Chem Factsheet

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The Chemistry of Climate Change

In this Factsheet, some of the causes and effects of climate change are highlighted from a chemistry perspective.

The causes of climate change can be the subject of debate, but this Factsheet follows the position of the UK Government Department for Energy and Climate Change (DECC) which states that "climate change is happening and is due to human activity, this includes global warming and greater risk of flooding, droughts and heat waves."

After working through this Factsheet you will be able to:
- describe the greenhouse effect
- explain why the greenhouse effect is vital to life on Earth
- describe the role of greenhouse gases in maintaining Earth's temperate climate
- understand global warming potentials of gases
- describe the sources of greenhouse gases including carbon dioxide and methane
- predict the consequences of increasing the concentration of greenhouse gases.

Background

The DECC states that there is clear evidence to show that climate change is happening. It comments that the average temperature at the Earth's surface has risen by approximately 0.8°C over the last century. Indeed, 13 of the 14 warmest years on record have occurred in since 2000 and in the last 30 years, each decade has been hotter than the previous one.

As well as the increase in the average temperature of the Earth's surface, other changes have been recorded including, warming of the oceans, melting of polar ice caps, rising sea levels and more extreme weather events.

Causes

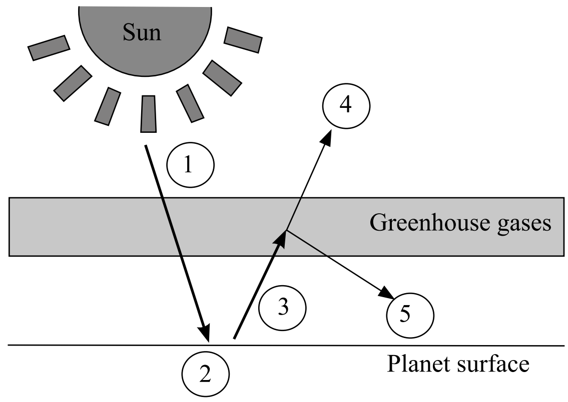
The DECC is clear in that it is human activity that is causing the changes seen in the climate and that the increase in the level of atmospheric carbon dioxide caused by human activity is driving the changes. Also, the release of methane, particularly as a result of farming activities is causing a change in the climate.

The Greenhouse Effect

The greenhouse effect is not a bad thing. Without the greenhouse effect the planet would not have the temperate climate it has and so would be unable to support life as we know it. It is an *intensification* of the greenhouse effect that is the cause of climate change and the increase in global temperatures.

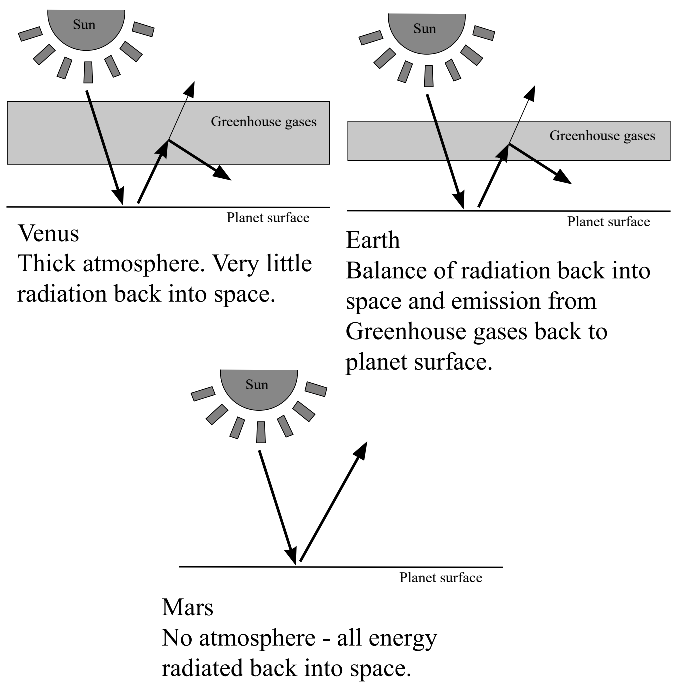
Fig. 1 summarises the greenhouse effect. Electromagnetic radiation from the sun (1) heats the surface of a planet (2). As the planet's surface warms, it radiates infrared radiation (3) some of which is then absorbed by gases in the atmosphere. The energy is then either radiated back out into space (4) or back to the surface of the planet "trapping" heat (5).

Fig. 1 - Greenhouse effect summary



By comparing the atmospheric and surface temperature fluctuations of our neighbouring planets, we can understand the critical role of the greenhouse effect in maintaining the temperate climate on Earth. See Fig. 2.

Fig. 2 - Comparing the greenhouse effect on Mars, Earth and Venus



Mars has no greenhouse effect because it has no atmosphere. The surface temperature of Mars at the equator during the Martian summer can vary from 20°C during the day to below -70°C at the same spot after sunset. The heat from the sun radiates quickly from the surface of the planet back out into space. As the planet revolves, and the surface moves away from the sun, it turns very cold very quickly.

Venus has an atmosphere of mainly carbon dioxide and has a surface temperature of approximately 460°C whether it is day or night.

The heat from the sun does not radiate back out into space as the planet revolves as it is trapped by the greenhouse gases in the atmosphere.

On Earth, the balance between radiation of energy back to the surface and escape of radiation into space results in an overall global climate that is neither too hot or too cold.

If the concentration of greenhouse gases in the atmosphere increases, more infrared radiation will be absorbed and radiated back to the surface causing it to remain warm as the planet revolves away from the sun. Conversely, if the concentration of greenhouses gases decreases, less infrared radiation is radiated back to the surface and more escapes into space. The surface of the planet cools very quickly.

The Greenhouse Gases

Greenhouse gases include carbon dioxide, water vapour and methane. When greenhouse gases absorb infrared radiation their bonds vibrate faster. The vibration in the molecule eventually causes the molecule to emit radiation which is then absorbed by other greenhouse gas molecules, radiated out into space or back to the Earth's surface. The absorption and subsequent emission cycle of radiation keeps the heat close to the surface of the planet.

Greenhouse gases occur in the environment naturally as a result of volcanic eruptions, respiration and burning or decay of organic materials. Also, the evaporation of water from lakes and oceans increases the levels of water vapour in the atmosphere. However, it is accepted that human activity has increased the concentration of these gases (see below) above their "natural" levels.

Global Warming Potential (GWP)

The global warming potential of a greenhouse gas is a measure of how much energy the emissions of one ton of a gas will absorb over a given time period, relative to carbon dioxide - which by definition has a given value of 1. It is normally calculated over a given time period for example 20, 100 or 500 years. It is related to the length of time a gas stays in the atmosphere, that is, how its concentration decays over time, as well as its ability to absorb infrared radiation.

A high GWP indicates a particular gas has a long atmospheric lifespan and a strong infrared absorption. The larger the GWP of a given gas, the more that gas warms the Earth over the given time period compared to carbon dioxide. The GWP was developed to allow the impacts on global warming of different gases to be compared.

A gas that is a strong absorber of infrared radiation but does not have a long lifespan in the atmosphere, or only absorbs radiation efficiently at a wavelength that other gases in the atmosphere already absorb will have a low GWP.

Methane is estimated to have a GWP of 28-36 over 100 years. Its lifespan is about 10 years, much shorter than carbon dioxide, but absorbs much more infrared radiation than carbon dioxide. However, there is over 200 times more carbon dioxide in the atmosphere than methane and so the amount of warming it contributes is only 28% of the warming of carbon dioxide.

Chlorofluorocarbons trap a lot more heat than the same mass of carbon dioxide and have a very long lifespan. Consequently the GWP for trichlorofluoromethane (CFC-11) is over 5000 for 100 years.

However, the concentration of CFCs in the atmosphere is much lower than that of methane.

Although water is a strong absorber of radiation, its GWP is difficult to estimate since its concentration in the atmosphere is highly dependent on Earth's surface temperature and water availability on land.

Question 1
Explain why the GWP of methane over 100 years is much higher than that of carbon dioxide, yet it only contributes a fraction of the warming of carbon dioxide.

Carbon dioxide

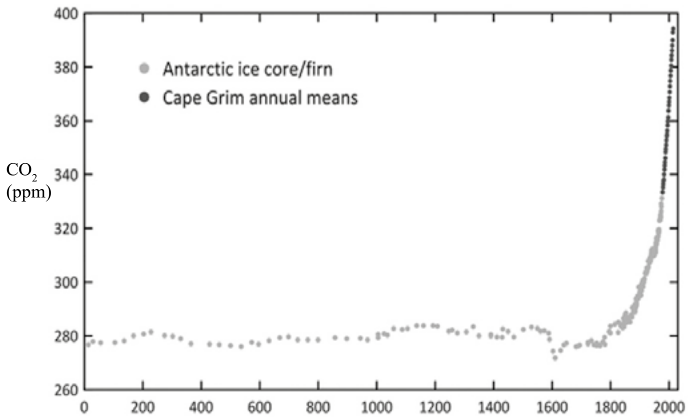
Carbon dioxide is an important constituent of the atmosphere. It is continuously exchanged between the atmosphere and living organisms. Levels of carbon dioxide are decreased through the process of photosynthesis and increased by the processes of respiration and decomposition. There is also an equilibrium between carbon dioxide dissolved in the oceans and free carbon dioxide in the air.

Photosynthesis	$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
Respiration	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
Solubility equilibrium	$CO_2 + H_2O \rightleftharpoons H_2CO_3$

Additionally, volcanic eruptions and the chemical weathering of rocks contribute a small amount of the atmospheric carbon dioxide levels.

The graph in Fig. 3 shows the levels of carbon dioxide over the last 2,000 years. These can be estimated by analysing the gas trapped in bubbles found in ice cores from the Antarctic.

Fig. 3 Atmospheric carbon dioxide concentration over the last 2,000 years



In 2012, the carbon dioxide level was about 40% higher than it was before the industrial revolution. The change has increased more rapidly since 1970 when the consumption of energy on a global scale accelerated. Evidence from isotopic analysis of the carbon dioxide indicates that the rise is largely due to the combustion of fossil fuels. The carbon atoms in these fuels generally have a low proportion of the carbon-13 isotope and this matches observations that the levels of this isotope in atmospheric carbon dioxide have decreased.

The delicately balanced cycling of carbon atoms around the environment has also been disrupted by deforestation. Natural processes to restore the levels of atmospheric carbon dioxide are too slow when compared to the rate human activities are adding it to the environment.

Question 2
Suggest how deforestation can lead to an increase in atmospheric carbon dioxide.

Carbon dioxide is soluble in water. When it dissolves, it forms the weak acid carbonic acid (H_2CO_3). This partially dissociates, increasing the concentration of H^+ ions and therefore lowering the pH.

$$CO_2(g) + H_2O(l) \rightleftharpoons H_2CO_3(aq) \rightleftharpoons H^+(aq) + HCO_3^-(aq)$$

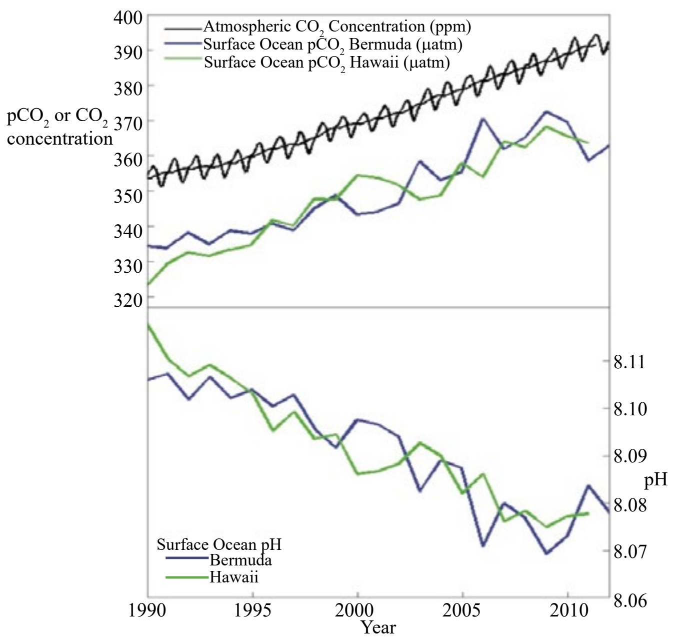
The oceans have already absorbed up to about one third of the carbon dioxide produced by the activity of humans. Consequently, the pH levels of the oceans are decreasing - becoming more acidic. As the atmospheric levels of carbon dioxide increase, it is expected that the pH of the oceans will continue to fall as more of the gas dissolves.

Question 3
Use Le Chatelier's Principle to explain why increasing the concentration of carbon dioxide is predicted to decrease oceanic pH.

Fig. 4 shows the levels of carbon dioxide in the atmosphere and the surface concentrations of carbon dioxide in the ocean at Bermuda and Hawaii since 1990. The changes in surface ocean pH at these locations are also shown.

Question 4
Describe the trends and patterns in the Fig. 4

Fig. 4: The change in pH of oceans with change in atmospheric carbon dioxide levels over time

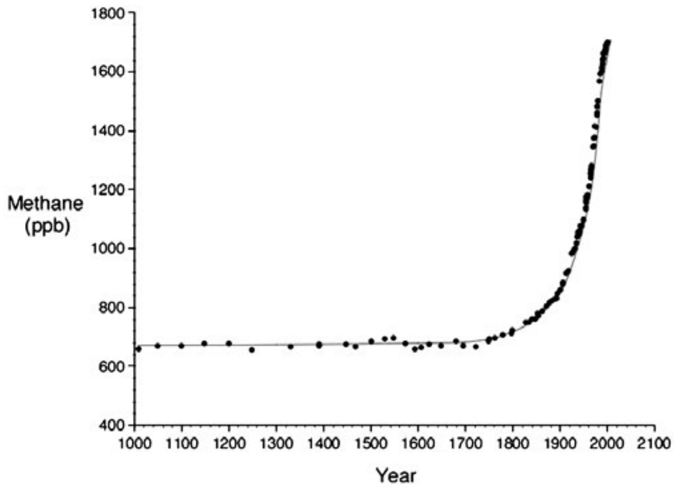


Calcium carbonate is a component of the shells of marine creatures and also reacts with acids to produce salts, water and carbon dioxide. There is evidence that some marine species develop misshapen shells and show lower growth rates in more acidic waters. In addition, the cycling of nutrients in the oceans is likely to be changed as the pH drops. This is predicted to alter the competitive advantage among marine species with the consequent, but as yet undetermined, impacts on marine food webs and ecosystems.

Methane

Historic atmospheric concentrations of methane can be determined, like those for carbon dioxide, by using data from ice cores. Levels have fluctuated naturally around 500 parts per billion (ppb) from 800,000 years ago to the early 1900s. Data from the atmosphere since 1988 shows an increase from approximately 1700 ppb to 1850 ppb, indicating a significant increase.

Fig. 5: Atmospheric methane concentration over the last 1,000 years



Although much lower in concentration than carbon dioxide, the ability of a methane molecule to absorb infrared radiation is much greater than carbon dioxide.

Methane comes from many sources, both manmade and natural. Natural sources of methane contribute about 36% of total methane emissions and include wetlands, oceans and termites, which rely on methane-producing bacteria in their digestive tract to digest the cellulose on which the termites feed.

Fig. 6 Human sources of methane

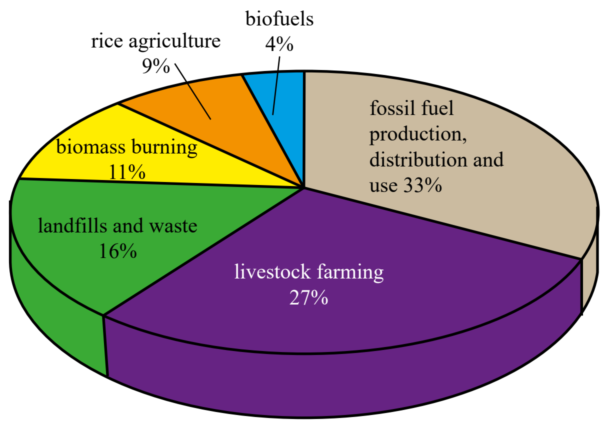


Fig. 6 shows the sources of atmospheric methane from human activities. The most significant industrial emissions are from the oil and gas industry, livestock farming (where methane is produced as a digestive by-product by cattle) and landfill sites where anaerobic decay of organic matter releases the gas. In addition, the growth of rice essentially requires large areas of man-made wetlands. Low levels of oxygen, a high degree of organic matter and high moisture content in the rice fields are perfect environments for the growth of methane-producing bacteria.

The use of fossil fuels and the intensification of livestock farming have been described as the cause, of the doubling of methane levels since the industrial revolution.

A significant amount of methane is also trapped in the crystal structure of water. It forms a solid with a similar structure to ice and has the nominal formula $(CH_4)_4(H_2O)_{23}$. This is called methane clathrates and significant deposits have been found under sediments on the ocean floors and deep freshwater lakes such as Lake Baikal in Siberia. The sudden release of large amounts of methane from such deposits has been suggested to be the cause of past climate changes, and consequently could cause future climate changes. Scientists have predicted that methane released from the large-scale thawing of Arctic permafrost regions - due to the current warming of the atmosphere - could cause runaway climate change that cannot be stopped. The Siberian Arctic showed methane concentrations up to 100 times above normal levels.

Question 5
Suggest how global temperature increase could cause a significant increase in the levels of methane in the atmosphere.

Answers

1 Methane absorbs more infrared radiation than the same mass of carbon dioxide but there is much less methane in the atmosphere so contributes much less to global warming.

2 Deforestation removes trees and so there is less photosynthesis removing carbon dioxide from the atmosphere. Furthermore, if the trees are burned after being chopped down, this releases more carbon dioxide into the atmosphere.

3 Increasing the concentration of carbon dioxide shifts the first equilibrium to the right hand side as the equilibrium counteracts the change. This increases the concentration of carbonic acid, which will shift the second equilibrium to the right hand side, increasing the concentration of H^+ ions. Increasing the concentration of H^+ ions decreases the pH.

4 The concentration of carbon dioxide in the atmosphere shows an increasing trend since 1990. This is matched by a general increase in the concentration of carbon dioxide at the ocean surface in both Bermuda and Hawaii. Over the same time period, the surface ocean pH at both locations shows a decreasing trend as a result of increasing concentrations of carbonic acid.

5 As the global temperature increases, this increases the likelihood of the melting of permafrost areas with the subsequent release of methane gas from methane clathrates. The increase in levels of methane in the atmosphere has the potential to increase the temperature further, since methane is a more potent greenhouse gas than carbon dioxide. Consequently more permafrost may melt and the cycle continue.

*__Acknowledgements:__ This **Factsheet** was researched and written by **Martin Scott**.*
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