CHAPTER 03

# Equilibrium systems in the environment

Since the start of the Industrial Revolution in the 1760s, there has been a dramatic increase in the combustion of fossil fuels. This has resulted in significantly increased levels of carbon dioxide in the atmosphere. Scientists believe that the increase in atmospheric carbon dioxide is causing an increase in global warming and that it is also responsible for an increase in ocean acidity. The higher levels of ocean acidity are predicted to affect marine ecosystems involving coral reefs and other marine organisms.

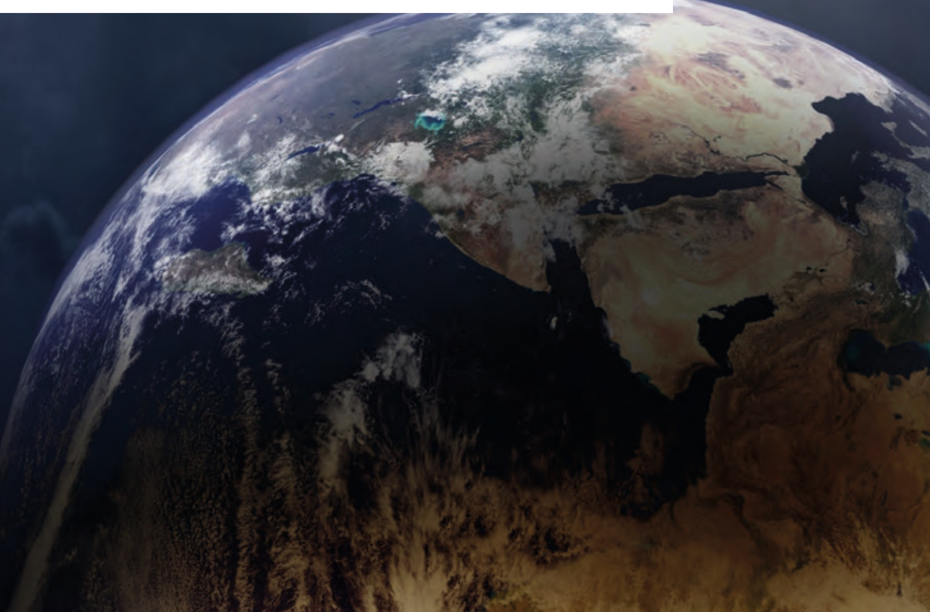
In this chapter, you will apply your understanding of equilibrium to study the effects of increasing levels of atmospheric carbon dioxide. You will consider the chemistry and potential effects of increased ocean acidity on the natural and human environment.

In addition, you will learn about the Kyoto Protocol and other international agreements that have been developed in an attempt to reduce production of greenhouse gases and slow global warming and its consequences. Australia's role in the development and implementation of carbon targets is also described.

## Science as a human endeavour

Levels of carbon dioxide in the atmosphere are rising and have a significant impact on global systems, including surface temperatures. The increasing level of carbon dioxide in the atmosphere causes more carbon dioxide to dissolve in the ocean, producing carbonic acid and leading to increased ocean acidity. This is predicted to have a range of negative consequences for marine ecosystems such as coral reefs. Calcification is the process that results in the formation of calcium carbonate structures in marine organisms. Acidification shifts the equilibrium of carbonate chemistry in sea water, decreasing the rate and amount of calcification among a wide range of marine organisms. The United Nations Kyoto Protocol and the Intergovernmental Panel on Climate Change aim to secure a global commitment to reducing greenhouse gas emissions over the next few decades.





# 3.1 Carbon dioxide in the atmosphere

The atmosphere consists of a mixture of gases extending about 100 km above the Earth's surface. Without the atmosphere, Earth could not support life as we know it. Daily temperatures would be extremely high, while nights would be extremely cold.

The Earth has maintained its average temperature over time because of the balance between the radiation received from the Sun and the radiation reflected back into space. This section describes how suitable living conditions are maintained on Earth and considers the effects of changing the amounts of atmospheric carbon dioxide.

## CARBON CYCLE

Equilibria involving carbon dioxide occur in a range of situations, including the production of glucose in plants, the formation of coral reefs and the process of respiration in cells and living things. Applying the principles of chemical equilibria to such systems allows the chemistry of these processes to be understood and hence the effects of changes to these systems can be predicted.

Carbon dioxide is essential to life on Earth. Although carbon dioxide occupies only about 0.04% of the total mass of the atmosphere, this concentration is sufficient to sustain life. Through the carbon cycle shown in Figure 3.1.1, carbon is exchanged between the atmosphere, oceans, rivers, lakes, soils and rocks.

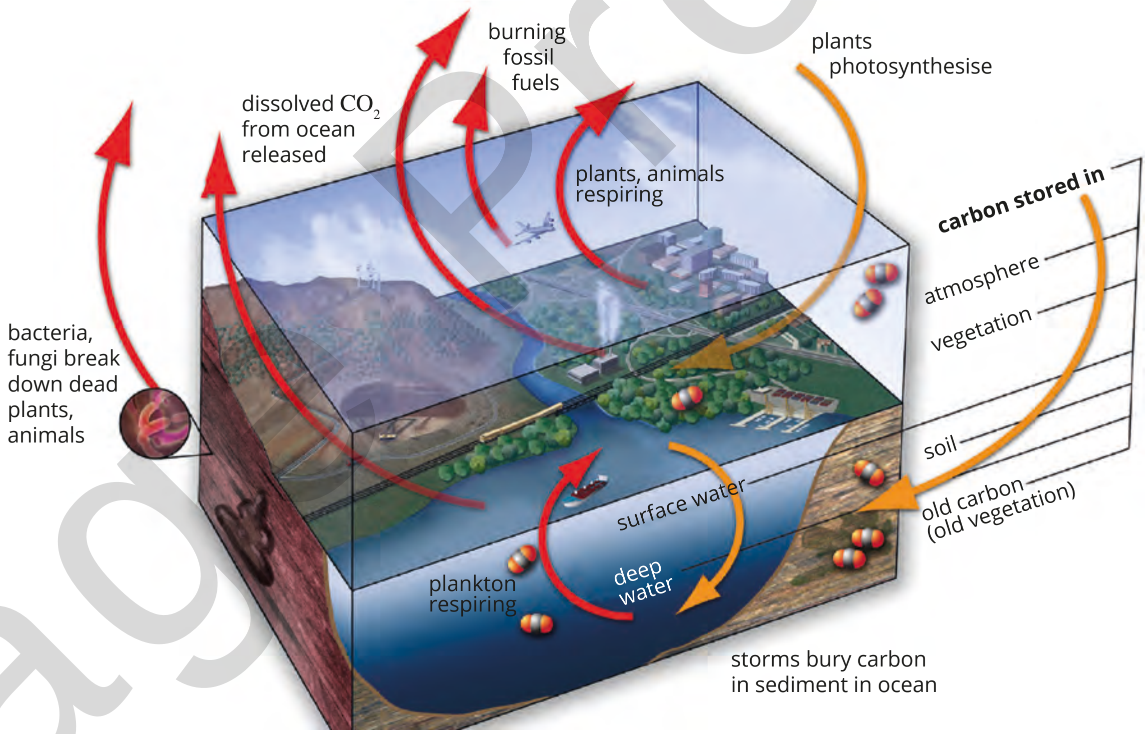



**FIGURE 3.1.1** The carbon cycle. Carbon cycles between land, the atmosphere and the oceans in billions of tonnes each year. It takes about 100 years for half the available carbon atoms to leave and re-enter the atmosphere.

### Photosynthesis

Plants take carbon dioxide from the atmosphere and, via **photosynthesis**, use it to make chemicals such as glucose ($C_6H_{12}O_6$) that act as an energy source. Plants can convert glucose into larger molecules that make up the structural parts within the plant. The process of photosynthesis can be summarised by the equation:

$$\text{ENERGY} + 6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$$

Photosynthesis involves an **endothermic** reaction that can only occur in the presence of sunlight and the pigment **chlorophyll** found in the green parts of the plant. This process converts solar energy to chemical energy, which is used as an energy source by all living things in another process called **respiration**.

Respiration can be summarised by the equation below. The overall reaction is an **exothermic** reaction and can be regarded as being the reverse of photosynthesis:

$$C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l) + \text{ENERGY}$$

As shown in Figure 3.1.1, carbon is released into the atmosphere through respiration and the decay of animal waste products and dead animals. Under some conditions, organisms do not fully decay and carbon is not returned to the atmosphere. The **non-renewable** energy resources coal, oil and natural gas were formed over a period of several million years from the remains of dead organisms. Carbon dioxide is released when these fuels are burnt.

The amount of carbon present at any particular stage of the carbon cycle depends on the rate at which it enters and leaves that stage. An equilibrium will exist when these rates are equal.

## GREENHOUSE EFFECT

The Earth receives visible and ultraviolet radiation from the Sun. This energy can pass through the atmosphere to the Earth's surface. The Earth then radiates this energy back into space as lower-energy infrared radiation.

Gases such as carbon dioxide, water vapour, methane, nitrogen oxides and ozone are called **greenhouse gases**. They absorb some of the infrared radiation before it can reach space and can re-radiate it back towards the Earth as heat. The higher the concentration of greenhouse gases, the more energy is trapped. This natural process is known as the **greenhouse effect**, because it warms the Earth's surface in a similar way to how the Sun's energy heats a greenhouse.

Atmospheric carbon dioxide and other greenhouse gases trap energy and re-radiate it back to Earth, maintaining the average surface temperature of the Earth.

Figure 3.1.2 shows how the greenhouse effect occurs naturally. Without the atmosphere, Earth would not maintain its average temperature. The effect has been essential for the evolution of life, because it sustains the equilibrium of the elements in the carbon cycle.

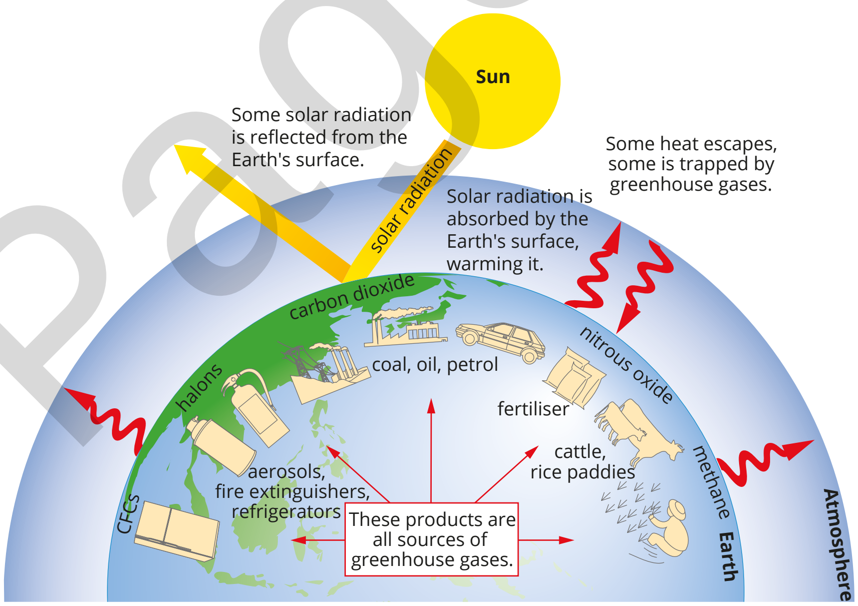



**FIGURE 3.1.2** The greenhouse effect. Greenhouse gases help to maintain the temperature at the Earth's surface.

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### Temperatures without an atmosphere

Without an atmosphere, temperatures on Earth would be similar to temperatures on the Moon (Figure 3.1.3). During the day, it would be more than 100°C, and at night it would be less than –150°C. The average temperature of the Earth would drop from a pleasant 16°C to an estimated –18°C.

**FIGURE 3.1.3** 'Blue' Earth view from the Moon's surface. Note the contrast between the oceans and green areas on Earth with the craters and desert appearance of the Moon surface where temperatures are extreme.

## GLOBAL WARMING

Studies have shown that the levels of atmospheric carbon dioxide have varied naturally over the last several thousand years. However, since the Industrial Revolution, an increase in the use of **fossil fuels** (such as coal, crude oil and natural gas) has caused the average global concentration of carbon dioxide in the atmosphere to rise by more than 40% (Figure 3.1.4). The result is an increase in the infrared radiation absorbed and re-radiated back towards the Earth.

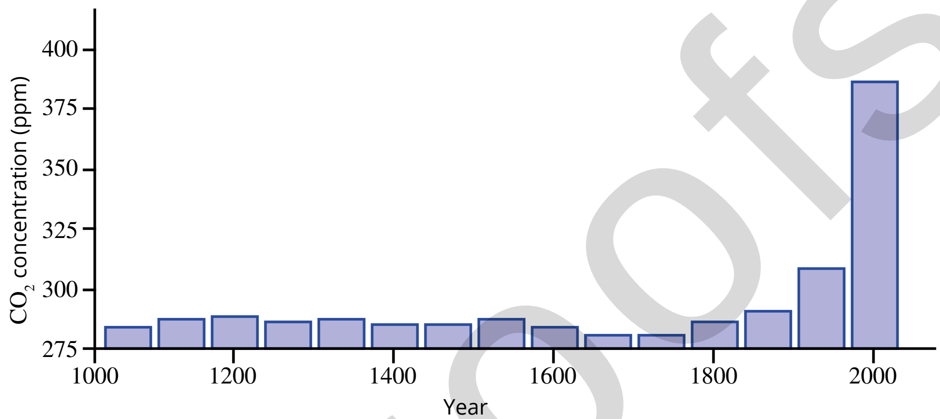


**FIGURE 3.1.4** Concentrations of atmospheric carbon dioxide for the last 1000 year.

Scientists are concerned that the increasing levels of greenhouse gases are influencing surface land and sea temperatures and causing **global warming**. This effect is referred to as the **enhanced greenhouse effect**. The higher global temperatures are thought to be responsible for rising sea levels and triggering shifts in snow and rainfall patterns, as well as some of the more extreme climate events in different parts of the world. These climate events include severe storms and cyclones, more frequent droughts and intense rainfall, causing flooding.

The maps of Australia in Figure 3.1.5 show the present annual average temperatures and the temperatures in the late 21st century that are predicted from studies by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). They indicate the change in climate that is expected due to global warming.

> The enhanced greenhouse effect is sometimes referred to as 'global warming'. It is due to increased amounts of carbon dioxide and other greenhouse gases in the atmospheric causing more heat to be trapped, raising the average temperature of the Earth's surface.

The graph shown in Figure 3.1.6 shows the changes in average global surface temperatures over time. A comparison of Figure 3.1.4 and Figure 3.1.6 shows the correlation between increasing levels of carbon dioxide and increasing surface temperatures.

Scientists use computer models of the Earth's climate system to understand the complex factors that affect the climate. The amount of future warming that is predicted by different models varies, but it is likely to be about 2°C by 2100, depending on the success of international action on climate change. You will learn more about climate modelling, projections for climate change and international action later in this chapter.

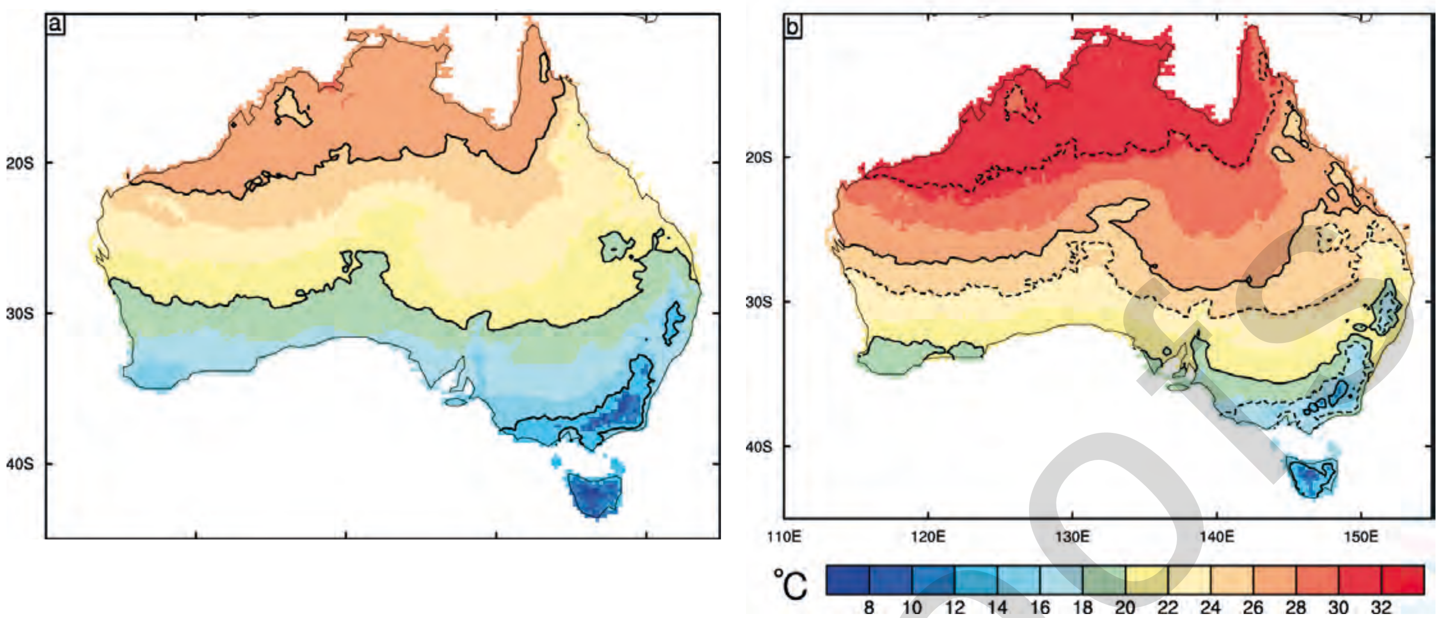


**FIGURE 3.1.5** (a) Map showing the annual mean temperatures in Australia at present. (b) The annual mean temperature for the late 21st century. On each map the contour lines for 14°C, 20°C and 26°C are shown as solid lines. In order to show the shifts in climate, the original solid lines in map (a) are shown as dotted lines in map (b).

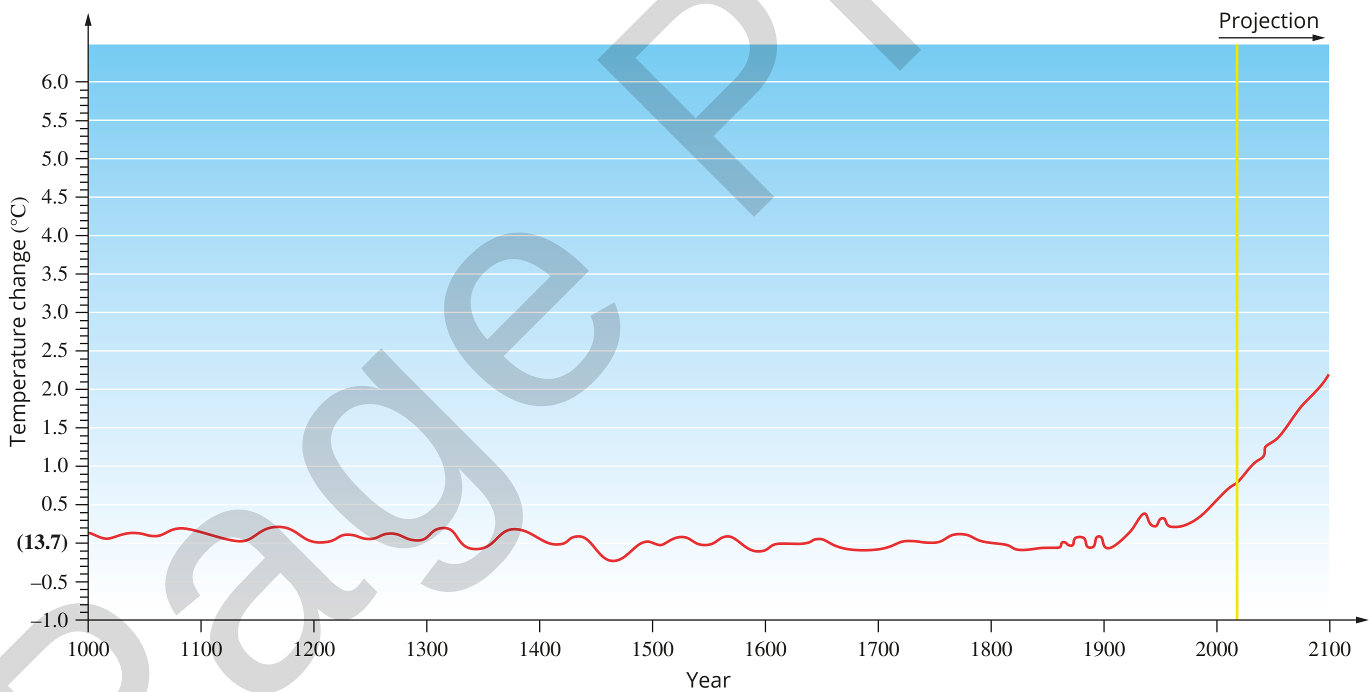


**FIGURE 3.1.6** Change in the average surface temperature of the Earth from the year 1000 projected to 2100. Estimates of future temperatures vary, depending on what assumptions are made about future energy use.

## 3.1 Review

**SUMMARY**

- Photosynthesis is an endothermic process that converts solar energy into chemical energy in glucose and oxygen molecules, in the presence of chlorophyll.
- The equation for photosynthesis is:
  $6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$
- Respiration can be described as the exothermic reverse reaction of photosynthesis.
- Greenhouse gases trap some solar energy and re-radiate some of it back towards Earth as heat.
- Carbon dioxide, methane, water vapour, nitrous oxide and ozone are greenhouses gases.
- The greenhouse effect warms the Earth's surface in a similar way to the heating of a greenhouse by the Sun.
- Higher global temperatures are predicted as a result of more greenhouses gases in the atmosphere.
- Global warming is referred to as the enhanced greenhouse effect.
- Some consequences of global warming are rising sea levels, the shifting of weather patterns and the occurrence of more extreme weather patterns.

**KEY QUESTIONS**

1 Which gas, present in small quantities in the atmosphere, is the basis of all food needed by plants and animals?

2 Write the equation for the process of photosynthesis.

3 Define a greenhouse gas and give three examples.

4 Briefly explain the term 'enhanced greenhouse effect', otherwise known as global warming.

# 3.2 Carbon dioxide in the oceans

Carbon dioxide is only slightly soluble in water. However, a series of inter related equilibria involving the small concentration of dissolved carbon dioxide in sea water controls the pH and carbonate ion ($CO_3^{2-}$) concentration of the oceans. As a consequence, these equilibria provide marine organisms with the materials needed to develop their skeletons and shells. In the parts of the oceans where life exists, calcium carbonate minerals saturate the sea water, keeping it slightly alkaline.

Changes in the concentration of carbon dioxide in the oceans will affect the acidity of the water and the concentrations of calcium and carbonate ions. In turn, this will affect coral reefs, fish stocks, algae and entire food chains upon which organisms in the oceans and coastal areas depend.

This section will examine the equilibria involving carbon dioxide in the oceans and the effects of increasing concentrations of carbon dioxide.

## EQUILIBRIA IN THE OCEAN

Carbon enters the ocean mainly by the dissolution of carbon dioxide gas. Therefore, as levels of carbon dioxide in the atmosphere increase, more carbon dioxide dissolves in the ocean. The reaction can be written as the equilibrium:

$$CO_2(g) \rightleftharpoons CO_2(aq)$$

Most of the carbon in sea water is present as $CO_2(aq)$, but some reacts further to form carbonic acid:

$$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$$

Carbonic acid is a weak **diprotic acid**, forming hydrogencarbonate ions, ($HCO_3^-$) and carbonate ions, ($CO_3^{2-}$):

$$H_2CO_3(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCO_3^-(aq)$$
$$HCO_3^-(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CO_3^{2-}(aq)$$

> There are inter related equilibria in sea water that involve carbon dioxide and the hydrogencarbonate ions ($HCO_3^-$) and carbonate ions, ($CO_3^{2-}$) ions.

These equilibria are illustrated in Figure 3.2.1.

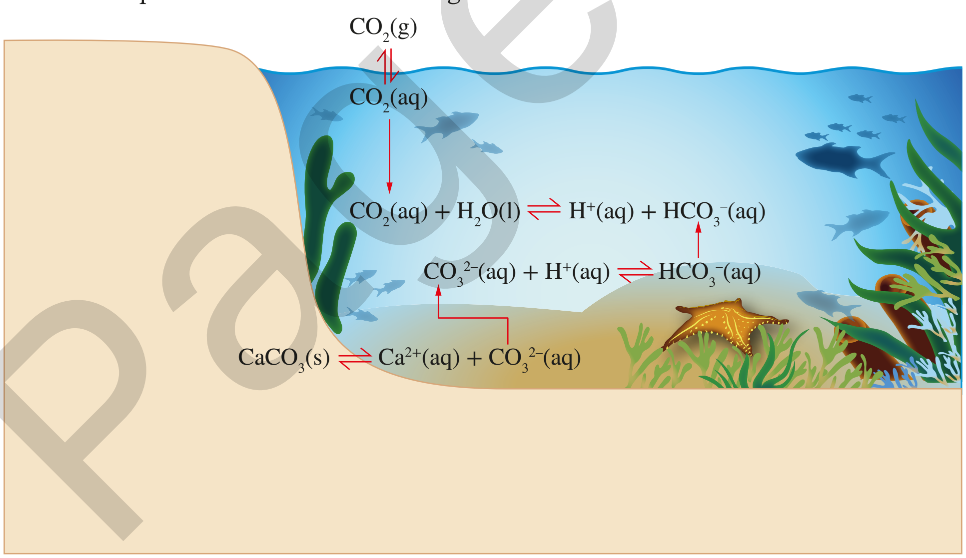


**FIGURE 3.2.1** There is an interrelated set of reactions involving carbon in the ocean.

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### 'Ocean acidity' does not mean a pH below 7

Sea water is slightly alkaline, with an average pH of 8.14. In the last 200 years, the pH of the oceans has dropped by 0.11. Because pH is a logarithmic scale (pH = $-\log[H^+]$, see Chapter 4), this is about a 30% increase in the concentration of hydrogen ions. If this trend continues, by 2100 it is estimated that this increase in concentration of $H^+$ will be 100%, resulting in a pH of about 7.85. Notice that the sea water will still be alkaline, but more acidic than it has ever been.

The alkalinity of sea water is due to the presence of limestone ($CaCO_3$) in the ocean. Solid $CaCO_3$ forms an equilibrium with $Ca^{2+}$ ions and $CO_3^{2-}$ ions. $CO_3^{2-}$ ions then react with water to form an alkaline solution:

$$CaCO_3(s) \rightleftharpoons Ca^{2+}(aq) + CO_3^{2-}(aq)$$

$$CO_3^{2-}(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + OH^-(aq)$$

When carbon dioxide dissolves in water it forms the weak acid carbonic acid. This results in a decrease in alkalinity and an increase in acidity.

## ACIDIFICATION

Applying Le Châtelier's principle to the previous equilibria, you can see that as the concentration of dissolved carbon dioxide increases, there will be an increase in the concentration of carbonic acid. This, in turn, increases the concentration of $H_3O^+(aq)$ ions, resulting in an increase in **ocean acidity**.

This process is called **acidification**. Over the past 300 years, the pH of the ocean has averaged 8.2. The pH is currently 8.14 and predicted to fall to about 7.85 by 2100. Carbon dioxide gas, as with other gases, is more soluble in cold water. As a result, ocean acidification is greater in the polar regions (Figure 3.2.2) and, in some cases, these effects have been noted since the middle of the 1990s.

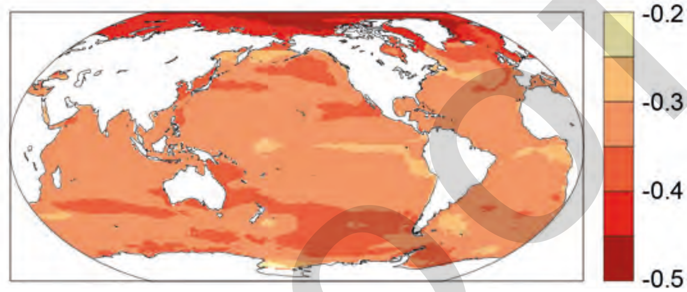


**FIGURE 3.2.2** Changes in surface pH of the oceans predicted by 2100. Note the changes are greater in polar regions.

> Ocean acidification is the decrease in pH that is occurring due to the absorption of carbon dioxide from the atmosphere.

The patterns of changes in pH and dissolved carbon dioxide predicted over time can be seen in the graph in Figure 3.2.3, which was produced by the US Institute of Climate Studies.

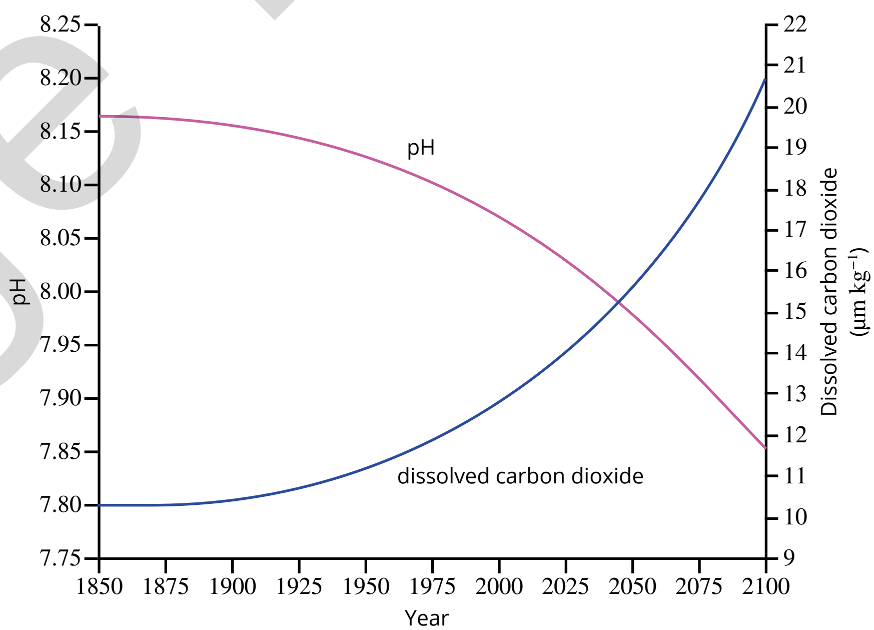


**FIGURE 3.2.3** Historical (from 1850) and projected (to 2100) pH and dissolved $CO_2$ levels in the ocean

**CHEMISTRY IN ACTION**

## Champagne sites

There are natural variations in the pH of sea water, depending on the season and region on Earth. Large amounts of carbon dioxide escape from undersea volcanoes, producing 'champagne sites' (Figure 3.2.4). By studying these regions, researchers can gain insight into the effects of future increases in levels of carbon dioxide. They are also able to see which plants and animals adapt to a lower pH and which cannot survive at all.

**FIGURE 3.2.4** An underwater volcanic vent called a white smoker. The volcano is part of the Japanese volcano chain. Mineral precipitates of calcium, barium and silicon form white columns. Because the vent is pumping out significant amounts of carbon dioxide, they are called 'champagne sites'. Due to the pressure at these depths, the carbon dioxide is in a liquid, not gaseous, state.

## CARBONATE EQUILIBRIA

Marine organisms such as corals, molluscs and crustaceans (Figure 3.2.5) use carbonate ions ($CO_3^{2-}$) to form protective coverings (exoskeletons) of calcium carbonate ($CaCO_3$), such as shells. The process is called **calcification**, and can be represented by the equation:

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3(s)$$

These organisms absorb calcium ions and carbonate ions from sea water to build and maintain the calcium carbonate structure essential for their survival.

Calcium carbonate is virtually insoluble in water and the oceans can be regarded as saturated solutions of calcium and carbonate ions. Once formed, calcium carbonate is usually quite stable. The health and growth of these marine organisms depend critically on the concentration of carbonate ions and therefore carbon dioxide in the oceans. Processes that disturb or change the $CO_2$ concentration, and therefore the concentration of $CO_3^{2-}$, will adversely affect these organisms.

Scientists have concluded that between one-third and one-half of the $CO_2$ emissions from human activity are absorbed by the oceans. Although this reduces the greenhouse effect of $CO_2$ in the atmosphere, it has decreased the pH of the oceans.

A decrease in pH (increase in $H^+$ concentration) affects the position of the following equilibrium with carbonate ions:

$$H^+(aq) + CO_3^{2-}(aq) \rightleftharpoons HCO_3^-(aq)$$

As the $H^+$ concentration increases, the equilibrium shifts to the right, consuming carbonate ions ($CO_3^{2-}$). This disturbs the following equilibrium with calcium ions, carbonate ions and solid calcium carbonate. A decrease in $CO_3^{2-}$ drives the reaction to the left, causing calcium carbonate to dissolve:

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightleftharpoons CaCO_3(s)$$

This makes it more difficult for marine organisms to produce and maintain their skeletons.

i As the level of dissolved $CO_2$ in the oceans increases, $[H^+]$ increases, pH decreases and solid $CaCO_3$ starts to dissolve.

**FIGURE 3.2.5** The Ningaloo Reef in Western Australia contains complex coral structures made from calcium carbonate. It is predicted that marine organisms such as coral will have greater difficulty producing exoskeletons as the acidity of the ocean increases.

i Calcification involves the precipitation of dissolved calcium and carbonate ions as calcium carbonate in the form of shells and corals. If the concentrations of ions in the water change due to higher acidity levels, the formation of corals and shells are reduced.

## EFFECTS OF INCREASED OCEAN ACIDITY

Scientists are concerned that increased levels of carbon dioxide will affect the equilibria that maintain the pH of the oceans and reduce the concentration of carbonate ions in the sea. This can, in turn, affect the formation of calcium carbonate needed for many marine organisms.

Globally, coral reefs and their marine ecosystems support industries such as tourism and fisheries. Millions of people depend on these industries for their livelihoods. As a consequence, an increased concentration of carbon dioxide in the atmosphere would have environmental, social and economic effects.

## Environmental impacts

### *Decalcification*

As oceans become more acidic, the additional hydrogen ions react with carbonate ions:

$$H^+(aq) + CO_3^{2-}(aq) \rightarrow HCO_3^-(aq)$$

This reaction has the effect of reducing the concentration of free $CO_3^{2-}$ ions in sea water, making the formation of calcium carbonate structures more difficult for marine creatures. This process is called **decalcification**. Because the pH of the ocean is predicted to fall in future years, the rate and amount of calcification is likely to decrease.

Figure 3.2.6 shows the effect of decalcification in sea-snails. These tiny free-swimming sea snails are an important food source for other marine animals. The snail on the left has a healthy glass-like shell with smooth edges. The shell of the snail on the right has been affected by increased ocean acidity. Weak spots in the shell have an opaque, cloudy appearance and the shell edges are more ragged.

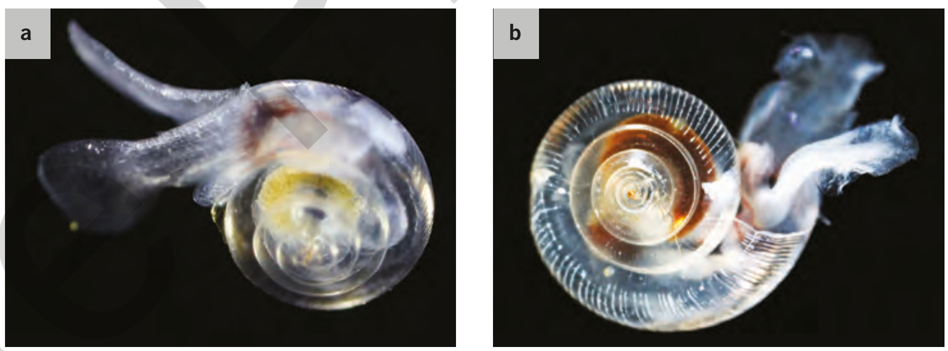


**FIGURE 3.2.6** Free-swimming sea snails are an important food source for other marine animals. The left hand specimen is healthy, while the right hand one has been affected by increased ocean acidity.

### *Food chains*

Increasing acidity has a detrimental effect on organisms, such as **plankton** and **krill** (Figure 3.2.7), that are at the bottom of the **food chain**.

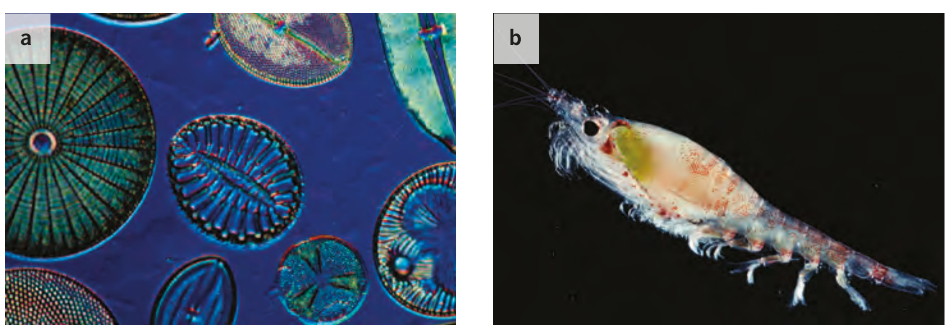


**FIGURE 3.2.7** (a) Diatoms are single-celled algae that are an important component of plankton that forms the base of marine and freshwater food chains. (b) Krill feed on plankton and can be found in swarms kilometres across. They are a major food source for many marine organisms, from small fish such as sardines to huge mammals such as whales.

Plankton, such as diatoms, are a food source for krill, which, in turn, are consumed by animals higher up in the food chain. An example of a food chain involving these organisms can be seen in Figure 3.2.8.

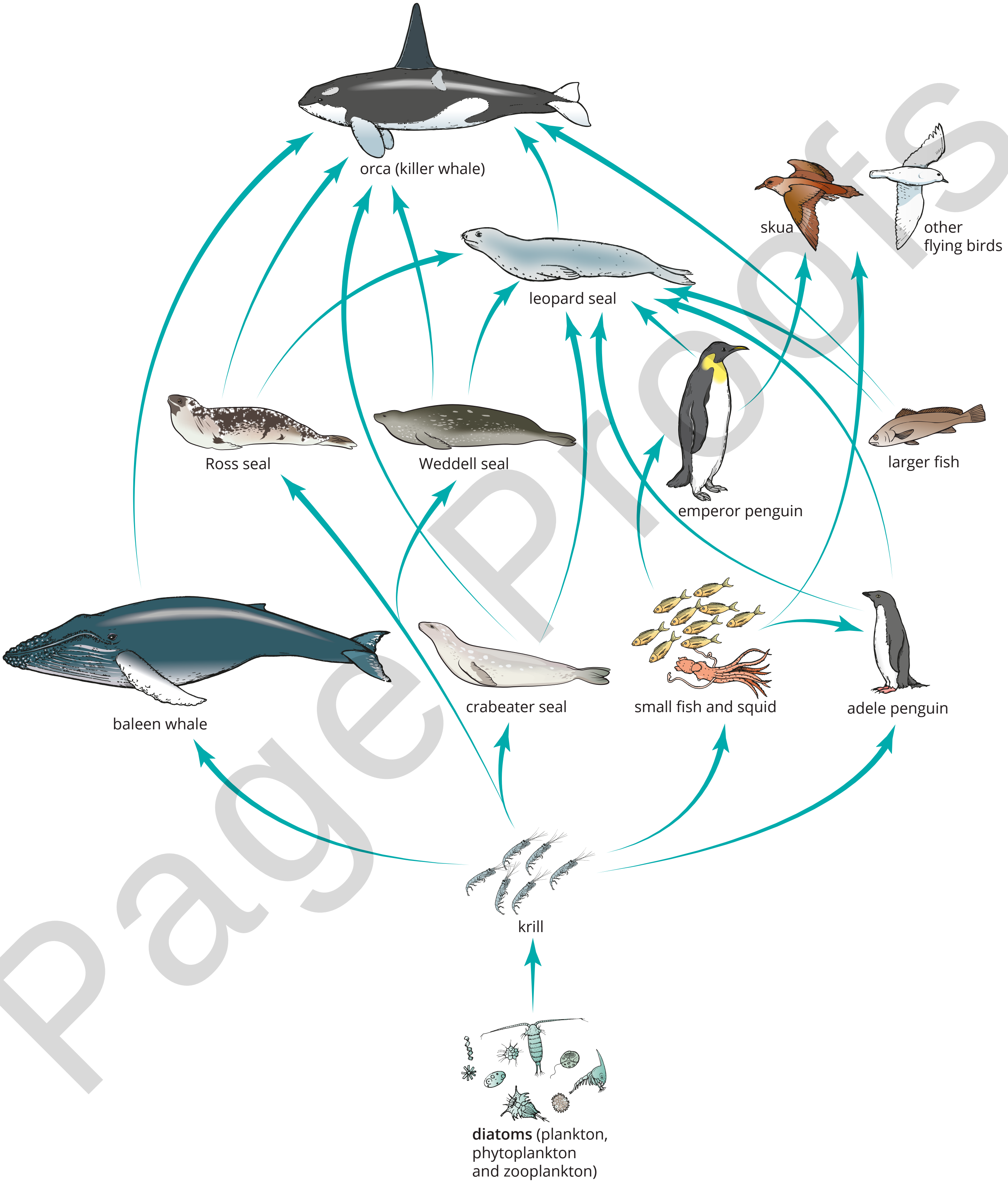


**FIGURE 3.2.8** A food web showing the relationship between animals that live in Antarctic waters

Krill eggs will not hatch successfully at a lower pH. Therefore, an increase in ocean acidity is predicted to have a harmful effect on the species of plankton and krill upon which other species depend for their survival. A collapse of the krill population coupled with ocean warming would have a disastrous effect on the **ecosystem** of the ocean.

## Social and economic impacts

The environmental impact of increased ocean acidity is predicted to have social and economic impacts as well, particularly for people in coastal communities. Increased ocean acidity will potentially effect:

- food supplies
- coastal protection
- tourism.

These social and economic effects are illustrated in Figure 3.2.9.

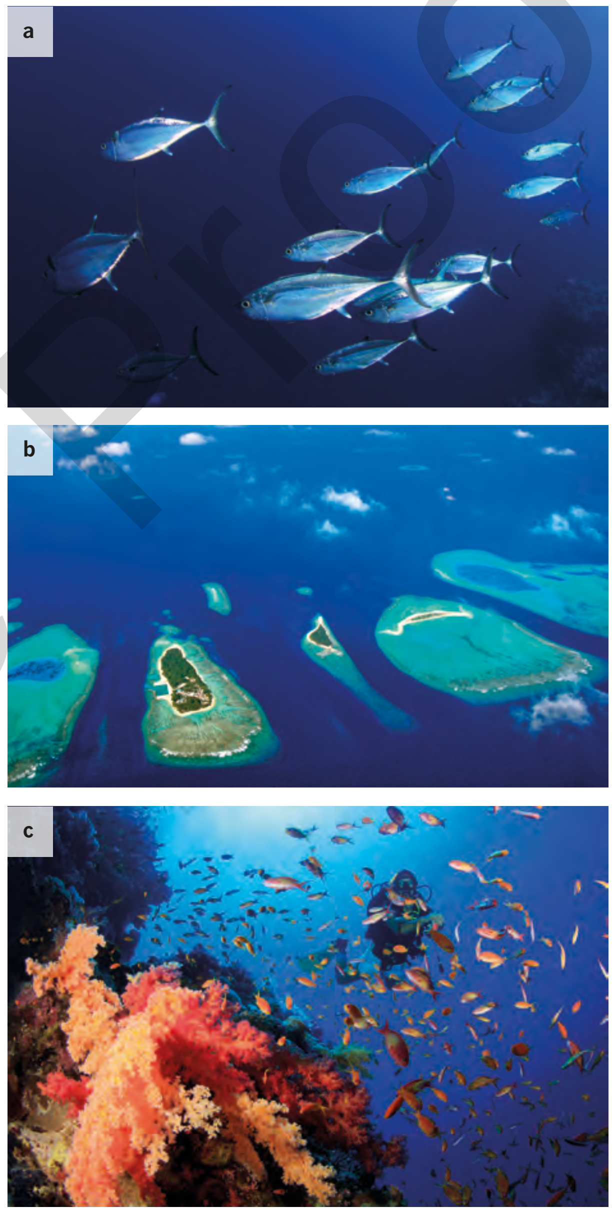


**FIGURE 3.2.9** (a) Food supplies: The oceans provide a diverse range of food sources for human consumption. Increased ocean acidity may affect stocks of fish, molluscs and crustaceans that are consumed by humans. (b) Coastal protection: Coral reefs provide protection from storm and erosion. The destruction of coral reefs could threaten coastal communities. (c) Tourism: The colour and diversity of coral reefs make them a popular tourist attraction. Their destruction will affect economies of communities reliant on tourism.

## 3.2 Review

**SUMMARY**

- Carbonic acid is a weak diprotic acid that reacts with water to produce hydronium ions, hydrogencarbonate ions and carbonate ions.
- An increased concentration of carbon dioxide in the atmosphere causes more carbon dioxide to dissolve in the oceans, producing more carbonic acid.
- Absorption of increased amounts of carbon dioxide increases the concentration of hydronium ions in sea water and lowers its pH. This process is called acidification.
- Calcification is the process that results in the formation of calcium carbonate structures such as coral reefs.
- An increase in ocean acidity causes some of the additional hydronium ions to react with carbonate ions according to the reaction: $H^+(aq) + CO_3^{2-}(aq) \rightarrow HCO_3^-(aq)$. This process is called decalcification.
- This reaction has the effect of reducing the concentration of free $CO_3^{2-}$ ions in sea water.
- Some marine organisms use calcium ions and carbonate ions to protect themselves with layers of calcium carbonate. Reduced carbonate ion concentration impairs the ability of some marine organisms to build and maintain calcium carbonate structures.

**KEY QUESTIONS**

1 Write balanced equations for the two steps in which carbonic acid ionises to form hydrogencarbonate ions and carbonate ions.

2 A solution contains the following equilibria:
$CO_2(g) \rightleftharpoons CO_2(aq)$
$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$
$H_2CO_3(aq) \rightleftharpoons HCO_3^-(aq) + H^+(aq)$
$HCO_3^-(aq) \rightleftharpoons CO_3^{2-}(aq) + H^+(aq)$
Circle the correct answers from the alternatives provided, to complete the sentences about these equilibria.
If more $CO_2$ gas were to dissolve, the concentration of $H_2CO_3$ would increase/decrease and the pH would increase/decrease. The addition of a small amount of acid would cause the concentration of $CO_3^{2-}$ ions to increase/decrease and the concentration of $CO_2(aq)$ to increase/decrease.

3 Write an equation to show how increased ocean acidity causes a decrease in the concentration of carbonate ions in sea water.

4 What is the name of the compound that forms a protective layer for many marine organisms? What is the name of the process for the formation of this layer?

5 Krill and plankton populations are expected to decrease with increasing ocean acidity.
   **a** What is the direct effect of ocean acidity on krill?
   **b** Why is the decrease of krill and plankton population numbers a concern for ecologists?

# 3.3 Modelling and responding to climate change

In this section, you will learn about some of the scientific research on **climate change** and the modelling that is being used to enhance our understanding of the effect of greenhouse gas emissions on weather patterns.

Figure 3.3.1 shows drought-affected country in Western Australia. Scientists report that extreme weather events such as droughts, storms and floods have become more widespread and have occurred more regularly over the last decade. There is considerable debate over the causes of climate change, although its existence is widely, although not universally, accepted.

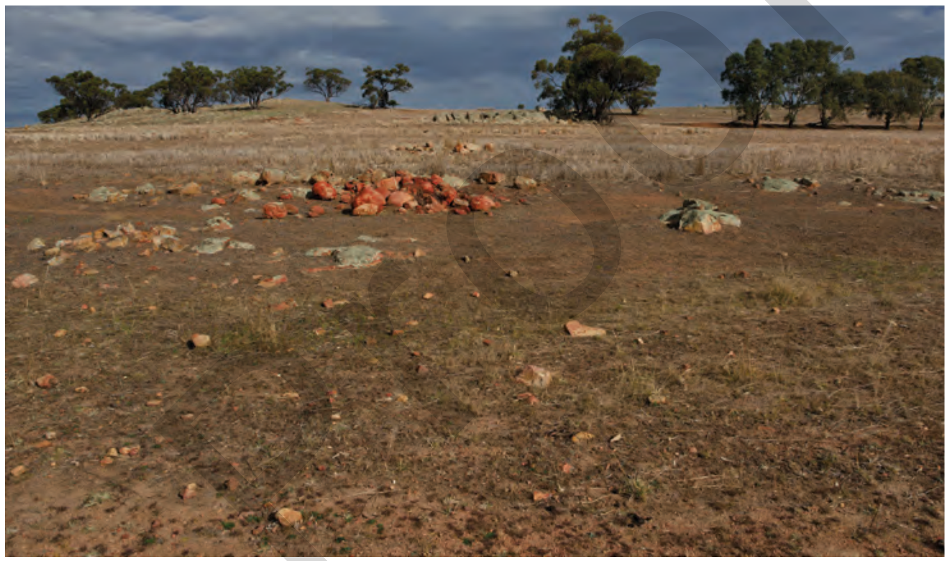

FIGURE 3.3.1 Unusable land near Mingenew in the wheat-growing region of Western Australia. The land has become salt-affected due to serious drought conditions.

The consensus among scientists is that human activity is the major influence on the warming of Earth that has been observed since the Industrial Revolution. Changes such as increasing temperatures of the atmosphere and oceans, reduction in snow and ice, rising sea levels and increasing concentrations of greenhouse gases have been observed since the mid-1800s.

An international response to these changes that involves nearly 200 countries has been negotiated to attempt to restrict temperature increases to less than 2°C above pre-industrial levels.

Most scientists agree that global warming is occurring and are near certain that human activity is the major influence.

**CHEMFILE**

### As ice melts more pollutants are released

Researchers from the National Aeronautics and Space Administration (NASA) in the United States have found that as the sea ice in the Arctic Ocean melts (Figure 3.3.2), deposits of mercury and bromine have been released. When there is a mix of salty ice, very low temperatures and sunlight, bromine is released into the air and this produces a complex series of chemical reactions. The reactions produce molecules of bromine monoxide (BrO), which then reacts with gaseous elemental mercury, producing mercury-containing pollutants that fall onto the Earth's surface.

FIGURE 3.3.2 The amount of sea ice has substantially reduced in the Arctic over the past decade. Conversely, the Antarctic sea ice has increased in area and thickness in recent years. Natural variations and wind changes are suggested as possible explanations.

## MODELLING CLIMATE CHANGE

Climate models are mathematical models based on the laws of physics. The models are run on supercomputers. These mathematical representations simulate the way that the atmosphere, oceans, land surface and ice interact and affect the Earth's climate system.

The models consider the incoming energy from the Sun and the radiation of outgoing energy into space. The equilibrium that exists between the incoming and outgoing energy can be disturbed and any imbalance results in a temperature change. Models can vary from extremely complex mathematical equations that use tens of thousands of items of data, including measurements from satellites, to simple heat transfer models.

More than 40 climate models have been developed by various scientific organisations around the world. The models vary in their ability to make successful predictions and are tested using simulations based on the recorded measurements of the climate in past decades, which develops confidence in the models and validates them.

Figure 3.3.3 show the interaction of the factors in a model called a coupled climate change model. Coupled climate models link the exchange of energy and moisture to vegetation, soil, ice and the atmosphere.

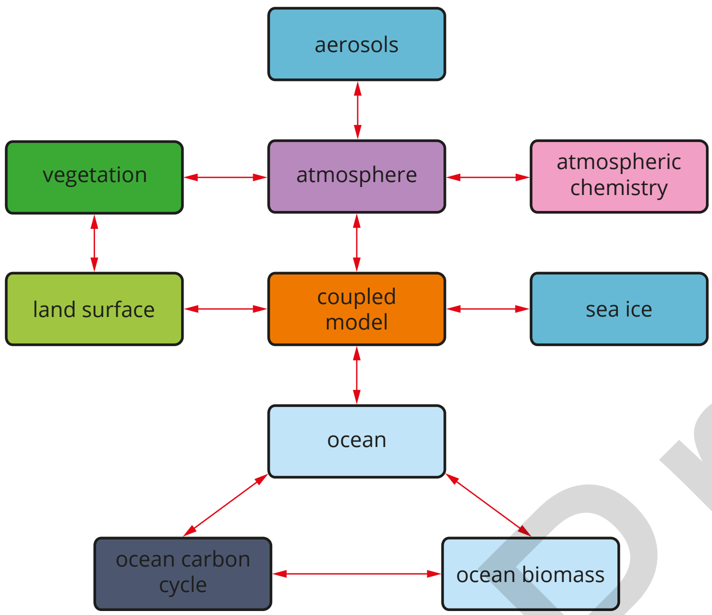


**FIGURE 3.3.3** Components of one global climate model. Modern climate models incorporate interactions between vegetation, soil, ice and land surface with the atmosphere.

These models allow scientists to predict the increase in temperature of both sea and land and future changes in ocean acidity. They also enable scientists to investigate the effects of the use of alternative fuels (such as biofuels) and other energy sources on the production of carbon dioxide. The research demonstrates that controlling the way these factors affect the equilibria in the carbon cycle, and particularly the cycling of carbon in the sea, will assist in slowing the effects of climate change and global warming.

Some of the main predictions of climate models are as follows.

- The average global temperature is expected to rise by 0.3–4.8°C over the next century.
- The amount of rainfall everywhere, particularly in tropical and high-altitude regions, is expected to increase.
- Tropical storms are likely to increase in wind strength and amount of rainfall.
- The sea level is expected to rise by 0.3–1.2 metres in the next century.
- Amounts of sea ice and snow are expected to decrease.

Climate models predict increased global temperatures, increased rainfall, increased wind strength of tropical storms and rising sea levels.

## CSIRO climate model

CSIRO climate scientists have developed a model called ACCESS (Australian Community Climate and Earth Simulator). You can see results from this model every time you look at the Bureau of Meteorology's Australian weather forecasts.

The model is used to make climate predictions for the coming century within Australia. More than 20 years of research and knowledge have been used to make these projections. ACCESS links models of the oceans, atmosphere, aerosols, chemistry, sea-ice, land surface and the global carbon cycle to simulate changes in the climate.

ACCESS involves researchers in CSIRO and Australian universities and employs some of the most powerful supercomputers, enabling scientists to contribute to major international climate modelling and predictions. The results so far include:

- accurate forecast of major weather events up to 3 days in advance, which allows greater certainty in planning
- tracking of tropical cyclones
- accurate forecast of the weather conditions that produce extreme bush fire and flood conditions
- projections of the future greenhouse gas emissions for the 21st century.

## POTENTIAL FUTURES

Figure 3.3.4 shows world energy production from different sources over time. There has been a marked increase in energy consumption since the 1800s.

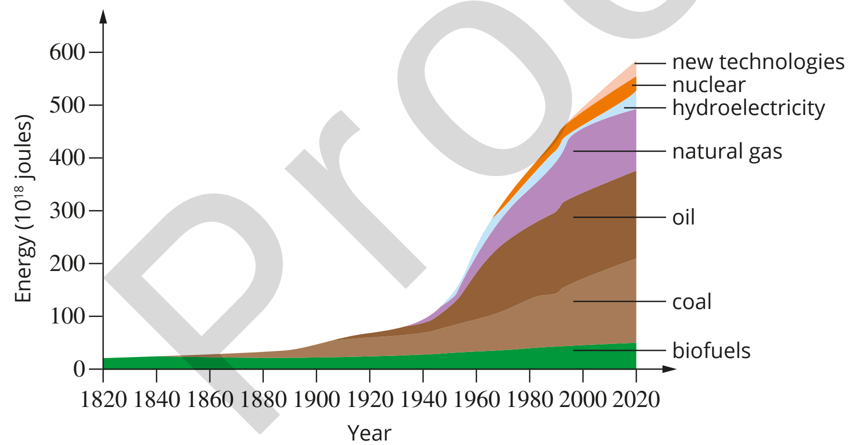


**FIGURE 3.3.4** The graph shows the increase in world energy production from different sources. Many countries, including Australia, are increasing their use of renewable energy in preference to fossil fuels.

Given the limited reserves of fossil fuels and evidence that the use of these fuels is linked to climate change, there is considerable interest in identifying and developing new energy sources with less environmental impact. The development of alternative sources for large-scale energy production is not a simple task, as replacement energy sources need to meet a range of requirements, such as being reliable, sustainable and cost-effective. To be **sustainable**, an energy source must be able to meet increasing human needs, without compromising future demands.

Governments and industry are exploring alternatives to fossil fuels to ensure that future energy needs can be met and to limit the impact of these fuels on the environment. Ideally, new sources of energy will be both sustainable and renewable. A **renewable** energy source needs to be widely available, naturally replaced and have a small environmental impact.

**Biofuels** are examples of renewable sources of energy. Biofuels are fuels derived from plant materials such as grains (maize, wheat, barley or sorghum), sugar cane or vegetable waste, and vegetable oils. The three main biofuels are **biogas**, **bioethanol** and **biodiesel**. Bioethanol and biodiesel can be used alone or blended with fossil fuels such as petrol and diesel and used as transport fuels. Biogas can be used for small-scale electricity generation.

As well as their advantage of being renewable, there is potential for biofuels to have less impact on the environment than fossil fuels. The plant materials used in the generation of biofuels are produced by photosynthesis, which removes carbon dioxide from the atmosphere and produces glucose ($C_6H_{12}O_6$) in the following reaction:

$$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$$

Plants convert the glucose into cellulose and starch. Carbon dioxide is released back into the atmosphere when the biofuel is burnt. The carbon dioxide can then be used to make more plant material, which in turn can be used as fuel, and so the cycle continues.

A fuel is described as **carbon neutral** if its use results in no overall release of carbon into the atmosphere. In practice, biofuels are not strictly carbon neutral. For example, bioethanol is not carbon neutral because energy is required, and emissions produced, in growing crops, transport and refining of the fuel. However, it is argued that the use of biofuels has the potential to produce less carbon dioxide than fossil fuels, depending on how they are produced.

Future changes in the use of renewable energy sources rather than fossil fuels is one factor that scientists try to take into account with projections from climate modelling. In Australia, the CSIRO predicts that alternative fuels will comprise 35% of the fuels used for transport by 2030.

**EXTENSION**

## Food versus fuel

The growing of crops for the production of biofuels, such as bioethanol (Figure 3.3.5), involves energy expenditure and the use of resources, such as water and fertiliser. Intensive farming can also lead to erosion and pollution. These issues are more significant if crops are grown solely to produce ethanol, but of less concern if waste from food crops is used as a raw material.

**FIGURE 3.3.5** Harvesting sugar cane in Queensland. Sugar cane can be used as a source of the raw materials for the production of bioethanol.

Biofuels are a renewable source of energy and current production levels are sustainable. However, biofuels produce only a small percentage of Australia's fuel needs. If biofuel production is to increase significantly, crops would need to be grown specifically for this purpose.

The use of land to grow crops for fuel production presents a number of issues, including land degradation and the widespread destruction of forests and bushland, which convert carbon dioxide into plant material more effectively than crops such as sugar cane.

Perhaps the most significant issue that arises is the use of agricultural land to grow fuel crops rather than food crops. If the use of biofuels increases, ensuring low-cost food supplies are maintained while meeting the demand for fuel will be a challenge.

**CHEMFILE**

### More $CO_2$—more photosynthesis

For marine plants which do not have shells, such as phytoplankton, seagrasses and kelp (Figure 3.3.6), an increase in the concentration of carbon dioxide in sea water due to climate change does not have an immediate negative consequence. Higher carbon dioxide levels increase the plants' ability to photosynthesise. This can lead to increased growth and also increase the food (glucose and therefore starch and cellulose) and oxygen in the surrounding waters, to the benefit of other nearby marine organisms.

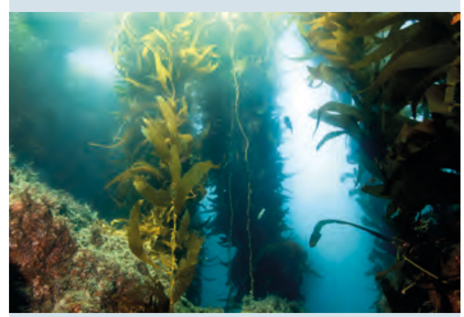

**FIGURE 3.3.6** Kelp forests underwater. With increased $CO_2$ concentrations, kelp and similar marine plants undergo more photosynthesis.

## INTERNATIONAL RESPONSE

In 1988, member nations of the United Nations requested the establishment of a scientific body called the Intergovernmental Panel on Climate Change (IPCC). The IPCC supports the main international treaty on climate change, known as the United Nations Framework Convention on Climate Change (UNFCCC), which was negotiated in 1992.

The main objective of the IPCC is to 'stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous human-induced interference with the climate system'. The IPCC is the authority on climate change and produces reports (Figure 3.3.7) that are accepted by leading climate scientists and participating governments. Different models, shown in Figure 3.3.7, and labeled A1F1, B2, etc, give different estimates of the expected temperature changes. The models predict an increase in temperature of between 2 and 4°C by 2100.

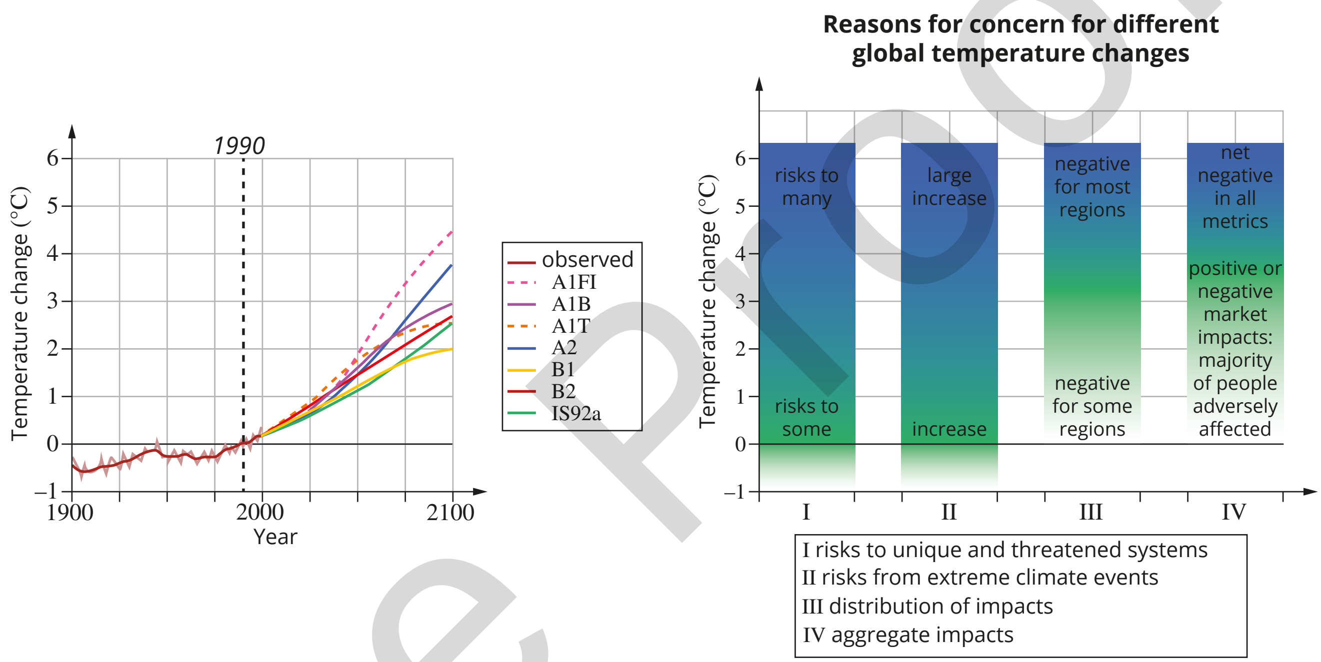


**FIGURE 3.3.7** Risks and impacts of climate change. This assessment of global warming based on different models and the associated risks was initially published in 2001 by the IPCC and has been subsequently updated.

## United Nations Kyoto Protocol

The Kyoto Protocol is an international agreement negotiated in 1997 that extended the United Nations Framework Convention on Climate Change. It established a commitment by 192 countries, including Australia, to binding reductions in greenhouse gas emissions to specified levels during the commitment period 2008–2012. The overriding aim of the protocol was to reduce the collective emissions of the countries by at least 5% from 1990 levels.

The achievements of the Kyoto Protocol were the:

- stimulation of many national policies
- creation of an international market for carbon
- development of emissions trading schemes.

Many countries developed their own methods to attempt to comply with the Kyoto Protocol and to address this environmental issue. The aim was to secure global commitment. This was difficult because the protocol is restricted by the:

- modest emission reduction limits
- lack of measures to achieve greater reductions
- absence of penalties for countries not achieving targets.

## Paris Agreement

In 2015, the Kyoto Protocol was further strengthened when 72 countries including the world's two largest greenhouse gas emitters, China and the United States, ratified an agreement for action on climate change called the Paris Agreement. The agreement requires countries to submit increasingly stringent pledges every 5 years. Unlike the Kyoto Protocol, which set commitment targets that have legal force, the Paris Agreement allows each country to determine their national targets. Nearly 200 countries, including Australia, have signed the treaty. However, in June 2017, President Donald Trump withdrew the United States from the Agreement, potentially weakening its power to ensure long-term reductions in greenhouse gas emissions across the globe.

Under the Paris Agreement, there is a goal to keep the increase in the global average temperature to below 2°C above pre-industrial levels and pursue efforts to keep warming below 1.5°C above pre-industrial levels.

## AUSTRALIAN RESPONSE

Scientists predict that changes in Australia's climate will have significant economic, social and environmental impacts on the nation.

The Australian Climate Change Science Program (ACCSP) is the basis for the Australian Government's response to climate change. It is a partnership between CSIRO, the Department of the Environment, the Bureau of Meteorology and other agencies.

The specific areas of research for ACCSP include:

- understanding the influence of the Southern Ocean on global climate (Figure 3.3.8)
- increasing our understanding of atmospheric processes such as aerosol behaviour and cloud properties
- developing a greater knowledge of Australia's unique biosphere
- assessing the climate variability in the Australian region
- improving projections through more sophisticated climate models
- improving communication of regional projections of future climate change.

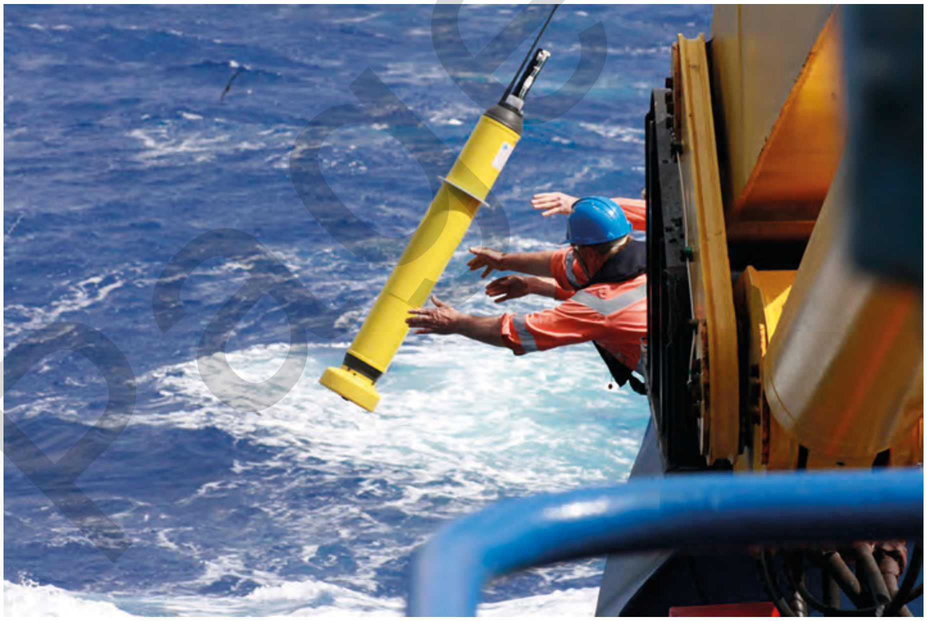

**FIGURE 3.3.8** Researchers launch an Argo robotic float from *Southern Surveyor*. Argo is a collection of 3800 freely drifting floats that measure the temperature, salinity and speed of the ocean. CSIRO and other organisations use data from these floats for climate modelling.

## Australian climate change targets

Australia is responsible for 1.3% of total global carbon emissions. While Australia is meeting its current climate change targets and supporting international agreements, there is considerable public and political debate over the most appropriate policies for reducing emissions and slowing global warming.

The Australian government has announced a target to reduce emissions by 26–28% by 2030 on the 2005 levels. This represents a 50–52% reduction in emissions per person between 2005 and 2030. The target being aimed for is similar to targets agreed to by countries such as United States, the European Union, Canada, New Zealand and Japan (Figure 3.3.9).

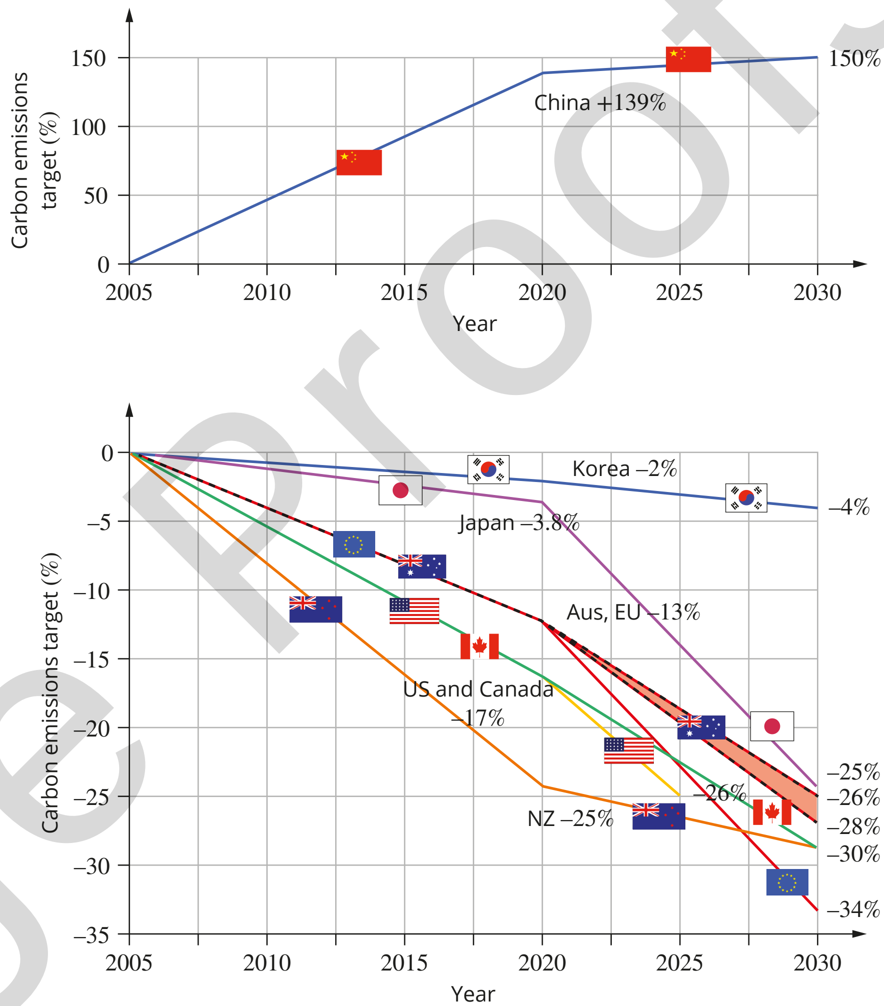


**FIGURE 3.3.9** A comparison of Australia's carbon emissions target with other countries, against a common base year (2005).

The Government aims to reduce carbon dioxide emissions by:

- using energy-efficient technologies such as innovative building design, LED lighting and electric cars
- phasing out inefficient energy producers producing greenhouse gases, such as coal-fired power stations
- investing in low-emissions technologies and practices, such as the use of solar energy.

## 3.3 Review

### SUMMARY

- Climate models are mathematical models based on the laws of physics and run on supercomputers. Scientists use these models to simulate the way that the atmosphere, oceans, land surface and ice interact and affect the Earth's climate system.
- Member nations of the United Nations have established a scientific body called the Intergovernmental Panel on Climate Change (IPCC) to secure a global commitment to reducing greenhouse gas emissions over the next few decades.
- The Kyoto Protocol is an international agreement that established a commitment by 192 countries, including Australia, to reduce greenhouse gas emissions to 5% from 1990 levels during the period 2008–2012.
- The Kyoto Protocol has stimulated national emissions policies, created an international market for carbon and developed emissions trading schemes.
- In 2015, the Paris Agreement required participating countries to submit increasingly stringent pledges every 5 years. The main goal of the Paris Agreement is to hold the increase in the global average temperature to below 2°C above pre-industrial levels.

### KEY QUESTIONS

**1** List three predictions of climate models.

**2** Many countries have agreed to reduce greenhouse gas emissions in order to slow global warming. What is the target for the maximum temperature rise?

**A** 1°C
**B** 2°C
**C** 5°C
**D** 10°C

**3** The Kyoto Protocol is an international agreement negotiated in 1997. State two achievements of the Kyoto Protocol.

**4** **a** What is the full name of the United Nations organisation known as the IPCC?
**b** What are the main goals of the IPCC?

**5** Complete the following paragraph about Australia's climate change goals and targets using terms from the list. Terms are used only once although some may not be used at all: natural gas, greenhouse gas, reduce, increase, London Declaration, Kyoto Protocol, greenhouse emissions, 26–28%, 50–52%, 2030, 2040, stabilised, solar energy.

Australia has signed the ________ ___________ and the Paris Agreement. The country has pledged to ___________ emissions so that the ____________ ________ concentrations in the atmosphere can be _________. The aim is to reduce _____________ ______________to __________% below the 2005 levels by the year ________. The Australian government intends to achieve its target by using energy efficient technologies, phasing out inefficient energy producers and investing in low emission technologies such as ______________ ________________.

**6** The 2015 Paris agreement was an international response to global warming in which all nations were asked to commit to keeping the global average temperature rise to below 2°C, through reductions in greenhouse gas emissions.
**a** What impact would adoption of the Paris Agreement have on Australia?
**b** Discuss the role that biofuels could play in helping Australia meet its targets for reducing greenhouse gas emissions.

# Chapter review

03

**KEY TERMS**

acidification
biodiesel
bioethanol
biofuel
biogas
calcification
carbon cycle
carbon neutral
chlorophyll
climate change
decalcification
diprotic acid
ecosystem
endothermic
enhanced greenhouse effect
exothermic
food chain
fossil fuel
global warming
greenhouse effect
greenhouse gas
krill
non-renewable
ocean acidity
photosynthesis
plankton
renewable
respiration
sustainable

## Carbon dioxide in the atmosphere

1 List two ways carbon dioxide is returned to the atmosphere in the carbon cycle.

2 **a** What is the 'greenhouse effect'? Why has it been important in the evolution of life on Earth?

**b** What are the main greenhouse gases?

3 The combustion of fossil fuels adds carbon dioxide to the atmosphere. Write an equation for the combustion of octane ($C_8H_{18}$) in excess oxygen.

4 Briefly explain the concept of the enhanced greenhouse effect and its effect on climate.

## Carbon dioxide in the oceans

5 Carbon dioxide levels are increasing in the atmosphere. Which one of the following statements about the impact on oceans is correct?

**A** As $[CO_2]$ increases, the oceans become more acidic and marine animals have less difficulty producing shells.

**B** As $[CO_2]$ increases, the oceans become less acidic and coral reefs are at risk.

**C** As $[CO_2]$ increases, the oceans become less acidic and coral reefs will spread more rapidly.

**D** As $[CO_2]$ increases, the oceans become more acidic and there is a reduction in $[CO_3^{2-}]$.

6 Which one of the following species is present in highest concentration in sea water?

**A** $CO_3^{2-}(aq)$

**B** $HCO_3^-(aq)$

**C** $H_2CO_3(aq)$

**D** $CO_2(aq)$

7 When excess amounts of $CO_2$ gas dissolve in the oceans, causing corals to dissolve, which one of the following equilibria is not disturbed?

**A** $CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$

**B** $H_2CO_3(aq) \rightleftharpoons H^+(aq) + HCO_3^-(aq)$

**C** $HCO_3^-(aq) \rightleftharpoons H^+(aq) + CO_3^{2-}(aq)$

**D** $CaO(s) + CO_2(g) \rightleftharpoons CaCO_3(s)$

8 The following four equibrium systems occur in the ocean:

**1** $CO_2(g) \rightleftharpoons CO_2(aq)$

**2** $CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$

**3** $H_2CO_3(aq) \rightleftharpoons HCO_3^-(aq) + H^+(aq)$

**4** $HCO_3^-(aq) \rightleftharpoons CO_3^{2-}(aq) + H^+(aq)$

Using the equations above, explain how increased carbon dioxide levels in the atmosphere reduces the pH of the oceans.

9 Classify the following statements as describing aspects of acidification or calcification.

**a** Results in the destruction of coral reefs

**b** Results in calcium carbonate structures such as coral reefs

**c** Is decreased by increased ocean acidity

**d** Is caused by a decrease in pH

**e** Results in more calcium carbonate dissolving

10 Which one of the following is not associated with the problem that ocean acidification is predicted to cause for marine organisms?

**A** Calcium carbonate will tend to dissolve.

**B** The ocean pH will decrease.

**C** The concentration of hydrogencarbonate ions will decrease.

**D** More carbon dioxide gas will dissolve in the ocean.

**11** Choose the correct alternatives from the pairs of terms listed to complete the sentences about carbon dioxide emissions.

A significant proportion of the carbon dioxide emissions from human activity is released/absorbed by the oceans. This reduces/increases the greenhouse effect in the atmosphere. The increased acidity of the oceans changes the position of the carbonate equilibrium:

$$H^+(aq) + CO_3^{2-}(aq) \rightleftharpoons HCO_3^-(aq)$$

As the $H^+$ concentration increases, the pH increases/decreases and the equilibrium shifts to the left/right, consuming carbonate ions. As a consequence, the equilibrium:

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightleftharpoons CaCO_3(s)$$

is disturbed.

The higher/lower concentration of $CO_3^{2-}$ ions causes solid $CaCO_3$ to precipitate/dissolve and the reaction shifts to the left/right, increasing/decreasing the rate of calcification and making it more difficult for marine creatures to produce shells and coral.

**12** As ocean acidity increases, corals become more at risk.

**a** What is this process called?

**b** Explain this process using appropriate equations.

## Modelling and responding to climate change

**13** Which one of the following statements about the Intergovernmental Panel on Climate Change (IPCC) is false?

**A** The IPCC aims to stabilise greenhouse gas concentrations in the atmosphere.

**B** The IPCC produces reports for climate scientists and governments.

**C** The IPCC aims to reduce the levels of atmospheric carbon dioxide.

**D** The IPCC was established by the United Nations.

**14** Which one of the following statements regarding the Kyoto Protocol and associated agreements is true?

**A** Successful emission targets have been achieved.

**B** Penalties are in place for countries that do not comply.

**C** Some countries have agreed to cut emissions by 5% below 1990 levels.

**D** Global commitment by all nations has been achieved.

**15** Complete the following sentences by choosing words from the list: stabilise, climate, atmosphere, human-induced, concentrations.

The United Nations Framework Convention on Climate Change is supported by reports from the IPCC (Intergovernmental Panel on Climate Change). The ultimate objective is 'to __________ greenhouse gas ____________ in the __________ at a level which prevents _____________ interference with the__________'.

## Connecting the main ideas

**16** **a** List three possible global consequences of the increasing levels of carbon dioxide in the atmosphere.

**b** Describe two strategies for reducing the levels of greenhouse gases in the atmosphere.

**17** A calcium carbonate/carbon dioxide equilibrium exists in the oceans and between the carbon dioxide in the atmosphere. Write the following equations in the correct order to show the sequence of reactions involved in the formation of calcium carbonate from carbon dioxide.

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightleftharpoons CaCO_3(s)$$

$$HCO_3^-(aq) \rightleftharpoons H^+(aq) + CO_3^{2-}(aq)$$

$$H_2CO_3(aq) \rightleftharpoons H^+(aq) + HCO_3^-(aq)$$

$$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$$

$$CO_2(g) \rightleftharpoons CO_2(aq)$$