

# 'Everything That You Wanted To Know About Climate Change But Could Not Find In A Text Book!'

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Resources that will assist South African science teachers  
teaching about the Atmosphere and Climate Change.

Produced as part of the SEEDS tour 2011

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## Acknowledgement

These articles were originally published in 'Science in Schools', the pan-European journal for science teachers. See [www.scienceinschools.org](http://www.scienceinschools.org)

Climate change modelling in the classroom;

<http://www.scienceinschool.org/2008/issue9/climate>

Practical demonstrations to augment climate change lessons;

<http://www.scienceinschool.org/2008/issue10/climate>

Fuelling interest: climate change experiments;

<http://www.scienceinschool.org/2009/issue11/climate>

Looking to the heavens: climate change experiments;

<http://www.scienceinschool.org/2009/issue12/climate>

A hole in the sky;

<http://www.scienceinschool.org/2010/issue17/ozone>

Is climate change all gloom and doom? Introducing stabilisation wedges

<http://www.scienceinschool.org/2011/issue20/wedges>

Many of the articles are also translated into several European languages.

## Practical demonstrations to augment climate change lessons

**Dudley Shallcross** and **Tim Harrison** from Bristol University, UK, illustrate chemistry experiments relevant to climate change.

There are a number of chemicals that are important to consider for climate change, either as contributors to global warming (soot and carbon dioxide) or as alternative fuels (methanol and hydrogen). In the second of two articles (see also Shallcross & Harrison, 2008), we present several classroom demonstrations and experiments to introduce these materials and describe how they can be used to enliven climate change lessons.

**Safety note:** Local rules and regulations on health and safety should be applied before trying these out. Always practice the experiments before presenting them in front of students.

### ***Soot / particulate carbon***

Soot fits into the category of airborne particulate matter<sup>w1</sup>. Particles are considered hazardous when they are less than five micrometres in diameter, as they are not filtered out by the upper respiratory tract before entering the lungs.

Black carbon will enhance global warming, but not all particles in the atmosphere do. It all depends on their optical properties: if the particles are very reflective, like a mirror (e.g. sea-salt particles), they can reflect incoming solar radiation back to space and decrease the radiation that reaches Earth, causing a reduction in surface temperature. If they are dark, such as soot, they will absorb incoming radiation and enhance warming.

Soot is a product of incomplete combustion, for example in car motors, central heating or power stations. There are a number of reactions that can produce soot. The simplest teacher demonstration is to burn small pieces of expanded polystyrene packaging, holding them with tongs over a heatproof mat. The yellow flame produced is very smoky, and the smoke contains black specks of carbon. However, this is not a suitable reaction for students to perform, as the polystyrene drips molten droplets of burning material; instead, the teacher should demonstrate.

If a class experiment to produce soot is needed, the combustion of freshly prepared acetylene (ethyne,  $C_2H_2$ ) gas is an entertaining reaction. Take a 250 ml glass beaker, place it on a heatproof mat and half fill the beaker with water. Add a good squirt of washing-up liquid to the water and also a few pieces of calcium carbide ( $CaC_2$ ). The reaction is immediate, liberating bubbles of acetylene. The teacher or student can then use a lit splint, taper or match to ignite the foam. This burns dramatically with a yellow flame with smuts of carbon (see images below).



**To produce soot, a beaker is filled with water and washing-up liquid. Adding a few pieces of calcium carbide ( $\text{CaC}_2$ ) liberates bubbles of acetylene. If ignited, this foam gives a yellow flame with smuts of carbon**

**Safety notes:** As with all experiments, safety glasses must be worn.

If the beaker is over-filled or too much calcium carbide is used, the bubbles can overflow onto the heatproof mat. These bubbles can also combust! Bubbles may continue to be ignited by others burning near them. This may go on for 30 seconds or so. Leave any used beaker in a fume cupboard until all the ethyne gas has been produced and the bubbling stops.

The residual solution is mainly alkaline calcium hydroxide solution.

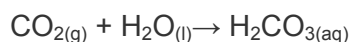
### ***Solubility of $\text{CO}_2$ in water / precipitation of calcium carbonate***

If dry ice is available, an interesting experiment can be performed to demonstrate the solubility of carbon dioxide in water. This can be used to introduce a discussion about the uptake of carbon dioxide ( $\text{CO}_2$ ) by the oceans as a possible mechanism for removing carbon dioxide from the atmosphere. For this very visually impressive reaction, add a handful of dry ice (take care to avoid cold temperature burns) to a large (1 l) beaker of water that has been made alkaline ( $\text{pH} = \sim 12$ ) with sodium hydroxide ( $\text{NaOH}$ ) solution, and to which a small volume of universal ( $\text{pH}$ ) indicator has been added.

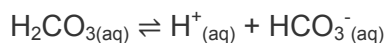
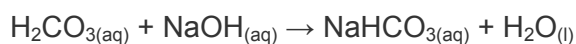


**Tim Harrison and Dudley Shallcross with dry ice reacting in alkaline water**

Apart from the impressive condensation of water vapour, forming a cloud above the beaker, the formation of carbonic acid (a weak acid) causes a series of colour changes to the indicator from purple through to orange (see image above). For a more impressive cloud, use hot water, as there is more water vapour to condense. The condensation is caused by very cold carbon dioxide gas produced when the dry ice sublimates, using energy from the much hotter water. Some of the carbon dioxide dissolves in the water.

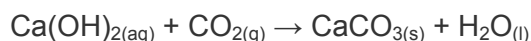


The carbonic acid formed neutralises the sodium hydroxide, forming sodium hydrogen carbonate.

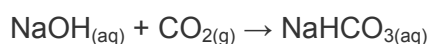


Excess  $\text{H}_2\text{CO}_{3(\text{aq})}$  is acidic because it dissociates in water, releasing hydrogen ions.

A small piece of dry ice placed in lime water (calcium hydroxide solution,  $\text{Ca}(\text{OH})_{2(\text{aq})}$ ) can also be used to show the precipitation of carbon dioxide as calcium carbonate. The oceans of the world dissolve carbon dioxide gas and can precipitate calcium carbonate, which is used in shell construction by numerous creatures. The rate of dissolution is too slow to compensate for the increase in atmospheric carbon dioxide:



If no dry ice is available, then a 2 l drinks bottle could be filled with carbon dioxide gas and about 30 cm<sup>3</sup> of 2 mol dm<sup>-3</sup> sodium hydroxide can be added. Place the top on the bottle and shake. The bottle should start to collapse as the carbon dioxide gas reacts with the sodium hydroxide, thus reducing the pressure inside the bottle. The solution forms exothermically so that it gets warm. This shows that carbon dioxide gas is acidic. This has implications for the change in the ocean's pH as the high concentrations dissolve over time.



**Safety notes:** Lime water (calcium hydroxide solution) is an alkaline solution, as is sodium hydroxide solution; safety glasses must be worn.

Dry ice (solid carbon dioxide) is -78 °C or less and will cause cold burns. Great care must be exercised in handling the solid. The use of suitable gloves is recommended. Dry ice should not be kept in a screw-top container because of the risk of explosion.

### ***Methanol whoosh bottle***

Methanol is a biofuel, an alternative to fossil or nuclear fuels, and this experiment can be used to demonstrate its combustion. In addition to being a renewable fuel, methanol has the advantage over fossil fuels of not releasing 'stored' carbon dioxide into the atmosphere; instead, it merely recycles carbon dioxide that is in the environment anyway.

Methanol vapour (which is toxic) can be ignited inside an 18 l plastic water bottle of the type used in water dispensers. Note that after the experiment, the container will no longer be fit for its original purpose!



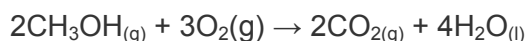
Pour around 20 ml of methanol (methyl alcohol, CH<sub>3</sub>OH) into a dry 18 l water canister and shake to vaporise. Pour out the surplus liquid methanol. In a warm room, you will be able to feel the pressure of the vapour if you hold your hand over the bottle mouth. Put the bottle behind a transparent safety screen on the floor and away from any overhead heat, flame, flash sensors or curtains. Put a lighted taper or match to the mouth of the water bottle, holding it at arm's length. A blue flame will erupt with a loud roar as the methanol completely combusts.

### **A methanol whoosh bottle ignited in a darkened room**

**Safety notes:** Avoid methanol coming directly into contact with your skin, as it is toxic. Any liquid methanol must be poured out of the container away from any flame source.

The water canister cannot subsequently be used for drinkable water.

The water bottle must be dry, as the tops of wet bottles tend to melt during the combustion!



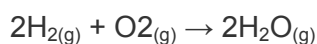
### **Hydrogen-filled balloons**

This teacher demonstration could be used to introduce hydrogen as an alternative fuel to replace fossil fuels, and especially to raise the question of whether the combustion product is a greenhouse gas.

One way to demonstrate that hydrogen is a fuel is to fill a balloon with hydrogen and tether it to a chair placed away from sensors and flammable materials (such as posters, blinds or curtains) using a piece of thin string. Ignite the balloon using a lit taper or match, fastened to the end of a metre ruler or a long pole at arm's length. Students should remain several metres away, as, during the resultant explosion, bits of the rubber balloon tend to fly in all directions. Those with sensitive hearing should place their hands over their ears. The flame and heat energy liberated are spectacular and should lead to discussion of hydrogen's suitability as a fuel.



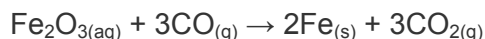
### **A 3 l hydrogen balloon on ignition**



**Safety note:** If in any doubt about the volume of flame produced, perform the experiment outside and away from glass windows.

### ***The reduction of iron oxide on a match head***

The use of blast furnaces in the iron and steel industries contributes to the atmospheric concentration of carbon dioxide. The crucial reaction, which reduces iron oxide to pure iron by means of carbon monoxide, is:



Students can mimic this reaction on the head of a match.

Moisten an unlit match with water and roll into sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) powder, and then in iron oxide powder ( $\text{Fe}_2\text{O}_3$ ), so that both stick to the match head. Use a second match to ignite the first and let it burn for a moment or two. Crunch the first match head onto a watch glass or Petri dish. Drag a magnet against the underside of the watch glass; the small particles of iron formed will be visible as they follow the magnet's pull. Try this with the starting materials, to show that no magnetic materials were initially present.

The match provides both the energy for the reaction and the carbon monoxide as a reducing agent. The sodium carbonate acts as a flux material.

**Safety note:** Spilled iron oxide or sodium carbonate powders should be wiped up with a cloth. Do not blow them away, as – like any other fine powder – they pose a respiratory hazard.

Students, unless warned, could burn themselves on the hot match heads!

### ***Further experiments***

Other experiments that can be performed as part of a project about climate change include:

- The use of Grätzel cells to show the generation of electricity from sunlight, using the colorant molecules in materials such as blackcurrants
- The use of alcohol burners to determine the energy stored in simple alcohols
- The preparation of biodiesel from vegetable oils
- The generation of electricity from alcohols using a fuel cell

### ***References***

Shallcross D, Harrison T (2008) Climate change modelling in the classroom. *Science in School* **9**: 28-33. [www.scienceinschool.org/2008/issue9/climate](http://www.scienceinschool.org/2008/issue9/climate)

### ***Web references***

w1 – For more information about particulate matter, see the Wikipedia page: <http://en.wikipedia.org/wiki/Particulate>

w2 – Why not discuss how to teach climate change with other teachers across Europe? Join the *Science in School* online discussion forum: [www.scienceinschool.org/forum](http://www.scienceinschool.org/forum)

### ***Resources***

- Harrison T, Shallcross D, Henshaw S (2006) Detecting CO<sub>2</sub> – the hunt for greenhouse-gas emissions. *Chemistry Review* **15**: 27-30
- Johnson S (2008) Planting ideas: climate-change activities for primary school. *Science in School* **10**: 55-63 [www.scienceinschool.org/2008/issue10/psclimate](http://www.scienceinschool.org/2008/issue10/psclimate)

- Pacala S, Socolow R (2004) Stabilisation wedges: solving the climate problem for the next 50 years with current technologies. *Science* **305**: 968-972. doi: 10.1126/science.1100103
- Shallcross D (2006) Dirty Air. *Education in Chemistry*, Sep. [www.rsc.org/Education/EiC/Restricted/2006/Sept/DirtyAir.asp](http://www.rsc.org/Education/EiC/Restricted/2006/Sept/DirtyAir.asp)
- For a full list of *Science in School* articles about climate change, see: [www.scienceinschool.org/climatechange](http://www.scienceinschool.org/climatechange)
- Numerous notes on air pollution, climate change and ozone depletion notes for schoolteachers by the authors can be found online at: [www.chemlabs.bristol.ac.uk/outreach/resources/Atmos.html](http://www.chemlabs.bristol.ac.uk/outreach/resources/Atmos.html)
- An excellent source of graphics and data relating to climate change can be found on the website of the GRID-Arendal collaborating centre of the United Nations Environment Programme: [www.grida.no/climate/vital/index.htm](http://www.grida.no/climate/vital/index.htm)
- For data from the Earth Station research laboratory Global Monitoring Station, see: [www.cmdl.noaa.gov](http://www.cmdl.noaa.gov)
- The website of the Intergovernmental Panel on Climate Change, which includes the Climate Change 2007 report and other data, can be found here: [www.ipcc.ch](http://www.ipcc.ch)

## Fuelling interest: climate change experiments



**Dudley Shallcross, Tim Harrison, Steve Henshaw and Linda Sellou** offer chemistry and physics experiments harnessing alternative energy sources, such as non-fossil fuels.

Discussions of climate change in the science classroom can be very wide-ranging, but will probably involve different sources of energy and their consequences. Relevant topics are likely to include different fuels that can be used, how effective they are and how they are produced, and alternatives to combustion. We suggest a couple of laboratory activities to support physics and chemistry lessons on climate change.

Image courtesy of sbayram /

iStockphoto; earth image

courtesy of NASA

### 1) Measuring fuel efficiency

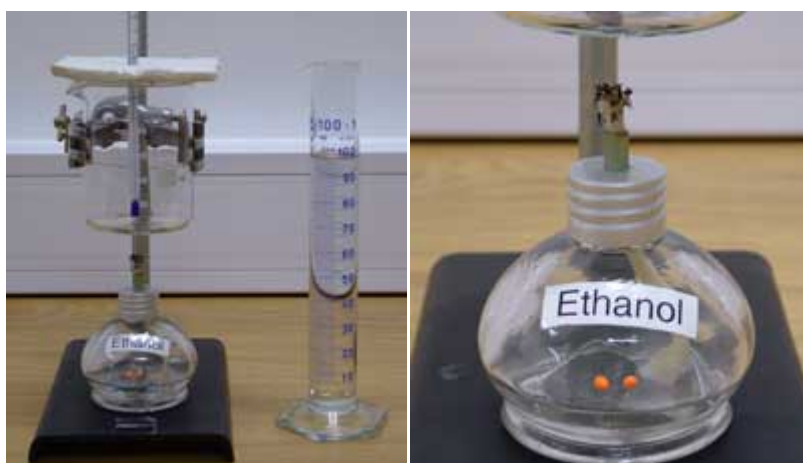
Unburned fuel evaporating into the atmosphere, during either storage or combustion, is an air pollutant, and also plays a role in determining the lifetime of greenhouse gases. One way to limit the damage is to use alcohols instead of more standard hydrocarbon fuels such as petrol and diesel.

Hydrocarbons in the atmosphere are oxidised by the hydroxyl radical ( $\bullet\text{OH}$ ) to form predominantly alcohols and carbonyls. Levels of atmospheric  $\bullet\text{OH}$  are important, as these radicals remove greenhouse gases that contain the C-H bond, such as  $\text{CH}_4$ . Computer simulations have shown that releasing alcohols into the atmosphere has a less damaging effect than releasing hydrocarbons, because fewer oxidation steps take place, removing smaller amounts of  $\bullet\text{OH}$ . Therefore, using alcohols instead of hydrocarbons as fuels has a positive effect on both air quality and the removal of greenhouse gases. Moreover, the smaller alcohols released into the atmosphere can be removed, to a small extent, by physical processes such as dry (taken up by a surface) and wet (rain, fogs, aerosols) deposition, whereas their hydrocarbon counterparts cannot.

Alcohols are used in fuel cells (see 'Fuel cells: energy from electrolysis') which have a wide range of potential applications, for example in short-range vehicles.

Of course, a good fuel is not only environmentally friendly – it must also be an efficient source of energy. The following experiment allows students to determine the energy released by burning different types of alcohols, and to compare their effectiveness with that of more standard fuels.

Alcohol burners are the small burners made of glass, complete with a wick, which usually come with children's chemistry sets and are readily available from schools equipment companies. They can be used to determine the energy released in the combustion of shorter primary alcohols such as methanol, ethanol, propan-1-ol, butan-1-ol and pentan-1-ol.



**Alcohol burner set up under a beaker to which a known volume of water is to be added**

The students can set up the experiment (see images above), in which the alcohol burner is filled with a known alcohol. First, weigh the burner and its contents. Measure out 150 ml of water accurately and place it in a 250 ml glass beaker. We assume that 1.0 ml of water weighs 1.0 g. Measure the water temperature at the beginning of the experiment and clamp the beaker above the burner, leaving a space of about 5 cm between the wick and the base of the beaker. Ignite the burner and place it centrally under the water container until the temperature has risen by 30 to 40 °C. Determine the temperature rise by recording the final temperature of the water. Weigh the final mass of the alcohol burner and its contents. It is at this stage that the students will not remember if they originally weighed the alcohol burner with the lid on or off! Calculate the mass of alcohol burned ( $M_B$ ).

The energy released in the combustion, used to raise the water temperature, can be calculated using equation (1)

$$\Delta H_C = -c \times M_{\text{water}} \times T_R \quad (1)$$

where:

$\Delta H_C$  = heat of combustion [kJ]

$c$  = the specific heat capacity of water = 4.187 kJ kg<sup>-1</sup> °C<sup>-1</sup>

$M_{\text{water}}$  = mass of water [kg]

$T_R$  = temperature rise of water [°C]

The combustion energy can then be expressed as energy per gram or energy per mole of the alcohol burnt, in order to compare the results obtained by several groups with the same alcohol or with different alcohols.

$$\text{Energy of combustion per gram} = \Delta H_C / M_B \quad (2)$$

$$\text{Energy of combustion per mole} = \Delta H_C \times M_r / M_B \quad (3)$$

where:

$M_r$  is the relative molecular mass of the alcohol being burnt,  
 $M_B$  is the mass of the burnt alcohol.

Further investigations that can be carried out by the students include:

- Change the alcohol that the burner uses. In practice, it is best to have sets of alcohol burners that use different alcohols, as it is very difficult to replace the alcohol in a wet wick
- An alternative to comparing several different alcohols is to compare just one alcohol with a night light (a small wax candle in a metal holder)
- Change the material that the beaker is made from, for example to copper or a galvanised steel food can
- Change the thickness of the material that the water container is made from
- Compare an insulated container (made from a heatproof material!) with a glass beaker
- Compare the open glass beaker being heated to one with a lid fitted on top, through which the thermometer is placed.
- Does it make a difference whether the water in the container is stirred or not?
- Does the height at which the beaker is clamped above the flame make any difference to the amount of heat absorbed by the water?
- Does it make a difference to have boards / heatproof mats placed around the burner to reduce draughts?
- Does the length of wick that is exposed make any difference?

Note that it is too dangerous to use petrol or diesel in these burners. Even without testing conventional fuels or different alcohols to compare the energies released by 'green' fuels, these experiments can be used to discuss experimental error and accuracy of measurement in general. It will be obvious from comparing the classroom experimental results with the textbook data or those available on Wikipedia<sup>w1</sup> (see table) that there are significant errors.

**Table 1: Heats of combustion for small primary alcohols (Handbook of chemistry and physics, 57th edition, CRC Press) and some common fuels (Wikipedia, [http://en.wikipedia.org/wiki/Heat\\_of\\_combustion](http://en.wikipedia.org/wiki/Heat_of_combustion), accessed 17/03/09)**

Name of alcohol / fuel	Standard heat of combustion [MJ / kg]
Peat (damp)	6.0
Peat (dry)	15.0

<b>Wood</b>	15.0
<b>Coal (Lignite)</b>	15.0
<b>Methanol</b>	22.7
<b>Coal (Anthracite)</b>	27.0
<b>Ethanol</b>	29.7
<b>Carbon</b>	32.8
<b>Propan-1-ol</b>	33.6
<b>Butan-1-ol</b>	36.2
<b>Pentan-1-ol</b>	37.7
<b>Diesel</b>	44.8
<b>Paraffin</b>	46.0
<b>Kerosene</b>	46.2
<b>Gasoline</b>	47.3
<b>Butane</b>	49.5
<b>Propane</b>	50.4
<b>Ethane</b>	51.9
<b>Natural gas (average, varies depending on source country)</b>	54.0
<b>Methane</b>	55.5
<b>Hydrogen</b>	141.8

## ***2) Producing biofuels from vegetable oil***

Biofuels are solid, liquid or gaseous fuels derived from relatively recently dead biological material, as opposed to fossil fuels, which are derived from long-dead biological material.

Whereas burning fossil fuels releases CO<sub>2</sub> which has been trapped for a long time, burning biofuels should only release CO<sub>2</sub> that has been recently captured from the atmosphere

during photosynthesis and converted to fuel. In theory, the process should therefore be carbon neutral. The production of biofuels, however, also generates CO<sub>2</sub>; the life-cycle emission (amount of CO<sub>2</sub> generated during production, use and waste disposal) of some first-generation biofuels even exceeds that of traditional fossil fuels.

So far, three generations of biofuels have been developed: first-generation biofuels are made from sugar, starch, vegetable oil, or animal fats. Besides having sub-optimal emission levels, first-generation biofuels have other important limitations: there is a threshold above which their production threatens food supplies and biodiversity. Moreover, they are more expensive than existing fossil fuels.



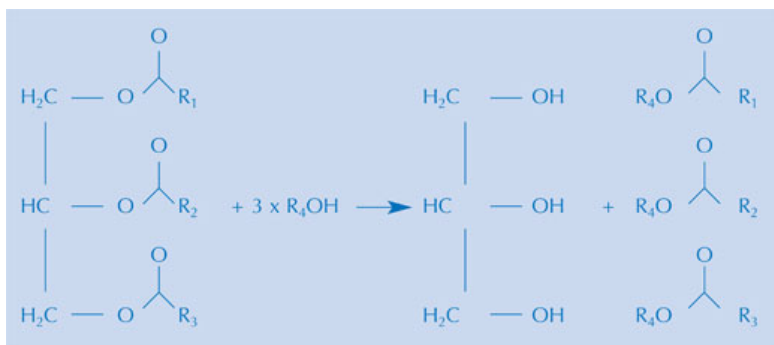
Image courtesy of alohaspirit / iStockphoto

This led to the development of second-generation biofuels, which can supply a larger proportion of our fuel supply sustainably, affordably and with greater environmental benefits. They use a variety of non-food crops, including waste biomass, the stalks of wheat, corn, and wood.

Still, land-based biofuels occupy land that could otherwise be used to grow food. Algae fuel, also called oilgae, is being developed as a third-generation biofuel to avoid this problem. These fuels can be produced in a low-input, high-yield manner, since algae produce 30 times more energy per acre than land crops such as soybeans.

Theoretically, biofuels can be produced from any biological carbon source, although the most common sources are photosynthetic plants and plant-derived materials. One advantage of many biofuels over most other fuel types is that they are biodegradable, and so relatively harmless to the environment if spilled.

There are a number of ways to make biofuels from a range of vegetable oils, but the reaction is essentially the same. A biofuel is made by alkaline hydrolysis of the triglycerides in a vegetable oil (see image above), and the following re-esterification of the triglycerides to the methyl ester. In practice, both steps can take place in the same preparation, provided a mixture of methanol in alkali is used, as is done commercially. This mixture contains the methoxide ion. During hydrolysis, a fatty acid is liberated from the triglyceride. Together with the methoxide ion, the methyl ester of the fatty acid is then formed.



### Transesterification of vegetable oil triglycerides

Glycerol (propan-1,2,3-triol) is a waste product of this last reaction. The disposal or use of the glycerol is one of the challenges for this growing industry.

For the experiment described below, you can either use a boiling tube or a reflux method involving Quickfit™ laboratory glassware.

In the simpler preparation without a reflux, 12-13 ml of a vegetable oil of choice are put into a boiling tube with 2 ml of potassium hydroxide in methanol (5% w/w). The liquids are mixed without shaking to prevent trapping air and foaming. The mixture is left to stand in a water bath at 60°C. The reaction rate can be followed by measuring the viscosity: you can time how long it takes for a small ball bearing (readily available, symmetric shape, smooth and dense) to drop through a defined depth of the mixture in the tube every 5 minutes at regular intervals for up to 2 hours.

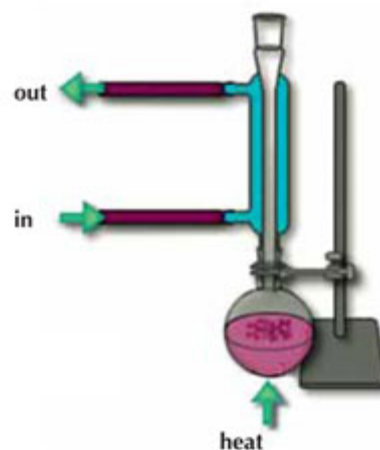
The larger triglyceride is broken down to smaller subunits (see image above), which will then have a smaller mass than the compound from which they are formed. Since the viscosity of a liquid is directly proportional to the mass of its molecules, the reaction will lead to a less viscous mixture. Furthermore, you can leave a sample for a whole day in these conditions to qualitatively observe the extent of hydrolysis.

Although the biofuel produced in this experiment still contains the glycerol formed as a waste product of the reaction, the change in viscosity can nevertheless be observed. If using a reflux condenser for the reaction, the biofuel can be separated from the glycerol by solvent extraction.

The biofuel produced by either method can then, for example, be used to run a small diesel engine.

**Note:** if using vegetable oil that has already been used for cooking, please remember to filter out any food residues first!

### 3) Fuel cells: energy from electrolysis



### Transesterification of vegetable oil triglycerides

Image courtesy of Bristol

ChemLabS

Both the previous experiments are based on the release of energy through combustion. While this is one way of oxidising a fuel to release energy, it is not the only way. Fuels can also be oxidised by electrolysis, as demonstrated in the following experiment.

Fuel cells produce electricity from a reaction between a fuel such as an alcohol or hydrogen at the anode, and an oxidising agent such as oxygen or chlorine at the cathode. The fuel and the oxidising agent react in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. A fuel cell works by catalysis, separating the component electrons and protons of the reactant fuel, and forcing the electrons to travel through a circuit, hence converting them to electrical power.

A fuel cell is different from a chemical battery because its reactants can be replenished (representing a thermodynamically open system), whereas the chemicals being consumed in a battery are not, as it is sealed (thermodynamically closed). A fuel cell will continue to work as long as its reactants are replaced.

A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. However, fuel cells can be combined in series and parallel circuits; series yield higher voltage, while parallel allows a stronger current to be drawn. Such a design is called a fuel cell stack. Furthermore, the cell surface area can be increased to allow stronger current from each cell.

Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks and rural locations. In the future, they could also power vehicles.



There are several demonstration fuel cells available for purchase<sup>w2</sup> (for about €20 each), to show the principle to students. The one we use is an alcohol/air fuel cell (see image to the left), which consists of two parts: an adapted plastic beaker with a conductive pad connected to a terminal (the anode), and an insert containing the catalyst. A defined volume of a source of alcohol (such as antifreeze), or of an alcohol itself (such as propan-1-ol) is mixed with 55 ml of alkali (such as sodium hydroxide) as an electrolyte, and put into the plastic beaker. The insert is put into the beaker to complete the cell. Air can pass through the insert into the alkaline alcohol mixture.

### Electricity generated from gin in a mini fuel cell

The chemical reaction that generates a current is the oxidation of the alcohol by the oxygen in the air – to a carbonyl or a carboxylic acid, depending on the degree of oxidation. The reaction is catalysed by platinised graphite in a pad at the base of the beaker.

At the cathode:  $4e^- + O_2 + 2H_2O \rightarrow 4OH^-$

At the anode:  $CH_3CH_2OH + 2OH^- \rightarrow CH_3CHO + 2H_2O + 2e^-$

The aldehyde  $CH_3CHO$  is also capable of being oxidised to a carboxylic acid, so it can continue to release an electric current. Incidentally, an alternative fuel for this particular type of fuel cell, which gives a greater voltage than an alcohol, is sodium tetrahydroborate (III)

(sodium borohydride,  $\text{NaBH}_4$ ). According to the manufacturer, only minute quantities (about 20 mg of  $\text{NaBH}_4$ ) are required to run the fuel cell for one hour. Note  $\text{NaBH}_4$  is toxic, harmful and an irritant.

The voltage produced by the fuel cell can easily be measured using a cheap multimeter.

These are some of the investigations that can be carried out by students using the fuel cells:

- Different types of alcohol may be used, as long as they are water-soluble: these include the alcohol series from methanol to pentan-1-ol, the secondary or tertiary isomers of these alcohols (where they exist) and different sources of alcohol, such as methylated spirits, car windscreen wash, antifreeze or even alcoholic drinks like vodka or gin. What effect does the type of alcohol have on the voltage produced?
- Students can investigate the effect of changing the initial concentration of alkali on the output voltage. They may also analyse whether the type of alkali used, for example sodium versus potassium hydroxide, makes any difference to the voltage produced by the fuel cell.
- Investigating the change in concentration of the alkali or the alcohol while the fuel cell is running can also be interesting.
- The whole setup can be placed in a cooled/heated water bath to change the temperature at which the reaction takes place. By measuring the output current, the effect of temperature on the rate of reaction can be investigated.

Suggestions for further experiments can be found in a couple of books or online<sup>w3</sup>.

### **Acknowledgement**

The authors wish to thank Will Davey at Sheffield University for the basis of the biofuel production experiment.

### **Web references**

- w1 – For heat of combustion tables of various fuels and organic compounds on Wikipedia, see: [http://en.wikipedia.org/wiki/Heat\\_of\\_combustion#Heat\\_of\\_combustion\\_tables](http://en.wikipedia.org/wiki/Heat_of_combustion#Heat_of_combustion_tables)
- w2 – One of many suppliers specialising in fuel cell technology for both industry and education is h-tec: [www.h-tec.com](http://www.h-tec.com)
- w3 – h-tec has also published a book on using fuel cells in the classroom:
- Voigt C, Hoeller S, Kueter U (2005) *Fuel Cell Technology for Classroom Instruction (Basic Principles, Experiments, Work Sheets)*. Luebeck, Germany: h-tec
- A collection of safe, inexpensive, educational and fun projects focusing on fuel cell technology is:
- Harper G (2008) *101 Fuel Cell Projects for the Evil Genius*. New York, USA: McGraw-Hill Professional
- For further experiments using fuel cells, see: [www.ectechnic.co.uk/exps.html](http://www.ectechnic.co.uk/exps.html)

### **Resources**

- Harrison T, Shallcross D, Henshaw S (2006) Detecting  $\text{CO}_2$  – the hunt for greenhouse-gas emissions. *Chemistry Review* **15**: 27-30
- Pacala S, Socolow R (2004) Stabilisation wedges: solving the climate problem for the next 50 years with current technologies. *Science* **305**: 968-972. doi: 10.1126/science.1100103
- Shallcross D, Harrison T (2008) Climate change modelling in the classroom. *Science in School* **9**: 28-33. [www.scienceinschool.org/2008/issue9/climate](http://www.scienceinschool.org/2008/issue9/climate)
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## Looking to the heavens: climate change experiments



Image courtesy of Alohaspirit /

iStockphoto

*In the second of two articles, **Dudley Shallcross, Tim Harrison, Steve Henshaw and Linda Sellou** offer chemistry and physics experiments to harness the Sun's energy and measure carbon dioxide levels.*

Discussions of climate change in the science classroom can be very wide-ranging, but different sources of energy and their consequences will probably have a role. The topics raised are likely to include different fuels that can be used, how effective they are and how they are produced; alternatives to combustion; solar energy; and the importance of carbon dioxide in global warming. Below, we suggest two laboratory activities to support physics and chemistry lessons on climate change. Three activities relating to fuels were published in Shallcross et al (2009).

### **1) Grätzel cells: energy from sunlight**

The Sun, of course, is the source of most used energy on Earth, besides geothermal and nuclear energy – including that released from fossil fuels or modern 'green' fuels. But sunlight can also be used directly as a source of energy, as can be demonstrated in the classroom using Grätzel cells, also called 'nanocrystalline dye solar cells' or 'organic solar cells'. Named after their inventor, the Swiss engineer Michael Grätzel, Grätzel cells convert sunlight directly into electricity by artificial photosynthesis using natural dyes found, for example, in cherries, blackberries, raspberries and blackcurrants. These purple-red dyes, known as anthocyanins<sup>w1</sup>, are very easy for school students to extract from fruits and leaves by simply boiling them in a small volume of water and filtering.

These cells are very promising because they are made of low-cost materials and do not need elaborate apparatus to manufacture. Although their conversion efficiency is less than that of the best thin-film cells, their price/performance ratio (kWh/M<sup>2</sup>/annum) is high enough to allow them to compete with electricity generation from fossil fuels. Commercial applications, which were held up due to chemical stability problems, are now forecast in the European Union Photovoltaic Roadmap<sup>w2</sup> to be a potentially significant contributor to renewable electricity generation by 2020.

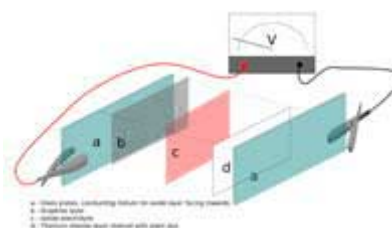
Grätzel cells separate the two functions provided by silicon in a traditional cell design: normally, the silicon acts as the source of photoelectrons, as well as providing the electric field to separate the charges and create a current. In the Grätzel cell, the bulk of the semiconductor is used solely for charge transport, while the photoelectrons are provided from a separate photosensitive dye (the

anthocyanin). Charge separation occurs at the surfaces between the dye, semiconductor and electrolyte.

The dye molecules are quite small (at the nanometre scale), so to capture a reasonable amount of the incoming light, the layer of dye molecules needs to be fairly thick – much thicker than the molecules themselves. To address this problem, a nanomaterial is used as a scaffold to hold large numbers of the dye molecules in a 3D matrix, increasing the number of molecules for any given surface area of the cell. In existing designs, this scaffolding is provided by the semiconductor material (titanium oxide), which serves double duty.

Grätzel cells can be made from scratch, but getting hold of the pre-treated glass that makes one side conductive is not easy. Moreover, baking the titanium dioxide paste into the glass surface requires the use of a furnace for about 24 hours. Therefore, it is easier to use commercial kits, such as those available from the Dutch company Mansolar<sup>w3</sup>, which allow six Grätzel cells to be assembled per set, costing approximately 80 Euros. If you already have some experience using the required equipment and prefer to build your own Grätzel cells, however, you will find an outline of the required steps below:

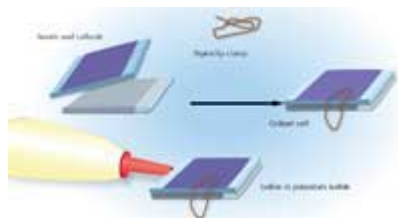
1. Take two glass plates, each about the size of a microscope slide, one side of which has been treated with indium tin oxide to render it electroconductive.
2. One plate needs to have titanium dioxide baked onto its uncoated side. The titanium dioxide forms a highly porous structure with a very high surface area, to which the dye can bind. A word of caution: it is very easy to scratch the titanium dioxide powder off the glass plate, and whilst you can purchase titanium dioxide paste, it is inconvenient to bake the plates for a considerable time with a new coating in a furnace. Storage is therefore a consideration. The easiest solution is to purchase the materials ready-made.
3. Cover the other plate with a layer of pencil graphite by simply rubbing a pencil over the uncoated surface of the glass.
4. Fill a Petri dish with anthocyanin dye. Soak the photosensitive anthocyanin dye onto the titanium dioxide by placing the corresponding plate in the Petri dish, then dry with a hair drier. The dye is left covalently bonded to the surface of the titanium dioxide. After use, it is easy to remove the old anthocyanin pigments using ethanol or propanone (acetone).
5. Assemble the cell as follows from bottom to top:
  - At the bottom will be the graphite plate, graphite side up, serving as a cathode.



**A Grätzel cell. Click to enlarge image**

Image courtesy of Marcus Medley, Bristol ChemLabS

- Use a solution of iodine dissolved in potassium iodide as an electrolyte and squirt between the plates.
- On top will be the dye-coated titanium dioxide plate, indium tin oxide side up. The indium tin oxide will serve as transparent anode.



6. Use a paper clip to keep the plates together.
7. Use two crocodile clips to clip the overlapping pieces of glass (top and bottom, see image) of the Grätzel cell and connect with two electrical leads to a multimeter to take readings.

A close-up diagram of the Grätzel

cell. Click to enlarge image

Image courtesy of Nicola Graf

8. Shine light onto the cell. If investigating this apparatus in northern Europe during the winter months, a microscope lamp or a desk lamp will be useful to provide the light.
9. Use a light meter to determine the light intensity falling on the Grätzel cells.

For amusement, the Grätzel cells can be used to power different mechanisms. For example, you can replace the batteries in a calculator with leads that allow several small Grätzel cells in series to power it. Alternatively, you can also power the music circuits from birthday greetings cards or small motors with the cells.

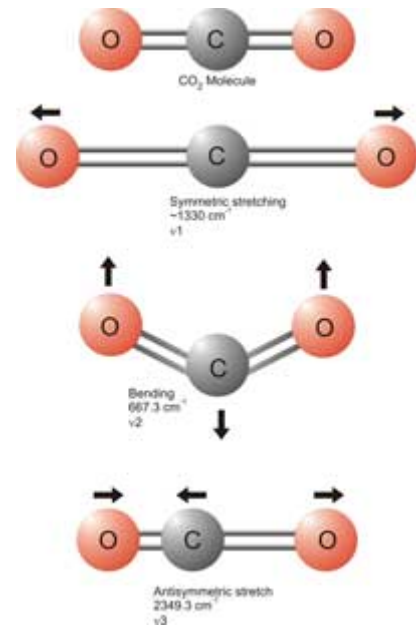
Students may carry out a number of investigations with these cells. These include how the current or voltage produced varies with:

- Anthocyanins from different sources
- Plant pigments other than anthocyanins
- The concentration of the anthocyanin solution used
- The area of the titanium dioxide layer exposed to anthocyanins
- The temperature of the cells
- The frequency of light (using coloured filters)
- Light intensity (using a microscope lamp as a light source)
- Several cells in series or in parallel.

Details on the chemistry behind these cells can be found in an online article<sup>w4</sup>.

## **2) Detecting atmospheric carbon dioxide levels**

CO<sub>2</sub> is the most commonly known greenhouse gas and one of the major concerns in discussions of climate change. One might well ask how levels of CO<sub>2</sub> are measured in air samples, particularly as their concentrations are so low: the answer is infra-red spectroscopy. Carbon dioxide molecules absorb specific frequencies of infra-red radiation, which affect the covalent bonds between the carbon and oxygen atoms, depending on the energy. Low energies cause a bond-bending motion, and high energies cause bond stretching. The frequencies at which this occurs are within the infra-red part of the electromagnetic spectrum (between 4000 and 650 wavenumbers). A wavenumber is the reciprocal of wavelength and is a unit commonly used in infra-red spectroscopy. This effect can be used to determine the CO<sub>2</sub> concentration as follows.



**Bond bending and stretching.**

**Click to enlarge image**

Image courtesy of Marcus Medley, Bristol ChemLabS

There are two main types of carbon dioxide sensor (see Harrison et al, 2006). The more expensive research sensors pump air through the sensor, whereas the cheaper devices rely on the diffusion of air. Air passes into an absorption cell, which is effectively a small darkened cylinder within the sensor.

At one end of the absorption cell, there is an infra-red light source coupled to a fixed wavelength filter, so as to provide a narrow band source of infra-red light around 2350 cm<sup>-1</sup> (wavenumbers). At the other end of the tube, there is an infra-red detector or photon counter that measures the infra-red light intensity. The more CO<sub>2</sub> molecules in the air sample, the more infra-red radiation is absorbed in the cell, and the less infra-red radiation reaches the detector. For small absorptions, the Beer-Lambert law tells us that



**A close-up of a carbon dioxide sensor**

$$\text{Concentration} = (1 - (I/I_0)) / \sigma l$$

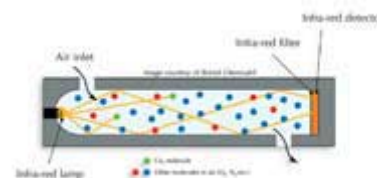
where:

- $l$  is the path length (length of the cell)
- $\sigma$  is the absorption cross-section for CO<sub>2</sub> at the wavelength being used and is known to a high accuracy
- $(I/I_0)$  is the ratio of infra-red radiation arriving at the detector when it has an air sample in it ( $I$ ) to when the cell is empty ( $I_0$ )

$I_0$  is not measured for each reading, but will be measured frequently to check that there are no appreciable fluctuations in the instrument's infra-red light intensity.

Students who have used such sensors, on loan from the University of Bristol, have been surprised that the measured CO<sub>2</sub> level inside an empty classroom is much greater than that outside, well above 0.037% (0.037/100 x 1 x 10<sup>6</sup> = 370 ppm) reported for the CO<sub>2</sub> atmospheric concentration in some textbooks. New school buildings in the UK appear to have windows that are not designed to be opened, so the exhaled CO<sub>2</sub> accumulates!

The CO<sub>2</sub> sensors that we use with students are tuned to the CO<sub>2</sub> v<sub>3</sub> asymmetric bond stretch at 2349 wavenumbers (Harrison et al, 2006). An asymmetric stretch is where the double bonds between carbon and oxygen (C=O) absorb energy, and one of the two bonds lengthens while the other one contracts (see diagram). For CO<sub>2</sub> there can only be one asymmetric stretch. This particular bond stretch is important because carbon dioxide is the only molecule present in high quantities in the atmosphere to absorb at 2349 wavenumbers. Therefore, only absorption by CO<sub>2</sub> can cause a change in infra-red light intensity at this wavelength.



**A diagram of an absorption cell from a CO<sub>2</sub> sensor. Click to enlarge image**

Image courtesy of Bristol ChemLabS

Bristol ChemLabS would be interested to hear from schools across Europe that would like to borrow one of these easy-to-use meters for research into the carbon dioxide concentration of air samples. Although the instruments are commercially available, they are quite expensive and thus not commonly available in schools or colleges.

## References

Harrison T, Shallcross D, Henshaw S (2006) Detecting CO<sub>2</sub> – the hunt for greenhouse-gas emissions. *Chemistry Review* **15**: 27-30

Shallcross D, Harrison T (2008a) Climate change modelling in the classroom. *Science in School* **9**: 28-33. [www.scienceinschool.org/2008/issue9/climate](http://www.scienceinschool.org/2008/issue9/climate)

Shallcross D, Harrison T (2008b) Practical demonstrations to augment climate change lessons. *Science in School* **10**: 46-50. [www.scienceinschool.org/2008/issue10/climate](http://www.scienceinschool.org/2008/issue10/climate)

Shallcross D, Harrison T, Henshaw S, Sellou L (2009) Fuelling interest: climate change experiments. *Science in School* **11**: 38-43. [www.scienceinschool.org/2009/issue11/climate](http://www.scienceinschool.org/2009/issue11/climate)

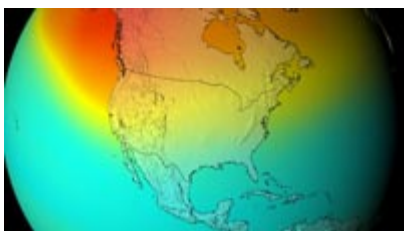
## Web references

- w1 – For more information on anthocyanins and their natural functions, see Wikipedia: <http://en.wikipedia.org/wiki/Anthocyanin>
- w2 – The 2002 European Union Photovoltaic Roadmap can be downloaded from the PV-NET website (<http://paris.fe.uni-lj.si/pvnet>) or here: <http://tinyurl.com/n8cwf>
- w3 – A supplier for Grätzel cell kits is the Dutch company Mansolar: [www.mansolar.com](http://www.mansolar.com)
- w4 – To find out more about the chemistry behind Grätzel cells, see the Royal Society of Chemistry website ([www.rsc.org](http://www.rsc.org)) or here: <http://tinyurl.com/mr3bec>

## Resources

- For a full list of *Science in School* articles about climate change, see: [www.scienceinschool.org/climatechange](http://www.scienceinschool.org/climatechange)
- For a full list of *Science in School* articles about energy, see: [www.scienceinschool.org/energy](http://www.scienceinschool.org/energy)
- SchoolCO2Web offers information and teaching material for measuring and sharing carbon dioxide data across schools in Europe: <http://fwn-school-co2-net.hosting.rug.nl>

## A hole in the sky



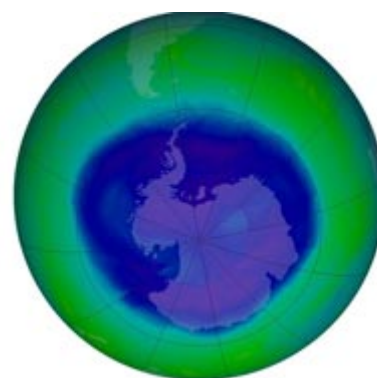
*Twenty-five years ago, the discovery of the hole in the ozone layer hit the news. How have things developed since? **Tim Harrison and Dudley Shallcross** investigate.*

NASA image courtesy of the  
Goddard Space Flight Center  
Scientific Visualization Studio

## Discovering the hole

It was a serendipitous find, as Jonathan Shanklin, one of the hole's discoverers, remembers: having joined the British Antarctic Survey<sup>w1</sup> in 1977, he was supposed to digitise their backlog of ozone measurements – until then, handwritten data sheets. As it turned out, this included the crucial decade, the 1970s, when ozone levels began to drop.

There had already been growing concern that industrial chlorofluorocarbons (CFCs) – organic compounds such as trichlorofluoromethane ( $\text{CFCl}_3$ ) and dichlorodifluoromethane ( $\text{CF}_2\text{Cl}_2$ ), then widely used as refrigerants, propellants (in spray cans) and solvents – might destroy the ozone layer. For an open day in 1983, Shanklin prepared a graph – ironically to show that the ozone data from that year were no different from 20 years before. Although this was true for the overall ozone levels, he noticed that the springtime values did look lower from one year to the next. Further studies corroborated this, and in 1985 Shanklin and his colleagues Joe Farman and Brian Gardiner published their findings: each Southern Hemisphere spring, a hole gaped in the ozone layer above the Antarctic, it was probably caused by CFCs, and it was growing (Farman et al., 1985).



**The Antarctic ozone hole at its annual maximum on 12 September 2008, stretching over 27 million square**

**kilometres. This is considered a moderately large ozone hole, according to NASA**

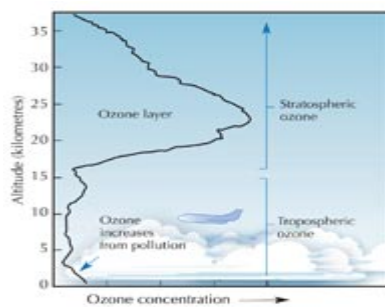
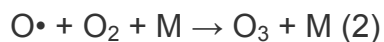
Image courtesy of NASA

What is the chemistry behind this, and why is the ozone hole dangerous?

### ***Ozone in the stratosphere***

Ozone (O<sub>3</sub>) is a much less stable triatomic form of oxygen (O<sub>2</sub>). It is a pale blue gas present at low concentrations throughout the atmosphere – and a double-edged sword: in the troposphere (see below), ozone is an air pollutant which can damage the respiratory systems of humans and other animals and burn sensitive plants. The ozone layer in the stratosphere, however, is beneficial, preventing most of the harmful ultraviolet (UV) light emitted by the Sun from reaching Earth's surface.

The rate of ozone formation maximises in the stratosphere, the second highest layer of Earth's atmosphere (at about 10-50 km altitude; see image), through a photochemical mechanism:



**Ozone is present throughout the lower atmosphere. Most ozone is in the stratospheric ozone layer. Near Earth's surface, the ozone levels increase as a result of pollution from human activities.**

**Click to enlarge image**

Public domain image; image source:

Wikimedia Commons

An oxygen molecule (O<sub>2</sub>) absorbs a photon of UV light (hν) with a wavelength (λ) around 200 nm and dissociates into two oxygen atoms (O•) (reaction 1). Each of these can then combine with another oxygen molecule to form ozone, if the pressure (M) is high enough (approximately one thousandth of an atmosphere) to stabilise the newly formed ozone molecule (reaction 2). The higher the altitude, the faster the rate of reaction 1 (below 20 km altitude, no 200 nm photons occur because they have all been absorbed in reaction 1). The rate of reaction 2, however, is faster closer to the ground, where atmospheric pressure is higher. As a result, the maximum amount of ozone is created between about 25 and 30 km altitude (see graph).

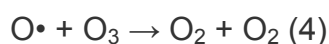
The stratosphere has two important consequences for life on Earth. First, ozone itself absorbs high-energy UV radiation at around 250 nm (reaction 3):



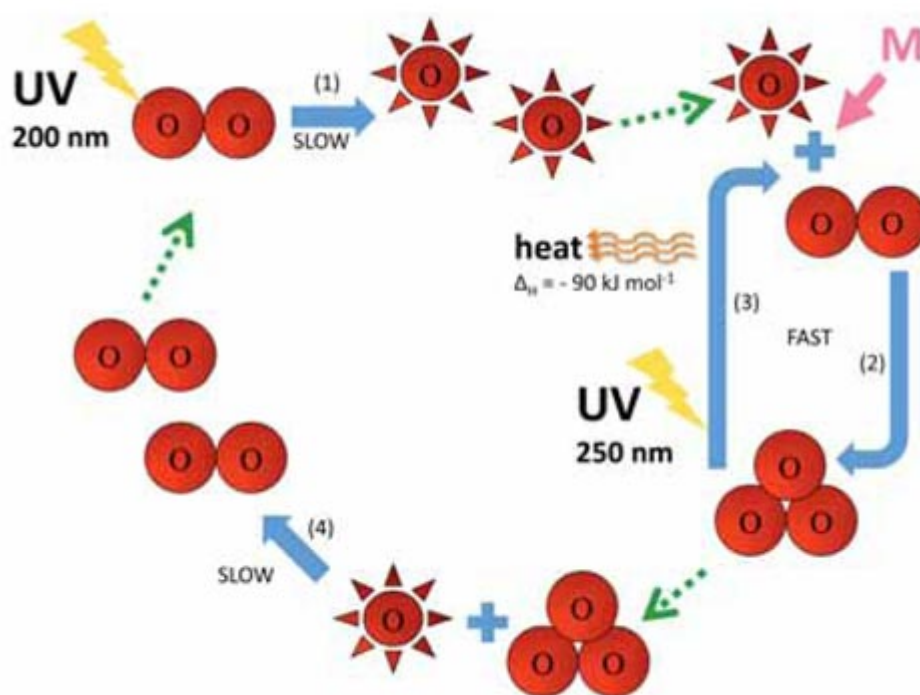
Between them, oxygen (reaction 1) and ozone (reaction 3) therefore filter out of the atmosphere most of the short-wave UV radiation between 200 and 300 nm, which would otherwise be very damaging to life on Earth.

Second, reaction 3 produces a lot of heat, so the stratosphere is a warmer layer than the top of the troposphere (see image below), making the weather in the troposphere less extreme than it would otherwise be.

Reactions 2 and 3 rapidly interconvert oxygen atoms and ozone. There is another slow reaction, though, which is known to destroy both oxygen atoms and ozone, namely the reaction between these two species:



Reactions 1-4 are summarised in the diagram below.

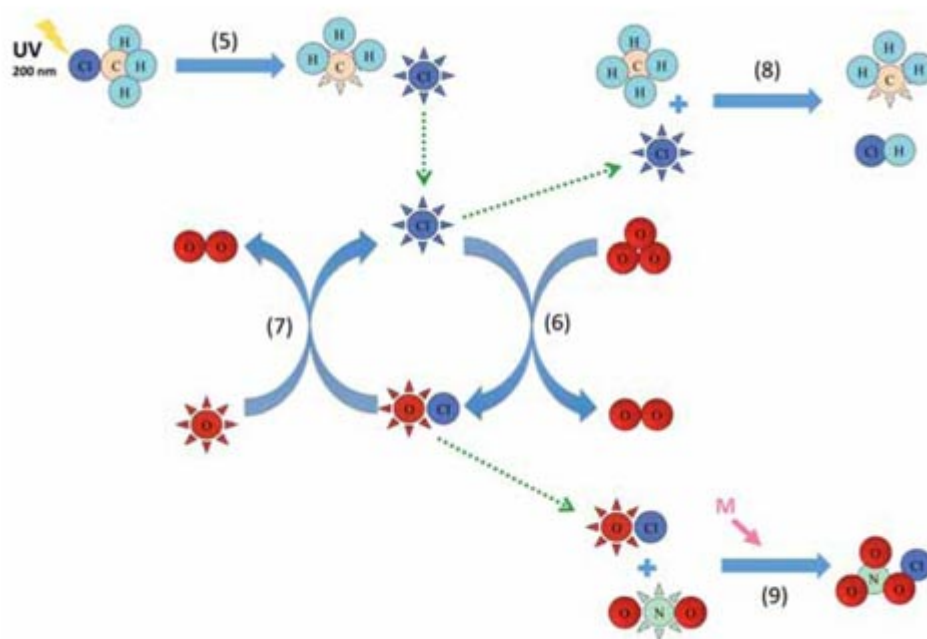


**The four main reactions of oxygen in the ozone layer. Blue arrows indicate reactions, green dotted arrows indicate that a molecule from one reaction goes on to take part in another reaction. M denotes the pressure required for reaction 2**

Image courtesy of Marlene Rau

## Natural catalytic cycles reduce the levels of ozone

In 1995, Paul Crutzen, Mario Molina and F Sherwood Rowland were awarded the Nobel Prize in Chemistry for their work on the formation and decomposition of ozone in the stratosphere. What had they learned? In the 1970s, Crutzen and others discovered the existence of natural catalytic cycles that speed up reaction 4 and reduce the amount of ozone in the stratosphere (Crutzen, 1970, 1971): water (H<sub>2</sub>O), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and chloromethane (CH<sub>3</sub>Cl) are released into the atmosphere from biological processes occurring on Earth's surface, and lead to the formation of radicals such as hydroxyl (OH•), nitric oxide (NO•) and chlorine (Cl•), which catalyse the decomposition of ozone.

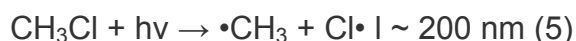


Chlorine

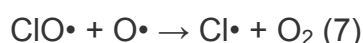
radicals (for example from reaction 5) enter a catalytic cycle (reactions 6 and 7) of net ozone decomposition, which can be terminated by reactions 8 and 9. Blue arrows indicate reactions, green dotted arrows indicate that a molecule from one reaction goes on to take part in another reaction. **M** denotes the pressure required for reaction 9

Image courtesy of Marlene Rau

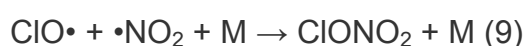
Reaction 5 shows how chloromethane releases chlorine radicals into the stratosphere through photolysis, and reactions 6 and 7 are an example of a catalytic cycle (see diagram above). The reactions of the other catalysts are analogous with reactions 6 and 7. Chloromethane is released in part by both marine and terrestrial organisms, such as red macroalgae, white rot fungi and higher plants, to regulate chloride ion levels in the cells and – after 30 to 40 years – can reach the upper stratosphere (around 40 km altitude) where it is broken down by sunlight (photolysis):



The resulting chlorine free radical ( $\text{Cl}\cdot$ ) can then participate in a catalytic cycle:



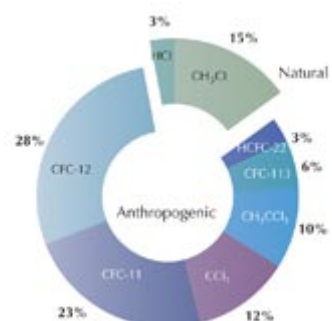
Reactions 6 and 7 taken together are in fact equivalent to reaction 4, but happen much faster – in the case of the chlorine / chlorine monoxide ( $\text{ClO}\cdot$ ) radical cycle, about 30 000 times faster. So why do these catalytic cycles not destroy all the ozone? The answer lies in the termination of these cycles via the formation of stable molecules:



Eventually, a chlorine free radical will encounter a methane molecule and react to form hydrochloric acid ( $\text{HCl}$ , reaction 8). Similarly, a chlorine monoxide radical will bind to a nitrogen dioxide radical, forming chlorine nitrate ( $\text{ClONO}_2$ , reaction 9) – another pressure-dependent reaction that therefore works better at lower altitudes. Both hydrochloric acid and chlorine nitrate are very stable, and the removal of chlorine and chlorine monoxide radicals eventually stops the catalytic cycle.

### ***The Antarctic ozone hole puzzle***

It was not long before scientists realised that CFCs could trigger a similar catalytic cycle of ozone degradation: in 1974, Molina and Rowland not only warned that levels of CFCs continued to increase without regulation, but also predicted that CFCs would cause a significant additional loss of ozone at around 40 km altitude (see Molina & Rowland, 1974). However, when the ozone hole was finally found in 1985, it was in fact at around 20 km altitude, over the South Pole in the Southern Hemisphere springtime (see Farman et al., 1985).



**Sources of stratospheric chlorine according to WMO / UNEP *Scientific Assessment of Ozone Depletion: 1998*. Click to enlarge image**

Image courtesy of Andrew Ryzhkov; image source: Wikimedia Commons

It soon emerged that chlorine free radicals from the CFCs were responsible, but many questions remained unanswered. Why did the hole occur over the Pole? If it

occurred over the South Pole, why not also over the North Pole? Why only in spring? And why was the ozone hole at 20 km altitude instead of at 40 km, as predicted? After all, CFCs could not be broken down by sunlight at an altitude as low as 20 km, since the photon density was insufficient. For the same reason, not enough oxygen atoms are produced at this altitude for reaction 7 to occur. Many years of further research revealed the complete story.

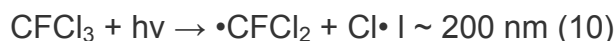


The

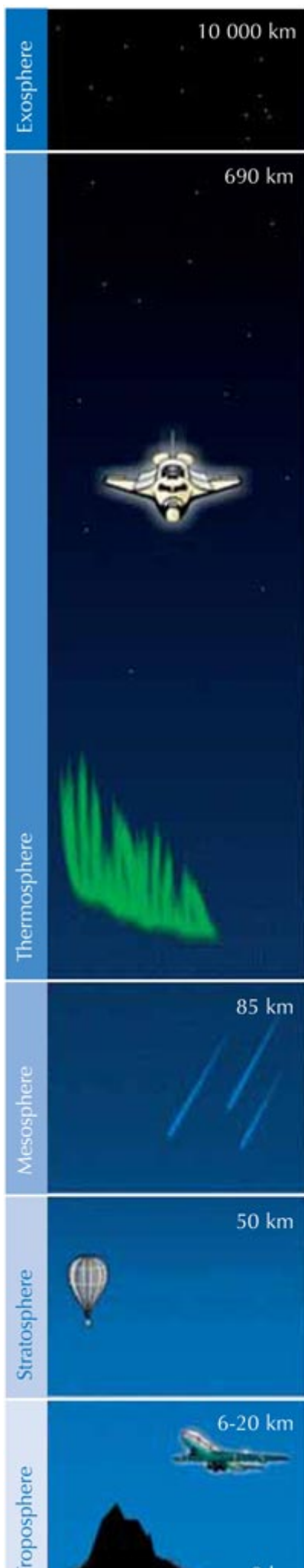
formation and dissolution of the ozone hole over the year. Reactions 5 to 9 happen over the Equator all year round, and over the South Pole in summer and autumn. In early winter, the vortex forms over the South Pole, followed by the formation of polar stratospheric clouds in winter. In early spring, the sunshine returns, but the vortex remains, and the reactions leading to ozone removal over the South Pole take their course. In late spring, the vortex breaks down, and ozone from mid-latitudes can mix in. [Click to enlarge image](#)

Image courtesy of Dudley Shallcross, Tim Harrison, Marlene Rau and Nicola Graf

First, chlorine free radicals released from the CFCs, e.g.



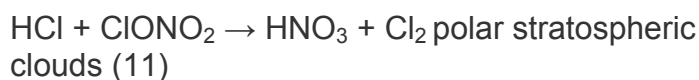
could react with methane (reaction 8) forming hydrochloric acid, or with ozone (reaction 6) forming chlorine monoxide radicals, and through reaction 9 could subsequently form chlorine nitrate. This sequence of reactions would increase the concentrations of hydrochloric acid and chlorine nitrate at around 40 km altitude globally.



Each Southern Hemisphere winter, the South Pole is plunged into darkness for approximately three months. The air in the stratosphere above the South Pole cools down; without UV radiation, reaction 3 does not occur, so no heat is released. The air sinks and Earth's rotation causes it to spin and form a vortex as it does so, like water going down a plughole. This vortex is so strong that no air from outside can get in, and no air from inside can get out. Air that is rich in hydrochloric acid and chlorine nitrate from 40 km altitude is drawn down into this cold and dark vortex.

In the extreme cold of the polar winter, the air in this vortex becomes so cold that below  $-78^{\circ}\text{C}$  (195 K) and at an altitude of 15-25 km, polar stratospheric clouds form from water and / or acid ice crystals.

The first peculiar bit of chemistry is that hydrochloric acid and chlorine nitrate can adsorb onto polar stratospheric clouds and undergo a fast heterogeneous reaction from gaseous to solid phase, producing nitric acid ( $\text{HNO}_3$ ) that becomes incorporated into the ice crystals, whilst the chlorine ( $\text{Cl}_2$ ) is released back into the gas phase.

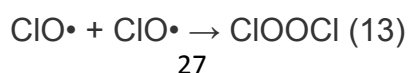


This reaction can take place all winter, if it is cold enough to form polar stratospheric clouds. When the sunshine returns in spring, there are plenty of chlorine molecules at around 15-25 km altitude, which are photolysed to produce chlorine radicals:



and subsequently chlorine monoxide radicals via reaction 6.

However, in the polar spring, reaction 7 (the formation of chlorine radicals and oxygen molecules from chlorine monoxide radicals and oxygen radicals) is very slow, since there are so few oxygen atoms present due to the lack of 200 nm photons at this altitude, and here is where a second peculiar piece of chemistry occurs. At low temperatures, such as in the polar vortex – which is still very cold even in spring – chlorine monoxide radicals can form a dimer, chlorine peroxide ( $\text{ClOOCi}$ ):



27

This dimer is unstable at room temperature but forms quite readily at low temperatures (below  $-30^{\circ}\text{C}$ ) and can be photolysed:

In what way does this differ from the natural catalytic cycles we looked at before – why is there a total removal of ozone at some altitudes in this vortex? First, reaction 8 (which removes chlorine radicals and can terminate the cycle) is very slow at the low temperatures found in the vortex, and therefore ineffective. Second, all the nitrogen dioxide required for reaction 9 (which could likewise terminate the cycle, through the formation of ClONO<sub>2</sub>) has been converted to nitric acid throughout the winter (e.g. through reactions 9 and 11) and it is not available to be regenerated since there is no upward flow in the vortex (at the base of the vortex, air flows from the South Pole to the Equator, where the upward flow takes place). Therefore the cycle carries on unchecked and destroys all the ozone at that level. Finally, without ozone, reaction 3, which would otherwise warm this region, is absent, and so the vortex lasts well into the spring, exacerbating the ozone depletion.

The only reason that the ozone hole is more severe over the South Pole than the North Pole is that the spring temperatures in the stratosphere above the North Pole are slightly warmer than those above the South Pole, because there are more mountain ranges in the mid to high latitudes of the Northern Hemisphere, which change the dynamics of atmospheric flow, so there are fewer polar stratospheric clouds.



**Polar stratospheric clouds in Asker, Norway**

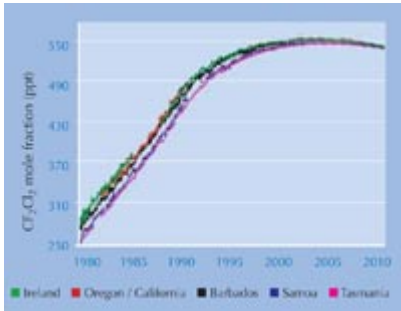
Public domain image; image source: Wikimedia Commons

In late spring, the flow of ozone-rich air from above eventually warms the vortex via reaction 3, allowing the vortex to eventually break down. Since exchange with other parts of the atmosphere then becomes possible again, the ozone hole is filled with ozone from the surrounding air.

In some years, the ozone hole over Antarctica has grown large enough to reach Australia, New Zealand, Chile and Argentina, growing to 1.5 times the size of the USA; and when the ozone hole breaks up, the ozone-depleted air drifts out into nearby (populated) areas, including South Africa. For the people in these countries, the ozone hole poses a direct health threat. The main concern is the increased exposure to UV, which may cause skin cancer and ocular cortical cataracts, as well as damage to the immune system. Furthermore, excessive UV radiation damages plants and building materials.

### ***CFCs and ozone today***

Today, we have a good understanding of the physics and chemistry governing the ozone layer.



The atmospheric concentration of CFCs increased rapidly and is now slowly decreasing again. Data are given for  $\text{CF}_2\text{Cl}_2$ , at the five AGAGE surface measurement stations from 1978 to the present day, taken from the AGAGE website<sup>w2</sup> in September 2010. Click to enlarge image

Image courtesy of the AGAGE project

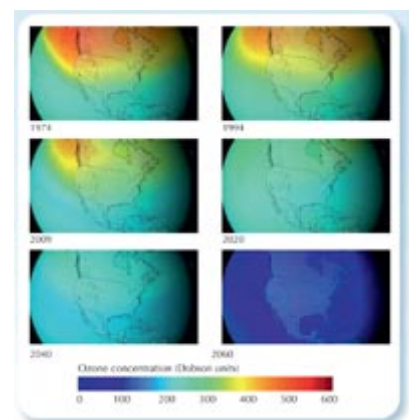
Once the true impact of CFCs on ozone depletion became apparent, governments passed regulations to stop the use of CFCs, replacing them with alternative, shorter-lived, species (hydrofluorocarbons and hydrochlorofluorocarbons), which were to be phased out eventually too: the Montreal Protocol of 1987 and especially its amendments in 1990 and 1992, which speeded up the phase-out, were an environmental success.

The most recent data from AGAGE (the Advanced Global Atmospheric Gases Experiment)<sup>w2</sup>, which has been monitoring levels of CFCs and their replacements since 1978, shows that even the atmospheric levels of dichlorodifluoromethane ( $\text{CF}_2\text{Cl}_2$ ), the longest-lived CFC, are now decreasing: the legislation has been effective (left). An ozone hole still forms each spring over the South Pole, but estimates are that by 2050 this will no longer happen, and that by 2080 the global ozone will return to 1950s levels.

The ozone hole is the result of an increased use of CFCs, which began in the 1930s – like any other gas, CFCs take 30-40 years to reach the upper stratosphere, which means that there is a corresponding lag in their effect on the ozone layer. We are currently experiencing the stratospheric chlorine peak resulting from the highest levels of CFC use in the 1980s – so the maximum size the ozone hole reaches each year should begin to decrease a few years from now.

Although recovery is slow, we have definitely stopped a disaster: scientists have calculated that if the use of CFCs had continued at its 1970s growth rate of 3% per year, this would have led to a global ozone hole by 2060, with all the health problems that would bring (see right; Newman et al., 2009).

Perhaps the most important lesson to be learned from the ozone hole is just how quickly our planet can change as a result of human impact – especially for the worse, but also for the better – and that change is possible if we take action concertedly, effectively and quickly.



This is how the ozone layer would look if CFCs had not been banned.

Click to enlarge image

NASA images courtesy of the Goddard Space Flight Center Scientific Visualization Studio

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## Web references

w1 – The British Antarctic Survey is responsible for the UK's national scientific activities in Antarctica. See: [www.antarctica.ac.uk](http://www.antarctica.ac.uk)

w2 – The Advanced Global Atmospheric Gases Experiment, AGAGE, is a NASA-sponsored initiative that has been measuring the composition of the global atmosphere continuously since 1978, including CFCs and most non-CO<sub>2</sub> greenhouse gases specified in the Kyoto protocol. To access their data and for more information, see: <http://agage.eas.gatech.edu>

## Resources

- Sidney Chapman first derived the photolytic mechanism by which ozone is formed and degraded. See:
- Chapman S (1930) On ozone and atomic oxygen in the upper atmosphere. *Philosophical Magazine Series 7* **10(64)**: 369-383. doi: 10.1080/14786443009461588
- Jonathan Shanklin, one of the scientists who discovered the ozone hole, published his reflections 25 years after the discovery:
- Shanklin J (2010) Reflections on the ozone hole. *Nature* **465**: 34-35. doi: 10.1038/465034a
- Download the article free of charge [here](#), or subscribe to *Nature* today: [www.nature.com/subscribe](http://www.nature.com/subscribe)
- *Nature* has also published a collection of articles that have advanced our understanding of the stratosphere and the ozone layer, or told the story of the discovery, some of which are freely available. See: [www.nature.com/nature/focus/ozonehole](http://www.nature.com/nature/focus/ozonehole)
- NASA's Ozone Hole Watch page offers historical ozone maps, ozone facts, an ozone-related multimedia gallery, a collection of teaching modules about ozone-related topics, and more. See: <http://ozonewatch.gsfc.nasa.gov>
- The University of Cambridge, UK, has compiled a virtual tour of the ozone hole, its history and science. The tour is available in English, French and German. See: [www.atm.ch.cam.ac.uk/tour](http://www.atm.ch.cam.ac.uk/tour)
- The 74 scientists who attended the panel review meeting for the 2002 ozone assessment in Les Diablerets, Switzerland, published *20 Questions and Answers about the Ozone Layer*, including the contributions of cycles of solar activity and volcanic eruptions. See: [www.gcric.org](http://www.gcric.org) or use the direct link: <http://tinyurl.com/2wvpv9r>

- *Introduction to Atmospheric Chemistry* by Harvard University's Professor Daniel J Jacob, which is freely accessible as a PDF, contains a section on ozone, including the diagram 'Chronology of the ozone hole' (chapter 10.3.3). See: <http://acmg.seas.harvard.edu/people> or use the direct link: <http://tinyurl.com/39vhy6a>
- Ozzy Ozone is a United Nations Environment Programme website offering educational cartoons, games, a glossary and more – including downloadable education packs with student and teacher handbooks for both primary and secondary school. All material is available in English, French, and Spanish. See: [www.ozzyozone.org](http://www.ozzyozone.org)
- The Ozone Depletion website by scientist and author Rod Jenkins contains comprehensive information: [www.ozonedepletion.info](http://www.ozonedepletion.info)
- The website of the United Nations Environment Programme's OzonAction branch provides a large collection of data and information about ozone and the Montreal Protocol. See: [www.unep.fr/ozonaction](http://www.unep.fr/ozonaction)
- See also the pages of the United Nations Environment Programme Ozone secretariat, in English, French and Spanish: <http://ozone.unep.org>
- NASA offers two online videos of atmospheric developments over the Arctic, as measured with the Upper Atmosphere Research Satellite (UARS).
- You can watch the increasing concentration of chlorine nitrate in February / March 1993. See [www.nasaimages.org](http://www.nasaimages.org) or use the direct link: <http://tinyurl.com/2w6wgh4>
- This video shows the formation of polar stratospheric clouds. See [www.nasaimages.org](http://www.nasaimages.org) or use the direct link: <http://tinyurl.com/33dfn6e>
- In addition, NASA has published images of a season in the life of the ozone hole. See: [www.nasa.gov/vision/earth/lookingatearth/25TOMSAGU.html](http://www.nasa.gov/vision/earth/lookingatearth/25TOMSAGU.html)

## Climate change modelling in the classroom



Image courtesy of C. Niva

*Why not get your students to make their own predictions of climate change – with the help of **Dudley Shallcross** and **Tim Harrison** from Bristol University, UK?*

Climate change and global warming are 'hot' topics and deserve an important place in the school science curriculum. But how do we predict how our climate is going to change? It seems timely to introduce students to simple climate modelling. In this article, we demonstrate that students can use a straightforward spreadsheet to investigate the major factors that affect Earth's climate.

### ***A first attempt to model the climate***

The simplest model of the climate is one in which incoming solar energy is equal to outgoing terrestrial energy emitted from the planet, i.e. an 'energy in equals energy out' model. In this article, the term 'energy' really means energy flux, i.e. energy per second. We know from measurements that the energy from the Sun reaching the top of the atmosphere (per second), termed the solar constant  $S$ , is  $1370 \text{ Wm}^{-2}$ .

We start by calculating the average surface temperature of Earth,  $T_E$ . If we take the radius of a perfectly spherical Earth to be  $R_E$ , in this very simple model we can see that Earth absorbs solar radiation over an area  $\pi R_E^2$  (i.e. a flat disc of atmosphere) but emits energy from an area  $4\pi R_E^2$  (i.e. from the entire surface).

(a) Energy in = energy out

and using the Stefan-Boltzmann Law (see box)

(b) Energy per unit area per unit time x total area<sub>(disc)</sub> = energy per unit area per unit time x total area<sub>(sphere)</sub>

$$(c) 1370 \times \pi R_E^2 = \sigma T_E^4 \times 4\pi R_E^2$$

Rearranging the equations gives:

$$\sigma T_E^4 = \frac{1370}{4} = S/4$$

$$T_E^4 = \frac{1370}{(4 \times 5.67 \times 10^{-8})}$$

$$T_E = 279 \text{ K } (6 \text{ }^\circ\text{C})$$

where  $\sigma$  is the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$ ).

At first glance, this looks like a sensible figure for such a crude model, although of course the actual average surface temperature of Earth is known to be  $16 \text{ }^\circ\text{C}$ . (There are several ways to work it out, such as by splitting Earth into latitude bands, working out the average temperature per band and summing and averaging all of these.) The problem with this very simple model, though, is that some solar energy is not absorbed by Earth, but is instead reflected back out to space by clouds and ice.

Approximately 24% of the incoming energy is reflected by clouds and another 6% is reflected by the surface, e.g. by ice. This gives a total reflectivity of Earth – known as the albedo ( $A$ ) – of 30% or 0.3. Therefore, the left-hand side of equation (c) must now be re-written as  $0.7 \times 1370 \times \pi R_E^2$  and the calculation of  $T_E$  becomes:

$$T_E^4 = \frac{1370 \times 0.7}{(4 \times 5.67 \times 10^{-8})}$$

$$T_E = 255 \text{ K } (-18 \text{ }^\circ\text{C})$$

This value is obviously far too low, and leads naturally to the question: why is Earth so warm? In order to answer this question we need a slightly more complex model.

*Essential background physics*

**Black body radiation and the Stefan-Boltzmann Law**

All bodies radiate energy as electromagnetic radiation. A black body absorbs all radiation falling on it. It emits radiation as a function of its surface temperature. The Stefan-Boltzmann Law describes the total energy,  $I$ , emitted by a black body at any temperature,  $T$ , by:

$$I(T) = \sigma T^4 \text{ (Equation 1)}$$

where:

$I$  is the energy per unit area emitted per second ( $Wm^{-2}$ )

$T$  is the absolute temperature (K)

$\sigma$  is the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} Wm^{-2}K^{-4}$ ).

### **The one-layer atmosphere model of Earth**

If we assume that the atmosphere is made up of a single layer of miscible gases, we can create a more accurate model that students can use with a spreadsheet. In this model, allowances are made for absorption by the atmosphere of the incoming visible light from the Sun and absorption of the outgoing infra-red light emitted from Earth.

The figure below summarises the elements of the model.  $F_S$  is the solar constant divided by 4 ( $S/4$ ), which arises from the difference between incoming energy spread over a disc,  $\pi r^2$ , and outgoing energy radiated from the surface of a sphere,  $4\pi r^2$  (the assumption made in the first model). The incoming energy from the Sun is then  $F_S(1-A)$ , where  $A$  is the albedo – the portion reflected back to space. This incoming energy is in the UV and visible regions.  $T_{VIS}$  is the proportion of this incoming energy that is not absorbed by the atmosphere: if the atmosphere absorbs it all,  $T_{VIS}$  is zero; if the atmosphere absorbs none of it,  $T_{VIS}$  is one. Hence the energy reaching the surface of the planet is  $F_S(1-A) \times T_{VIS}$ .

Earth will behave similarly to a black body and will emit the energy denoted as  $F_g$  from its surface. This terrestrial radiation is centred in the infra-red region of the spectrum. Certain gases in the atmosphere absorb the infra-red energy (greenhouse gases). Similar to  $T_{VIS}$ ,  $T_{IR}$  is the proportion of infra-red energy not absorbed by these gases in the atmosphere, and so the outgoing energy is  $F_g \times T_{IR}$ .

Assuming that the energy from the atmosphere is denoted as  $F_a$  and that energy in and out at the surface of Earth and the top of the atmosphere are both balanced, then:

at the surface of Earth:

$$F_S(1-A) \times T_{VIS} + F_a = F_g \text{ (Equation 2)}$$

and at the top of the atmosphere:

$$F_g \times T_{IR} + F_a = F_S(1-A) \text{ (Equation 3)}$$

Combining Equations 2 and 3 gives:

$$F_g = \frac{F_S(1-A)(1 + T_{VIS})}{(1 + T_{IR})}$$

Finally,

$$F_g = \sigma T_E^4 = \frac{F_S(1-A)(1 + \tau_{VIS})}{(1 + \tau_{IR})}$$

$$T_E = \left[ \frac{F_S(1-A)(1 + \tau_{VIS})}{\sigma(1 + \tau_{IR})} \right]^{0.25} \quad (\text{Equation 4})$$

If we take the following values:

$$F_S = 1370/4 = 342.5 \text{ Wm}^{-2} \text{ (solar constant divided by 4)}$$

$$A = 0.3$$

$$\tau_{VIS} = 0.8$$

$$\tau_{IR} = 0.1$$

Equation 4 gives us:

$$T_E = 288.5 \text{ K (15.5 } ^\circ\text{C)},$$

which is a close approximation to the current average surface temperature of Earth.

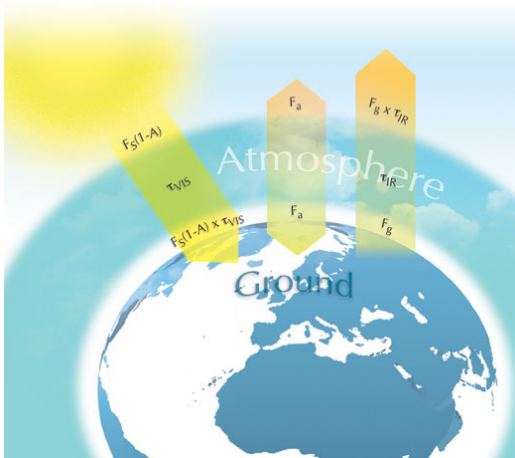


Image courtesy of Nicola Graf

It is Equation 4 that can be put into a programme such as Microsoft Excel so that students can see the changes in global temperature when the equation parameters are changed. This has been done and an interactive version can be used online or downloaded from the Bristol University website<sup>w1</sup>.

Table 1 shows examples of the output if the variables  $A$ ,  $\tau_{VIS}$  and  $\tau_{IR}$  are altered. In Example 1 we assume that the atmosphere does not absorb any of the incoming or outgoing energy fluxes (i.e. both  $\tau_{VIS}$  and  $\tau_{IR}$  are equal to 1.0) and the albedo is 0.3, giving a temperature of 255 K. In Example 2, we assume that there are no clouds or ice (i.e.  $A = 0.0$ ), which raises the temperature of Earth to 279 K, showing the importance of the albedo. In Example 3, there are also no clouds or ice ( $A = 0.0$ ) but the atmosphere now absorbs all the outgoing

infra-red radiation (i.e.  $\tau_{IR} = 0.0$ ) and Earth warms to 331 K. If we now reintroduce clouds and ice in Example 4 ( $A = 0.3$ ), the temperature drops to 303 K.

Example no.	1	2	3	4
$S$ ( $\text{Wm}^{-2}$ )	1370	1370	1370	1370
$A$	0.3	0.0	0.0	0.3
$\tau_{VIS}$	1.0	1.0	1.0	1.0
$\tau_{IR}$	1.0	1.0	0.0	0.0
$T_E$ (K)	255	279	331	303
$T_E$ ( $^{\circ}\text{C}$ )	-19	5	57	29

### **Possible questions**

Typical questions that could be asked, and which would require students to use this model, are:

1. Which of the variables has the greatest effect on average global temperature?
2. If the average distance from Earth to the Sun was increased by 1% of the current value, the solar constant would be reduced by a factor of 1.0201, i.e. it would become  $1343 \text{ Wm}^{-2}$ . What would the temperature be? Assume an albedo of 0.3,  $\tau_{IR}$  of 0.3 and  $\tau_{VIS}$  of 0.6.

(The solar constant will scale with distance squared, so moving Earth 10% closer to the Sun will mean  $S = 1370/(0.9)^2 = 1691 \text{ Wm}^{-2}$  and moving Earth 1% further away will mean  $S = 1370/(1.01)^2 = 1343 \text{ Wm}^{-2}$ )

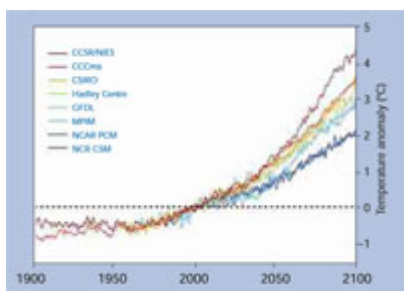
Of course, far more challenging questions could be asked.

3. If the sand in the Sahara desert could be made into a glass mirror (sand can be melted into glass),
  - a. How big would the mirror have to be in order to cool the planet by  $1^{\circ}\text{C}$ ?
  - b. What fraction of the Sahara desert would that be?

### **A more sophisticated model**

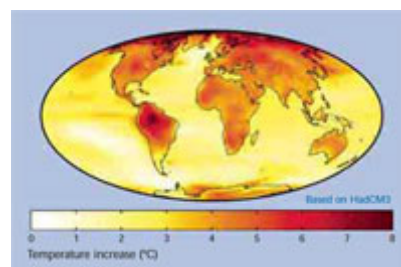
How does the simple model compare with more sophisticated models such as the Hadley Centre climate model used by the UK's Meteorological Office (see images below)? In fact, the two models are very similar, except that the Hadley Centre model does not consider the atmosphere as one layer, but splits it into a number of boxes based on altitude, latitude and longitude. For each box, the model directly calculates the amount of incoming UV/visible radiation transmitted and scattered within that box, and the amount of outgoing infra-red radiation transmitted by that box, based on the concentrations of key greenhouse gases and

the surface area of cloud and ice. The most sophisticated versions of the Hadley Centre model also consider the heat flux into and out of the ocean and the uptake of CO<sub>2</sub> by vegetation. But if you understand the principles of the simple model, you are well on your way to understanding the more complicated real climate models.



**Global warming projections. Climate model predictions for global warming relative to average global temperature in 2000. The model data used was taken from the Intergovernmental Panel on Climate Change Data Distribution Centre. [Click to enlarge image](#)**

Image courtesy of Robert A. Rohde;  
image source: Wikimedia Commons



**Global warming predictions: 2070-2100 prediction vs. 1960-1990 average. A map of predicted global warming at the end of the 21st century. This model has an average warming of 3.0°C and uses the Hadley Centre HadCM3 climate model. [Click to enlarge image](#)**

Image courtesy of Robert A. Rohde;  
image source: Wikimedia Commons

### ***Taking part in a real climate simulation***

Climateprediction.net<sup>w2</sup> is the largest experiment to try and produce a forecast of the climate for the 21st century. It does this by recruiting help from people around the world who can offer time on their computers – such as when the computers are switched on, but are not being used to their full capacity. The full climate model has many parameters that can be adjusted; to explore all of these parameters, a phenomenal number of simulations must be performed. Even with the computer resources available to the climateprediction.net team, such an ensemble of simulations would take a very long time. The idea behind climateprediction.net is that anyone can download a version of the model that will explore one of these particular parameters (preset). The model will take about three months to run in the background while you work, without compromising the speed of the computer.

Calculations are performed in three parts. The first part runs calculations using data from the years 1850 to 1900, checking the resulting predictions against temperature records: this is known as the calibration run. The second part runs a simulation from 1901 to the present day. The third stage then runs a simulation of the future climate (2000-2100) with one parameter changed, for example the sensitivity of climate to uncertainties in the sulphur cycle. Once the calculations are complete, the data is automatically uploaded to the UK's Meteorology Office the next time that the computer is online. The interface software provided (free of charge) with the simulation gives the computer user a graph of the changes to the climate, as they are calculated. Temperature variations by season with latitude, longitude and altitude are just some of the variables that can be visualised. Such features would enable a cross-curricular school project linking geography and the physical sciences.

In the next issue of *Science in School*, the authors suggest some chemistry experiments relevant to climate change.

## Web references

w1 – An interactive version of the simple climate model can be used online or downloaded here: [www.chm.bris.ac.uk/acrg/model/simple\\_climate\\_model/prediction\\_model.html](http://www.chm.bris.ac.uk/acrg/model/simple_climate_model/prediction_model.html)  
Use the sliders to change the variables.

w2 – For more details about the experiment and how to get involved, see <http://climateprediction.net>.

The climateprediction.net website also offers information and resources specifically for schools, available both in English and Spanish: <http://climateprediction.net/schools/resources.php>

## Resources

- Harrison T, Shallcross D, Henshaw S (2006) Detecting CO<sub>2</sub> - the hunt for greenhouse-gas emissions. *Chemistry Review* **15**: 27-30
- Pacala S, Socolow R (2004) Stabilisation wedges: solving the climate problem for the next 50 years with current technologies. *Science* **305**: 968-972. doi: 10.1126/science.1100103
- Shallcross D (2006) Dirty Air. *Education in Chemistry*, **43 (5)**: 131-135
- Numerous notes for schoolteachers on air pollution, climate change and ozone depletion by the authors can be found here: [www.chemlabs.bristol.ac.uk/outreach/resources/Atmos.html](http://www.chemlabs.bristol.ac.uk/outreach/resources/Atmos.html)
- For an excellent source of graphics and data relating to climate change, see: [www.grida.no/climate/vital/index.htm](http://www.grida.no/climate/vital/index.htm)
- Data from the Earth System Research Laboratory Global Monitoring Station can be found here: [www.cmdl.noaa.gov](http://www.cmdl.noaa.gov)
- The website of the Intergovernmental Panel on Climate Change, from which the Climate Change 2007 report and other data may be located, is: [www.ipcc.ch](http://www.ipcc.ch)
- Haubold B (2008) An Inconvenient Truth. *Science in School* **9**: 72. [www.scienceinschool.org/2008/issue9/inconvenient](http://www.scienceinschool.org/2008/issue9/inconvenient)

# Is climate change all gloom and doom?

## Introducing stabilisation wedges



*How can we tackle climate change? Using activities and technologies that already exist – as **Dudley Shallcross** and **Tim Harrison** explain.*

When learning about climate change, students and the general public can easily become despondent: if the global catastrophe is inevitable, why even discuss ways to avert it? But they should not despair: there are ways to tackle one of the most important contributors to climate change: carbon dioxide (CO<sub>2</sub>). In this article, we draw on the ideas of two leading climate scientists (Pacala & Socolow, 2004; Socolow & Pacala, 2006) for stabilising carbon dioxide emissions using technologies that already exist. We then offer some ideas on how to use the topic at school.

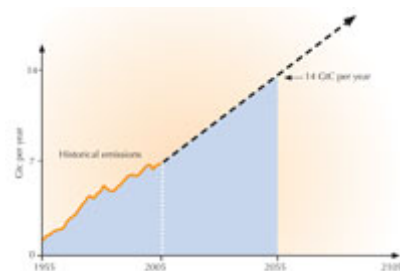
Image courtesy of Kellermeister / pixelio.de

### **The challenge**

Figure 1 (below) shows how global carbon dioxide emissions have increased over the past 50 years and how they are predicted (based largely on changes in population) to change in the next 50 years. Carbon dioxide emissions are quantified as the mass of carbon that is emitted as CO<sub>2</sub>. If we take no action, by 2055, it is predicted that global annual carbon emissions will double to 14 gigatonnes of carbon (GtC; 1 Gt = 10<sup>9</sup> t).

This will give a level of carbon dioxide in the atmosphere three times higher than that observed before the Industrial Revolution. Our planet has not had such a high level (around 850 ppm) for 30 million years, and it is predicted to cause a rise in Earth's average surface temperature of 1 to 5 °C.

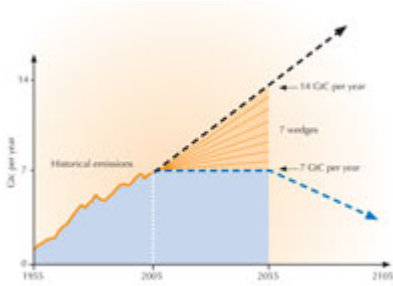
Is this unavoidable? Pacala and Socolow believe not. They suggest that we try to maintain carbon emissions at their current levels of 7 GtC per year and because no one method will achieve this, they have devised the idea of stabilisation wedges.



**Figure 1: Historical, current and predicted levels of carbon emissions (modelled in 2005).**

**Click on image to enlarge**

Image adapted from the work of Pacala and Socolow



**Figure 2: How stabilisation wedges could maintain carbon emissions at current levels. Click on image to enlarge**

Image adapted from the work of Pacala and Socolow

A wedge represents an activity or technology that reduces carbon emissions to the atmosphere; the reduction starts at zero today and increases linearly until, in 50 years time, it accounts for a reduction in predicted emissions of 1 GtC per year (Figure 2).

Over 50 years, the cumulative total of one wedge is therefore a reduction in predicted emissions of 25 GtC. A combination of seven wedges would achieve Pacala and Socolow's aim: annual emissions of 7 GtC in 2055 rather than the predicted 14 GtC.

Because the model assumes a starting year of 2005, there are now fewer than 50 years to achieve the reductions, but the concepts are just as valid.

### ***How could we save a wedge?***

1. More efficient cars. It is predicted that in 2055, there will be 2 billion ( $2 \times 10^9$ ) cars in use, four times the number today. If they averaged 16 000 km per year (as they do today) but operated at 4.7 l per 100 km of fuel instead of 9.4 l per 100 km (the current value), this could save one wedge of carbon.



Image courtesy of sassi / pixelio.de



2. Reduced car use: by 2055, assuming 2 billion cars and no improvement in car efficiency, one wedge could be saved if the distance travelled per year was halved, from 16 000 km to 8000 km.

Both of these options could save more than one wedge if the number of cars in use by 2055 has been over-predicted.

Image courtesy of Wendell; image source: Flickr

For example, more use of telecommunication (such as web conferencing and home working) and public transport would reduce the number of cars needed.

3. More efficient buildings: many savings can be made. For example, replacing all the world's incandescent light bulbs with compact fluorescent lights would save  $\frac{1}{4}$  wedge. Even larger savings are possible with heating and cooling. To save a whole wedge, we would need to reduce carbon emissions from buildings by 25%.



Image courtesy of designritter /  
pixelio.de



Image courtesy of Timo Newton-Syms; image source: Flickr

4. Improved power plant efficiency: coal-powered plants currently operate at about 32% efficiency and are responsible for about 25% of all carbon emissions. Improving plant efficiency to 60%, e.g. with fuel cells or better turbines, would save half a wedge if the quantity of coal-based electricity were unchanged.

5. Decarbonisation of electricity and fuels: for example, per unit of electricity, carbon emissions from natural-gas power plants are half those of coal-based power plants. One wedge could be saved if, by 2055, 1400 GW that is currently produced from coal were instead produced from gas.

6. Increased use of renewable, non-fossil, energy sources including nuclear fission, wind electricity, photovoltaic electricity and biofuels.

- A wind-electricity wedge would require a wind farm with a combined land area the size of Germany.
- A photovoltaic electricity wedge would need an array of photovoltaic panels with a combined area about 12 times that of metropolitan London, UK.
- One wedge of first-generation biofuels would require planting an area the size of India with biofuel crops.

All these options are based on current technologies, and therefore some may provide even more savings as technology improves. There are also conservation options for saving wedges that do not involve modern technology:



Image courtesy of Paul-Georg Meister / pixelio.de

More vegetarianism and thus reduced levels of meat farming would also reduce carbon (and methane) emissions.

7. Deforestation: eliminating clear-cutting of primary tropical forest over the next 50 years would save half a wedge. A further half a wedge would be saved if 250 million hectares of tropical land were reforested,

or 400 million hectares of temperate land (current areas of tropical and temperate forests are 1500 and 700 million hectares, respectively) over 50 years.

8. Soil management: conversion of forest or natural grassland to cropland aerates the soil through annual tilling, accelerating the decomposition of stored carbon and releasing it back into the atmosphere. It is believed that, historically, 55 GtC (2 wedges worth) have been released in this way. Currently, of a total of 1600 million hectares of cropland worldwide, only 110 million hectares undergo conservation tilling, whereby the soil is not disrupted. Examples of conservation tilling include soil-erosion control, planting of cover crops, and drilling of seeds without ploughing. Conservation tilling of all croplands could save from a half to one whole wedge.

### **Classroom activities**

*Carbon dioxide emissions and the measures taken to reduce them will affect the young more than their teachers or the authors, so this is an important topic for schools. It could be used for a number of individual, group or class activities.*

- Choose a carbon-saving activity or technology and either produce a poster or give a presentation to the rest of the class explaining how it works and how it could decrease atmospheric carbon.
- Investigate how you would save the requisite seven wedges. Which solutions would you use? What consequences would they have for people?
- If only three carbon-saving activities or technologies could be implemented, which would you choose and why?
- One carbon-reducing method could be to forbid cars to be driven by people under 24 years of age. Discuss the advantages and disadvantages.
- Identify the effects on ecosystems of any one of the carbon-saving technologies.
- Which carbon-saving solutions could be introduced at school and at home? Investigate the cost of powering your school by various methods (e.g. electricity, natural gas, butane, propane and fuel oil) and the savings made by any alternative-energy methods employed by your school.
- Should citizens of all countries be required to save carbon equally? Should developed and developing countries be treated differently?
- What do you think about the concept of stabilisation wedges? Is it sufficient to aim to keep carbon dioxide emissions at their current levels by 2055 or do we need to reduce them even further? Is that manageable? If so, how?
- Write a 250-word essay to your grandparents, explaining why the reduction of carbon is necessary and what they could do about it.

### **References**

Pacala S, Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* **305(5686)**: 968-972. doi: 10.1126/science.1100103

Socolow RH, Pacala SW (2006) A plan to keep carbon in check. *Scientific American* **September 2006**: 28-35. [www.scientificamerican.com/article.cfm?id=a-plan-to-keep-carbon-in](http://www.scientificamerican.com/article.cfm?id=a-plan-to-keep-carbon-in)

### **Web reference**

w1 – For further details about Stephen Pacala and Robert Socolow's work, see the website of the Carbon Mitigation Initiative at Princeton University, USA: <http://cmi.princeton.edu>

In particular, a free board game and supporting materials can be downloaded here: <http://cmi.princeton.edu/wedges>

### **Resources**

The *Scientific American* website offers a slide show about 'The World's 10 Largest Renewable Energy Projects'. See [www.scientificamerican.com](http://www.scientificamerican.com) or use the direct link: <http://tinyurl.com/3qr2mpc>

To read more about stabilisation wedges and introducing them into your life, see:

Biello B (2007) 10 solutions for climate change: ten possibilities for staving off catastrophic climate change. *Scientific American*. See [www.scientificamerican.com](http://www.scientificamerican.com) or use the direct link: <http://tinyurl.com/3p9h22r>

Calculate your own carbon footprint on The Nature Conservancy website:  
[www.nature.org/greenliving/carboncalculator](http://www.nature.org/greenliving/carboncalculator)

or the website of Conservation International: [www.conservation.org/act/live\\_green/carboncalc](http://www.conservation.org/act/live_green/carboncalc)

To introduce primary-school children to carbon dioxide, see:

Rau M (2011) Fizzy fun: CO<sub>2</sub> in primary school science. *Science in School* **20**: 24-29.  
[www.scienceinschool.org/2011/issue20/co2](http://www.scienceinschool.org/2011/issue20/co2)

Find out more about the sustainable use of energy and how to teach it:

Haubold B (2011) Review of *Sustainable Energy – without the hot air*. *Science in School* **20**.  
[www.scienceinschool.org/2011/issue20/sustain](http://www.scienceinschool.org/2011/issue20/sustain)

You may also enjoy the other climate-change related articles in *Science in School*, including several by the current authors. See: [www.scienceinschool.org/climatechange](http://www.scienceinschool.org/climatechange)

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