The chemistry of climate change

Resources for students aged 16-18 years

The chemistry of climate change - contents

Resources for advanced (16-18) students

Climate change

Written by Vicky Wong

Introduction

Is it one of the biggest challenges facing humanity or a huge swindle by the global scientific community? Is it happening at all? Is it caused by us?

There are few scientific issues which dominate the headlines in the way that climate change does. All students will have heard of it; many will have opinions about it; some may be trying to live differently to try to mitigate the effects of it.

Media reporting on the issue tends to focus on the extremes of opinion or the direst consequences for our civilisation of changes to the environment. It is probably fair to say that the consequences of the policy makers getting it wrong are potentially devastating – whether climate change is happening or not.

There are conflicting demands on governments. Environmental groups, big business, motoring organisations etc all have pressure groups who try to dominate the headlines with their point of view. Each will have a 'scientist' to speak for them or will claim that science supports their point of view. Many claim that the others are biased.

Through all of this there are the conflicts of our national interest as a country – we need to try to maintain our place in the world and our standard of living – against the need to make the world a place where all citizens can live.

There are moral arguments – should we tie our promises of aid to desperately poor countries to their promise to keep their emissions at low levels, effectively denying them electricity and other modern amenities while at the same time failing to decrease our own carbon emissions?

There are economic arguments. Lord Stern concluded in a review for the UK government in 2006 that failure to invest in avoiding the worst effects of climate change now could cost us dearly in the future.

This is not an issue in which any one person or country can be effective in isolation – so should we try to lead a 'low carbon life' when doing so individually is likely to make no difference to the global picture?

The United Nations was sufficiently concerned that in 1988 it set up the IPCC (Inter-governmental Panel on Climate Change). This is made up of scientists who review the research which is published on the subject in academic journals worldwide. They have been criticised for being too cautious about the potential effects of climate change and also for stating the case too strongly. Their 2007 Fourth Assessment Report (AR4) concluded that it is 95% certain that humans are causing the global climate to change.

The emphasis in these resources is on the science of climate change: what data is available, how it is collected and how it is interpreted. They could all be completed as a unit of work about climate change or alternatively they can be used individually to support teaching of one aspect of the science.

If they are all covered together, a suggested order could be:

Introduction Background information for teachers

Climate change resources on the net Links to a variety of resources including video, animations and background information

The greenhouse effect and global warming
This covers the greenhouse effect from a chemical perspective, looking at how molecules interact with IR radiation

Climate change and carbon dioxide
This activity looks at the evidence for the increase in temperature and carbon dioxide concentration in the atmosphere

Carbon dioxide is not the only greenhouse gas
A study of some of the other gases which contribute to the greenhouse effect, including another look at how molecules interact with IR radiation

Climate feedbacks
This activity aims to help students think about factors which affect the energy flow and therefore the temperature of the earth, the weather and the climate. This links to a look at how climate modelling is undertaken

Paleoclimatology and ice core chemistry
This is a fascinating activity which tells the story of how ice cores are extracted and analysed, including a discussion of the importance of knowing and understanding the errors in data

Earth surface temperature data
Students use up-to-date online information and data from various weather stations around the globe to look at the evidence for climate change

If students have covered all the material above they could hold a poster conference. This is one way in which scientists communicate with each other.

Each student or small group could research and produce a poster about the area which most interests them and then they could present their findings to the class. The 'climate change resources on the net' information could be used to give them a few places to start their research.

Some of the activities in this resource are based on the previous Royal Society of Chemistry publication, Warren, D., *Climate Change*, Royal Society of Chemistry, 2001.

Vicky Wong
November 2008

Climate change resources on the net

The following websites contain information which may be useful when teaching climate change. The resources are classified as follows:

W	written activity including discussion activities
P	practical activity (for students)
D	practical demonstration
V	video
B	background information
T	teaching ideas
G	game
A	animation
Da	data

Mainly video

http://www.rmets.org/video/talking-heads/rmets.html V

From the Royal Meterological Society this site has various questions about climate change answered by various eminent speakers. Each clip is short, but there are about 2 hours of video in total here. It is possible to search by theme. Could be a useful classroom resource as part of a lesson.

http://www.bbc.co.uk/bbcfour/documentaries/features/climate-shorts.shtml V

8 short films about the consequences of global warming, including a very interesting one about wine making in UK.

http://www.vega.org.uk/video/programme/118 V

This is an interview with F. Sherwood Rowland who won the Nobel prize in Chemistry for his work on Atmospheric Chemistry in 1995. He worked particularly on the formation and decomposition of ozone, but is also asked about climate change. The interview is quite long (45 minutes) but is potentially a very useful resource.

Activities for students

http://www.begbroke.ox.ac.uk/climate/interface.html B

Climate prediction and modelling from Oxford University. Excellent site, very clear. Could be useful as a presentation to a class or for students to work through.

http://www.bbc.co.uk/sn/hottopics/climatechange/climate_challenge/ G

Simulation game. You are president of EU and have to reduce emissions and still get re-elected. Takes quite a long time, but might be worth showing to students.

http://climateprediction.net/schools/resource_SPU.php W, P

The resources on this site are aimed at AS Science for Public Understanding but could also be useful for Advanced level Chemistry.

Demonstrations and animations

www.chemistryteachers.org D

Search for 'climate change' to get a pdf of a demonstration of how CO_2 makes a beaker heat up faster as a useful introduction to the greenhouse effect. (This is also available as demonstration 67 in Lister, T., *Classic Chemistry Demonstrations*, Royal Society of Chemistry, London, 1996.)

http://www.kcvs.ca/projects/climate/climate.php A
Animations about how climate change may affect temperature, how IR interacts with matter and others related to climate change.

http://www.chem.purdue.edu/gchelp/vibs/ch4.html (chime needed) A
Shows the various vibrations (and details which are IR active) of a number of molecules including methane, carbon dioxide, nitrogen and oxygen. It might be very useful to show these to students to help them understand why some vibrations are IR active and some are not.

Background information for teachers and students

www.sep.org.uk/catalyst B

Several magazine articles aimed at students on various issues surrounding climate change. These are mainly aimed at 14-16 year olds but more advanced students might find useful information here too.

http://www.sciencemuseum.org.uk/antenna/climatechange/ B

From the Science museum – an online exhibition.

http://www.peep.ac.uk/content/608.0.html B

Includes nice model of thermohaline circulation.

http://www.beep.ac.uk/content/215.0.html B

This is more about the consequences than the causes and also includes some discussion-type activities.

http://www.senseaboutscience.org.uk/pdf/Weather&Climate.pdf B

From Sense about Science, this document is quite detailed but aimed at a non-technical audience.

http://www.metoffice.gov.uk/corporate/pressoffice/myths/index.html B

Information from the UK met office about climate myths refuting some of the arguments given for why human activity is not responsible for climate change.

http://royalsociety.org/page.asp?id=6229 B

Good site from the Royal Society about climate change controversies (there is more here about climate change too).

www.antarctica.ac.uk and http://www.discoveringantarctica.org.uk/ B

The main website of the British Antarctic Survey which includes further information about their work. The latter site is aimed at school students.

http://www.defra.gov.uk/environment/airquality/publications/airqual-climatechange/index.htm B, Da
The Air Quality Expert Group (AQEG) is an expert group which reports to the UK government. Their 3rd report is available on the Defra website. The main theme of the report are the links between air quality and climate change.

http://www.noaanews.noaa.gov/stories2006/s2709.htm B, Da
Discussion of possible causes of the slow-down in the rate of increase of methane in the atmosphere.

Data

http://www.esrl.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html Da
The most up-to-date data on the changes to carbon dioxide in the atmosphere.

www.ipcc.ch B, Da
The official website of the IPCC (Intergovernmental Panel on Climate Change). From here it is possible to download the reports of the various working groups and most up-to-date information. Working group 1 report: 'The physical science basis' which is part of the Fourth Assessment Report (AR4) was published at the start of 2007 and is likely to be the most relevant for background information to this activity.

http://www.esrl.noaa.gov/gmd/Photo_Gallery/GMD_Figures/ccgg_figures/tn/ch4_tr_global.png.html Da
Up-to-date plot of concentration of methane in the atmosphere. This is updated annually in the summer.

http://www.mlo.noaa.gov/programs/esrl/methane/methane.html Da
Details about the measurement of methane levels at Mauna Loa.
[CHECK THIS ONE OUT – WASN'T LOADING PROPERLY LAST TIME I LOOKED]

Media

For information in the media, try searching the websites of New Scientist (some of the content is restricted to subscribers) or major newspapers. For example:
http://environment.newscientist.com/channel/Earth/climate-change/ or try the New Scientist homepage: www.newscientist.com
www.timesonline.co.uk
www.telegraph.co.uk
www.independent.co.uk

The BBC website also has a wealth of information: www.bbc.co.uk

(All last accessed April 2008)

The greenhouse effect and global warming – Teachers' notes

Background information

Radiation from the sun reaches the Earth. Some of this radiation is absorbed by the Earth and warms it up. A steady state is reached where the amount of radiation coming in is matched by the radiation escaping from the atmosphere, resulting in a fairly stable temperature and climate.

Anthropogenic (man-made) emissions are changing the composition of the atmosphere, both by adding additional amounts of gases naturally present, such as carbon dioxide and methane and also by the introduction of gases which do not occur naturally, such as CFCs (chlorofluorocarbons).

It is worth noting that the sun emits ultraviolet (UV), visible and also infrared (IR) radiation. This IR radiation is mainly absorbed by water vapour in the atmosphere and also contributes to the warming of the Earth. This additional complication has been left out of the activity for students, although some may be aware of it.

It is important to differentiate between the natural greenhouse effect, which is essential for life to exist, and the enhanced greenhouse effect. This is the additional effect caused by the anthropogenic emissions and it is what is generally thought to be causing global warming.

When molecules interact with UV radiation the energy they absorb tends to break bonds. This is because the energy of a photon of UV radiation corresponds to transitions between electronic energy levels in a molecule, so when a molecule absorbs UV radiation it is excited to a higher electronic energy state which may result in bond fission. IR radiation is less energetic as the photons contain less energy. Rather than breaking bonds it causes them to vibrate. Advanced theory shows that a molecule will absorb IR radiation if the vibration causes a change in dipole moment. Consequently, nitrogen and oxygen are not IR active, but many of the gases present in the atmosphere in lower concentrations such as water vapour and carbon dioxide are.

How science works

- Use theories, models and ideas to develop and modify scientific explanations
- Use knowledge and understanding to present scientific arguments and ideas
- Analyse and interpret data to provide evidence
- Appreciate the tentative nature of scientific knowledge
- Communicate information and ideas.

Answers to Questions

1. The bend and the asymmetric stretch (b and c).

2. Nitrogen will not – it is a symmetrical molecule like O_2 and so there will be no change in dipole moment when it vibrates; water will.

3. Water.

4. The Earth does not emit significant IR radiation at 4 μm and so this cannot be absorbed by gases in the atmosphere.

5. Clouds prevent the Sun's rays reaching the Earth's surface.

6. If the Earth is warmer, more water will evaporate from the oceans and so the amount of water vapour in the atmosphere will increase. Note: The rate of the whole water cycle,

including precipitation, will increase too – but the vapour pressure of water will be higher at a higher temperature and so the air will be able to hold more water.

7. As the amount of water vapour increases, the temperature is likely to increase too – this is an example of positive feedback.

Possible response to Summary

8. Gases in the atmosphere will absorb IR radiation if the vibrations which result cause a change in dipole moment of the gas. The Earth emits IR radiation in the 4-100 μm range. If the gas absorbs in this range it will absorb the IR emitted by the Earth, preventing it from escaping to space. This causes the Earth to be warmer than it would otherwise be.

9. The natural greenhouse effect is that which is caused by gases at their natural levels in the atmosphere. The enhanced greenhouse effect is the additional warming caused by anthropogenic emissions of naturally present gases such as CO_2 and CH_4 and also gases which are not naturally present in the atmosphere such as CFCs.

10. Areas of uncertainty include: how the various feedback processes will affect the temperature of the Earth; predicting the behaviour of water in the atmosphere; the processes operating in clouds.

Further reading

There is a very helpful animation of the interaction of carbon dioxide with IR radiation called 'Collisional heating by CO_2 in the atmosphere' available on http://www.kcvs.ca/projects/climate/climate.php.

http://www.chem.purdue.edu/gchelp/vibs/ch4.html (chime needed) is a website which shows the various vibrations (and details which are IR active) of a number of molecules including methane, carbon dioxide, nitrogen and oxygen. It might be very useful to show these to students to help them understand why some vibrations are IR active and some are not.

(All last accessed November 2008.)

The greenhouse effect and global warming

The sun produces radiation mainly in the ultraviolet (UV), visible (vis) and infrared (IR) regions of the electromagnetic spectrum. When these reach the Earth, part is reflected back into space and part of it is absorbed by the Earth's surface. The part which is absorbed heats up the Earth which in turn then radiates some of its energy out into space. The frequency at which any object emits radiation depends on its temperature. The Earth, being that much cooler than the Sun, emits energy at a lower frequency and therefore longer wavelength – in the IR region.

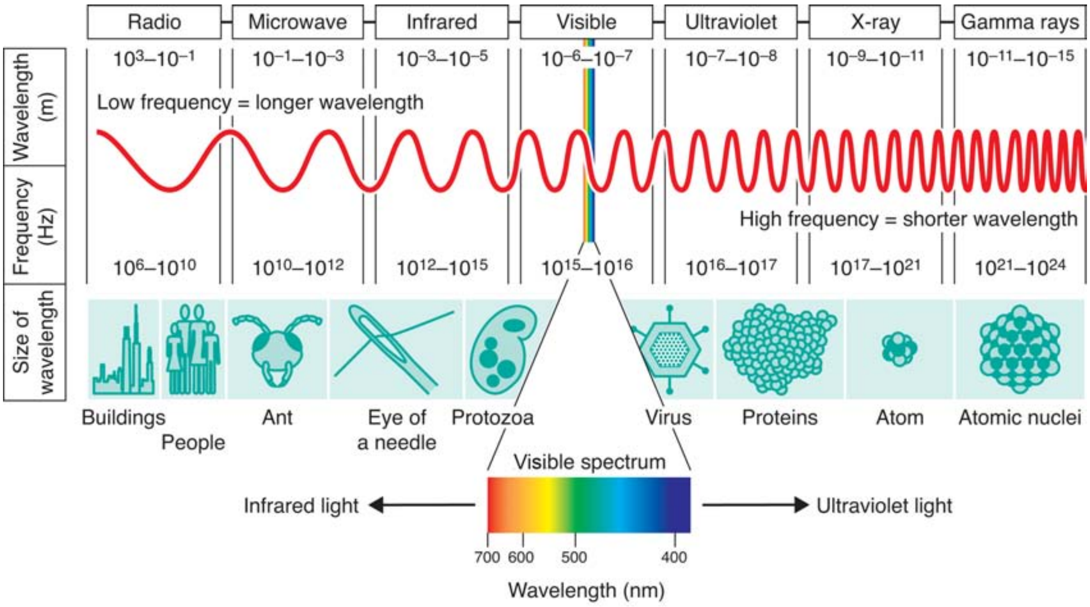


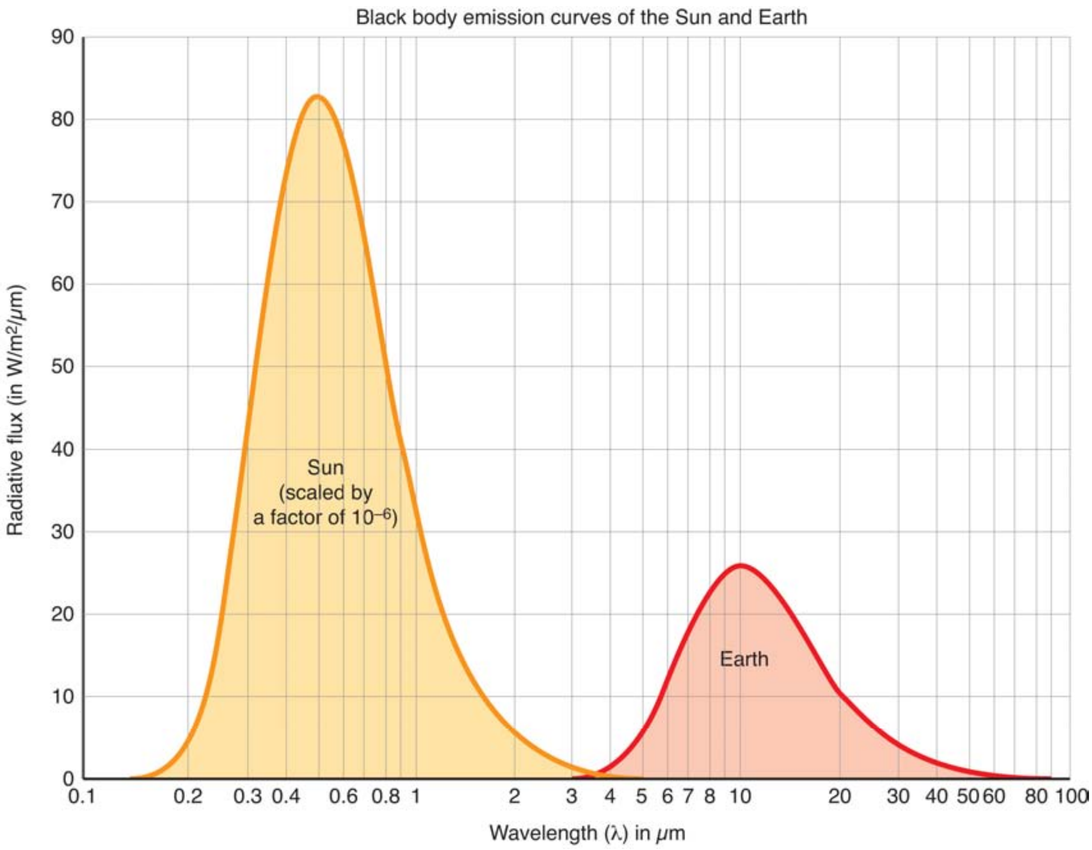
Image above adapted from http://www.andor.com/printpage.asp?app=331.

Figure 1. The electromagnetic spectrum.

Please note: Some of the graphs in this resource may use units which are unfamiliar, e.g.

1 μm = 10^{-6} m

1 cm^{-1} is the unit used to measure wavenumber and defined as the the reciprocal of wavelength (1 / wavelength)



Adapted from http://www.ldeo.columbia.edu/~kushnir/MPA-ENVP/Climate/lectures/energy/blackbody.gif.

Figure 2. The energy emissions of the Earth and the Sun.
Note: 'radiance' is a measure of how much light is emitted from an object (in this case, the Earth.)

A steady state is reached where the Earth is absorbing and radiating energy at the same rate, resulting in a fairly constant average temperature. If there were no greenhouse effect at all then the surface temperature would be about 256K or -17˚C (about the temperature of a domestic freezer) and life as we know it could not exist because water, the which is fundamental to life, would be a solid. However, the IR radiation emitted by the Earth can be absorbed by gases in the troposphere and become trapped. The radiation is then re-emitted in all directions; some back towards the Earth, which is known as the 'greenhouse effect'. This leads to an increase in temperature and global warming, making the average surface temperature of the Earth about 286K or 13˚C. It is an essential part of keeping our planet hospitable and helps to sustain life. The gases which absorb and then re-emit IR are known as 'greenhouse gases.'

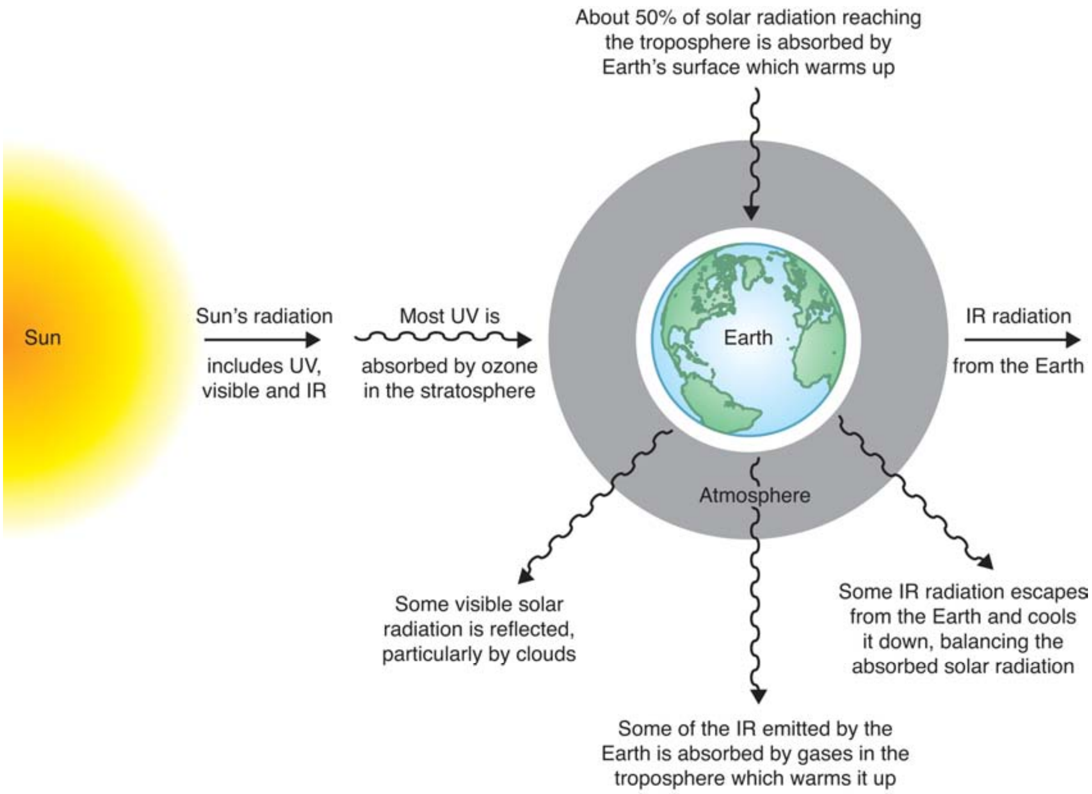


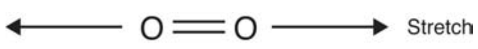
Figure 3. Energy balance of the earth.

Properties of a greenhouse gas

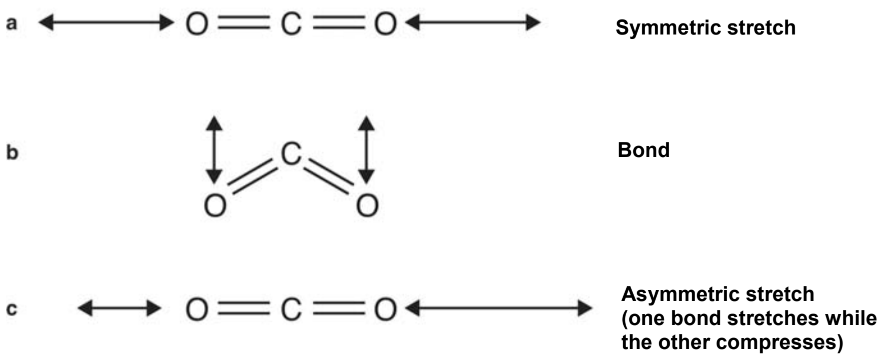
1. A greenhouse gas absorbs infrared radiation

When molecules interact with UV radiation the energy they absorb can break bonds. IR radiation is less powerful as the photons contains less energy. Rather than breaking bonds it causes them to vibrate more energetically. Advanced theory shows that a molecule will absorb IR radiation if the vibration causes a change in its dipole moment.

Oxygen, O=O, vibrates as a stretching and compression of the bond. Oxygen does not absorb IR radiation as the molecule is symmetrical and does not have a dipole moment – so there can be no change in dipole moment on vibration.



pCarbon dioxide, CO_2, vibrates in three different ways:

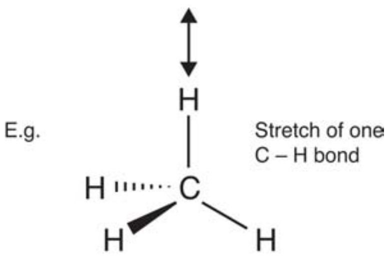


1. Which of the vibrations (a, b, c) will cause a change in dipole moment and so absorb IR radiation?

2. Two other gases which are present in the atmosphere are nitrogen, N_2, and water vapour, H_2O. Predict whether they will absorb IR radiation.

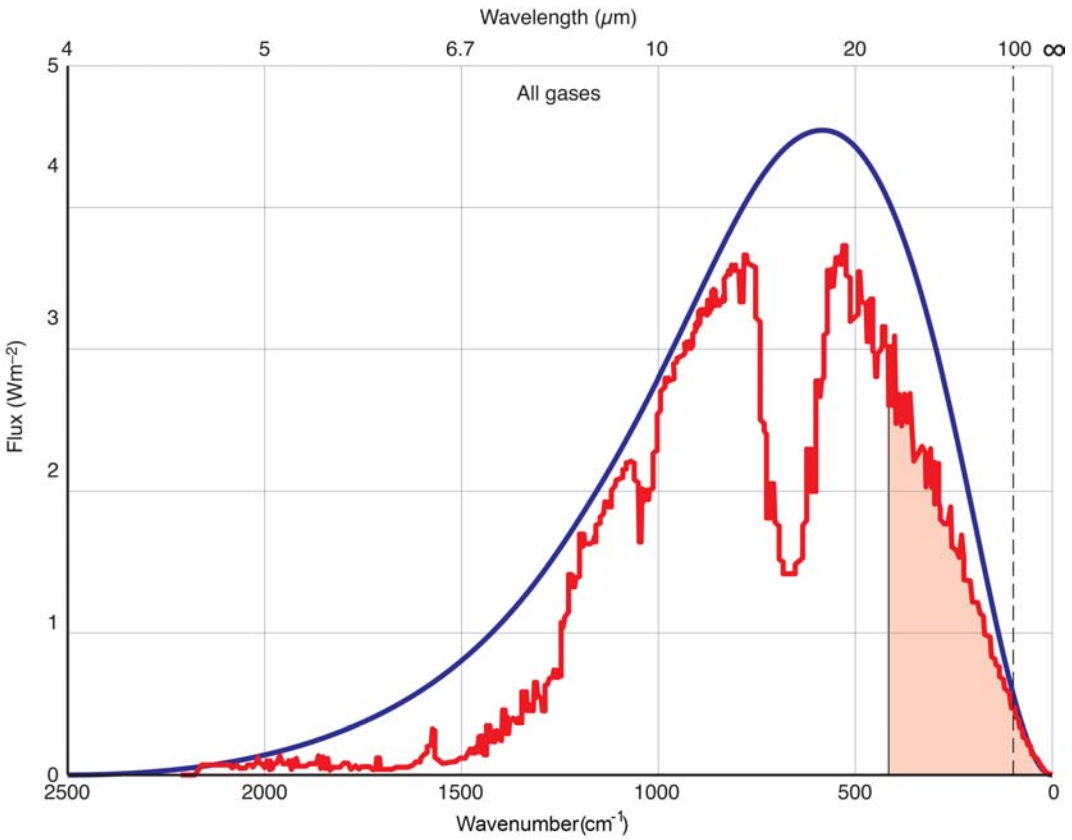
3. Of these gases which absorb IR radiation in the atmosphere, which is present in the highest concentration?

Methane, CH_4, is another greenhouse gas. Although it is symmetrical and has no permanent dipole moment, it can vibrate in ways which change its dipole moment and so will absorb IR radiation.



Note: This is a simplified version of the methane stretches. They are shown in full and animated on http://www.chem.purdue.edu/gchelp/vibs/ch4.html. (Last accessed November 2008.)

2. A greenhouse gas absorbs energy in the wavelenth range 5-100 μm



Used with permission from Prof Keith Shine at the University of Reading.

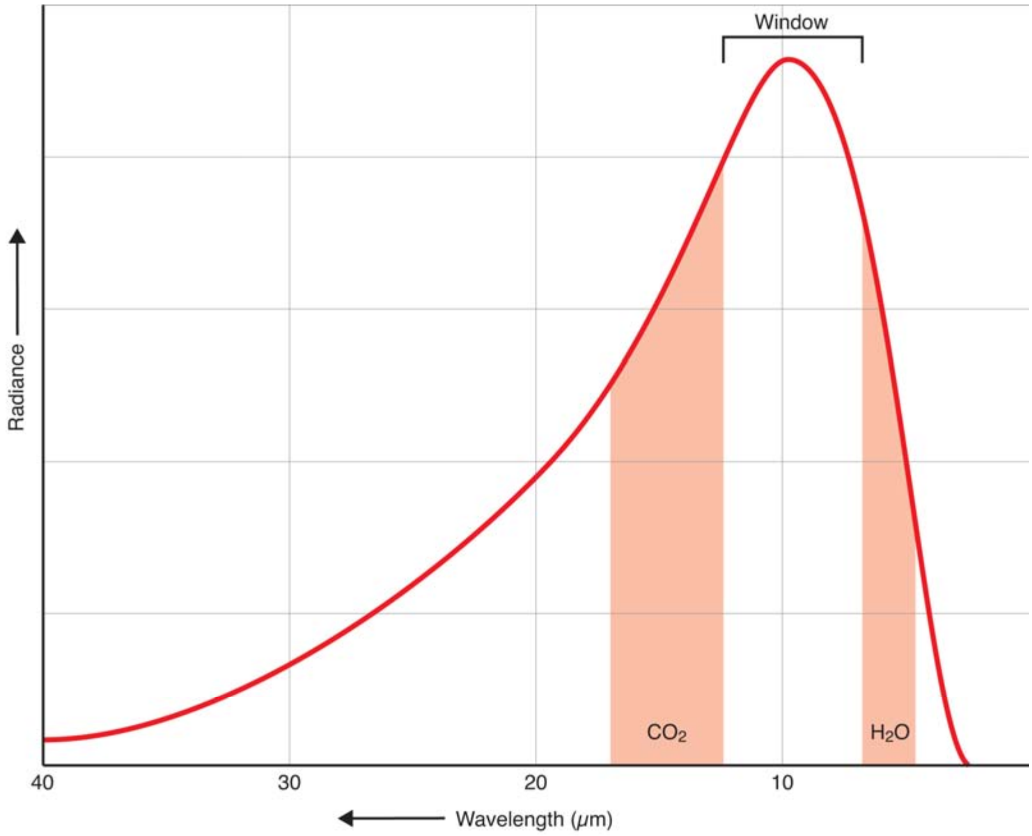
Figure 4. A computer generated typical radiance spectrum of the Earth (red line) and the theoretical (or black body) emission at the Earth's surface (blue line). Radiance is a measure of how much light is being emitted by an object (in this case, the Earth.)

The Earth does not emit much radiation outside the 5-100 μm range and so any gases which absorb other wavelengths will not contribute significantly to the greenhouse effect.

4. Explain why a gas which absorbs IR radiation at 4 μm does not contribute to the greenhouse effect.

Enhanced greenhouse effect

The two most significant greenhouse gases in the atmosphere are carbon dioxide and water vapour. Water makes the bigger contribution (about 60%) to the natural greenhouse effect. Between the absorptions caused by carbon dioxide and water there is a 'window' where the majority of the infrared radiation can escape with relatively little absorption (except for a narrow band where ozone absorbs.) About 70% of Earth's radiation escapes into space through this 'window.'



Adapted from *Salters Advanced Chemistry: Chemical Storylines AS,* published by Heinemann.

Figure 5. A simplified version of Figure 4, showing the Earth's radiation spectrum with the regions where CO_2 and H_2O absorb. Between these two absorptions is the 'window' where the majority of the IR emitted by the Earth escapes.

Gases produced by human activities can increase the natural greenhouse effect of the atmosphere. This is often known as the enhanced greenhouse effect. There are two types of these gases:

- Gases already present in the atmosphere but an increased amount is added by human activities. This includes carbon dioxide and methane. Carbon dioxide contributes the most to the enhanced greenhouse effect.
- Gases which are not naturally present. These can sometimes absorb in the 'window' through which radiation would normally escape into space. This can cause them to have a very large greenhouse effect. CFCs (chlorofluorocarbons) are an example.

The concentration of carbon dioxide is currently about 380 ppm (parts per million) in the atmosphere and is rising by about 0.45% per year. Modellers use a scenario of doubled CO_2 concentration to assess the sensitivity of the Earth's climate system to changes in greenhouse gas concentration. They predict rises of about 1.5-4.5˚C. This is not just due to the direct effect of carbon dioxide – there are a large number of feedback processes which amplify the effect of the carbon dioxide.

Carbon dioxide is about 0.03% of the Earth's atmosphere; water is more variable, but at the surface is usually about 1-4% of the atmosphere.

5. Water in the Earth's atmosphere can also cause cooling. Explain how. (Hint: think about cloudy days.)

6. As the Earth warms up, what will happen to the amount of water vapour in the atmosphere? (Hint: think about the water cycle.)

7. As the amount of water vapour increases, what will happen to the temperature?

Climate models run on computers are used by climate scientists to try to predict changes to the Earth's climate. The water in the atmosphere is crucial for these models. The amount of water can be modelled well – it just depends on evaporation and condensation. As the temperature increases, the amount of water which the atmosphere can hold increases. Predicting the behaviour of the water is much harder and is one of the causes of uncertainty in the predictions. Water vapour in the atmosphere can condense to form clouds consisting of water droplets or ice particles. The processes operating in clouds are relatively poorly understood and therefore harder to model and predict, as is the resulting effect on temperature.

Understanding how the climate system works, and the likely effects of adding more greenhouse gases to the atmosphere, are subjects of extensive research by scientists from around the world. Better understanding can help to build better models which give more reliable predictions about the climate of the future.

Summary

8. Explain why some gases in the atmosphere cause the greenhouse effect.

9. Explain the difference between the natural and the enhanced greenhouse effect.

10. List some of the areas of uncertainty or poorly understood parts of the process where further research is required.

Climate change and carbon dioxide – Teachers' notes

Background information

See 'The greenhouse effect and global warming.'

How science works

- Use theories, models and ideas to develop and modify scientific explanations
- Use knowledge and understanding to present scientific arguments and scientific ideas
- Analyse and interpret data to provide evidence
- Evaluate methodology, evidence and data and resolve conflicting evidence
- Appreciate the tentative nature of scientific knowledge
- Communicate information and ideas using appropriate terminology.

Answers to questions

1. Fossil fuels contain carbon, which when burnt in sufficient oxygen produces carbon dioxide. Eg:
   $C_8H_{18} + 25/2\ O_2 \rightarrow 8\ CO_2 + 9H_2O$
   Alternatively, the large hydrocarbons in oil can be represented simply by CH_2 which undergoes complete combustion as:
   $CH_2 + 3/2\ O_2 \rightarrow CO_2 + H_2O$.

2. Sources of CO_2 include respiration (animals and plants), decay of dead organisms, volcanic activity, the oceans (as they warm up the CO_2 can come out of solution.) Sinks for CO_2 include photosynthesis, the oceans (which dissolve a large amount), carbonate structures such as shells of molluscs and corals.

3. There are no local emissions to distort the readings.

4. Regular calibration is important to ensure that the readings are as accurate as possible and that there is no 'drift' in the data.

5. Winter will be higher – the rate of photosynthesis will be lower and emissions for heating etc will be higher.

6. 0.038%.

7. The rate at which carbon dioxide concentrations are rising is increasing.

8. The global average temperature has been mainly increasing through the century, with the exception of the 1940s when the temperature decreased.

9. As the century has progressed, the blue line has got thinner. This shows that the level of confidence in the data has increased as the uncertainties have been reduced.

10. No.

11. ^{16}O contains 8 neutrons and ^{18}O contains 10.

12. To ensure that they do not contaminate the ice cores.

13. The pattern is regular with an interval of aproximately 100 000 years.

14. Yes.

15. Temperature.

16. No, CO_2 concentrations have never been this high before.

17. As concentrations this high have never been seen before we do not know how the Earth will respond and particularly what will happen to the temperatures. This is effectively a massive chemistry experiment with the Earth's entire atmosphere.

Possible response to summary

Possible causes of climate change over the last half a million years:

- The variation in solar radiation reaching the Earth (Milankovich cycles)
- Rising temperature and carbon dioxide working in feedback with each other.

Possible causes of climate change over the last 150 years:

- Rising temperature and carbon dioxide working in feedback with each other
- Anthropogenic (man-made) carbon dioxide emissions
- Changes in the activity of the Sun – the more sunspots, the more solar energy reaches the Earth.

Parts of the climate and carbon dioxide link which are well understood:

- CO_2 does absorb infrared radiation
- There have been cycles/variations in the temperature of the Earth.
- The temperature of the Antarctic and the concentration of carbon dioxide follow a similar pattern. This is consistent with CO_2 acting as an amplifier of climate change.
- There are natural sources and sinks of carbon dioxide
- Humans are putting carbon dioxide into the atmosphere at a rate never seen before and the concentration is higher than at any time in the last 800 000 years.

Parts of the climate and carbon dioxide link which are not fully understood and where further research is required:

- There is less data for how the temperature of the Earth, apart from Antarctica, has varied in the last 800 000 years.
- It is not known in detail why carbon dioxide concentration and temperature followed a similar pattern in the past.
- It is not certain whether carbon dioxide or temperature began to rise first at the end of the ice ages.
- While it is expected that temperature will rise if carbon dioxide increases, the exact magnitude of the rise is not known.

Further reading

There is a huge amount of information in the media and on the web about climate change and carbon dioxide.

For information in the media, try searching the websites of New Scientist (some of the content is restricted to subscribers) or major newspapers. For example: http://environment.newscientist.com/channel/Earth/climate-change/ or try the New Scientist homepage: www.newscientist.com

www.timesonline.co.uk
www.telegraph.co.uk
www.independent.co.uk

For an article about sunspots see http://news.bbc.co.uk/1/hi/sci/tech/3869753.stm.

There have been some major studies into the likelihood and implications of climate change. Even the summaries of these are long, but could be understood by most students. Try www.ipcc.ch; this will give access to the assessment reports. The most relevant to this activity is the Working group 1 report: 'The physical science basis'. The Fourth Assessment Report (AR4) was published at the start of 2007.
For a British version, see the Air Quality Expert Group (AQEG) 3rd report available on the Defra website: http://www.defra.gov.uk/environment/airquality/publications/airqual-climatechange/index.htm.

For information about the British Antarctic Survery (who participate in drilling and analysing ice cores) see: www.antarctica.ac.uk.

The Royal Society website has a section on climate change controversies which is clear and easy to understand: http://www.royalsoc.ac.uk/page.asp?id=6229.

For the most up-to-date data on carbon dioxide concentrations as measured at Mauna Loa see: http://www.esrl.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html.

(All last accessed November 2008.)

Climate change and carbon dioxide

There is a wide range of scientific evidence which shows that the Earth's climate has always been changing. Over the last few hundreds of thousands of years, there have been periods of global warming and global cooling. The cooler periods correspond to ice ages when much of the northern hemisphere land was covered with sheets of ice many kilometers thick. It is only in the last few decades that some of the changes in the last 200 years have been attributed to the consequences of human activity. These are called anthropogenic changes.

The temperature of the Earth is determined by a balance between the energy coming in from the Sun, and the energy being re-radiated into space. Carbon dioxide is known to be a greenhouse gas: it absorbs infrared energy emitted from the Earth.

Change in the last century

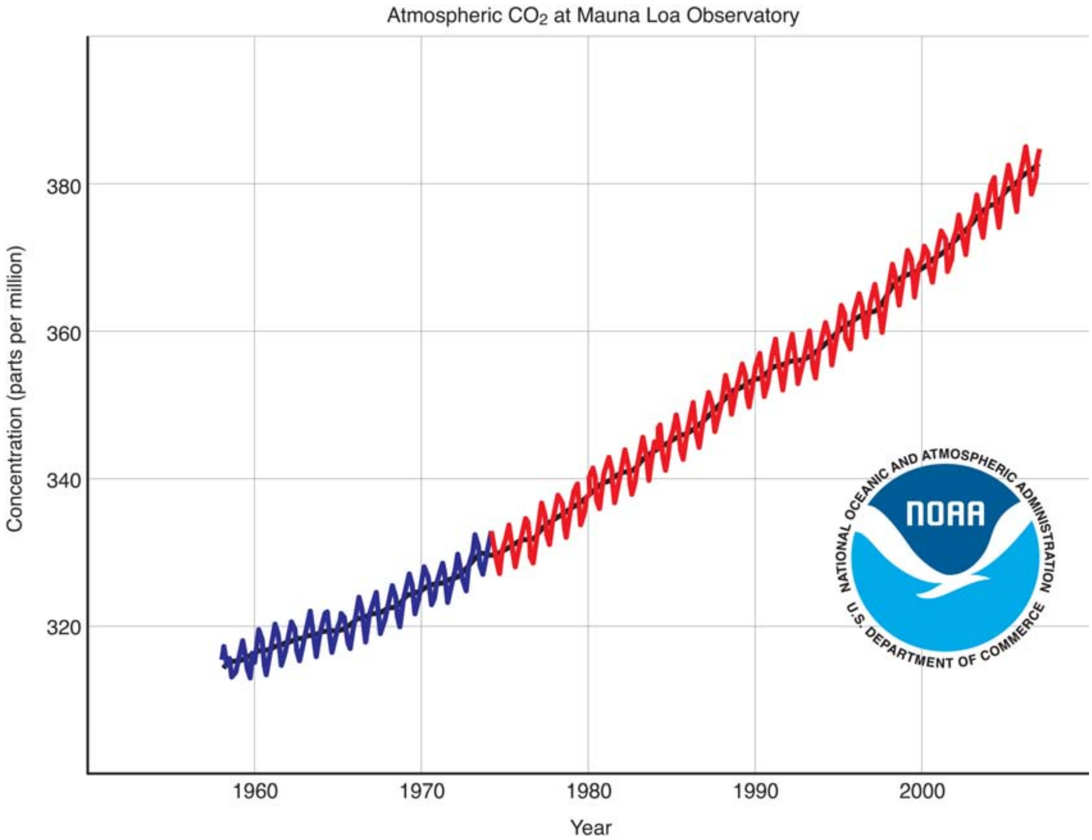
Since the industrial revolution, carbon containing fuels (and particularly fossil fuels) have been burnt on a scale never known before. These fuels produce carbon dioxide which goes into the atmosphere.

1. Explain why burning fossil fuels produces carbon dioxide. Use at least one equation in your answer.

Carbon dioxide is naturally present in the atmosphere and has a lifetime of about 50-100 years. This means that a molecule will spend on average this amount of time in the atmosphere before being removed. Processes which add carbon dioxide to the atmosphere are known as *sources* and those which remove it are known as *sinks.*

2. Suggest some natural *sources* and *sinks* of carbon dioxide in the atmosphere.

When all the sources are adding carbon dioxide to the atmosphere at the same rate that all the sinks are removing it, then the total concentration of carbon dioxide will remain constant (it will be in equilibrium). At present, carbon dioxide from human activity is going into the atmosphere faster than the sinks can remove it. As a consequence the concentration of carbon dioxide in the atmosphere is rising. At Mauna Loa in Hawaii, the concentration of carbon dioxide in the air has been measured regularly since the middle of the last century and this rise can be seen clearly.



Dr. Pieter Tans, NOAA/ESRL www.esrl.noaa.gov/gmd/cgg/trends
From http://www.esrl.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html and used with permission.

Figure 1. This graph shows the carbon dioxide concentration in the air. Data are reported as a dry mole fraction which is defined as the number of molecules of carbon dioxide divided by the number of molecules of dry air multiplied by one million (ppm). The black line shows the seasonal (6 monthly) average. The information is obtained by passing a stream of air through an infrared gas analyser which has a water vapour freeze trap attached. The machine is regularly calibrated by passing reference samples, which contain a known concentration of carbon dioxide, through it.

Afapted from http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm.

Figure 2. Map showing the location of Mauna Loa.

Mauna Loa in Hawaii is a barren lava field a long way off the coast of the USA in the Pacific Ocean. Although there are other places where CO_2 is measured, this is considered to be one of the most reliable records.

3. Why is this data more reliable than if were recorded somewhere like mainland Britain?

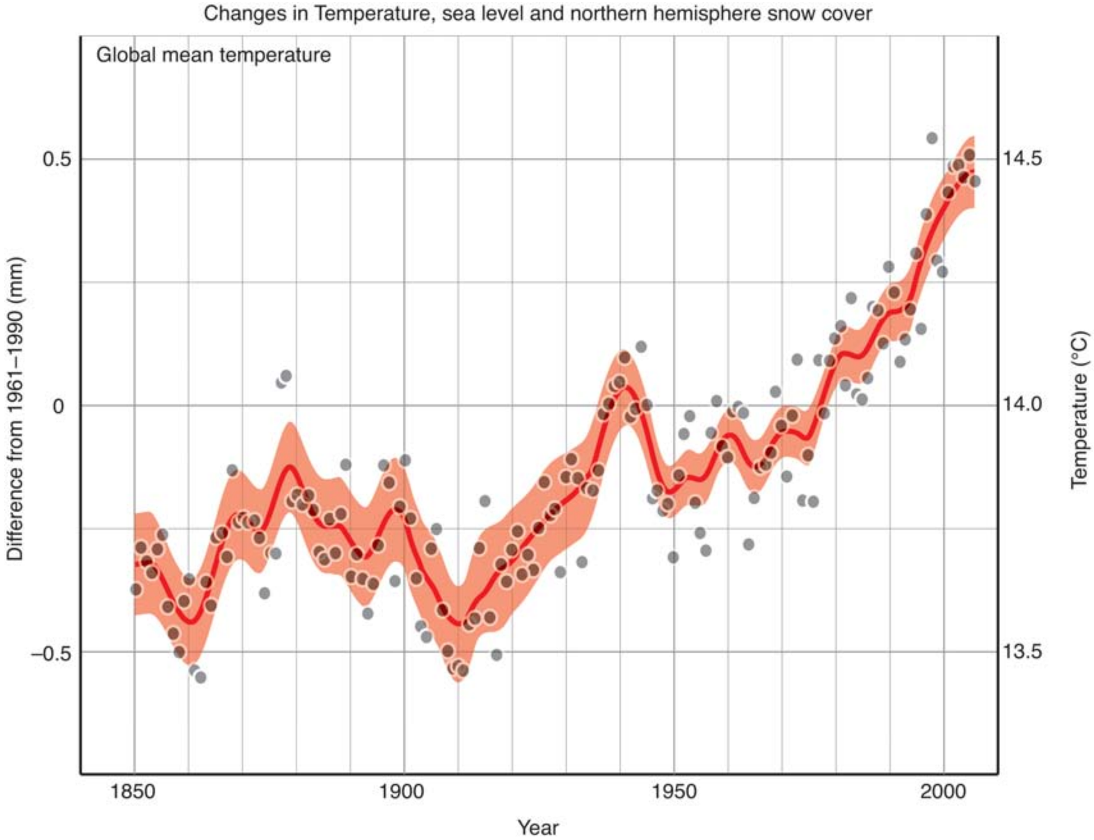
4. Why is regular calibration of the infrared gas analyser important

5. The concentration rises and falls in a regular pattern which matches the seasons. Would you expect the summer or the winter to have the higher value? Explain your answer.

6. What is the percentage of carbon dioxide in the air by volume? (Assume the concentration is 380 ppm.)

7. What is happening to the rate of the increase in concentration of carbon dioxide in the air?

Temperatures have been measured directly in a number of places around the globe since about 1850. These can be used to show how the average global temperature has changed in that time.



From Intergovernmental Panel on Climate Change 4AR (http://www.ipcc.ch/) .

Figure 3. This graph shows how the global temperature has changed since the mid-1800s (when records began.) The axis on the right shows the average global temperature; the one on the left shows how this temperature differs from the average temperatures measured during the period from 1961-1990. The circles show the yearly values and the red line the averaged values over a ten year period. The pink shaded areas are the estimated uncertainties in the values.

8. Describe how the temperature changed between 1900-2000.

9. What has happened to the thickness of the pink line as the century has progressed? What does this show?

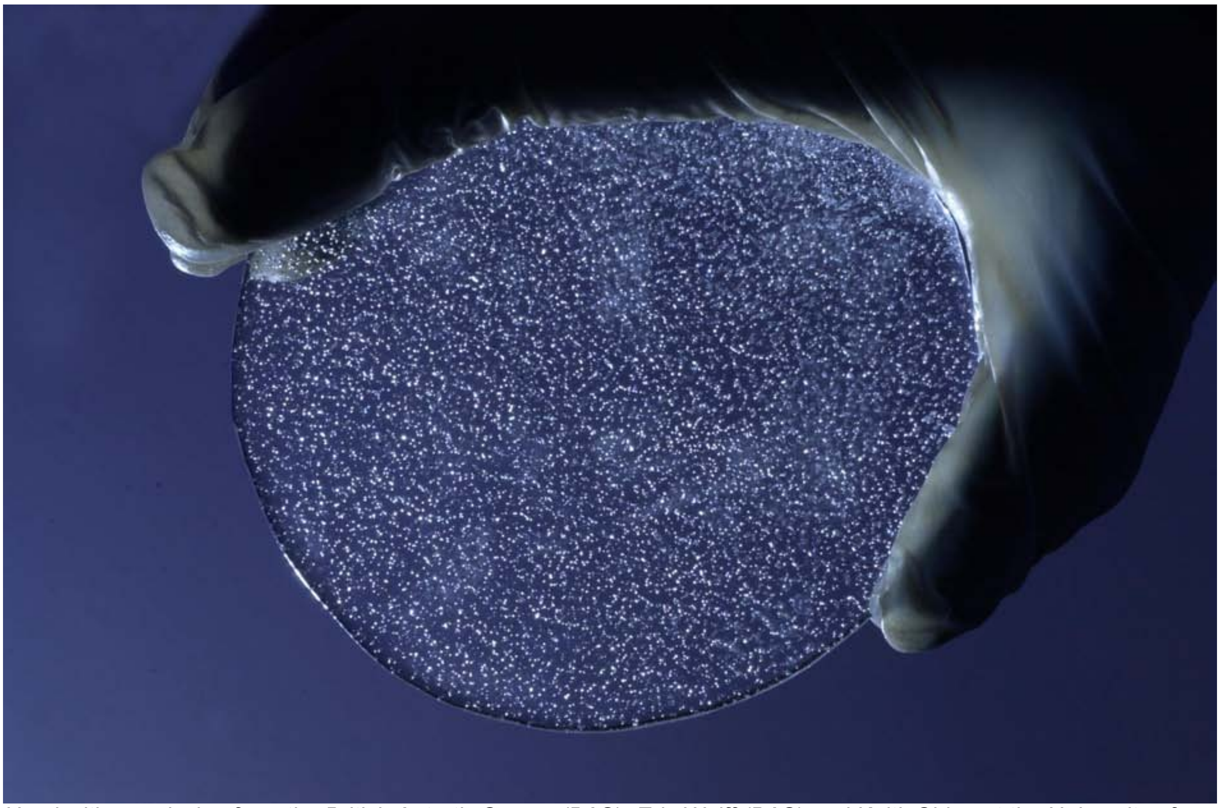
10. Is there a direct correlation between the change in the concentration of carbon dioxide and the change in temperature?

The differences in the shapes of the temperature and carbon dioxide graphs suggest that the link between temperature and carbon dioxide is not straightforward. Carbon dioxide is not the only factor which can cause temperature change. Many other factors can also cause warming (such as the gas methane); some cause cooling. Small particles in the atmosphere called aerosols can cause cooling. The aerosols contain sulfate ions which can come from natural sources such as volcanic eruptions or they may come from burning fuels without controls on emissions. It is widely accepted that the cooling in the middle of the 20th century was caused by these particles.

Climate Change over much longer time scales

To help in the search for information about climate change in the past, ice cores have been drilled in both the Arctic and the Antarctic. These ice cores are long, thin cylinders of ice which go down several kilometers into the glaciers near the poles. As snow is successively laid down, bubbles of air become trapped and can be analysed to find out historical concentrations of gases including carbon dioxide. In addition, by examining the ratios of ^{16}O and ^{18}O as well as ^{1}H and ^{2}H, the temperature of the Earth at the time can be calculated. The ice cores at Vostok have yielded data going back more than 400 000 years; those at EPICA Dome C nearly 800 000 years.

11. What is the difference between ^{16}O and ^{18}O atoms?



Used with permission from the British Antartic Survey (BAS), Eric Wolff (BAS) and Keith Shine at the University of Reading.

Figure 4. An ice core showing bubbles of air trapped in the ice.

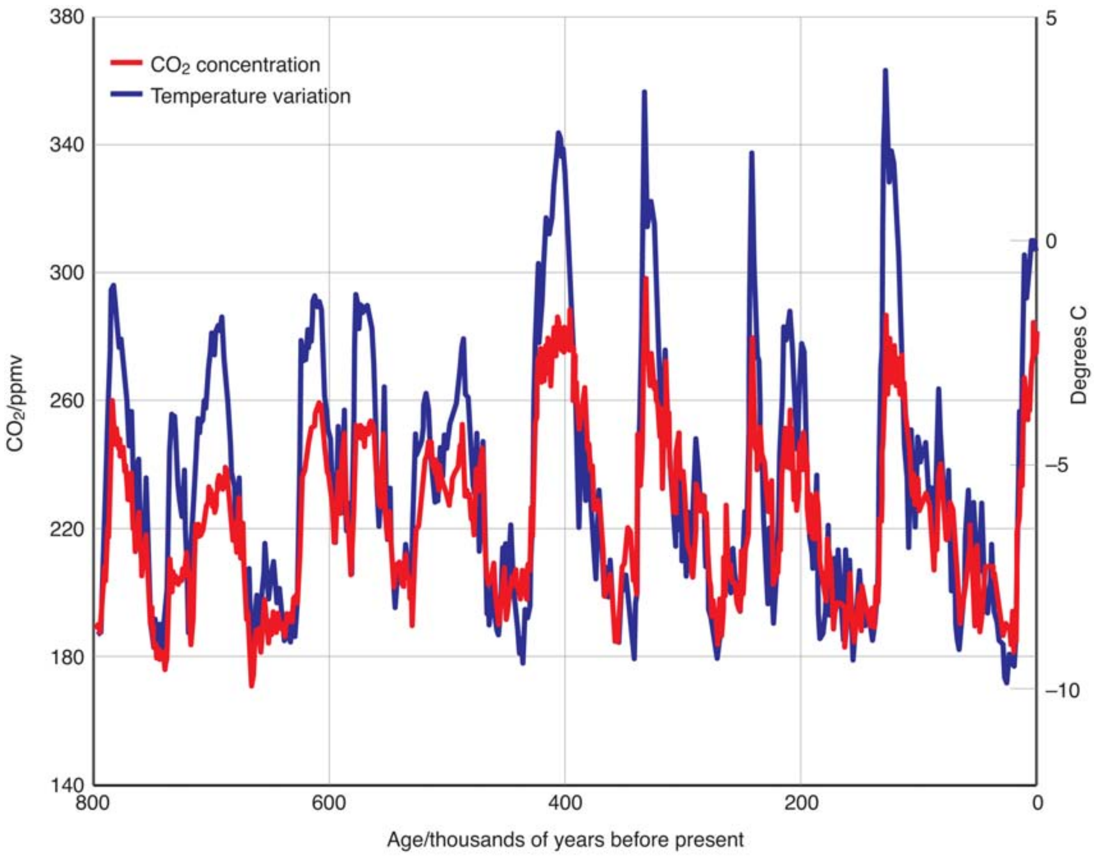
Used with permission from the British Antartic Survey (BAS), Eric Wolff (BAS) and Keith Shine at the University of Reading.

Figure 5. A scientist operating an ice core drill in a pit.

From http://www.discoveringantarctica.org.uk/photo_lib/hi/scientist05.jpg. Used with permission from the British Antartic Survey (BAS), Eric Wolff (BAS) and Keith Shine at the University of Reading.

Figure 6. Scientists examining an ice core in Atarctica.

12. In Figure 6, the scientists are seen to be wearing a lot of protective gear including full body suit, gloves and masks. Explain why this is necessary.



Plots courtesy of EPICA. Data from Luethi et al 2008 (CO_2) and Jouzel et al 2007 (temperatures). Thanks to Eric Wolff of British Antartic Survey (BAS) for supplying the information.

Figure 7. Antarctic Ice Core Data.

13. What do you notice about the pattern of temperature rises and falls (shown in blue)?

14. Does the carbon dioxide concentration (shown in red) show a similar pattern to the temperature rises?

15. Which appears to rise first – temperature or carbon dioxide concentration?

Issues with dating the ice cores (and in particular, dating the temperature and carbon dioxide measurements relative to each other) mean that it is not possible to be completely certain which rises first, but it appears to be the temperature. Current thinking is that the temperature began to rise which caused the carbon dioxide concentration to rise. The extra carbon dioxide in turn helped to heat up the Earth, which caused more carbon dioxide to enter the atmosphere. This is what is known as feedback and it can amplify a small change into a much larger one. The carbon dioxide could come from a number of sources including the oceans; as the temperature rises, carbon dioxide becomes less soluble and comes out of solution.

The exact nature of the relationship between temperature and carbon dioxide concentration is still not well understood and there is no one fully-accepted explanation for the patterns seen in the ice cores. It does seem to be that it is not high carbon dioxide concentration causing the temperature to begin to rise in the first place.

The regular shape of the temperature graph suggests an almost mathematical function which in turn suggests that one of the causes of the temperature variations might be astronomical in nature. In the 1920s a Serbian astronomer called Milutin Milankovitch developed the theory that ice ages were controlled by the amount of solar energy reaching high northern latitudes in midsummer because this was the area where ice would begin to advance if solar energy dropped. Milankovitch proposed that variations in solar energy were caused by the orientation of the Earth as it moved around the Sun. Combinations of three factors in the Earth's motion (eccentricity, precession and obliquity or amount of tilt) altered the amount of energy received by the Earth at different latitudes and seasons giving rise to what are known as Milankovitch cycles. The Milankovitch Theory of ice ages is generally accepted today.

The graph below shows the amount of solar energy in watts per square metre reaching lattitude 65 deg N calculated over the last 160 thousand years.

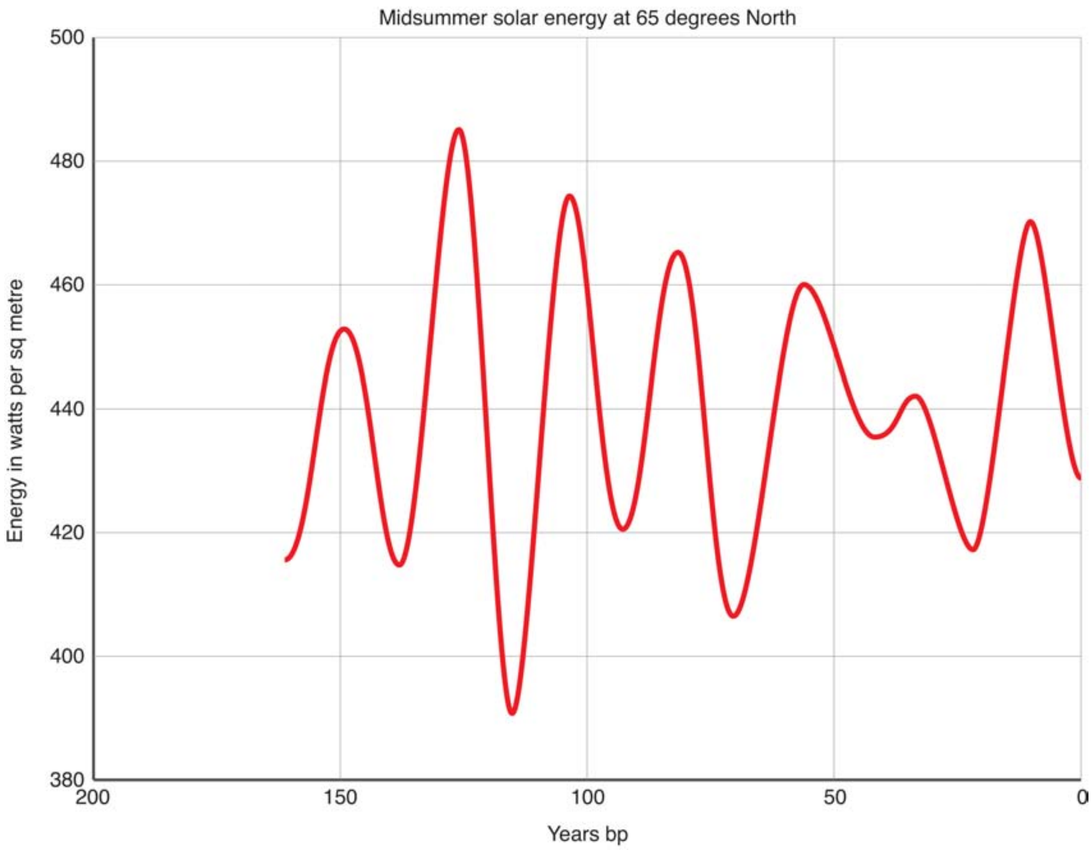


Figure 8. Amount of solar energy reaching latitude 65 degrees North over the last 160 years.

If this is superimposed on the Vostok ice core data (Figure 7) the peaks in the two curves seem to coincide (see Figure 9) and this is also true further back in time. Milankovitch obviously did not have the ice core data and so the match between it and what his theory predicts is particularly striking.

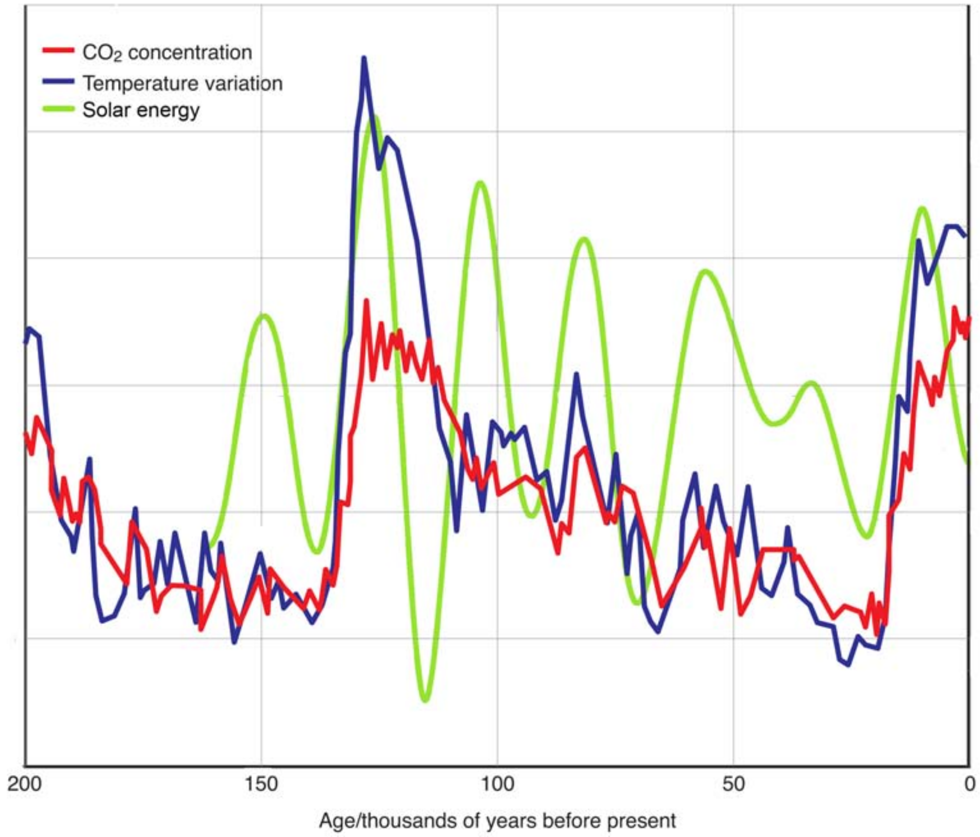


Figure 9. Figure 7 superimposed onto Figure 8 to allow a comparison of the shape of the graphs. Vertical axes have been removed.

This offers a hypothetical explanation of why the temperature varies as it did over half a million years, although it is still difficult to understand the magnitude of the temperature reaction.

16. Carbon dioxide concentrations today are about 380 ppm. Has the concentration been higher than this in the last 400 000 years?

17. Why is this high concentration of carbon dioxide a concern?

It seems from the Antarctica data that the temperature there has been higher than at present in the last half a million years. It is not clear, however, whether the average temperature of the Earth has ever been higher as the ice cores give a local not a global picture.

Sunspots

In addition to the Milankovitch cycles, the amount of solar energy reaching the Earth is dependent on the number of ‘sunspots’ on the Sun’s surface. Roughly, the higher the number of sunspots the hotter the Sun is and therefore more energy will reach us. The number of sunspots also affects how much solar wind reaches Earth and reflects changes in the Sun’s magnetic field. Exactly how and how much this affects the climate of the Earth is still a subject for much debate and research. A team of scientists in Zurich have recently shown that the number of sunspots is at a 1000-year high and say that anthropogenic climate change is amplifying the warming already being produced by the sun.

Summary

Summarise the possible causes of climate change:

a. Over the last half a million years
b. Over the last 150 years

In your own words, explain the relationship between changes in the climate and concentration of carbon dioxide in the atmosphere. Indicate where the areas of uncertainty are and suggest what further research is required. Explain why what is happening now is different to the changes in climate which have occurred in the Earth's past.

Carbon dioxide is not the only greenhouse gas – Teachers' notes

Background information

While carbon dioxide is the gas which seems to be having the most impact on climate, it is not the only greenhouse gas. Indeed, on a molecule for molecule basis it has a much smaller effect than most other greenhouse gases.

Two measures are used to determine the relative effects of the different gases – radiative forcing and global warming potential (GWP). Radiative forcing is a measure of the change in the earth's energy balance which is being caused by that substance and has the units $W\ m^{-2}$. This takes account of the amount which is present in the atmosphere.

Global warming potential is a measure of global warming which would be caused by an instantaneous (or pulse) emission of a gas in 100 years, relative to carbon dioxide which is given the arbitrary value of 1. This measure takes account of the lifetime of the gas in the atmosphere.

The so-called 'super greenhouse gases' have very long lifetimes (giving them long global warming potentials) and many are increasing in the atmosphere a high rate. Most contain fluorine. They absorb IR radiation in the 'window' where few other gases absorb which causes them to have an even greater impact on global warming than they might otherwise. HFC-134a is the name given to the refrigerant 1,1-difluoroethane which is used in place of CFCs. It does not react with stratospheric ozone, but is a significant greenhouse gas.

How science works

- Use theories, models and ideas to develop and modify scientific explanations
- Use knowledge and understanding to pose scientific questions, define scientific problems, present scientific arguments and scientific ideas
- Analyse and interpret data to provide evidence
- Appreciate the tentative nature of scientific knowledge
- Communicate information and ideas using appropriate terminology
- Appreciate the ways in which society uses science to inform decision making.

Answers to questions

1. CF_4

2. SF_6

3. HFC-134a

4. They are causing concern because they have very long lifetimes (effectively infinite in the case of CF_4) and high global warming potentials.

5. They contain fluorine.

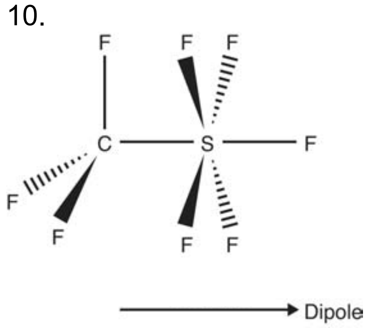
6. $SF_6 \xrightarrow{\text{UV light}} {}^{\cdot}SF_5 + {}^{\cdot}F$

7. ${}^{\cdot}SF_5 + {}^{\cdot}CF_3 \rightarrow CF_3SF_5$

8. Tetrahedral

9. Octahedral

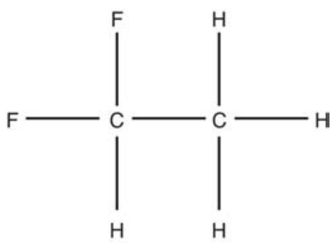
10.



11. The molecule is not symmetrical across the SF bond axis and therefore a vibration will produce a change in dipole moment. This is the requirement for a molecule to be IR active.

12. This molecule can have a significant contribution to the greenhouse effect because the IR radiation it absorbs (at 8 μm and 9.1 μm) is in the range which is produced by the Earth. (It will have a greater effect as there are few other molecules which absorb much at those wavelengths.)

13. 1, 1-difluoroethane



Possible responses to Summary

The report on super-greenhouse gases should include the following:

- they are gases which have very long lifetimes in the atmosphere and high radiative forcings or global warming potentials. They often contain fluorine.
- They are of anthropogenic origin although CF_4 occurs naturally in miniscule quantities.
- They could cause significant global warming problems due to the combination of very long lifetimes and high radiative forcings.

Methane is the second most important greenhouse gas after carbon dioxide. Exactly how much it is contributing to the enhanced greenhouse effect is difficult to ascertain, however, because it is a very reactive gas with a fairly short lifetime in the atmosphere. Through a series of radical reactions, methane causes an increase in the concentration of ozone and water vapour to rise in the atmosphere and both of these are also greenhouse gases.

The concentration of methane in the atmosphere has stopped rising and it is not clear why this is. As methane is an important gas, being able to predict the concentrations of it is critical when modelling future climate. For this reason it is important that there is more research into the behaviour of methane in the atmosphere.

Further reading

There is an animation of how a CFC molecule interacts with various wavelengths of radiation and an interactive IR spectrum with the spectra of various atmospheric gases showing the closing of the 'IR window' available on http://www.kcvs.ca/projects/climate/climate.php.

For the details of the concentration of methane in the atmosphere and how it has changed over time, see http://www.noaanews.noaa.gov/stories2006/s2709.htm. Not all of this is directly measured data as it is with the similar CO_2 graph. This site also includes a discussion about the reasons for the global slow-down in the rise in methane concentrations. More details about the measurement of methane levels in the atmosphere at Mauna Loa can be found at http://www.mlo.noaa.gov/programs/esrl/methane/methane.html.

(All last accessed November 2008.)

CO_2 is not the only greenhouse gas

Although carbon dioxide is an important greenhouse gas, it is not the only gas which contributes to the enhanced greenhouse effect. It is believed to be the cause of about 60% of the enhanced greenhouse effect, which means that 40% is due to other gases. Different gases can be compared for their potential as greenhouse gases using a measure called 'Global Warming Potential' or GWP. This is a measure of the global warming caused by the gas in 100 years, relative to the same amount of carbon dioxide which is given a value of 1. The table below shows data for six greenhouse gases:

Greenhouse gas	**CO_2**	**CH_4**	**SF_6**	**CF_4**	**HFC-134a**	**CF_3SF_5**
Concentration in ppm	380	1.75	5.6×10^{-6}	74×10^{-6}	35×10^{-6}	$<10^{-6}$
% Increase in concentration each year	0.45	0.60	Approx. 7	Approx. 2	> 10	Approx. 6
Atmospheric lifetime in years	50-200	12	3200	50 000	14.6	800
Radiative forcing ($W\ m^{-2}$)	1.4	0.5	0.003	0.007	0.005	7.2×10^{-5}
Global Warming Potential	1	23	22800	7390	1430	17700

Lifetime and GWP figures from http://www.epa.gov/nonco2/econ-inv/table.html

1. Which of the gases has the highest global warming potential?
2. Which has the longest lifetime?
3. Which is increasing at the highest rate?
4. Why are they causing concern among climate scientists?

Super-greenhouse gases

SF_6, CF_4, and CF_3SF_5 are in a class of gases sometimes known as 'super-greenhouse gases.' On a 'per-molecule' basis they contribute more to the greenhouse effect than any others known. Their lifetimes are so long that once in the atmosphere they are essentially permanent. Currently their concentrations are so low that their combined contribution to the enhanced greenhouse effect is very small; but if their current growth rates are sustained they could become significant.

5. What do these three molecules (SF_6, CF_4, and CF_3SF_5) have in common?

CF_4 has a small natural source and over many millennia the atmosphere accumulated about 35 ppt (parts per trillion) of it (this measurement comes from ice cores.) Since the 1950s this concentration has more than doubled (see figure 2). The anthropogenic (man-made) sources of SF_6 and CF_4 include aluminium and magnesium smelting and computer chip production. The origins of CF_3SF_5 are not fully understood but it is thought that it is not directly released into the atmosphere. Fluoropolymers produce $^{\cdot}CF_3$ radicals and SF_6 produces $^{\cdot}SF_5$ radicals and some scientists think that these may combine to produce the gas.

6. Write an equation to show the formation of the $^{\cdot}SF_5$ radical in the atmosphere.
7. Write an equation to show the possible formation of CF_3SF_5 by two radicals combining.

8. Use VSEPR theory to predict what shape you would expect the $-CF_3$ part of the molecule to have. (Hint: Don't forget the bond to the sulfur.)

9. Use VSEPR theory to predict what shape you would expect the $-SF_5$ part of the molecule to have.

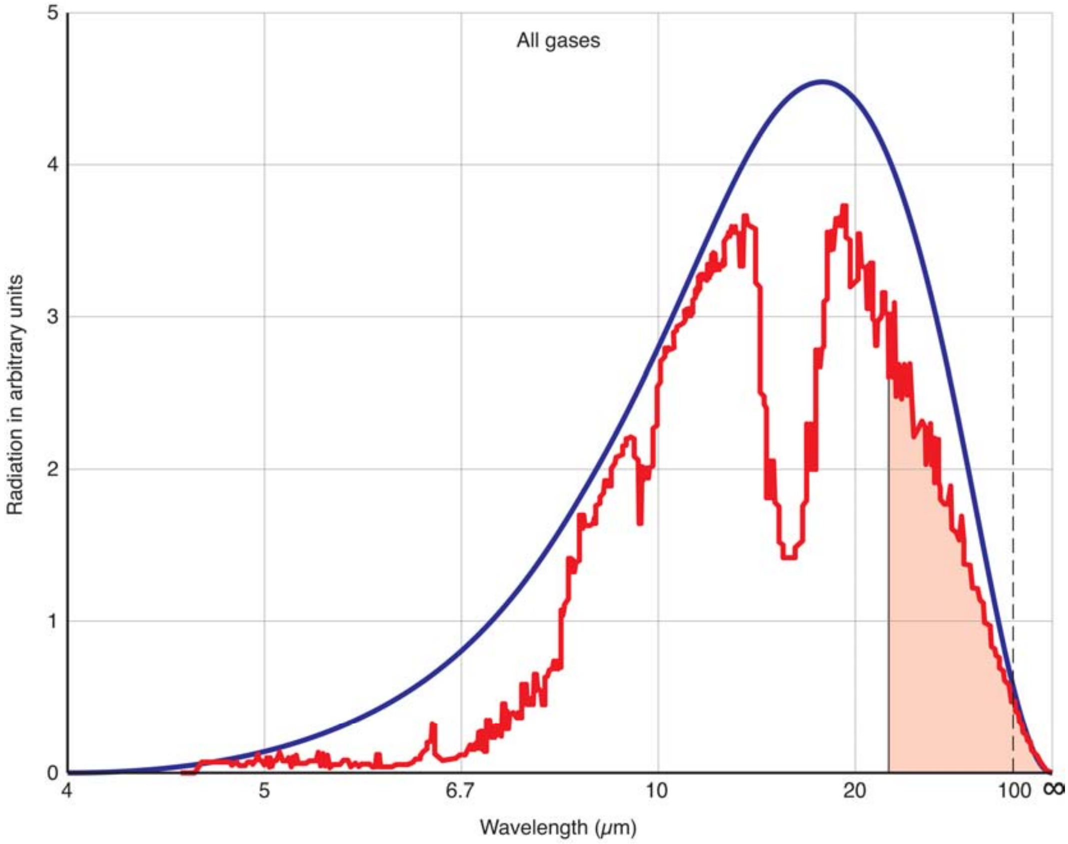
10. Draw the structural formula of CF_3SF_5 and indicate the dipole moment.

CF_3SF_5 has many vibrational modes, 6 of which are IR active and cause a peak on an IR spectrum. (To be IR active a vibration must cause a change in the dipole moment of the molecule.)

Of these, only two fall into the range which can cause the greenhouse effect. Both of the vibrations involve the C-S bond.

11. Explain why a vibration of the C-S bond in this molecule will be IR active.

The two vibrations occur at 8 μm and 9.1 μm.



Used with permission from Prof Keith Shine at the University of Reading.

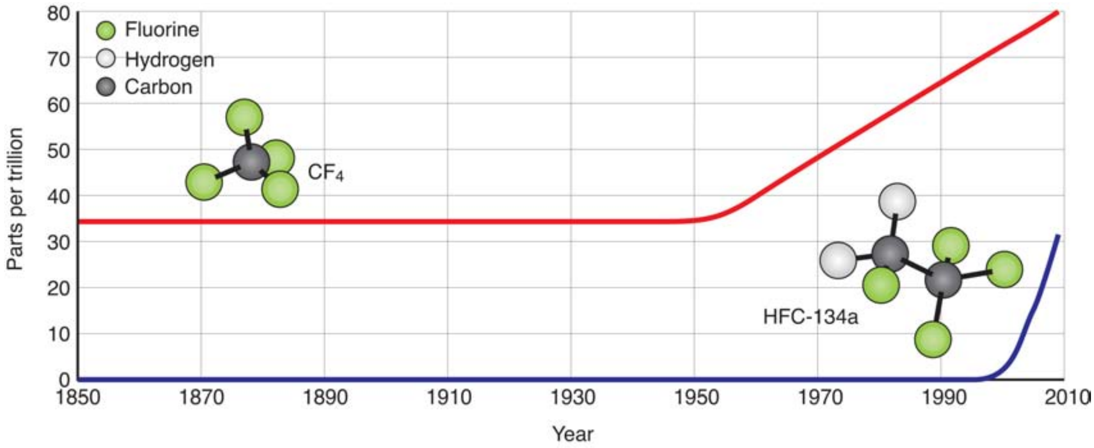
Figure 1. A computer generated typical radiance spectrum of the earth (the red line) and the theoretical (or black body) emission at the earth's surface (blue line).

12. Explain why these vibrations can cause a significant contribution to the greenhouse effect.

The other super-greenhouse gases also absorb IR in the 'window' region, which is why a small amount of them can cause a relatively big change.

HFCs

Hydrofluorocarbons (HFCs) were introduced as replacements for CFCs in the mid-1990s. CFCs are being phased out as they produce chlorine radicals which react with ozone and destroy it. HFCs do not, but they are powerful greenhouse gases. The most abundant of these is HFC-134a. During the mid-1990s, the concentration in the atmosphere more than doubled each year and it is currently increasing at a rate of about 10% each year.



*From Shine and Sturges, Science, **315**, p1804. Prof Keith Shine has given permission for us to use the data*

Figure 2: The abundance of CF_4 and HFC-134a in the atmosphere over the last 150 years.

13. Draw a structural formula for HFC-134a and give its systematic name.

Methane

Enhanced global warming is caused by a change in the earth's energy balance as less energy is emitted by the earth. This change is shown by a measure called 'radiative forcing' (units: W m^{-2}) which is an indicator of the impact a substance has on the climate.

The largest contributor to this is carbon dioxide with a radiative forcing of 1.4 W m^{-2}. The other greenhouse gases contribute 1 W m^{-2} and methane is the largest contributor to this remaining portion (about 0.5 W m^{-2}). Methane is naturally occuring and there are several natural sources including wetlands, soils and the oceans. However, in the 20^{th} century concentrations have increased by a factor of more than 2.5 . Anthropogenic sources include fossil fuel use and agriculture. Rice paddies and livestock (farmed animals) are a significant part of this and the rise in methane is linked fairly closely to the rise in the human population.

Assessing the exact impact of methane is complicated because it is a reactive gas and through a complex series of radical reactions in the atmosphere, a rise in methane can cause a rise in both ozone and water vapour concentrations in the atmosphere. As these are themselves greenhouse gases it is possible that the contribution of methane could be closer to 0.9 W m^{-2} which is equivalent to more than half of that caused by CO_2.

The steady rise in methane has slowed considerably since the mid-1990s which further complicates the story as the reasons for this are not fully understood. The explanation could include methane emissions no longer increasing or the lifetime of methane in the atmosphere may be less as it is reacting faster either as a result of a rise in temperature or because there are more radicals to react with it in the atmosphere. Until this slow down is understood it is very difficult to predict future changes in methane concentrations. This has implications for modelling and predicting future climate change as methane is the second most important greenhouse gas.

Long lived molecules

Scientist Ravishankara writing in 1994*, 6 years before the CF_3SF_5 story began, said:

> ‘When CFCs were invented and released into the atmosphere, their deleterious effects were not known. Fortunately, CFCs are relatively short-lived (*ca.* 100 years) compared to perfluorocarbons, CxFy *(ca.* 1000 years) ; it will take only about a century for CFCs to be removed from the atmosphere once their emissions are curtailed.
>
> The release of any very long-lived species into the atmosphere should be viewed with great concern. Perfluorocarbon lifetimes, though long on historical timescales, are short compared to evolutionary timescales. Life on Earth may not be able to adapt to the changes these emissions may cause.
>
> Thus, it seems prudent to ask if a long-lived molecule should be considered ‘guilty’, unless proven otherwise.’

*In *JCS Faraday Trans.,* (1994) **90**, 2159

Summary

- Write a letter to your MP, a report for a newspaper, a script for a short documentary or radio broadcast or another style of report about super-greenhouse gases; what they are, where they come from, the problems which they could potentially cause and what you think should be done.
- Summarise why predicting the effects of methane on the climate is difficult and why it is important that there is more research in this area.

Climate feedbacks – Teachers' notes

Background information

Climate models are huge computer simulations covering the entire surface of the Earth.

This activity aims to get students thinking about some of the complexities which face the modellers.

The results from the climate models are generally referred to as 'predictions.' Current thinking, however, is that the word 'projection' might be better as 'prediction' suggests that there is a single truth which can be obtained. Both words are used in this resource.

How science works

- Use theories, models and ideas to develop and modify scientific explanations
- Use knowledge and understanding to present scientific arguments and ideas
- Appreciate the tentative nature of scientific knowledge
- Communicate information and ideas using appropriate terminology.

Answers to questions

Factor which is increased	**Effect on the amount of radiation from the Sun which is absorbed by the Earth**	**Effect on the amount of radiation being emitted from the Earth**
1. Water vapour in the atmosphere (but not as clouds)	No effect on absorption of light and UV radiation. (It is worth noting that the Sun also emits IR radiation and that this is absorbed by water vapour.)	Water vapour is IR active in the region in which the Earth radiates and so will absorb the radiation emitted by the Earth. This will reduce the amount of radiation emitted into space.
2. Cloud cover	Clouds look white which means that they reflect light. Clouds therefore tend to reflect the Sun's radiation and reduce the amount being absorbed by the Earth. This is further complicated, however, as different types of clouds at different levels in the atmosphere have different effects. This is not fully understood.	As above for water vapour.
3. Ice/snow cover	Ice and snow are white, meaning that they reflect light. They tend to reduce the amount of radiation being absorbed.	No effect.

4. Dust/aerosols (small particles) in the atmosphere	Some particles can be reflective and therefore reduce the amount of radiation being absorbed. (Some volcanoes emit so much particulate matter when they erupt that they reduce the overall temperature of the Earth for a few years afterwards.) Some particles (eg soot) absorb the Sun's radiation, reducing the amount of radiation which is reflected back to space.	Very little
5. Amount of CO_2 in the atmosphere	Very little effect.	CO_2 is IR active in the region in which the Earth radiates and so will absorb the radiation emitted by the Earth. This will reduce the amount of radiation emitted into space.
6. Amount of CO_2 in the ocean	No effect.	No effect – it is the amount of CO_2 in the atmosphere which is important. If an increase in CO_2 in the ocean meant that less was in the atmosphere then it would increase the amount of radiation emitted into space.
7. Amount of plant cover and photosynthesis	Green plants reflect less Sun than bare rock which would tend to increase the amount of radiation absorbed. More plants would tend to decrease the amount of dust in the atmosphere. How much impact this has will depend on the type of plant and where it is (tropical plants will have a different impact than those in higher lattitudes).	This will depend on the balance between photosynthesis and respiration. On the whole, plants tend to use more CO_2 during photosynthesis and remove it from the atmosphere. This will increase the amount radiation that the Earth emits into space. Again, it depends where on the Earth's surface the plant is – tropical plants photosynthesise a lot faster than those nearer the poles. The exact impacts that plants have on climate is not fully understood.

1. All of the factors could be affected by an increase in the Earth's temperature.

   Water vapour will increase as the amount of evaporation from the oceans increases. (And the vapour pressure of the water increases.)

   Cloud cover could increase or decrease as more water is in the atmosphere –cloud formation is complex and is not linked in a simple way to the concentration of water in the atmosphere as it also depends on the temperature change and the number of particles available for water droplets to condense on.

   Ice/snow cover will reduce in some places as they get warmer (this is happening the Arctic at the moment) but could increase in others if the amount of precipitation increases.

   Dust/aerosols in the atmosphere could increase if there are less plants and deserts expand.

   The amount of CO_2 in the ocean would decrease as the temperature rose as CO_2 is less soluble in warmer water.

   The amount of CO_2 in the atmosphere would depend on how plants and animals react to increasing temperatures.

   The amount of plant cover and photosynthesis could change in a number of ways. Plants could become more productive, especially if the factor limiting their growth was availability of CO_2. In some regions plants are likely to become less productive and possibly die out causing expansion of deserts.

This list of factors is not intended to be exhaustive. Students may be able to think of others which will affect the radiation either being absorbed or reflected by the Earth. Concentration of methane in the atmosphere, the amount of cattle being farmed, human population on the Earth and many more will have an impact.

2. Factors giving positive feedback
   - CO_2 in the oceans
   - Water vapour in the atmosphere
   - Ice and snow cover

   Factors giving negative feedback
   - None

   Factors where the feedback is unknown
   - Cloud cover
   - Dust/pollutants in the atmosphere
   - Amount of CO_2 in the atmosphere – especially as emitted by animals and plants
   - Amount of plant cover

Further information

If students would like to know more about how climate models, a good place to direct them to is www.climateprediction.net which has a very good section about how the models are constructed. (Last accessed May 2008.)

Acknowledgements
This activity was based on a resource from the climateprediction.net teaching resources section, funded by the Nuffield Foundation - http://climateprediction.net/schools/resources.php (last accessed November 2008).

Climate feedbacks

Weather forecasts and climate projections are made using numerical models. These are huge computer codes, bringing together the equations we know govern the way the atmosphere (and oceans) work, observations from weather stations and satellites and projections of how the factors that 'force' the weather will change – such as day turning to night, changes in solar activity and changes in atmospheric composition.
The Met Office in the UK uniquely uses the same model to make daily weather forecasts and to make climate projections for the next century. The same model is used by the climateprediction.net project and is distributed to hundreds of thousands of people around the world to run as a screensaver, generating vast quantities of data for climate scientists. Climate models all work by dividing the atmosphere into a grid of boxes, and time into increments. So, at each time step (typically half an hour) the state of the atmosphere in each box is calculated using all the equations needed to understand the way the atmosphere moves, the carbon cycle, the water cycle etc. The more boxes that are used to cover the Earth or the further into the future the projection is, the longer it takes to complete all these calculations. This means that whereas a relatively fine grid can be used for a 5 day weather forecast (forecasts with 2.5 km resolution are currently being made) it is only possible to use a fairly coarse grid for a 100 year climate simulation – 6 grid boxes typically cover the whole of the United Kingdom. The better the resolution, the more physical processes like the development of an individual cloud can be included in the model, but the longer the simulation takes to complete.

The aim of this activity is for you to think about some of the complexities which face the modellers.

The temperature of the Earth, the weather and the climate are controlled by the energy flowing into and out of the system. Various factors can affect the energy flow and therefore have an effect on the weather and, in the long term, the climate.

Climate modellers try to understand these changes in order to ensure that their computer models are accurate. This activity will help you to begin to appreciate the complexity of the task they face.

For the various factors below, consider the effect of increasing them on:

- The amount of radiation (mainly light and UV) from the Sun which is absorbed by the Earth
- The amount of radiation (mainly IR) being emitted from the Earth.

Factor which is increased	Effect on the amount of radiation from the Sun which is absorbed by the Earth	Effect on the amount of radiation being emitted from the Earth
1. Water vapour in the atmosphere (but not as clouds)		
2. Cloud cover		
3. Ice/snow cover		
4. Dust/aerosols (small particles) in the atmosphere		
5. Amount of CO_2 in the ocean		
6. Amount of CO_2 in the atmosphere		
7. Amount of plant cover and photosynthesis		

If the amount of energy coming into the system is greater than the amount leaving the system, then the Earth will warm up; the opposite is also true.

1. Which of the 7 factors will be affected if the Earth warms up? Explain how in each case.

2. Which factors will act to increase the temperature even more (this is called positive feedback) and which will act to reduce the temperature (negative feedback)? (Some will not cause any feedback.)

For some of the questions above the answers are well understood by science. Some are poorly understood and some are variable depending on a large number of other factors. A climate model can only ever be as good as the information which is fed into it – one wrong assumption can lead to inaccurate predictions. Climate models (for example those on www.climateprediction.net) are run using a range of inputs and then tested by using them to 'predict' the climate in the past. The closer the model gets to what is known about past climates, the more accurate it is assumed to be in its projections for the future, although models that are equally good at reproducing the past might yield very different predictions for the future. It is important to remember, though, that any projection of the future is based on a number of assumptions such as how the world might develop, which volcanoes may erupt and how active the Sun will be amongst others. Modelled climate projections can, at best, tell us how the climate might change, and what the range of possible future climates is.

Paleoclimatology and ice core chemistry – Teachers'notes

How science works

- Use theories, models and ideas to develop scientific explanations
- Use knowledge and understanding to present scientific arguments and ideas
- Analyse and interpret data to provide evidence
- Evaluate methodology, evidence and data
- Appreciate the tentative nature of scientific knowledge
- Communicate information and ideas using scientific terminology.

Answers to questions

1. a 18   b 20   c 19. 18 will occur most frequently, followed by 20 then 19.

2. As the temperature rises, the proportion of heavy water in the ice increases.

3. The measurements of carbon dioxide concentration in ice bubbles are unique because they are a direct measurement – it is a bubble of old air which is being analysed – and not a proxy.

4. The peaks in temperature and carbon dioxide concentration occur at about the same time.

5. It is difficult to say for certain because of the uncertainties in the dating of the temperature data compared to the carbon dioxide data. As the air bubbles containing the carbon dioxide were laid down much later than the ice containing the water and therefore the temperature proxy data, it is not straightforward to date them accurately. As there are several different variables and uncertainties it is not possible at present to decide which came first. If error bars were drawn onto the lines of carbon dioxide and water on the graph then they would overlap.

Possible responses to Summary

6. Studying ice cores is important in understanding climate change because the ice can provide an almost unique historical record of temperature and unique record of concentrations of gases stretching back over millenia. The data provided are essential in understanding the climate of the past and unless we can do this there is little chance of predicting accurately what is likely to happen in the future.   Past climates also provide a way of checking climate models and the ice cores provide the data which allow these checks to be made.

7. The ice core data has shown for certain:

- The temperature (in Antarctica at least) has varied considerably over the last 800 000 years.
- In the past, peaks in carbon dioxide concentrations and temperature in Antarctica happened at roughly the same time.
- That the concentrations of greenhouse gases such as carbon dioxide have not been higher in the last 800 000 years.

8. Uncertainties/areas for further research/questions raised by the ice core data:
- Which rose first in the past – temperature or carbon dioxide? Further research is required to allow more accurate dating of the temperature and carbon dioxide data in order to answer this question.
- Ice cores tell us about the temperatures at the poles – it is not well known how well this correlates to global temperatures.

Further reading

For more information about the British Antarctic Survey, who are part of the EPICA group drilling ice cores, see www.antarctica.ac.uk.

Paleoclimatology and ice core chemistry

Paleoclimatology is the study of past climate. It is most often done by examining the physical, chemical or biological properties of a sequence of sediments. In various parts of the world marine sediments, lake sediments, peat bogs, corals, ice cores, speleothems (stalagmites and stalactites) and tree rings are studied. For more ancient times, fossils found in sedimentary rocks can indicate what past environments were like.

Obtaining Ice Cores

Studying ice might not sound very exciting or like it would provide much information – ice is, after all, just frozen water. Ice cores come from ice sheets, however, and these along with glaciers and snow contain traces of everything which is stable in the atmosphere. All the impurities remain as long as the ice persists.

Ice cores can be drilled anywhere where the ice builds up year by year and does not melt. Most cores come from Antarctica or Greenland, but there have also been cores dug closer to the equator at high altitude locations in the Andes and Himalayas.

Retrieving the cores is demanding and technical. The European Project for Ice Coring in Antarctica (EPICA) project recently completed drilling at a region called Dome C. Situated at 3200m above sea level, the average annual temperature is just -54˚C and on the warmest summer days it reaches just above -20˚C which is still colder than most freezers. All the equipment has to come from the coast which is about 1000km away. Work can only be carried out in high summer, between November and early February. The air is extremely dry due to the low temperatures. As a result the annual snowfall is equivalent to only 3cm of ice.

Large electromechanical drills are used to retrieve the 10 cm diameter cores, about 3m of ice at a time. When the drill has pulled up one section, it is slowly lowered back into the hole to begin drilling the next.

Once the ice is at the surface it is labelled and cut into sections for different analyses. Some of the analysis is carried out in the field; other sections are returned to Europe. This can potentially cause contamination as the concentrations of some of the chemicals being measured are very low in comparison to those in our environment. The dirty outside ice is removed and the analyses are generally carried out in clean laboratories with filtered air.

Used with permission from the British Antartic Survey (BAS), Eric Wolff (BAS) and Keith Shine at the University of Reading.
Figure 1. Ice core drilling operations in Antarctica.

Used with permission from the British Antartic Survey (BAS), Eric Wolff (BAS) and Keith Shine at the University of Reading.
Figure 2. Ice core drilling operations in Antarctica.

Ice in the cores is laid down successively, so the youngest ice is at the top and the ice gets older the deeper it is bored.

Box 1 Water isotopes as a temperature proxy

Most water molecules are made of hydrogen with an atomic mass of 1 and oxygen with an atomic mass of 16. About 1 molecule in 500 contains the heavier isotope of oxygen, ^{18}O. Occuring even less often is water containing 1 atom of deuterium (D) which is hydrogen with an atomic mass of 2. These isotopes are stable (not radioactive) and do not decay. Measuring the relative proportions of them provides a proxy for temperature.

Rain and snow are formed from water which has evaporated from an ocean, condensed as a cloud and then fallen to the Earth. Heavier molecules have lower vapour pressures which means that when water evaporates the vapour is depleted in these molecules and when it condenses out the liquid water is enriched in them. As the air moves from the warm oceans towards the poles, water enriched in the heavier isotopes condenses out. As this happens, the water vapour becomes more depleted in the heavier isotope. The result of this is that when the air arrives in Antarctica the amount of water remaining and the proportion of the water which contains the heavier isotopes is mainly temperature dependent.

The concentration of ^{18}O or D is normally expressed as the change ($\delta^{18}O$ or δD) from average ocean values in parts per 1000.. In Antarctica, this value is always very negative, as the temperature is always very low. The colder it is, the fewer heavy isotopes there are and the more negative the isotopic value.

Box 2 Ice Formation

The snow in Antarctica does not melt, it just gets compressed by the snow falling on top of it. Initially, air can circulate around the ice crystals and it can still diffuse in and out to a depth of about 60-100 m. At this depth the crystals are so compacted together that they form a solid ice matrix and the air is trapped in tiny bubbles which are unable to diffuse away.

As a result of this, the age of the air bubbles is different to the age of the ice. The air that is currently being enclosed in bubbles in central Antarctica at maybe 100 m depth is from the late twentieth century, but the ice (containing the temperature data) at the same depth is hundreds or even thousands of years old (depending on the snow accumulation rate). If we want to look at the phasing between climate and trace gas changes in old ice, we have to correct for this ice age-air age difference, and this can lead to substantial uncertainty.

Information from Ice Cores

There are three different types of information which can be extracted from the ice cores.

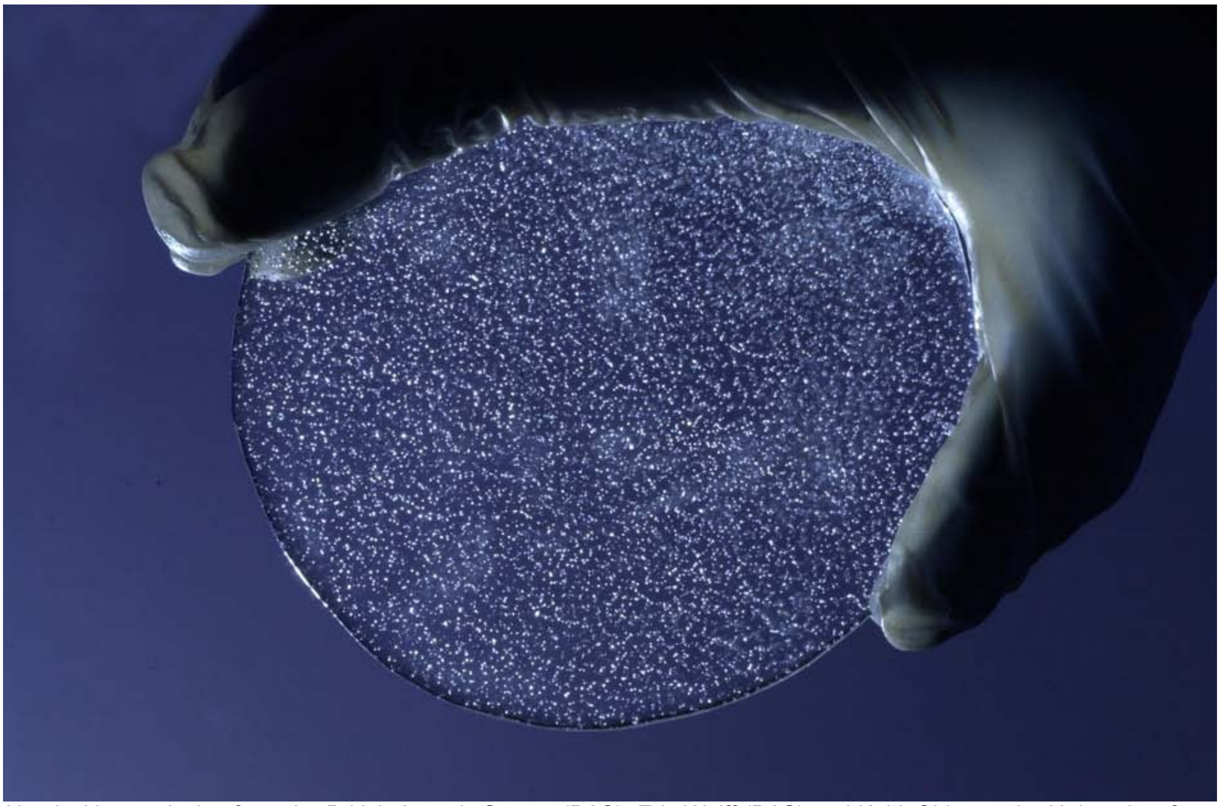
1. Water molecules in the ice cores

The isotopes present in the water molecules themselves give important information. The amount of heavy water, particularly that containing deuterium, is related to the temperature (see box 1) and so the temperature of Antarctica at the time that the ice was laid down can be closely aproximated from the proportion of deuterium in the ice.

This type of measurement is known as a *proxy* and is common in paleoclimatology. The temperature of the Earth thousands of years ago cannot be measured directly, but by measuring the proxy the temperature can be calculated.

2. Chemical impurities
As the snow falls it takes with it a sample of the small particles in the atmosphere (called aerosol) as well as 'sticky' or hydrophilic gases such as nitric acid. Included will be dust from the continents, ions from sea salt, pollutants such as lead and sulfuric acid and sulfate ions from volcanic eruptions.

3. Ancient atmosphere in the gas bubbles
As the snow gets deeper the loose mixture of snow and air becomes compacted and is under pressure from the snow above. At about 60-100m it turns into solid ice with air bubbles trapped inside (see Box 2).



Used with permission from the British Antartic Survey (BAS), Eric Wolff (BAS) and Keith Shine at the University of Reading.

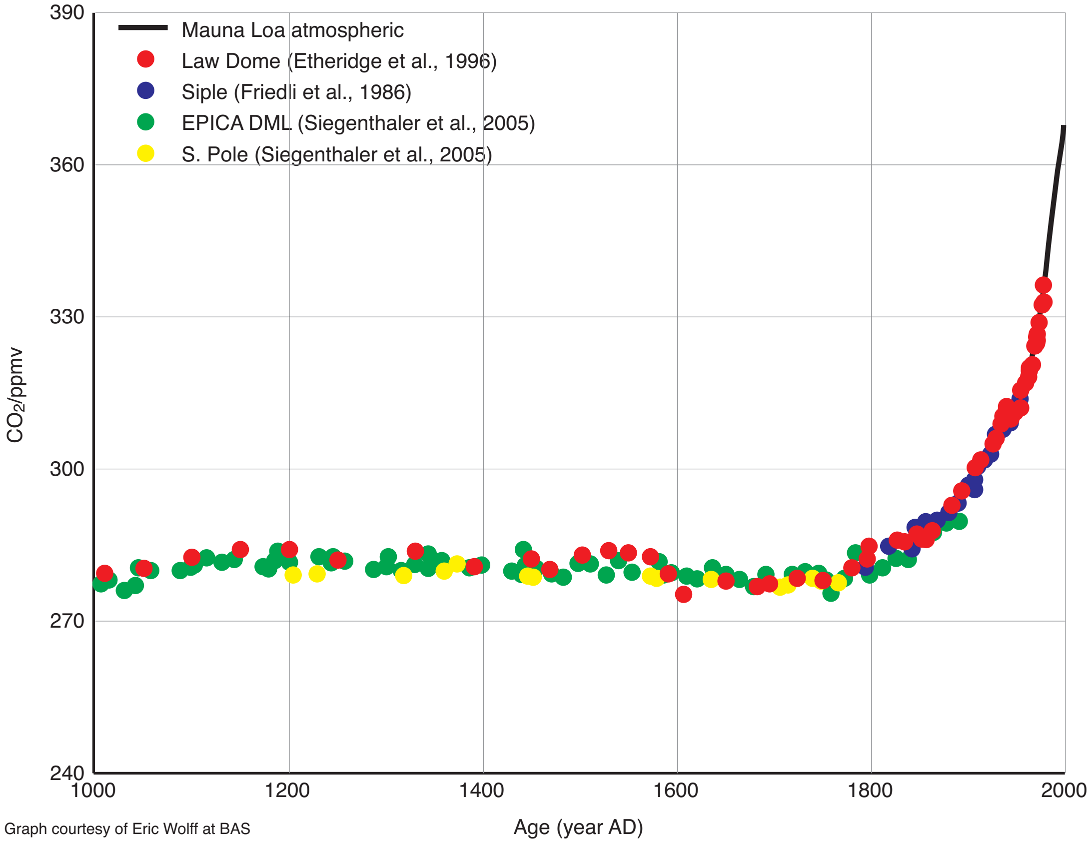
Figure 3. The tiny bubbles trapped in this ancient ice can be opened and examined.

These air bubbles can really be thought of as tiny canisters of air from an earlier time. They can be opened and analysed for their concentrations of stable trace gases. It is in this component that the past atmospheric concentration of carbon dioxide and other greenhouse gases can be measured. These measurements are unusual because they are not proxies – it is possible to measure actual concentrations of gases in a sample of old air.

The ice sample is placed into a container which is evacuated (all the air is sucked out.) It is then crushed into small pieces to allow all the gas bubbles to break down and the gas to escape. The carbon dioxide concentration is measured by either infrared laser spectroscopy or gas chromatography; other gases tend to be measured by mass spectroscopy.

Greenhouse Gases

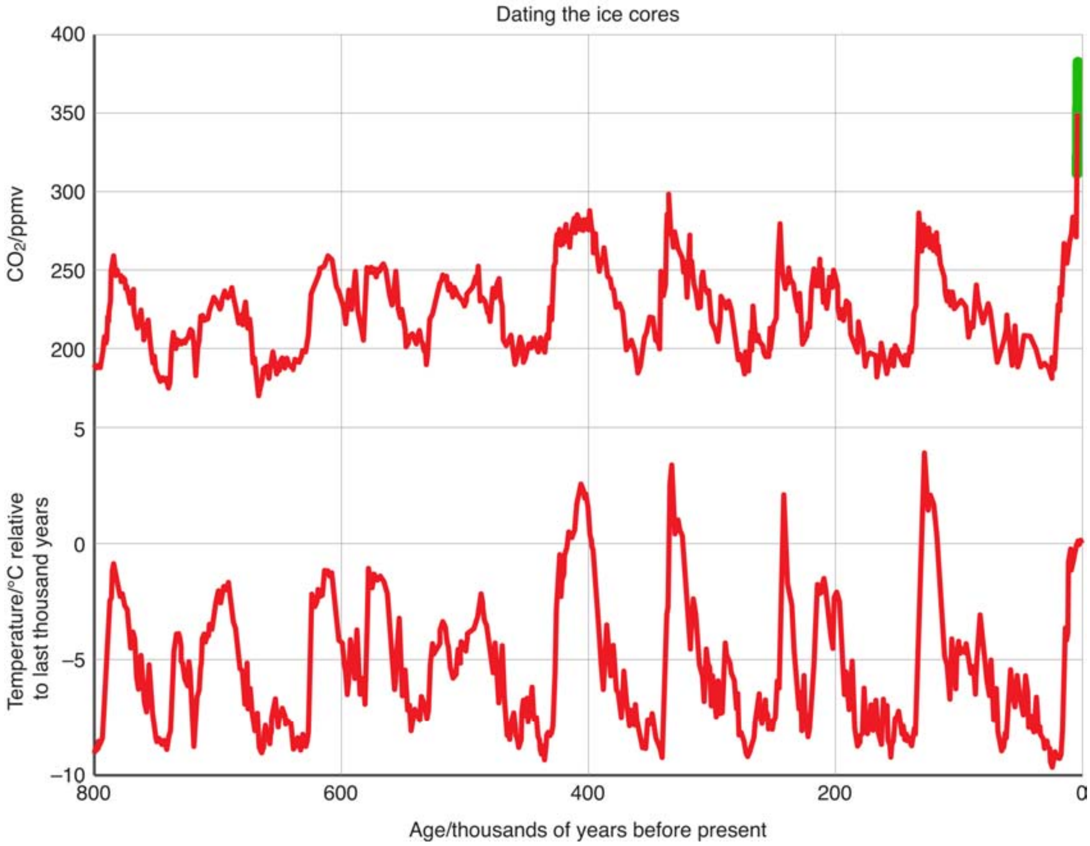
Regular measuring of carbon dioxide concentrations in the atmosphere began only in 1958; regular measuring of methane began as late as the 1980s. Ice core data is the only evidence we have of pre-industrial concentrations of these gases – see figures 4 and 5. They show without a doubt that the concentrations today are far in excess of anything seen for the last nearly 1 million years.



Graph courtesy of Eric Wolff at BAS.

Figure 4. Atmospheric carbon dioxide over the last millennium. The data from Mauna Loa is directly measured in the atmosphere (shown with the black line) the other data is from ice cores.

Dating the Ice Cores



Plots courtesy of EPICA. Data from Luethi et al 2008 (CO_2) and Jouzel et al 2007 (temperatures). Thanks to Eric Wolff of BAS for supplying the information.

Figure 5. The top plot shows levels of carbon dioxide in the atmosphere. The data shown in green is actual concentrations measured at Mauna Loa in Hawaii. The red line on the CO_2 plot is from Law Dome and the remaining data from two other ice core sites in Antarctica; Vostok and Dome C.

In order to give dates to the data, the age of the ice has to be worked out. In regions with a high snowfall it is possible to count the years in a similar way to counting the rings of a tree. To do this something is needed which varies between summer and winter. The easiest thing is the isotope content of the water. The $^{18}O/^{16}O$ ratio varies with temperature and is higher in summer than in winter. Several samples for each year are taken and the summer maxima can be identified and counted. In Greenland at least 10 000 years were counted in this way.

There can be errors; years can seem to be missing if there is only a little snowfall or double counted if there is a cold spell in the middle of the summer. This can be checked and corrected for by looking for layers of a known age. Whenever there is a large volanic eruption, sulfur dioxide is put into the upper atmosphere and this shows up in the ice core as a spike of sulfuric acid. The presence of the acid also provides a way of correlating data from separate cores – as long as it is certain that the acid spikes are from the same eruption.

At sites with low snowfall and very old ice it is much harder to count the years and a different method needs to be used. The ice flows and thins following physical laws and this is modelled. The assumption is made that snow fall is relatively consistent (which may not be the case) and this method is inevitably less reliable than counting the years. However, it is possible to check and correct by looking for events for which dates are known from other sources. Isotopes are again used for this – in this case ^{10}Be.

Most naturally occuring beryllium is ^{9}Be but ^{10}Be is produced by cosmic rays. There are more of these rays when the Earth's magnetic field is weak, as it is known to have been 780 000 years ago when the Earth's polarity reversed. Comparing dates from modelling the flow of the ice with the spike of ^{10}Be can provide a very useful way of validating the dating.

From the past to the future

It may seem odd to expend time and energy looking at the climate of the past when what we need to know is what it will be like in the future, but the information provided by paleoclimatology is vital in understanding the climate system. Unless we understand the historical changes to the climate, we cannot hope to predict what will happen in the future. In addition, past climates provide a means of checking on the predictions made by climate modellers. Unless the models can accurately reproduce what we know to have been the climate in the past, it is hard to be confident about what they predict for the future.

Questions

1. Calculate the molecular mass of water containing:
   a ^{16}O and ^{1}H
   b ^{18}O and ^{1}H
   c ^{16}O, ^{2}H and ^{1}H.
   Which of these isotopes will be most prevalent in the ice? Put them in order from most to least frequent.

2. What will happen to the proportion of heavy water in the ice as the temperature rises?

3. Explain why measurements of carbon dioxide concentration in ice bubbles are unique in paleoclimatology.

4. What is noticable about the peaks in temperature and carbon dioxide concentration?

5. Why is it difficult to say for certain whether temperature or carbon dioxide rose first?

Summary

6. Explain why studying ice cores is important in understanding climate change.

7. What has the ice core data shown for certain about climate change?

8. What are the uncertainties, areas for further research or questions raised by the data from the ice cores?

Earth surface temperature data – Teachers' notes

Background information

Data on the temperature of the Earth comes from direct measurement with a thermometer and also from satellite observations. The earliest and longest continually running temperature record is the Central England Temperature Record which has been going since the late 1600s. Global records began in the mid-1850s. This data clearly shows that in during this time the Earth has warmed up. The phrase 'since records began' is often used in the media when temperature data is being discussed. This usually refers to the data since around 1850.

Temperature and climate data are also used by climate scientists to enable them to build climate models. These computer simulations are tested to ensure that they can accurately 'predict' past climates and then run to try to predict or project what the climate might be like in the future. Models which can accurately 'predict' the past still give very different projections for the future, however, so this is not an exact science.

How science works

- Use ICT to answer scientific questions
- Carry out investigative activities
- Analyse and interpret data to provide evidence.

Answers to questions

1. The number of temperature stations is decreasing.

2. In the mid-1800s.

3. a. 15% b. 65-70% c. 75-80%

4. Auckland and Christchurch both show quite large variations in temperatures, but no overall pattern of either a rise or a fall.

5. Just from those 6 sets of data one could conclude that there is no particular trend for a change in temperature.

6. The changes in the southern hemisphere show a similar pattern to those in the northern hemisphere, but to a lesser extent. There seems to be less warming.

7. The trouble with using a small number of data sets is that it can give a misleading picture.

8.
   a Temperature increasing
   b Temperature decreasing – this is widely accepted as being due to sulfate and other particulate emissions from industry. As legislation to improve air quality came into force the number of these emissions decreased and the temperature began to rise again.
   c Temperature increasing.
9. From 1695 to 1733 there is a rise of about 2˚C.

10. Overall in this period there is no warming although the temperatures rise from 1900 through to the 1950s.

11. The temperature increases significantly (by about 1.2˚C).

Further reading

For an animation of the changes in temperature seen over the last few decades and those predicted for the next 100 years see 'Visualising climate change' on http://www.kcvs.ca/projects/climate/climate.php. For a discussion of 'Is the current climate change unusual compared to earlier changes in earth's history' from the IPCC see http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch06.pdf p 465 (page 33 of 66 in this document).

(Last accessed November 2008.)

Earth surface temperature data

Direct measurement (recent) data

In order to ensure that you are using the most up-to-date information possible, you will need to access the data required over the internet.

It is widely accepted that our planet is warming up – but what evidence is this based on? We can only directly measure weather. 'Climate' is usually defined as a 30 year average of weather data.

Direct measurement of temperature using a thermometer began in the mid-1800s in a number of locations around the globe. Some of these have had continuous daily measurements taken ever since and these are particularly useful when looking at trends.

The following site allows you to access the data from these stations.

http://data.giss.nasa.gov/gistemp/station_data/

1. Given current concerns about global warming, what could be surprising about the number of currently operating temperature recording stations?

2. Newspapers often quote temperature changes as being 'since records began.' When did these records begin?

3. Approximately what proportion of the globe was within 1200km of a reporting station in
    a. 1850
    b. 1950
    c. 2000

Although the number of temperature recording stations are decreasing, the amount of data available is not, as most of the information now comes from satellites.

If you go to 'download station data' you can search for the temperature records of individual stations. Try looking for a few from different areas of the globe.

Cities are generally hotter than the surrounding countryside – an effect known as the urban heat island (for more details see http://www.metoffice.gov.uk/education/secondary/students/microclimates.html)

For a possible example of the urban heat island effect, look at the data from New York, Central Park. When records began this was a rural location but it is now in the heart of New York City. Compare this plot to that of the nearest rural station, Boonton, which is just 39 km away.

While the difference looks significant, the urban heat island effect is well understood and is accounted for in records of climate.

Look at some southern hemisphere sites. Try Auckland (Airport) and Christchurch in New Zealand.

4. What pattern is shown by each of these sets of data?

Even further south is the Scott Base in the Antarctic. Some other southern hemisphere sites in various continents include: Bahia Blanca (South America), Chiang Mai (South East Asia), Bulawayo (Southern Africa). Look at at least one these.

5. From the southern hemisphere sites mentioned, what can you conclude about temperature changes there?

This is a only a small set of the available data. To see a fuller picture of temperature change in the southern hemisphere go to the UK met office climate indicators page:
http://www.metoffice.gov.uk/research/hadleycentre/obsdata/climateindicators.html#GlobHem

Find graphs showing temperatures in each hemisphere.

6. How do the changes in the southern hemisphere compare to those in the northern hemisphere?

7. What is the danger of using a small number of data sets to draw a conclusion (as in Q6 above)?

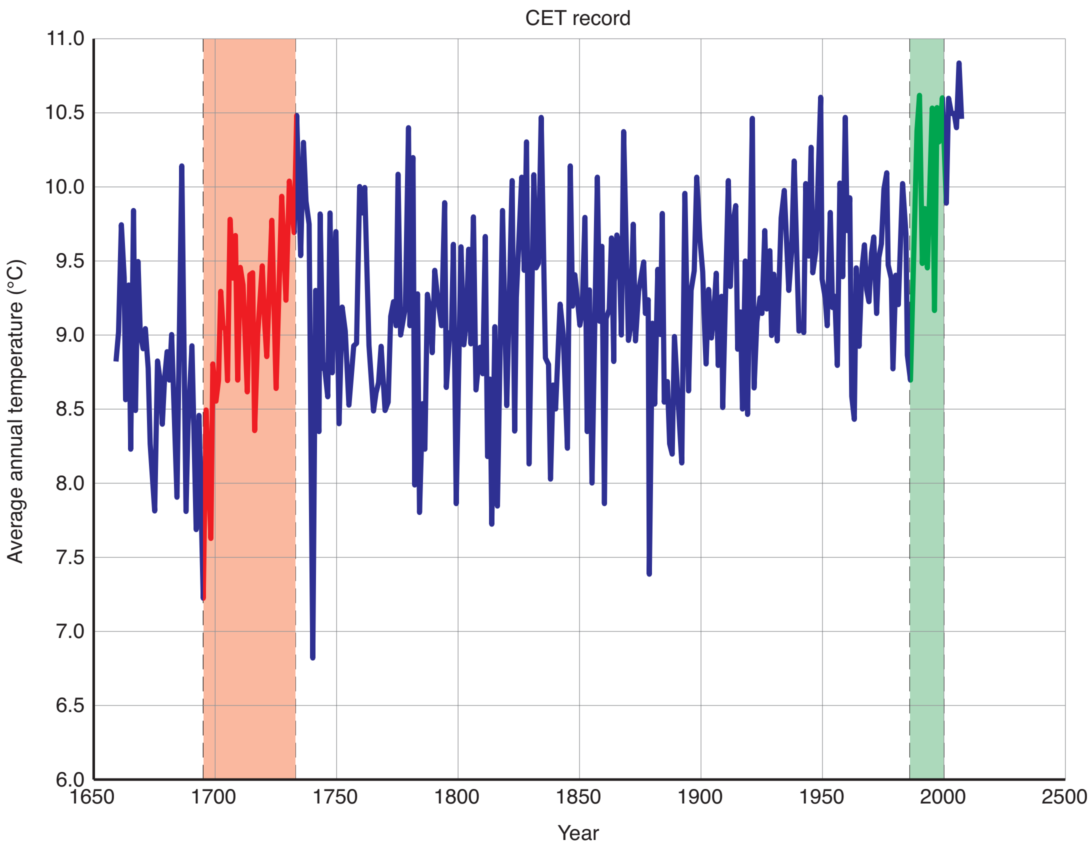
Part of the same site includes global average temperature plots:
http://www.metoffice.gov.uk/research/hadleycentre/obsdata/HadCRUGNS.html

Look at the graphs for annual global temperatures and monthly anomolies.

8. What is the general global temperature trend from
    - a 1900-1940?
    - b 1940-1950?
    - c 1990-2006?

Since 1659, temperature measurements in England have been amalgamated to form the 'Central England Temperature record' or CET. This is an incredibly valuable resource because of its length.

From 1659 through to about 1700 is the end of a period known as the ‘little ice age’ in Europe. There is no direct data prior to 1659, but there are stories of the Thames freezing over and temperature proxies (data which can be studied to infer what the temperature was like) such as tree ring width show that it was much colder than it is now.



Graph courtesy of Wilson Flood. Adapted from Crown Copyright data supplied by the Met Office.

9. What do you notice about the period from 1695 to 1733, marked in red on the graph above?

You can see a similar graph of data up to the present on http://hadobs.metoffice.com/hadcet/.

10. Is there a pattern of warming from around 1800 through to the mid 1900s (when carbon dioxide levels were on the increase)?

11. From 1986 through to 2000 what happened to the temperature?

Taking direct temperature measurements together with satellite data and other observations it is possible to say that the temperature of the earth is definitely increasing. Eleven of the last 12 years (1995-2006) rank among the 12 warmest years in records of global surface temperature since 1850. This data on its own does not tell us why there is an increase – just that one can be observed.

This temperature information is important as climate scientists analyse weather observations for changes in patterns with time and also need reliable observations to allow them to build computer models of the climate. These models allow them to try to predict what might happen in the future. If a model cannot accurately reproduce key aspects of past climate, its simulations of the future are of limited value. The observations are also crucial for initialising model simulations; at the start of a simulation, a model must have an accurate picture of current weather if it is to accurately predict how those patterns will evolve over the coming days and years.