, so that if the input or output is adjusted, the water level will change until a new steady state is achieved.

As the inflow or outflow are changed, the water level (Earth's global temperature) will change until a new equilibrium is established (but at a higher or lower temperature).

RESOURCES NEEDED

- Steady state bottle kit
- Plastic bottle, 1 litre, with base cut off
- Clamp stand, clamp, 2 bossheads
- Rubber tubing for tap
- Access to a tap and sink.

Activity A3: The natural greenhouse effect

Students use an energy balance spreadsheet model of the climate system to investigate the effect of an atmosphere on the Earth's surface temperature (see also page 7 of this booklet 'Components of the Earth's energy balance').

LEARNING OBJECTIVES

Students will:

- use a computer model to investigate the effect of the Earth's atmosphere on global mean surface temperature
- explain the results obtained from the model
- suggest some limitations to the model.

NOTES

In Task A, students should find that the surface temperature of the model Earth without an atmosphere is -18 °C. In Task B, they should find that when an atmosphere is added, the Earth's temperature is 15 °C. They should therefore conclude that an atmosphere has a large effect on the surface temperature of the Earth.

When an atmosphere is added students will see that the emission of energy from the Earth/atmosphere decreases. This is because a greater proportion of the energy is being absorbed (or trapped) by the atmosphere. The Earth's surface temperature has to increase for a new equilibrium to be established.

A description of the equations underlying the energy balance model used in the spreadsheet can be found in *Background Science* on page 44.

RESOURCES NEEDED

Each group will need:

- Access to computer running Microsoft Excel
- Computer spreadsheet: MCC_EnergyBalance.xls.

Activity A4: Absorption by the atmosphere

Students measure the absorption of infrared by water and use a spreadsheet model to predict the effect of increasing greenhouse gases (see also page 7 of this booklet 'Components of the Earth's energy balance').

LEARNING OBJECTIVES

Students will:

- investigate infrared (IR) absorption by water
- model the effect of increasing greenhouse gases on IR absorption
- make and record observations
- plot, analyse and interpret observations.

NOTES

In Task A, the amount of water in the beaker is being used as an analogy for the concentration of greenhouse gases in the atmosphere. Like the atmosphere, the water lets visible light pass through it, but it absorbs some infrared radiation. Students should conclude that the more water (greater the concentration of greenhouse gases), the more IR radiation is absorbed (and thus more energy is trapped in the atmosphere).

In Task B, students return to the energy balance model spreadsheet, but in the next section of the model they are able to alter the transmission of infrared radiation from the Earth's surface through the atmosphere. As greenhouse gases increase, the transmission of infrared through the atmosphere decreases. (Note that the values of 30% and 20% in the student activity are arbitrary - the current value of transmission is 10%.)

Students will see that as they decrease the transmission of infrared through the atmosphere, the emission of terrestrial radiation to space decreases. Students need to increase surface temperature to re-establish an energy balance.

RESOURCES NEEDED

Each group will need:

TASK A

- SEP infrared emitter kit
- SEP infrared detector kit
- Beaker, glass, 50 cm^3
- Clamp stand, 3 clamps, 3 bossheads
- Measuring cylinder, 50 cm^3
- Digital multimeter
- 2 plug-plug leads (1 red, 1 black).

TASK B

- Access to computer running Microsoft Excel
- Computer spreadsheet: MCC_EnergyBalance.xls.

Activity A5: Ice and reflectivity

Students use thermocolour film and a spreadsheet model to investigate the link between colour, reflectivity, absorption and the temperature of the Earth (see also page 7 of this booklet 'Components of the Earth's energy balance' and page 14 'Introducing complexity').

LEARNING OBJECTIVES

Students will:

- investigate how surface colour affects the absorption of electromagnetic radiation
- use a computer model to relate the Earth's reflectivity to its surface temperature.

NOTES

In Task A, white card should be stuck on one half of the back of a piece of thermocolour film and *dark* green card on the other half. Use as dark a green as possible. If it is a warm sunny day, the thermocolour film could be put on a south facing window sill instead of using a desk lamp.

Using the energy balance model in Task B, students should find out that a decrease in reflectivity increases the solar radiation absorbed (if less is reflected, more must be absorbed). They will need to increase the Earth's surface temperature to re-establish an energy balance.

You may wish to encourage students to think about the effects of ice melting and of positive feedback (this idea is followed up in more detail in the next activity). This feedback explains why scientists expect the largest warming (as a result of increasing greenhouse gases) at high latitudes.

As an extension to this activity, you could use secondary sources to show students global maps of the observed warming to date and expected future warming. These can be found on the internet (see the 'Useful links' section for this publication on the SEP website).

RESOURCES NEEDED

Each group will need:

TASK A

- Thermocolour sheet, approx 15 cm x 15 cm
- White and dark green card
- Desk lamp.

TASK B

- Access to computer running Microsoft Excel
- Computer spreadsheet: MCC_EnergyBalance.xls.

Activity A6: Modelling positive feedbacks

Students observe a teacher demonstration of a bottle with water inflow and outflow, which models energy flow and positive feedback (see also page 14 of this booklet 'Introducing complexity').

LEARNING OBJECTIVES

Students will:

- infer from a physical model the mechanism of positive feedback
- explain how an increase in greenhouse gases is likely to generate positive feedback.

NOTES

Initially the steady state bottle should be set up as in Activity A2 to model negative feedback. This can be used to remind students how such a system behaves.

The stand can then be rotated so that it presses on the outflow tube. Then, as the water level rises, the outflow will decrease and the water level will rise faster and faster – a positive feedback.

Start with a fairly low water level and then ask students to observe what happens as the water level rises. For maximum impact you can let the water level continue to rise until the bottle overflows.

You can link this demonstration of positive feedback to the climate system. As greenhouse gases increase, temperature increases – this warming leads to other changes (e.g., increased water vapour, melting ice/snow), which in turn lead to further warming.

It is important to stress that in the real atmosphere while positive feedbacks add to the initial warming due to greenhouse gases, scientists do not expect a 'run-away' warming effect. This is because there is a balance between positive and negative feedbacks in the climate system.

RESOURCES NEEDED

- Steady state bottle kit
- Plastic bottle, 1 litre, with base cut off
- Clamp stand, clamp, 2 bossheads
- Rubber tubing for tap
- Access to a tap and sink.

Activity A7: Factors affecting climate change

Students use a spreadsheet model of the climate system to predict how temperature is affected by changes in the flow of energy from the Sun, volcanic eruptions and increasing greenhouse gases (see also page 11 of this booklet 'What causes the global temperature to change?').

LEARNING OBJECTIVES

Students will:

- use a computer model to make predictions about effects on the global temperature
- explain differences between predicted values of temperature change and those observed
- consider the limitations of the computer model.

NOTES

In Task A, students reduce the flow of energy from the Sun from 342 W/m^2 to 322 W/m^2. They should find the temperature at equilibrium decreases from 15.3 °C to 11.0 °C. It is important to stress that, in reality, changes in the flow of energy from the Sun are actually much smaller than 20 W/m^2.

In Task B, students increase reflectivity from 30% to 31%. They should find temperature at equilibrium decreases from 15.3 °C to 14.3 °C.

In Task C, to model a doubling of carbon dioxide in the atmosphere, students decrease the transmission of terrestrial radiation from 10% to 8%. They should find temperature at equilibrium increases from 15.3 °C to 16.6 °C.

RESOURCES NEEDED

Each group will need:

- Access to computer running Microsoft Excel
- Computer spreadsheet: MCC_EnergyBalance.xls.

Activity A8: Making a cloud in a bottle

Students create a cloud in a bottle and observe that simply cooling saturated air is not sufficient to create a cloud (see also page 14 of this booklet 'Introducing complexity').

LEARNING OBJECTIVES

Students will:

- find out what conditions are needed for a cloud to form
- relate these results to the complexity of processes in the climate system.

NOTES

CAUTION: Smoke may cause irritation to the respiratory system especially in asthmatics. Lighted splints could cause burns.

You may need to remind students that as the bottle is squeezed the temperature of the air inside will rise. As the bottle is released it will cool.

To model the atmosphere where clouds are formed moist air must be introduced into the bottle. This is achieved by adding warm water to the bottle and waiting a few minutes until the air has become warm and moist.

This activity could be done as a classroom demonstration, so the teacher could light the splint and introduce the cloud condensation nuclei into the bottle. The bottle can then be passed around the class and it should be possible to make the cloud disappear and reappear as students squeeze and release the plastic bottle.

A piece of black card held behind the bottle makes the cloud easier to see.

RESOURCES NEEDED

- Clear plastic bottle with cap (ideally at least 1 litre)
- Black card (A3 size)
- Splints
- Bunsen burner and mat.

Activity A9: Global temperature change model

Students use a web-based climate model to investigate the causes of past temperature change and predict how temperature might change in the future (see also page 17 of this booklet 'Understanding past temperature and predicting the future').

LEARNING OBJECTIVES
Students will:
- investigate the causes of climate change over the 20th century and what this could mean for future climate
- compare modelled results with observations
- be able to explain some of the issues of uncertainty in climate prediction.

NOTES
The web-based climate model allows students to explore various forcing factors that can cause climate to change. They can look at past climate change and explore what might happen to temperature in the future.

In Task A, the best agreement with observations is achieved by selecting all forcing factors. If users switch off man-made factors, then the model does not produce a warming trend from 1850 to 2000. So, assuming you trust the model, this must mean that man-made factors are responsible for a large part of the warming since 1850.

In Task B, students can explore what might happen to temperature in the future, and should understand the uncertainty in future predictions. They should also consider the assumptions and limitations of the model. For example, the model tells us nothing about the spatial pattern of warming, and nothing about changes in rainfall, or extreme events like storms.

RESOURCES NEEDED
Each group will need:
- Computer with internet access to use model at www.walker-institute.ac.uk/climatemodel

Activity A10: Analysing observed climate change

Students calculate summary statistics and determine trends for observed rainfall and temperature data (see also page 19 of this booklet 'Observing climate change').

LEARNING OBJECTIVES
Students will:
- plot time series data of temperature and rainfall and analyse trends
- calculate annual averages and temperature anomalies
- draw conclusions consistent with results about the way that climate has changed.

NOTES
The datasets used in this activity are contained within the Excel spreadsheet provided:
- Daily temperature (°C) and rainfall (mm/day) for Reading, Berkshire 1971-2000
- Monthly mean temperature (°C) and rainfall (mm/month) for Reading, Berkshire 1971-2000
- Annual mean temperature for Reading for 1971-2000
- Quarterly mean temperature for Central England for 1971-2000
- Annual temperature anomalies for the globe 1971-2000.

The daily data are provided to show where the monthly and annual data come from; they are not used by students.

You can find more information about the data on the University of Reading and Met Office websites (see *References and further reading* on page 49).

In Task A, students should find that: warmest July is 1983 (20.6 °C), coldest July is 1980 (14.8 °C), driest July is 1990 (9.5 mm), wettest July is 1988 (78.4 mm).

In Task B, for Reading, the mean temperatures have increased by 0.4 °C per decade (or 0.04 °C per year), and rainfall has increased by 0.7 mm per decade. Data show a lot of variability from year to year.

In Task C, the trends per decade are:
- Reading temperature: +0.4 °C
- Central England temperature: +0.3 °C
- Global temperature: +0.1 °C.

Reading and Central England have warmed considerably more than the global mean over the period 1971-2000. Reading and Central England data are much more variable from year to year.

RESOURCES NEEDED
Each group will need:
- Access to computer running Microsoft Excel
- Computer spreadsheet: MCC_DataAnalysis.xls.

Extension X1: Energy flow from the Sun

Students use a light bulb to estimate a value for the flow of energy from the Sun (see also page 7 of this booklet 'Components of the Earth's energy balance').

LEARNING OBJECTIVES
Students will:
- estimate the energy flow from the Sun using a light bulb
- explain why the calculated value might differ from observed.

NOTES
CAUTION: Students should be asked to take care not to touch the hot bulb as it could cause burns.

The Sun's energy is transferred to the Earth by radiation only (due to the vacuum of space). The lamp transfers a proportion of energy by convection as well as by radiation, but even so it is still a useful model for the Sun.

Students are asked to move their hand towards the lamp until if feels like a warm summer's day. This gives an *estimate* of the energy flow from the Sun received at the Earth's surface. For the UK, at noon, on a typical summer's day this value is around 1200 W/m^2. At the top of the atmosphere the average value is 1370 W/m^2.

Any point source of radiation such as the Sun or a lamp emits radiation in all directions, a sphere. (A desk lamp is approximately a point source though the shade means that energy is not emitted evenly in all directions.) Therefore, the distance that the students measure is actually the distance of the radius of the sphere over which the radiation is spread. An Excel spreadsheet could be set up to calculate energy flow, so that students just enter the distance (r).

As an extension, students could be asked to consider how the energy flow changes as r changes, as it is an example of the inverse square law. Students may be familiar with this in relation to gravitational attraction or the power of light intercepted by a solar panel.

In Task B students are asked to consider if their results are accurate. The light bulb estimate is based on a single location and a single time of year and is an estimate of solar radiation at the surface of the Earth. Some solar radiation is reflected by the atmosphere/surface and some is absorbed by the atmosphere. The students' values are therefore likely to be an underestimate of the average solar irradiance at the top of the atmosphere of 1370 W/m^2.

For further information see *Background science* on page 44.

RESOURCES NEEDED
Each group will need:
- Lamp with 60 W bulb
- Ruler, 30 cm
- Calculator.

Extension X2: Radiation from the Sun and Earth

Students find the average temperatures of the Earth and Sun from secondary sources, and use the data in a computer model to compare the electromagnetic radiation emitted by each (see also page 4 of this booklet 'Understanding solar and terrestrial radiation').

LEARNING OBJECTIVES
Students will:
- investigate how temperature affects the spectrum of electromagnetic radiation emitted by an object
- describe and explain the differences between the spectrum of electromagnetic radiation emitted by the Sun and the Earth.

NOTES
Students should find out that the average temperature of the Earth is about 15 ^{o}C, and that the average surface temperature of the Sun is about 5700 ^{o}C. (Note that the students will need to convert these temperatures to K for the computer model.)

There are two versions of the model of black body radiation. A web-based model is currently available at http://phet.colorado.edu/simulations/sims.php?sim=Blackbody_Spectrum (if this is no longer at this address, check the SEP website for further information). If this model is unavailable you could use a spreadsheet model which is available on the SEP website).

From the model, students should conclude that terrestrial radiation has longer wavelengths in general than solar radiation. These different wavelengths are fundamental when considering the greenhouse effect in the atmosphere, because the shorter wavelength solar radiation can pass through more easily than the longer wavelength (far infrared) terrestrial radiation.

For further information see *Background science* on page 44.

RESOURCES NEEDED
Each group will need:
- Access to secondary sources of information
- Computer with internet access (or access to computer running Microsoft Excel and computer spreadsheet: MCC_BlackBody.xls).

MODELLING CLIMATE CHANGE: INFRARED RADIATION FROM THE EARTH

The Earth's surface and atmosphere give out energy as electromagnetic radiation in the infrared (IR) part of the electromagnetic spectrum. This IR radiation is invisible to our eyes, but can be detected by an IR thermometer. In this activity you will use an IR thermometer to look at the world in infrared. The higher the temperature, the more IR radiation is emitted.

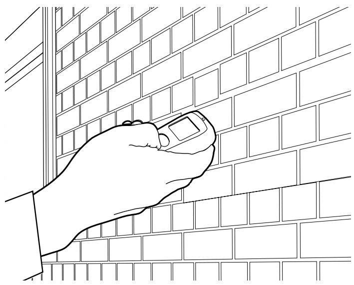
Task A Seeing the infrared world

1. Choose an outdoor area. Point the IR thermometer at some different surfaces to find out their temperature. Record your results in a table like the one shown below.
2. Add information about the colour of each surface that you measure. What do you notice about the temperature and colour of the surface?
3. Identify some similar vertical surfaces that are facing in different directions. Measure their temperatures, and use a compass to find the directions they are facing. What do you notice about the temperatures and the direction of the surface?
4. Using your results, think about what temperature the clouds and the sky might be. Point your IR thermometer upwards and record the temperature of clouds and of clear sky in your table. Are you surprised by your results?

Task B Making a thermogram

A thermogram is a kind of picture that uses colours to represent different temperatures.

5. Draw a simple sketch of the area that you investigated for Task A.
6. Choose four colours for different temperature ranges and make a key. Colour in your sketch using your data taken in Task A. How could a thermogram be used? Why might a thermogram be confusing?



Surface	Temperature (°C)	Colour
Tarmac		
Grass		
Brick		
Glass		
etc.		

Science Enhancement Programme

MODELLING CLIMATE CHANGE: ENERGY BALANCE AS A LEAKY BOTTLE

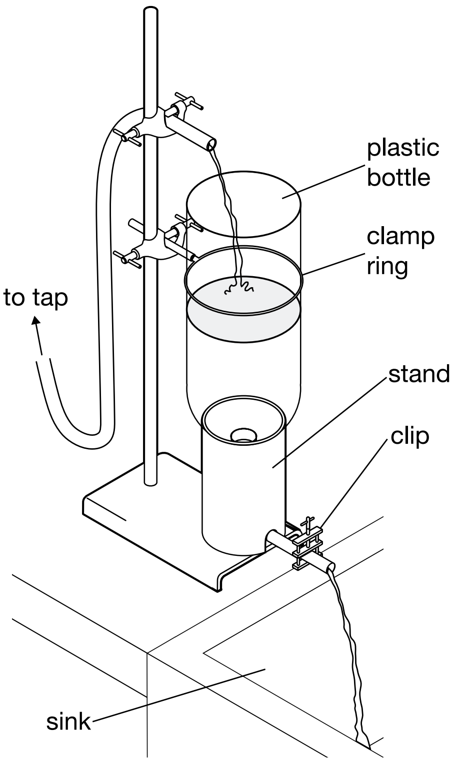
In this activity your teacher will demonstrate how energy flows and temperature changes can be modelled with a 'leaky bottle'. This model can be used to represent solar radiation, terrestrial radiation and the Earth's temperature. When energy inflow equals energy outflow the Earth's temperature is steady.

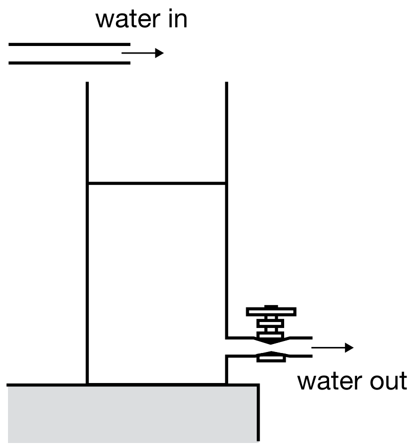
Task A Exploring energy flow and energy balance

1. Your teacher will demonstrate how a 'leaky bottle' can be used as a model of heating and cooling. What represents energy? What represents temperature?
2. The bottle is now set up so that water can flow into and out of the bottle at the same time. What happens to the level of the water? What can you say about the inflow rate and outflow rate once the water is steady?
3. Your teacher will now increase the inflow of water. What do you predict will happen? What do you observe?
4. What do you predict will happen if the water outflow is reduced?

Task B Exploring changes in the Earth's energy balance

5. The bottle model can be used to represent the energy transfer between the Sun, the Earth and space. What represents the temperature of the Earth? What represents the flow of energy from the Sun? What represents energy emitted by the Earth?
6. With the water level steady, your teacher will decrease the outflow rate very slightly. What does this model? What do you observe? What can you say about the system now?
7. Use your observations of the model to explain what happens to the Earth's temperature if emission of terrestrial radiation decreases (e.g. because of an increase in greenhouse gases).





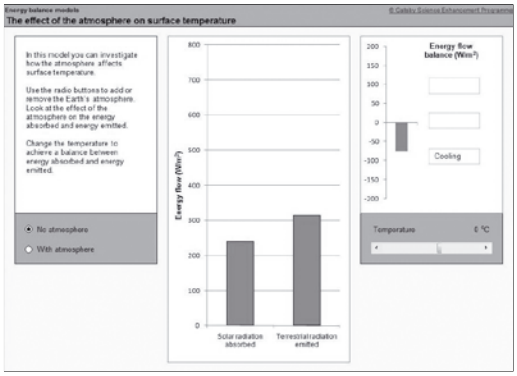
Science Enhancement Programme

MODELLING CLIMATE CHANGE:
THE NATURAL GREENHOUSE EFFECT

A simple computer model on a spreadsheet can be used to calculate estimates of the Earth's average surface temperature. With this energy balance model of the climate system you will see how the Earth's atmosphere keeps the surface warm – the 'natural greenhouse effect'.

Task A Estimating the Earth's surface temperature with no atmosphere

1. Open the Excel spreadsheet *MCC_EnergyBalance* and click on the tab 'Model 1'. Click on the button 'No atmosphere'.
2. The two bars on the graph show the energy absorbed and energy emitted at the Earth's surface. Move the 'surface temperature' slider bar backwards and forwards. What happens to the energy absorbed and the energy emitted?
3. Adjust the temperature until the energy absorbed by the Earth is equal to the energy emitted by the Earth. The model is now in equilibrium. Record the temperature that this happened at in a table like the one shown.



Surface	Temperature at equilibrium (°C)
No atmosphere	
With atmosphere	

Task B How does the atmosphere affect surface temperature?

4. Click on the button 'With atmosphere'. What happens to the amount of energy emitted by the Earth? Can you explain the change?
5. Move the temperature slider bar again. What happens as you increase and decrease the temperature?
6. Find the temperature at which the model is in equilibrium. Record this temperature in the table.
7. What effect does the atmosphere have on the surface temperature of the Earth? Can you explain why the atmosphere has this effect?
8. What are the limits of this model?

Science Enhancement Programme

MODELLING CLIMATE CHANGE: ABSORPTION BY THE ATMOSPHERE

Gases like water vapour and carbon dioxide trap infrared radiation emitted by the Earth. So the atmosphere is like a blanket keeping the Earth warm. In this activity you will investigate the absorption of infrared (IR) radiation.

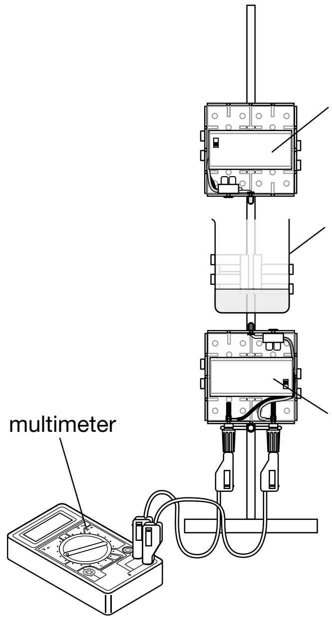
Task A Measuring infrared absorption

1. Using a stand, and three sets of clamps, hold a 100 cm^3 beaker between an IR emitter and an IR receiver.

2. Use the multimeter set on the 2000 mV scale to measure the voltage when the beaker is empty and record your result in a table like the one shown here.

3. Add 25 cm^3 of water to the beaker. Do you think the voltage measurement will be higher or lower? Measure and record your result.

4. Add another 25 cm^3 of water and record the voltage again. Can you explain the pattern in your results?



Volume of water (cm^3)	Voltage (mV)
0	
25	
50	

Task B Modelling the greenhouse effect

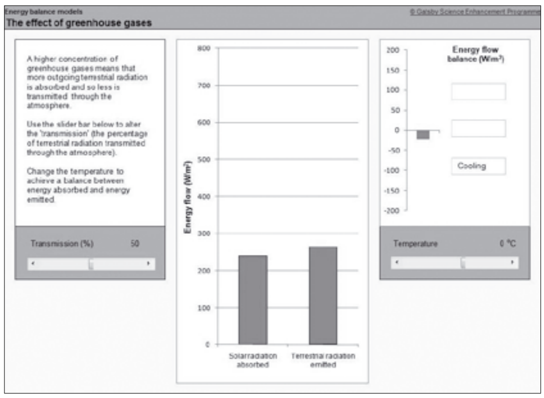
5. Open the Excel spreadsheet *MCC_EnergyBalance* and click on the tab 'Model 2'.

6. Change the percentage of terrestrial radiation transmitted through the atmosphere using the slider bar. What happens to the energy absorbed? What happens to the energy emitted? Can you explain your results?

7. Set the transmission at 20%, alter the temperature to achieve a balance and record the temperature.

8. Predict whether the equilibrium temperature would be higher or lower if transmission was set at 30%. Use the model to find out.

9. How could you use this model to simulate the effect of increasing carbon dioxide in the atmosphere? What is the effect on surface temperature?



Science Enhancement Programme

MODELLING CLIMATE CHANGE: ICE AND REFLECTIVITY

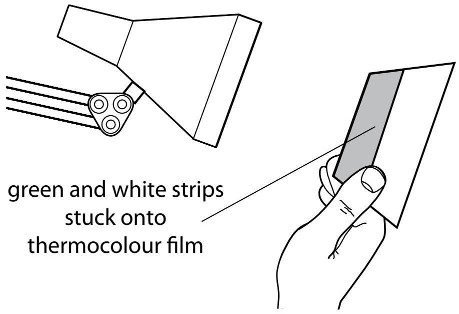
As the climate warms, snow and sea-ice are melting revealing a darker surface below. This will affect the amount of radiation that is reflected from the Earth's surface. In this activity you will explore how colour affects the reflectivity of a surface, and you will use a computer model to find out the effect that reflectivity has on the Earth's temperature.

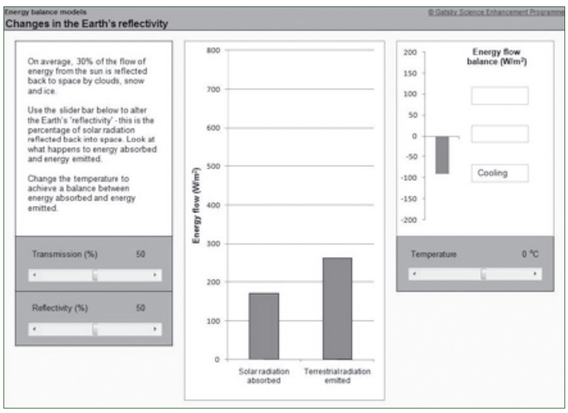
Task A Temperature and colour

1. Stick a piece of white paper on one half of a sheet of thermocolour film and a piece of dark green paper on the other half. What do the white and green areas represent?
2. Shine a desk lamp on the paper for 30 seconds and observe the thermocolour film.
3. What do you observe? Why did the different areas of the thermocolour film warm differently?

Task B Changing the Earth's reflectivity

4. Open the Excel spreadsheet *MCC_EnergyBalance* and click on the tab 'Model 3'.
5. Set the reflectivity to 30%. Why is this value chosen? Move the temperature slider bar until the energy is in equilibrium. Record the size of the energy flow absorbed by the Earth and the temperature at equilibrium.
6. Set the reflectivity to 25%. What could cause the Earth's reflectivity to decrease from 30% to 25%? Move the temperature slider bar until the energy is in equilibrium. Record the size of the energy flow absorbed by the Earth and the temperature at equilibrium.
7. Scientists predict that as increasing greenhouse gases warm the Earth, the average reflectivity will decrease. What effect do you think this will have on our climate?





Reflectivity (%)	Energy flow absorbed (W/m²)	Equilibrium temperature (°C)
30		
25		

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MODELLING CLIMATE CHANGE: MODELLING POSITIVE FEEDBACKS

As greenhouse gases increase in our atmosphere we are observing a warming effect. This in turn increases the amount of atmospheric water vapour. Water vapour absorbs infrared radiation and produces a further warming effect. This is one example of a *positive feedback.*

In this activity your teacher will use a 'leaky' bottle with water to demonstrate positive feedback.

1. Your teacher will set up a 'leaky bottle' to model the energy transfers between the Sun, the Earth and space.

2. What represents the flow of energy from the Sun? What represents energy emitted by the Earth? What represents the temperature of the Earth?

3. What happens to the level of the water in the bottle if the rate of water flowing into or out of the bottle is changed?

4. The system is left until it achieves a balance, with the rate of water flowing in equal to that flowing out. The stand that the bottle is resting on is now turned round so that the weight of the bottle presses down on the outflow tube.

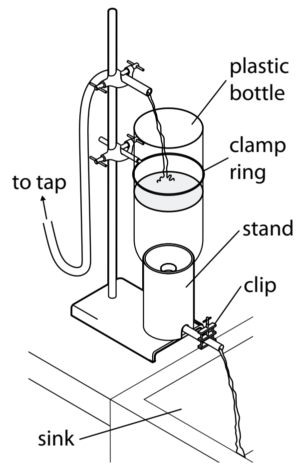
5. What happens to the water level in the bottle? Can you explain why this happens? Will this system reach a balance with the rate of water flowing in equal to that flowing out?

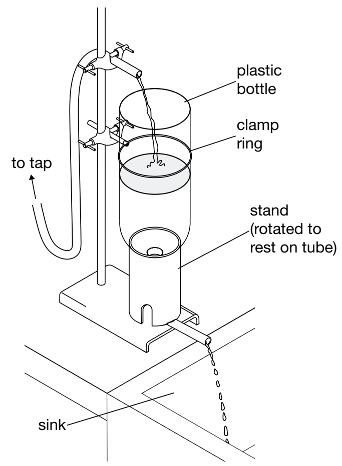
In the first experiment, a balance is achieved because of *negative feedback*. In the second experiment, a 'run-away' situation is created because of *positive feedback*.

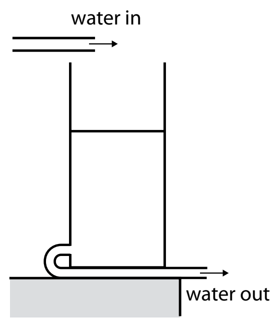
6. Use your observations of the model to explain how melting snow and sea-ice can lead to positive feedback.

7. In a similar way, explain how increases in water vapour in the atmosphere can lead to positive feedback.

8. What could happen to the Earth's temperature as the amounts of greenhouse gases in the atmosphere increase and positive feedbacks come into play?







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MODELLING CLIMATE CHANGE:
FACTORS AFFECTING CLIMATE CHANGE

Volcanic eruptions and changes in the output from the Sun are natural factors that affect climate. People can also affect global climate through emissions of greenhouse gases. Using an energy balance model you will investigate factors that cause climate change.

Task A Changes in energy from the Sun

1. Open the Excel spreadsheet *MCC_EnergyBalance* and click on the tab 'Model 4'.

2. The flow of energy from the Sun is on average 342 W/m^2. Use the model to predict how much the global temperature would change, if the Sun's output decreased by 20 W/m^2.

3. The flow of energy from the Sun does change, but it has only changed by around 0.5 W/m^2 over the last 400 years. How big an effect on temperature might this have?

Task B Changes in the Earth's reflectivity

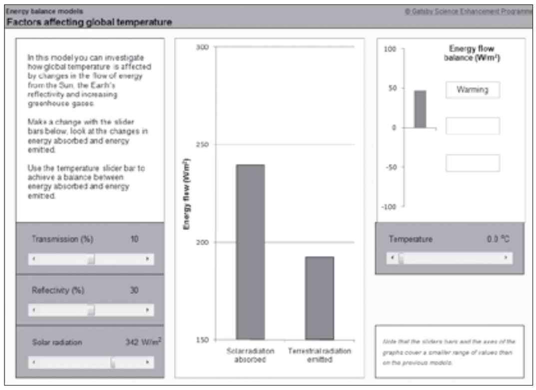
4. The eruption of Mt Pinatubo in 1991 caused an additional 3 W/m^2 to be reflected by the Earth – an increase in reflectivity from 30% to 31%. Predict how this might affect temperature. Use the model to find out how much the temperature changes.

5. In reality, global temperature decreased by around 0.2 °C for 1 or 2 years after this. How does the observed value compare with your calculated temperature change?

Task C Changes in greenhouse gas levels

6. A doubling of carbon dioxide levels in the atmosphere would decrease transmission of infrared radiation from 10% to 8%. How would you expect this to affect temperature? Use the model to find out how much the temperature changes.

7. Scientists predict that a doubling of carbon dioxide levels would increase global temperature by 2.5 °C. How does this compare with your calculated value?



When using this model, reset the factors to today's values each time, before looking at the effect of changing one of them:

solar radiation	=	342 W/m^2
reflectivity	=	30%
transmission	=	10%

Science Enhancement Programme

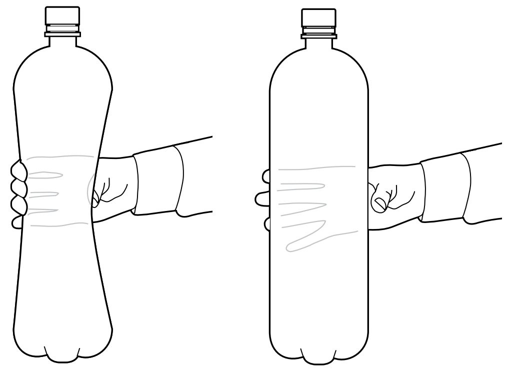
MODELLING CLIMATE CHANGE: MAKING A CLOUD IN A BOTTLE

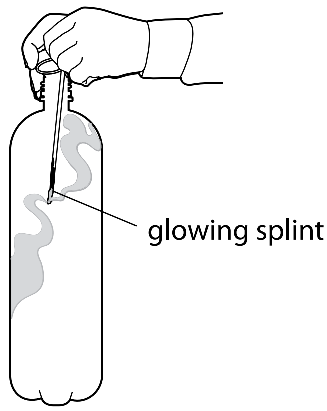
Clouds are made of water which can absorb radiation giving a heating effect to the Earth. However, clouds can also reflect solar radiation giving a cooling effect. Different types of clouds absorb and reflect different amounts of radiation.

In this activity you will find out what is needed for a cloud to form.

1. Put a little warm water into a plastic drinks bottle and screw on the cap. This will make the air inside moist, because of the evaporation from the warm water.
2. Squeeze the bottle and then release it. Nothing appears to happen.

   In fact, there is a change in temperature of the air inside as you squeeze and release the bottle, though it is too small to observe. When you squeeze the bottle, the increase in pressure causes the air inside to become a little warmer, and when you release it, the air expands and becomes a little cooler.
3. Now light a splint and tap it out so that it glows and makes smoke. Unscrew the bottle cap and waft some smoke into it. Then remove the splint and replace the cap.
4. Squeeze the bottle hard for a few seconds and then suddenly release it. Do this a few times. What happens when you squeeze and release the bottle?
5. Think about what you have done and what you have observed. What conditions are needed to make a cloud?





SEP
Science Enhancement Programme

MODELLING CLIMATE CHANGE: GLOBAL TEMPERATURE CHANGE MODEL

We have seen global temperature rise by almost 1 °C over the 20th century. A number of things cause the climate to change, some natural and some due to human activities. These are known as *forcing factors*.

In this activity you will use a web-based model to investigate the effect of forcing factors on past climate and to predict future climate.

Task A Understanding the past

1. Open your web browser and go to: www.walker-institute.ac.uk/climatemodel. First look at the section 'Past temperature'.

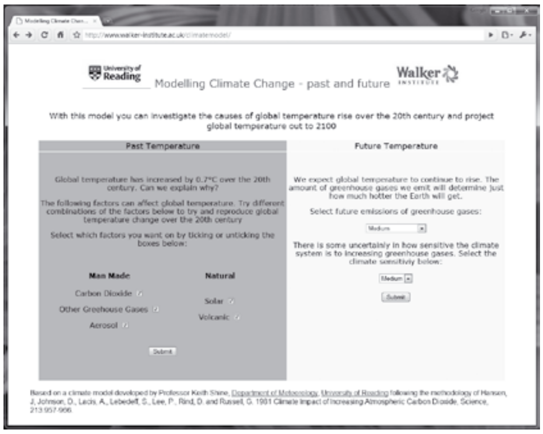
   The model allows you to look at the effect of *forcing factors* (i.e. factors that cause the climate to change) on past climate.

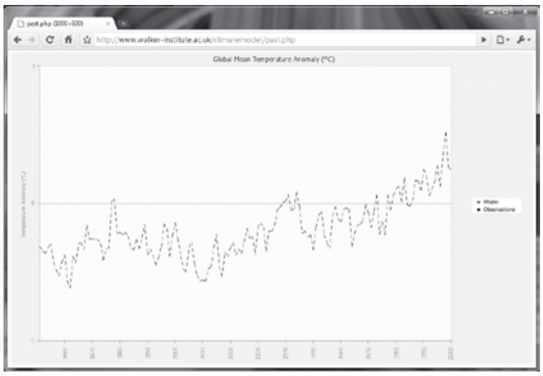
2. Uncheck all the man-made and natural forcing factor boxes. Click 'Submit'.

3. The graph produced shows a plot of 'annual global temperature anomalies'. These are the deviations from the long-term mean global temperature. Look at the observed data – how has temperature changed over the 20th century? Look at the 'model' plot – what does this look like?

4. Now repeat, checking each man-made and natural forcing factor in turn to investigate how they have affected temperature. How have volcanic eruptions affected temperature? How has increasing carbon dioxide affected temperature?

5. Combine different forcing factors to get the best match with the observed temperatures. Which combination of factors gives the best fit? What does this tell you about the causes of temperature change over the 20th century?





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MODELLING CLIMATE CHANGE:

GLOBAL TEMPERATURE CHANGE MODEL

Task B Predicting the future

6. Go back to the home page, and look at the section 'Future temperature'.

To calculate what might happen to the temperature in the future we must make assumptions about the quantity of greenhouse gases being emitted into the atmosphere. The model lets you select different *scenarios* representing different levels of emissions.

7. Set the scenario to low and climate sensitivity to medium, and click 'Submit'. The model produces a graph showing the predicted temperature change. Read off the value of the temperature change in 2100 and record it in a table similar to the one shown here.

8. Repeat, setting the scenario to medium and then to high, keeping the climate sensitivity set to medium each time. Record the values in your table.

Climate sensitivity is a measure of how sensitive the climate system is to change. Scientists don't know the climate sensitivity precisely. It is another important source of uncertainty.

9. Try changing the value of climate sensitivity. What happens to temperature as you change the climate sensitivity from low to high? Record the temperature change in 2100 in your table.

10. How much will temperature change by 2100? What do your results tell you about uncertainty in future global temperature change?

11. All models have limits. Can you think of things that this model does not tell us about future climate?

Future emissions scenario	Climate sensitivity	Temperature change by 2100 (°C)
Low emissions	low	
	medium	
	high	
Medium emissions	low	
	medium	
	high	
High emissions	low	
	medium	
	high	

Science Enhancement Programme

MODELLING CLIMATE CHANGE:
ANALYSING OBSERVED CLIMATE CHANGE

Studying climate change isn't just about models, observations are needed too.

In this activity, you will analyse temperature and rainfall observations from Reading for the last 30 years, and compare these with data for Central England and the whole globe.

Task A The climate of Reading, Berkshire

1. Open the Excel spreadsheet *MCC_DataAnalysis* and click on the tab 'Reading monthly'. This shows monthly mean temperature and rainfall. What period of time does the data cover?

2. Look at the July temperature data. In which year was the warmest July? And the coldest? Calculate the range of July temperatures over the period 1971 to 2000.

3. Using the July rainfall data, find the range of rainfall over the period 1971 to 2000.

Task B Climate change at Reading

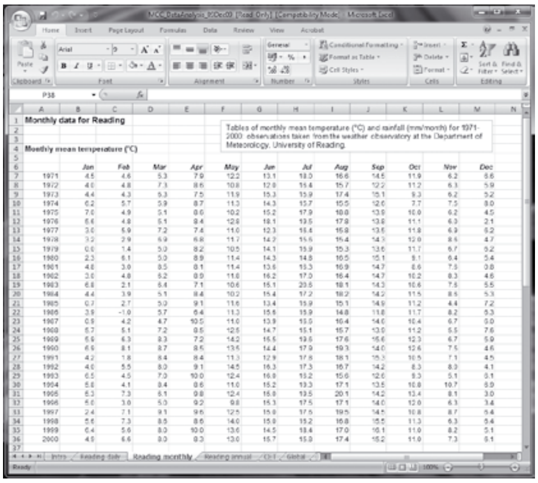
4. Using the data on the tab 'Reading monthly', calculate the annual mean temperatures. Plot annual mean temperature against year.

5. Calculate the annual mean rainfall for each year and plot against time.

6. Look at your two graphs. How have temperature and rainfall changed over time? What do you notice about how they vary from year to year?

7. Fit a linear trendline through each plot (select the chart, and from the 'Layout' menu, in the Analysis section, select 'Trendline'). The slope of the line gives you the linear trend.

8. Over the period 1971-2000 how much has temperature and rainfall changed per decade?



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MODELLING CLIMATE CHANGE:

ANALYSING OBSERVED CLIMATE CHANGE

Task C Climate change at Reading compared with global climate change

Another common technique used by climate scientists is to look at the data in terms of a difference from a long-term mean – known as an *anomaly*.

9. Go to the tab 'Reading annual'. Plot the 'annual anomaly' against time. What do you notice?

10. Select the tab 'CET' – this gives mean quarterly temperatures for Central England. Calculate the annual average, and the anomaly. Plot the anomalies against time. What do you notice?

11. Choose the tab 'Global' – this gives global temperature anomalies. These data are derived from data collected by stations across the whole world. Plot the anomalies against time. What do you notice?

12. On the 'Central England' and 'Global' graphs, adjust the scales of the vertical axes so that they are the same as on the 'Reading' graph. What do you notice about the three graphs?

13. Fit trend lines through the three graphs (Reading, Central England and Global). What do these graphs show and what can you say about the trend in °C per decade?

Science Enhancement Programme

MODELLING CLIMATE CHANGE:
ESTIMATING ENERGY FLOW FROM THE SUN

All of our weather and climate is driven by energy from the Sun. The energy from the Sun is transferred to the Earth by radiation. In this activity you will use a lamp to estimate the flow of energy from the Sun.

Do not touch the hot light bulb.

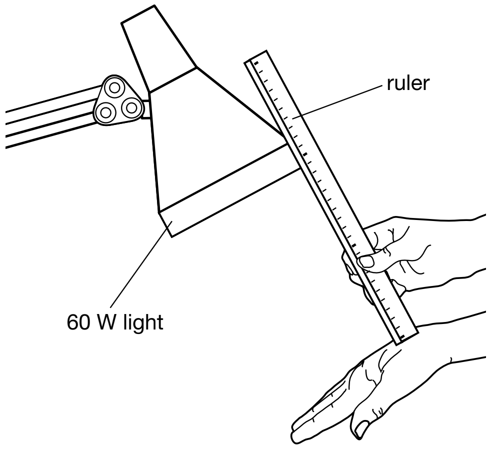
1. Switch on the lamp and put your hand about 20 cm from the light bulb. Can you feel anything? How is energy being transferred from the lamp to your hand? In what way is the lamp like the Sun?
2. Move your hand closer to the lamp and stop when the warmth feels similar to the Sun on a warm day. Measure and record the distance from the centre of your hand to the light bulb.

   The energy spreads out in all directions from the bulb. You can think of your hand as being part of a 'sphere' with an area of $4\pi r^2$ where r is the distance from the centre of the bulb to your hand.
3. Use the following equation to work out the value of the energy flow at the position of your hand:

$$\text{energy flow (W/m}^2) = \frac{\text{power of bulb (W)}}{\text{area (m}^2)}$$

$$= \frac{\text{power of bulb (W)}}{4\pi r^2 (\text{m}^2)}$$

4. Repeat with other students in your group and record the results in a table like the one shown. Use these results to calculate an average (mean).
5. The actual energy flow from the Sun at midday on a sunny mid-summer day in the UK is typically 1200 W/m². At the top of the Earth's atmosphere the value is around 1370 W/m². Is your estimate accurate?
6. Can you suggest any reasons why your estimated value may differ from the observed data?



Run	Distance (m)	Area (m²)	Energy flow (W/m²)
1			
2			
3			
4			
5			
Mean			

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MODELLING CLIMATE CHANGE: RADIATION FROM THE SUN AND EARTH

Climate scientists use the terms 'solar radiation' to refer to the electromagnetic radiation emitted by the Sun and 'terrestrial radiation' to refer to the electromagnetic radiation emitted by the Earth. In this activity, you will investigate how the very different temperature of the Sun and Earth affect the range of wavelengths of electromagnetic radiation they emit.

1. Use secondary sources such as the internet or books from the school library to find out the approximate average temperature of the Earth and the Sun. Record the information in a table like the one shown here.
2. You will now need to use a computer simulation that models the radiation given off by a hot object. Set the temperature to that of the Sun, using the value you found from your research. How does the solar radiation compare with the wavelengths of the visible spectrum?
3. Use the graph to read off the lowest and highest wavelengths, and the wavelength at the highest intensity, and record the values in a table like the one shown here.
4. Now repeat this, setting the temperature to that of the Earth. How does the terrestrial radiation compare with the wavelengths of the visible spectrum?
5. Use the graph to read off the wavelengths again and record the values in the table.
6. Use secondary sources to find a diagram of the electromagnetic spectrum and make a copy. Mark the range of wavelengths and maximum intensity of solar and terrestrial radiation. Add a key to your diagram.
7. Look carefully at your diagram. Which radiation has the longest wavelengths? How does this relate to energy?

Object	Average temperature (°C)
Earth	
Sun	

Object	Lowest wavelength (nm)	Highest wavelength (nm)	Highest intensity wavelength (nm)
Earth			
Sun			

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MODELLING CLIMATE CHANGE: GLOSSARY OF TECHNICAL TERMS

Word	Definition
Albedo	The proportion of solar energy that is reflected by the Earth.
Anomaly	The difference from a long-term mean.
Climate	The mean 'weather' (e.g. temperature, rainfall or sunshine hours) over a period of tens to thousands of years. More strictly, climate is the mean, variability and other statistical characteristics of weather. A period of 30 years is often used to define climate.
Climate change	Any change in weather statistics (e.g. mean temperature and rainfall) due to natural causes or to human activity.
Climate sensitivity	The amount of warming or cooling that occurs in response to a change in a forcing factor (e.g. a change in the flow of energy from the Sun).
Enhanced greenhouse effect	The extra warming caused by an increase in greenhouse gases.
Equilibrium	A stable situation where the input is in balance with the output.
Forcing / forcing factors	Things that cause the climate to change; some are natural (e.g. changes in the flow of energy from the Sun) and some are man-made (e.g. increasing greenhouse gases).
Global warming	The increase in globally averaged temperature over the 20th century, due to the burning of fossil fuels and the release of greenhouse gases into the atmosphere.
Greenhouse gas	A gas that contributes to the natural or enhanced greenhouse effect by absorbing infrared radiation. Examples are carbon dioxide, water vapour and methane.
Model	An approximation to a real-life situation which uses only the most important variables. This can be used to help us understand complex scientific observations and make predictions.
Natural greenhouse effect	A natural effect where gases in the atmosphere absorb infrared radiation and act like a blanket to keep the Earth warm.
Negative feedback	When the response of a system acts to weaken the effect of an initial change. For example, as the Earth warms, emission of terrestrial radiation increases and this acts to cool the planet.
Positive feedback	When the response of a system acts to amplify the effect of an initial change. For example, as the Earth warms, ice and snow melt, more solar radiation is absorbed and so the atmosphere warms further.
Solar radiation	Incoming energy from the Sun.
Steady state	Where a system does not change over time because inputs into the system are balanced by outputs from the system.
Trend line	A line on a graph which connects significant points to show a statistical trend; this is not necessarily the same as the line of best fit.
Terrestrial radiation	Outgoing energy emitted by the Earth.

Science Enhancement Programme

BACKGROUND SCIENCE

This section gives further information about the magnitude of the energy flow from the Sun, the differences between solar and terrestrial radiation and their absorption by the atmosphere, and the mathematics underpinning a simple energy balance model of the atmosphere.

THE FLOW OF ENERGY FROM THE SUN

The flow of energy from the Sun, called the solar irradiance, is defined as the amount of incoming solar electromagnetic radiation per unit area that would be incident on a plane perpendicular to the Sun's rays at the top of the Earth's atmosphere. Imagine being at the top of the atmosphere and pointing a 1 m^2 piece of paper directly toward the Sun. The amount of energy falling on this piece of paper in 1 second is defined as the solar irradiance (units of W/m^2). Solar irradiance is often referred to as the 'solar constant', a rather confusing term as, in reality, the flow of energy from the Sun is not constant, but varies very slightly. On average the solar irradiance is 1370 W/m^2.

The total amount of solar radiation received by the Earth is determined by its cross-sectional area (πR_E^2), but this energy is distributed across the Earth's entire surface area ($4\pi R_E^2$). Hence the average incoming solar radiation, taking into account the angle at which the rays strike and that at any one moment half the planet does not receive any solar radiation, is one quarter of the solar irradiance. This gives a value of approximately 342 W/m^2. At any given moment, the amount of solar radiation received at a particular location on the Earth's surface depends on the state of the atmosphere, the latitude, time of day and season.

Estimating the flow of energy from the Sun using a light bulb

The same flow of energy can be received from a far-away object emitting a large amount of energy as a closer and less powerful emitter. The Sun's power (*P*) is 3.8×10^{26} W; this energy is emitted in all directions. So the flow of energy at a distance *r* from the Sun will be spread over the surface area of a sphere with radius *r*:

$$\text{energy flow} = \frac{P}{4\pi r^2}$$

At the top of the Earth's atmosphere, this distance is 1.49×10^{11} m (the average distance from the Earth to the Sun), and the energy flow will be:

$$\text{Sun's energy flow at the top of the atmosphere} = \frac{3.8 \times 10^{26}}{4\pi(1.49 \times 10^{11})^2} = 1362 \text{ W/m}^2$$

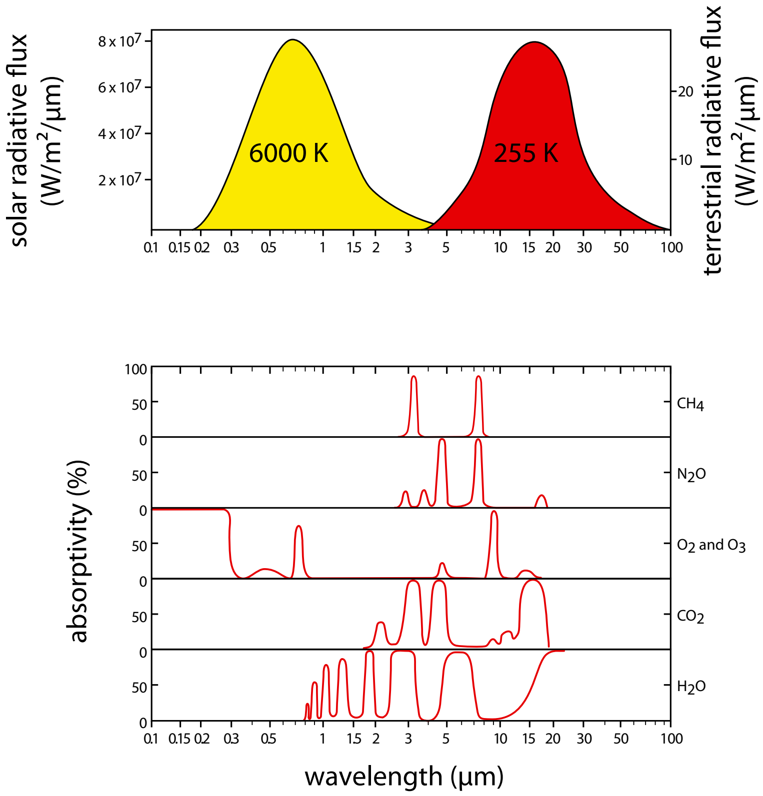
This is close to the average observed value of 1370 W/m^2. A 60 W light bulb positioned around 6 to 7 cm away will produce a similar flow of energy as received from the Sun at the top of the atmosphere:

$$\text{energy flow} = \frac{60}{4\pi \times 0.06^2} = 1326 \text{ W/m}^2$$

CHARACTERISTICS OF SOLAR AND TERRESTRIAL RADIATION

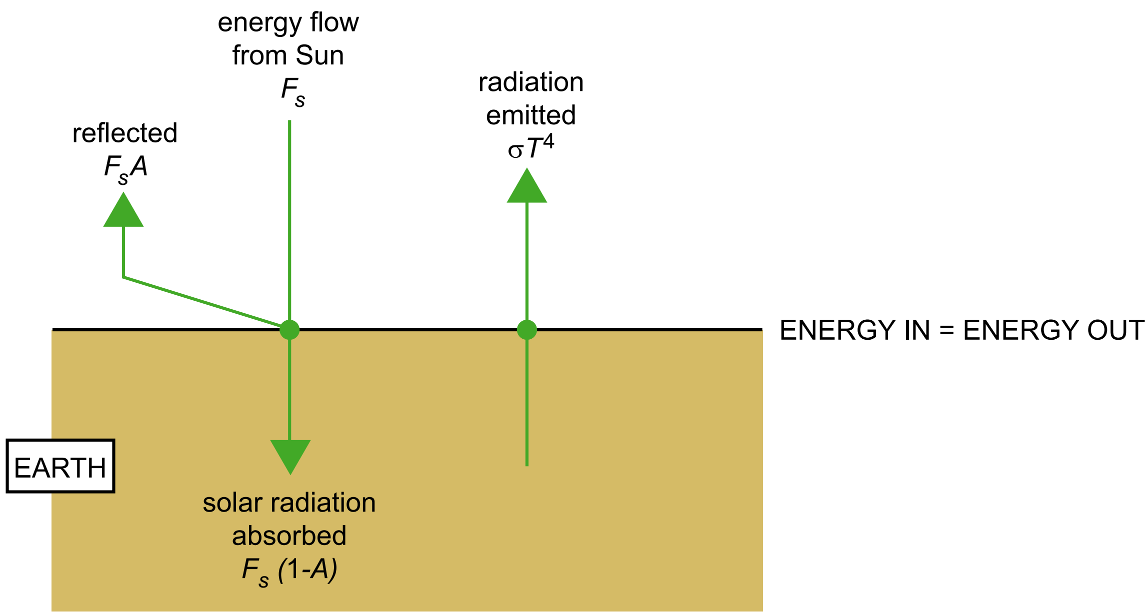
The Earth and the Sun are at very different temperatures and this means that they emit very different wavelengths of electromagnetic radiation. The Sun emits electromagnetic radiation most strongly at 0.5 – 1 μm, while the Earth emits most strongly at 10 – 20 μm. Because there is little overlap in the wavelengths of emission by the Sun and by the Earth, climate scientists treat them separately – as solar and terrestrial radiation.

The absorption of electromagnetic radiation in the Earth's atmosphere varies according to wavelength. The longer wavelengths of terrestrial radiation are absorbed strongly by water vapour, carbon dioxide, methane and other greenhouse gases. Solar radiation is absorbed more weakly and so passes through the atmosphere to be absorbed directly by the Earth's surface.



AN ENERGY BALANCE MODEL OF THE CLIMATE SYSTEM

A very simple model of the climate system can be developed based on the radiative energy balance between solar radiation absorbed and terrestrial radiation emitted. Initially we ignore the effect of the Earth's atmosphere.



In this case, there is a balance between solar radiation absorbed, $F_s(1\text{-}A)$, and terrestrial radiation emitted to space, σT^4, that is:

$$F_s(1-A) = \sigma T^4$$

Where:

F_s = Solar irradiance x ¼ (342 W/m^2)

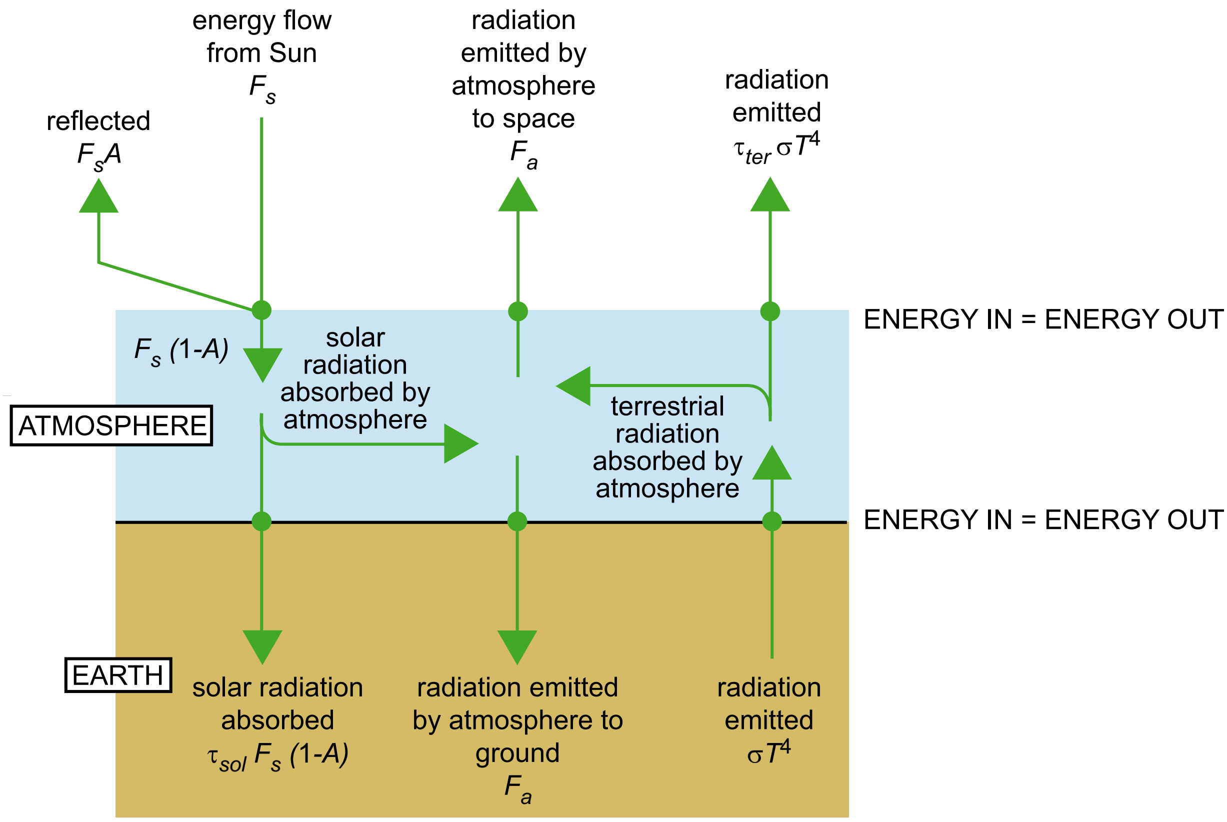
A = Earth's albedo (the amount of solar radiation reflected ≈ 0.3 or 30%)

σ = Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2/K^4)

T = Earth's average surface temperature.

Using the values F_s = 342 W/m^2 and A = 0.3, the calculated temperature is 255 K or -18 °C. The temperature is cold because we have ignored the absorption of radiation by the atmosphere.

Now we add in the effect of the Earth's atmosphere and introduce terms for the transmission of solar radiation through the atmosphere (τ_{sol}) and the transmission of terrestrial radiation through the atmosphere (τ_{ter}). If all terrestrial radiation passes through the atmosphere without being absorbed then τ_{ter} = 1.0; if all terrestrial radiation is absorbed by the atmosphere then τ_{ter} = 0.0. If all solar radiation passes through the atmosphere without being absorbed then τ_{sol} = 1.0; if all solar radiation is absorbed by the atmosphere then τ_{sol} = 0.0.



The atmosphere also emits infrared radiation in all directions - up into space (F_a) and the same amount down to the ground (F_a). We can now consider the energy balance at the top of the atmosphere and the energy balance at the ground:

At the top of the atmosphere: $F_s(1-A) = F_a + \tau_{ter}\sigma T_s^4$ (1)

At the ground: $\tau_{sol}F_s(1-A) + F_a = \sigma T_s^4$ (2)

Where:

τ_{ter} is the proportion of terrestrial radiation (i.e., the radiation emitted by the Earth) that passes through the atmosphere and escapes to space

τ_{sol} is the proportion of solar radiation that passes through the atmosphere and reaches the surface.

The left-hand side of equation (1), F_s(1-A), represents the flow of energy from the Sun entering the atmosphere, and the right-hand side represents the flow of energy leaving the atmosphere. To re-express the right-hand side to eliminate F_a, it can be substituted using equation (2), to give:

$$F_s(1-A) = \sigma T^4 - \tau_{sol}F_s(1-A) + \tau_{ter}\sigma T^4$$

Rearranging this gives:

$$F_s(1-A) = \frac{1+\tau_{ter}}{1+\tau_{sol}}\sigma T_s^4 \qquad (3)$$

The atmosphere absorbs much of the terrestrial radiation emitted by the Earth, so transmission of terrestrial radiation is low: τ_{ter} is approximately 0.1 (in today's atmosphere). Comparatively little solar radiation is absorbed by the atmosphere, so transmission of solar radiation is high: τ_{sol} is approximately 0.8.

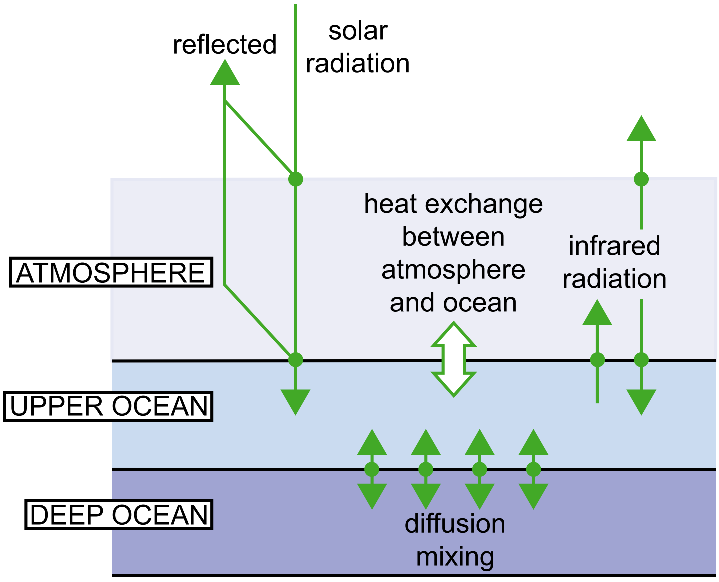
Now if we use equation (3) to calculate the Earth's temperature we get 288.3 K or 15.3 °C because the absorption of terrestrial radiation by the atmosphere keeps the surface warm (this is the natural greenhouse effect).

This energy balance model based on equation (3) is the one that is used in the various versions of the spreadsheet model that accompany the student activities. The left-hand side of equation (3) gives the calculated value for 'solar radiation absorbed' (the left-hand bar of the spreadsheet model graph); the right-hand side of the equation gives the value for 'terrestrial radiation emitted' (the right-hand bar of the graph). Note that in the spreadsheet model, τ_{sol} is kept constant at 0.8. Note this model ignores transfer of energy from the surface by convection and evaporation.

A MORE COMPLEX MODEL OF THE CLIMATE SYSTEM

The more complex model used in Activity A9 is a global mean, one-dimensional climate model which is based on a simple atmosphere and ocean. The atmospheric part of the model includes the effect of incoming solar radiation and outgoing infrared radiation. As well as radiative energy exchange, it also includes the effect of convection which transports heat from the surface into the atmosphere. The effect of the ocean is incorporated in the model, and this acts to slow the response of the climate system. The ocean has a mixed-layer (typically 100 metres deep) coupled to a deep ocean by diffusion. The model takes account of the effects of climate feedbacks (such as, water vapour feedback and ice/reflectivity feedback) as a single variable – the climate sensitivity. The exact value of climate sensitivity is not known and is the subject of much scientific research.

The model is initially assumed to be in balance. Various forcing factors (see below) can be included which perturb this balance; the model responds to this imbalance by changing its temperature. The climate sensitivity determines the magnitude of temperature change for a given imbalance.



The model is provided with a web interface, and can be used to investigate how natural and man-made factors have influenced temperature over the 20th century and to predict how global temperature might change over the 21st century.

To investigate past climate change, students can switch various forcing factors on and off:

- man-made
  - carbon dioxide
  - other greenhouse gases
  - aerosols
- natural
  - volcanic eruptions
  - variations in the flow of energy from the Sun.

Scientists do not know exactly how the man-made and natural forcing factors above have changed over the 20th century (or over longer timescales). Carbon dioxide forcing is best known, while aerosols and variations in the flow of energy from the Sun over century timescales are least well known.

To look at the future, users can specify a scenario of future greenhouse gas emissions (high, medium and low). A high scenario assumes continuing rapid population growth and high dependency on fossil fuels; a low scenario assumes a slowdown in population growth and greater reliance on renewable and other non-carbon based fuels. Users can also specify the climate sensitivity (high, medium and low). This quantity reflects how sensitive the climate system is to a change in forcing. For example, a low climate sensitivity means less warming for a given increase in greenhouse gases.

REFERENCES AND FURTHER READING

Websites

Additional resources can be found on the SEP website (see page 50). Links to other particularly relevant websites are also listed on the SEP website. Some examples are given below:

Met Office (www.metoffice.com)
The Met Office has an extensive weather and climate learning section with resources for teachers and activities for pupils from ages 5 to 16.

Climateprediction.net (http://climateprediction.net)
Here you can run a climate model on your home computer and take part in a worldwide experiment to investigate future climate change. Within the 'Support' section of the website there is a range of science activities for 11-16 year olds.

Royal Meteorological Society (www.rmets.org)
This organisation aims to promote education on all aspects of meteorology and related sciences. Resources for school children and teachers can be found within the 'Our Activities' section.

BBC (www.bbc.co.uk/climate and www.bbc.co.uk/schools/bitesize)
The BBC website has an extensive section on climate change which provides useful background information. There are climate change related resources for students and teachers within the BBC Bitesize section.

Catalyst: Secondary Science Review (www.sep.org.uk/catalyst)
This topical magazine for secondary school students has articles on a wide range of subjects across the science curriculum, bringing them to life with insights into cutting-edge research. There are a number of articles about the climate, computer modelling and the effects of climate change.

Books and other publications

Teach Yourself Weather
Inness P (2008) Publisher: Hodder Education (ISBN: 978-0340966419)
A comprehensive and practical guide to the workings of the atmosphere.

Global Warming: The Complete Briefing
Houghton J (2009 4th Edition). Publisher: Cambridge University Press (ISBN: 978-0521709163)
A clear and comprehensive guide to climate change, its impacts and mitigation policies.

SOURCES

The following diagrams are from Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Publisher: Cambridge University Press): climate system on page 3 (FAQ 1.2 Fig. 1), Earth's energy balance on page 8 (FAQ 1.1 Fig. 1), solar irradiance on page 11 (2.17), carbon dioxide concentration on page 11 (SPM 1), observed temperature trend on page 17 (TS.6), future temperature change on page 18 (SPM 5), pattern of temperature and rainfall change on page 18 (SPM 6, SPM 7). The following photos have been reproduced from Bigstock.com: rendered illustration of Sun on page 4 (© Sebastian Kaulitzki), Earth as seen from space on page 4 (© Lars Lentz), Mount St. Helens volcano on page 12 (© Corey Ford), industrial smoke stack on page 12 (© Darren Baker), field cut in Amazon rainforest on page 12 (© Mika Makelainen), open water with pack ice near Antarctic on page 14 (© Armin Rose), and clouds on page 15 (© Silvia Bukovac).

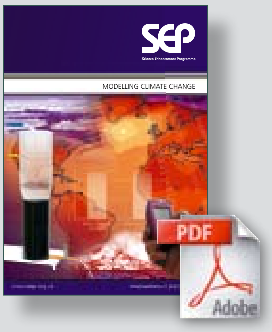
The climate model used in Activity A9 was developed by Professor Keith Shine, Department of Meteorology, University of Reading following the methodology of Hansen, J, Johnson, D, Lacis, A, Lebedeff, S, Lee, P, Rind, D and Russell, G (1981) Climate Impact of Increasing Atmospheric Carbon Dioxide, *Science*, 213:957-966. The data used in Activity 10 are from Department of Meteorology, University of Reading (data for Reading, Berkshire) and from the Met Office (Central England and global temperature).

DOWNLOADING RESOURCES FROM THE SEP WEBSITE

SEP produces a range of digital resources to accompany each of its publications. These are available from the 'SEP Associates' area of the website (www.sep.org.uk).

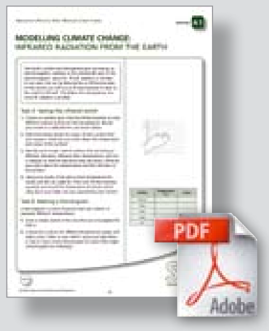
Membership of SEP Associates is free to all science teachers and technicians in UK schools. To join, fill in the online form on the website. SEP is wholly funded by the Gatsby Charitable Foundation, and joining SEP Associates entitles its members to additional benefits, including offers of free publications and other resources.

www.sep.org.uk



PDF file of booklet

On the SEP website there is a downloadable PDF file of the whole booklet that can be printed or viewed on screen.

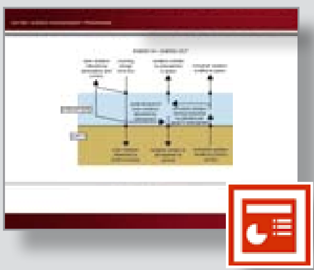


PDF files of student sheets

In addition to the whole booklet, the student activities are available as separate PDF files.

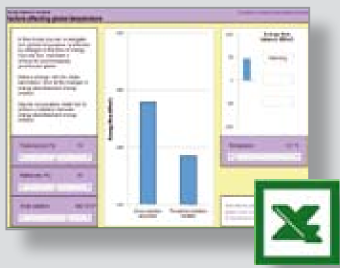
Word files of student sheets

Each student sheet also exists as a Word file. These files can be edited in order to adapt the activities to suit individual circumstances.



PowerPoint presentations

These contain the photographs and drawings shown in this booklet. They can be used to create custom-made presentations.



Spreadsheet files

These include the energy balance model of the climate system, and the weather data for Reading, Central England and the globe as a whole.

Links to other sites

The SEP website provides links to other useful websites on this topic.

MUTR.co.uk in association with Middlesex University

OBTAINING THE PRACTICAL RESOURCES

SEP works in close partnership with Middlesex University Teaching Resources (MUTR) in identifying and developing low-cost practical resources to accompany its publications. Many other resources for school science and technology can also be purchased from MUTR.

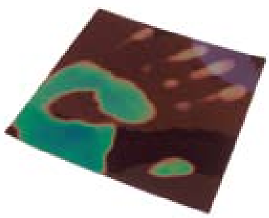
The latest prices of the products shown below and further information can be obtained from www.mutr.co.uk, or by requesting their latest catalogue. Orders can be made by post, telephone, fax or email by providing an official school order number or by credit card.

The kit contains the parts required to make the system (plastic drinks bottle and clip not included).

Steady state bottle kit
SEP 230
The steady state bottle kit can be used to model how the temperature of a steady state system is determined by the flow of energy in and the flow of energy out of the system.

Infrared thermometer
161-300
A non-contact infrared thermometer measuring from -20 to +220 °C (precision 0.1 °C).

Magnetic compass
BLC 002
A low-cost large diameter magnetic compass.



Thermocolour film
IT9 001
Self-adhesive sheet that changes colour of the temperature range 25 – 30 °C.

Infrared emitter kit
SEP 038
This consists of an infrared LED connected to a battery box.

Infrared detector kit
SEP 039
A red LED lights up when infrared radiation is detected by the phototransistor at the front of the kit.

You can download the written materials in this booklet, and find further information from: Science Enhancement Programme www.sep.org.uk

The Science Enhancement Programme (SEP) is part of Gatsby Technical Education Projects. It undertakes a range of activities concerned with the development of curriculum resources and with teacher education.

Gatsby Science Enhancement Programme
Middlesex University
S37 Stable Yard
Bramley Road
London N14 4YZ
Email: info@sep.org.uk
Web: www.sep.org.uk

The Gatsby Charitable Foundation

The University of Reading's Walker Institute for Climate System Research aims to improve understanding of future climate and its impacts.
Web: www.walker-institute.ac.uk

You can order a range of practical resources to support the teaching of climate change from Middlesex University Teaching Resources.

Teaching Resources
Middlesex University
Unit 10, The IO Centre
Lea Road, Waltham Cross
Hertfordshire EN9 1AS
Tel: 01992 716052
Fax: 01992 719474
Email: sales@muventures.co.uk
Web: www.mutr.co.uk

www.sep.org.uk

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