Changing climate and rising seas:

Understanding the science

November 2014

Parliamentary Commissioner for the Environment
Te Kaitiaki Taiao a Te Whare Pāremata

Acknowledgements

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Photography

Cover: Northern Motorway flooded by storm surge in January 2011.
Photo from Gareth Robins

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Overview

I first heard about climate change in 1979 sitting in a lecture theatre at the University of California, Berkeley. In the same year, the Shah of Iran fled his country, exports of oil from the Middle East fell, and the second oil crisis began. In a world focused on securing supplies of oil, few were aware that the First World Climate Conference had been held in February that year. I clearly recall the professor delivering the lecture saying it was possible that our biggest problem in the future would not be energy security, but rather the carbon dioxide emitted from burning oil and other fossil fuels.

That possibility has become reality. The warming of the planet following from rising concentrations of heat-trapping carbon dioxide and other greenhouse gases in the atmosphere has indeed become the big problem.

During my seven years as Commissioner, I have consistently said that climate change is the biggest environmental issue we face. This investigation has provided an opportunity to develop a deeper understanding of what is causing climate change and one of its major and most certain impacts – the rising level of the sea. The aim of this report is to share that understanding with others to provide a basis for public engagement and policy development.

As my own understanding of the science has evolved through this investigation, my concern has grown. I had hoped to find greater reason for optimism, but unfortunately the opposite has occurred.

I had not, for instance, appreciated the strength of the positive feedbacks that are amplifying the warming. I had long known about the feedback from the loss of sea ice floating in the Arctic Ocean – when white reflective ice melts it becomes dark green seawater, absorbing much more of the Sun's heat. But I had not understood the far more powerful impact of increasing water vapour – as the atmosphere warms, more and more water evaporates and traps more and more heat.

The climate change that is underway will have many impacts. One of these – rising sea level – is already evident and is the focus of this report.

The sea has risen and fallen many times in the past as the Earth has moved in and out of ice ages. Whenever the Earth warmed, as it is doing now, seawater expanded, ice melted, and coastlines moved inland.

Over the last century, the average sea level around the world has risen by about 20 centimetres. The Intergovernmental Panel on Climate Change (IPCC) expects it to rise about another 30 centimetres or so by the middle of the century and up to a metre by the end of the century.

There are three processes driving this rise – expanding seawater, retreating glaciers, and shrinking ice sheets. Thus far, the last – shrinking ice sheets – has contributed relatively little to sea level rise, but its potential is enormous.

Ice sheets are huge blankets of ice covering land sitting astride the polar continents. There are three – one covering Greenland, one covering West Antarctica, and the largest covering East Antarctica. The amount of ice in these ice sheets is so vast that were it all to melt, the sea would rise about 64 metres. That is not going to happen any time soon. But it does mean that the stability of these ice sheets is of critical importance. The Greenland and West Antarctic ice sheets are now losing ice.

Around much of Antarctica, floating platforms of ice known as 'ice shelves' act as retaining walls holding the ice sheets on the land. The collapse of some of the ice shelves along the Antarctic Peninsula is a warning sign. The Larsen B ice shelf, which was the size of Stewart Island, broke up in five dramatic weeks in 2002.

New Zealand has long had strong connections with Antarctica. Robert Falcon Scott sailed from Lyttelton on his ill-fated attempt to be the first to reach the South Pole, and many artefacts from that famous expedition are held in the Canterbury Museum. As a child growing up in Christchurch, I did not find the remains of Scott's beaten-up tractor very enthralling; now as an adult I am amazed by the risks they took in such a harsh environment.[1]

In contrast with other polar explorers, Scott saw the main purpose of his expedition as scientific. One of his team commented *"We were out for everything we could add to the world's store of knowledge about the Antarctic"*.[2] Today, New Zealand scientists at Scott Base are playing a critically important role contributing to that knowledge. For instance, analysis of a recently drilled 750 metre deep ice core will help determine how sensitive the Ross Ice Shelf is to a warming climate.

The IPCC is inherently cautious since it relies on hundreds of scientists from many countries reaching consensus. The IPCC's prediction of about a 30 centimetre rise in average sea level by the middle of the century is 'locked in' – it is expected to occur regardless of action taken to reduce greenhouse gas emissions. It is not until the second half of the century that the effect of any such action will be seen.

A 30 centimetre rise may not sound like much, but it will be disastrous for the millions of people in Bangladesh and other countries who live in low-lying river deltas. The continued existence of Pacific island nations such as Tuvalu and Kiribati is questionable. In New Zealand, the impact will be significant at a national level and potentially devastating for some land owners.

In some parts of the country, damaging coastal floods will become increasingly frequent. Many Aucklanders will remember the flooding of the Northwestern Motorway and some of the eastern suburbs three years ago when a storm surge coincided with a king tide. In April this year, another storm brought the sea into properties along Tamaki Drive.

Some areas of Christchurch have experienced an effective sea level rise of half a metre or more due to land dropping after the Canterbury earthquakes. Flood insurance has become harder to get and more expensive for some homeowners in the city. On the day I am writing this, the Insurance Council of New Zealand has released a 15-point plan on dealing with natural hazards, with the chief executive making special mention of sea level rise.[3]

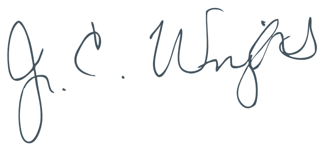
Councils are obliged under law to plan and prepare for the impacts of a rising sea. But it is far from easy to introduce changes that may lower the value of people's homes or restrict development along sought-after coastal areas. In August 2012, the Kapiti District Council put coastal erosion risk on the Land Information Memorandum (LIM) reports of 1,800 houses, which was challenged by those who were affected. Such conflicts are understandable and inevitable.

The President of Local Government New Zealand, Lawrence Yule, has called for greater direction from central government. *"Without any central government directive it is quite difficult for councils to do what effectively might be the right thing for the future, but is seen as being too aggressive for the people of the present"*.[4]

It is not just private property that will be affected. Councils and central government will need to prepare for increased costs because some public infrastructure such as roads, waste water systems, and buildings will be affected by rising seas.

The impacts of sea level rise will vary from place to place. In 2015, I expect to release a second report on this topic. This will show in some detail which areas of the coastline around the country are most vulnerable to sea level rise and assess the risk to the infrastructure in those areas.

A rising sea will be with us for a long time to come – one way or another we will have to adapt. But how high and how fast the water rises will be influenced by the speed at which the world – including New Zealand – reduces greenhouse gas emissions over the coming decades.



Dr Jan Wright

Parliamentary Commissioner for the Environment

1 Introduction

The level of the sea is constantly changing everywhere on Earth as tides rise and fall in predictable patterns. Both the timing and height of high tides are forecast accurately because they depend on the relative positions of the Earth, the Moon, and the Sun. However, tides are just *variations* on average water levels – they are not *changes* in average water levels.

Less widely understood is that sea levels have changed much more dramatically in the past as the Earth has moved in and out of ice ages. In cold periods the sea has been low and in warm periods the sea has been high. Thus the sea has risen and fallen by over a hundred metres many times in the history of the Earth. But over the last few thousand years the climate has been relatively stable and the sea level has varied only a little.

However, since about 1900, sea levels have risen by about 20 centimetres. There is a strong consensus among scientists that rising sea levels are largely a consequence of increasing concentrations of carbon dioxide and other greenhouse gases in the atmosphere raising global temperatures.

The Intergovernmental Panel on Climate Change (IPCC) currently expects sea level to rise a further 30 to 100 centimetres by 2100, and to continue rising for several centuries.[5] How much the sea actually rises by 2100 and beyond will depend on what action is taken to reduce greenhouse gas emissions in the coming decades.

Three processes drive this rise in sea level – seawater expands as it warms, glaciers melt and retreat, and ice sheets shrink. Although expanding seawater and melting glaciers can be modelled with high confidence, there are still big questions around how the massive ice sheets that cover Antarctica and Greenland will react.

Sea level rise is not the only consequence of a warming world, but it is a particularly sobering one since many millions live just above the high tide mark.[6] New Zealanders are not as vulnerable as those who live on low-lying islands and in river deltas, but as a coastal nation the impact on our beaches, buildings, roads and other infrastructure, and on our communities will be considerable.

1.1 Purpose of the report

The Parliamentary Commissioner for the Environment is an independent Officer of Parliament, with functions and powers granted by the Environment Act 1986. She provides Members of Parliament with independent advice in their consideration of matters that may have impacts on the quality of the environment.

Sea level rise is a subject of concern for many, and will become increasingly so for those who live on low-lying land near the coast.

Councils have a legal obligation under the Resource Management Act 1991 to deal with the effects of climate change: *"In achieving the purpose of this Act, all persons exercising functions and powers under it, in relation to managing the use, development, and protection of natural and physical resources, shall have particular regard to: … the effects of climate change"*.[7]

The Ministry for the Environment has issued guidance to councils on how to prepare for sea level rise. Planning for the impacts of this rise is currently devolved to regional and district councils. In the Ministry's view, councils "*Local councils ... are best placed to know what is appropriate for their region*".[8] The Ministry for the Environment is currently reviewing its 2008 guidance.

Some councils have begun such planning, focussing on coastal flooding, impacts on groundwater, and erosion. However, the implications make conflict inevitable. When the Kapiti District Council put coastal erosion risk on Land Information Memorandum (LIM) reports, local property owners challenged the Council in the High Court.[9]

Meanwhile, Local Government New Zealand and the Insurance Council have called for greater central government direction. Earlier this month, the Chief Executive of the Insurance Council, said: *"At the moment we put a huge price on living as close as possible to the sea. Well we know in 50 years' time that will be a very costly price and who is going to be picking up that price? That's either got to be picked up by central or local government and at that time we will wonder why did we ever make these decisions".*[11]

The science of the IPCC reports draws on a range of academic disciplines and has been intensely scrutinised. Much is highly technical and not accessible to a general audience. This report has been written with the intent of making the science of climate change, and sea level rise in particular, both accessible and relevant for New Zealanders. Certainly the impacts of sea level rise will vary from place to place. But an understanding and acceptance of the basic science provides a basis for the debate on what action must be taken.

1.2 What this report does not cover

This report does not include any detailed discussion or analysis of the following:

- Climate change mitigation
- Climate change adaptation
- Economic analysis of infrastructure at risk
- Other effects of climate change such as acidification of the oceans and increases in the frequency of extreme weather events such as droughts.

Source: Jessica Desmond.

Figure 1.1 Tamaki Drive in Auckland was flooded in April 2014 when a powerful storm surge generated by ex-tropical cyclone Ita coincided with a high tide.

1.3 What comes next

The remainder of this report is structured as follows:

Chapter 2 tells the story of how scientists uncovered the history of the Earth's climate. It also serves as an introduction to some key aspects of climate science such as the insulating properties of greenhouse gases in the atmosphere and feedback loops.

Chapter 3 describes how the climate change now underway is different from what has occurred in the past. It also shows how carbon dioxide in the atmosphere, mean global temperatures, and sea level have all risen over the last century or so.

Chapter 4 describes the three processes that are driving rising sea levels – expanding water in the oceans, retreating glaciers, and shrinking ice sheets. It also contains projections of future sea level rises.

Chapter 5 is a summary of the report.

Looking back at the Earth's climate

"… a place does not always remain land or sea throughout all time, but where there was dry land there comes to be sea …"[12]

—Aristotle (384–322 BC)

Scientists now have a clear picture of how the Earth's sea level and climate have changed over millions of years. Shorelines were low when the climate was cold. When the climate warmed, ice melted and seawater expanded, so shorelines rose.

This chapter tells the story of how scientists uncovered the climatic history of the Earth. It contains three sections.

The first section is the story of how scientists began to catch glimpses of the Earth's ancient past. It begins with nineteenth century 'natural philosophers' puzzling over geological anomalies.

The second section describes how the new science of paleoclimatology came into its own in the twentieth century. The layers in deep sea sediment cores and ice cores are like the pages in a book that contain the history of the Earth's climate. Now satellites record huge amounts of data on the atmosphere, oceans, and ice across the globe.

The last section shows how greatly the Earth's climate has varied over geological time. The last seven thousand years has been a time of relative climatic stability, but this is now changing.

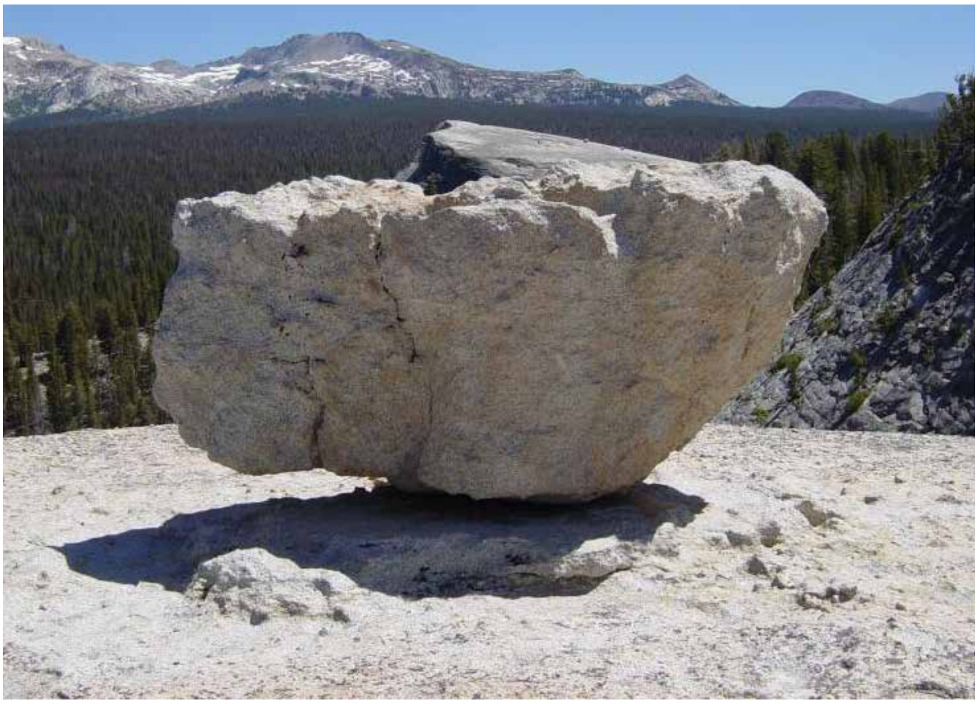
2.1 Glimpses of the Earth's past

Discovering ice ages

For a long time it was thought that the Earth was only thousands of years old, and that strange rock layers such as those containing fossil sea shells high in the mountains could be explained by the Biblical flood. However, towards the end of the eighteenth century, James Hutton, the 'Father of Modern Geology', studied erosion and sedimentation, and realised that the Earth must be much older.[13]

In the Swiss Alps, early gentlemen scientists ('natural philosophers') were puzzled by the presence of rocks that bore no relation to rocks nearby but were the same as rocks hundreds of kilometres away. Such 'erratics', as they were dubbed, included granite boulders sitting high on limestone slopes, which clearly could not have been carried there by water. The explanation for erratics and other geological phenomena, such as scratches on rock faces and U-shaped valleys, turned out to be the advance and retreat of glaciers. Erratics had been carried by the advancing ice; when the ice melted, the boulders were set down far from their origin.

As the same phenomena were observed across Europe, it became clear that at some time in the past, the continent must have been covered in ice. In 1837, the German botanist Karl Schimper coined the term '*eiszeit*', that is to say, 'ice age'. Over the next century scientists speculated about the number and causes of ice ages.



Source: Daniel Mayer, Wikimedia Commons, CC BY-SA 3.0.

Figure 2.1 A glacial erratic on Lambert Dome, Yosemite National Park, California. Glaciers carried large boulders far from their source, providing clues to past ice ages.

In 1842, the French mathematician Joseph Adhémar suggested that variations in the orbit of the Earth around the Sun might trigger ice ages. In 1864, self-taught scientist James Croll made the first calculations of the orbital variations. His work was repeated with greater precision by Serbian geophysicist Milutin Milankovitch in the 1920s. However, the work of Croll and Milankovitch was largely ignored for many decades.[14]

Deducing that the sea level must change

Humans have been measuring the level of the tides for hundreds of years for maritime trade and fishing. Understanding fluctuations in high and low tides was critical to ensure that ships did not run aground.

In the eighteenth century, systematic recording of tide levels began at some ports in Europe.[15] Two centuries later, these records of tide levels were to prove useful in measuring sea levels.

In 1842, Charles MacLaren, a Scottish journalist and geologist, made the connection between glaciers and sea level. He deduced that when the Earth cooled into an ice age, water would freeze, glaciers would advance and the level of the sea would fall. Conversely, when the Earth warmed, ice would melt, glaciers would retreat and the level of the sea would rise. Like the work of Milankovitch and Croll, it would take many years before the importance of this connection was realised.

Discovering the greenhouse effect

By the early nineteenth century, physicists had realised that the Earth's atmosphere was acting as an insulator. A pivotal experiment had earlier shown how layers of glass trapped heat – the origin of the term 'greenhouse effect'.[16]

In 1859, Irish physicist John Tyndall discovered that water vapour was largely responsible for the insulating effect of the atmosphere.[17] He also found that carbon dioxide and methane were strong absorbers of infrared radiation.[18] Carbon dioxide, methane, and other heat-absorbing gases in the atmosphere are now called greenhouse gases. Without such heat-trapping gases, Tyndall wrote: "*The warmth of our fields and gardens would pour itself unrequited into space, and the Sun would rise upon an island held fast in the iron grip of frost*".[19]

In 1895, Swedish chemist Svante Arrhenius linked Tyndall's greenhouse effect to the idea of human-induced climate change. Arrhenius surmised that the carbon dioxide being added from burning coal would heat the Earth, but thought that this would take thousands of years. Doubtless influenced by the Swedish weather, he also saw a rise in temperature as beneficial.

Arrhenius understood the critical importance of feedback loops. For instance, he recognised that while an increase in carbon dioxide might only increase the global temperature a little, it would lead to more water evaporating into the atmosphere and temperature would rise further.

However, Arrhenius' theory did not gain traction in the scientific world until 1938, when Guy Callendar, an English steam engineer, attributed a warming trend to increasing carbon dioxide in the atmosphere. At the time Callendar's analysis did not stand up to scrutiny by other scientists, but his contribution was pivotal and has gone largely unrecognised.[20]

Source: Wikimedia Commons: Luis Alberto 9919/CC-BY-3.0 (A), unknown author (B), New York Public Library Archives/CC-BY-SA 3.0 (C), unknown author (D), University of East Anglia Archives (E).

Figure 2.2 Some of the scientists who made key discoveries in climate history.

A. Scottish scientist James Croll was the first to calculate how variations in the Earth's orbit had triggered ice ages. Croll worked as a janitor at a university in Glasgow, but spent much of his time in the library teaching himself science.

B. Serbian geophysicist Milutin Milankovitch calculated the link between variations in the Earth's orbit and ice ages when he was under house arrest as a prisoner of war during World War I.

C. Irish physicist John Tyndall helped discover the greenhouse effect after experimenting on the capacity of certain gases to absorb heat.

D. Swedish chemist Svante Arrhenius drew the link between the greenhouse effect and the burning of fossil fuels.

E. British steam engineer Guy Callendar attributed a warming trend to the increased carbon dioxide in the atmosphere.

2.2 The new science of paleoclimatology flourishes

The Greek word *palaeo* means older or ancient and is used as a prefix to denote geological past. Thus 'paleoclimatology' is the study of changes in the Earth's climate over the whole history of the Earth. Although the term was coined in the 1920s, it was not until the middle of the twentieth century that the new science came into its own.

Measuring changes in the level of the sea

In the 1930s, glaciologists observed that glaciers were melting and deduced that the volume of water in the sea must be increasing. By 1940, the Icelandic geologist Sigurdur Thorarinsson concluded that *"the majority of the glaciers in practically every glacier district of the world are now receding"*. He estimated that the melting of the glaciers was causing a rise in the world's oceans equivalent to about 0.5 millimetres a year.[21]

Thorarinsson did not mean that the level of the sea was rising at this rate everywhere around the world. Rather he was referring to what is known as 'eustatic' sea level change – the change to the average global sea level caused by a change in the volume of water in the oceans. Changes to sea levels at particular localities are influenced by many other factors such as movements in the Earth's crust, gravitational changes, ocean currents, and different rates of ocean warming (Figure 2.3).

In 1941 the seismologist Beno Gutenberg analysed historic records from 69 tide gauge stations from around the world and found that since around 1900, the sea had been rising at a rate of about 1.1 millimetres a year – more than Thorarinsson's estimate.[22] Over the 1950s and 1960s, the efforts of other researchers led to similar estimates.[23, 24]

Source: Seppo Lammi.

Figure 2.3 One major complexity in measuring changes in sea level rise is land rising or subsiding. The photographs show land rising and new islands emerging in the Kvarken area of Sweden and Finland (white lines indicate where the shoreline was in 1978). In this area the Earth's crust was pushed down hundreds of metres by the weight of the Scandinavian Ice Sheet. The post-glacial rebound, as it is known, is more rapid than the rise in sea level.

Deep sea sediment cores – measuring temperature and sea level

Understanding how the climate has changed over millions of years took a great leap forward in the 1940s and 1950s with the collection and analysis of deep sea sediment cores. The layers of sediment that build up on the floor of the ocean hold an enormous amount of information about Earth's climatic history.

In 1947 the American geophysicist Maurice Ewing took his first deep sea sediment cores from a ship off the coast of Bermuda. Over the following three decades Ewing and his team collected and preserved thousands of deep sea cores.[25] At that time there was no reliable method for dating the ages of different layers in the cores.

In 1971, the CLIMAP (Climate Mapping) project was launched, and scientists began analysing the cores, focusing on the fossilised shells of tiny marine creatures called foraminifera. With radiocarbon dating now available, the scientists were able to estimate the ages of different foraminifera fossils and thus the ages of the sediment layers in which they were found.[26] Other techniques were developed that revealed features of the climate over time – ocean surface temperature, salinity, ice cover, and so on.[27]

At the end of 1976, the CLIMAP team published a landmark paper in the journal *Science* titled *'Variations in Earth's Orbit: Pacemaker of the Ice Ages'* showing conclusively that changes in the Earth's orbit had triggered the Earth's past ice ages.[28] The orbital variations are now known as Milankovitch cycles in honour of the pioneering work of Milankovitch and Croll many decades earlier.

Ice cores – measuring temperature, sea level, and carbon dioxide

"Snowflakes fall to earth and leave a message …"[29]

—Glaciologist Henri Bader

In the same way as layers of sediment build up on the ocean floor, layers of ice build-up in ice sheets in the polar regions and leave a record of past climates. The snow that falls each year is eventually compacted into a layer of ice.

In 1954, the Danish paleoclimatologist Willi Dansgaard proposed that these layers of ice could provide a history of the climate.[30] He foresaw that analysis of the tiny bubbles of air trapped in the ice would reveal much about the past. By 1966, Dansgaard was finally able to obtain ice samples from a core drilled in Greenland by the United States army. This core had been drilled down nearly 1,400 metres to the bedrock and turned out to contain nearly a hundred thousand years of climate history.[31] A core recently drilled in Antarctica dates back nearly a million years.[32]

A greater range of climate information can be obtained from ice cores than from sediment cores.[33] Importantly, analysis of the air bubbles provides a record of past temperatures and concentrations of carbon dioxide and other greenhouse gases in the atmosphere – it showed that the concentration of carbon dioxide had been low in cold periods and high in warm periods.[34]

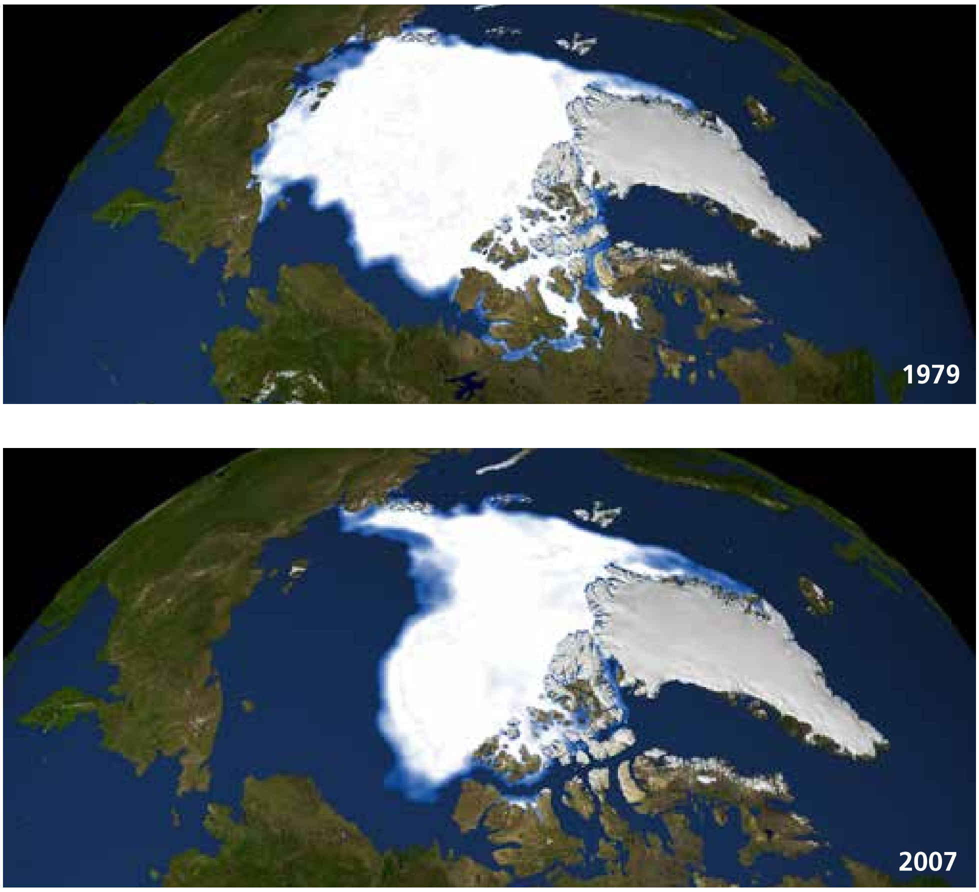
While sediment cores showed the outline of the peaks and troughs of glacial cycles, records from the ice cores filled in the detail of what happened within these cycles. Ice cores showed that temperature, carbon dioxide, and sea level were very closely linked.

One important discovery was that the Earth had experienced very rapid temperature increases at times in the past. Cores drilled in Greenland in the 1980s showed a number of rapid warming events, followed by gradual cooling, known as Dansgaard-Oeschger cycles.[35] The fastest was a warming of more than 10 degrees in 40 years around 40,000 years ago.[36]

Satellites – measuring across the entire globe

A new era for understanding the climate began with the deployment of increasingly sophisticated satellites in the 1990s. With satellites scientists were no longer restricted to collecting information at locations they could access – now they could gather information about the atmosphere, oceans, and ice anywhere around the world.

This has led to a vastly improved understanding of weather patterns, such as the El Niño Southern Oscillation that influences New Zealand's climate every few years. Importantly, satellites have revolutionised scientific understanding of the Earth's climate. Many different satellites now provide data on the mass of ice sheets in polar regions, flow rates of glaciers, seasonal sea ice cover, ocean depths, ocean temperatures, air temperatures, and concentrations of carbon dioxide and other gases in the atmosphere.



Source: NASA.

Figure 2.4 These satellite images show the sea ice extent in summer in 1979 and 2007. Since the 1970s there has been a dramatic decrease in both the extent and thickness of sea ice in the Arctic. Sea ice in the Arctic has continued to decline since 2007 and the Arctic is expected to be nearly ice free in summer by the middle of the century.

2.3 A climate that is far from stable

Two centuries of research have revealed how greatly the Earth's climate has varied in the past.

At times it has been much hotter than it is now. Early in the Eocene epoch around 50 million years ago, the polar regions were virtually ice free. The world was a completely different place – the sea was about 70 metres higher than it is now, and atmospheric carbon dioxide levels were very high.[37,38] On the other hand, it has been so cold at times in the deep past, that the Earth was mostly covered in ice; the term 'Snowball Earth' is used to refer to such periods.[39]

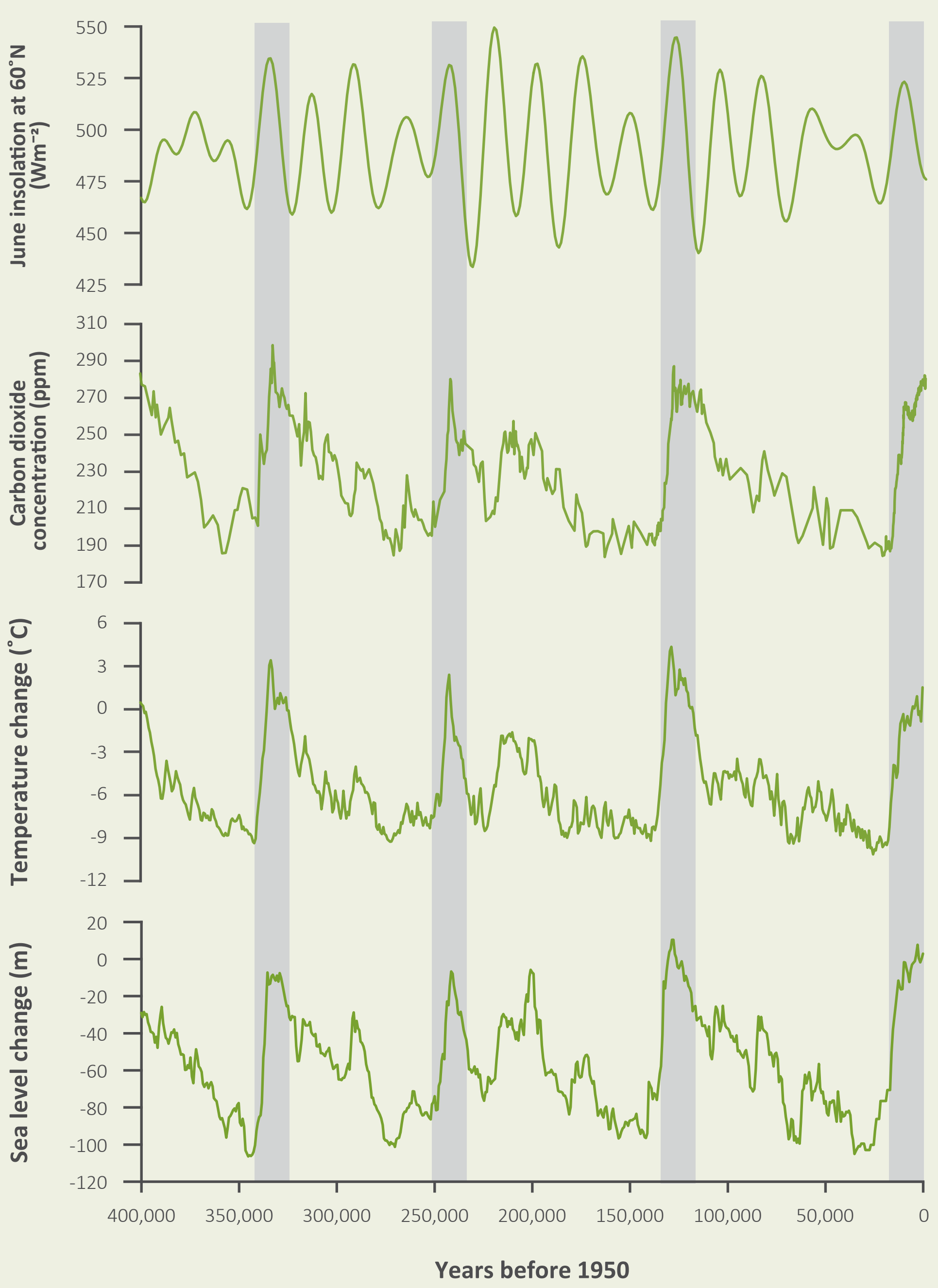
Over the last million years the climate has repeated the same cycle roughly every 100,000 years – slowly cooling into an ice age, and then rapidly warming into an interglacial period.

Figure 2.5 shows how carbon dioxide, temperature, and sea level have all varied together over the last half million years. Variations in the Earth's orbit (Milankovitch cycles) change the amount of solar energy reaching the Earth. Changes in temperature are followed by changes in atmospheric carbon dioxide and sea level. Over this time, carbon dioxide levels varied within a range of 190 to 290 parts per million (ppm).

The last warm period was at its maximum about 120,000 years ago. The elevations of some sand dunes along the Kaipara Harbour and Awhitu Peninsula coastlines indicate that the sea in the Auckland region may have been four to five metres higher than it is now.[40]

The Earth then cooled into its most recent ice age. At its peak, 25,000 years ago, Central Otago lay under a kilometre of ice, and the sea was so low that the North and South Islands were joined by a land bridge.[41]

The Swedish chemist Arrhenius – who first theorised that burning fossil fuels would warm the world – did not live to see how significant his hypothesis would become. Increasing concentrations of carbon dioxide and other greenhouse gases are now driving climate change. In the next chapter, this new phenomenon is explained further.



Data: Berger, 1992; Lüthi et al., 2008; Jouzel et al., 2007; Rohling et al., 2009.

Figure 2.5 For the last 400,000 years the amount of the Sun's energy reaching the Earth (June insolation) – driven by Milankovitch cycles – has caused the Earth to go in and out of ice ages. Temperature, carbon dioxide, and sea level have risen and fallen together.

3

The end of the Holocene?

Over many millennia, the Earth has moved in and out of ice ages with warmer periods in between known as 'interglacials'. The current geological epoch is an interglacial called the Holocene.

The term Holocene is derived from two Greek words – *holos* meaning 'entire' and *kainos* meaning 'recent'. The Holocene began after the last ice age about 12,000 years ago – to geologists, the last 12,000 years is 'entirely recent'. Over the last 7,000 years the climate has been relatively warm and stable.

As described in Chapter 2, the periods of cooling and warming in the past have been triggered by small variations in the Earth's orbit – Milankovitch cycles. These orbital variations lead to changes in the intensity of solar energy on different parts of the Earth's surface. But now we are seeing a warming of the climate that has not been triggered in this way, but rather by deforestation and the burning of fossil fuels over the last 150 years. The first section in this chapter describes this change.

The following three sections describe the changes underway that are relevant to this report:

- The first is the rising concentration of carbon dioxide in the atmosphere
- The second is the rising average temperature at the surface of the Earth
- The third is one of the consequences, and is the focus of this report – the rising mean global sea level.

The impact of human activity on the climate has now become so significant that it has been suggested that the Holocene epoch has come to an end, and the Earth is now entering a new epoch dubbed the Anthropocene. This is briefly described in the final section.

3.1 A new reason for a warming climate

In the distant past when a warming climate was triggered by variations in the Earth's orbit, rising temperatures led to rising concentrations of carbon dioxide.[42]

As temperatures began to rise, more carbon dioxide was released from the ocean into the atmosphere. Because more carbon dioxide in the atmosphere strengthens the greenhouse effect, more heat is then trapped in the atmosphere.[43] This positive feedback speeds up the warming. Other feedbacks come into play, and two are particularly strong – water vapour and ice cover.

Water vapour is the main component of the Earth's greenhouse blanket. The amount of water vapour in the atmosphere depends on its temperature. As temperatures increase, more water evaporates and rises into the atmosphere, causing more warming.

Ice cover shrinks in response to rising temperatures. Ice is very reflective – in scientific language, it has a high 'albedo'. As temperatures rise and ice melts, the area of the Earth covered in ice decreases, and less of the Sun's energy is reflected back into space, causing yet more warming.

Although it is the Milankovitch variations in the Earth's orbit that triggered both warming and cooling cycles in the past, once climate changes have begun, they are rapidly dominated by feedbacks. Positive feedbacks like those described above exacerbate the change; negative feedbacks, such as absorption of carbon dioxide by the ocean, partly offset it.[44]

The warming of the climate that is now underway has not been triggered by a Milankovitch variation. Instead, the combustion of ever-increasing quantities of fossil fuels – coal, oil, and gas – over the last two centuries has raised the concentration of carbon dioxide in the atmosphere.[45, 46] Now, in contrast with the way in which past warming periods began, carbon dioxide is *leading*, rather than *following*, the increase in temperature.

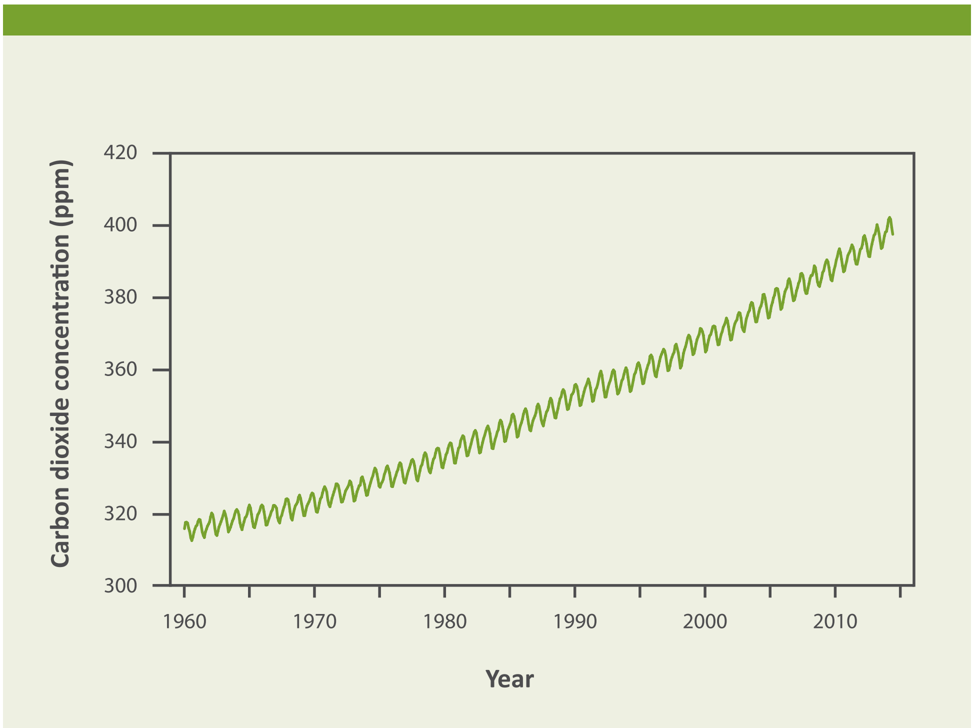
3.2 Rising carbon dioxide

In the 1950s, American scientist Charles Keeling developed an accurate system for measuring the concentration of carbon dioxide in the atmosphere.

In 1958 Keeling set up a measuring station at the Mauna Loa Observatory near the top of one of the volcanoes on the Big Island of Hawaii.[47] Several years later, he produced the first version of the now-famous Keeling Curve, showing year-on-year increases in the concentration of carbon dioxide in the atmosphere (Figure 3.1).

The sawtooth pattern of carbon dioxide levels in the Keeling Curve has been described as the Earth 'breathing'. In the spring and summer, levels fall as trees absorb carbon dioxide when they grow fastest. In the autumn and winter, levels rise as growth slows, and leaves fall and decay, releasing carbon dioxide.

There are now many measuring stations scattered across many countries, including one in New Zealand. All show the same rising trend in carbon dioxide concentrations.[48]



Data: Scripps Institution of Oceanography.

Figure 3.1 The Keeling Curve shows year-on-year increases in the concentration of carbon dioxide in the atmosphere.

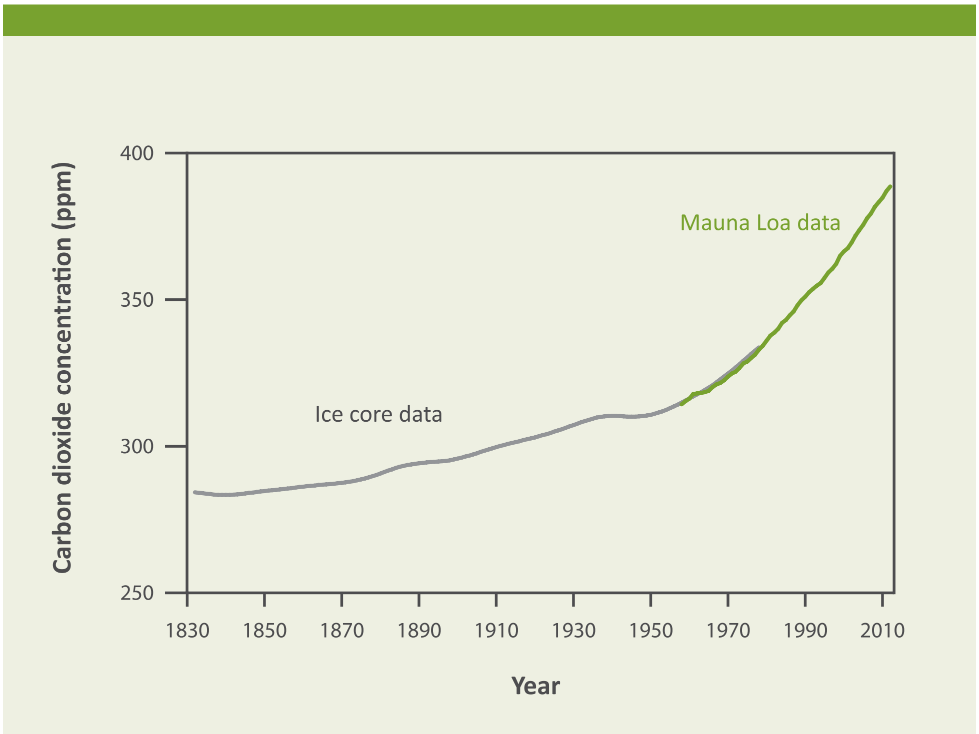
Source: David Lowe.

Figure 3.2 In 1970 New Zealand scientist David Lowe was asked by Keeling to set up a measuring station in the South Pacific. *"Lowe found the windiest, most barren headland he could – Baring Head near the entrance to Wellington Harbour … He had to make sure there was nothing to change the air between him and Antarctica – no plants, no cars, no fires. During a southerly at Baring Head, the Antarctic winds come straight over the ocean"*.[49] This photo shows David Lowe taking an air sample using a 'Keeling flask' at Baring Head in New Zealand in the early 1970s.

It is well-established that most of the additional carbon dioxide in the atmosphere has come from burning fossil fuels and from burning and clearing forests. Particularly strong evidence comes from measuring how the ratio of different carbon isotopes in atmospheric carbon dioxide has changed over time.[50]

As described in Chapter 2, analysis of the bubbles of air trapped in ice cores has made it possible to determine the composition of the atmosphere in the past. This has provided a continuous record of carbon dioxide levels in the atmosphere going back hundreds of thousands of years.

Figure 3.3 shows how atmospheric carbon dioxide began to rise during the Industrial Revolution as the burning of coal on a large scale began.[51]



Data: Scripps Institution of Oceanography and Etheridge et al., 1998.

Figure 3.3 Carbon dioxide concentrations from the early 1800s. Concentrations from 1958 onwards were measured at Mauna Loa Observatory in Hawaii. Concentrations prior to that were analysed from bubbles in ice cores.

3.3 Rising temperatures

Surface air and ocean temperatures have risen over the last century.

Temperature trends based on short records cannot be used to deduce long term changes in global temperatures. This is because of the natural variability in the climate.[52] One example of this variability familiar to New Zealanders is El Niño.

Figure 3.4 shows the trend in global mean surface temperature relative to the average in the 30-year period between 1961 and 1990.[53]

The cooling period from around 1940 to 1970 has been attributed to a number of factors including sulphate aerosols emitted from the increased industrial activity following the Second World War.[54] The plateau in surface temperature over the last few years is a result of natural variability.[55]

In its latest report, the Intergovernmental Panel on Climate Change (IPCC) summarises this trend:

"It is certain that the Global Mean Surface Temperature has increased since the late 19th century. Each of the past three decades has been successively warmer at the Earth's surface than all the previous decades in the instrumental record, and the first decade of the 21st century has been the warmest".[56]

In some areas of the world, temperatures have risen much more than in others. Warming in recent decades has been greatest in the Arctic. This is known as 'polar amplification' and is due to powerful positive feedbacks such as sea ice melting.[57]

Over the last century New Zealand has warmed at a similar rate to the global average.[58]

Data: Morice et al., 2012.

Figure 3.4 Global mean surface temperatures relative to the 1961-1990 average. Surface air and ocean temperatures have risen over the last century.

3.4 Rising sea level

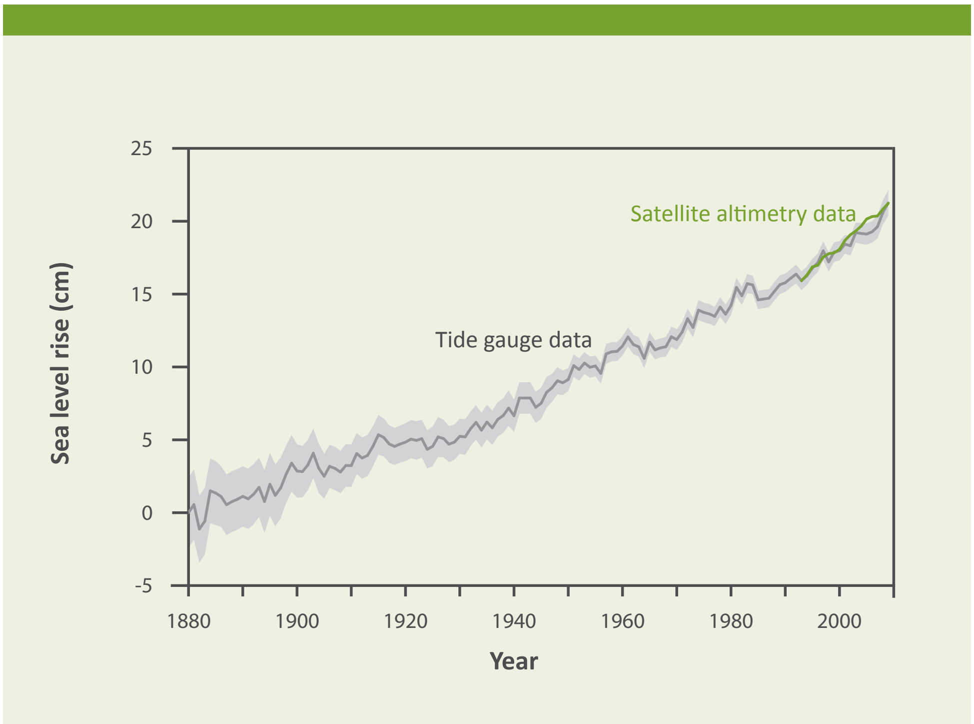
One of the consequences of climate change that is already evident is a rise in the average sea level around the world.

Data from tide gauges around the world have been collated and show that average sea level has been rising since the beginning of the twentieth century. Figure 3.5 shows that global average sea level has risen by about 20 centimetres since then.

Greater global coverage and precision has been achieved since 1992 with satellite measurements. These measurements also show sea level has increased in the last two decades.[59]

The rises in sea level at particular locations around the Earth vary widely due to a number of factors.

One factor is the vertical movement of land. In some cases, land is moving upward, effectively reducing the rise in the sea level – the post-glacial rebound in part of Scandinavia illustrated in Figure 2.3 is an extreme example. In others, land is moving downward so the local rise in the sea level is greater than average – this is occurring along the Eastern Seaboard of the United States and the south coast of England. In tectonically active New Zealand, land can move up or down very rapidly in earthquakes. Another important factor discussed in the next chapter is the gravitational pull of large land or ice masses (Box 4.1).



Data: Church and White, 2011.

Figure 3.5 Global mean sea level rise relative to 1880.

3.5 The start of the Anthropocene?

Because the impact of humans on the Earth is now so significant, the term 'Anthropocene' has been coined to describe a new geological epoch.[60]

The warming of the climate that is now underway has not been triggered by a Milankovitch variation in the Earth's orbit, but by the burning of huge quantities of fossil fuels and the loss of forests. Without this human 'disturbance', the climate would have been expected to stay relatively stable for tens of thousands of years to come before cooling into another ice age.[61]

During warm periods (interglacials) over the last half million years, carbon dioxide levels have peaked at about 290 ppm.[62] Now carbon dioxide levels have risen much higher, recently exceeding 400 ppm. The geological record shows that the last time this happened was about 3 million years ago.[63]

The *direct* warming effect of this increase in carbon dioxide is magnified by positive feedbacks. Two are particularly powerful – the increasing amount of heat-trapping water vapour in the atmosphere and the loss of reflective ice cover.

Some of the predicted impacts of increasing global temperatures are becoming increasingly evident. One of these – rising sea level – is the focus of this report. The next chapter describes the physical processes that are driving this change.

4

Rising seas

Increasing concentrations of carbon dioxide and other greenhouse gases are leading to a warmer world. One major consequence is an increase in the global mean sea level.

There are three main ways in which warming air temperatures are causing sea level to rise:

- Water in the sea is expanding
- Mountain glaciers are retreating
- Polar ice sheets are losing ice into the sea.

The first and second processes are well understood. As air temperatures rise, ocean temperatures slowly follow and the volume of water in the sea expands, raising the sea level. And as air temperatures rise, mountain glaciers retreat as ice melts and the meltwater flows into the sea, raising the sea level further.

In contrast, the third process – the loss of ice from the polar ice sheets – is complex, and is a focus of intense scientific research. Like glaciers, ice sheets will also lose ice with warming temperatures, but the way it happens is more complicated. So while the recent loss of ice from ice sheets has been measured, predicting future ice loss is a huge challenge.

This chapter describes these three processes in turn, explaining how each contributes to rising sea level. In the final section, the latest scientific projections of future sea level rise are presented.

4.1 Expanding water

The climate change now underway is heating the ocean as well as the atmosphere. Indeed, the vast majority of heat has gone into the ocean.[64]

Many substances expand when heated. Mercury is one such substance – when the mercury in a glass thermometer is warmed, it expands and rises, reflecting the increasing temperature. Water behaves in the same way, so as the ocean becomes warmer, its volume increases and the global mean sea level rises.[65]

In recent years, using data from thousands of robotic temperature floats, scientists have developed a much better understanding of how the ocean warms and expands (Figure 4.1).[66]

Ocean temperatures will continue to rise for a long time to come, regardless of how much action is taken to reduce emissions of greenhouse gases. This is because extra heat added to the upper layers of the ocean takes a long time to mix into the deep ocean.[67]

Because the basic science of ocean expansion is well understood, scientists can accurately predict its contribution to global sea level rise.

Source: NIWA.

Figure 4.1 Since the early 2000s, thousands of robotic Argo floats have collected data enabling scientists to measure how the ocean has warmed and expanded.

4.2 Melting glaciers

Glaciers are 'rivers of ice'. A glacier is fed by snow at the top, which turns into ice and, under its own weight, flows very slowly downhill. At the bottom the ice melts into rivers that flow to the sea.

Glaciers advance when the accumulating snow outpaces the melting ice, and retreat when the melting ice outpaces the snowfall. When the Earth enters ice ages, global temperatures plummet and glaciers advance.

In the past century, glaciers worldwide have thinned out and retreated, adding water to the oceans and raising the global mean sea level. There are some exceptions where changing weather patterns have tipped the balance between snow accumulation and meltwater the other way.[68]

In New Zealand, aerial surveys have shown that a third of the permanent snow and ice on the Southern Alps has disappeared between 1977 and 2014.[69]

Mountain glaciers respond quickly to changes in *air* temperature. How fast air temperatures change in the years to come will be largely determined by the emission rates of greenhouse gases into the atmosphere.

Source: adapted from Anthony Cramp, Flickr, CC-BY-2.0.

Figure 4.2 The Franz Josef Glacier has both retreated and thinned since 1865. Lines and shading showing the extent of the glacier in 1865 have been added.

4.3 Shrinking polar ice sheets

In considering sea level rise, it is important to distinguish between two kinds of ice in the polar regions – sea ice and ice sheets.

Sea ice is frozen seawater that floats on the surface of the ocean. It varies in its extent and thickness over the year – it is at its maximum in winter and its minimum in summer. But outside of the seasonal variation, an overall decline in sea ice cover is occurring. It is anticipated that the ocean at the North Pole will be nearly free of sea ice in summer by the middle of this century.[70]

However, when sea ice melts, it has only a very minor direct effect on sea level.[71] In contrast, the impact on sea level of melting *ice sheets* could be very large indeed.

Ice sheets are huge blankets of ice covering land. They sit astride the polar continents and in some areas are kilometres thick. There are three ice sheets – one covering Greenland, one covering West Antarctica and one covering East Antarctica.

Like alpine glaciers, ice sheets are fed by falling snow, and move downward under their own weight. Ice streams form and flow outwards and downwards to the sea. If the loss of ice into the sea outpaces the accumulating snowfall, the ice sheet shrinks.

The amount of ice held in the polar ice sheets is so vast that if all of it were to melt, the sea level would rise about 64 metres – 7 metres from the Greenland Ice Sheet, 4 metres from the West Antarctic Ice Sheet, and 53 metres from the colossal East Antarctic Ice Sheet.[72]

Until recently scientists were not able to estimate with any accuracy how much ice the polar ice sheets contained, and so were unable to assess whether they were stable or gaining or losing ice. This has changed with the use of satellite technology.

Source: Sam Doyle, Prifysgol Aberystwyth University.

Figure 4.3 Meltwater on the surface of Russell Glacier, Greenland Ice Sheet.

The **Greenland Ice Sheet** lies behind mountains around the coast. Large outlet glaciers carry ice through valleys to the sea where icebergs calve off into the ocean.

Greenland is considerably warmer than Antarctica. Meltwater from the surface of the glaciers is trickling down underneath the ice, 'lubricating' the glaciers and speeding their advance to the sea. Greenland is also melting at its margins where ice is in contact with a warming ocean. As a result the Greenland Ice Sheet is losing ice at an accelerating rate from its periphery.[73]

The massive Jakobshavn Glacier – which is thought to have calved the iceberg that sunk the Titanic – is now carrying ice into the Atlantic Ocean nearly three times as fast as it did in the mid-1990s.[74]

Although Greenland is warmer and losing ice at a faster rate than Antarctica, there is also great concern about the stability of the Antarctic ice sheets. In Greenland, the ice sheet is held in place by mountains around the coast, but in Antarctica the stability of the ice sheets is very dependent on 'ice shelves'.[75]

Around much of the Antarctic coastline, ice shelves – thick floating platforms of ice – jut out into the ocean. Ice shelves form within bays. The largest – the Ross Ice Shelf – is hundreds of metres thick and floats on an area of the Ross Sea the size of France.

Ice shelves act as retaining walls holding back the flow of the ice sheets from the land to the ocean. They have been compared to the flying buttresses that so beautifully support Notre Dame and other Gothic churches. Without these the church walls would collapse outwards (Figure 4.4).

Rising ocean temperatures can weaken ice shelves, and if they break away the ice sheet behind becomes less stable and flows faster into the ocean.

Source: Jean Lemoine, Flickr CC-BY-SA-2.0.

Figure 4.4 Ice shelves act like the flying buttresses used in some Gothic churches. The photo shows the buttresses on the Notre Dame Cathedral in Paris.

Figure 4.5 Map of Antarctica showing West Antarctica and East Antarctica separated by the Transantarctic Mountains.

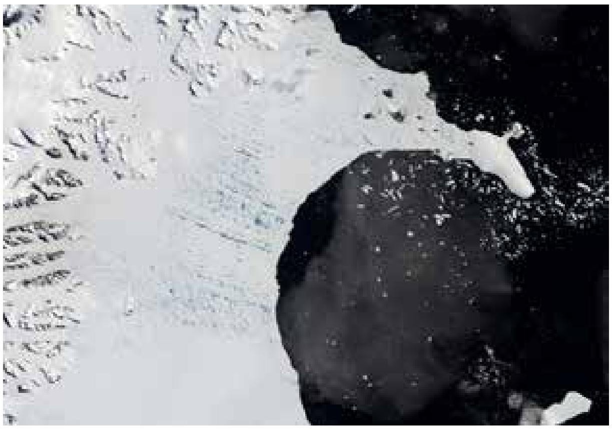
The **West Antarctic Ice Sheet** is particularly vulnerable to a warming climate.

In 1978, glaciologist John H. Mercer stated that "*One of the warning signs that a dangerous warming trend is under way in Antarctica will be the breakup of ice shelves on both coasts of the Antarctic Peninsula, starting with the northernmost and extending gradually southward*".[76]

That breakup is already underway. Ice shelves on the West Antarctic Peninsula that have collapsed in recent years include Larsen-A in 1995 and Larsen-B in 2002 (Figure 4.6) on the east coast, and Wilkins in 2008 on the west coast.

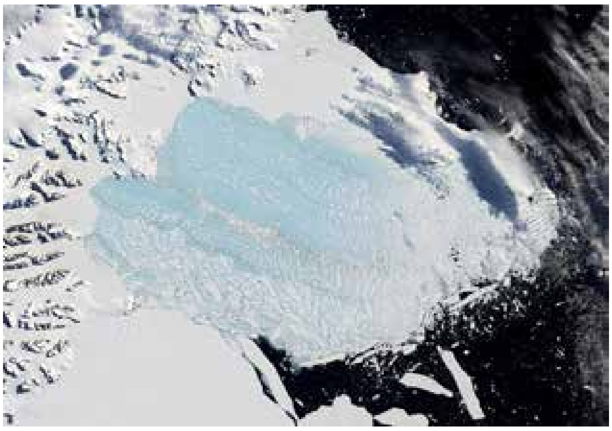
In 1981, Terence Hughes suggested that Pine Island Bay in the Amundsen Sea is the "*weak underbelly*" of the West Antarctic Ice Sheet.[77] This is because there are no large ice shelves holding back the flow of the glaciers that drain into Pine Island Bay. Moreover, the ground beneath the West Antarctic Ice Sheet slopes down inland from the coast to far below sea level. If seawater is able to flow in under the ice, it will melt it from below. Analysis of two decades of data show that this is happening.[78]

31 January 2002



23 February 2002

7 March 2002



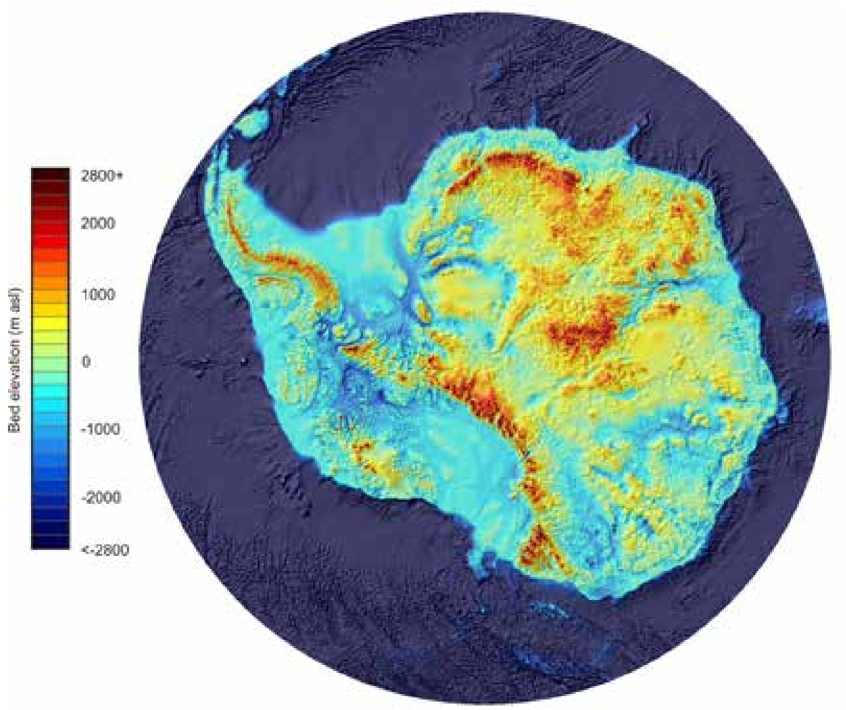
Source: NASA.

Figure 4.6 The Larsen-B ice shelf on the east coast of the Antarctic Peninsula was about twice the size of Stewart Island. It collapsed over a 35-day period in 2002. The Antarctic Peninsula is one of the fastest-warming places on Earth.

The vast **East Antarctic Ice Sheet** has long been considered stable and thought unlikely to shrink much in a warming world. However, that understanding has changed recently with more accurate mapping of the ice surface, the ice thickness, and the topography of the ground below.

It is now known that two regions of East Antarctica – the Aurora Basin and the Wilkes Basin – lie below sea level and contain ice up to 2.5 kilometres thick. The ground beneath the ice slopes down inland from the coast. Should the ice shelves protecting these regions break up, seawater could get in below the ice, and the same destabilisation that is underway in the West Antarctic could begin.[79]

Predicting *how much* and *how rapidly* each of the three ice sheets could shrink in a warming world is a complex task. The study of the movement of ice sheets – 'ice sheet dynamics' – is developing rapidly and lies at the frontier of scientific research.



Source: Fretwell et al., 2013.

Figure 4.7 A map of Antarctica showing the elevation of the bedrock below the ice. Most of the west of Antarctica is coloured blue, showing that the ground is below sea level. The Aurora and Wilkes Basins are in the south east of Antarctica. They are the most vulnerable parts of the East Antarctic Ice Sheet, and contain a vast quantity of ice.

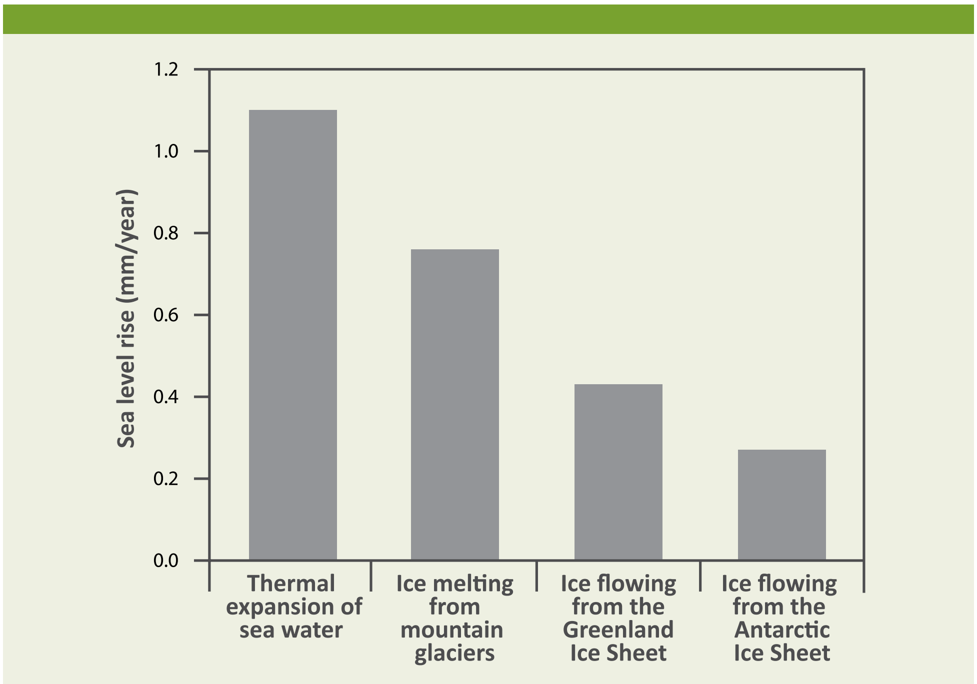
4.4 How much will the sea rise in the future?

Predicting how much and how fast sea levels will rise as the atmosphere and oceans warm is a Herculean task. Besides the scientific uncertainty, there is the big question of how much the world will slow its emissions of carbon dioxide and other greenhouse gases.

In the last century, global average sea level has risen about 20 centimetres, mainly due to seawater expanding and alpine glaciers melting. In recent decades the polar ice sheets have been losing more ice and may be accelerating the rate of sea level rise.

As part of its regular reviews of the current state of knowledge about climate change, the Intergovernmental Panel on Climate Change (IPCC) predicts future sea level rises. The IPCC, established in 1988, publishes an assessment report every five or six years, which reflect the consensus view of the participants. Hundreds of experts are involved and thousands of scientific papers are cited.

The IPCC considers only published peer-reviewed papers, and physical processes that are not understood well are either omitted or simplified in their analysis. Because polar ice sheet dynamics is such an evolving field, it was not until 2013 that the IPCC directly included a contribution from the ice sheets in the sea level rise projections.[80]



Data: IPCC.

Figure 4.8 Contributions to global sea level rise between 1993 and 2010 from expanding oceans, retreating glaciers, and shrinking ice sheets.

The IPCC projects that, from around the end of the 20th century, sea level will rise 20 to 40 centimetres by the middle of the century, and 30 to 100 centimetres by 2100. These projections encompass four scenarios of future greenhouse gas emissions.[81]

Under its 'Business-as-Usual' scenario for greenhouse gas emissions, the IPCC estimated that sea level would rise by between 52 and 98 centimetres by 2100. A recent survey of 90 experts on sea level rise found that most estimated a larger sea level rise by 2100 than the projections in the 2013 IPCC report. Under the same 'Business-as-Usual' scenario, they predict a rise of between 70 and 120 centimetres.[82]

In the decades ahead, expanding seawater, retreating glaciers, and shrinking ice sheets will increasingly contribute to a rise in sea level.[83]

As the surface layer of the ocean absorbs more heat from the atmosphere and as ocean currents mix the extra heat into the deep ocean, the volume of seawater will continue to expand.

Alpine glaciers will continue to retreat, but in total they hold only enough ice to raise sea level by about 35 to 60 centimetres.[84]

Ice loss from Antarctica and Greenland is accelerating, and in the longer term is expected to be the main contributor to sea level rise. Just how big that contribution will be by the end of this century is not well known. However, scientists working at the cutting edge of research into ice sheet dynamics are suggesting that it could be very significant.

Sea level rise will vary around the world depending on factors such as weather patterns and gravitational attractions of large land and ice masses (Box 4.1).

The longer major reductions in greenhouse gas emissions are delayed, the more change in the climate becomes inevitable, and the more sea level will rise.

Box 4.1 Sea level rise will vary around the world

It can come as a surprise to hear that the sea has a topography, that like land it has contours that can be mapped. This is because the surface of the sea is warped by the gravitational pull of land and ice masses.[85]

A mountain range on the seabed pulls the sea towards it, creating a bump in the surface of the sea. Conversely, a trough on the seabed creates a hollow in the sea above it. Thus, the topography of the seabed is 'mirrored' by the topography of the sea surface.

Similarly, a coastal mountain range will draw the sea towards it. The massive polar ice sheets have the same effect on the surrounding sea. As the ice sheets shrink, so does their gravitational pull on the oceans that encircle them.

If the West Antarctic Ice Sheet were to completely melt, the global *mean* sea level rise would be about five metres. But the extra seawater would not be distributed evenly around the Earth. Because the gravitational pull of West Antarctica would be so much weaker without the mass of the ice, the sea level would actually fall in the Southern Ocean but rise relatively more further north. For instance, it has been estimated that the sea on the United States mid-Atlantic coast would rise about 6 metres.[86]

5 In conclusion

The modern understanding of climate change and sea level rise is the culmination of scientific thinking that spans two centuries. The effects on New Zealand's coastline will become increasingly evident in coming decades and be with us for a long time. We will need to prepare for and adapt to these changes. However, the rate at which the sea rises can be slowed by reducing the world's – including New Zealand's – greenhouse gas emissions.

Changing climate

In the 1800s geologists began to systematically study the history of the Earth. The discovery that vast sheets of ice had once covered much of the planet must have startled the scientific establishment. As the new field of paleoclimatology developed, it became clear that there have been many such ice ages in the past, separated by shorter warm periods known as 'interglacials'.

The current geological epoch – the Holocene – is an interglacial period that began about twelve thousand years ago. Over the last seven thousand years the climate has been relatively stable, but now a significant change is underway. Some experts have categorised this change as the beginning of a new geological epoch dubbed the Anthropocene – the epoch of human influence.

The change can be traced back to the Industrial Revolution when the burning of huge quantities of coal began. The combustion of fossil fuel – coal, oil, and natural gas – releases carbon dioxide into the atmosphere. Carbon dioxide and some other gases, most notably methane, are called greenhouse gases because they trap heat in the atmosphere.

The concentration of carbon dioxide in the atmosphere has risen over the last two hundred years – from 290 parts per million to around 400 parts per million today. This may not seem very significant since carbon dioxide is only a 'trace' atmospheric gas, but the impact is multiplied (or greatly exacerbated) by positive feedbacks. Over the twentieth century, a rise in the global mean temperature at the surface of the Earth has followed the increase in greenhouse gas concentrations.

Worldwide, thousands of scientists are working at the leading edge of climate science. Much, such as the impact on and effect of clouds, is still imperfectly understood. However, the basic science of climate change is well understood and each year brings more evidence and greater understanding.

Rising seas

A major impact of climate change that has already become evident is the rising level of the sea. On average, sea levels around the world have risen around 20 centimetres since the beginning of the twentieth century.

Three processes are driving the rise in sea level – an expanding volume of water in the oceans, melting glaciers, and shrinking polar ice sheets.

The enormous volume of the three ice sheets covering the land in Greenland, West Antarctica, and East Antarctica is equivalent to many metres of sea level rise. Thus, the stability of these ice sheets is of great importance. Developing a greater understanding of ice sheet dynamics is critical.

In its latest report, the IPCC predicts that sea levels will rise by a further 20 to 40 centimetres by the middle of this century. This increase is 'locked in' – it is forecast under all IPCC scenarios.[87] New Zealand, like other countries, needs to adapt.

After 2050, the forecast rises in sea level become increasingly dependent on the actions taken to reduce future greenhouse gas emissions. Under IPCC's 'Business-as-Usual' scenario, the mean sea level is forecast to be as much as a metre higher in 2100. But this is not inevitable. Reducing greenhouse gas emissions will make a difference in the future.

A small rise in sea level can have big impacts

New Zealand is a coastal nation. The impacts of sea level rise will vary around the coastline. Some areas are low lying and prone to flooding. Some are exposed and vulnerable to erosion. Some are subsiding resulting in higher sea level rises.

A rise in sea level of 20 to 40 centimetres may sound minor, but each successive centimetre has a bigger effect than the last.

The impacts of a rise in sea level are most evident during storm surges when wind and waves pile up water against the coast. Flooding is worse when a storm surge coincides with a high tide, and especially so if the high tide is one of the 'king' tides that occur a few times a year.

In January 2011, a storm surge hit downtown Auckland, flooding shops, homes, and roads. The Northwestern Motorway flooded (Figure 5.1) and stormwater systems backed up. The flooding was worse than that caused by a similar size storm that hit Auckland in 1936 – largely because the sea was 11 centimetres higher.[88]

The National Institute of Water and Atmospheric Research (NIWA) has projected that in 30 years' time, this level of flooding in Auckland will occur about once every ten years. A few decades later, such flooding is expected to occur every year if the world takes no action to reduce greenhouse gas emissions.[89]

Source: Peter Mitchell, NZTA.

Figure 5.1 In January 2011 Auckland's Northwestern Motorway flooded in a storm surge. This type of flooding is set to become more common this century.

Source: Roger Grace

Figure 5.2 Omaha Beach north of Auckland is particularly prone to erosion. A severe storm hit in 1978, destroying the old sea wall. An Act of Parliament was passed for emergency remedial work including the construction of rock groynes and sand renourishment.

A second report on sea level rise is planned for release in 2015. This will show in some detail which areas of the coastline around the country are most vulnerable to sea level rise and assess the risk to infrastructure in those areas.

In a recent report, Local Government New Zealand expressed its concern about the impacts of sea level rise, saying that it would "*… increase the impact of storm surges, exacerbate coastal erosion (or decrease coastal accretion), increase ground water levels in coastal areas, and in low lying areas result in coastal inundation.*"[90]

Many coastal properties and homes around the country will be affected, along with infrastructure in low lying areas, such as roads, railways, waste water systems, and public buildings.

Some parts of Christchurch have experienced an effective sea level rise of half a metre or more due to land subsidence from the Canterbury earthquakes.[91] In some places flooding is now occurring more frequently. In March 2014, a particularly devastating flood occurred in some areas that had experienced subsidence when very heavy rain coincided with a high tide and a storm surge (Figure 5.3).[92]

The insurance industry is becoming aware of, and responding to, the increased flooding risk. In a Christchurch *Press* article titled "*Flood insurance harder to get*", Tim Grafton, Chief Executive of the Insurance Council of New Zealand, was quoted as saying: "*What we are seeing in parts of Christchurch is almost a fast-forward of the future with climate change*".[93]

Rising seas will increasingly affect some parts of our coast and threaten homes and infrastructure. Some hard questions and difficult choices lie ahead of us. Not least is the challenge of joining with other countries to take real action on greenhouse gas emissions.

Source: Fairfax NZ / The Press.

Figure 5.3 Flooding in Burwood, Christchurch, from the Avon River in March 2014, when heavy rain coincided with a high tide and a storm surge.

Notes

[1] After I had written this sentence, one of my staff pointed out that the tractor in the Canterbury Museum belonged to Shackleton. Apparently Scott's tractors fell through the ice. But I decided to leave my childhood memory intact.

[2] Cherry-Garrard, 1922.

[3] Insurance Council of New Zealand, 4 November 2014, *Action required to protect New Zealand from natural hazards impact*, press release.

[4] Radio New Zealand, 1 April 2014, *No directives on climate change*.

[5] IPCC 2013, Working Group 1, Chapter 13, p.1182. For more on past sea level rise see section 3.4. For more on sea level rise projections see section 4.4.

[6] Climate Central, 23 September 2014, *New analysis shows global exposure to sea level rise*.

[7] Resource Management Act 1991, s7.

[8] *New Zealand's framework for adapting to climate change*. Ministry for the Environment. 2014.

[9] Weir vs Kapiti Coast District Council [2013]. NZHC 3522.

[10] [Removed]

[11] TVNZ, 5 November 2014, *Natural disasters could cost you higher insurance premiums*.

[12] Barnes, 1984, p.572.

[13] He knew, for instance, that Hadrian's Wall had been exposed to the elements for 1,500 years, but observed that it had weathered far less than nearby mountains. He deduced that the mountains were much older. See, for example, Rice, 2007, p.200, and Church, 2010, p.62.

[14] Changes in the Earth's orbit change how much solar energy reaches different parts of the Earth and so can set off a warming or cooling climate. However, it is feedbacks (discussed in Chapter 3) that continue the warming or cooling, sending the Earth into a warm period or an ice age.

[15] The tide records from Stockholm, Amsterdam, and Liverpool date back three centuries. The Stockholm records began in 1774 and are the longest mean sea level series in the world that is still in continuation. The Amsterdam records began in 1700 and are the oldest mean sea level series in the world but were discontinued in 1925. Liverpool records began in 1768; these are a high water series only, but the longest of its kind. Ekman, 2000, p.9; Church et al., 2010, p.123.

[16] The Swiss physicist Horace-Bénédict de Saussure carried out early experiments in the 1760s. It was the French physicist Joseph Fourier that first proposed in the early nineteenth century that the atmosphere was acting as an insulator, keeping the Earth warm.

[17] Water vapour is now understood to contribute two to three times more to the natural greenhouse effect than carbon dioxide. IPCC 2013, Working Group 1, Chapter 8, p.666.

[18] Hulme, 2009.

[19] Tyndall, 1870, p.417.

[20] "*While he could not prove that greenhouse effect warming was underway, he had given sound reasons to reconsider the question. We owe much to Callendar's courage. His claims rescued the idea of global warming from obscurity and thrust it into the marketplace of scientific ideas"*. American Institute of Physics, *The discovery of global warming: The Carbon Dioxide Greenhouse Gas Effect*, http://www.aip.org/history/climate/co2.htm [Accessed 3 October 2014].

[21] "*The ice-thinning in the last few decades of the world's glacier districts … has thus … resulted in the ocean levels being raised eustatically about 0.05 cm per annum*". Thorarinsson, 1940, pp.147, 151.

[22] Gutenberg, 1941, p.729. As above, this is an estimate of the eustatic change.

[23] Lisitzin, 1974, pp.179-180.

[24] Tide gauge data provides valuable insight into changes in sea level, but this is not their primary purpose and the data is limited in various ways. Tide gauges are attached to the ground so were also measuring land subsidence or uplift as well as changes in sea level. Scientists found ways to correct for these limitations, but there were other problems too. For instance, tide gauges were mostly installed in ports, so there was no data for sea levels in the middle of the ocean.

[25] These cores are now kept in the Core Repository at Columbia University where 19,000 cores are available for scientists to use. Lamont-Doherty Earth Observatory, *History of the Core Repository*, http://www.ldeo.columbia.edu/core-repository/about-us/core-repository-history [Accessed 3 October 2014].

[26] CLIMAP Project Members, 1976.

[27] One technique that is still used measures the relative amounts of the two oxygen isotopes (^{16}O and ^{18}O) in the foraminifera to determine whether they had been alive in a warm period or a cold period.

[28] Hays et al., 1976.

[29] Langway, 2008.

[30] Ice contains pockets of air – this is a sample of the atmosphere at the time the ice was formed. As with the deep sea sediment cores, these were analysed using oxygen isotopes. This method reveals what the temperature and climate was like at different times in the past.

[31] Dansgaard et al., 1969.

[32] This ice core was drilled in as part of the European Project for Ice Coring in Antarctica (EPICA).

[33] Finding the ages of different layers of ice is more complicated than dating the layers in sediment cores. Instead of radiocarbon dating, a variety of methods are used. Some layers are visible and so can be counted like tree rings. Substances trapped within the ice, such as ash from volcanic eruptions, also help provide information on the age of different ice layers.

[34] Ice cores can also be used to reconstruct past temperatures. This can be done by measuring oxygen isotopes in air bubbles in the ice and hydrogen isotopes in melted ice.

[35] National Oceanic and Atmospheric Administration (NOAA), *Heinrich and Dansgaard-Oeschger events*, http://www.ncdc.noaa.gov/paleo/abrupt/data3.html [Accessed 3 October 2014]. Ice cores drilled in Antarctica have shown shifts in climate that correlate with the Greenland records, although they are generally thought to be smaller and slower. Alley, 2000.

[36] British Antarctic Survey, *Ice cores and climate change*, http://www.antarctica.ac.uk/bas_research/science_briefings/icecorebriefing.php [Accessed 3 October 2014].

[37] Sluijs et al., 2008, p.2; IPCC 2013, Working Group 1, Chapter 5, p.399.

[38] Carbon dioxide in the atmosphere rose as high as 1,000 parts per million during the early Eocene epoch. IPCC 2013, Working Group 1, Chapter 5, p.399.

[39] National Geographic, 4 March 2010, *"Snowball Earth" confirmed: ice covered equator*.

[40] Hannah et al., 2010, p.12.

[41] Mathews, 1967.

[42] See, for instance, Shakun et al., 2012.

[43] Although rising temperature triggered rising carbon dioxide levels, the carbon dioxide feedback takes over. Ninety per cent of warming occurs after carbon dioxide levels increase. Shakun et al., 2012.

[44] More water vapour in the atmosphere is likely to lead to the formation of more clouds. Clouds have a positive feedback effect when they reflect heat back down to the Earth and a negative feedback effect when they reflect the Sun's rays back out to space. The role that clouds will play as the climate changes is one of the biggest 'unknowns' in climate science. IPCC 2013, Working Group 1, Chapter 7, p.573.

[45] Carbon dioxide is not the only greenhouse gas being added to the atmosphere as a consequence of human activities, but it is responsible for about two thirds of the current warming of the climate. Other significant greenhouse gases include methane and nitrous oxide. IPCC 2013, Working Group 1, Chapter 8, pp.677-678.

[46] Combustion of fossil fuels is not the only reason for increasing carbon dioxide in the atmosphere. Another major reason is the clearing of forests since trees and other green plants absorb carbon dioxide as they grow.

[47] Mauna Loa is a good location for measuring carbon dioxide levels because it is away from large sources of carbon dioxide such as big industrial cities.

[48] Satellites now provide measurements of carbon dioxide throughout the upper atmosphere and this record also shows the same trend. NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC), *Satellite observations of carbon dioxide: Why are they important; and what CO2 data from different NASA missions tell us*, http://disc.sci.gsfc.nasa.gov/featured-items/airs_acos_co2_satellite_observations [Accessed 25 September 2014].

[49] New Zealand Herald, 5 December 2009, *Measuring the air that we breathe*. The seasonal 'sawtooth' variation is much smaller for measurements taken in the Southern Hemisphere because there is less land and thus much less forest.

[50] IPCC 2013, Working Group 1, Chapter 6, pp.493-494.

[51] The ice core record shows that the concentration of atmospheric carbon dioxide was stable over the last thousand years or so until it began to rise early in the nineteenth century. The concentration of another major greenhouse gas, methane, has more than doubled over the same period. British Antarctic Survey, *Ice cores and climate change*, http://www.antarctica.ac.uk/bas_research/science_briefings/icecorebriefing.php [Accessed 10 November 2014].

[52] IPCC 2013, Working Group 1, Chapter 2, p.162.

[53] The period from about 1500 to 1800 is known as the Little Ice Age – this period was relatively cooler due to changes in volcanic and solar activity. In contrast, the recent warming is mainly attributed to carbon emissions, with little contribution from natural factors. Miller et al., 2012; IPCC 2013, Working Group 1, Summary for Policy Makers, pp.13-14.

[54] IPCC 2007, Working Group 1, Chapter 3, p.253. Most aerosols (fine particles suspended in the atmosphere), including sulphates, reflect solar radiation back into space, cooling the atmosphere.

[55] IPCC 2013, Working Group 1, Chapter 2, p.162. In 1998 a particularly strong El Niño occurred. Measurements show that over this period, the ocean continued to accumulate heat lower down. IPCC 2013, Working Group 1, Chapter 3, p.262.

[56] IPCC 2013, Working Group 1, Chapter 2, pp.161-162. Emphasis added. It has been suggested that much of the measured increase in global temperatures has been caused by the relative warmth of cities compared to surrounding rural areas – the urban heat island effect. The IPCC found it unlikely that any uncorrected effects due to urban heat islands and land use changes account for more than 10% of the reported temperature trend. IPCC 2013, Working Group 1, Chapter 2, p.162.

[57] IPCC 2013, Working Group 1, Chapter 5, pp.396-398.

[58] National Institute of Water and Atmospheric Research (NIWA), *Past climate variations over New Zealand*, http://www.niwa.co.nz/our-science/climate/information-and-resources/clivar/pastclimate [Accessed 10 September 2014].

[59] Since 1992, global mean sea level has risen by about 3.2 millimetres a year. University of Colorado Sea Level Research Group, *Global Mean Sea Level Time Series*, http://sealevel.colorado.edu/content/global-mean-sea-level-time-series-seasonal-signals-removed [Accessed 4 September 2014].

[60] *Anthropos* is the Greek word for human. Paul Crutzen, one of the winners of the Nobel prize for his role in explaining the chemistry of the ozone layer, has suggested that the Anthropocene began when concentrations of carbon dioxide and methane started to rise in the atmosphere. Crutzen, 2002.

[61] Berger and Loutre, 2002; IPCC 2013, Working Group 1, Chapter 5, p.387.

[62] See Figure 2.5.

[63] IPCC 2013, Working Group 1, Chapter 5, p.399. Carbon dioxide levels were also around 400 parts per million (ppm) about 15 million years ago; temperatures were about 3 to 6 degrees warmer and the sea level 25 to 40 metres higher than now. Tripati et al., 2009.

[64] IPCC 2013, Working Group 1, Chapter 3, p. 266.

[65] Because the density of freshwater is at a maximum at 4°C, freshwater actually contracts as its temperature rises from 0°C to 4°C, and then expands as its temperature rises further. For every 0.1 degree rise in temperature in the oceans, a 1000 metre deep water column will expand 1 to 2 cm. Church et al., 2010, p.143.

[66] Early ocean temperature measurements were based on observations taken from ships. In the 1960s, more systematic observations were collected using thermometers on wires dropped from ships, which recorded temperatures over a depth profile. In the 1990s, scientists started collecting more accurate and reliable temperature profile data across a series of transects around the globe as part of the World Ocean Circulation Experiment. Since 2004, around 3600 submersible Argo floats have been deployed around the world. These floats measure the temperature and salinity of the water at different depths, and have revolutionised understanding of the ocean temperatures. Murray-Wallace and Woodroffe, 2014, pp.383-384; CSIRO, *Monitoring our oceans with robotic floats,* http://www.csiro.au/Outcomes/Climate/Understanding/Ocean-Robotic-Floats.aspx [Accessed 7 November 2014].

[67] IPCC 2013, Working Group 1, Chapter 3, p. 266. Water expands more under pressure – a one-degree rise in temperature deep down in a water column leads to a greater rise in the height of the column than a one-degree rise near the surface of the column. Church et al., 2010, p.143.

[68] United Nations Environment Program, *Global Glacier Changes: facts and figures*, http://www.grid.unep.ch/glaciers/ [Accessed 30 September 2014]. For most of the twentieth century, mountain glaciers contributed 0.54 mm per year on average to sea level rise. This rate has since increased to about 0.83 mm per year for the period from 2005 to 2009. IPCC 2013, Working Group 1, Chapter 13, p.1153. In the IPCC's Fourth Assessment Report, it was mistakenly stated that Himalayan glaciers could disappear by 2035. The mistake was subsequently acknowledged and corrected. IPCC, 20 January 2010, IPCC *statement on the melting of the Himalayan glaciers,* media release.

[69] The Conversation, 29 July 2014, *New Zealand's Southern Alps have lost a third of their ice*.

[70] Overland and Wang, 2013. Conversely, sea ice in Antarctica has grown since the 1970s, probably due to regional changes in weather. Parkinson and Cavalieri, 2012.

[71] Shepherd et al., 2010. The melting of sea ice will however speed up climate change indirectly because of the 'ice-albedo feedback'. As white ice is replaced by dark ocean, the reflectivity of the Earth (the albedo) declines and more solar radiation is absorbed, causing the Earth to warm more and the sea to rise.

[72] Bamber et al, 2013; Fretwell et al., 2013.

[73] The rate of ice loss from the east and west of the Greenland Ice Sheet increased from 90 to 200 cubic kilometres per year between 1996 and 2006. Rignot and Kanagaratnam, 2006.

[74] Joughin et al., 2014a.

[75] Ice shelves in Antarctica are about 1.5 million square kilometres in area, compared to only a few hundred square kilometres in Greenland. Greenland ice shelves "*are little more than floating ice tongues*". Church et al., 2010, p.191.

[76] Mercer, 1978.

[77] Hughes, 1981.

[78] The authors of a 2014 NASA study concluded "*… this sector of West Antarctica is undergoing a marine ice sheet instability that will significantly contribute to sea level rise in decades to centuries to come*". Rignot et al., 2014. See also Joughin et al., 2014b; Tinto and Bell, 2011; NASA, *The "unstable" West Antarctic Ice Sheet: a primer*, http://www.nasa.gov/jpl/news/antarctic-ice-sheet-20140512/ [Accessed 4 November 2014].

[79] Mengel and Levermann, 2014.

[80] In the 2007 report, the IPCC acknowledged that the polar ice sheets could contribute an extra 10 to 20 centimetres to sea level by 2100. The contribution from the ice sheets was included in IPCC's 2013 projections because ice sheet dynamics were more certain and only about 60% of *observed* sea level rise was accounted for in the modelling in the 2007 report. IPCC 2007, Working Group 1, Chapter 10, p.821; IPCC 2013, Working Group 1, Chapter 13, pp.1179, 1182.

[81] IPCC 2013, Working Group 1, Chapter 13, p.1182. The IPCC uses the average sea level between 1986 and 2005 as a baseline for these projections. The exact figures given by the IPCC are 17–38 centimetres by the middle of the century (the average sea level between 2046 and 2065) and 28–98 centimetres by 2100. These projections are based on four scenarios. The 'Business-as-Usual' scenario assumes greenhouse gas emissions continue on the same trend. The 'Low Emissions' scenario assumes that greenhouse gas emissions are reduced now and emissions are zero by 2080. There are also two moderate emissions scenarios.

[82] Horton et al., 2014. Only experts "*with a strong publication record on sea level*" were invited to participate in the survey.

[83] Land water storage may also contribute to sea level rise in this period. Water that is taken from aquifers and used, in irrigation for example, runs off into rivers and down into the ocean, adding to sea level rise. Likewise, building dams to store water can reduce sea level rise, at least initially, as the water doesn't go on to flow down the river to the ocean. Depending on how many dams are being built and how much water is being extracted, the contribution of land water storage to sea level rise can be positive or negative. This is unlike thermal expansion, melting glaciers and ice sheets, which positively contribute to sea level rise. Land water storage is not well studied and it is difficult to predict how land water storage would contribute to sea level rise in the future. IPCC 2013, Working Group 1, Chapter 13, pp.1176-1179.

[84] Radic and Hock, 2010; Grinsted, 2013.

[85] The topography of the sea is also affected by other factors, such as the prevailing winds that drive water up against land and the rotation of the Earth.

[86] Mitrovica et al., 2009. See also Yale Environment 360, 22 March 2010, *The secret of sea level rise: it will vary greatly by region*; Bamber et al., 2009; Kopp et al., 2010.

[87] The IPCC models four scenarios. The 'Business-as-Usual' scenario assumes greenhouse gas emissions continue on the same trend. The 'Low Emissions' scenario assumes that greenhouse gas emissions are reduced now and emissions are zero by 2080. There are also two moderate emissions scenarios.

[88] Stephens et al., 2013, p.27.

[89] Unpublished data provided by Dr Scott Stephens, NIWA, October 2014.

[90] Local Government New Zealand, 2014, p.12.

[91] Tonkin & Taylor, 2013, p.15.

[92] Allen et al, 2014. Chapters 2, 7.

[93] The Press, 1 May 2014, *Flood insurance harder to get*.

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