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Topic 1: Monitoring the environment

1.1 Global warming and climate change

Science understanding

Some gases in the atmosphere, called ‘greenhouse gases’, keep the Earth’s atmosphere warmer than it would be without these gases. This is known as the ‘greenhouse effect’.

Describe the action of the common greenhouse gases, carbon dioxide and methane, to maintain a steady temperature in the Earth’s atmosphere.

The greenhouse effect

Figure 1.1.1: Solar radiation entering Earth’s atmosphere.

Solar radiation entering Earth’s atmosphere consists of infrared radiation, visible light and ultraviolet radiation (UV). Solar radiation is composed largely of visible wavelengths, longer infrared wavelengths, and a smaller component of shorter ultraviolet wavelengths.

Approximately 30% of the solar radiation reaching Earth is reflected to space due to the **albedo** (reflectivity) of the Earth’s surface and atmosphere. Land and sea ice, snow coverage and the clouds are all highly reflective. Approximately 22% of the solar radiation reaching Earth is absorbed by the atmosphere. A component of ultraviolet radiation is absorbed by gases present in the stratosphere, importantly by the ozone molecule. The remaining 48% of solar radiation is absorbed by the surface of the Earth, warming it (Figure 1.1.1). Of the absorbed solar radiation, approximately 17% is reradiated from the Earth at lower energies and therefore longer wavelengths. The wavelengths emitted correspond to the **thermal infrared region** (longer wavelengths at lower energy than visible light) of the electromagnetic spectrum.

Approximately 12% of this thermal radiation passes directly through the atmosphere into space, but a component of approximately 5% is absorbed by molecules in the atmosphere, collectively referred to as **greenhouse gases**. These molecules in turn reradiate the thermal radiation to other molecules in the atmosphere, into space, and back to the surface of the Earth. The effect of this is to warm the surface of the Earth and the **troposphere** (the lower layer of the atmosphere) (Figure 1.1.2).

This naturally occurring process is referred to as the **greenhouse effect**. The greenhouse effect serves to maintain a relatively stable average temperature of approximately 15°C, sustaining life on Earth.

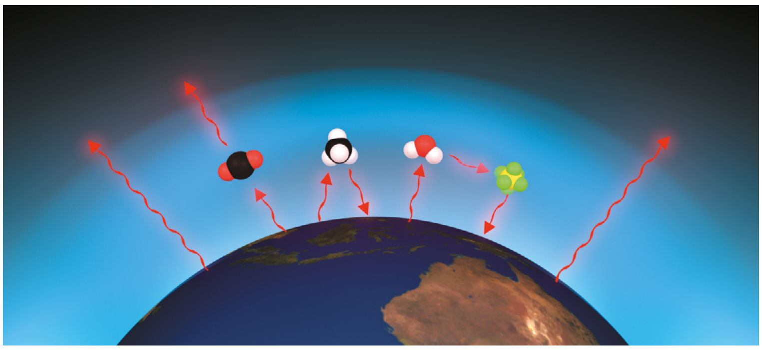
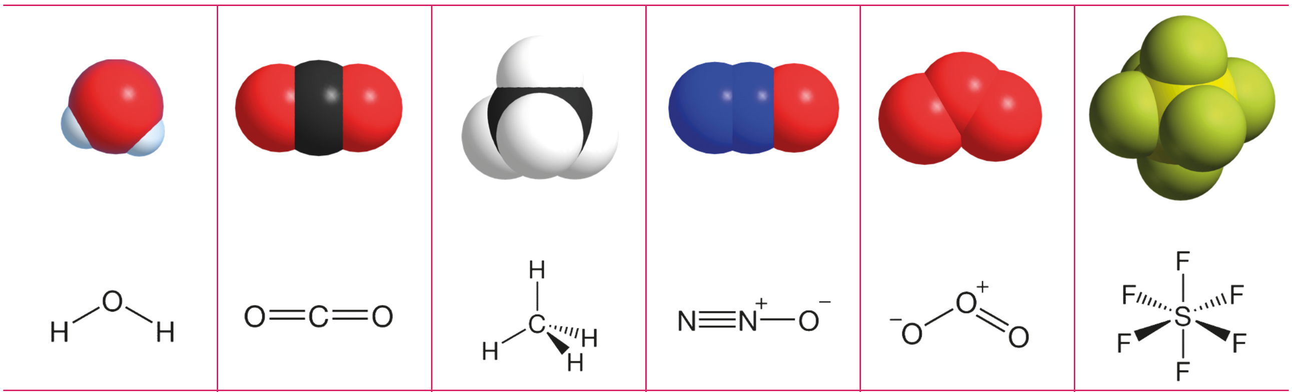


Figure 1.1.2: The natural greenhouse effect.

Greenhouse gases

Greenhouse gases absorb thermal radiation in the infrared region of the electromagnetic spectrum. Greenhouse gases originate from both natural and synthetic sources (Figure 1.1.3).



H_2O	CO_2	CH_4	N_2O	O_3	SF_6
v-shaped	linear	tetrahedral	linear	v-shaped	octahedral
water (vapour)	carbon dioxide	methane	nitrous oxide	ozone	sulfur hexafluoride (Synthetic sources only)

Figure 1.1.3: Natural and synthetic greenhouse gases.

Cycles in nature, such as the **carbon cycle,** the **water cycle** and **nitrogen cycle**, are responsible for the formation of naturally occurring greenhouse gases that enter the atmosphere. **Anthropogenic** (originating from human activity) influences have added to the concentrations of naturally occurring greenhouse gases, while also introducing synthetic greenhouse gases.

Greenhouse gas	Natural sources
water vapour	Water is present in the atmosphere as water vapour and clouds. Water moves between the soil, natural bodies of water (such as oceans and lakes), and the atmosphere via the water cycle.
carbon dioxide	Carbon dioxide is released during **aerobic** (presence of oxygen) respiration in animals, humans and soil-dwelling microbes, aerobic decomposition of organic matter, the combustion of natural vegetation, and volcanic activity.
methane	Methane is released during the **anaerobic** (absence of oxygen) decomposition of organic matter in soil. Methane is also released when sea ice, containing methane hydrates, melts.
nitrous oxide	Nitrous oxide is formed through **denitrification** (reduction of nitrate ions) in natural vegetation in soil and in the oceans.
ozone	Ozone occurs naturally in the stratosphere and is created and destroyed through the absorption of ultraviolet radiation in **photochemical** (light-absorbing) reactions.

Earth's thermal balance

On average, the temperature at the Earth's surface is approximately 32°C higher than it would be in the absence of greenhouse gases. The greenhouse effect is most strongly influenced by carbon dioxide and water vapour.

Mean surface temperature (°C) (without the greenhouse effect)	−17
Mean surface temperature (°C) (with the greenhouse effect)	15
Greenhouse warming	32

For thousands of years, the temperature of the Earth's atmosphere has been in **thermal balance**, with the amount of thermal radiation entering the atmosphere in equilibrium with the amount of thermal radiation emitted back into space (Figure 1.1.4).

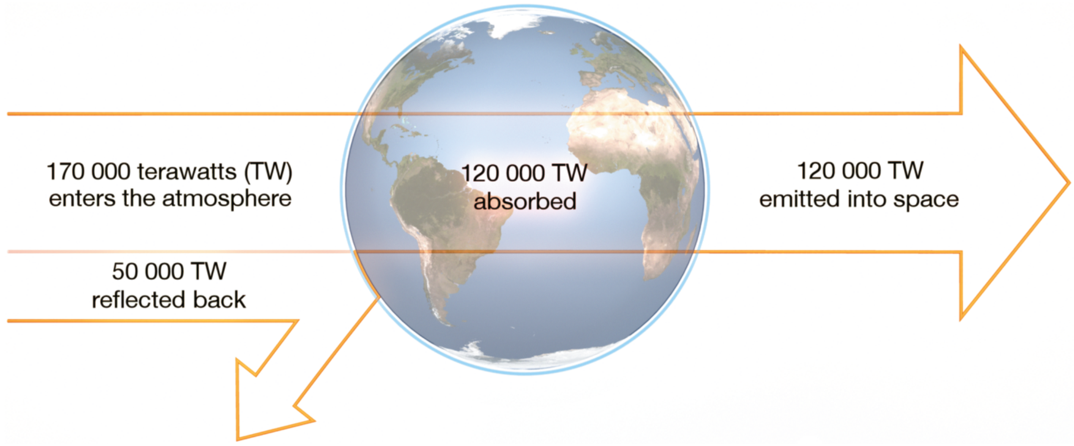


Figure 1.1.4: Thermal balance.

Science understanding

Anthropogenic increases in greenhouse gases disrupt the thermal balance of the atmosphere.

Explain the warming associated with global climate change and its consequences for the environment.

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Global warming

As concentrations of greenhouse gases have risen due to anthropogenic activities, less thermal radiation is escaping the Earth, generating a **thermal imbalance**. A new equilibrium is established with an average temperature that exceeds the current value (Figure 1.1.5). This resulting increase in temperature is referred to as **global warming**.

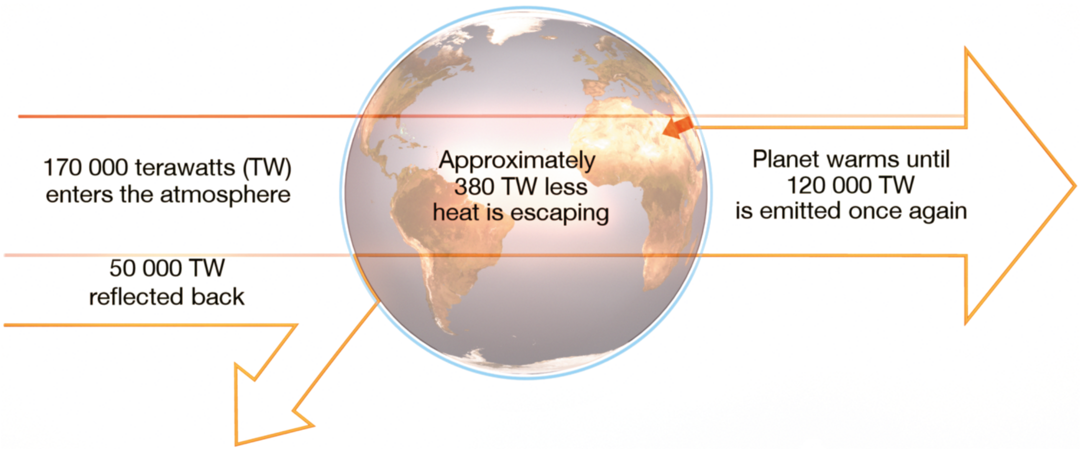


Figure 1.1.5: Thermal imbalance.

Questions

1. The impact of warming due to greenhouse gases can be seen by comparing Earth to other planets in our solar system. The details are summarised in the table below.

	Reflectivity (albedo) (%)	Mean surface temperature (without greenhouse effect) (°C)	Mean surface temperature (with greenhouse effect) (°C)	Greenhouse warming (°C)	Carbon dioxide present in the atmosphere (%w/v)
Earth	36	–17	15	32	0.040
Mars	25	–55	–50	5	95 (very thin atmosphere)
Venus	72	–42	467	509	96

(a) Earth's atmosphere maintains temperatures that are suitable to sustain life.

(i) **State** the mean surface temperature experienced on Earth without the greenhouse effect.

(1 mark) **IAE3**

(ii) **Explain** how two greenhouse gases, carbon dioxide and methane, assist in maintaining a stable temperature in the Earth's troposphere.

(3 marks) **KA1**

(b) Albedo refers to the reflectivity of the surface and atmosphere of the planet.

Suggest why albedo is taken into account when determining greenhouse warming.

(2 marks) **KA2**

(c) Venus has a mean surface temperature of 467°C and Mars –50°C.

(i) **Explain**, using data in the table, why the mean surface temperature of Venus is considerably higher than that of Earth.

(2 marks) **IAE3**

(ii) The percentages of carbon dioxide in the atmospheres of Mars and Venus are almost equal.

Suggest one reason for the difference in the mean surface temperature of Mars and Venus.

(1 mark) **KA2**

2. An investigation was undertaken to determine the action of carbon dioxide as a greenhouse gas.

STEP 1: Two 2 L plastic bottles were assembled, one containing air and the other a small pellet of dry ice (solid carbon dioxide), with the lids removed. A carbon dioxide sensor was inserted into each bottle to measure the concentration of carbon dioxide. The concentration of carbon dioxide present in the air in the first bottle was found to be 404 ppm. On sublimation, the dry ice produced a concentration of 826 ppm of carbon dioxide in the second bottle.

STEP 2: A temperature sensor was inserted into each bottle and the opening sealed.

STEP 3: Both bottles were placed at equal distances from a 60-watt incandescent lamp and the temperature recorded at five-minute intervals for a period of 30 minutes.

(a) From the procedure outlined,

(i) **Identify** and **discuss** the importance of the control of one factor in the investigation

(2 marks) **IAE1**

(ii) **Identify** the independent variable in the investigation.

(1 mark) **IAE1**

(iii) Hence, **state** a suitable hypothesis for the investigation.

(2 marks) **IAE1**

(iv) **Suggest** one improvement that could be made to the design to increase the validity of the procedure.

(1 mark) **IAE4**

(b) The results obtained are summarised in the table below.

	Concentration of CO_2	
	404 ppm	**826 ppm**
Time (min)	**Temperature (°C)**	**Temperature (°C)**
0	22.0	22.0
5	22.5	24.0
10	24.0	25.5
15	25.0	28.0
20	26.0	29.5
25	26.5	31.0
30	27.0	33.0

Using the data obtained,

(i) **Graph** both sets of data on the same set of axes.

(6 marks) **IAE2**

(ii) **Discuss** the conclusions that can be drawn from the data in relation to carbon dioxide as a greenhouse gas.

(3 marks) **IAE3**

Anthropogenic (human) influences

The atmospheric concentrations of carbon dioxide and other greenhouse gases have shown steady increase over the past 250 years. The most significant change has been the increase recorded in atmospheric carbon dioxide.

Increased concentrations of carbon dioxide may be directly attributed to human activities. Since the industrial revolution (c. 1750), carbon deposits that had been stable for millions of years as **fossil fuels** (coal, crude oil and natural gas) have been mined, processed, consumed for energy production, and used as **feedstock** (raw material) for the chemical industry. A growing population, living in an increasingly industrialised world, has led to greater demand for natural resources and the subsequent increased release of greenhouse gases.

Greenhouse gases exist for different periods of time in the atmosphere (**atmospheric residence time**). They undergo chemical reactions to form products that result in the removal of the gases from the atmosphere. For example, carbon dioxide is used during photosynthesis or absorbed into oceans. Greenhouse gases can be compared to carbon dioxide in their relative ability to absorb thermal radiation. This value is referred to as the **global warming potential (GWP)**.

Greenhouse gas	Anthropogenic sources	Atmospheric residence (years)	Global Warming Potential
carbon dioxide	Carbon dioxide is released in considerable quantities during the combustion of fuels in the internal combustion engines of motor vehicles. Carbon dioxide is released from the combustion of fuels during electricity generation in power stations and other industry applications. Widespread deforestation and land-clearing has reduced the amount of natural vegetation available to remove carbon dioxide from the atmosphere through photosynthesis.	5 – 200	1
methane	Methane is released in mining, and during the production and use of fuels. Methane is released during digestion in ruminant animals. Atmospheric concentrations have increased due to intensive livestock farming. Rice farming releases methane due to the anaerobic conditions generated in rice fields. Landfill releases small quantities of methane from the natural anaerobic decay of organic matter.	12.4	28
nitrous oxide	Nitrous oxide is released from the use of natural and synthetic fertilisers and the cultivation of soil in agriculture. Catalytic converters in motor vehicles produce small quantities of nitrous oxide.	120	265
sulfur hexafluoride	Sulfur hexafluoride is produced synthetically for use in the electrical industry as an electrical insulator. It is also used in the industrial casting of magnesium. Sulfur hexafluoride may be released in small quantities during production, use and disposal.	3200	23500
chlorofluorocarbons (CFCs)	CFCs and HFCs have been synthetically produced for applications as aerosols and foams, refrigerants, and as insulation in electrical cabling.	45 – 1020	6310 – 11700
hydrofluorocarbons (HFCs)	They may be released in small quantities during production, use and disposal.	Days – 244	<1 – 10800

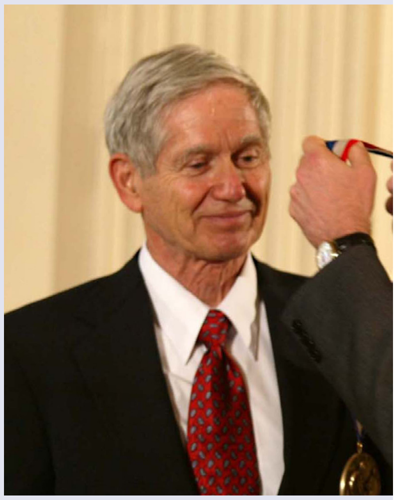
Global measurements

Atmospheric carbon dioxide concentrations have been accurately and reliably recorded by the scientific community for over 50 years.

Science as a human endeavour

Keeling's Curve

Charles Keeling of Scripps Institution of Oceanography was one of the first scientists to make regular measurements of atmospheric carbon dioxide concentrations. In 1958, Keeling began taking measurements of carbon dioxide concentration from Hawaii's Mauna Lao volcano observatory and at the South Pole. Before Keeling's measurements the scientific community had generally thought that concentrations of carbon dioxide in the atmosphere were highly variable with no significant trends apparent in recorded values.



Keeling's measurements initially revealed variation over the day and between seasons. The decay of plant matter over winter increases carbon dioxide levels; new growth of plants in spring reduces carbon dioxide levels due to increased levels of photosynthesis.

The long-term trend from measurements taken since 1958 at Mauna Lao observatory revealed a steady increase in atmospheric carbon dioxide concentrations, Keeling correlated this increase with the increased combustion of fossil fuels around the globe.

Today, carbon dioxide levels are monitored from sites all over the globe using increasingly sophisticated methods. Charles Keeling passed away in 2006. His son, Ralph Keeling, has carried on with his father's research.

The recorded concentrations of carbon dioxide from atmospheric monitoring have been combined with carbon dioxide readings obtained from ice-core samples (Figure 1.1.6). Together, these readings represent thousands of years of data.

There is strong evidence to suggest that carbon dioxide levels have increased considerably over the past 1000 years. Although there is cyclical variation over periods of tens of thousands of years, carbon dioxide concentrations in the atmosphere are currently at the highest recorded levels in human history, with values exceeding 400 ppm. This trend correlates very closely with measurements taken for average global temperature.

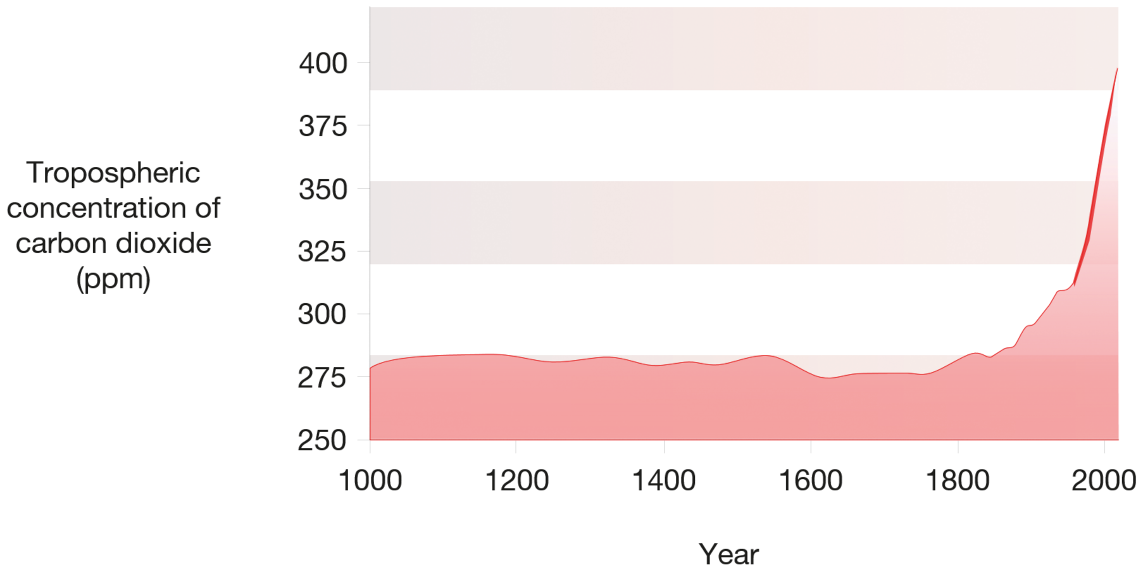


Figure 1.1.6: Variation in the tropospheric concentration of CO_2 over the past 1000 years.

Climate change

Climate can be monitored over periods of decades through the record of measurable patterns in the weather, such as temperature and rainfall. There is growing scientific evidence that the impacts of global climate change are accelerating.

Global temperature rise

Globally, temperatures have risen by approximately 0.8°C over the last 100 years. Average global surface air temperature has shown a steady increase (Figure 1.1.7).

Global feedback mechanisms have also driven further increases in temperature. For example, at higher temperatures more water vapour is present in the atmosphere due to greater evaporation, which in turn absorbs more energy while acting as a greenhouse gas, increasing temperatures in the troposphere.

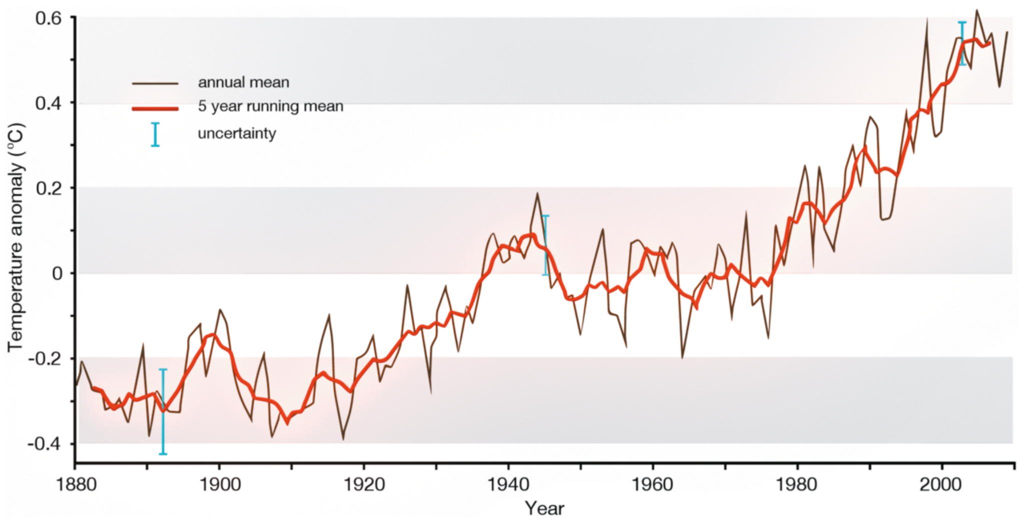


Figure 1.1.7: Global surface air temperature.

An Australian perspective

Over the past 100 years, the average surface temperature in Australia has increased by 1.0°C.

Declining artic sea ice, shrinking ice sheets, and retreating glaciers

Melting land ice and sea ice enter the Earth's oceans, causing a rise in sea level and altering salinity. The input of fresh water from land ice and glaciers alters the temperature and salinity (hence density) in regions of the ocean. These changes are predicted to affect the circulation of global ocean currents. Ocean currents impact upon weather and hence climate.

The loss of reflectivity has a significant impact. With a decline in ice and snow, the albedo of the Earth is reduced, resulting in a decrease in reflected solar radiation and increased global temperatures, once again altering the global climate.

Artic sea ice has been declining at a rate of approximately 13% per decade (Figure 1.1.8).

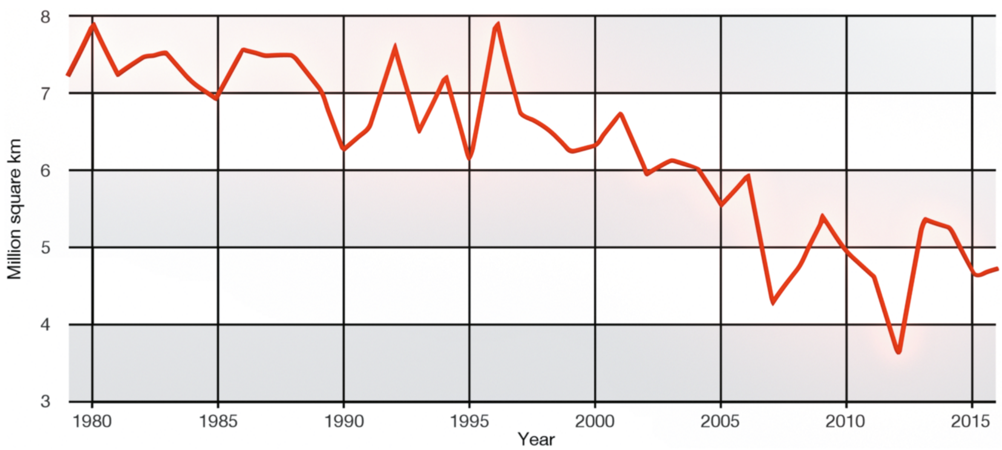


Figure 1.1.8: Arctic sea ice (1979–2017).

Similar decline has been recorded in land ice mass and the loss of glaciers (Figures 1.1.9 and 1.1.10).

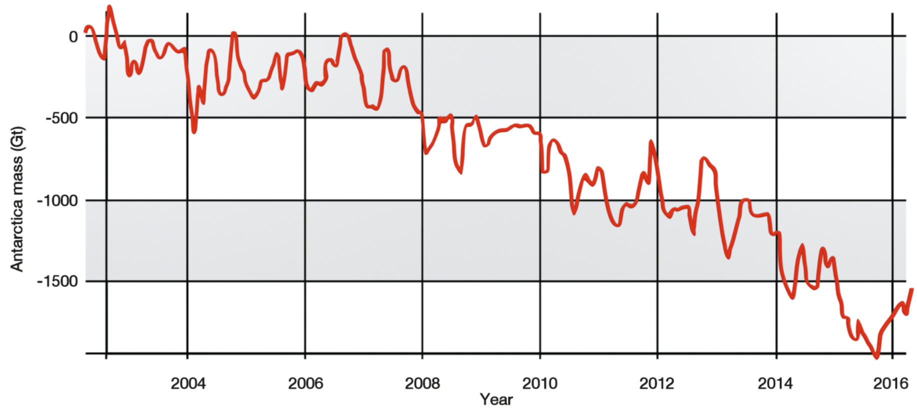


Figure 1.1.9: Ice mass measurements, Antarctica (2002–2017).

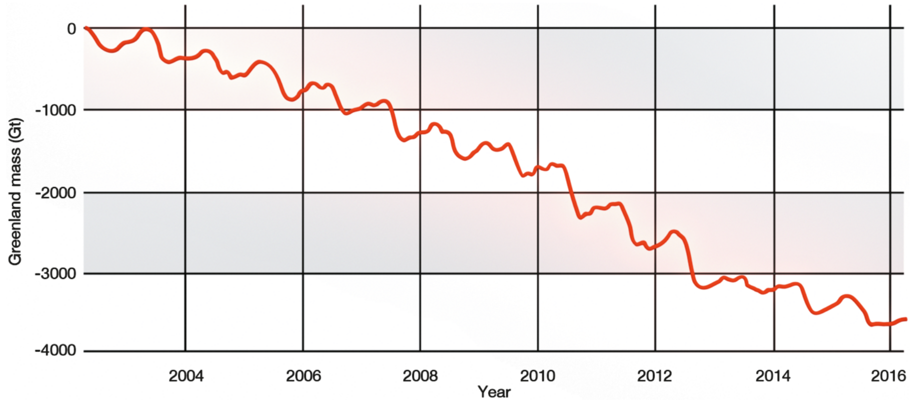


Figure 1.1.10: Ice mass measurements, Greenland (2002–2017).

Thawing permafrost (frozen soil and rock) in Greenland, Alaska and Siberia has also led to the release of methane (from methane hydrates in the ice) and other trapped greenhouse gases formed during the anaerobic decay of organic matter, contributing further to global warming.

Rising sea levels

Globally, sea levels have risen by approximately 17 cm in the last 100 years (Figure 1.1.11). As ocean temperatures increase, the water in the oceans undergoes thermal expansion increasing in volume, causing a subsequent rise in sea levels. Rising sea levels threaten low-lying coastal communities in localised regions such as the Maldives and Torres Strait Islands.

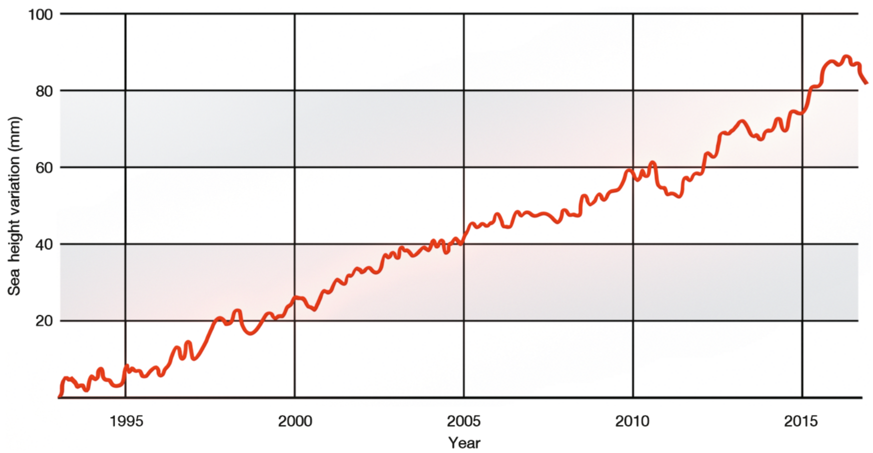


Figure 1.1.11: Satellite measurements of variation in sea height (1993–2017).

An Australian perspective

Rates of sea level rise to the north, west, and south-east of Australia have been higher than the global average.

Climate and extreme weather events

As the global climate system experiences warming, changes have occurred in both the frequency and severity of weather events. Changes to climate and severe weather events impede global crop production and alter distribution of natural vegetation. As landscapes and habitats are altered, plant and animal species must adapt or risk extinction. Climate change has led to extinction of susceptible species, resulting in permanent changes to biodiversity in ecosystems.

An Australian perspective

In Australia, the most evident change has been extreme temperature events. There have been more frequent occurrences of bushfires, increases in extreme fire weather, and longer fire seasons. There has been greater variability in trends in rainfall patterns, leading to drought and flooding. An increase in the severity of tropical cyclones (such as Cyclone Debbie in 2017) has also been noted.

Warming of oceans

Ocean temperatures and ocean heat content have steadily increased globally. The majority of the additional heat generated by the enhanced greenhouse effect is being absorbed by the world's oceans. The high specific heat capacity of water allows large quantities of energy to be absorbed. Much of the impact of the enhanced greenhouse effect on the surface of the globe has been masked by this absorption of energy.

An Australian perspective

Oceans around Australia have warmed, threatening ocean ecosystems like the Great Barrier Reef through coral bleaching and ocean acidification.

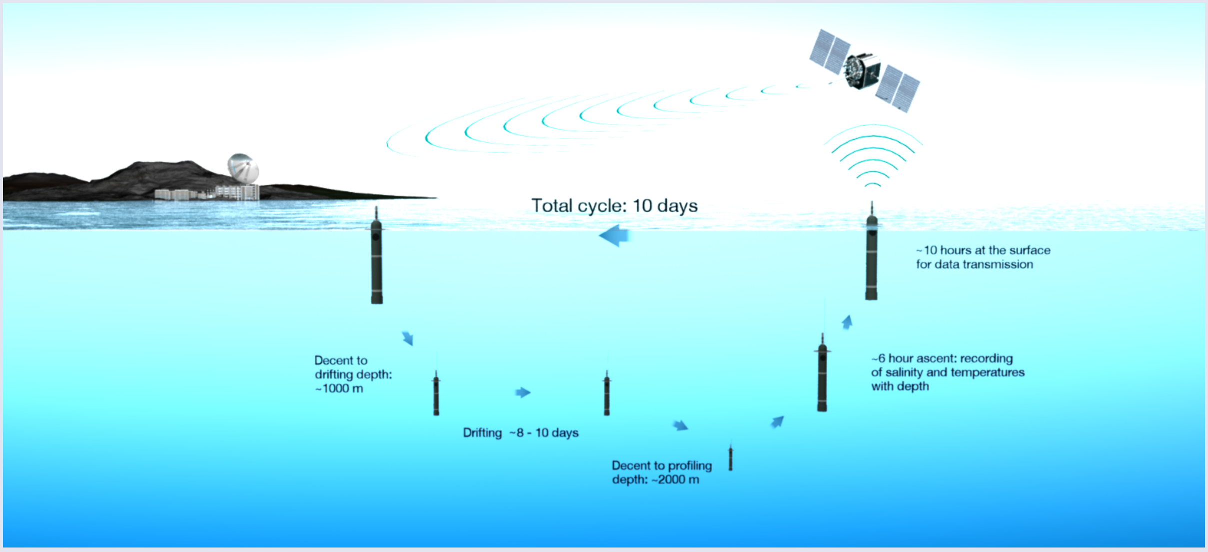
Science as a human endeavour

Argo – integrated global observation strategy

The Argo submersible program is an example of international collaboration with the support of more than 30 nations worldwide.

Argo consists of an array of more than 3800 submersible floats distributed throughout the world's oceans. The array is being used to record real-time data of ocean temperature, salinity and currents.

Submersible floats descend slowly to a depth of 2000 m and drift with the ocean currents while communicating with satellites to register global positioning and transfer data. Measurements of ocean temperature during the submersibles, descents have revealed that warming has extended to at least these recorded depths worldwide.



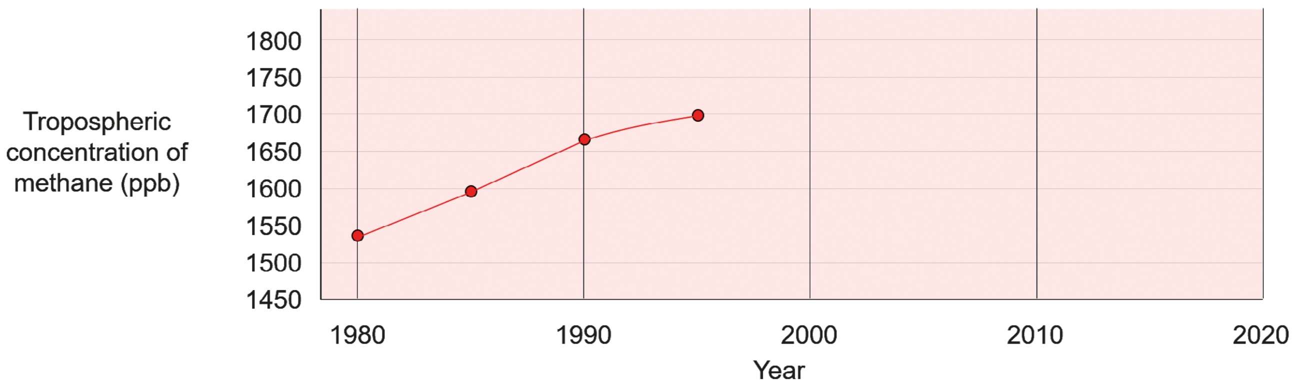
Question

3. Atmospheric methane concentrations have increased steadily over the last century.

(a) Methane concentrations have been recorded by the CSIRO, at Cape Grim near Tasmania, since 1978. Changes in the atmospheric concentration of methane can be seen in the table and graph below.

Year	Methane concentration (ppb)
1980	1540
1985	1602
1990	1666
1995	1701
2000	1732
2005	1731
2010	1751
2015	1789

Plot the remaining data for methane.



(b) Large sinkholes have appeared in regions of Siberia, where trapped methane hydrate deposits in surface ice have suddenly and violently escaped into the atmosphere.

(i) Methane sinkholes have been appearing more frequently across regions of Siberia in recent years.

Suggest one reason why the rate of formation of methane sinkholes has increased in recent years.

(1 mark) **KA2**

(ii) **Explain** how methane emissions contribute to increased temperature in the Earth's troposphere.

(3 marks) **KA2**

(iii) Methane is approximately 30 times more effective than carbon dioxide as a greenhouse gas. **Suggest**, however, one reason why the contribution of methane to global warming is less significant than carbon dioxide.

(1 mark) **KA2**

(c) Methane is also formed from the decay of organic matter in landfill.

(i) **State** one other source of methane derived from human activities.

(1 mark) **KA1**

(ii) Methane generated in landfill may be collected in pipes below the landfill and burnt as a fuel source to produce electricity.

Discuss one advantage and one disadvantage of this process, in terms of greenhouse emissions.

(2 marks) **KA3**

Science understanding

Ocean acidification is caused by the ocean absorbing higher levels of carbon dioxide from the atmosphere.

Describe and write equations to show how carbon dioxide lowers the pH of the oceans.

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Ocean acidification

A large proportion of the carbon dioxide released from anthropogenic activities is absorbed by the oceans and natural bodies of water (Figure 1.1.12)

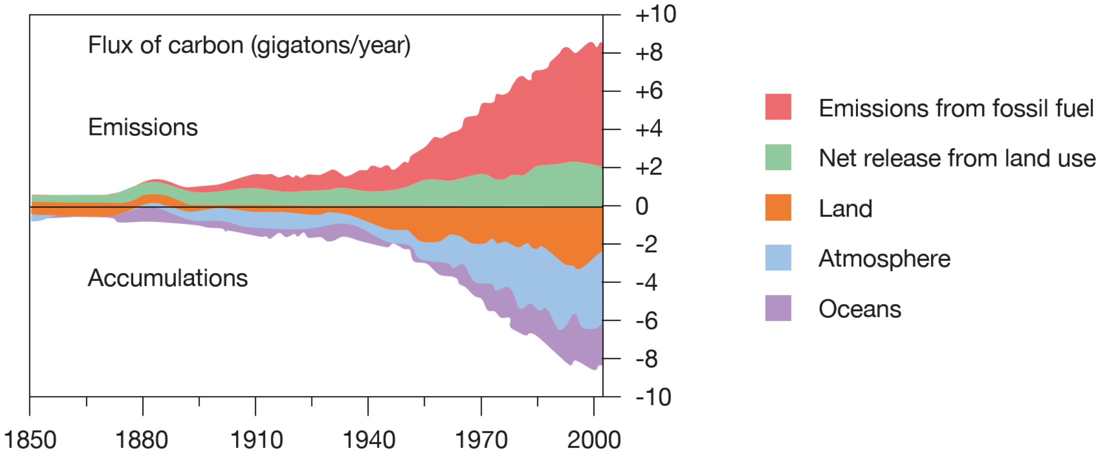

Figure 1.1.12: Carbon dioxide emissions and accumulation

Carbon dioxide is soluble in the sea and reacts to form carbonic acid (H_2CO_3).

$$CO_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)}$$

Carbonic acid is a weak acid and partially ionises, forming hydronium ions (H_3O^+) and hydrogencarbonate ions (HCO_3^-).

$$H_2CO_{3(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq)} + HCO^-_{3(aq)}$$

Hydrogencarbonate ions further ionise to form carbonate ions (CO_3^{2-}). This conversion (H_2CO_3) is pH dependent.

$$HCO^-_{3(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq)} + CO^{2-}_{3(aq)}$$

An increase in the concentration of hydronium ions results in a decrease in the pH of the oceans.

The oceans on Earth are slightly alkaline, on average recording a pH of approximately 8.2. Human intervention has seen the pH of the oceans decrease by a value of approximately 0.1. Although this is a small change in pH, it represents a nearly 30% increase in hydronium ion concentration in the oceans.

Science understanding

Calculate the pH of solutions given the concentration of H^+ or OH^-, and vice versa.

The ionic product of water, K_w

Water is an amphiprotic substance that can both donate and accept a proton.

$$2H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq)} + OH^-_{(aq)}$$

The resulting equilibrium, established at 25°C, results in an equal concentration of both hydronium ions (H_3O^+) and hydroxide ions (OH^-). Both ions are present at a concentration of 1.0×10^{-7} mol L^{-1} under these conditions.

This relationship gives rise to the following mathematical expression.

$$K_w = [H_3O^+] \times [OH^-]$$
$$K_w = (1.0 \times 10^{-7}) \times (1.0 \times 10^{-7})$$
$$K_w = 1.0 \times 10^{-14}$$

When the negative logarithm is taken for each of the components in the expression, a simpler expression results.

$$pK_w = -\log_{10} (1.0 \times 10^{-14}) = 14$$
$$pH = -\log_{10} [H_3O^+]$$
$$pOH = -\log_{10} [OH^-]$$
$$pH + pOH = 14$$

The concentrations of hydronium ions and hydroxide ions present in solution are extremely small. It is more convenient to express these concentrations as values on the **pH scale**.

pH is calculated from the concentration of hydronium ions present, and represents the **acidity** of an aqueous solution. **pOH** is calculated from the concentration of hydroxide ions present, and represents the **alkalinity** of an aqueous solution.

Calculations of pH and concentration of hydronium ions

To calculate the pH of a solution, the concentration of hydronium ions, $[H_3O^+]$, expressed in mol L^{-1}, is required.

$$pH = -\log_{10} [H_3O^+]$$

For a strong monoprotic acid, the concentration of hydronium ions is equivalent to the concentration of the acid.

Example

Nitric acid is generated in the atmosphere from nitrogen dioxide present in exhaust emissions. This can lead to the formation of acid rain. In one sample of acid rain, the concentration of nitric acid was determined to be 6.31×10^{-5} L^{-1}. Calculate the pH of the sample.

	Explanation	Calculation
STEP 1	Nitric acid is a strong monoprotic acid, therefore the concentration of hydronium ions is equal to the concentration of the acid.	$[H_3O^+] = [HNO_3]$ $\therefore [H_3O^+] = 6.31 \times 10^{-5}$ mol L^{-1}
STEP 2	The value is substituted into the expression for pH.	$pH = -\log_{10} [H_3O^+]$ $pH = -\log_{10} (6.31 \times 10^{-5})$ $pH = 4.21$

To calculate the concentration of hydronium ions, $[H_3O^+]$, in solution, the pH value is substituted into a rearrangement of the pH equation.

$$[H_3O^+] = 10^{-pH}$$

Example

Acid rain in some industrialised cities has been recorded at pH values as low as 2.4.

Calculate the concentration of hydronium ions at this pH.

	Explanation	Calculation
STEP 1	The pH value is substituted into the expression.	$[H_3O^+] = 10^{-pH}$ $[H_3O^+] = 10^{-2.4}$
STEP 2	Concentration units are applied to the value.	$[H_3O^+] = 3.98 \times 10^{-3}$ mol L^{-1}

Question

4. Changes in the population and diversity of species of frogs near creeks and rivers can be used to assess the health of a waterway. Some species of frogs are able to tolerate pH values ranging from 6.5 to 4.0.

(a) (i) **Calculate** the concentration of hydronium ions, in mol L^{-1}, at a pH of 6.5 and 4.0 and hence determine the highest concentration of hydronium ions present.

(5 marks) **KA4**

(ii) **State** whether a shift in pH from 6.5 to 4.0 represents an increase or decrease in the acidity of the waterway.

(iii) **Explain** why a small shift in pH from 6.5 to 4.0 represents a significant shift in hydronium ion concentration.

(2 marks) **KA2**

(b) **Suggest** one human activity that could contribute to lowering the pH to a value of 4.0 in the waterway.

(1 mark) **KA1**

(c) Frog eggs are made from calcium carbonate, $CaCO_3$.

Suggest why lowered pH in creeks and rivers may lead to their damage

(1 mark) **KA2**

Calculations of pOH and pH from the concentration of hydroxide ions

To calculate the pOH of a solution, the concentration of hydroxide ions, $[OH^-]$, expressed in mol L^{-1}, is required.

$$pOH = -\log_{10} [OH^-]$$

For a strong base, the concentration of the hydroxide ions is determined using the formula of the compound. The concentration of the base is multiplied by the number of hydroxide ions, $[OH^-]$, present in the formula.

To calculate the concentration of hydroxide ions in solution, the pOH value is substituted into a rearrangement of the pH equation.

$$[OH^-] = 10^{-pOH}$$

pH is then determined using the equation for the ionic product of water, linking pH to pOH.

$$pH + pOH = 14$$

Example

Flue Gas Desulfurization (FGD) is a process used to neutralise sulfur dioxide emissions formed during the generation of electricity in coal-fired power stations. Sulfur dioxide is passed over a wet slurry of sodium hydroxide (NaOH) at a concentration of 0.0100 mol L^{-1} and calcium hydroxide ($Ca(OH)_2$) at a concentration of 0.0203 mol L^{-1}.

Calculate the pH of the sodium hydroxide and calcium hydroxide in the solution.

	Explanation	Calculation
STEP 1	Sodium hydroxide is a strong base therefore the concentration of hydroxide ions is equal to the concentration of the formula unit.	$[OH^-] = [NaOH]$ $[OH^-] = 0.0100$ mol L^{-1}
STEP 2	The value is substituted into the expression for pOH.	$pOH = -\log_{10} [OH^-]$ $pOH = -\log_{10} (0.0100)$ $pOH = 2.00$
STEP 3	The equation linking pH to pOH is rearranged and the value for pOH subtracted from 14.	$pH = 14 - pOH$ $pH = 14 - 2.00$ $pH = 12.0$

	Explanation	Calculation
STEP 1	Calcium hydroxide is a strong base therefore the concentration of hydroxide ions is double the concentration of the formula unit.	$[OH^-] = 2 \times [Ca(OH)_2]$ $\therefore [OH^-] = 2 \times 0.0203$ $[OH^-] = 0.0406$ mol L^{-1}
STEP 2	The value is substituted into the expression for pOH.	$pOH = -\log_{10} [OH^-]$ $pOH = -\log_{10} (0.0406)$ $pOH = 1.39$
STEP 3	The equation linking pH to pOH is rearranged and the value for pOH subtracted from 14.	$pH = 14 - pOH$ $pH = 14 - 1.49$ $pH = 12.6$

Science understanding

The skeletons and shells of many marine organisms are made of calcium carbonate and are vulnerable to dissolution at low pH.

Write equations for carbonates reacting in acidic conditions.

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Reaction of acids and carbonates

Acids react with metal carbonates and hydrogen carbonates to form carbon dioxide, water and a salt as products. These reactions can be expressed as both **fully balanced chemical equations** and **ionic equations**.

Example

Calcium carbonate ($CaCO_3$) is commonly found as limestone in the sedimentary geology of marine environments. Limestone cliffs can be eroded from exposure to sulfuric acid formed in air pollution from nearby industries.

Write a fully balanced chemical equation and an ionic equation for the reaction of sulfuric acid with calcium carbonate.

Full equation: $CaCO_{3(s)} + H_2SO_{4(aq)} \rightarrow CO_{2(g)} + H_2O_{(l)} + CaSO_{4(aq)}$

Ionic equation: $CaCO_{3(s)} + 2H^+_{(aq)} \rightarrow CO_{2(g)} + H_2O_{(l)} + Ca^{2+}_{(aq)}$

pH and carbonates

Seawater is saturated (maximum concentration of solute) with calcium carbonate. Marine calcifying organisms build their shells and skeletons from calcium carbonate. A delicate **equilibrium** (the reaction occurs in both forward and backward directions) exists between carbonate and hydrogen carbonate ions in the ocean, which is affected by changes in pH (Figure 1.1.13).

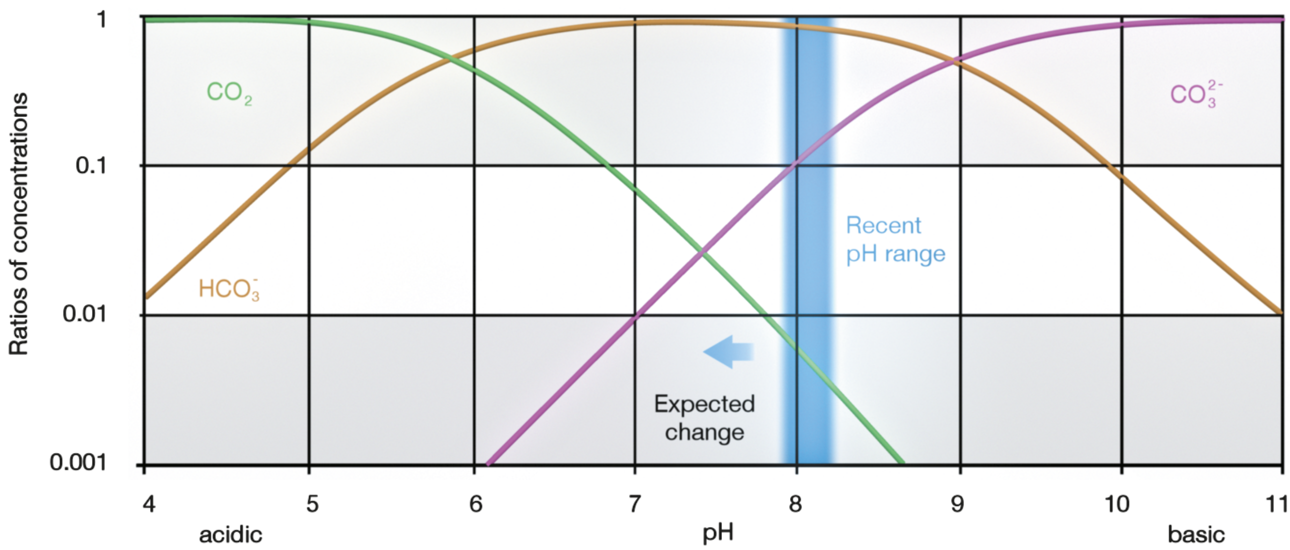

Figure 1.1.13: Chemical species present at varying ocean pH.

As pH decreases, the concentration of available carbonate ions decreases, limiting the ability of marine calcifying organisms to form shells and skeletons. Also as pH decreases, dissolution rates of calcium carbonate increase, weakening calcium carbonate structures of marine species, while also limiting the formation of new structures.

For example, ocean acidification has been found to significantly impact upon the ability of reef-building corals to form exoskeletons (outer skeletons) and reproduce. Ocean acidification has the potential to significantly affect marine ecosystems.

Question

5. Natural bodies of water, such as lakes and oceans, register differing acidity and alkalinity based upon the concentration of dissolved ions present.

   (a) Rainwater entering natural bodies of water has a pH of approximately 5.6 due to dissolved carbon dioxide from the atmosphere.

   (i) **State** whether this results in a pH of rainwater that is slightly acidic or alkaline.

   (1 mark) **KA1**

   (ii) **Write an equation** for the formation of carbonic acid from carbon dioxide gas dissolving in water in the atmosphere.

   (2 marks) **KA4**

   (b) Lake Natron in Tanzania has a pH of 10.5 due to sodium carbonate and other minerals flowing into the lake from surrounding hills.

   (i) Sodium carbonate can be dissolved by acidic water running through rocks and soil.

   Write an ionic equation for the reaction between sodium carbonate and acidic water.

   (2 marks) **KA4**

   (ii) **Calculate** the concentration of hydroxide ions, in mol L^{-1}, present in the water at a pH of 10.5.

   (3 marks) **KA2**

1.2 Photochemical smog

Science understanding

Nitrogen oxides are formed in high-temperature engines and furnaces.

Write equations for the formation of nitrogen oxides NO and NO_2.

Composition of the Earth's atmosphere

The **atmosphere** consists of a complex mixture of gases that form a thin layer surrounding the planet that is critical to sustaining life on Earth. Concentrations of gaseous components are variable in the atmosphere due to natural phenomena and human activity. The average chemical composition of the atmosphere is described in Figure 1.2.1.

Element	Percent by volume (%)	Concentration (ppm)
Major constituents		
nitrogen (N_2)	78.084	780840
oxygen (O_2)	20.946	209460
Minor constituents		
argon (Ar)	0.934	9340
carbon dioxide (CO_2)	0.0400	400
neon (Ne)	0.00182	18.2
helium (He)	0.000524	5.24
methane (CH_4)	0.000170	1.70
krypton (Kr)	0.000114	1.14
hydrogen (H_2)	0.0000550	0.550
nitrous oxide (N_2O)	0.0000500	0.500
xenon (Xe)	0.00000900	0.0900
ozone (O_3)	0.00000700	0.0700
nitrogen dioxide (NO_2)	0.00000200	0.0200
Water		
water vapour (H_2O)	Variable between 0.00100 and 5.00	

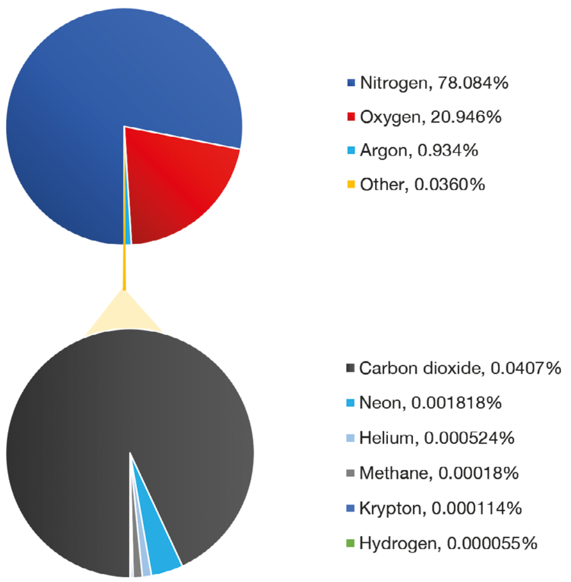

Figure 1.2.1: Average composition of the Earth's atmosphere.

Formation of oxides of nitrogen

Nitrogen (N_2) exists in the atmosphere as a diatomic molecule, with nitrogen atoms held together by a strong covalent triple bond. A large input of energy is required to break the triple bond in the formation of new compounds, hence nitrogen is a relatively stable and inert molecule in the atmosphere.

The energy required for the conversion of nitrogen to new compounds can be provided through both natural phenomena and anthropogenic activities.

Natural	Anthropogenic
Lightning	Internal combustion engines
Volcanic activity	Jet engines
Bushfires	Industrial kilns and furnaces

Sufficient energy is provided at the high temperatures encountered during these events to break the existing bonds in nitrogen and oxygen (reactants) and form nitric oxide (NO) (product).

$$N_{2(g)} + O_{2(g)} \rightarrow 2NO_{(g)}$$

Nitric oxide is further oxidised in the atmosphere to form nitrogen dioxide (NO_2) (product).

$$2NO_{(g)} + O_{2(g)} \rightarrow 2NO_{2(g)}$$

Science understanding

Nitrogen oxides and ozone are pollutants in the troposphere that are associated with photochemical smog.

Describe and write equations showing the role of nitrogen oxides in the formation of ozone in the troposphere.

The troposphere

The troposphere is the lowest layer of the atmosphere (closest to the surface of the Earth; Figure 1.2.2) and its composition is most affected by human activities.

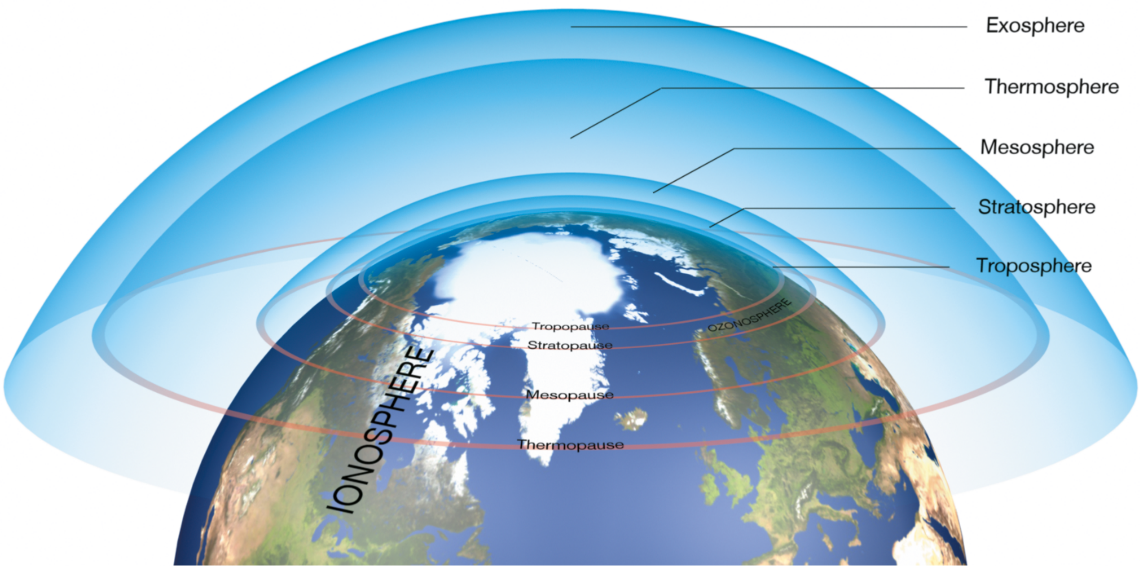

Figure 1.2.2: Layers of the atmosphere.

The troposphere contains a substantial component (75% by mass) of all the gases present in the atmosphere. It also contains nearly all the available water vapour present in the atmosphere. Human activities are responsible for releasing many pollutants directly into the troposphere.

Photochemical smog

Photochemical smog is a complex mixture of chemicals that have been output directly from the source (**primary pollutants**), or formed from the secondary reactions (many involving light and heat) between pollutants and molecules that exist in the atmosphere (**secondary pollutants**).

Photochemical smog is typically experienced in densely populated urban areas, where there is a reliance on the combustion of fossil fuels for transportation, industry, and electricity production. The following conditions are necessary for the formation of photochemical smog.

Condition	Explanation
High concentration of pollutants	Photochemical smog tends to form in densely populated areas in industrialised cities, with concentrations of pollutants changing periodically over the day.
Sunlight	Many reactions in the formation of photochemical smog are initiated by the absorption of ultraviolet radiation (UV) and heat.
Still air mass	Pollution can be dispersed or displaced depending upon prevailing weather patterns.
Temperature inversion	Warmer air containing pollutants becomes trapped between layers of cooler denser air (Figure 1.2.3).

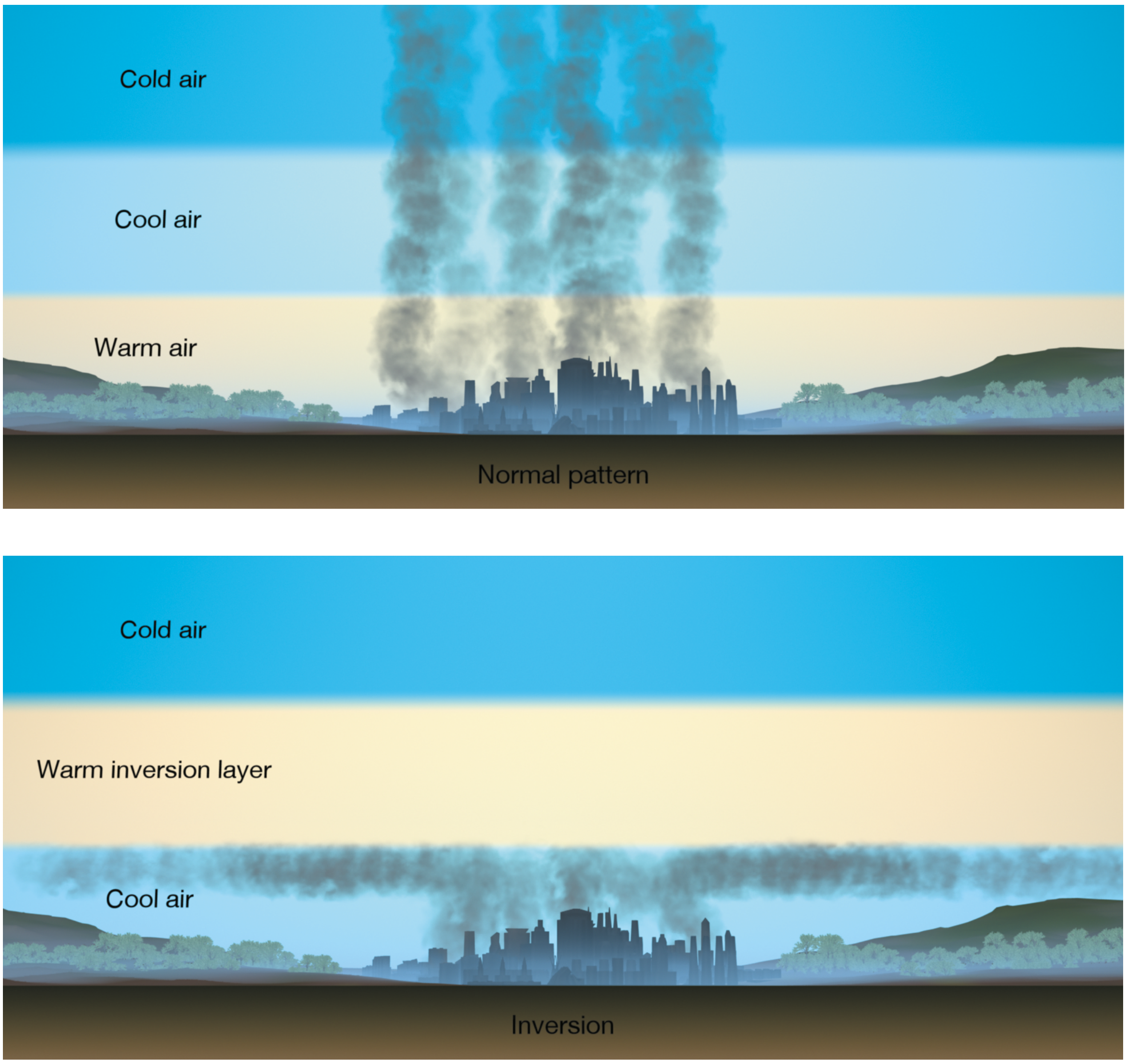

Figure 1.2.3: Temperature inversion during smog formation.