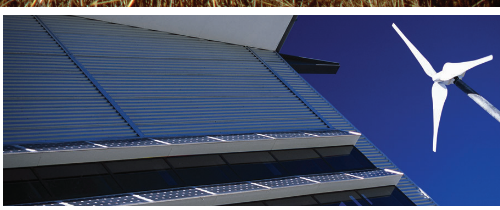
SCIENCE AND SOLUTIONS FOR AUSTRALIA

CLIMATE CHANGE



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Editors: Helen Cleugh, Mark Stafford Smith,
Michael Battaglia, and Paul Graham

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Foreword

By Megan Clark, CSIRO Chief Executive

CSIRO is committed to providing scientific advice on the major challenges and opportunities that face Australia. I commend to you this summary of the latest scientific knowledge on understanding, adapting to, and mitigating against changes in our climate.

Australia has one of the most variable climates in the world, and a history of adapting to the extremes that are part of this country is embedded in who we are. It is no surprise that our society is increasingly seeking information about the evidence and causes of our changing climate, and how we might adapt and respond to it. This book seeks to provide a bridge from the peer-reviewed scientific literature to a broader audience of society while providing the depth of science that this complex issue demands and deserves. The chapters cover what we have already observed in the global and Australian climate; how greenhouse gases affect climate; our modelling of the future; how we might adapt to and prepare for climate change and how we might mitigate to reduce greenhouse emissions. These aspects are all important as we seek a comprehensive response to climate change.

CSIRO is conducting research to help Australia and the world respond to the challenges and opportunities of climate change. For more than 50 years our scientists have been contributing to the growing body of global scientific knowledge about climate change and are now seeking and finding new ways in which Australian communities, industries, ecosystems, and economies can minimise the negative impacts of climate change and benefit from the opportunities.

We cannot do this important work without the numerous national and international deep partnerships, collaborations, and networks. We collaborate with Australian and international universities, industry groups, research organisations, government agencies, and governments at every level to undertake excellent science and find and implement practical, scientifically based solutions.

As your national science agency we will continue to provide scientific input and solutions to the community, industry, and government on understanding, adapting to, and mitigating against climate change.

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Introduction

By Bruce Mapstone

Climate change is one of the greatest ecological, economic, and social challenges facing us today. The scientific evidence that human activities are contributing to climate change is compelling, but society is increasingly seeking information about the nature of the evidence and what can be done in response to a changing climate. This book provides some of that much-needed information from some of Australia's leading climate scientists.

It is worth considering a couple of important distinctions. The terms 'weather' and 'climate' are frequently considered to be interchangeable, but weather and climate refer to different things. Weather is the brief, rapidly changing condition of the atmosphere at a given place and time, influenced by the movement of air masses. Climate, on the other hand, should more accurately be the term applied to the average weather conditions over longer periods of years to decades.

One may often hear mention of 'climate variability' and 'climate change' together. They are different facets of climate. Climate variability refers to the year-to-year variations, or noise, in the average conditions – meaning that consecutive summers, for example, will not all be the same, with some cooler and some warmer than the long-term average. Climate change refers to any long-term trends in climate over many years or decades, around which climate variability may be evident year on year. Hence, a single warmer or cooler year on its own is not sufficient evidence to assert that climate is changing, but systematic changes in average conditions over many years do provide evidence of a changing climate.

This book is based on rigorous peer-reviewed scientific literature to articulate how human activities affect our climate, what changes we have seen already, what further changes we can expect, and what we might do to reduce future changes and live with those that are now inevitable. The wealth of science behind this book reflects decades of research by researchers in Australia and internationally, including many from CSIRO.

Earth's climate has always changed, alternating between long periods of warm (interglacial) and cool (glacial) conditions, cycling over tens to hundreds of thousands of years. These changes are driven by both external influences and dynamics internal to the Earth system. Key external influences include fluctuations in the amount of energy emitted by the Sun, and changes in the Earth's orbit and axial tilt that affect the intensity and distribution of the Sun's energy across the Earth. Internal influences on climate include changes in the surface reflectivity due to the presence or absence of ice, changes in atmospheric composition of greenhouse gases, variations in ocean currents, drifting continents, the cooling effect of volcanic dust, and other geological processes.

Richard Merry/CSIRO

Gases in the atmosphere, such as carbon dioxide (CO_2), methane, and water vapour, are essential to retain heat and keep the planet warm enough to sustain life – hence the reference to them as greenhouse gases. Solar energy warms the Earth's surface, which then radiates energy back through the atmosphere into space. The greenhouse effect is the process whereby greenhouse gases in the atmosphere absorb the radiation released by the Earth's surface and then radiate heat in all directions, including back towards the ground – adding to the heat the ground receives from the Sun. The surface of the planet would be more than 30ºC cooler than it is now without this natural greenhouse effect, and life as we know it would not be possible.

Greenhouse gases also are stored in various forms in many parts of the Earth system. For example, carbon, in various forms, is stored in the oceans, in frozen tundra, in vegetation and soils, in limestone, and in hydrocarbons. Slight changes in the environment, especially in temperature and moisture, can lead to changes in the uptake and/or loss of greenhouse gases. Higher temperatures can lead to more CO_2 being emitted to the atmosphere due to feedback processes. This in turn causes further warming, and so on. Cooling reverses this feedback cycle, which is a major driver of the long-term fluctuations in climate in ways that are still the subject of intense research.

The Earth in the distant past has been both warmer and cooler than today. The Cretaceous Period (120 to 65 million years ago) was 5º to 7ºC warmer than today and CO_2 concentrations were much higher. Cooling then occurred from the Tertiary Period to the Quaternary Period (2.5 million years ago). The past million years has generally seen a series of changes from major ice ages (glacial periods) to interglacial periods about every 100 000 years, and other variations with shorter periods.

So what makes the climate change we are now experiencing different? The modern climate is changing far more quickly than in the geological past. There is now strong evidence that recent rapid climate changes are driven largely by a range of human activities. Greenhouse gases are

Gregory Heath/CSIRO

released into the atmosphere by burning fossil fuels, clearing forests, cement manufacture, and by many other industrial and agricultural activities, thereby increasing the amount of radiation trapped near the Earth's surface and driving accelerated warming. This process, called the enhanced greenhouse effect, is caused by a forced release of greenhouse gases from their terrestrial store into the atmosphere that has no precedent in history. The associated increases in global temperatures are changing fundamental climate processes. Some of those changes may be beneficial in some areas, but it is expected that most will cause more harm than good. Most of these human contributions to climate change have occurred over the last 200–300 years, following the agricultural and industrial revolutions.

Climate change due to human activities is superimposed on natural climate variability, and is sometimes masked by, and is sometimes exacerbating, natural processes.

Why should we care about climate change? Historical records of temperature show that although temperatures vary naturally between ice ages and warm periods there is no record of temperatures within human history ever having increased as rapidly as they have over the past 100 years. Many other aspects of the Earth's climate also have changed over the past century or more. Some regions have become wetter, while others have suffered increased periods of drought. Frosts have decreased, and heatwaves have increased, in many parts of the world. Mountain glaciers have shrunk and the sea level has risen.

Humans have responded and adapted to small variations in climate for thousands of years but now the changes are accelerating and humanity, more than ever before, is bound to lifestyles that are dependent on immensely complex infrastructure and agriculture for continued survival. Never before, for example, have there been around 150 million people living permanently within 1 m of existing sea level. Not everyone can easily relocate to avoid rising sea level and storm surges, as many cultures might have done in the past.

Gregory Heath/CSIRO

Nick Pitsas/CSIRO

Careful measurements tell us how our climate has been changing over the last 100 years. Judging how to respond to future changes, however, requires that we project what our future climate will be like. The most powerful available mechanism to make those future projections is by computer modelling of the Earth's climate system.

Scientific monitoring and analysis over many years – showing the links between human activities and terrestrial, marine, and atmospheric climate processes – are central to crafting the computer models that are most likely to provide us with reasonable projections of future climate. These projections allow us to infer many of the likely effects of climate change on the Earth's systems and humanity in general and, therefore, underpin our plans to both adapt to what is now inevitable change and mitigate, or reduce, even greater changes.

Climate change adaptation involves taking action to adjust to, or respond to, the effects of changes in climate, such as reduced rainfall or rising sea level. Climate change mitigation refers to actions that aim to reduce the amount of climate change, typically by limiting the future increases in concentrations of greenhouse gases in the atmosphere – either by reducing emissions from a wide range of our industrial and agricultural activities, or by increasing the amount of CO_2 taken up and stored in natural 'sinks' such as forests and soils. Actions that reduce greenhouse gas emissions in many cases also improve our preparedness for future climate change. Some of the ways in which we can adapt to various facets of expected climate change, or mitigate further change, are discussed in this book.

Humanity has learned to live with climate variability and will continue to do so in familiar ways. Modern climate change, however, represents many new challenges for this generation and for those to come. Climate change will mean that the underlying conditions that affect almost every aspect of our lives and the environment in which we live, and on which we depend, will become consistently different. Increasingly, it will influence the year-to-year variations with which we have become familiar. This book describes what the recent changes have been, what we understand future changes are likely to be, how those changes will affect us, and what we may need to do to live in a world different from anything we have experienced before.

Observations of global and Australian climate

By Karl Braganza and John A Church

Key messages

- There is a great deal of evidence that the Earth's climate has warmed over the last century. Warming is apparent in a range of climate indicators including increasing temperatures over land and in the oceans, and increases in sea level.
- Global average temperatures have risen in line with climate model projections for the last 20 years, while global average sea levels are rising near the upper end of the climate model projections.
- There is evidence that the observed changes to the climate system are consistent with changes expected due to increasing greenhouse gases. It is very likely that most of the warming over the last 60 years is due to increases in greenhouse gas emissions due to human activity.

Observations of temperature (on land and in the oceans), rainfall, sea level, ocean acidity and salinity, and other aspects of the climate system combine to give us a picture of our climate over time and enable us to identify trends and changes in key climate features. Instrumental observations are used in conjunction with climate models and palaeo-climate data to help us understand the causes of climate variability and change.

Global and Australian climate records extend over varying periods and depend on the number, location, and quality of instrumental observations. Observational data sets are continually and extensively analysed, to ensure they provide the best possible picture of global and Australian climate.

Australian terrestrial temperature

Surface temperature has been recorded at many sites across Australia since the mid-to-late 19th century. A network of standard thermometers and standard thermometer shelters was progressively introduced throughout Australia between 1890 and 1910.[1, 2] This network has provided an accurate picture of temperature changes since 1910. The Australian temperature record has been extensively analysed by the Bureau of Meteorology and researchers at CSIRO, Australian universities, and international research institutions.

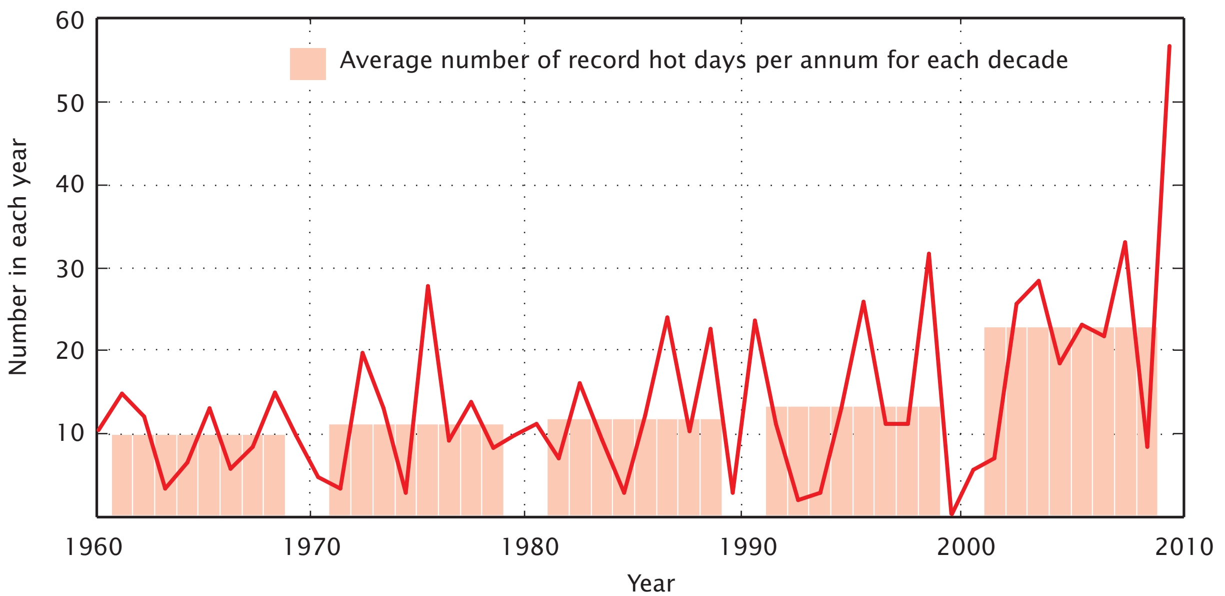
These records show that surface temperatures in Australia rose by just under 1ºC over the 100 years from 1910 to 2009. Global average temperatures have risen by about 0.7ºC over the past century. Warming was modest in Australia in the early part of the 20th century, followed by a slight decline from around 1935 to 1950, and then a rapid increase until 2010. Australian average temperature has increased by around 0.7ºC since the middle of the 20th century.[3] This trend is continuing: the second half of 2009 was the warmest on record for Australia and 2010 was one of the hottest years in the instrumental climate record. The past decade (2000 to 2009) was Australia's warmest decade on record.

Temperature changes during the 20th century have varied across the continent owing to a number of different factors. For instance, years of high rainfall are typically associated with cooler than average temperatures, while years of low rainfall and drought are typically warmer than average.[4] Season-to-season and year-to-year changes in prevailing weather systems also cause significant temperature variability across the continent.

CSIRO

Almost all of Australia has warmed over the 50 years since 1960. Some regions have experienced temperature increases of up to 2ºC over this time, while other regions have experienced little or no change. The weakest warming trends are in north-western Australia, which has also seen an increase in rainfall since 1960. The long-term trend in Australia-wide average temperature, however, is clear and distinct from the observed background variability. Warming has occurred in all seasons, with the strongest warming occurring in spring (0.9ºC) and the weakest in summer (0.4ºC). Minimum (night-time) temperatures increased more rapidly than maximum (day-time) temperatures over most of the 20th century.

Overall, the frequency of extreme cold weather has decreased across most of Australia, while the frequency of warm weather has increased. For example, the number of days with record hot temperatures has increased each decade over the past 50 years (Figure 1.1). Evidence is emerging of increased frequency of severe heatwaves and warm extremes.[5, 6] The strongest trends in the frequency of hot days and warm nights have occurred in the north-east of the country since the mid-20th century, while the strongest declines in the frequency of cold days have occurred across the south.



▲ ***Figure 1.1**: Average number of record hot days per year for each decade for the period 1960 to 2010.*

Australian sea surface temperature

Temperatures measured at the surface of the oceans show that they have also warmed considerably in the past 120 years. As with land temperatures, changes in local sea surface temperatures are affected by both long-term global warming and year-to-year influences, such as the El Niño-Southern Oscillation.

Globally averaged sea surface temperatures have increased by about 0.7ºC. Temperatures of the surface waters surrounding Australia have warmed by about 0.9ºC since 1900, with about 0.4ºC of that warming having taken place in the past 50 years. Changes in sea surface temperatures also display regional variation, as with temperature over land. The south-eastern coastal regions of Australia have experienced the strongest warming over the 20th century. Significant seasonal warmth caused notable episodes of coral bleaching on the Great Barrier Reef in both 1998 and 2002.

Australian rainfall

Australia is an island-continent and different regions have quite different patterns of rainfall, both in terms of seasonality and the amount of rainfall. Rainfall in the tropical north is generally monsoonal, with a pronounced wet season over the summer months and dry for the remainder of the year. Rainfall in the south of the continent, by contrast, is dominated by winter storm activity. Much of the rest of the continent, particularly the interior, is either arid or semi-arid. This very large regional variability means that Australian average rainfall is not such a meaningful national measure as Australian average temperature.

Australia is subject to extreme rainfall variability compared with many regions of the world, including other arid regions such as the Sahara or Gobi deserts. Incursions of moist tropical air and tropical cyclones result in occasional deluges across the desert and semi-desert interior. Similarly, vast movements of oceanic heat and atmospheric circulation over the Pacific Ocean, known as the El Niño-Southern Oscillation, are associated with periodic droughts (El Niño) and, alternatively, heavy rainfall (La Niña) across the eastern and southern parts of the continent. Sea surface temperatures in the Indian and Southern oceans, as well as atmospheric circulation around the Southern Hemisphere as a whole, also make strong contributions to Australian rainfall variability.[7–9]

It is difficult to characterise long-term changes in Australian rainfall amidst this background of large, natural, year-to-year and decade-to-decade variability. For instance, while much of southern Queensland and northern New South Wales experienced (on average) severe and prolonged dry periods in recent decades, the longer term trend is not sufficiently clear to be able to distinguish whether these recent dry periods are different from the large decade-to-decade variability that is a natural feature of climate in these regions. Indeed, record- and drought-breaking rain during 2010 across Queensland and NSW is consistent with long-term natural variability.

Cool season (April to November) rainfall in the south-west of Western Australia (SWWA) and in south-eastern Australia over the last 15 to 30 years has shown changes that are large compared with natural variability. This is particularly true for SWWA, where winter season rainfall has declined by around 15% since the mid-1970s.

The rainfall declines across south-eastern parts of the country, including the lower Murray–Darling Basin (MDB), have been associated with widespread, long-term drought. As with SWWA, the most statistically significant rainfall reductions have occurred during the autumn and winter seasons, and have occurred since the mid-1990s. While heavy rainfall across the south-east during 2010 brought an end to a 13-year sequence of below average annual rainfall in Victoria, the heavy rainfall mostly occurred during spring and summer.

Significantly, the 15% decline in autumn/winter rainfall has been associated with much larger reductions in stream flow (up to 60% for SWWA and the lower MDB).[10, 11] Several factors have most likely caused the dramatic reduction in stream flow, and hence water storages, in southern drought-affected regions. There is a general tendency for changes in rainfall to be amplified in changes in stream flow. The timing of the rainfall deficits is important, because this can amplify the impact on soil moisture, water storages, and stream flows. Typically, rainfall in autumn and early winter soaks the catchments so that surface water runs off into creeks and water storages during late winter and spring. Catchments are generally drier during the winter season when autumn rain fails. This means that more winter rainfall is taken up by vegetation and dry soils, resulting in less rainfall making its way into water storages. It is notable that, despite heavy rainfall in Victoria during the second half of the year, Melbourne recorded its 14th consecutive year of below average inflows to water storages during 2010.

Attribution of observed climate changes

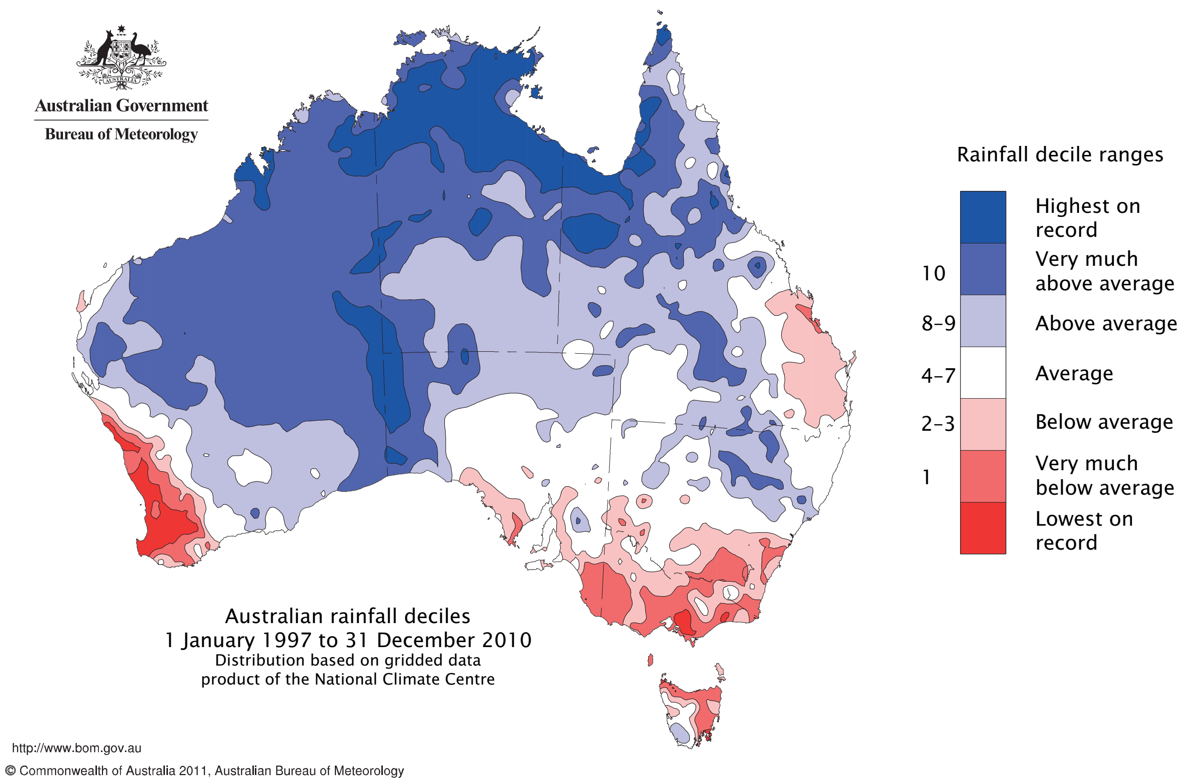
Climate change attribution is a field of climate science that seeks to determine cause and effect in the climate system. Attribution studies investigate the role that increasing greenhouse gases have played in climate change during the 20th century. Such studies compare changes in observed climate with various simulations or experiments using coupled atmosphere–ocean general circulation models, also known as Coupled Global Climate Models or Earth System Models (see Chapter 3).

The combination of observations and climate models are currently the best tools available to differentiate the natural and human-induced effects on the climate system because experimentation with real climate systems is not practically possible. Experiments using climate models typically include increasing greenhouse gases, changing solar radiation, changing atmospheric aerosols due to volcanoes and industrial pollution, and changing stratospheric ozone. These models, harnessing the strength of modern computing power, have been shown to be skilful enough in their representation of the real climate system to provide meaningful insights into the causes of recent climate change.

Studies have linked most of the warming in global temperatures in the past 100 to 120 years, especially in the last 50 years, to increasing greenhouse gases and the enhanced greenhouse effect.[12] It is extremely unlikely that the observed global-scale warming is due to natural variability. Simulations of the last 100 years of climate that include both human and natural influences on climate successfully reproduce observed patterns of global temperature change, whereas simulations that do not include human factors fail to reproduce the observed patterns. This contrast indicates that recent changes in temperature cannot be explained adequately by natural causes alone. Consistency between warming over land and warming over oceans during the 20th century provides further evidence that temperature changes are real rather than an artefact of recording practices. This is because land and sea temperatures are recorded very differently and are influenced by quite different factors, yet they reveal the same patterns of warming.

It generally is easier to attribute changes in temperature over large regions, such as the globe or a hemisphere, to greenhouse gas increases than it is to attribute regional temperature changes. This is because natural variability from year to year in individual regions is larger than it is over the globe as a whole, thereby making it more difficult to separate the effect of longer term changes from natural variability. Nonetheless, studies have shown that changes in Australian regional temperatures are most likely due to greenhouse gas increases and not due to natural processes alone.[4, 13, 14]

Scientists have a much more difficult task attributing Australian rainfall changes to human-induced climate change because it is difficult to separate naturally occurring drought from long-term declines in rainfall. The issue of largest interest has been the causes of the recent, long-term drought in the south-west and south-east of the continent.[15] Drought conditions persisted in the south-east from around 1996 to 2010 (see Figure 1.2). Research has shown that some aspects of this drought are consistent with global warming, but it has not been possible to unequivocally attribute this dry period to the enhanced greenhouse effect.[16] The drought in the south-west of WA has been particularly prolonged, such that it is often characterised as a long-term decline in rainfall, or an increase in aridity, rather than drought. The reduction in rain has been linked with shifts in prevailing weather patterns (e.g. storms and cold fronts) and a general reduction in rainfall associated with those systems. Some of these changes have been shown to be consistent with human influences (greenhouse gas increases and decreases in stratospheric ozone) in combination with natural climate variability.[17–23] Similarly, increased atmospheric pressure in the region, particularly in the subtropical ridge (a zone of high pressure or descending dry air across the southern half of the continent, associated with clear skies and low rainfall), has also been shown to be associated with the decline in rainfall across southern Australia, as well as being consistent with human-induced climate change.[24–26]



▲ ***Figure 1.2**: Summary of rainfall 1 January 1997 to 31 December 2010.*

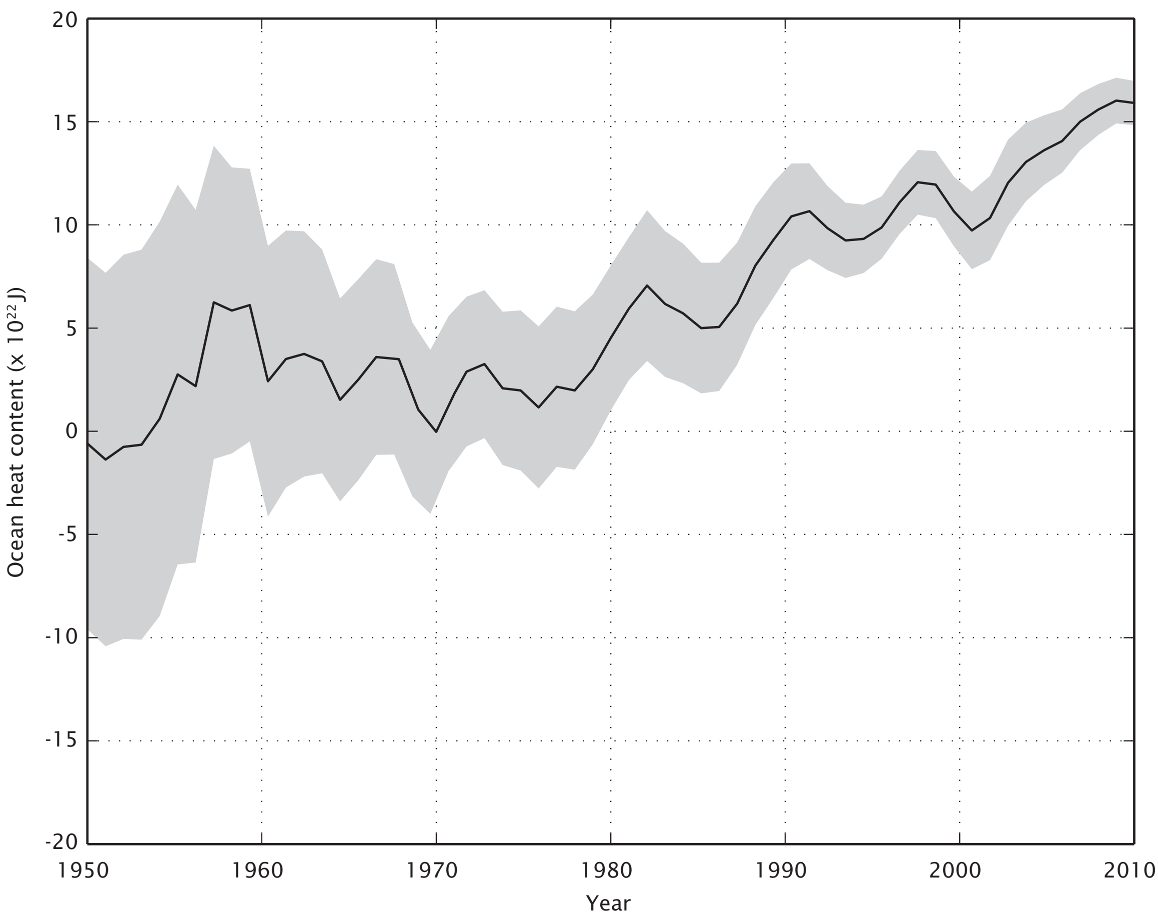
There is no unequivocal evidence that long-term changes in the Indian and Pacific oceans, such as changes to the El Niño-Southern Oscillation, have had a major influence on rainfall trends over Australia, despite studies that have identified possible changes over the 20th century in these large features of climate variability.[27] This is an area of active research in Australia, and internationally.

Observations from the oceans

Temperature

The oceans are the Earth's true thermometer. Their changing heat content provides measurable evidence of the warming of the planet. The vast amounts of heat that the oceans have absorbed in recent decades are causing them to expand and therefore to rise – just as heat makes the mercury in a thermometer rise – and to change in profound ways.[28]

The change in heat content of the world's oceans is prodigious: observations between 1961 and 2008 indicate that the upper few hundred metres of the ocean absorbed well over 100 billion trillion joules of energy (Figure 1.3).[29–31] This vast heat storage slows the rate of warming in the atmosphere and affects the regional distribution of these changes.

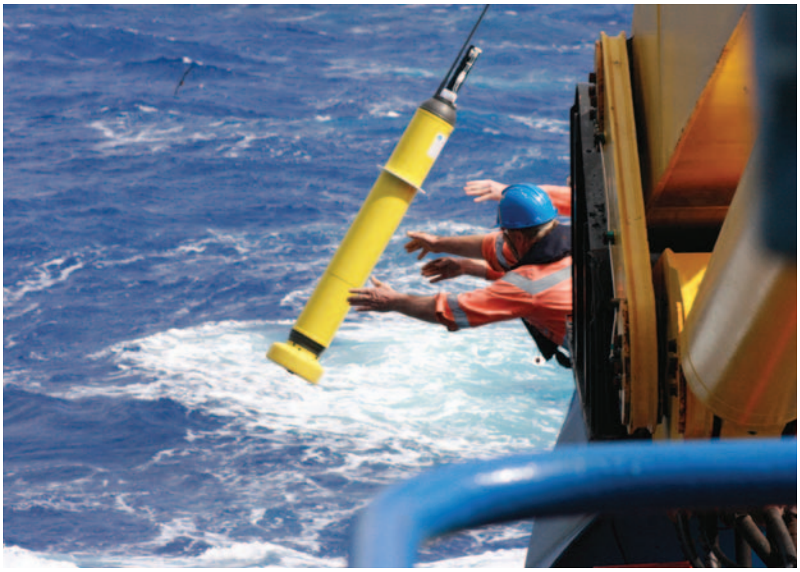


▲ ***Figure 1.3**: Updated estimates of changes in upper ocean heat content relative to 1970. The time series updated by Domingues* et al. *(2008)[29] is shown in black, with one standard deviation uncertainty estimates indicated by the shading. Uncertainties for recent periods are smaller than earlier periods because recent observations of ocean temperature are both more numerous and accurate.*

Salinity

Another measure of the changing oceans and climate are changes in ocean salinity. Parts of the sea that are naturally quite saline have become measurably saltier owing to increased evaporation or less rainfall, or both, while other parts have become fresher as they are diluted by increased rainfall or decreased evaporation, or both. These patterns taken together point to far-reaching changes in the global hydrological cycle.[32]

Regional ocean currents are also changing. For example, there has been a southward shift of the Antarctic Circumpolar Current – the vast current that circles the planet around Antarctica[33] – and an increasing southward extension of the East Australian Current associated with wind changes in the southern Pacific.[34] There also are indications of recent changes in the temperatures and salinities of deep ocean currents, such as those that carry cold bottom water northwards away from Antarctica.[35] These currents bear careful watching because they are key components in the distribution of heat around the planet.



Alicia Navidad/CSIRO

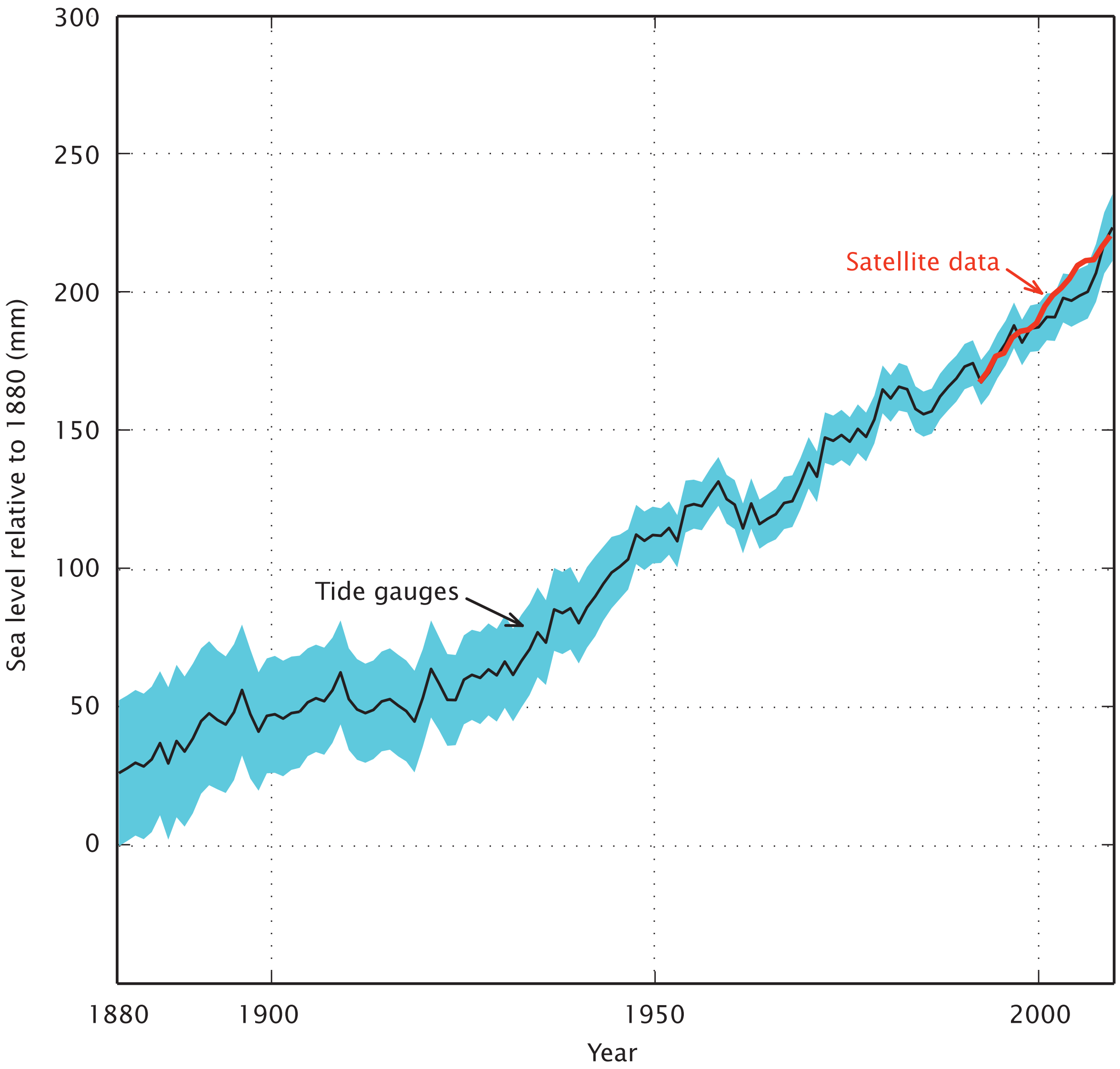
Acidification

The oceans also absorb vast amounts of CO_2, as well as storing heat. They currently remove about 25% of the emissions of CO_2 produced by human activities, as described further in Chapter 2. However, this sequestration comes at a price. A direct result of this CO_2 uptake is the gradual acidification of the oceans. Ocean absorption of CO_2 in the last 250 years has decreased near-surface ocean pH by about 0.1 and is expected to decrease it by a further 0.2–0.3 by 2100. This could have profound effects on corals and plankton, and other marine organisms with carbonate skeletons. These organisms span the entire marine food chain.

Sea levels

Sea-level rise and fall is nothing new and earlier populations have experienced large fluctuations in sea level.

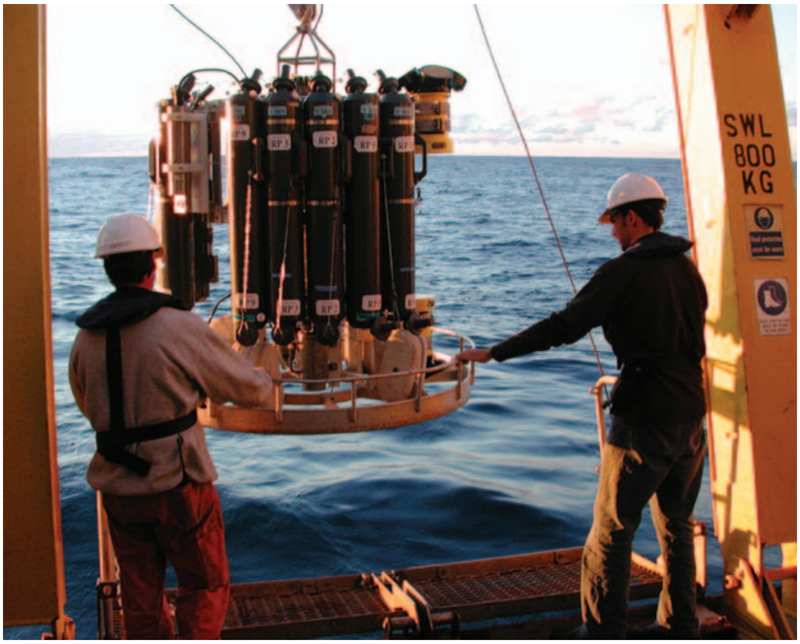
Geological records indicate that sea level peaked at between 6 m and 9 m higher than today during the last interglacial period, about 125 000 years ago.[36] Sea level was more than 120 m below today's levels at the peak of the last ice age (about 20 000 years ago).[37] Rates of sea-level rise coming out of the last ice age averaged about 1 m per century for many thousands of years, with maximum rates of 2–4 m a century.[38] Sea level stabilised around 3000 years ago and archaeological data indicate a period of small rates of change in global averaged sea level for the 2000 years before about 1800. Sea level began to rise again in the late 19th century.[39]



Sedentary coastal societies have developed during this period of stable sea level and they are potentially vulnerable to future sea-level changes. About 150 million people live within about a metre of high tide levels today and the near-coastal zone generates some US$1 trillion of global economic activity.[40]

Global sea levels are currently rising at around 3.2 mm a year, nearly twice the average rate (1.7 mm per year) experienced during the 20th century as a whole (Figure 1.4)[28, 41] and at a rate near the upper end of the Intergovernmental Panel on Climate Change projections. Rising sea levels have already significantly increased the frequency of high coastal sea-level events in Australia[42] and overseas. These occur when storms and strong onshore winds coincide with high tides.

Current climate models project that by 2100 sea level could be about 20 to 60 cm above 1990 values.[43] However, current models do not adequately represent the recently observed contribution of the ice sheets in response to warming. If this contribution was to grow linearly with temperature, then sea level could rise a further 10 to 20 cm (for a total range in 2100 of about 20 to 80 cm).[43] Note, however, that current understanding of ice sheet processes is inadequate



Lucy Potts/CSIRO

◂ ***Figure 1.4***: *Global averaged sea-level anomalies relative to 1880. The solid black line is estimated from coastal and island tide gauges and the red line is sea level measured by satellite altimeters. The average rate of rise from 1900 to 2000 was about 1.7 mm/year. The rate of rise measured by satellite altimeters since 1993 has been about 3.2 mm/year and from tide gauges about 2.8 mm/year.*[41]

and larger values cannot be excluded.[43] There have been a number of attempts to better quantify this upper end of the potential sea-level rise during the 21st century. For example, a study for the Netherlands Government suggested a high end value for sea-level rise of 110 cm above 1990 levels by 2100.[44]

The main contributions to sea-level rise in the past half century have been expansion of the upper layers of the oceans as they warm and increased discharge from glaciers worldwide.[45] Ice sheets over Greenland and Antarctica have played a comparatively smaller role in raising sea level so far, but there are indications they may contribute more in the future. The future evolution of ice sheets is critically important because the Greenland ice sheet alone contains enough water to raise the global sea levels by about 7 m and the West Antarctic ice sheet could add about a further 5 m. An ice-sheet's contribution to sea level is a balance between snowfall accumulating on the ice sheet (which is likely to increase in a warming world) and melting of the snow and ice and the sliding of ice sheets into the ocean. Melting is increasing in Greenland and there are indications of a recent increase of the flow of ice into the ocean from both Greenland and Antarctica (particularly in West Antarctica). This follows the penetration of warm ocean water onto the continental shelf under the ice shelves, which is melting the ice shelves at their base and contributing to their decay with a resultant more rapid flow of ice into the ocean. This phenomenon has been observed already in the Antarctic Peninsula. One of the major uncertainties in our knowledge of how much ice sheet loss will contribute to future rises in sea level is how much these rapid dynamic responses of the ice sheets will add to other contributions to sea-level rise. This uncertainty remains controversial because the contributing processes are not well understood.[43] Current rates of emissions of

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greenhouse gases mean that global average temperature is likely, late in the 21st century, to cross the threshold that leads to ongoing and potentially irreversible melting of the Greenland Ice Sheet, even without the above dynamic response, committing the world to metres of sea-level rise.[46]

The rise in sea level projected for the 21st century would be likely to cause coastal flooding events that now occur once a century to occur more than once a year by 2100 at many Australian locations. Tens of millions more people worldwide will be exposed to the hazards and cost of adapting to increased coastal flooding and erosion.[45] Many of the world's megacities, from Dhaka and Shanghai to New York, would be threatened by a sea-level rise of metres over the longer term if greenhouse gas emissions continue unabated.

Longer term commitment

The huge heat and carbon storage capacity of the ocean and the long time scales over which the ocean responds to changes in atmospheric conditions mean that the oceans will continue to warm and affect the Earth's climate for centuries to come, even if greenhouse gas emissions are stabilised at levels substantially lower than in the late 20th century.

Conclusion

High-quality climate observational data sets will continue to play a significant role in our quest to understand our changing climate. This is particularly the case as we endeavour to determine the full extent of the impact of greenhouse gases, aerosols, and climate feedbacks, which we explore further in the following chapter.

Further reading

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Church JA and White NJ (2006) A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* **33**, L01602, doi:10.1029/2005GL024826.

Church JA, Woodworth PL, Aarup T and Stanley Wilson W (eds) (2010) *Understanding Sea-level Rise and Variability*. Wiley-Blackwell Publishing, Chichester, UK.

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Climate and greenhouse gases

By Michael Raupach and Paul Fraser

Key messages

- Greenhouse gases (GHGs) influence the Earth's climate because they interact with flows of heat energy in the atmosphere.
- The main GHGs influenced directly by human activities are carbon dioxide (CO_2), methane, nitrous oxide, ozone, and synthetic gases. Water vapour, although an important GHG, is not influenced directly by human activities.
- The amount of warming produced by a given rise in GHG concentrations depends on 'feedback' processes in the climate system, which can either amplify or dampen a change. The net effect of all climate feedbacks is to amplify the warming caused by increasing CO_2 and other GHGs of human origin.
- The atmospheric level of CO_2 (the most important GHG influenced by human activities) rose from about 280 ppm in 1800 to 386 ppm in 2009, and is currently increasing at nearly 2 ppm per year.
- CO_2 levels are rising mainly because of the burning of fossil fuels and deforestation. Over half of this CO_2 input to the atmosphere is offset by natural CO_2 'sinks' in the land and oceans, which constitute a massive natural ecosystem service helping to mitigate humanity's emissions.
- To have a 50:50 chance of keeping human-induced average global warming below 2ºC, it will be necessary to stop almost all CO_2 emissions before cumulative emissions reach one trillion tonnes of carbon. The world has already emitted more than half of this quota since the industrial revolution, and (at current growth rates for CO_2 emissions) the rest will be emitted by the middle of this century.
- Climate change is a risk management issue – the longer we take to act and the weaker our actions, the greater the risk of dangerous outcomes.

Greenhouse gases and the Earth's climate

Life on Earth depends on the presence of greenhouse gases in the atmosphere to insulate our planet's surface against the chill of space. The main GHGs influenced directly by human activities are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and synthetic gases, such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). Water vapour is also a major greenhouse gas, but its concentration in the atmosphere is not influenced directly by human activities; rather, it is controlled mainly by the Earth's temperature.

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Greenhouse gases influence Earth's climate because they interact with energy flows. The atmosphere (including its GHGs) is largely transparent to the Sun's energy, most of which arrives in the form of light. At the Earth's surface, this energy is partly reflected and partly absorbed and re-radiated as heat. Paler ice- and snow-covered surfaces of the planet reflect much more energy than darker surfaces, such as forests and oceans. The GHGs in the atmosphere absorb and re-radiate much of the outgoing heat energy. At the same time, minute particles or droplets floating in the atmosphere, known as aerosols, act both to reflect incoming solar radiation (light) and to absorb and re-radiate outgoing heat.

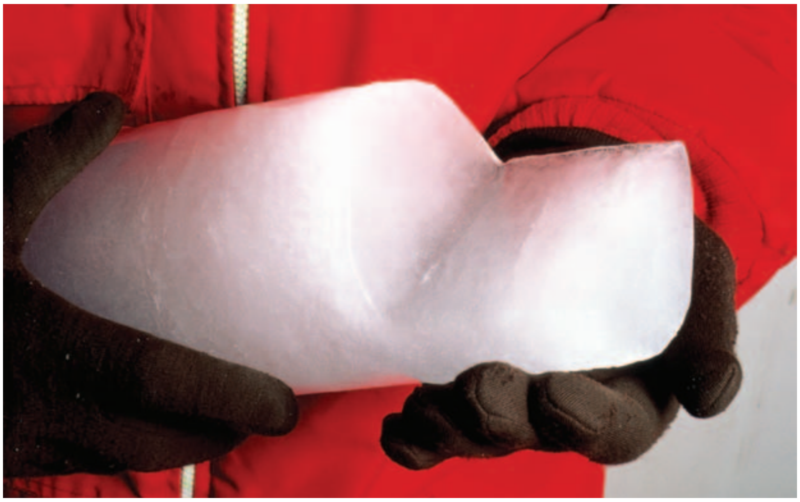
The Earth's climate is influenced by all of these factors, which together maintain the planet at about 32ºC warmer than it would otherwise be. Their combined effect is measured by a quantity called net radiative forcing, which is basically the net rate of input of heat energy to the entire planet due to all the processes described above. Extra heat builds up in the atmosphere and oceans when the rate of energy input is positive, causing the planet to warm. The net radiative forcing in 2005 was +1.6 W/m^2 (Watts per square metre), with uncertainty discussed below.[1] This is equivalent to the energy input from running a 1 kW electric radiator on an area the size of a suburban block – day and night, all year round, for every block-sized patch of the entire planet's surface. It is this massive input of energy to the Earth's surface and lower atmosphere that is causing global temperatures to increase.

There are several important factors affecting the net radiative forcing, as shown in Figure 2.1 (2005 values). The contributions fall into three main groups:

- CO_2 contributes about 1.7 W/m^2
- the other GHGs, including methane, nitrous oxide, synthetic gases, and ozone, together contribute about 1.3 W/m^2
- aerosols, together with some other physical processes such as changes in the Sun's energy output and the brightness of the Earth's surface, have a net effect of reducing radiative forcing by 1.1 W/m^2. There is a significant degree of uncertainty in this estimate, however, because the effects of aerosols are complex. For example, dark aerosols, such as carbon in fire smoke, tend to absorb solar radiation and enhance warming, while pale-coloured aerosols, such as sulphate particles formed from many kinds of industrial emissions, reflect solar radiation back to space and exert a cooling effect.

The combination of these and other minor contributions gives a net positive radiative forcing of about 1.6 W/m^2, causing a net warming of the atmosphere. This is similar to the radiative forcing from CO_2 alone, because at present the contributions from non-CO_2 GHGs and from aerosols approximately cancel one another out. This approximate cancellation is unlikely to continue, because a probable future decrease in pollution-based aerosols in the atmosphere will reduce the negative (that is, cooling) aerosol contribution to radiative forcing, resulting in increased warming.

Figure 2.2 shows how the contributions to radiative forcing from the long-lived GHGs (CO_2, methane, nitrous oxide, and synthetic gases) have built up from 1900 to 2009, based on measurements from CSIRO,[2] the Advanced Global Atmospheric Gases Experiment (AGAGE) global GHG networks,[3] and CSIRO measurements of air trapped in Antarctic ice[4] and near-surface levels of ice known as firn.[5]



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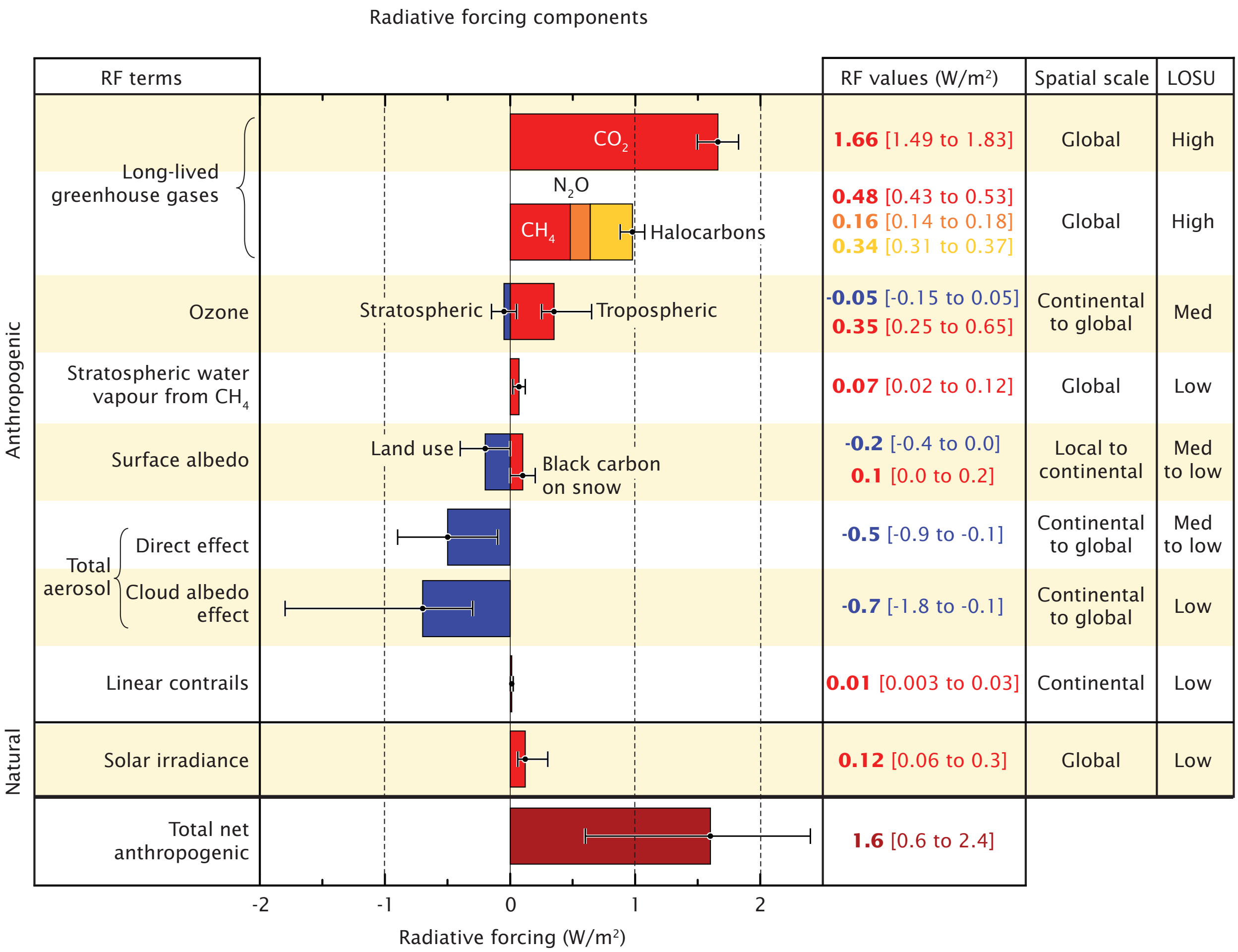
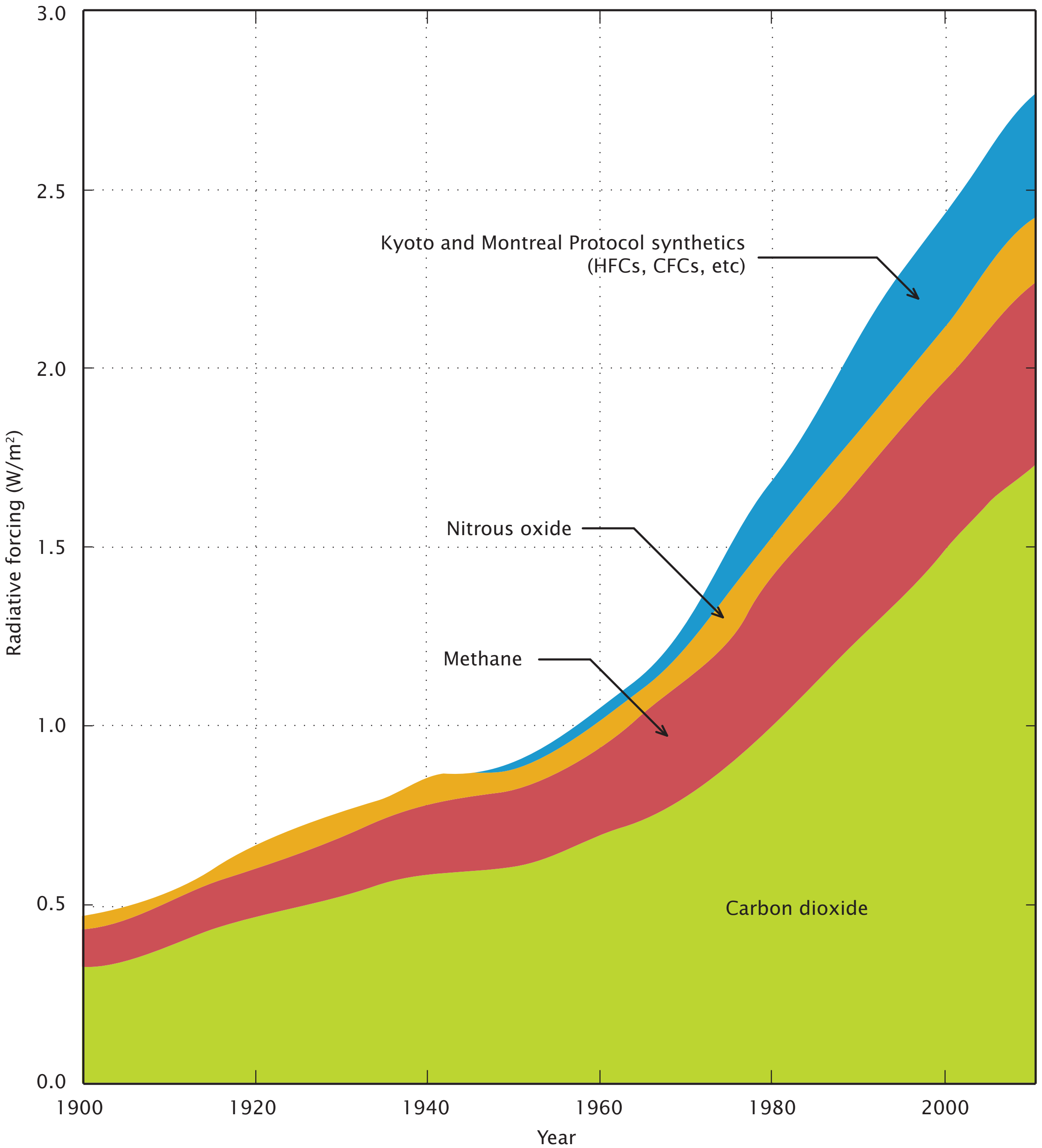


▲ ***Figure 2.1***: *Global-average radiative forcing (RF) in 2005 (best estimates and 5–95% uncertainty ranges) with respect to 1750 for CO_2, CH_4, N_2O, and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). Aerosols from explosive volcanic eruptions contribute an additional episodic cooling term for a few years following an eruption. The range for linear contrails does not include other possible effects of aviation on cloudiness. Note that the total net human-induced radiative forcing (1.6 W/m²) is not a simple sum of components. Reproduced from Figure 2.4 of the IPCC (2007) Synthesis Report.*[1]



▲ ***Figure 2.2**: Global radiative forcing due to long-lived GHGs from 1900 to 2009 assessed from data measured in the CSIRO[2] and AGAGE[3] networks, which are archived annually in international GHG data archives [World Meteorological Organization World Data Centre for Greenhouse Gases, WMO-WDCGG: http://gaw.kishou.go.jp/wdcgg/ and US Dept of Energy Carbon Dioxide Information Analysis Center (CDIAC): htpp://cdiac.oprnl.gov] and from CSIRO measurements on air trapped in Antarctic ice[4] and firn.[5]*

Table 2.1 shows how CSIRO's measurements of the radiative forcing from these GHGs compare with those reported by the IPCC.[6] The small differences between the CSIRO and IPCC measurements result from the different global observational networks used by CSIRO (CSIRO and AGAGE) and IPCC (CSIRO, NOAA, and AGAGE). The CSIRO 2009 data are very likely to be almost identical to IPCC data for 2009, which are yet to be published.

Table 2.1: Concentrations (ppm – parts per million molar; ppb – parts per billion molar) and radiative forcings (W/m²) for 1998, 2005, and 2009 due to long-lived GHGs as reported by the IPCC[6] and calculated from data collected in the CSIRO[2] and AGAGE[3] networks

Gas	Concentrations					Radiative forcing				
	1998		2005		2009	1998		2005		2009
	IPCC	CSIRO	IPCC	CSIRO	CSIRO	IPCC	CSIRO	IPCC	CSIRO	CSIRO
CO_2 (ppm)	366	366	379	379	386	1.47	1.46	1.66	1.65	1.76
CH_4 (ppb)	1763	1764	1774	1771	1789	0.48	0.49	0.48	0.49	0.50
N_2O (ppb)	314	314	319	320	323	0.14	0.15	0.16	0.16	0.18
Synthetic GHGs (ppb)	1.27	1.33	1.32	1.33	1.35	0.33	0.33	0.34	0.33	0.34
Total						2.42	2.43	2.64	2.65	2.77

North Sullivan Photography/CSIRO

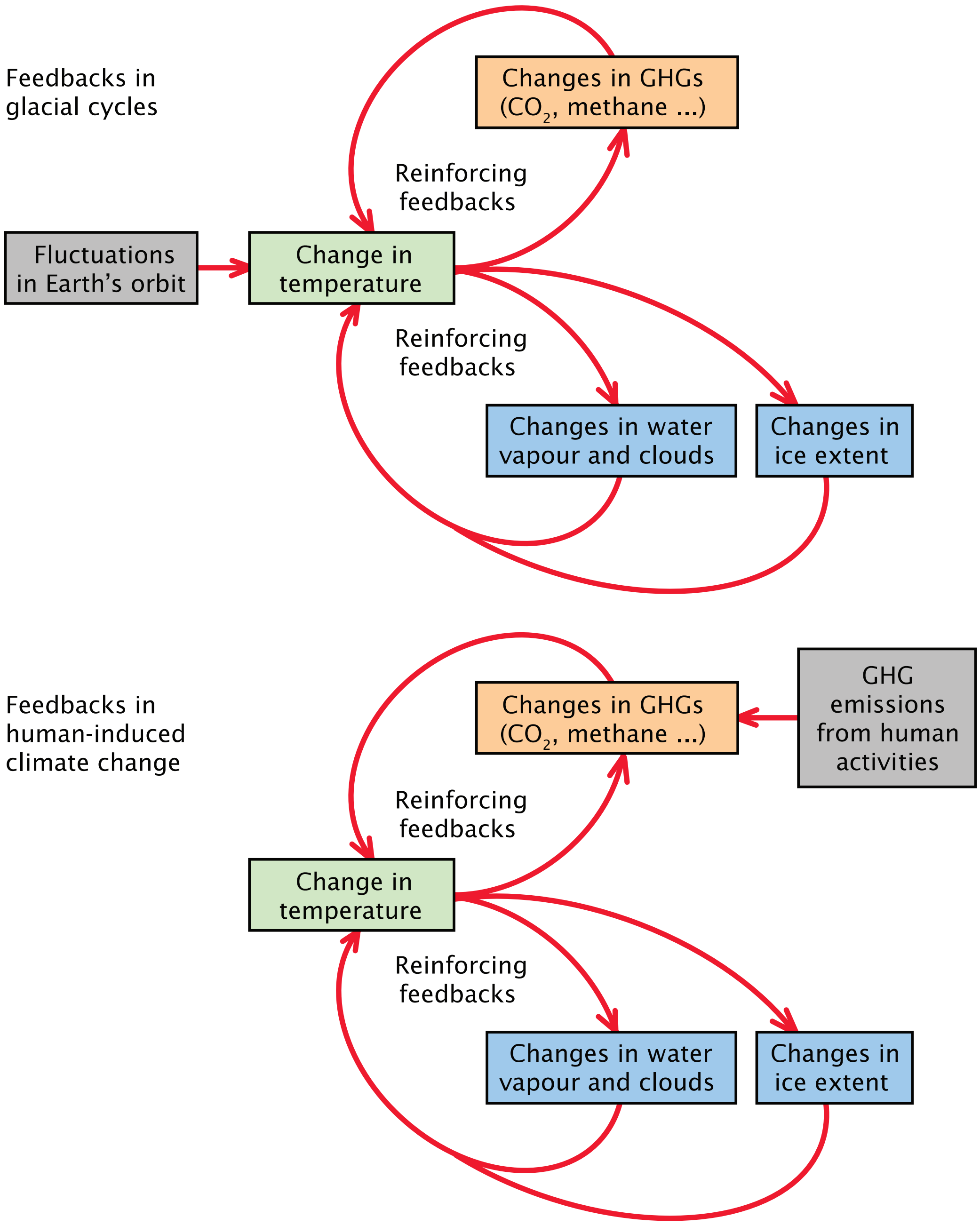
Feedbacks in the climate system

Knowledge of the radiative forcing tells us how much extra energy the Earth is retaining in the lower atmosphere, but it does not tell us the resulting warming. The amount of warming depends on many internal 'feedbacks' in the climate system. These are processes whereby a change in one component of the system ripples through to other components and back again, either to reinforce or dampen the original change.

As shown in Figure 2.3, feedback processes connect the atmospheric levels of GHGs (CO_2, methane, and others), water vapour, cloudiness, the extent of polar ice caps, and global temperature. The global average concentration of water vapour quickly increases in response to an increase in global temperature, due to the increased water-retaining capacity of a warmer atmosphere. Because water vapour is a GHG, the original warming is amplified. This reinforcing feedback approximately doubles the amount of warming that would otherwise be produced by a given amount of radiative forcing. A second, much slower, reinforcing feedback arises from the interaction between the surface area of polar ice caps and global temperature: as warming initiates a melting of the ice, the consequent darkening of the surface (as land or ocean from under the ice is exposed) leads to the absorption of more radiation, and thus further warming. A third important class of feedbacks involves the natural cycles of greenhouse gases, such as CO_2 and methane, which respond to temperature and moisture in ways that can amplify an initial warming.

The net effect of all these processes is a set of feedbacks that have an overall reinforcing effect. A doubling in CO_2 from pre-industrial levels (280 ppm) to around 550 ppm without feedbacks would result in a global warming of about 1ºC. Factoring in the effects of water vapour and other 'fast' feedbacks, however, means that a CO_2 doubling will amplify the long-term average warming to about 3ºC. This important number, called the 'fast climate sensitivity', is somewhat uncertain and could vary between 2º and 4.5ºC according to IPCC estimates based on a range of climate models.[1]

The conclusion that water vapour and related feedbacks have an overall amplifying effect is critical. It can be substantiated entirely independently from climate models using ice-core records of climate fluctuations over the last 850 000 years.[7] These show that small fluctuations in the Earth's orbit around the Sun led to large changes in global temperature through the same set of feedbacks that operates to amplify the climate change from human emissions of CO_2 and other GHGs. These records yield a value of about 3ºC for fast climate sensitivity to a doubling of CO_2, similar to the estimates from various climate models.[7]



▲ ***Figure 2.3***: *There are close connections between global temperature, atmospheric water vapour and cloudiness, the extent of polar ice caps, and levels of greenhouse gases in the atmosphere. When one of these is disturbed, such as by human activity, the others react through processes that amplify the original disturbance until a new, different, climate equilibrium is reached. The disturbance driving the glacial cycles over the last million years came mainly from fluctuations in the Earth's orbit around the Sun (grey box in upper diagram). This changed temperatures (green box), in turn changing water vapour and ice caps (blue boxes), and greenhouse gas levels (orange box). The disturbance in modern climate change comes largely from human-induced changes in atmospheric* CO_2 *and other greenhouse gas levels (grey box in lower diagram). The disturbance is amplified by similar reinforcing processes in both cases.*[8]

The carbon dioxide budget of the Earth's atmosphere

Radiative forcing from carbon dioxide is the largest single contributor to human-induced climate change (Figures 2.1, 2.2). Half a century or more of atmospheric measurements testify to a steady rise in CO_2 concentrations in the Earth's atmosphere. Measurements have been taken at places such as Mauna Loa, Hawaii (since 1956) and Cape Grim, Tasmania (since 1976), the latter as part of a joint Australian Bureau of Meteorology and CSIRO program to study global atmospheric composition. Furthermore, tiny air bubbles trapped in ice and firn cores taken from places such as Law Dome in Antarctica reveal what the atmosphere was like in earlier times.[4] Together, all these measurements allow us to trace the dramatic rise in CO_2 levels from about 280 ppm before the start of the industrial era around 1800 to 386 ppm in 2009 (Figure 2.4). CO_2 levels rose through the decade 2000–2009 at an average rate of almost 2 ppm per year, although the rate fluctuates from year to year.

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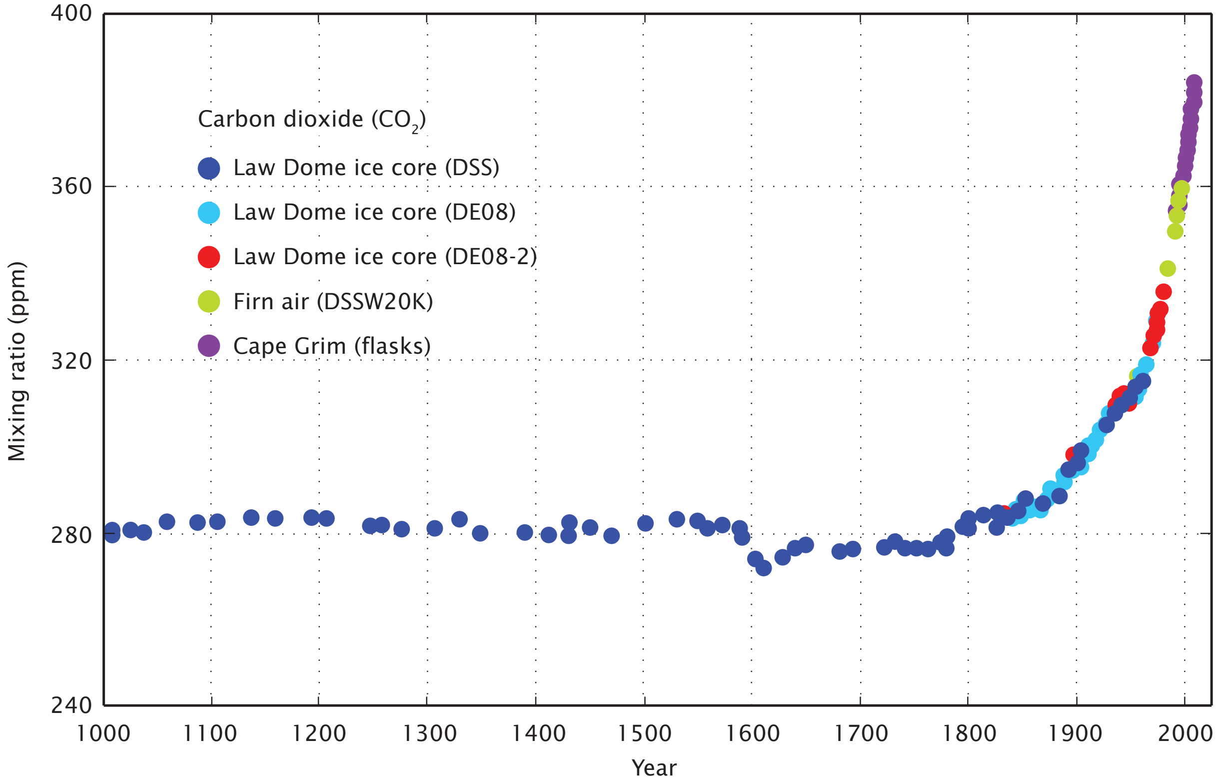
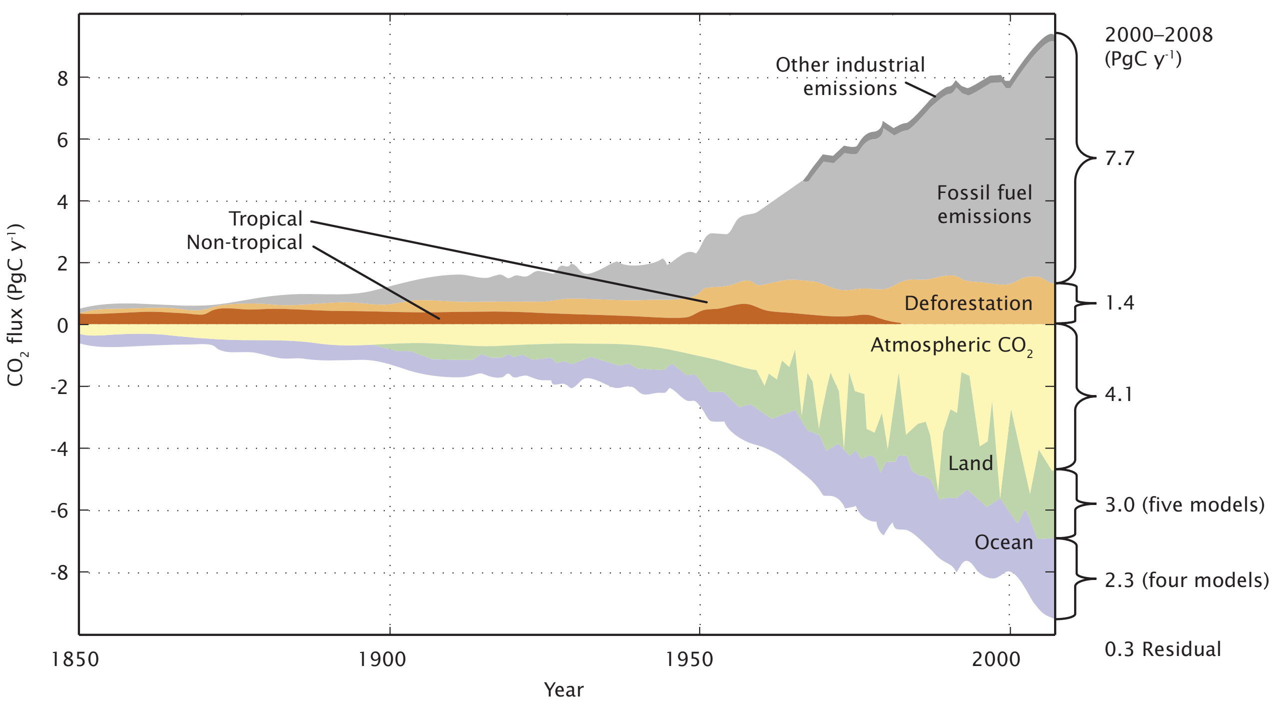


▲ ***Figure 2.4****: Southern Hemisphere atmospheric CO_2 levels over the past 1000 years, sourced from CSIRO data.*[2, 4]

Why are CO_2 levels rising as they are? The amount of CO_2 accumulating in the Earth's atmosphere is determined by the balance between inflows and outflows: in other words, a 'CO_2 budget'. For several millennia before the industrial revolution started around 1800, the CO_2 budget of the atmosphere was nearly in balance: natural inflows (transfers of carbon from land and ocean systems into the atmosphere as CO_2, together with small contributions from volcanic activity) were approximately equal to natural outflows (transfers of carbon out of the atmosphere into land and ocean systems). This nearly balanced budget meant that CO_2 levels in that atmosphere did not change significantly over centennial time scales (Figure 2.4).

Since around 1800, there has been an additional large inflow of CO_2 to the atmosphere from emissions due to human activities, including contributions from (1) the burning of fossil fuels (coal, oil, and gas), (2) cement production and other industrial processes, and (3) deforestation or land clearing (occurring now almost entirely in tropical regions). This inflow is partly offset by natural CO_2 'sinks' in the land and oceans. The land CO_2 sink derives from an imbalance between plant growth (through photosynthesis) and plant decay. Several factors are responsible: the stimulation of photosynthesis by increasing atmospheric CO_2 levels (though other nutrients must also be available for a sustained increase in plant growth); forest regrowth after deforestation that occurred many decades ago; changes in fire regimes; and changes in ecosystem structure, such as the replacement of tropical C4 grasses by woody C3 plants that store more biomass. The ocean CO_2 sink occurs because CO_2 dissolves in ocean waters (also increasing ocean acidity) when atmospheric CO_2 concentrations are higher than those at the ocean's surface. This dissolved carbon is then transported to the deep ocean both by overturning circulations and by the sinking of dead organisms that have derived their carbon by consuming phytoplankton (tiny photosynthesising organisms that convert CO_2 to organic carbon).

Figure 2.5 shows how the inflows and outflows of CO_2 interact to produce the current rapid increase in atmospheric CO_2 levels in the atmosphere.[9, 10] In the period 2000–2008, 82% of humanity's CO_2 emissions came from the burning of fossil fuels, primarily coal, oil, and gas, and 3% from other industrial sources. These emissions together grew by 3.4% per year.[10] The remaining 15% of emissions, from deforestation, were steady. We know these emissions originate from human activity because of chemical 'fingerprints' in the atmosphere, such as the oxygen level and the fractions of carbon isotopes (^{13}C and ^{14}C) in CO_2, which all indicate that the origin of the increased CO_2 is largely fossil fuels. For example, the observed decrease with time of the carbon isotope ratio ($^{13}C/^{12}C$) in the atmosphere is consistent with the impact of a fossil fuel source, because the $^{13}C/^{12}C$ ratio in fossil carbon is lower than that in the atmosphere. Such approaches also help to determine the magnitude of the terrestrial and oceanic CO_2 sinks.



▲ ***Figure 2.5***: *Sources and sinks of atmospheric CO_2. Those above the zero-line represent anthropogenic additions to the atmosphere (inflows); those below are sinks for CO_2 (outflows), together with the accumulation in the atmosphere. Units are in petagrams of carbon per year (Pg = petagram; 1 petagram = 10^{15} grams = 1 billion tonnes). The small residual reflects minor discrepancies in independent measurements of different terms.*[10]

Land and ocean CO_2 sinks respectively removed 30% and 25% of all anthropogenic CO_2 emissions over the period 2000–2008,[9–11] leaving about 45% to accumulate in the atmosphere. The Earth's CO_2 sinks, in both land and oceans, thus constitute a massive ecosystem service that helps to mitigate humanity's emissions.

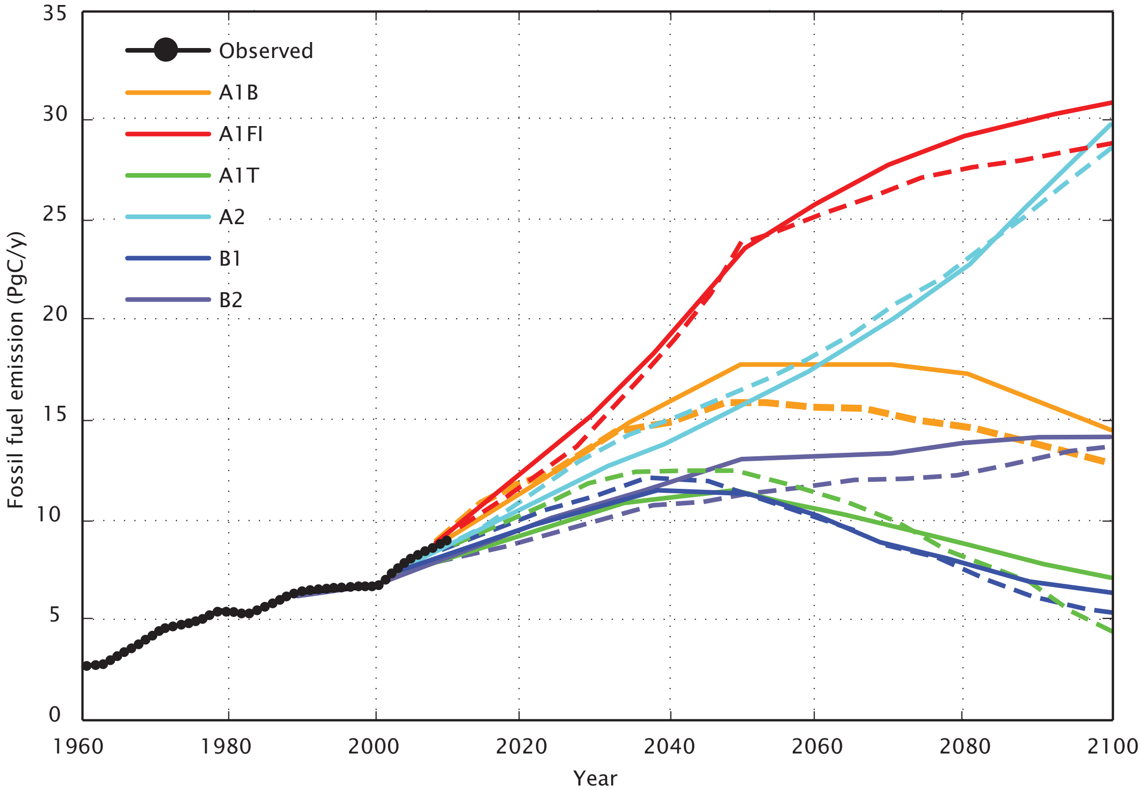
The fraction of CO_2 emissions staying in the atmosphere (about 45%) is known as the airborne fraction, or AF. There has been a small increasing trend in the AF over the period from 1960 to 2008,[9–11] which indicates that even though the land and ocean CO_2 sinks are continuing to grow with the rise in atmospheric CO_2, they are progressively 'losing the race' against the even more rapidly growing emissions. This is occurring for many reasons,[12] both for land and ocean sinks. For instance, on land, plants experience 'diminishing returns' in extra CO_2-induced growth with rising concentrations of atmospheric CO_2. On the oceans, climate change and ozone depletion drive stronger winds over the Southern Ocean – the largest ocean carbon sink – which may cause deep carbon-rich waters to upwell and release their CO_2 back into the atmosphere, thus reducing the net sink. An important consequence of the increasing AF is that the ecosystem service provided by the Earth's CO_2 sinks in soaking up a steady fraction of our CO_2 emissions has diminished in recent decades.

Trends in CO_2 emissions from fossil fuels

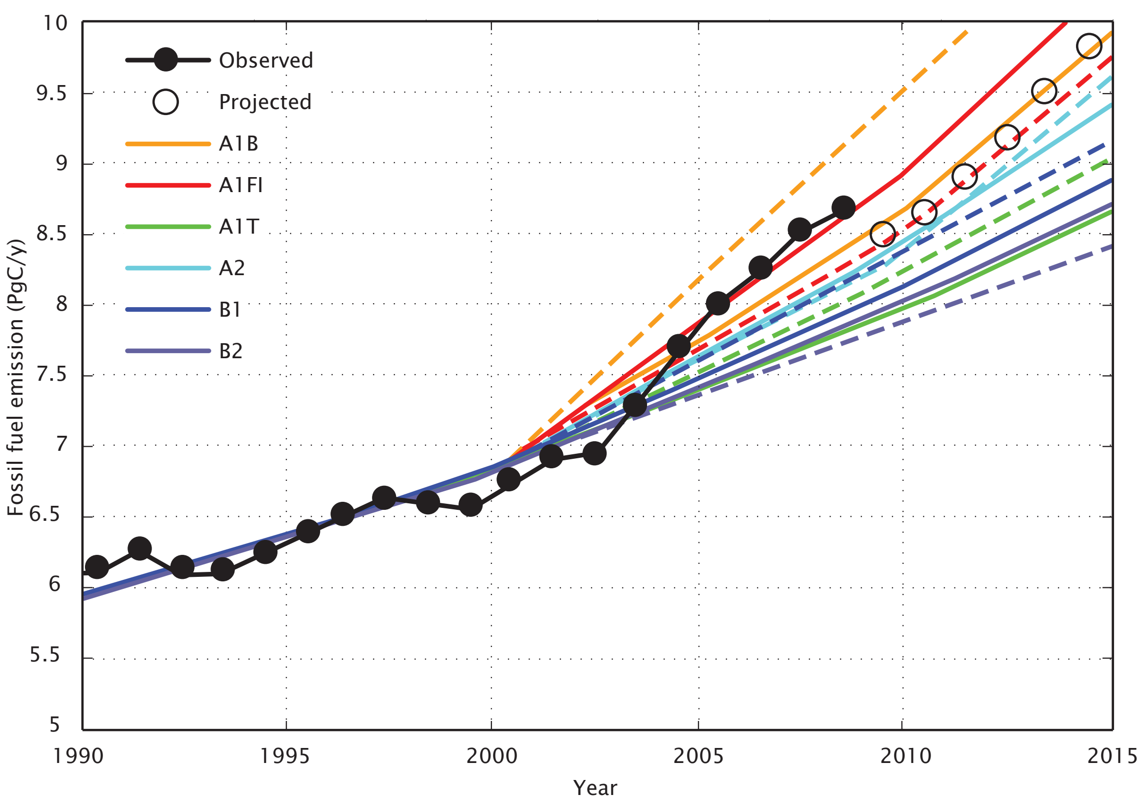
Critical to the rate of future climate change is how CO_2 emissions from the burning of coal, oil, and gas evolve over the coming decades. Figure 2.6 shows past emissions back to 1960 and a range of possible future scenarios out to 2100, as modelled by the IPCC in its *Special Report on Emissions Scenarios (SRES)*.[13] These scenarios involve assumptions about demographic, economic, and technological factors likely to influence future economic development and greenhouse gas emissions. Scenarios depend on factors such as rates of population increase, global economic growth, and humanity's relative success or failure at slowing emissions from the burning of coal, oil, and gas.

▸ ***Figure 2.6****: CO_2 emissions from fossil fuels[14, 15] measured in petagrams of carbon emitted per year (see Figure 2.5 caption for definition of petagrams). Observed data are shown as black and grey points. Solid coloured lines are average future emissions in six scenario families from the* IPCC Special Report on Emissions Scenarios (SRES).*[13] Corresponding dashed coloured lines denote marker scenarios used in IPCC climate change projections.[1] Scenarios are rescaled slightly to match actual emissions over the period 1990–2000. The upper (a) and lower (b) panels show the periods 1960–2100 and 1990–2015, respectively. Open circles in (b) are estimated emissions based on Gross World Product (GWP) projections[16] and an assumed carbon intensity of the economy (emissions/GWP) scaled to 2008 and reducing at 1.2%/year, the average value for 2000–2008.*

(a)


Observed
A1B
A1FI
A1T
A2
B1
B2
Fossil fuel emission (PgC/y)
Year
0
5
10
15
20
25
30
35
1960
1980
2000
2020
2040
2060
2080
2100

(b)


Observed
Projected
A1B
A1FI
A1T
A2
B1
B2
Fossil fuel emission (PgC/y)
Year
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
1990
1995
2000
2005
2010
2015

An important feature is seen in the lower part of Figure 2.6, which focusses on the 25-year period 1990–2015. This highlights a jump in fossil-fuel emissions growth[15] that took place soon after 2000. From 2000 to 2007, the growth rate of observed emissions was 3.4% per year, which exceeds almost all assumed scenarios generated in the late 1990s. This pulse of CO_2 emissions growth is attributable to strong global economic growth centred in China, India, and other rapidly developing economies, and the lack of effective reductions in emissions in developed countries. The pattern of growing emissions over the past two decades (whether a shorter term rapid increase in the early 2000s or a longer term increase starting in the 1990s) is an evolving research topic.[17]

The global financial crisis of 2008–2009 caused a temporary slowdown in global emissions growth, which is discernible in a dip in the upward trend of the line formed by the open circles in Figure 2.6. This dip was equivalent to about 6 weeks' worth of total global emissions. Allowing for the dip, the average growth rate in fossil-fuel emissions over the whole decade 2000–2009 was still high, at 3.0%. Assuming a return to rapid worldwide economic growth after the financial crisis, high growth in emissions is liable to continue unless rapid steps are taken to reduce the carbon intensity of the global economy.[14]

Budgets for other greenhouse gases

There is a similar global budget for the second most influential greenhouse gas, methane.[12] Here the dominant natural source (input to the budget) is wetlands, with a smaller natural source from termite activity. Additional major sources arise from human activities, through agriculture (rice and ruminant livestock production), waste disposal in landfill, gas leaks from pipelines and coal mines, and biomass burning. In recent decades, sources from human activities have exceeded the combined natural sources by two-fold or more. The main sink for methane is chemical degradation in the atmosphere.

Willem van Aken/CSIRO

The average atmospheric methane level in 2009 was 1789 parts per billion – more than twice what it was in the pre-industrial era. There has been little growth in methane levels over the past decade, suggesting that methane emissions and their removal from the atmosphere by oxidation to CO_2 are coming into balance. This has been attributed in part to a gradual reduction of leaks from natural gas pipelines and from other industrial sources such as coal mining and landfill sites.

The nitrous oxide concentration in 2009 was 323 ppb, about 20% above its pre-industrial level. The dominant human-influenced source is agriculture. Emissions of nitrous oxide, like CO_2, continue unabated.

There has also been significant radiative forcing (about 0.16 W/m^2) caused by synthetic GHGs – largely chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs) – as shown in Figure 2.2. The aggregate atmospheric concentration of these gases has recently stopped growing, but growth in concentrations is likely to resume[18] because of the large projected growth in future emissions of HFCs, which are currently widely used in modern refrigerators and air-conditioners. Ironically, HFCs were introduced to replace the use of the CFCs, which were causing stratospheric ozone depletion.

Greenhouse gases and climate in the future

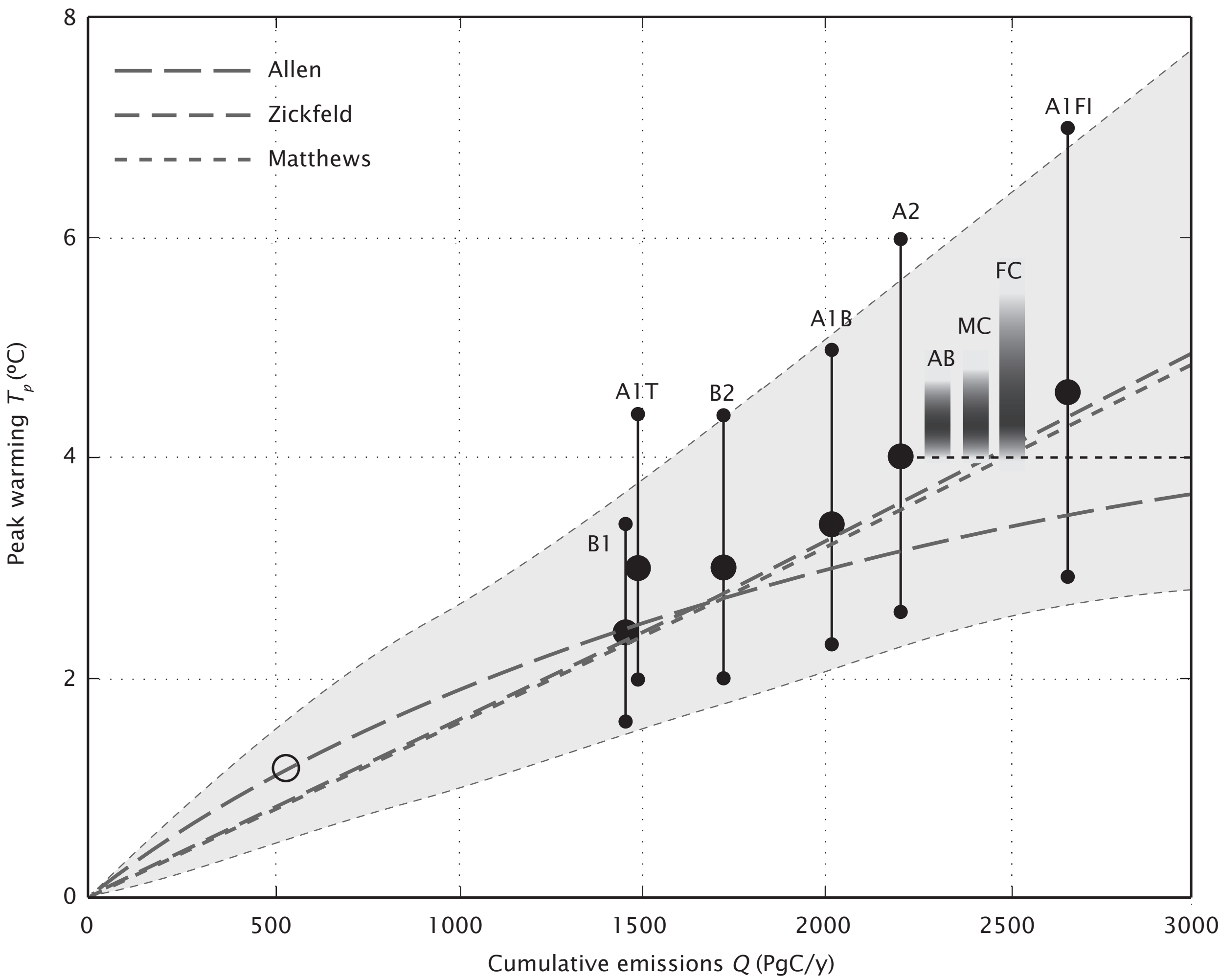
Whether climate change is ‘dangerous’ is a complex issue because different global regions will be affected in different ways. Nevertheless, a globally averaged warming of 2ºC above pre-industrial temperatures is widely used as a benchmark[19] at which the effects of climate change start to have dangerous risks and impacts. Chapters 1 and 3 describe some of these in more detail, such as sea-level rise, increased frequency of extreme weather, and so on.

The cumulative total amount of CO_2 emitted from all human sources in the past 250 years is now around 530 billion tonnes. To have a 50:50 chance of keeping global warming below 2ºC, it will be necessary to stop almost all CO_2 emissions before our cumulative emissions reach 1000 billion (one trillion) tonnes.[20–22] If CO_2 emissions keep growing at their present (2000–2010) rate, we will emit another 470 billion tonnes by around 2045. If we stabilise emissions from the present time (2010) onward without further growth, we will reach 1000 billion tonnes by around 2060. Any further emission leads to a greater chance of dangerous climate change. However, 50:50 is not good odds when it comes to avoiding danger; to improve those odds, the cap on cumulative emissions needs to be lower.

This underlines the fact that climate change is a risk management issue – the longer we take to act and the weaker our actions, the greater the risk of dangerous outcomes. The level of risk we incur is directly related to the strength and speed of our actions. It also makes it clear that setting and adhering to clearly defined targets is an important way of reducing risks of harm from climate change.

The assessment of risk from climate change, and its relationship to future greenhouse gas emissions, is made more complicated by uncertainties about the magnitude and speed of the response of climate to a given radiative forcing. These uncertainties stem mainly from the feedbacks illustrated in Figure 2.3. Although feedback processes can either reinforce or dampen climate change, the risks associated with these two possibilities are not evenly distributed: reinforcing feedbacks are particularly important because they lead to increased risks of very serious outcomes.

Figure 2.7 includes an assessment of the way that several processes might affect the peak warming induced by a given cumulative input of CO_2.



▲ ***Figure 2.7**: Peak warming from pre-industrial times, plotted against cumulative emissions of CO_2 (in petagrams of carbon per year) from both fossil fuels and land-use change, from 1750 to the far future. Dashed and dotted lines[20, 23, 24] represent the most likely warming from three studies in 2009, and the shaded band represents an uncertainty range. Current assessments are that warming is likely to fall within this range. Solid points show IPCC scenarios for 2100,[1] with uncertainty bars giving likely ranges. Shaded bars[14] show ranges of possible effects, relative to the IPCC A2 scenario as a reference, from FC (coupled carbon-climate feedbacks on carbon sink strength), MC (mobilisation of previously immobile carbon pools), and AB (release of aerosol brake). All ranges are indicative only. Open circle shows cumulative emissions to 2008 and the resulting peak warming of 1.2ºC (including 0.7ºC of warming observed to date plus 0.5ºC of committed warming with radiative forcing stabilised at 2008 levels).[1]*

Feedbacks on land and ocean CO_2 sinks

The influence of climate change on land and ocean CO_2 sinks occurs both through changes in atmospheric composition, particularly rising CO_2, and changes in climate, particularly the averages and distributions of temperature and rainfall. Recent studies[25, 26] have found that feedbacks between carbon dioxide concentrations and changes in climate tend to increase warming, but the possible range of responses remains large. An additional factor is that there are limits to the supply of nutrients (e.g. nitrogen and phosphorus), which are essential to maintain the land CO_2 sink. The uncertainty in consequent warming is conservatively indicated by the 'FC' bar in Figure 2.7.

Mobilisation of carbon from disturbed pools

Vast quantities of carbon currently lie locked up in huge natural reservoirs that can be disturbed by climate change, causing release of this carbon into the atmosphere as either CO_2 or methane, hence further accelerating warming. One such reservoir is the carbon locked up in frozen soils in the Arctic region, which is estimated at nearly 1700 billion tonnes in total.[27] Thawing as a result of warming over the next 100 years could release around 100 billion tonnes of this carbon to the atmosphere as CO_2 or methane.[28] Another large quantity of carbon exists in tropical peatland soils, mainly in South-East Asia – around 30 billion tonnes of this carbon could be released as CO_2 or methane by drainage or fire.[29] Net releases of carbon from forest ecosystems are also possible through fire, insect attack, and ecological transitions such as conversion of tropical forests to grasslands. An as yet unquantified risk exists in frozen deposits of ancient methane beneath the Arctic seabed. The 'MC' bar in Figure 2.7 shows a conservative range for the overall warming consequences of these risks.

Release of the 'aerosol brake'

Some types of aerosols help to cool the Earth and offset the effect of radiative forcing, as described earlier. It is still highly uncertain how large this effect may be but it is possible that measures taken to improve air quality in the world's big cities could reduce the amount of sulphate aerosols entering the atmosphere and so release the 'aerosol brake' (that is, cooling effect) on warming.[30] A possible range for the resulting additional warming is shown by the 'AB' bar in Figure 2.7.

Unfortunately, these uncertainties act mainly to further increase warming, although by how much remains unclear. The possibility exists that there are further unidentified, but significant, dampening and reinforcing feedbacks.

Conclusion

There is a great deal of evidence that the Earth's climate has warmed over the last century. It is very likely that the primary cause of this warming is the emission of greenhouse gases (CO_2 and others) due to a range of human activities and the resulting increase in the concentrations of greenhouse gases in the atmosphere.

Climate models indicate that it is also very likely that warming and other climate changes will continue and accelerate through the coming century if emissions of greenhouse gases continue to increase. Our growing understanding of the feedbacks that can both dampen and reinforce climate change suggest that, in aggregate, these feedbacks reinforce the warming trend. Ultimately, there is always a difficult-to-quantify risk of crossing an important threshold and triggering serious, unexpected change that is potentially irreversible for a long time.

Climate change will pose an increased risk to human wellbeing in the future. The nature and consequences of the effects on ocean and air temperatures, sea-level rise, frequency of extreme events, ecosystems, agriculture, and more are described in the following chapters.

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Future Australian climate scenarios

By Penny Whetton

Key messages

- Important advances in climate science in recent years, both at the global and the Australian scales, enable us to use computer simulations to explore with increasing confidence the consequences for our climate of various levels of emissions of greenhouse gases from human activities.
- The best estimate of annual average warming by 2030 (above 1990 temperatures) is around 1.0ºC across Australia, with warming of 0.7–0.9ºC in coastal areas and 1–1.2ºC inland.
- Drying is likely in southern areas of Australia, especially in winter, and in southern and eastern areas in spring, due to a contraction in the rainfall belt towards the higher latitudes of the southern hemisphere. Changes in summer tropical rainfall in northern Australia remain highly uncertain.
- Intense rainfall events in most locations will become more extreme, driven by a warmer, wetter atmosphere. The combination of drying and increased evaporation means soil moisture is likely to decline over much of southern Australia. An increase in fire-weather risk is likely with warmer and drier conditions.

Climate models are mathematical representations of the Earth's climate system that are based on the laws of physics and are used to project the future climate. Climate models remain the best tools we have for exploring the climate of the future, even though they have some well-recognised limitations, such as the degree to which they capture the complexity of climate processes. The projections from climate models also depend on the extent of greenhouse gas emissions assumed to occur in the future.

Climate projections for Australia

A number of important advances in climate science have been made in recent years, both at the global and the Australian scales, which enable us to explore with increasing confidence the consequences for our climate of various levels of emissions of greenhouse gases from human activities. Two main uncertainties continue to qualify the projections of future climate, however: the level of humanity's future greenhouse gas emissions; and the precise response of the Earth's climate system to those emissions. These uncertain factors will affect the speed and extent of expected climate change.

As described in Chapter 2, it is already clear that greenhouse gas emissions are growing strongly, with observed emissions from 2000 to 2007 exceeding almost all assumed emission scenarios generated in the late 1990s. Much will depend on whether emissions continue to rise steeply or whether the world's emitters manage to control and reduce emissions.

Climate projections for Australia are based on combining results from the best available of the global climate models (GCMs). These models produce projections for factors such as temperature and rainfall both globally and in individual regions, which is why most projections are usually stated as a range. The range of projections will narrow as the models improve and uncertainty in emissions scenarios and climate dynamics diminishes.

Rainfall is one of the most difficult phenomena to predict, but climate projections suggest increased rainfall in the Earth's mid-to-high latitudes, decreased rainfall in the mid-latitudes around 25–30º north or south of the Equator (where southern Australia sits), and increases near the Equator. All the GCMs generally agree on this, although some draw the boundaries at slightly different latitudes.[1]

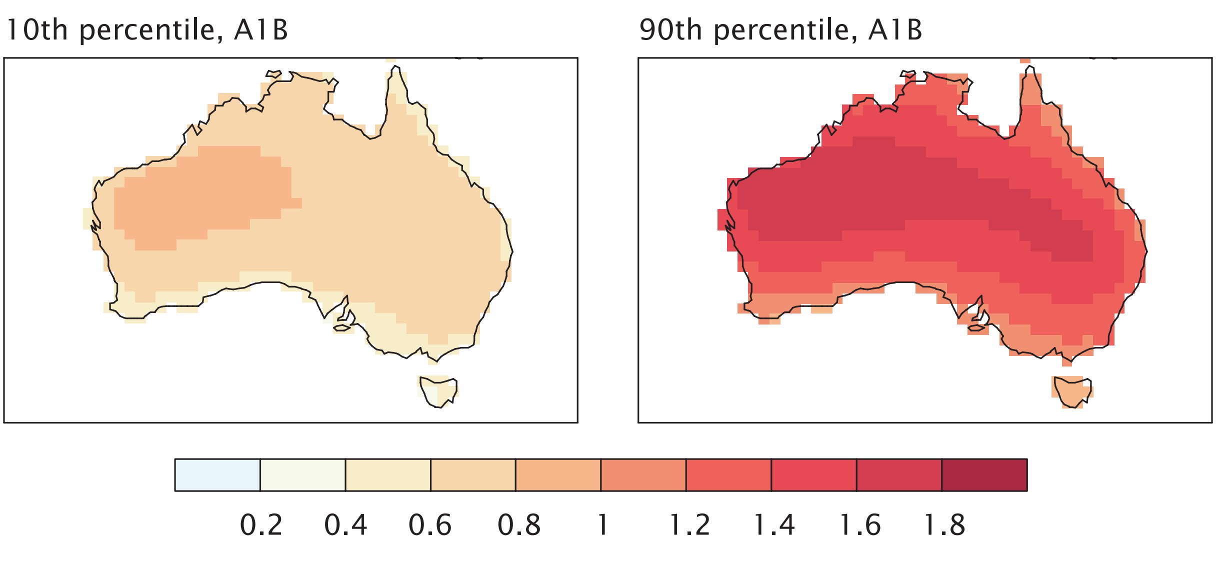
Temperature predictions have a higher degree of confidence than rainfall predictions. The main uncertainty in temperature projections relates to how much CO_2 and other greenhouse gases will be emitted between now and the latter part of this century. All of the GCMs point to global warming, but the pace and extent depend on the level of human emissions and on feedback mechanisms in the Earth's climate system captured in the models. There is a general tendency for warming to be stronger over land than over sea.[1]

Projections for Australia

The Earth already is committed to further warming and climate change due to existing greenhouse gas concentrations in the atmosphere, irrespective of any future increases. The general expectations are described below and are drawn from the *Climate change in Australia* technical report from CSIRO and the Bureau of Meteorology in 2007.[2]

Temperature

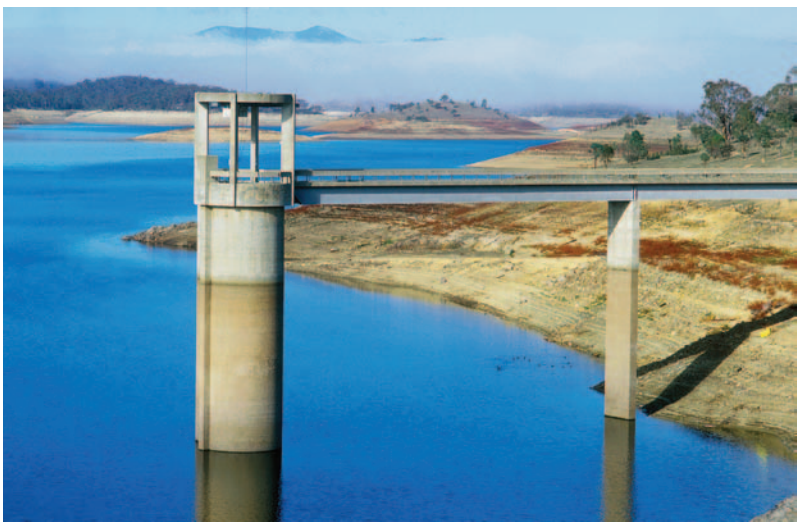
The best estimate of annual average warming by 2030 (above 1990 temperatures) is around 1.0ºC across Australia, with warming of 0.7–0.9ºC in coastal areas and 1–1.2ºC inland. The range of uncertainty is about 0.6–1.5ºC in each season for most of Australia. Projected warming by 2050 ranges from 0.8 to 1.8ºC (low greenhouse gas emission scenario) and 1.5 to 2.8ºC (high greenhouse gas emission scenario). By 2070 warming is expected to be between 2.2ºC (low greenhouse gas emissions scenario) and 5ºC (high emissions). Figure 3.1 illustrates the spatial distribution of high and low warming estimates for 2030.



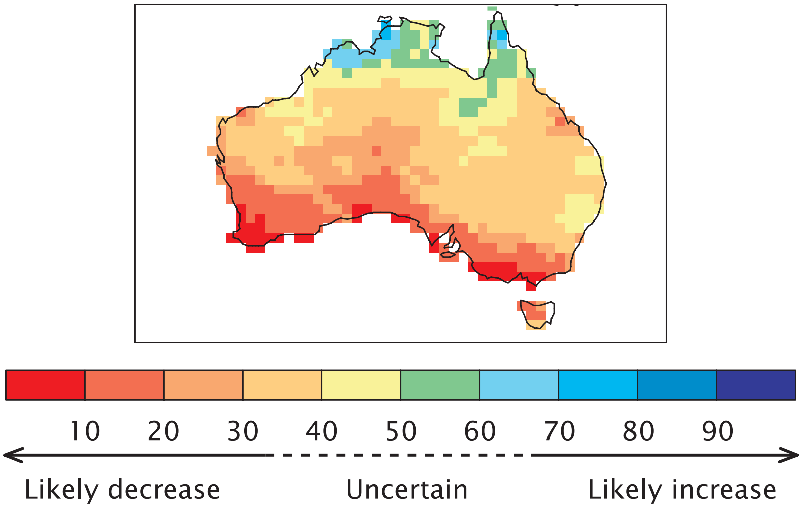
▲ ***Figure 3.1****: Projected changes in annual average temperatures across Australia in 2030 (compared with 1990). Image at left shows the warming very likely to be exceeded (10% of model results show less warming) and the image at right shows the warming that is very unlikely to be exceeded (90% of model results show less warming).*

Rainfall

Climate models indicate that there is likely to be less rainfall in southern areas of Australia, especially in winter, and in southern and eastern areas in spring, caused by the contraction in the rainfall belt towards the higher (more southern) latitudes (Figure 3.2). Future changes in summer tropical rainfall in northern Australia remain highly uncertain. It is also likely that the most intense rainfall events in most locations will become more extreme, driven by a warmer, wetter atmosphere.



Gregory Heath/CSIRO



◂ ***Figure 3.2***: *Percentage of climate modelling experiments showing future increases in annual precipitation. In general, this gives an indication of the likely direction of precipitation change (but not magnitude of change). Widespread likely decreases are shown for southern Australia.*

Regional climate changes

The following regional snapshots[2] exemplify how these general projections of broad scale trends in climate are most likely to play out as changes in particular parts of the continent. The range of values depicting likely changes is due to an allowance for uncertainty in future emissions of greenhouse gases and the response of the climate system. The examples of potential impacts that may affect these regions have been drawn from various studies.

New South Wales and ACT

- Average stream flow decreases across the Murray–Darling Basin by 2030.
- 10–40% increase in the number of extreme fire danger days in Canberra by 2020.
- Annual heat-related deaths in Sydney rise from 176 (1990s) to 364–417 by 2020.

Sydney	Present average (1971–2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Annual temperature (ºC)	18.3	19.2 (18.9–19.6)	19.9 (19.4–20.5)	21.3 (20.5–22.6)
No. days over 35ºC	3.5	4.4 (4.1–5.1)	5.3 (4.5–6.6)	8.2 (6–12)
Annual rainfall (mm)	1277	1238 (1162–1315)	1225 (1098–1340)	1174 (957–1404

Victoria

- Area inundated by a 1-in-100-year storm surge in Gippsland may increase 15–30% by 2070.
- Area with at least one day of snow cover per year on average shrinks 10–40% by 2020 and 20–85% by 2050.
- 20–65% increase in the number of extreme fire danger days in the Bendigo region by 2020.
- Potential doubling in the number of days over 35ºC in Melbourne by 2070.

Melbourne	Present average (1971–2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Annual temperature (ºC)	15.7	16.6 (16.3–16.9)	17.1 (16.7–17.7)	18.5 (17.6–19.5)
No. days over 35ºC	9.1	11.4 (11–13)	14 (12–17)	20 (15–26)
Annual rainfall (mm)	654	628 (596–661)	615 (563–668)	582 (491–674)

South-East Queensland

- Less water for cities, industries, agriculture, and natural ecosystems.
- Less frost damage to crops, higher wheat yields but lower wheat quality, increased pest and disease risk.
- 20% increase in intensity of a 1-in-100-year rainstorm could, for example, inundate 7000 properties in the Nerang catchment in southern Queensland.

Bruce Miller/CSIRO

Brisbane	Present average (1971–2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Annual temperature (ºC)	20.5	21.5 (21.2–21.9)	22.1 (21.6–22.8)	23.6 (22.6–24.9)
No. days over 35ºC	1.0	2.0 (1.5–2.5)	3.0 (2.1–4.6)	7.6 (4–21)
Annual rainfall (mm)	1192	1109 (978–1230)	1133 (978–1300)	1085 (799–1395)

Southern South Australia

- Sea-level rise may increase the cost of sand replenishment on Adelaide beaches.
- Farming of land at the drier fringe likely to be increasingly marginal if rainfall declines substantially.
- Grape quality in the Barossa Valley likely to decline due to higher temperatures.
- Potential doubling in the number of days over 35ºC in Adelaide by 2070.

Adelaide	Present average (1971–2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Annual temperature (ºC)	16.5	17.4 (17.1–17.8)	18.0 (17.5–18.6)	19.3 (18.4–20.5)
No. days over 35ºC	17	23 (21–26)	26 (24–31)	36 (29–47)
Annual rainfall (mm)	463	444 (412–472)	430 (379–481)	403 (315–500)

South-west Western Australia

- Decline in annual stream flow.
- Wheat yield significantly reduced by 2070.
- Potential almost doubling of the number of days over 35ºC in Perth by 2070.

Perth	Present average (1971–2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Annual temperature (ºC)	18.5	19.3 (19.1–19.7)	19.9 (19.5–20.5)	21.2 (20.4–22.3)
No. days over 35ºC	28	35 (33–39)	41 (36–46)	54 (44–67)
Annual rainfall (mm)	747	702 (650–754)	665 (590–754)	605 (471–762)

Northern coastal Queensland

- Sea-level rise likely to cause salt-water intrusion and inundation in some Torres Strait Islands.
- Significant loss of biodiversity in the Great Barrier Reef and Queensland Wet Tropics by 2020.
- Risk of inundation by a 1-in-100-year storm surge in Cairns area may more than double by 2050.

Cairns	Present average (1971–2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Annual temperature (ºC)	24.9	25.8 (25.5–26.1)	26.4 (26.0–26.9)	27.8 (26.9–28.8)
No. days over 35ºC	3.8	6.6 (5.4–9.1)	12 (8–22)	44 (19–96)
Annual rainfall (mm)	2112	2112 (1943–2281)	2091 (1816–2387)	2091 (1584–2640)

Tasmania

- 21% of the Tasmanian coast is at risk of erosion and recession from sea-level rise.
- Strengthening of the East Australian Current may result in subtropical marine species moving into temperate waters, altering the habitat of many species.
- Changes in climate will favour a shift to warm-season grape varieties.

Hobart	Present average (1971–2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Annual temperature (ºC)	13.0	13.6 (13.4–13.9)	14.1 (13.7–14.5)	15.1 (14.5–15.9)
No. days over 35ºC	1.4	1.7 (1.6–1.8)	1.8 (1.7–2.0)	2.4 (2.0–3.4)
Annual rainfall (mm)	576	571 (542–594)	559 (519–600)	542 (467–623)

Top End

- Remote area communities to face increased exposure to heat stress, fire, diseases, extreme rainfall events, and flooding.
- 80% loss of biodiversity in Kakadu wetlands for a 30 cm sea-level rise.

Darwin	**Present average (1971–2000)**	**2030 average (mid emissions)**	**2070 average (low emissions)**	**2070 average (high emissions)**
Annual temperature (ºC)	27.8	28.8 (28.5–29.2)	29.5 (29.0–30.1)	31.0 (30.1–32.2)
No. days over 35ºC	11	44 (28–69)	89 (49–153)	227 (141–308)
Annual rainfall (mm)	1847	1847 (1718–1960)	1829 (1644–2032)	1829 (1459–2217)

Extreme events

The combination of drying and increased evaporation means that soil moisture is likely to decline over much of southern Australia. The frequency of very dry conditions is expected to increase in Victoria and Tasmania and south-west Western Australia, based on 13 climate model simulations over the period 2010–2040.[3]

An increase in fire-weather risk is likely with warmer and drier conditions. Simulations show that the number of days with very high fire danger ratings increases by 2% to 30% by 2020 and by 5% to 100% by 2050. The number of days with extreme fire danger ratings increases between 5% and 65% by 2020 and between 10% and 300% by 2050. For example, Canberra may have an annual average of 19 to 25 very high or extreme fire danger days by 2020 and 22 to 38 days by 2050, compared with the present average of 17 days. It is also likely that the fire season will lengthen over and above this likely increase in frequency of fire-weather days.[4]

CSIRO

There is potential for significant increases in flooding due to higher mean sea level and more intense weather systems. Studies in the Australian region point to a likely increase in the proportion of tropical cyclones in the more intense categories (category 4 or 5), but a possible decrease in the total number of cyclones per year.

Abrupt changes and tipping points

Climate change does not proceed smoothly for a given change in radiative forcing from changing greenhouse gas levels. There is a risk of abrupt changes as the climate shifts from one state to another as a result of feedbacks in the climate system. This raises the possibility of events such as major changes in the ocean's thermohaline circulation: the global ocean current that distributes heat around the planet, leading to step-changes in warming or in extreme events. These are known as tipping points. Their hazard lies in the fact that, once they have occurred, it may be hard for the planet to return to its previous steady state. For example, once Greenland's ice cap is committed to melting it is unlikely to reform for thousands of years, leading eventually to sea-level rises of several metres.

Conclusion

Australia's climate projections have been under development for more than 20 years. They are achieved by combining the output from global climate models from around the world with those developed specifically in Australia, to produce projections with a range of most likely outcomes, as described above.

These projections can then be used to assess the possible impacts of climate change on our society, economy, and the environment by examining the implications of a changing climate on agricultural production, water availability, health-care issues, bushfire danger, and vulnerability to storms or flood damage at national and regional level.

Understanding the likely future changes to climate makes it possible to start drawing up action plans at national, state, regional, and local levels to adapt to the most likely changes. The difficulty of projecting changes in local climate conditions with accuracy should not be underestimated, however, which would make it sensible to prepare for a range of possible eventualities. Considerations of climate impacts and how to adapt to these are covered in the ensuing chapters.

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Climate change impacts

By Kevin Hennessy

Key messages

- The impacts of climate change are already clearly visible in Australia. Further impacts predicted to occur will be experienced across all sectors of the economy and in all ecosystems.
- Southern and eastern Australia's water supply reliability is expected to decline as a result of reduced rainfall and increased evaporation, affecting irrigation, domestic and industrial water use, and environmental flows. This is likely to be accompanied by a growth in water demand due to population growth.
- Development and population growth in Australia's coastal regions will exacerbate the risks from sea-level rise and increase the likely severity and frequency of coastal flooding.
- Significant losses of unique Australian animal and plant species are expected to occur in sites such as the Great Barrier Reef, the Queensland Wet Tropics, the Kakadu wetlands, south-west Australia, eastern alpine areas, and Australia's sub-Antarctic islands, disrupting ecosystem function and causing the loss of ecosystem services.
- The risks to infrastructure include the failure of urban drainage and sewerage systems, more blackouts, transport disruption, and greater building damage. Higher temperatures, altered groundwater and soil conditions, sea-level rise and changed rainfall regimes may also lead to accelerated degradation of materials.
- Heatwaves, storms and floods are likely to have a direct impact on the health of Australians, such as causing an increase in heat-related deaths. Biological processes such as infectious diseases and physical processes such as air pollution may affect health indirectly; for example, by increasing exposure to dengue fever.
- Moderate warming in the absence of rainfall declines can be beneficial to some agricultural crops, and higher levels of carbon dioxide can stimulate plant growth. However, these positive effects can be offset by changes in temperature, rainfall, pests, and the availability of nutrients. Production from cropping and livestock is projected to decline over much of southern Australia, as is the quality of grain, grape, vegetable, fruit, and other crops.

Introduction

Australia is the driest inhabited continent in the world. In addition, the climate is inherently variable as noted in our literary history – ‘of droughts and flooding rains’. There is now strong evidence that our climate is also changing, with Australia warming by about 0.8ºC since 1960, and more heatwaves, fewer frosts, more rain in north-west Australia, less rain in southern and eastern Australia, an increase in the intensity of droughts, and a rise in global sea level of 77 mm from 1961–2003 (see Chapter 1). The impact of these changes, which are due to a combination of natural variability and changes in greenhouse gas concentrations from human activities, can now be clearly seen in stresses on our water supplies and farming, changed natural ecosystems, coastal impacts, and reduced seasonal snow cover.[1,2]

It is now likely that the world will see 2ºC global warming on top of changes already experienced within the lifetime of the current generation. Without rapid action to reduce CO_2 emissions, there is a serious risk that global warming could be as much as 4ºC by later this century.[3]

For Australia, heatwaves, fires, floods, and southern Australian droughts are all expected to become more frequent and more intense in the coming decades. Snow and frost are very likely to become rarer or less intense events. Locally and regionally, the greatest impacts will be felt through changes in water availability and sea level, and extreme weather events.

Australia is highly vulnerable to these projected changes in climate and this highlights the need for adaptation to the unfolding and unavoidable changes that lie ahead (see Chapter 5). Adaptation needs to be informed by a good understanding of the impacts of climate change. Global and national assessments show that a changing climate affects food production, disturbs coastal margins, displaces species, and changes economies. New extremes in temperature and sea level will exceed the habitable limit for some species.[4] Shifting population patterns of plants, animals, and people will bring more changes.

Although the impacts of climate change are on the whole negative for the environment and the economy, not all climate changes will be deleterious, especially in the next few decades. Moderate warming in the absence of rainfall declines can actually be beneficial for some agricultural crops. Therefore it is important to understand how the likely impacts of climate change will be distributed.

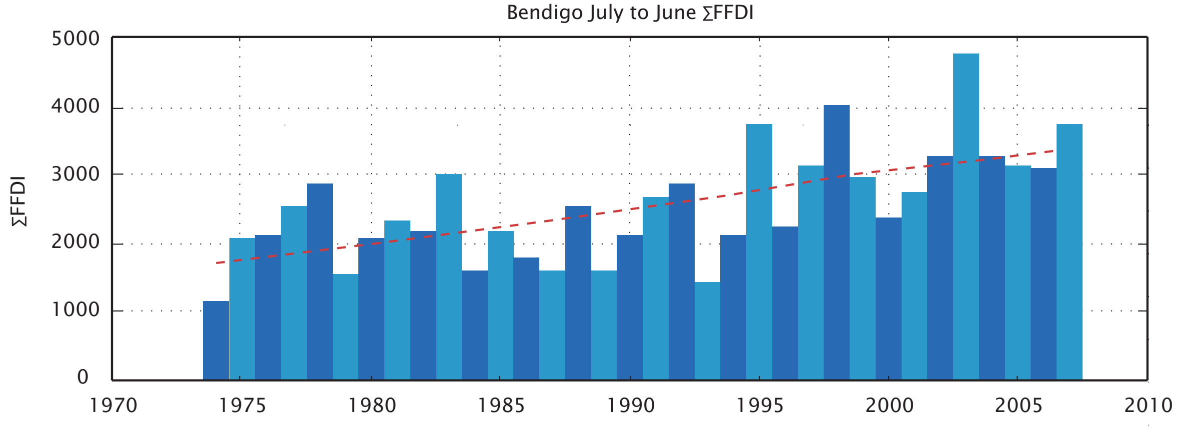
▸ ***Figure 4.1***: *Change in annual total Forest Fire Danger Index (FFDI) from 1974 to 2007 at Bendigo.[5] The dotted trend line shows an increase of 51 FFDI units per year.*

Climate extremes – a window into understanding the impacts of climate change

Climate change impacts will increasingly be experienced first through extreme events rather than gradual changes in mean temperature or rainfall. Consideration of current vulnerability to extreme events helps to establish the context for assessing changes in vulnerability due to future changes in extremes. Extreme weather and climatic events that we experience today are most likely a combination of climate variability combined with an underlying change in climate associated with anthropogenic greenhouse gas emissions (see Chapter 1). The evidence for a human contribution through increases in greenhouse gases varies regionally and for different climate variables, and it is very difficult to attribute specific causes to individual extreme weather events. However, there are statistical methods for assessing whether an extreme event may have been made more likely because of increases in greenhouse gases.[6] Regardless of the cause, it is important to understand the impacts of existing extreme weather and climate events and use these as a window into future climate change in an enhanced greenhouse world.

A good case study of how we can look at the impacts of current extreme events and assess their importance in the future is the Victorian bushfires event in early February 2009, which killed 173 people and more than 1 million animals, destroyed more than 2000 homes, burnt about 430 000 hectares, and cost about $4.4 billion.[7] Conditions leading into that fire were extreme, with high temperatures, low humidity, high winds, and very dry fuel as a result of years of drought, all of which combined to produce an extreme forest fire danger index (FFDI). When the daily FFDI is greater than 50, the risk rating is 'Extreme' and a 'Total Fire Ban' is usually declared. The bushfires of February 2009 had a FFDI that greatly exceeded 100 in many locations and, as a consequence, an additional fire rating 'Catastrophic' has since been added to the rating system.

An analysis of the annual total FFDI (i.e. the sum of daily FFDI indices) for the last 30 years shows that in southern Australia the index has been trending upwards, primarily in response to increasing temperatures and a worsening drought since the mid-1990s (Figure 4.1).[5]



In terms of future fire-weather risk, a modelling study conducted by the Bushfire CRC, the Bureau of Meteorology, and CSIRO[5] found that the simulated annual-average number of days with 'Extreme' fire danger increases by 5–25% by 2020 relative to 1990, for a 0.4ºC global warming. For a 1ºC global warming, the number of 'Extreme' days increases by 15–65% by 2020. By 2050, the number of 'Extreme' days increases by 10–50% for 0.7ºC global warming and by 100–300% for 2.9ºC global warming.

This example illustrates how examining today's extreme weather events can be important for understanding impacts in the future. Chapter 6 further illustrates how understanding extreme events such as coastal flooding and heatwaves can inform adaptation.

Climate change impacts across Australia's economy and environment

Climate change impacts will be experienced across all sectors of the economy and in all ecosystems. There are six areas in particular where the impacts will be significant: (1) water security, (2) coastal development, (3) natural ecosystems, (4) infrastructure, (5) agriculture and forestry, and (6) health.

Water security

Water security, or reliability of water supply, in southern and eastern Australia is expected to decline in future as a result of reduced rainfall and higher rates of evaporation.[2] There is likely to be less water available for irrigation, domestic use, and industry, and lower environmental flows. For example, median stream flow in the Melbourne catchments is estimated to decline by 10% by 2030[8] and median stream flow in south-western Australia is estimated to decline by 25% by 2030.[9]

The decline in water supply is likely to be accompanied by a growth in water demand as our population expands. It is the combination of growing demand and reduced supply that makes water potentially one of Australia's most critical national issues. A CSIRO report on water availability in the Murray–Darling Basin (MDB) found that water resource development in conjunction with drought has caused major changes in the flood regimes that are important for floodplain wetland systems.[10] The report found that run-off in the southern MDB between 1997 and 2006 was the lowest ever recorded. Such conditions are likely to be increasingly common by 2030 and beyond. Surface water availability across the entire MDB is more likely to decline than to increase, especially in the south, where the reduction could be substantial. The median decline expected for the MDB is 9% in the north of the basin and 13% in the south. This could further reduce flow at the Murray River mouth by around a quarter under present water-sharing arrangements. In the driest years, water availability in the Condamine–Balonne basin could fall by over 20%, around 40–50% in the NSW water regions (except the Lachlan basin), over 70% in the Murray region, and 80–90% in the main Victorian regions.[10]

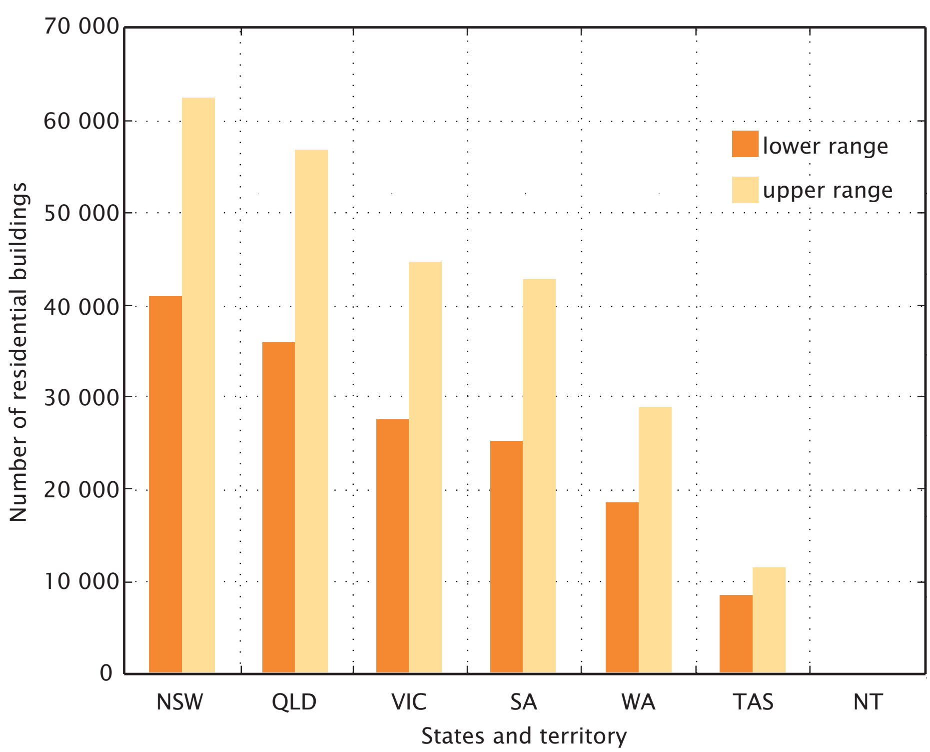
Greg Rinder/CSIRO

These impacts point to a growing need for adaptive strategies (see Chapters 5 and 6), many of which are in hand already. They include, for example, the Murray–Darling Basin Water Agreement, the conversion of open irrigation channels to pipelines, desalination plants, the introduction of state water conservation plans, and the adoption of the 'water-proofing' of Adelaide as a model for other cities.

Coastal development

Continued development and population growth in Australia's coastal regions – where around 85% of the population now resides – will exacerbate risks from sea-level rise and increase the likely severity and frequency of coastal flooding caused by climate change.[2] There is likely to be an increased risk of coastal flooding, especially in low-lying areas exposed to cyclones and storm surges (see Figure 4.2). For example, the area of Cairns at risk of flooding by a 1-in-100-year storm surge is likely to more than double by 2050.[2]

A 2009 report titled *Climate change risks to Australia's coasts* stated that, 'many coastal environments such as beaches, estuaries, coral reefs, wetlands and low-lying islands are closely linked to sea level. There is a lack of detailed knowledge as to how these environments will respond to sea-level rise, but the risk of beach loss, salinisation of wetlands and inundation of low-lying areas and reefs beyond their capacity to keep pace must be recognised. With a "mid-range" sea-level rise of 0.5 m in the 21st century, events that now happen every 10 years would happen about every 10 days in 2100. The current 1-in-100-year event could occur several times a year' (see Chapters 1 and 6).



▲ ***Figure 4.2***: *Estimated number of residential buildings at risk of inundation from a 1.1 m sea-level rise (including 1-in-100-year storm tide for NSW, Victoria, and Tasmania and high tide event for others).*[1]

Furthermore, sea-level rise is expected to begin eroding many of Australia's sand beaches faster than they can form if current rates of rise continue through the 21st century. Some beaches could recede by hundreds of metres over the course of this century.[2] Remote Indigenous communities in the north of Australia and communities living on the low-lying Torres Strait Islands are particularly vulnerable to sea-level rise. Together, these impacts will raise the pressure for wiser and safer forms of coastal development (see Chapter 6).

Natural ecosystems

Among the most significant impacts of climate change may be the loss of unique Australian animal and plant species and the gradual changing of quintessentially Australian landscapes.

Significant losses of biodiversity are projected to occur in iconic sites such as the Great Barrier Reef, the Queensland Wet Tropics, the Kakadu wetlands, south-west Australia, our sub-Antarctic islands, and eastern alpine areas.[2]

A recent study concluded that this loss of diversity is likely to disrupt ecosystem function and cause the loss of ecosystem services.[11] These changes have major implications for Australia's 9000 protected areas, including national parks, nature reserves, private conservation reserves, Indigenous Protected Areas, and other reserve types that cover 88 million hectares (11.5% of the continent). The four main threats are the arrival of new (native and exotic) species in a region, altered fire regimes, land-use changes, and altered hydrology. In response, one of the key tasks will be to protect native habitat at the landscape scale, ensuring habitat connectivity so that native species can readily relocate as climatic conditions change (see Chapter 5).

Changes to marine ecosystems will be among the most serious impacts. For example, a 0.5°C warming of the tropical oceans may cause bleaching of 30% of the Great Barrier Reef and a 1°C warming may bleach 65%.[12] Such changes could directly affect a tourism industry worth $5 billion a year and supporting around 70 000 employees.[2]

A CSIRO assessment[13] outlines a range of other projected marine climate impacts including:

- the expansion of mangroves into newly flooded coastal lands
- declines in seagrass meadows and seaweed beds due to storms and warmer water
- the southward migration of tropical pelagic fish and other marine species
- a loss of diversity in coral fish and other coral-dependent organisms
- a risk to marine food chains from ocean acidification, potentially affecting fisheries.

Changes in coastal ecosystems are already taking place, with the southward migration of some species, particularly along the south-east coast of Australia. A major question for several coastal ecosystems is whether only a modest climate change may induce a threshold beyond which some ecosystems might 'flip' into a different state. The initial responses to climate change by a range of ecosystems will be to migrate either inland or polewards, raising the issue of 'coastal squeeze' in southern Australia where populated areas stand in the way of this natural adaptive response and the expanse of the Southern Ocean sets a boundary to southward migration of shallow water organisms. The coastal systems most at risk are estuaries and associated wetlands, coral reefs, tidal flat communities and salt marshes, and beaches where there is a lack of sand for replenishment.

Infrastructure

Infrastructure is particularly sensitive to changes in extreme weather in addition to more gradual changes in rainfall or sea-level rise. Today's design criteria for extreme events are likely to be exceeded more frequently in future.[2] Typical risks include the failure of floodplain protection and urban drainage and sewerage systems, more heatwaves causing blackouts or buildings failing under excessive wind loads. Examples include the January–February 2011 floods in eastern Australia, the January 2009 heatwave in south-eastern Australia,[14] the February 2009 fires in Victoria, and Cyclone Larry in March 2006. In addition to these acute impacts, there are a whole range of chronic impacts such as accelerated degradation of materials and infrastructure (such as water pipes, road surfaces, transmission lines, foundations, and building materials) associated with higher temperatures, altered groundwater and soil conditions, sea-level rise, and changed rainfall regimes. There are also indirect effects such as the increasing urban heat island effect (that is, an increase in temperature caused by heat-retaining materials in the urban environment) putting more demand on energy for air-conditioning.

The Victorian Government, with significant input from CSIRO, conducted a risk assessment of its infrastructure in the context of climate change. Table 4.1 shows a summary of the exposure and sensitivity of Victoria's infrastructure to climate change.[15] Victoria's water, electricity, and buildings are particularly sensitive. Buildings have the greatest exposure and sensitivity to climate change by 2030, especially in relation to foundations, storm and flood damage, and bushfire risk.

Table 4.1: Climate change exposure and infrastructure sensitivity matrix for Victoria by the year 2030[15]

Infrastructure type	Climate change impacts: Increased solar radiation	Decrease in available moisture	Increased variation in wet/dry spells	Increased temperature and heatwaves	Decrease in rainfall	Increase in extreme daily rainfall	Increase in frequency and intensity of storms	Increase in intensity of extreme wind	Increased electrical storm activity	Increase in bushfires	Sea-level rise	Humidity
Water	Negligible	Definite	Definite	Definite	Definite	Definite	Definite	Negligible	Negligible	Definite	Negligible	Negligible
Sewer	Negligible	Definite	Definite	Negligible	Definite	Definite	Definite	Negligible	Negligible	Negligible	Definite	Negligible
Stormwater	Negligible	Definite	Definite	Definite	Negligible	Definite	Definite	Negligible	Negligible	Negligible	Definite	Negligible
Electricity	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Negligible	Negligible
Gas and oil	Negligible	Definite	Definite	Negligible	Negligible	Definite	Definite	Negligible	Negligible	Definite	Definite	Negligible
Fixed line telecom network	Definite	Negligible	Negligible	Definite	Negligible	Definite	Definite	Definite	Definite	Definite	Definite	Negligible
Mobile network	Negligible	Definite	Negligible	Negligible	Negligible	Negligible	Negligible	Definite	Negligible	Negligible	Negligible	Negligible
Roads	Definite	Definite	Definite	Definite	Negligible	Definite	Definite	Negligible	Negligible	Negligible	Negligible	Negligible
Rail	Negligible	Negligible	Negligible	Definite	Negligible	Definite	Definite	Negligible	Definite	Negligible	Negligible	Negligible
Bridges	Definite	Negligible	Negligible	Definite	Negligible	Definite	Definite	Definite	Negligible	Negligible	Negligible	Negligible
Tunnels	Negligible	Negligible	Negligible	Negligible	Definite	Definite	Definite	Negligible	Negligible	Negligible	Definite	Negligible
Airports	Definite	Definite	Definite	Definite	Negligible	Definite	Definite	Definite	Negligible	Definite	Negligible	Negligible
Ports	Negligible	Negligible	Negligible	Negligible	Negligible	Definite	Definite	Definite	Negligible	Negligible	Definite	Negligible
Buildings and structures	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite	Definite
Urban facilities	Definite	Definite	Definite	Definite	Negligible	Definite	Definite	Definite	Definite	Definite	Definite	Negligible

Table key	
Negligible risk – Presents 'negligible' risk within the probability of natural variation	(grey)
Definite risk – Presents 'definite' risk within the probability of natural variation	(orange)

Agriculture and forestry

Unlike most other sectors, where there are few positive impacts of climate change, agriculture and forestry is different because plants can respond positively to higher concentrations of CO_2 in the atmosphere.[16] Higher levels of CO_2 increase the rate of photosynthesis and improve the efficiency of water use in plants, hence stimulating plant growth (known as CO_2 fertilisation). Experiments where CO_2 concentrations have been increased by around 50% (to approximately 550 ppm) have produced growth increases of around 15%[17] in crops and 10–50% in tropical savanna grasses.[18] In studies where CO_2 has been increased up to 700 ppm, wheat yields have risen by 10–50%, cotton biomass by 35%, whole boll yields by 40%, and lint yields by 60%.[19] Data supporting these conclusions have been collected in major field experiment studies in Australia (Wheat FACE experiment at Horsham in Victoria and OZFace experiment in Townsville, Queensland – see Figure 4.3).

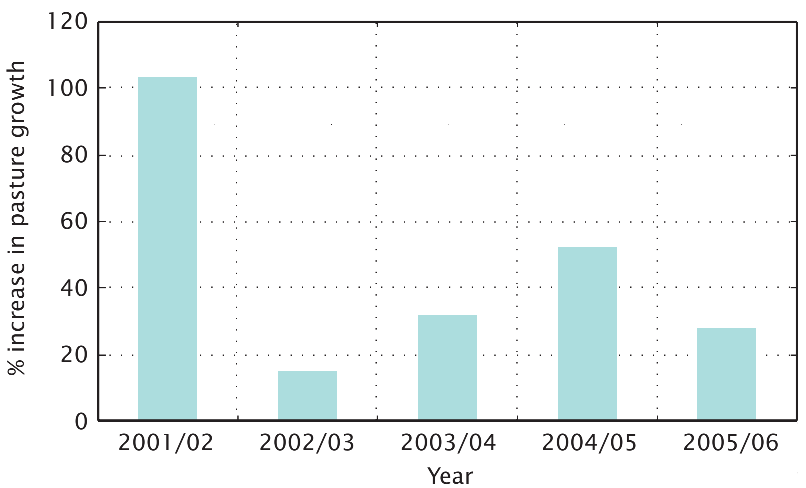


***Figure 4.3**: Relative growth response of tropical native pasture when exposed to 550 ppm CO_2 concentration compared with current concentrations (380 ppm).*[18]

However, the positive effects of CO_2 can be more than offset by accompanying changes in temperature, precipitation, pests, and the availability of nutrients. As a consequence, production from cropping and livestock is projected to decline by 2030 over much of southern Australia due to increased drought[2] and the fact that the availability of nutrients will limit productivity in most Australian landscapes. Heat and drought are likely to reduce the quality of grain, grape, vegetable, fruit, and other crops. A 20% reduction in rainfall could reduce pasture productivity by 15%, and livestock weight gain by 12%, which would substantially reduce farm income. There is likely to be a southward movement of pests and diseases as the southern regions warm. The forestry and plantation industries are likely to face greater risk of fire.[2]

John Coppi/CSIRO

There are likely to be some additional positive effects beyond that of CO_2 fertilisation, such as a likely reduction in frost, and the prospect of longer growing seasons for some crops. See Chapter 7 and the CSIRO report *Adapting Agriculture to Climate Change*[20] for a discussion of the adaptation options for agriculture, and Chapter 5 for a general discussion of the issue of adaptation.

Health

Climate change has an impact on health both directly and indirectly (Figure 4.4). Direct impacts are via heatwaves, fires, storms, and floods. For Australia, heatwaves are likely to have a major impact on human health. Heat-related deaths for people aged over 65 in six of Australia's largest cities are likely to increase from around 1100 per year at present to around 2300–2500 by 2020 and 4300–6300 by 2050 (allowing for demographic change). During a 2-week heatwave in early 2009, 374 heat-related deaths were recorded in Victoria (see Chapter 6). While most attention is focussed on extreme heat events, there is also the chronic effect of increased heat loads, which is exacerbated in urban environments by the urban heat island effect.

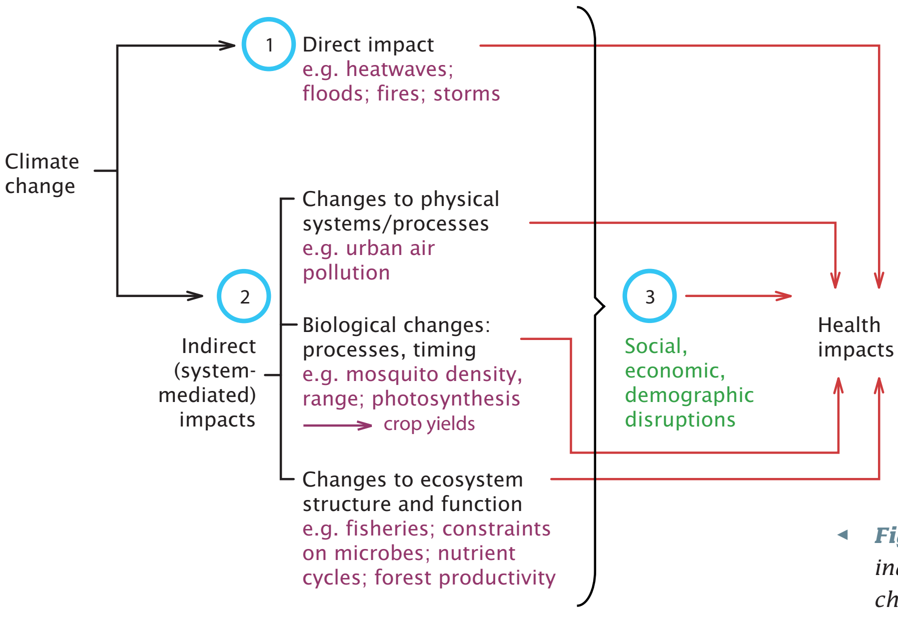


***Figure 4.4**: Direct and indirect impacts of climate change on human health.*[21]

Health is also affected by climate change indirectly, principally through biological processes such as vector-borne and other infectious diseases and physical processes such as air pollution. For example, Australia can expect an increase in disease due to the spread of insect vectors, with 0.6 to 1.4 million more people exposed to dengue fever by 2050, as well as a rise in water-borne and food-borne diseases.[2] Higher temperatures are likely to cause an increase in the concentrations of volatile organic compounds and ozone in the atmosphere. An analysis of future climate found that under an SRES A2 (relatively high emission) scenario, increased ozone pollution is projected to cause a 40% increase in the projected number of hospital admissions by the period 2020–2030, relative to 1996–2005, and a 200% increase by the period 2050–2060.[22]

Conclusion

The impacts of climate change on Australia's economy, society, and environment over the coming decades will be significant. Some impacts will be unavoidable in the short term because of climate changes already locked in due to past and current greenhouse emissions. Adaptation on a scale far more extensive than is currently occurring will be essential in all walks of life in order to limit these impacts, but significant environmental, economic, social, and institutional barriers to adaptation remain (see Chapters 5 and 6). Adaptation alone cannot absorb all the projected impacts of climate change, especially over the long term. Some of these impacts can be further avoided, reduced, or delayed by reducing global net greenhouse gas emissions, so it is clear that Australia's approach to climate change needs to embody both adaptation and emission reduction strategies.[23]

Further reading

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Adaptation: reducing risk, gaining opportunity

By Mark Stafford Smith and Andrew Ash

Key messages

- The less we reduce emissions, the more we will have to adapt; for warming greater than 2ºC, many Australian sectors will be very vulnerable.
- The most sensitive sectors in Australia, which will require most early adaptation, are: water, the natural environments, cities and infrastructure, the coastal zone, and agriculture.
- Adapting in these areas presents significant challenges, but can also create great opportunities; early action will maximise our ability to capture these opportunities.
- Successful adaptation will depend on developing the knowledge and skills base in the industries and communities most affected, as well as enhancing the adaptive capacity of government agencies to provide the best policy context for adaptation.

As noted in earlier chapters, some climate change and consequent impacts are unavoidable due to the greenhouse gases that are already in the atmosphere and as future emissions increase due to our slow mitigation response. To limit the social, economic, and environmental impacts of these changes, we need to adapt.

Adaptation in Australia

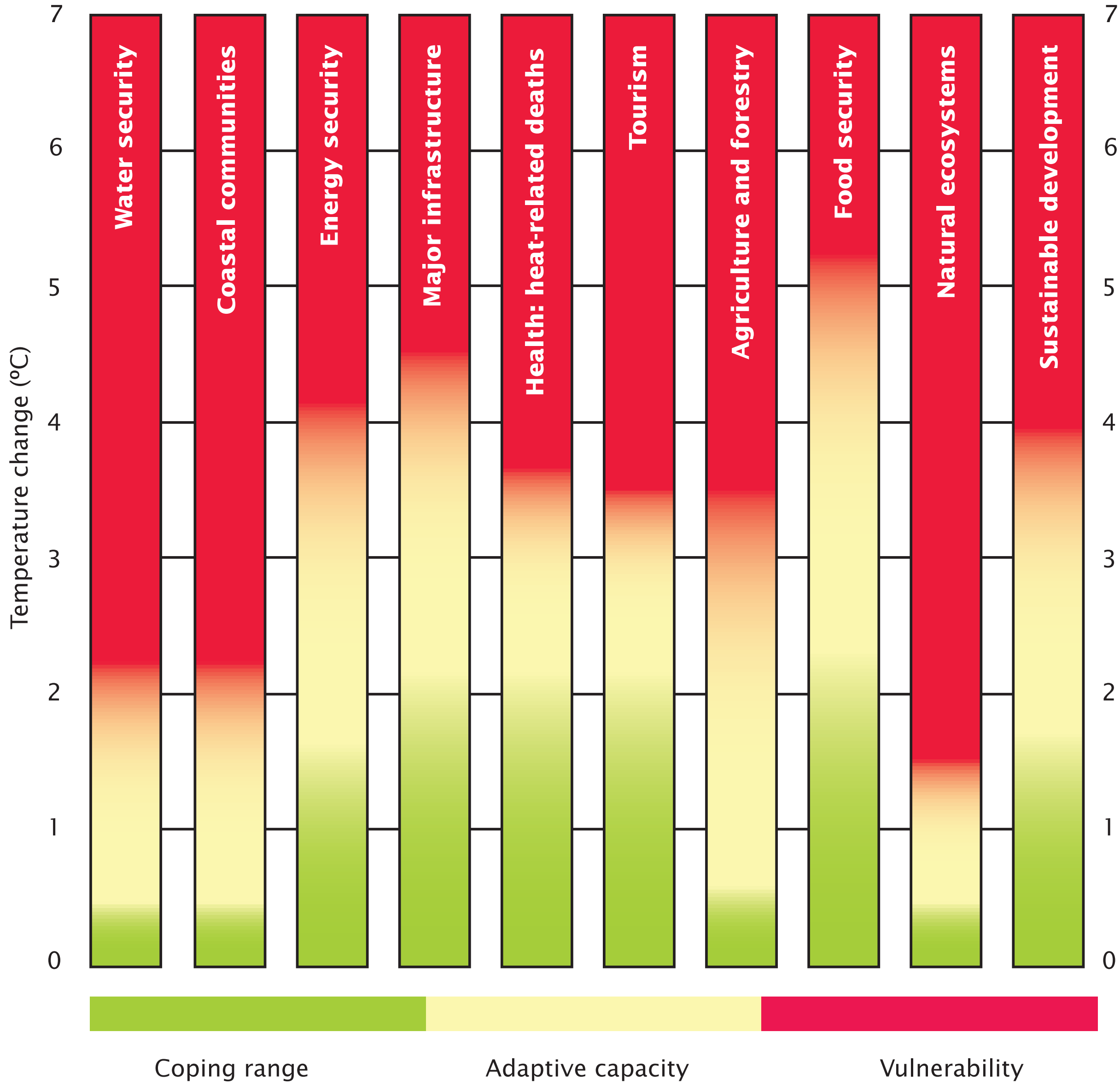
Australians are superb adapters. Indeed our entire history on this continent, both Aboriginal and European, is one of constantly adapting to its challenging climates, resources, and natural conditions – from bountiful seasons and baking summers to frost, fire, storms, flood, and drought. It is clear that the observed and predicted trends in our climate will confront us with further necessity to adapt and, indeed, with fresh opportunities that will make adaptation both worthwhile and profitable, as well as essential.

Adaptation is about coping with the changes that are already happening or that appear unavoidable in the future. Just as early settlers progressively adapted European farming systems to Australian landscapes and conditions or built their homes with wide verandas to suit our long, hot summers, so now we will need to change many of our society's activities, systems, and habits to make allowance for warmer, more variable, and extreme climatic conditions, as well as rising sea levels and other global environmental changes.

Adaptation and mitigation (that is, reducing the amount of climate change that occurs – see Chapters 8 to 10) are closely linked: the less we mitigate, the more we will be forced to adapt to inevitable changes in the climate, and the bigger the adaptations will have to be. Conversely, success in mitigation through early and deep cuts to greenhouse emissions will necessitate fewer, less extreme adaptations in the long run.[1]

There is now wide scientific agreement that the world is heading for at least 2ºC warming, and possibly 4ºC, by 2070[2] and that adaptation to the changed conditions that this implies has become a vital concern.[3] As the increase in average temperature begins to rise above 2ºC, the challenges faced by societies will become increasingly significant; planned adaptation will help, but, even so, disruptions to economies, livelihoods, and lifestyles are likely.

There is no doubt that Australia is vulnerable to climate change. Figure 5.1 indicates just how vulnerable we are to various increases in temperature. At the green end of the temperature bars, up to about 1–1.5ºC of global mean temperature rise for many sectors, we can cope pretty much as we do today. However, the yellow range, between 1.5ºC and 3–4ºC, indicates the need to take more extensive action in the various sectors listed to adapt to the changing conditions. At a global mean temperature rise above 4ºC, life becomes far more difficult and our society increasingly vulnerable. Some sectors are more sensitive than others in Australia – notably water, coastal communities, natural ecosystems, and, to some extent, agriculture come under stress at lower temperature changes than the others.



▲ ***Figure 5.1****: This figure, drawn from the IPCC's Fourth Assessment in 2007,[4] shows the aggregated relative vulnerability to climate change for key sectors, as assessed for the Australia and New Zealand region. The vertical axis shows increasing levels of global mean temperature rise from 0 to 7ºC, while the colours show how much change the sector can cope with normally (green), how much it can adapt to autonomously (yellow), and when it becomes vulnerable (red). In Australia, water security, coastal communities, and natural ecosystems stand out as being particularly vulnerable to small temperature rises.*

From this, it can readily be seen that adaptation is a vital strategy for the extent of climate change that is now expected to occur by the latter part of the 21st century, and that no part of society, no industry, and no individual will remain untouched by it or be able to avoid it. Indeed, our natural ecosystems, water resources, farm sector, and coastal communities are already feeling the pinch.

So Australians cannot avoid having to adapt. Even with 2ºC of global mean temperature rise we will have to cope with changed conditions such as sea-level rise, increased frequency and intensity of bushfires and tropical storms, more frequent heatwaves, droughts and water scarcity, and year-round higher temperatures. These new conditions may involve changes as far-reaching as the progressive relocation of farming industries to more favourable climatic regions, or the imposition of planning controls in coastal shires to prevent people building in areas at risk from flooding, storm surges, and shoreline erosion.[5] However, not all of these adaptations need to happen at the same time or immediately: many can be achieved progressively over time; many will also lead to fresh opportunities, new markets, and more sustainable technologies. In other words, with good preparation, adaptation can be win–win.

Malcolm Paterson/CSIRO

Types of adaptation

Just as adaptation to change in the past has involved all parts of society, adaptation to climate change will engage all Australians, in every industry, in each community and as individuals in our daily lives, our work, our consumer choices and recreation. Domains that are emerging as priorities are:

- urban areas, including homes, offices, industries, transportation, water and energy systems, and overall design of towns and cities themselves
- coastal zones and estuaries and all areas at risk of sea-level rise, storm surges, and floods
- agriculture, the food supply, and other primary production, including mining
- our natural environment, including forests, woodlands, grasslands, lakes, rivers, and deserts and all the plant and animal species within them.

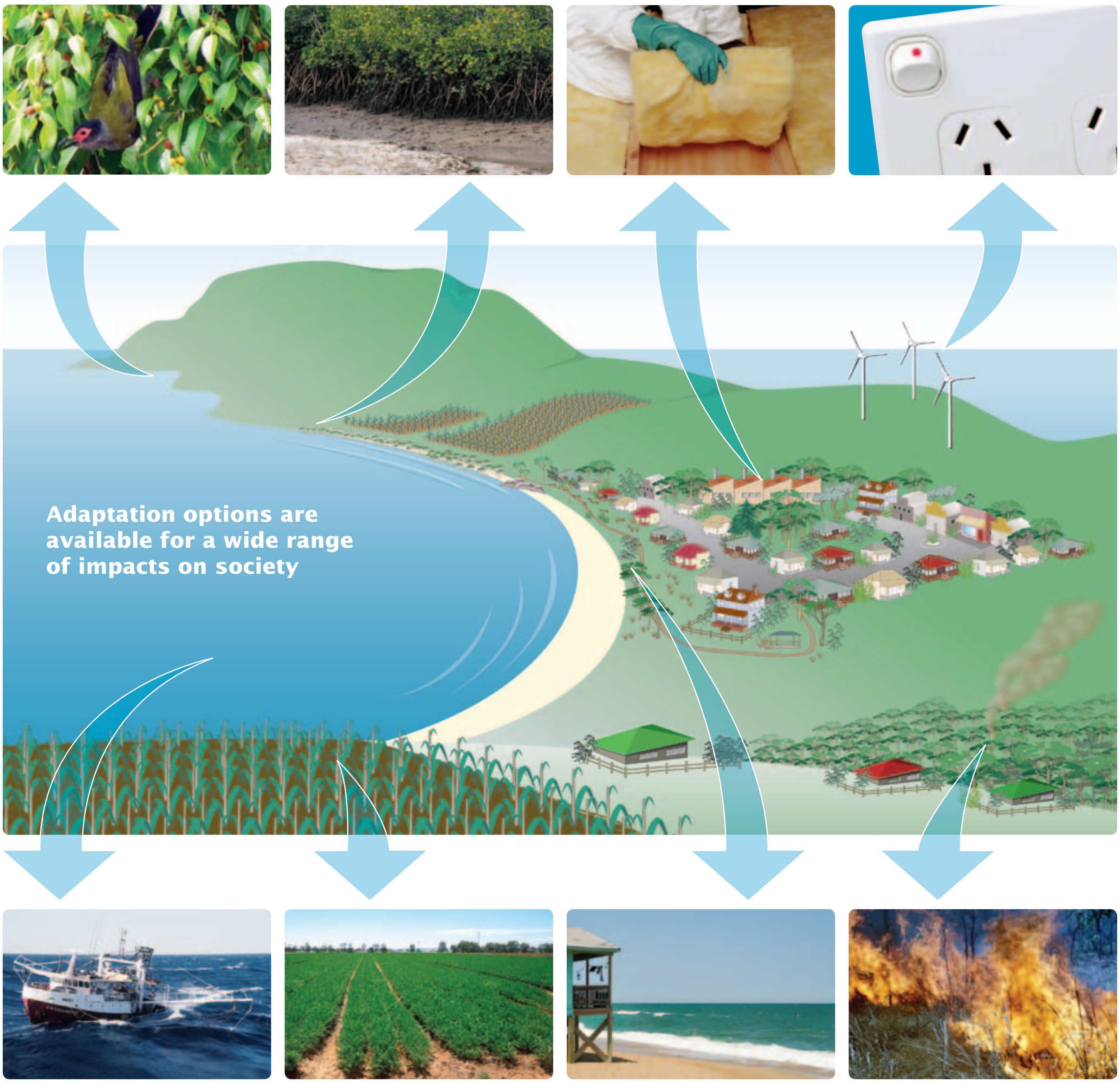
Given the wide range of adaptations to be undertaken across Australian society (see Figure 5.2), the challenge may appear complex to the point of overwhelming. This challenge is exacerbated by the uncertainties of what future climate change will actually be in different regions. There is a risk that the combined weight of the adaptation challenges and uncertainties associated with climate change projections will paralyse decision making. However, not all uncertainties are equal and not all decisions are equally difficult.[6] There are tried and tested methods for making decisions in the presence of uncertainty that are applied daily in other areas of Australian life, such as banking and finance, insurance, risk management, strategic business, and military planning. Some decisions are relatively straightforward, and can be founded on secure knowledge of what has happened with the climate so far: an example is the almost universal adoption of water saving measures around Australia to take account of drought conditions and local water shortages, and the apparently enduring decisions by millions of individual Australians to be more sparing in their private use of water (see Figure 5.6).

Conservation: actively manage long-lived species; enhance resilience of existing ecosystems

Coastal erosion: coastal defences; protective mangroves and marshes; changed recreation expectations

Heatwaves: support for elderly at risk; heat-resilient transport systems; urban greening to reduce heat stress

Energy supply: heat-tolerant transformers; more resilient distributed energy systems; reduced demand in extremes



Fisheries: reduce overfishing; allow landward migration of intertidal zone

Food production: new drought tolerant and high CO_2 cultivars; changed planting practices; relocation

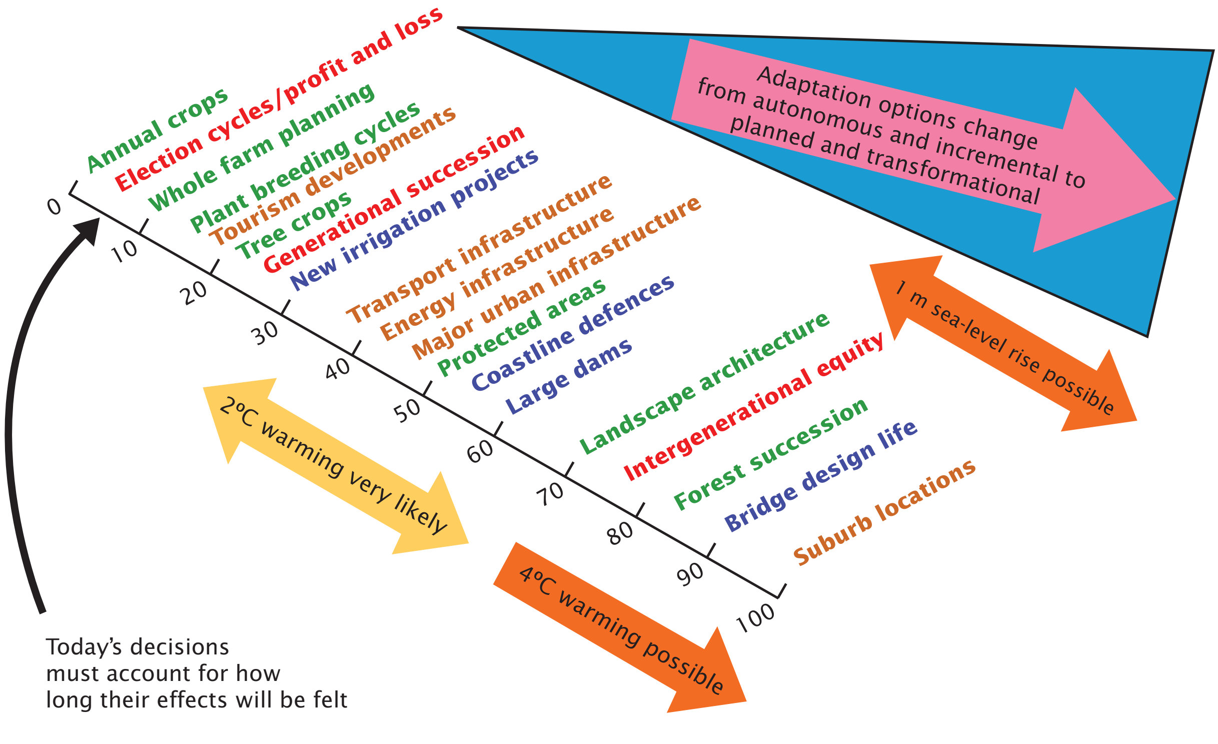
Coastal flooding: flood-tolerant building designs; movable infrastructure; flood barriers

Fire: fireproof building designs; better early warning systems; avoiding building in risky places

▲ ***Figure 5.2**: Adaptation is needed in many different areas of decision making in Australia.*[7]

Preparing for adaptation

One of the most important things to note about adaptation is that not all decisions have to be taken right away, or even in the next year or two. Some decisions do need to be taken as soon as possible, but there are others that we need to start planning for now, even though action on the ground may come later, and others still that we can consciously postpone while we monitor and assess what unfolds. Thus some decisions, such as choosing which annual crop cultivar to plant this year or what colour to paint our roofs, are very short term and adjustable, and can be re-assessed next year and the year after; this sort of decision only needs to take account of climate change as it happens. By contrast, the engineering design of a large dam or the location of a new coastal suburb locks in infrastructure for many decades or even centuries. These sorts of decisions today must take account of the uncertain state of the climate in 50 years' time and beyond. Figure 5.3 illustrates how different decisions play out over time.



▲ ***Figure 5.3***: *Different types of decisions play out over different time periods (years, on x-axis) and therefore intersect with different degrees of likely climate change.*[8]

The types of decisions and technologies required for successful adaptation are therefore a mixture of incremental and transformational.

Incremental adaptation is what we tend to do throughout our normal lives as we cope with changed circumstances, gain new knowledge, acquire new technologies, or move to different places and jobs: we adapt constantly, and we do not fear it. In its early stages, climate change will mostly require incremental change, such as a farmer making a decision to plant a crop that is more drought-tolerant to suit drier conditions, householders choosing to insulate their homes to reduce heat stress, or architects ensuring that their building designs are ready for possible increased wind gust speeds.[9] Incremental adaptation is a gradual process of adjustment.

Bob Schuster/CSIRO

Transformational adaptation, on the other hand, requires far more profound change in people and the way they go about their work and lives. A transformational change, for example, might involve the relocation of an entire industry or community to avoid increasingly unfavourable conditions such as rising sea levels, floods, bushfires, or persistent drought. This demands careful planning with long lead times and usually a degree of support from all levels of government because of the disruption it can cause to people's lives and the psychological break with what they are used to. Such changes have been accomplished many times in our past – for example, when old mines or factories are closed and new ones opened, or when we built the Snowy Mountains hydroelectric scheme and had to relocate the townships of Jindabyne and Adaminaby. However, it is important to prepare the affected communities or industries well in advance and to engage them in the planning of their new future and the opportunities it affords.

Attitudes to adaptation

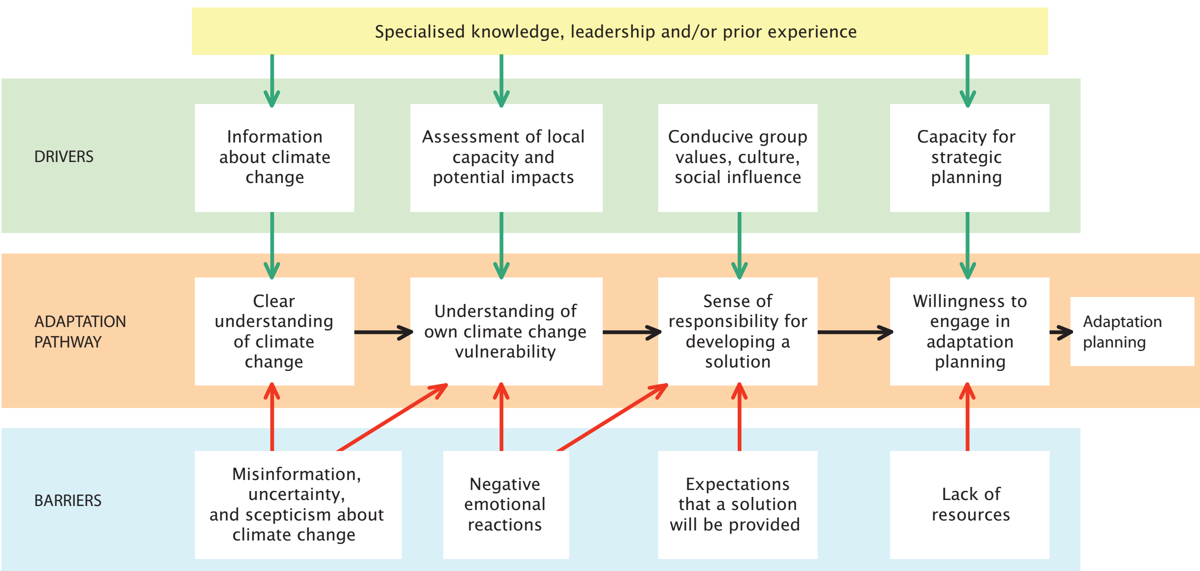
Australians currently hold mixed attitudes to adaptation, as a CSIRO survey of industry and government organisations reveals.[10] This found that the extent of adaptation activity now taking place appears to be linked to the organisation's knowledge and beliefs about climate change. Organisations that rate climate change, adaptation, and mitigation as important – and those with greater knowledge about adaptation and mitigation – are more likely to have carried out a vulnerability assessment of their operations to climate change and to have begun planning to adapt.

Adaptation was most notable in large organisations with longer planning horizons (such as water resource and energy system companies) and with strong links to expert organisations who can provide them with advice. Once an organisation has carried out a vulnerability assessment, especially if it turns out to be highly vulnerable, it is much more likely to embark on adaptation planning. Encouraging businesses, government bodies, and communities to conduct vulnerability assessments as early as possible will greatly help them to plan how they are going to adapt – and to identify opportunities for win–win or 'no regrets' outcomes.

Another thing clear from the survey is that many professionals are vexed with the imprecision and lack of certainty of climate projections. 'Tell us how high the sea levels will rise and by when, and we'll know how high to build the sea wall ...' or 'Tell me how bad the droughts will be and I'll know what changes to make to my farm' are typical responses. Unfortunately, while climate change itself and its general direction are highly predictable, its extent and speed are uncertain, particularly over longer timeframes. Over these time periods the major uncertainty arises from whether the global community responds by controlling its greenhouse gas emissions or not – a political uncertainty not amenable to scientific modelling. This means that adaptation strategies must apply well-established methods for risk management to encompass probabilities of different climatic outcomes, to be flexible, and to allow for worst-case scenarios.

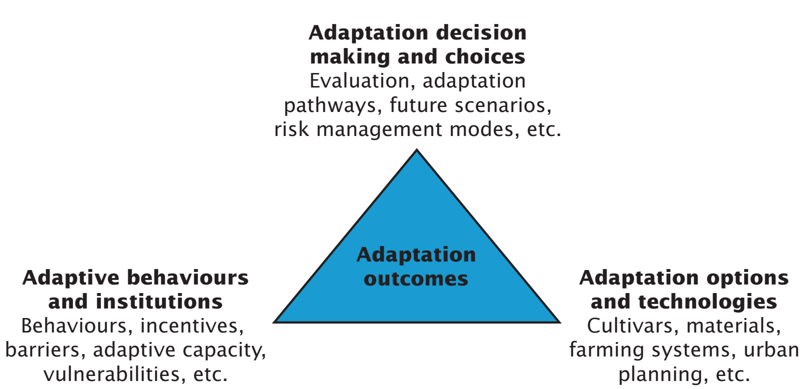
Pathways to adaptation

The essential step is to start building pathways to adaptation – to position our sectors, regions, and communities so they are flexible and ready to change when the time comes, by building immediately their biophysical, social, and institutional capacity to adapt. Figure 5.4 illustrates the stages communities or organisations are likely to go through to do this, the factors that will drive them, and the obstacles they are likely to encounter on the way.



▲ ***Figure 5.4****: A pathway for adaptation engagement with associated drivers and barriers.*[11]

Three areas are critical to successful adaptation to climate change (see Figure 5.5) – decision making and how to go about it, the development of specific solutions (technical and other) to climate challenges, and the analysis of barriers to the adoption of systems and technologies that will help us adapt. Australia is leading the way in the coordinated approach to these areas of adaptation research.



◄ ***Figure 5.5****: Adaptation can be seen through at least three very different lenses, but understanding arising from all three is needed for good adaptation outcomes.*

An important concept is that adaptation occurs at different scales, ranging from the individual to the community or industry, to the city, to the nation, as well as over varying time scales. For adaptation to occur successfully depends on what has been put in place by the different levels of government – national, state, and local – which underlines the importance of government leadership and coordination in helping Australia adjust to the impacts of climate change. Often, what happens at local government level depends, in turn, on policies adopted by state and/or federal agencies. For example, effective coastal planning controls by local government may rely on higher levels of government indemnifying and supporting local authorities. Likewise, the redevelopment of agriculture in the Murray–Darling Basin will require a coordinated approach by all levels of government.

Gregory Heath/CSIRO

Opportunities for adaptation

Humans often dislike having to change – yet, equally, we know from past experience that it also brings wonderful opportunities and, indeed, has been the chief driver in the advance of civilisation over millennia. Adapting to climate change is no different: while sometimes inconvenient, it will also offer us profound opportunities for enhancing our wellbeing, sustainability, and economic progress.

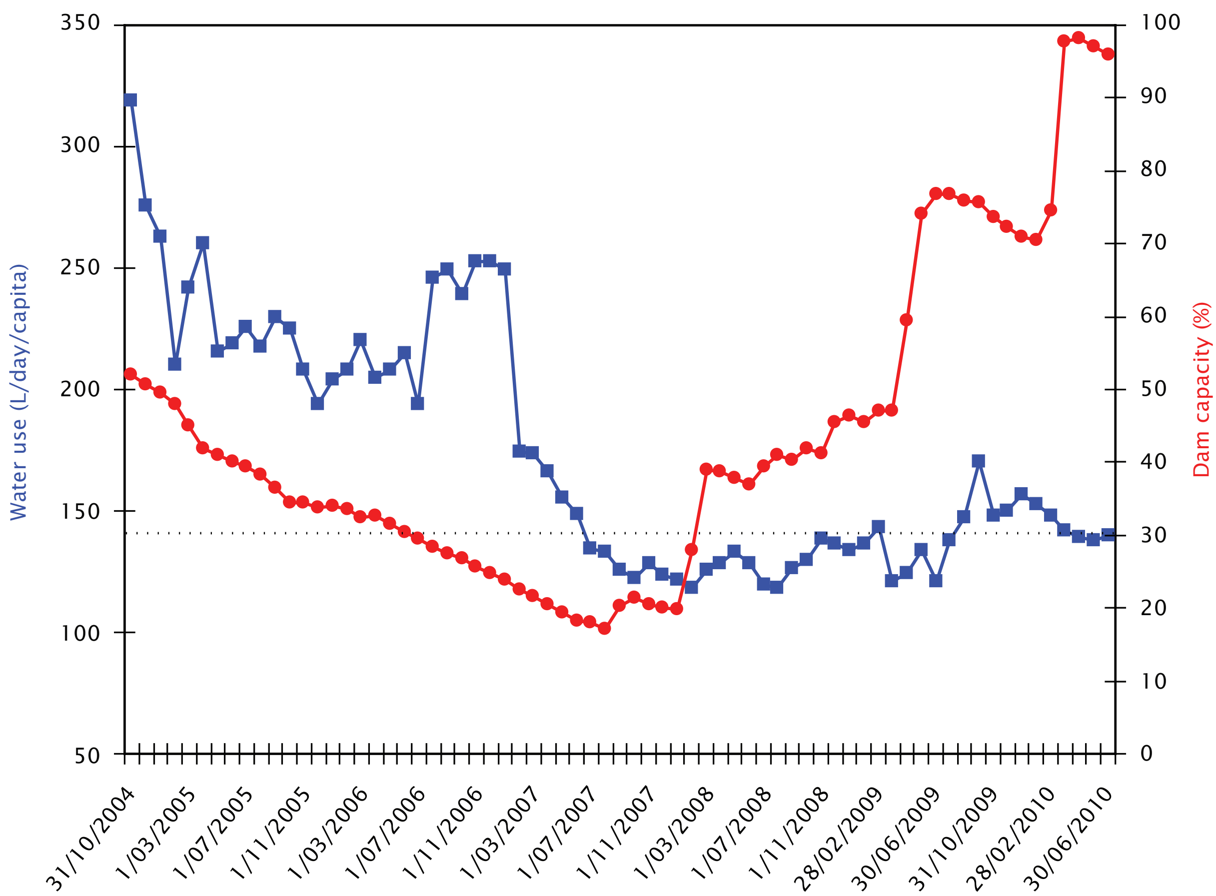
A central aspect of adaptation is to identify the opportunities, as well as the threats, we have to deal with. These will include both 'no regrets' measures – things we can do which make good sense anyway, like saving water – and 'win–win' activities, where adapting to climate change generates new industries, wealth, jobs, or other desirable outcomes.

In this category lie opportunities for Australia to reinvent itself as a global pioneer and exporter of green, effective, and successful adaptation strategies and technologies (as countries such as Denmark are already doing with wind power). In a very wide array of industries, CSIRO research is already hard at work developing the new systems, technologies, and products that will enable this national transition to occur.[12]

Here we provide just three examples of the many opportunities in adaptation through new technologies and 'no regrets' decisions:

1. For a treasured minority of decisions, the nature and extent of the response needs to be the same whatever the future climate – this leads to the classic 'no regrets' decision. For example, it has been observed that the core rules for systematic selection of conservation reserves – the so-called CAR (comprehensive, adequate, and representative) principles – remain the same under any future climate, because representing all environments in the reserve system is most likely to provide habitat for the maximum number of species, even if these no longer occur in their current locations.[13]
2. Australia has a long history of innovation in agriculture in adapting to a highly variable climate. We have the opportunity to lead the world in successful adaptation to a changing climate. Indeed, we have already seen adaptation to a warming climate through earlier planting of winter grain crops to take advantage of reduced frost incidence and these benefits can be large if frost risk is explicitly factored in to planting strategies.[14] While work on improving drought tolerance of crops through breeding has been underway for some years, work is also in hand to adapt crops to higher temperatures and a higher CO_2 environment to create a more system-wide approach to 'climate ready crops'.
3. A wonderful example of adaptation to a water crisis is evident in South-East Queensland. In response to a very long drought and dam levels dropping to record low levels, the region's water authorities gradually began introducing water restrictions in May 2005 to reduce water consumption from the then 300 L/capita/day. By April 2007, these restrictions had progressed to Level 5 and, although water usage had dropped, the risk of

the region running out of water was still very real. At that time the focus of community awareness and education shifted from the increasingly tough water restrictions as a regulatory control to target personal levels of consumption (the program was called Target 140 – targeting 140 L/capita/day consumption). This target approach for personal usage was combined with rebates and incentives for water tanks and other water saving devices (e.g. low-flow taps and showerheads), rates notices clearly illustrating household water use in comparison with the surrounding neighbourhood and the city, community education programs, and enforced water restrictions; together these led to the achievement of Target 140 by the middle of 2007. The true success of this adaptation strategy is that the water saving behaviours now seem embedded in the community, as shown in Figure 5.6. During 2009–2010, rainfall increased, the dams filled, restrictions on use of water were eased, including for watering gardens and lawns, and a permanent



▲ ***Figure 5.6***: *Combined dam capacity in South-East Queensland (red line) and water consumption per head (blue line) in the central part of the region from 2004–2010, showing how the consumption declined as water restrictions came into place, but did not rise again once they were relaxed.*

water conservation target of 230 L/capita/day was introduced. However, water consumption remained at around the same levels as at the height of the crisis in 2007 and 2008, with average water consumption of approximately 145 L/capita/day across the region in the winter of 2010. This largely 'no regrets' approach has provided a win–win benefit, because the building of expensive new storages can be planned and implemented over a longer timeframe.

Conclusion

In considering new opportunities for adaptation in a global context, social attitudes and equity are vital considerations – the equal sharing of the costs, burdens, and benefits that climate change implies. There will be many losers if we fail to adapt well, both here in Australia and in overseas countries. Australians, with our long history of egalitarianism, our belief in 'a fair go', and our willingness to share our knowledge and expertise with other people, are natural leaders when it comes to helping establish the ethics by which the world will adapt to the climates of tomorrow. Australia's agriculture has to cope with large climatic variability, its cities are already exposed to heatwaves, and a large percentage of the population lives near a coastline vulnerable to flooding. As a consequence, we are well positioned to lead global adaptation efforts to these challenges, which we explore in the following chapters.

Further reading

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Adapting to heatwaves and coastal flooding

By Xiaoming Wang and Ryan RJ McAllister

Key messages

- With an expected increase in the incidence of heatwaves and heat-related deaths, adaptation options are required that may include developing early warning systems to reach all citizens, preparation of the health system and hospital emergency departments, encouragement of behavioural changes to reduce exposure to heat stress, and better designed homes.
- Australia's built environment suffers from heatwaves on very hot days. Adaptation options include applying 'cool cities' concepts to reducing urban heat islands, increasing the resilience of cities to heat-related failures through upgraded engineering design standards, the use of less heat-sensitive materials in key infrastructure, better maintenance routines, emergency response plans that foster adaptability through collaboration across agencies and scales, and management of peak demand loading on the electricity grid.
- With increasing exposure of Australian property and infrastructure to coastal flooding in various ways along the Australian coastline, adapting to coastal inundation represents a case for thinking nationally or regionally, but analysing and acting locally.
- Options for adaptation to coastal flooding include retrofitting existing developed areas or building beach defences, changing building codes, planning and design standards to accommodate extreme and unpredictable conditions, converting current land uses to those less sensitive to flooding, encouraging house insurance rates that send a clear signal about the advisability of living in flood-prone areas, and developing effective early warning systems and evacuation pathways for extreme events.
- Early precautionary action may involve significant benefits in lives saved and property protected, fewer costs and sacrifices, and some new opportunities.

Heatwaves and coastal flooding are two impacts of climate change likely to be experienced by very large numbers of Australians during coming decades. Although it remains difficult to attribute an individual weather event directly to the effects of global warming, the nation is nevertheless likely to experience an increase in the number of days where daytime temperatures rise above 35ºC and in the frequency and seriousness of coastal flooding events as the global climate changes.[1]

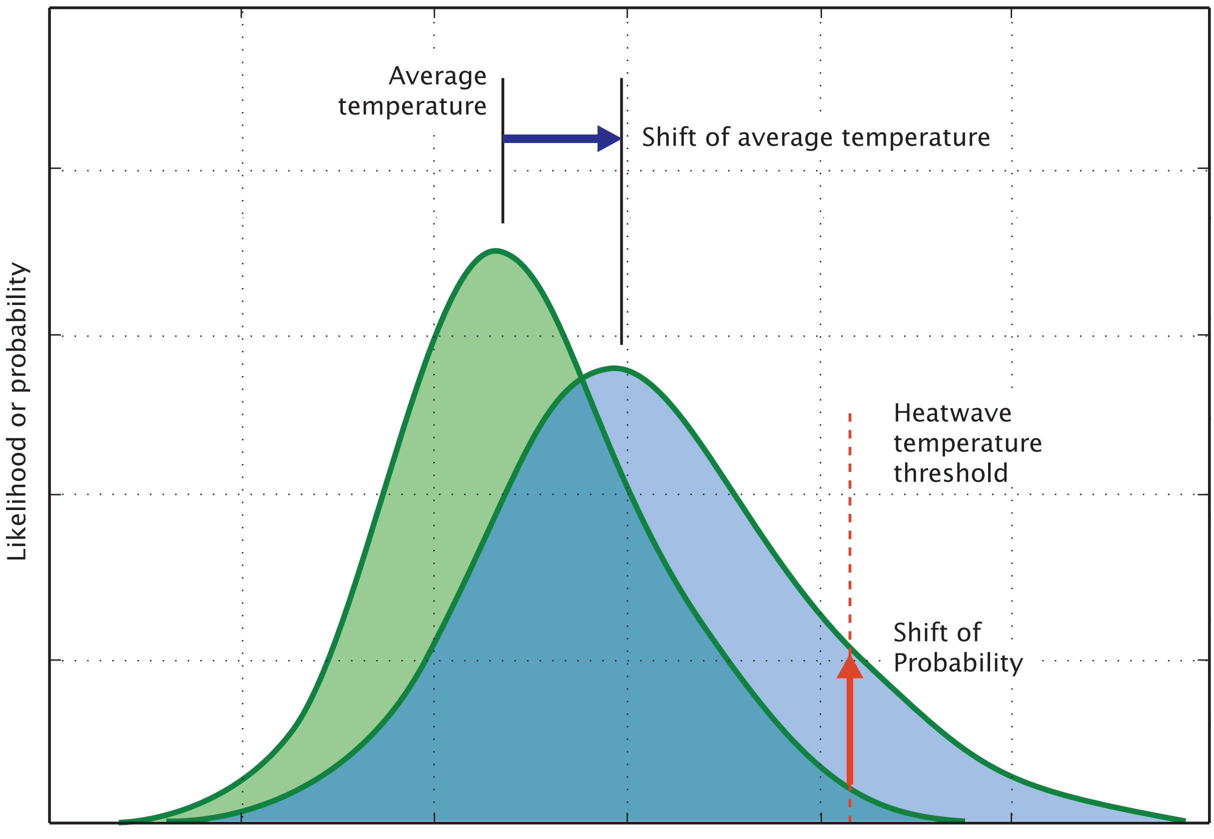
The fact that more Australians are exposed to these impacts is not, however, due to climate change alone. It is also significantly attributable to our rapid population growth, which has meant that more people now live in flood-prone areas – while our cities, with fewer green areas, are also becoming hotter places in which to live as they become more heavily built-up. It is also a part of who we are: many Australians prefer to live on the coast, in cities and, increasingly, in the tropics and subtropics.

Our exposure to future heatwaves and floods is thus likely to arise from a convergence of climate change with strong population growth, personal preferences, and planning that fails to take account of these issues.

Heatwaves

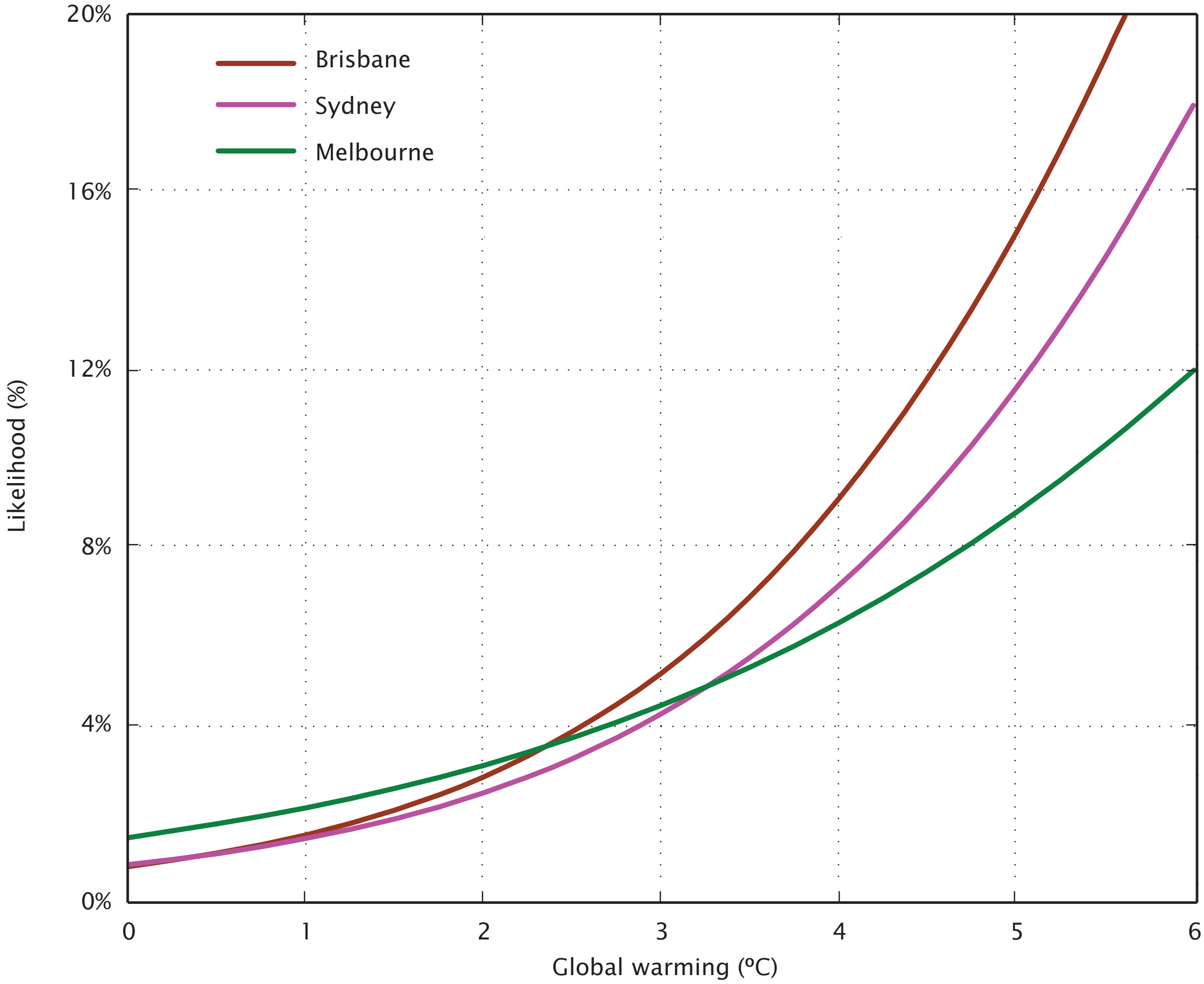
A heatwave is an event where temperatures are so high they pose a serious risk to individual health, as well as to public and private infrastructure. In Australia, heatwave conditions are often defined as periods in which daytime maximum temperatures are above a key threshold, usually 35ºC.

Australia has already experienced five of its hottest years in the last decade. As our climate warms in step with the global climate, average local temperatures will also increase across the continent, raising the likelihood of more days exceeding 35ºC, as Figure 6.1 shows. Based on the typical meteorological year weather (i.e. typical annual weather and long-term average at a given location based on historical observations) in Melbourne,[2] the number of days with daily maximum temperature above 35ºC is likely to more than double with a global temperature increase of 2ºC. The trend is summarised in Figure 6.2, which also includes Sydney and Brisbane.



▲ ***Figure 6.1**: A conceptual illustration of the increase in likelihood of higher daily maximum temperatures in response to the shift of average temperature.*

Meanwhile, under the IPCC's high emission (or A1FI) scenario,[3] which the world is tracking, the incidence of very hot days in major capital cities can be expected to increase substantially by 2030 and 2070. Data in Chapter 3 suggest, for example, that residents of Adelaide and Melbourne may experience twice as many very hot days in 2070, while residents of Darwin could find 35ºC days occurring for up to two-thirds of their year.[4]



▲ ***Figure 6.2****: Likelihood of yearly occurrence of daily maximum temperature greater than 35ºC, based on typical meteorological year weather.*[2]

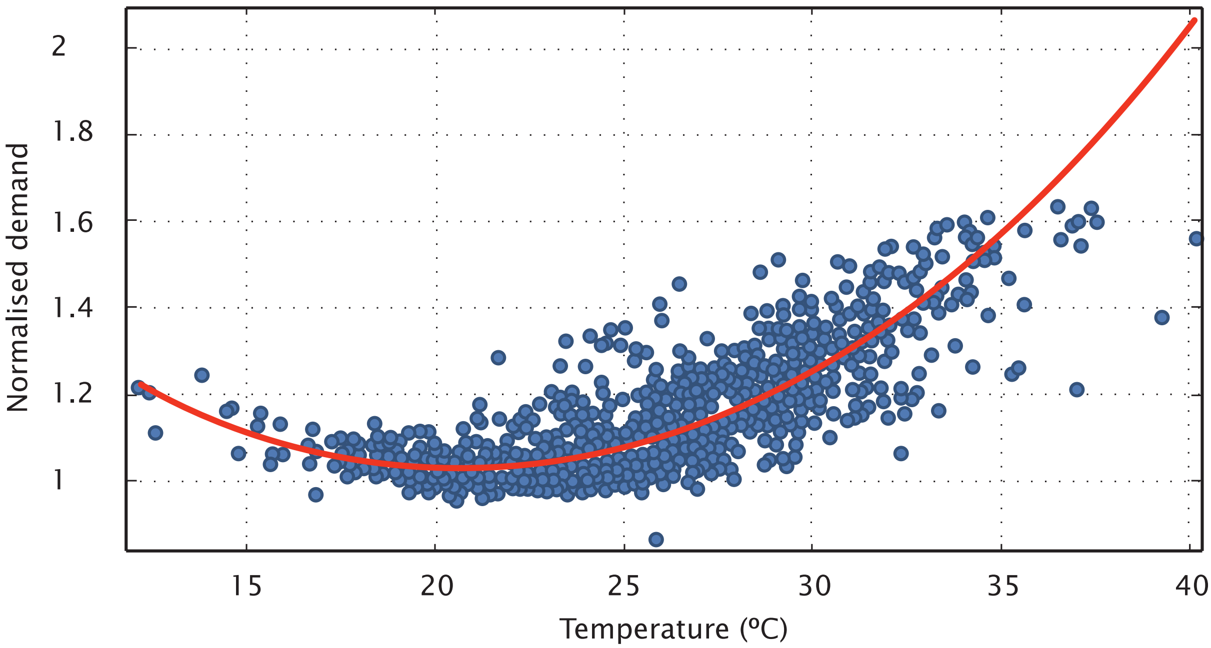
In health, the most publicised impact is the increase in premature deaths that occurs during a severe hot spell. The numbers of these fatalities can be considerable: the southern Australian heatwave of 1938 is estimated to have claimed 438 lives, while that of January 2009 led to 374 deaths, even in the age of air-conditioning (and not including the 173 bushfire deaths in February 2009), as recorded in the disaster database managed by the Attorney-General's Department, Australia. The people most vulnerable to heat stress include infants, the aged, people with chronic ill-health, those who are overweight, and the socially disadvantaged such as those on low incomes. People living in the urban environment have a relatively greater exposure to heat stress because of the urban heat island effect that may increase mortality. However, the time lag before heat stress affects the health of individuals makes accurate assessment of mortality difficult. During the heatwave peak, health-care and emergency services can be overstretched. Health effects also play out in the wider economy, not only in medical costs but also in the form of disruption to services due to absence from work.

Adaptation may include:

- reshaping health-care services to developing early warning systems to reach all citizens (with a social network back-up for those most at risk)
- preparation of the health system and hospital emergency departments, and improvements in maintenance programs for essential services
- encouragement of behavioural changes by the public to reduce exposure to heat stress
- retrofitting of old houses with better insulation
- development of emergency response plans for heatwaves in all regions.

Australia's infrastructure also suffers from heatwaves on very hot days, an example being the failure of Victoria's rail network due to buckled rails in 2009. Poorly cooled or ventilated buildings may become temporarily uninhabitable without air-conditioning. Entire communities and their infrastructure may find themselves at increased risk from bushfires. These factors, too, considerably increase the economic impact of heatwaves. Adaptation options include applying 'cool cities' concepts to reducing urban heat islands, increasing the resilience of cities to heat-related failures through upgraded engineering design standards, the use of less heat-sensitive materials in key infrastructure, better maintenance routines, and emergency response plans that foster adaptability through collaboration across agencies and scales.

One of the greatest impacts of heatwaves is on energy supply, with the massive demand for air-conditioning leading to failures in the electricity transmission network and blackouts. In general, Australia's high peak demand for electricity tends to occur during hot spells in summer (Figure 6.3). The frequency of high peak demand will increase in response to rising global temperatures. For example, it may triple for residential housing as the Earth warms by 2ºC.[5] A key adaptation will be the management of peak demand loading on the grid, as well as in the home and workplace, to avoid disruptions to supply. If peak demand is not reduced through the better design of buildings and suburbs, centralised energy supply systems will struggle to cope with the increased demands deriving from climate change. Renewable energy and storage may be used to reduce peak demand and dependence on grid electricity, but designing cooler buildings and cities is equally important.



▲ ***Figure 6.3**: The impact of temperature on energy demand in South-East Queensland between 3.00 and 3.30 pm (normalised so that the average across the year equals 1).*

The economic costs of heatwaves extend beyond infrastructure damage and premature deaths. Illness and transport disruptions cause loss of human productivity, while crop and horticulture damage reduces agricultural productivity. Because most of the global warming that will occur in the next few decades is now built into the Earth's system because of historical and current greenhouse gas emissions, and is largely unavoidable, the likelihood of more heatwaves makes it very clear that Australians face considerable adaptation challenges now – in our daily lives, in how we build our homes, plan our cities, go about our work, and take care of our health. All of us will be exposed to the effects of increasing heatwaves. Research underlines that it is both sensible and economically far more cost-effective to start planning and to take action as soon as possible in order to minimise the effects.

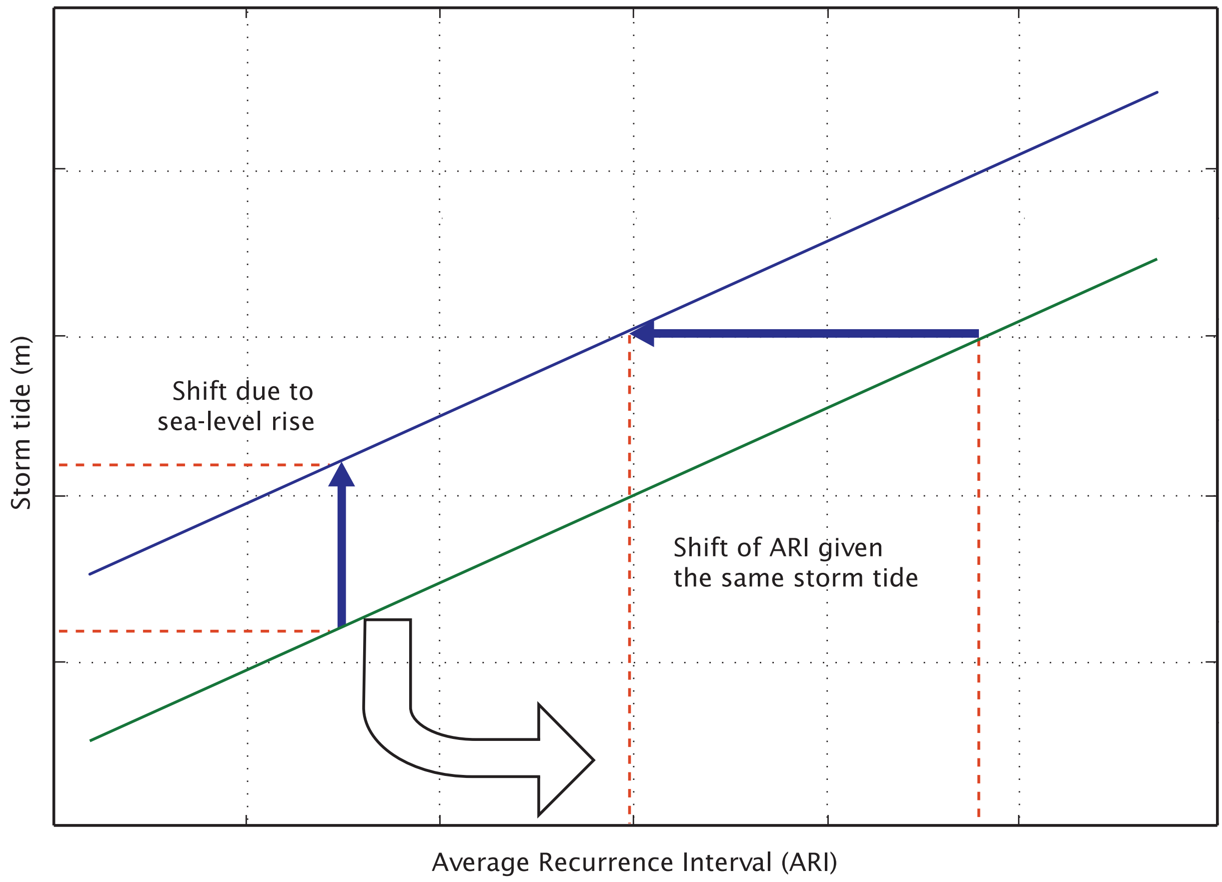
Australians, wherever they live, have adapted to periods of very hot conditions – with varying degrees of success – by designing their houses, clothing, diets, and work patterns to suit. So the adaptations that lie ahead in the coming decades are less likely to come as a shock, will often make good sense, and will frequently involve win–win outcomes, such as the creation of new jobs in a more sustainable economy.

Coastal inundation

Today, coastal inundation is caused by storm surges, which usually occur when low-pressure weather systems, cyclones, or storm winds combine with high tides to drive sea water onshore and swamp areas normally regarded as dry land. Minor inundation can also result from large king tide events. Over the next few decades, the risk of coastal inundation is expected to increase owing to sea-level rise and potential increases in storm intensity and frequency driven by the changing climate. Continuing growth in our coastal populations means that more Australians, their property, and infrastructure will be exposed.[6] Minimising these risks calls for a strategic approach that involves governments, industries, communities, and individuals working together to come up with practical and affordable solutions.

CSIRO

Sea level is projected to rise by 20–80 cm above 1990 values by 2100; however, larger estimates that take ice sheet melting into account cannot be excluded – a study for the Netherlands Government suggested a high end value for sea-level rise of 110 cm by 2100 (see Chapter 1). Higher sea levels will likely increase the occurrence of coastal flood events. Storm surges due to extreme weather events are likely to become more intense and frequent, with a current 1-in-100-year[7] inundation event occurring nearly twice as frequently by 2030 and many times more often by the latter part of the century, because of sea-level rise. This is illustrated by Figure 6.4, which shows that sea-level rise will lead to more frequent extreme flooding events. Although rare, such events can lead to large loss of life, as was the case in 1899 when 400 people died as a result of a cyclonic storm surge in Bathurst Bay, Queensland.



▲ ***Figure 6.4****: A conceptual illustration of the reduction of average recurrence interval of the same height of storm tide due to sea-level rise*

The Australian Government report *Climate change risks to Australia's coasts*[6] (see Chapter 4), found that, out of 711 000 existing residential buildings close to the sea, between 157 000 and 247 600 properties were potentially exposed to flooding with a sea-level rise of 1.1 m. Furthermore, nearly 39 000 buildings located within 110 m of 'soft' shorelines would be at risk from accelerated erosion due to sea-level rise and changing climate conditions. If all these buildings were destroyed, the cost of replacing them was estimated at AU$41–63 billion. Besides homes, 258 police, fire and ambulance stations, five power stations or sub stations, 75 hospitals and health centres, 41 landfill sites, three water treatment plants, and 11 emergency services facilities would also all be at risk, being located within 200 m of the sea shore. Essential services such as electricity generation and wastewater management would be also at risk from flooding, erosion, the intrusion of sea water into coastal freshwater systems and drainage systems, and increased corrosion. Almost all of our existing coastal buildings and infrastructure were constructed under planning rules that did not factor in the impacts of climate change, though state governments are now taking account of sea-level rise through their planning policies. Just as the building codes and rules for Darwin changed in the wake of Cyclone Tracy, so they should now be re-assessed for each region and locality in Australia to take account of climate change.

It is important to note that risks from coastal flooding are not uniform. They vary all along the Australian coastline, affected by local climate, topography of both the land and seabed, rainfall in local catchments leading to riverine and estuarine flooding co-incident with storm surge, tidal characteristics and demography, buildings and other infrastructure in the affected zone, as well as local adaptive capacity. This makes adapting to coastal inundation a clear case for thinking nationally or regionally, but analysing and acting locally.

To illustrate the extent of the risk and what must be done to minimise it, CSIRO has completed a study of inundation in South-East Queensland.[8] This provides a model for the type of issues and options that coastal communities around the continent will need to consider. It found that the current storm surge events will occur more frequently on average as a result of sea-level rise, as shown in Table 6.1. The current 1-in-100-year storm surge event, for example, would occur about every 61 years with a sea-level rise of 20 cm, and every 9 years with a sea-level rise of 1 m – that is, it will be more than 10 times more frequent. Currently about 230 000 southern Queenslanders are at risk from a 1-in-100-year storm surge. However, population growth will interact with climate change and the number of people at risk could rise to 400 000. The cost of dealing with such events would increase from AU$1.12 to AU$1.97 billion (Table 6.2).

Table 6.1: Average recurrence interval (years) in relation to different levels of sea-level rise for inundation events in South-East Queensland that currently have recurrence intervals of 50, 100, 500, or 1000 years

Current events	0.2 m sea-level rise	0.4 m sea-level rise	0.6 m sea-level rise	0.8 m sea-level rise	1.0 m sea-level rise
1-in-50	31	19	12	7	4
1-in-100	61	38	23	14	9
1-in-500	306	188	115	70	43
1-in-1000	613	375	230	141	86

Table 6.2: Estimate of people and homes exposed to major flooding events in South-East Queensland			
	Scenario 1 Today	**Scenario 2 No adaptation, 2030**	**Scenario 3 Adaptation, 2030**
Population	Today's population	2030 population	With no population growth in vulnerable locations
Buildings	Today's buildings	2030 buildings	With no building growth in vulnerable locations
Storm tide	2.5 m	2.7 m (2030)	2.7 m (2030)
Exposed populations	230 000	400 000	250 000
Exposed residential buildings	35 000	62 000	40 000
Costs ($bn)	1.12	1.97	1.28

This study shows there are considerable benefits from taking early, proactive adaptation measures to limit the possible damage from storm tide events, such as to:

- retrofit existing developed areas with structures designed to reduce flood risk or enable water to subside quickly, protect key infrastructure from minor flooding, and build beach defences where it is economic and advisable to do so (recognising they will eventually be overwhelmed).
- change design standards for new buildings within existing developed areas so they are more able to withstand periodic inundation, e.g. minimum floor heights above sea level, flood-tolerant lower floors, and demountable homes that are easily moved.
- encourage house insurance rates that send a clear signal about the advisability of living in flood-prone areas.
- introduce building codes that allow for extreme events. These could even prevent or discourage new developments in at-risk areas. Convert current land uses to those less sensitive to occasional flooding (e.g. parks and recreational areas).
- develop nationally consistent planning principles that ensure higher levels of government support and build capacity in local government for protecting local communities. Develop more flexible local and regional planning to accommodate extreme and unpredictable conditions.
- develop effective early warning systems and evacuation pathways for extreme events.

The benefits of successful adaptation are substantial. In the case of South-East Queensland, as summarised in Table 6.2, if nothing is done then the number of people at risk of a major (2.7 m by 2030) flood event will grow from 230 000 today, to 400 000 in 2030. Preventing new at-risk developments would protect about 150 000 people and save AU$0.7 billion in a major storm event by 2030. Retrofitting or reclaiming flood-prone land on top of this would protect 170 000 people and save AU$0.9 billion in a major event affecting South-East Queensland in 2030.

Conclusion

Australians' options in adapting to heatwaves and floods can be either proactive or reactive. They usually involve all levels of society, from the individual to the local community and local government, to regional, state and federal governments. As illustrated by the case of South-East Queensland, early precautionary action will almost always involve significant benefits in lives saved and property protected, as well as fewer costs and sacrifices. This action will also open up new opportunities, such as the colder parts of Australia decreasing their energy use for heating, new industries, technologies, and jobs arising out of climate adaptation, and a leadership role for Australia in global adaptation to heatwaves and coastal inundation.

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Adapting agriculture to climate change

By Chris Stokes and Mark Howden

Key messages

- There is a national imperative to equip Australian agriculture to be prepared to adapt to climate change.
- Some agricultural communities, industries, or regions will have a greater capacity to adapt than others: understanding their constraints and incentives is important in ensuring that they do so successfully.
- An early part of adapting agriculture to climate change involves helping communities to understand why adaptation is a needed part of today's vision of the future and therefore of their management strategies.
- Successful adaptation to climate change will require flexible, risk-based approaches that deal with future uncertainty and provide strategies that are robust enough to cope with a range of possible local climate outcomes and variations.
- Many climate adaptation options for agriculture are similar to existing 'best practice' and good natural resource management, and do not require farmers to make radical changes to their operations and industries in the near term. These options can, and should be, prioritised as part of a 'no regrets' or win–win strategy for agriculture because they will provide immediate and ongoing benefits as well as preparing the sector for climate change.

There is a clear imperative for action to prepare agriculture to adapt to climate change. Worldwide, agriculture in general is highly sensitive to variations in climate, and in Australia especially so. The Australian climate is already changing and these changes have a measurable impact on primary production, as the drying of the Murray–Darling Basin and parts of the wheatbelt bear witness.[1] Early development of the technologies, skills, and policies that will allow adjustment to a changing climate is likely to provide significant national benefit.

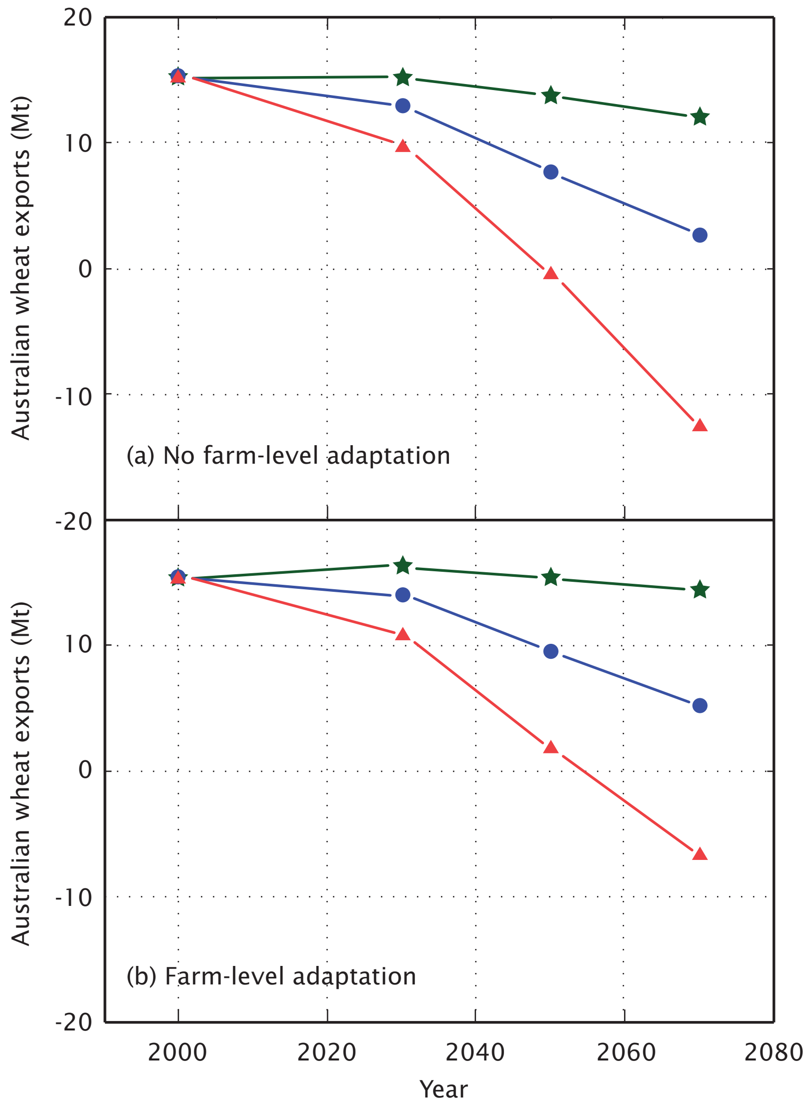
Carl Davies/CSIRO

Adapting Australian agriculture

Australia's agricultural sector (including fishing and forestry) already has to cope with a harsh and highly variable environment, and primary producers have proved adept at continually adjusting management practices to deal with these and other challenges. However, there have also been tough lessons learned from inappropriate responses that have had negative impacts on enterprises and the land.[2] Climate change is likely to add a new dimension to these challenges, through projected negative impacts on the amount, quality, and reliability of our food and fibre production (as briefly outlined in Chapter 4).

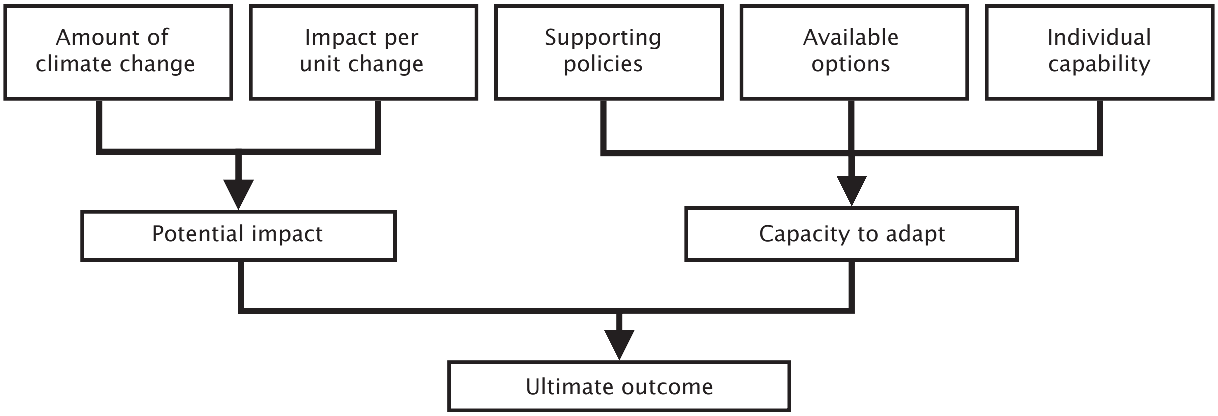
However, besides the negative effects, potential benefits and fresh opportunities also arise from climate change. Higher temperatures may enhance production from horticulture and pastures in the continent's cool regions and the positive effects of higher levels of CO_2 on plant growth may partly offset the negative effects of higher evaporation or decreased rainfall.

Timely and effective adaptation will likely also bring opportunities and benefits. For example, as Figure 7.1 illustrates, adapting to the expected changes in climate and population-driven food demand could significantly offset declines in Australia's currently large wheat export surplus, reducing the risk of needing to import grain in some years.



▸ ***Figure 7.1****: Estimated Australian wheat exports (Mt/year) for the years 2030, 2050, and 2070, with and without farm-level adaptation.[3] The lines indicate maximum, average, and minimum scenarios for each year. Values below the zero line mean that imports may be required.*

The impact of increased greenhouse gases on Australian agricultural activity depends on the magnitude of climate change locally (e.g. shifts in local temperature, rainfall patterns, and extreme events), how strongly each amount of change in the climate affects farm productivity, and lastly the actions taken in response to the climate changes (see Figure 7.2). The ultimate effect of climate change on farm enterprises and the rural economy therefore depends not only on how the climate affects farm production directly, but also on the way that individual farmers, communities, and whole industries respond to the changes.



▲ ***Figure 7.2***: *Both climate and human factors determine ultimate outcomes.*[4]

Action at all scales

The performance of Australian agriculture in adapting to climate change and counteracting its negative effects will be influenced by three key drivers:

(1) the policies adopted by government at various levels and the signals they send to farmers and others in the food chain

(2) the development and availability of effective adaptation choices

(3) the capacity and motivation of individuals and industries to implement the appropriate adaptations and obtain support for doing so.

These factors make it clear that adaptation is not something that can be left to farmers, or indeed to governments, alone. Everyone involved in the food industry – including policy makers, research and development providers, and enterprise managers – can contribute to solutions by working in collaboration. Governments, for example, can ensure that water and drought policies accord with successful farm adaptation and do not impede it.[5] R&D providers, working with farmers, can help to ensure a choice of effective adaptation options and technologies – such as suitable crop varieties, water use efficiency measures, or new farming, forestry, or fishing methods – are available and delivered when needed. And farmers need the skills, the capital, access to the right information and advice, and suitable incentives to make the necessary changes. Successful adaptation is likely to be helped by considering the system-wide consequences of proposed adaptation measures at all social levels, at all points in the food chain, and in relation to other concurrent challenges (such as meeting the growing demand for food and fibre). Hence, there is likely to be increasing demand for strong science–policy linkages, analysis of alternative governance models, and stronger focus on the institutional arrangements to support adaptation in agriculture.[5–7]

A core issue confronting governments is that some communities, industries, or regions will have a greater capacity to adapt than others; understanding the constraints and incentives that bear on them is important in ensuring that they do so successfully. As climate impacts are often unpredictable, or may be perceived to be 'in the distant future', an early part of this task involves helping communities to understand why adaptation is a needed part of today's vision of the future, and therefore of their management strategies.

Coping with uncertainty

Successful adaptation to climate change will require flexible, risk-based approaches that deal with future uncertainty and provide strategies that are robust enough to cope with a range of possible local climate outcomes and variations.[8, 9]

Every strategy should derive from working with farmers, fishers, and foresters to develop a choice of alternative adaptations to suit the range of likely climates they may encounter, and building the skills to evaluate, choose, and implement these as required. This is preferable to trying to second-guess actual climate outcomes in particular places and times and trying to adapt to something that may turn out differently. It will be important for government policies in areas such as drought assistance, Landcare, and water provision to help hone this capacity in the farming community.

Successful adaptation requires both strategic preparation and tactical responses. These should initially be based on current 'best practices' for coping with adverse conditions such as drought. There are a wide range of actions, among individual farmers and across the whole of agriculture, that can help to promote adaptation (see box on page 90).

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Contributors to successful adaptation[10]

(1) confidence among farmers and others that the climate really is changing and that inaction is not an option

(2) the motivation to change, to avoid negative impacts, or seize opportunities

(3) wide communication and demonstration of the benefits of new climate adaptations

(4) support for farmers as they make the transition to new systems, new land uses, or new forms of livelihood

(5) building capacity in farming communities to take up and implement adaptation strategies

(6) a rapidly evolving transport, market, and financial infrastructure to support the most climate-efficient forms of agriculture

(7) an effective system for monitoring climate change impacts and human adaptive responses, so that policy and management can develop 'ahead of the game'.

Adaptation priorities and opportunities

Some adaptation priorities apply broadly across the whole agricultural sector. Among these is the need to improve and promote existing management strategies for dealing with climate variability. This will enhance farmers' capacity to plan for, and deal with, extreme events (droughts, floods, fire, hail, etc.) in the medium and longer term. Using climate forecasts at a range of time scales to make pre-emptive, tactical management adjustments will help to track the early stages of climate change, until the longer term trends and necessary adaptations in particular regions become clearer.

Examples of likely adaptations include:

- **Information delivery** to farmers from climate analyses can be enhanced by providing projections of management- and policy-relevant weather metrics (e.g. cold indices for stone fruit), providing climate information at scales relevant to the decisions being made, and combining information on both climate variability and trends in seasonal and medium-term (decadal) forecasts.
- **Biotechnology** and traditional plant and animal breeding have the potential to develop new 'climate-ready' varieties and new crops or pastures pre-adapted to future climates.
- **Plant nutrition** can be adjusted by measures such as precision fertiliser use, legume rotations, and varietal selection to maintain the quality of grain, fruit, fibre, and forage sources.

Willem van Aken/CSIRO

- **Irrigation efficiency** will become critical as water resources become more constrained, particularly in southern Australia. This can be assisted by identifying less water-intensive production options, by developing better water delivery technologies, and by implementing water markets and water-sharing arrangements.
- **Soil and water conservation methods** and new systems become even more important as climates fluctuate more and extreme events become more frequent.
- **Biosecurity, quarantine, monitoring, and control measures** can be strengthened to control the spread of pests, weeds, and diseases under a warming climate.
- **Better models of agricultural systems** can assess climate change impacts and more reliably explore and improve adaptation options.
- **Monitoring and evaluation systems** are needed to track changes in climate, impacts on agriculture, and the effectiveness of adaptation measures, to help decide when to implement particular options and to refine them over time.
- **Policy and management decisions** require timely inclusion of climate information as it becomes available, as well as closer collaboration between policy makers, managers, researchers, extension agencies, and farmers.

It is important to note that many climate adaptation options are similar to existing 'best practice' and good natural resource management, and do not require farmers to make radical changes to their operations and industries in the near term. These options can, and should, be prioritised as part of a 'no regrets' or win–win strategy for agriculture because they will provide immediate and ongoing benefits, as well as preparing the sector for climate change.

At the time of writing, few adaptation options have been fully evaluated. Those that have been evaluated suggest that the benefits of adaptation are so significant that further systems analyses are warranted. For example, in the wheat industry alone, relatively straightforward adaptations to future climate change, such as the growing of new varieties, adjustment of planting times, and the practising of moisture conservation may be worth between AU$100 million to AU$500 million per annum at the farm gate.[11] Further benefits are likely if a wider range of adaptations is practised, but these remain to be assessed.

Preparing for step-changes in adaptation

The benefits obtained from each major type of adaptation are likely to plateau as more extreme climate changes come into play over future decades, as Figure 7.3 indicates. This means that there are likely to be limits to the effectiveness of incremental adaptations within a given farming system and that, at some point, a step-change or transformational adaptation will be called for. This has been found in both national and global studies.[3] Part of the cause for this is that initially positive impacts of climate change – of higher CO_2 on plant growth for example – may be outweighed by negative effects (such as higher temperatures or drought) as conditions become more extreme.

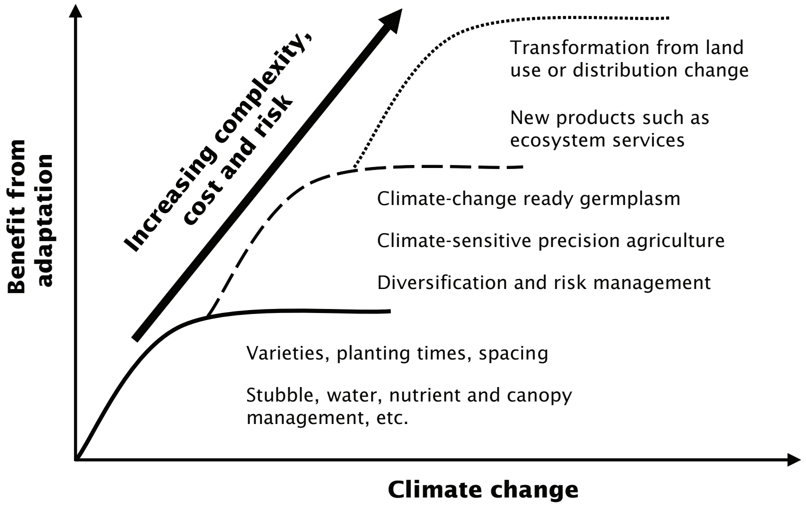

Figure 7.3: The potential benefit from different levels of adaptation with increasing climate change from incremental, within-system responses, to system-level changes to transformational changes. Greater levels of climate change would overwhelm the maximum potential of simple adaptation options, requiring additional strategies that involve increasing risk, cost, complexity, and time to develop and implement.[3]

As incremental adaptations are rendered less effective by changing conditions, larger adaptations, such as changes in land use, the re-location of significant industries or diversification into new activities, such as carbon sequestration or farming for energy provision, may become desirable. Inevitably, as we move from incremental to transformational change, the complexity, cost, and risk of actions will also increase, and these must be planned well.

Areas of farming that are economically marginal today are among the most vulnerable to climate change; here, impacts are most likely to exceed the region's adaptive capacity, stressing their communities, farming systems, and natural resources. Such areas include outer wheatbelt zones subject to drying, warmer dairying or fruit growing areas, or irrigation communities whose water resources are in decline – all areas where quite small changes in climate can have quite large economic and social consequences. An early priority is to identify particular regions, and indeed industries, where climate change risks and opportunities require strong policy intervention (beyond simple incremental adjustments to existing agricultural practices) so that the affected communities can be appropriately supported through the transition.

Greg Rinder/CSIRO

It is equally important to investigate the adaptive capacity of local farmers, communities, and industry groups region by region, so as to identify and rectify factors that may hinder successful adaptation.[7] This will enable policy makers to identify broad areas where action can be taken. Self-assessment of capacity to adapt is currently used for local evaluation and consequent improvement in adaptive capacity.[12] However, the scaling-back in state agricultural agencies and decline in support for activities such as Landcare over recent decades has made this task more difficult at regional and national scales, although the emergence of grower groups has partly offset this. Effectively, this means that there is less analytical capability in Australian agriculture and less advice and support available to farmers just at the time it is most needed.

Issues requiring urgent enhancement include all those factors most likely to limit (or accelerate) farmers' ability to take up and implement the necessary adaptations: their health, education, and skill profiles, their access to capital and knowledge, and whether or not the social structure of their community is conducive to far-reaching changes and the exploitation of new opportunities. This underlines the main point that responding to climate change is as much a social as a technical or policy challenge.

Past climate policy has focussed primarily on mitigation (reducing emissions) rather than considering adaptation (coping with changes that do occur). With delays in global action on mitigation, there is likely to be growing demand by both farming and policy communities for information on how to cope with emerging climate challenges and for approaches that consider adaptation and mitigation together. Importantly, this should ensure that adaptations do not increase GHG emissions, so making the underlying cause worse – and, similarly, that mitigation options do not undermine adaptation efforts.

Conclusion

As climate change unfolds through the early decades of the 21st century, adaptation will become the pivotal response by Australia to maintain its own food security and self-sufficiency, to retain vibrant rural communities, and to sustain globally important agricultural exports.

Much needs to be done to enable Australian society to adapt to conditions that are already changing, and to further change, which may now be largely unavoidable. Early preparation to adapt is both sound practice and likely to confer national benefit and competitive advantage under almost any likely climatic outcome. Furthermore, it is highly likely that many of the adaptations developed in Australia will have great value in helping other countries and societies to stabilise food production and to offset or avoid some of the more serious consequences of climate change. This is a role for which Australia's past contributions and current expertise equip it well to contribute solutions to this global challenge.

Carl Davies/CSIRO

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Greenhouse gas mitigation: sources and sinks in agriculture and forestry

By Michael Battaglia

Key messages

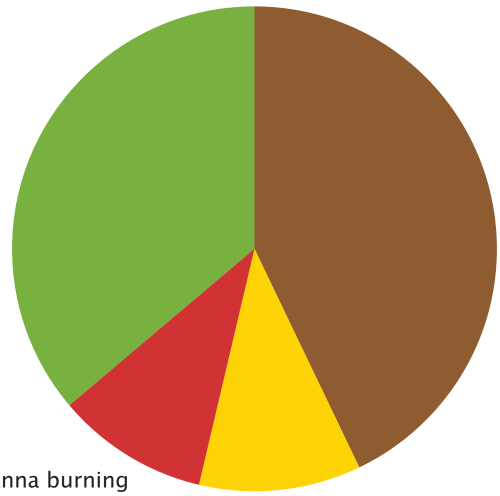
- Agriculture and forestry can make a valuable contribution to lowering Australia's greenhouse gas emissions by reducing their own direct emissions and by increasing the amount of carbon stored in soils and landscapes.
- Our soils and forests store large quantities of carbon: somewhere between 100 and 200 times Australia's current annual emissions. We can potentially increase these stores in our rural lands and perhaps store or mitigate enough greenhouse gases to offset up to 20% or more of Australia's emissions during the next 40 years.
- Forest plantings are the most straightforward way to sequester carbon in rural landscapes and, along with reduced land clearing, provide the most immediate, significant, and realisable carbon sequestration opportunity.
- Nearly a third of Australia's terrestrial carbon is stored in tropical savannas: the continent's most fire-prone biome in which half or more of the land may burn each year. These fires currently contribute 2–3% of the nation's total accountable emissions and have an important bearing on rates of carbon sequestration.
- Ruminant animals (such as sheep and cattle) emit methane as a by-product of digesting feed. In 2008, this contributed 9.6% of Australia's total greenhouse gas emissions and was the largest component of agricultural emissions.

In Australia, agriculture and forestry can make a major contribution to lowering our greenhouse gas emissions, both by reducing their own direct emissions and by increasing the amount of carbon stored in soils and landscapes. The way we choose to manage our rural lands will have a significant impact on Australia's future net greenhouse gas emissions.

Nick Pitsas/CSIRO

Reducing emissions from Australian land use

In 2008, Australia's agricultural sector and land clearing accounted for about 15% and 9%, respectively, of the nation's gross greenhouse gas emissions. In that year, afforestation and reforestation offset around 17% of the agricultural emissions.[1] The agriculture share of national emissions is high compared with that in many developed nations (at between 5 and 10%, for example, for the USA and the UK) and reflects both the large land base per capita in Australia and our significant agriculture sector. These emissions consist of carbon losses due to land clearing and land-use change (36%), livestock methane emissions and manure management (43%), savanna burning including both naturally caused wildfires and deliberate burning for pasture management (10%), and cropping and agricultural soils emissions (11%) (Figure 8.1).



▸ ***Figure 8.1**: Percentage net contribution of different sources to agriculture, land use, land-use change, and forestry greenhouse gas emissions in 2008.[1] These are gross emissions and do not account for offsets due to afforestation.*

Our soils and forests store large quantities of carbon: somewhere between 100 and 200 times Australia's current annual emissions.[2] We can potentially increase these stores in our rural lands, and perhaps store or mitigate enough greenhouse gases to offset up to 20% or more of Australia's emissions during the next 40 years[3] – but it must be recognised that many factors, such as carbon pricing and other incentives, government policy, technology, and social attitudes will have a major bearing on how much carbon is ultimately sequestered in our landscapes. In attaining this carbon sequestration, other benefits such as restoring biodiversity and ecosystem services, improving soil productivity, controlling salinity and erosion, and improving water quality also may be realised. Unlike many other mitigation options (e.g. rebuilding the power generation sector), forestry and land-management options do not require major investment in infrastructure. Instead, they involve changes in land use and land management and consequently there are trade-offs, as well as benefits, from such large-scale carbon storage: potentially these include lower food, fibre, and timber production and, if unregulated, altered regional water flows. Furthermore, there remain significant uncertainties over estimates of greenhouse gas mitigation or soil carbon storage potential.

In the following sections we explore different options for reducing emissions or increasing carbon storage from different land-use and management activities.

Afforestation

Forest plantings are the most straightforward way to sequester carbon in rural landscapes and, along with reduced land clearing, provide the most immediate, significant, and realisable carbon sequestration opportunity. They are eligible for carbon credits under existing agreements, they are effective (they store significant quantities of CO_2 per hectare), and carbon sequestration is easily verifiable. At the present time, to qualify as a 'carbon forest', both reforestation and afforestation need to meet the requirements of Article 3.3 of the Kyoto Protocol – for example, forests would need to be planted after 1990 on agricultural land cleared before 1990.

Australia's landscapes offer many opportunities to integrate trees as part of mixed farming, landscape rehabilitation, or catchment management. Research indicates that it is possible over the next 40 years to store on average 9 tonnes of carbon dioxide equivalent (CO_2-e – that is, the amount of all greenhouse gases that would give the same warming as the equivalent concentration of CO_2 alone) per hectare per year. However, this depends on many local and external factors, which lead to a variation in storage amount in the range 3–20 tonnes of CO_2-e per hectare per year.

Willem van Aken/CSIRO

Doing this over a sufficiently large area to reduce significantly national net greenhouse gas emissions by 2020 presents challenges: sufficient suitable land must be found, a great deal of seed is needed, and the trees must survive and grow well. A doubling in the national plantation estate of 2 million hectares could sequester around 20 million tonnes (Mt) of CO_2-e per hectare per year over a 40-year cycle – but it would have to be as carbon forest and remain unharvested (at least on a net area basis if carbon stocks were pooled across harvested and newly planted areas). Maximum rates of afforestation in Australia in recent times have been around 100 000 hectares per year, suggesting it will take around 20 years to achieve 20 Mt of CO_2-e per year of abatement potential.

To achieve the full benefits of carbon storage, carbon forests need to be managed (and their carbon counted) according to natural cycles of death and decay, including the periodic impact of fire. The long-term aim might be to manage forests of a range of ages: the amount of carbon registered being an average of old and young forest, rather than the maximum possible for any given hectare.

Analysis has shown that, at even a modest carbon price (AU$10–20 per tonne of CO_2-e), forestry could be a competitive land use across large areas, with many tens of millions of tonnes of abatement generated. However, many factors, including community and landowner attitudes, will govern where carbon forests can be planted. Water availability is also an important consideration, but carbon forests are only likely to have an impact on water supplies where a large plantation is established in a continuous block and, in most cases, existing policy and analysis tools are in place to prevent negative impacts. Because carbon forests do not need to be near processing facilities, they can be scattered across the landscape, lowering the risk of carbon release by fire, pests, and storms, and spreading their impact on water supplies. Many farmers now integrate trees into farmland as part of a mixed agricultural enterprise. Areas of land where on-farm productivity is limited by unmanageable constraints (e.g. shallow soil depth) offer prime locations for afforestation, although the rates of carbon capture may be low. Trees occupying about 10% of the farm can be used as shelter for livestock, wind breaks, for controlling salinity, enhancing native biodiversity, and adding to capital value. Sensible afforestation, optimising the sequestration of carbon with the production of food across the nation, could achieve significant national carbon sequestration, have minimal impact on food production, and accrue many environmental benefits.

Native ecosystems

Native ecosystems are vital to Australia's greenhouse gas dynamics because they both store and emit large volumes of greenhouse gases, which fluctuate depending on disturbance and climate variability. Australia is the world's most fire-prone continent, and fire is a particularly influential factor on the carbon cycle in many native ecosystems. This is also influenced by the climate, through the effects of temperature and rainfall on plant growth and its impact on fire regimes.

Deforestation contributes significantly to Australia's greenhouse emissions (9% in 2008, much reduced from levels in the 1980s and 1990s). This contribution has been reduced with recent land-clearing restrictions. Around half of these emissions result from the clearing of regrowth on grazing properties. As with integrating trees into farming landscapes through afforestation, strategically retaining strips of regrowth in pastoral landscapes has been suggested as a low-cost abatement opportunity, with little impact on productivity and with the potential to improve the condition of surrounding pasture by reducing wind and erosion, as well as providing shelter for stock.

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Nearly a third of Australia's terrestrial carbon is stored in tropical savannas, the continent's most fire-prone biome in which half or more of the land may burn each year. These fires currently contribute 2–3% of the nation's total accountable emissions and have an important bearing on rates of carbon sequestration. Consequently, there is growing interest in curbing the extent and severity of these fires using Aboriginal early season mosaic burning techniques, which produce cooler, less-destructive fires. This could generate livelihoods in remote Aboriginal communities, reduce the risk of wildfires, encourage native species and – through reduced greenhouse gas emissions and increased carbon storage – help to lower Australia's emissions. An existing project using this approach has been estimated to reduce emissions from a 28 000 km^2 area by 100 000 tonnes CO_2-e/year.[4]

It may also be possible to increase carbon stocks in stands of managed native forests. Based on the findings of the *Green carbon* report,[5] CSIRO has examined the idea that harvesting of native forests reduces carbon stocks and cessation of harvesting activities in native forests would allow carbon stocks to build. A high level of uncertainty surrounds this option, and future research needs to refine the estimates of carbon stocks, the longer term impacts of harvesting and fire, and the fate of carbon stored in forests and timber products.

Finally, it is important to realise that native forests dominate the carbon and water cycles in Australia and that climate change poses a significant threat to native forests and to their carbon stocks. Droughts, fires, pests, and disease in these native ecosystems could potentially overwhelm any gains made in carbon storage.

Soil organic carbon and biochar

Carbon exists in soils in organic and inorganic forms. Only the organic component is currently considered in greenhouse gas emissions accounting. Soil organic carbon can consist of materials ranging from recently decomposed plant residues through to well-decomposed materials and particles of charcoal. Typically, soil organic carbon accounts for less than 5% of the mass of upper soil layers and diminishes with depth. The total store in the top 30 cm (the depth over which most organic soil carbon is held) for Australian soils usually ranges between 5 and 250 t C/ha.

Although methods exist to quantify the amount of organic carbon contained in a soil at any one location, spatial and temporal variations can contribute significant uncertainty to estimates of soil carbon stocks. Spatial variations of up to 20 t C/ha within paddocks are common, with much greater variations existing between soil and landscape types. Soil organic carbon can also vary within and between years according to climate and farming methods used. Collectively, these factors present a major challenge to measuring changes in soil organic carbon stocks over time at individual paddock and landscape scales with any significant degree of confidence.

The amount of organic carbon present in a soil is determined by the rate at which organic matter is added and the rate at which it decomposes. Organic carbon in soils turns over constantly. New carbon is regularly added to soil though the growth of plants and the addition of organic matter in and on the soil. The carbon fixed over short time periods by photosynthesis in growing plants is an input to the soil carbon system, but does not in itself represent long-term carbon storage. Decomposition converts part of the existing soil organic carbon and plant residue carbon back into CO_2. Temperature, rainfall, land management, soil nutrition, and soil type all influence the size of the soil carbon pool by determining the rates of plant and vegetation inputs and decomposition. The term sequestration means achieving and maintaining a net increase in the amount of organic carbon present in a soil.

There are two main ways to build soil carbon: by increasing the amount of organic matter entering the soil or by reducing CO_2 losses – and Australia's approach to soil carbon management will depend on both. For example, reduced tillage of some cropping land may reduce the rate at which soil organic carbon decomposes. Retaining plant residues (e.g. stubble) increases plant growth through reduced fallow periods and the addition of organic residues or biochar can also help lift soil carbon by increasing carbon addition rates or by adding materials that do not readily decompose.

Past clearing of farmland and tillage has generally led to declines in the organic carbon content of most soil types. Some land-management practices may reduce the rate of soil organic carbon decline or potentially increase soil organic carbon compared with more traditional management practices. Minimum tillage and no-till are already practised on much of Australia's 27 million hectares of cropping land and, if such practices were extended across the other 9 million hectares, croplands may offer 2 to 5 Mt CO_2-e abatement per year. Other practices such as changes to cropping systems (stubble retention, changing crop rotations, increasing frequency of pasture leys, and increasing fertilisation), increasing production by incorporating a higher proportion of legumes (nitrogen fixers), and reversal of existing degradation (saline, acidic, and eroded land) by planting perennial species may all contribute. The biggest gains are likely to come from converting cropping land to secondary forest or pasture. The area converted will depend on the economics of land-use change, the opportunity costs of forgone food production, and social factors.

The 400 million hectares of Australia's rangelands represent the biggest theoretical opportunity for locking up carbon in landscapes outside forestry options. Estimates of sequestration potential in these landscapes are based heavily on evaluations of the extent of their degradation, and assumptions about the extent to which carbon stocks can be increased by reducing grazing or changes in pasture management. Recent estimates of what might be attainable nationally are in the order of 4–50 Mt CO_2-e per year.[3, 6, 7] At present too little is known to be confident of these estimates.

Biochar is a form of charcoal created by burning organic matter in a closed system under conditions of low oxygen availability. In closed systems, the gases released during the formation of biochar can be captured and used for energy generation. The chemical nature of biochar stabilises this form of organic carbon against biological decomposition. It can act as a long-term carbon storage material relative to the typically more decomposable material from which it was created. The chemical and physical properties of different biochars depend on the original material used and conditions under which the biochar was produced. The most beneficial sources of organic material for biochar production are carbon-rich waste streams, including human wastes, forest thinning (or custom-grown carbon forests), and agricultural by-products. The removal of crop residues explicitly for the creation of biochar is not recommended because it may lead to reductions in soil organic carbon levels, soil biological activity, and nutrient cycling. This may result in detrimental effects on soil productivity (and ultimately soil organic carbon content), reducing carbon sequestration gains made through the creation and application of biochar.

The process of generating biomass, producing biochar, and applying biochar to soil has the potential of sequestering carbon from the atmosphere and storing it in a stable form in soil. However, a full life-cycle analysis of all processes involved in the creation and land application of biochar is needed to define the net impact on reducing greenhouse gas emissions. The production of biochar also has the potential to yield bioenergy in the form of synthesis gas (or 'syngas') or biofuels that can substitute for carbon-polluting fossil fuels. Additionally, some biochars have been shown to enhance soil fertility. This can reduce fertiliser requirements and thereby emissions associated with fertiliser production, delivery, and application.

In order for biochar to be a useful sequestration and soil amendment tool, it is important that pyrolysis facilities are close to biomass production sites and locations for biochar use: otherwise greenhouse gas emissions and costs associated with transport would reduce the magnitude of any offsets and affect the economics of the operation. In the immediate future, and with existing production technologies, biochar is only likely to operate on a limited scale in situations where existing processing plants collect organic material for biochar production. One example is the potential to use biomass waste from the sugar cane industry (bagasse).[3] Estimates of sequestration potential from this process in Queensland are around 4 Mt CO_2-e per year.

Livestock methane

Ruminant animals (such as sheep and cattle) emit methane as a by-product of digesting feed. In 2008, this contributed 55 Mt of CO_2-e to Australia's national Kyoto accounts, corresponding to 9.6% of Australia's total greenhouse gas emissions and the largest component of agricultural emissions. The contribution is defined by the total number of animals and the emission rate per animal, which, in turn, is controlled by the animal's diet and management. Methane production by these animals represents lost energy that would otherwise be directed towards animal growth; hence, reducing methane emissions offers a win–win situation by increasing livestock productivity and reducing livestock greenhouse gas emissions per animal.

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Reducing stock numbers would, at first glance, appear the most practical way to reduce Australia's livestock emissions. However, because most grazing land is unsuitable for other productive uses, this would have an adverse impact on food production and employment. Ecological interactions also make the abatement gains from this action difficult to calculate. For example, in some parts of Australia's rangelands, grazing reduces grass biomass, fire frequency, and competition with tree and shrub seedlings, potentially allowing regeneration of shrubs and trees, which might increase carbon stock in the long run. It has also been suggested that, in the absence of a parallel reduction in demand for meat, reduced livestock numbers in Australia would likely be offset to some extent by increased production overseas.

There is no single, high-impact strategy currently available to reduce emissions per animal. A range of approaches, tailored to specific industry sector constraints, could be expected to reduce per animal emissions by 10–20% in the next decade, and perhaps up to 40% in the longer term.[3] Options include dietary manipulation, modification of rumen fermentation, feedstock quality, and selective breeding for reduced emissions. Dietary manipulation is an option available today, while others, such as the modification of rumen fermentation and animal breeding, will take longer to have an impact. In general, options that increase animal growth rates and reproductive performance can reduce emissions intensity and increase producer profitability. Often, best-management practices that reduce emissions per unit of saleable product (emissions intensity) also offer advantages in restoring land condition by removing livestock from marginal or sensitive areas and increasing biodiversity.

In addition to direct emissions from sheep and cattle, methane can also be produced from manure. Such emissions are generally low in grazing situations, but more-intensive production systems where manure is concentrated in lagoons or ponds can cause more significant levels of methane production. Emissions from manure contribute over 1.5 Mt of CO_2-e per year to our national emissions, principally from dairy and piggery sources.[1] In intensive and large operations, this methane can be captured and used to displace fossil fuel use. Realistically, two-thirds of these emissions could be abated with appropriate incentives, with additional abatement from avoided fossil fuel use in energy production.[8]

Willem van Aken/CSIRO

Cropping emissions

In 2008, agricultural soils contributed 15 Mt CO_2-e, principally from nitrous oxide (N_2O) emissions associated with the use of fertilisers.[1] Emissions of N_2O from soils under cropping systems occur principally when excess inorganic nitrogen is present in the form of nitrate. High soil nitrogen levels, particularly under wet soil conditions, are a significant driver of greenhouse gas emissions associated with fertiliser use. Both cost savings and greenhouse gas emissions abatement are possible by controlling inputs of nitrogen fertiliser, with the aim of improving the match between crop nitrogen demand and nitrogen supply. Benefits can be obtained by matching the timing, rate, and method of application (for example, surface placement versus incorporated or banded, and liquid versus solid forms). The main goal is to minimise the potential occurrences of denitrification and nitrification. In many cases, the actions required to reduce emissions through fertiliser use in agriculture are identical to best-practice strategies to maximise the efficiency of fertiliser use and minimise undesirable environmental impacts such as the contamination of waterways.

Conclusion

Although there is significant potential to build vegetation and soil carbon stocks, offset emissions, and enhance the productivity of Australia's soils, this is limited by our climate, by the soil's own capacity, by the necessity for Australia to continue to balance land use for the range of production, environmental, and livelihood needs of its people, and by biodiversity considerations. For these reasons, carbon prices or incentives to store carbon will have to be sufficient to encourage the widespread adoption of carbon sequestration practices by landholders. With clear evaluation of the wider benefits to productivity and environmental services, and appropriate incentives and complementary measures, carbon storage can be part of 'win–win–win' outcomes for greenhouse gas abatement, food production, and the environment. Using our land and modifying our land management wisely can give us time to reduce sources of emissions from other sectors of the economy and may offer some ongoing carbon pollution abatement potential (while affording landscape and production benefits) that reduces the overall cost to the economy of climate-change action. Additionally, the generation of carbon credits or offsets from agricultural land has the potential to be a major source of income in rural Australia, allowing landowners to further diversify income streams. As we identify opportunities to use our rural lands for carbon sequestration, we need to be mindful of the liabilities and constraints we might impose on future landowners: engaging in carbon forestry or changing land management to increase soil carbon pools restricts future land management decisions and, in some cases, places an onus on land managers to maintain particular land-management regimes. Finally, as we act, we need to consider the implications of our decisions on existing – and developing – international agreements on greenhouse gas abatement, and on global food security.

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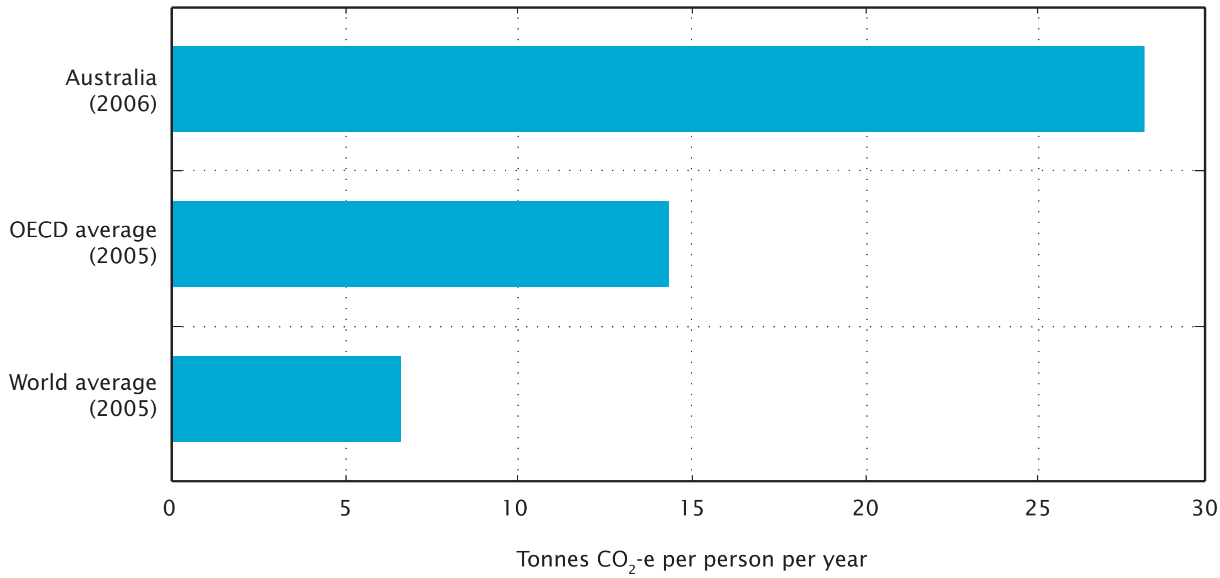
Mitigation strategies for energy and transport

By Jim Smitham, Jenny Hayward, Paul Graham, and John Carras

Key messages

- Australia has an abundance of clean energy options from which to choose. Its future will undoubtedly involve a wider range of different energy sources, which are suited to particular niches.
- Renewables are expected to feature more prominently in Australia's energy mix by the 2020s.
- Promising technologies exist for coal with carbon capture and storage for base-load power generation, but these will depend critically on the price society places on carbon. Prolonged uncertainty over carbon pricing could risk delays in investment, because generators will be reluctant to invest in any technology that may be 'stranded' by subsequent policy decisions.
- Energy saving technologies, demand reduction, and distributed power generation will help to lower national carbon emissions.
- Changes in the transport sector will be driven far more by oil prices than by carbon prices. Electricity may become the transport fuel of choice with Australian motorists and transport operators, with the use of some LNG gas, diesel, and biofuels. Hydrogen fuel cells may eventually replace batteries in electric vehicles.

Australia has a high per capita emissions intensity and has a higher energy use per unit of GDP than the OECD average (Figure 9.1). This is a function of the structure of the economy and Australia's international comparative advantages. Among these advantages are low-cost fossil fuel and mineral resource extraction and processing industries. The main disadvantage is large transport distances, both within Australia and to its overseas customers. The position of Australia relative to other countries in terms of emissions per person is shown in Figure 9.1 and in terms of energy sources in Table 9.1. This is the starting point for changes in mitigation strategies for Australia compared with the rest of the world.



▲ ***Figure 9.1**: Per capita greenhouse gas emissions.*[1]

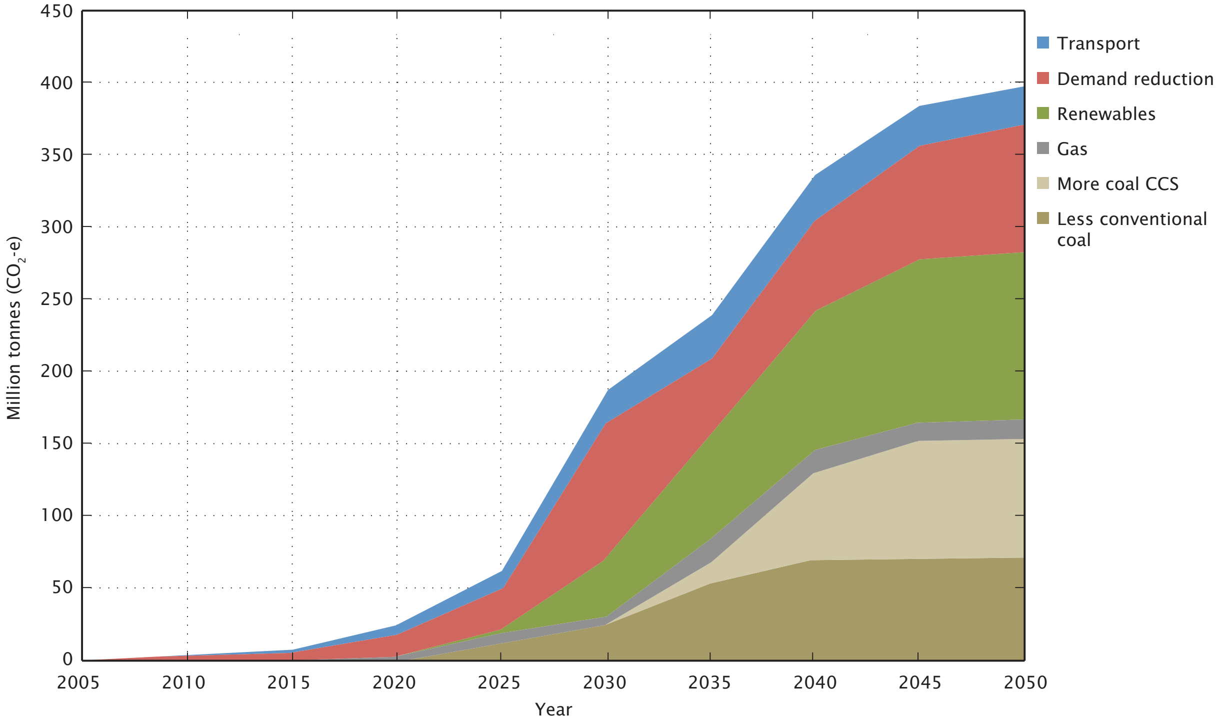
Table 9.1: Fuel mix contributing to primary energy supply[2, 3]

Fuel	**OECD 2006 Share (%)**	**Australia 2007–8 Share (%)**
Coal	20	37
Oil	41	36
Gas	23	22
Nuclear	10	0
Renewables	6	5
Total	100	100

Australia's use of oil primarily reflects the transport sector, which is dependent on oil for 94% of its energy usage. The remaining oil is used in the agriculture, mining, and chemical industries. Coal is mainly used for electricity generation, which is dependent on coal for 80% of its energy generation. This is in contrast to the average for the OECD, which uses proportionately less coal, but generates 10% of its electricity using nuclear power.

For electricity production, Australia has over three times the greenhouse gas emissions per capita than the OECD average, while for transport Australia's per capita emissions are some 30% higher. Consequently, a significant portion of the future reductions in greenhouse gas abatement will need to come from these sectors.

Taking into account a variety of drivers discussed further below, CSIRO's modelling has produced a number of scenarios, one of which is shown in Figure 9.2. This shows how much of, and where, the greenhouse gas savings may be found in energy and transport in trying to achieve 550 ppm CO_2-e in the atmosphere by 2100.



▲ ***Figure 9.2****: The projected level of emissions to be saved by different mitigation strategies (compared with expected 'business as usual' emissions, which includes 20% renewables by 2020 – as mandated by government). (CCS = carbon capture and storage)*

In broad terms, the modelling shows that, after taking into account the retirement of existing coal plants and some adoption of efficient vehicles and low-emission fuels, around one-third of the nation's energy greenhouse emissions savings could be expected to come from energy efficiency plus demand reduction, one-third from renewables, and one-third from carbon capture and storage (CCS).

Major drivers for change, uncertainties and implications

There is no simple path to selecting the most effective technologies for mitigation. It is a complex interplay between uncertain technology costs, future energy prices, and policy options.

The main drivers of innovation and the rate of take-up of new energy technologies are the cost of petroleum for the transport sector, the price of carbon for the power generation sector, and the uncertainty of future technology costs. These factors are also fraught with the greatest uncertainty.

Recent projections from modelling by the Australian Treasury Carbon Pollution Reduction Scheme suggest a gradual increase in the price of carbon of around 4% per annum over several decades to 2050.[4] If this rate of increase was built into a cost for carbon emissions, such as a national emissions trading scheme or similar, it would imply a gradual, rather than a rapid, shift to new technologies. Gradual adjustments make the transitions for the economy easier. That means that it will take longer for carbon prices to reach the break-even point whereby some low-emission power station investments recoup the cost of emissions reduction, compared with a power station without emissions reduction. Investors need a high level of confidence that a project will be viable, given that the normal life of a power plant is several decades. In the absence of a clear indication of a carbon price in the near term, the only certain policy driver for the sector is the 20% renewables target.

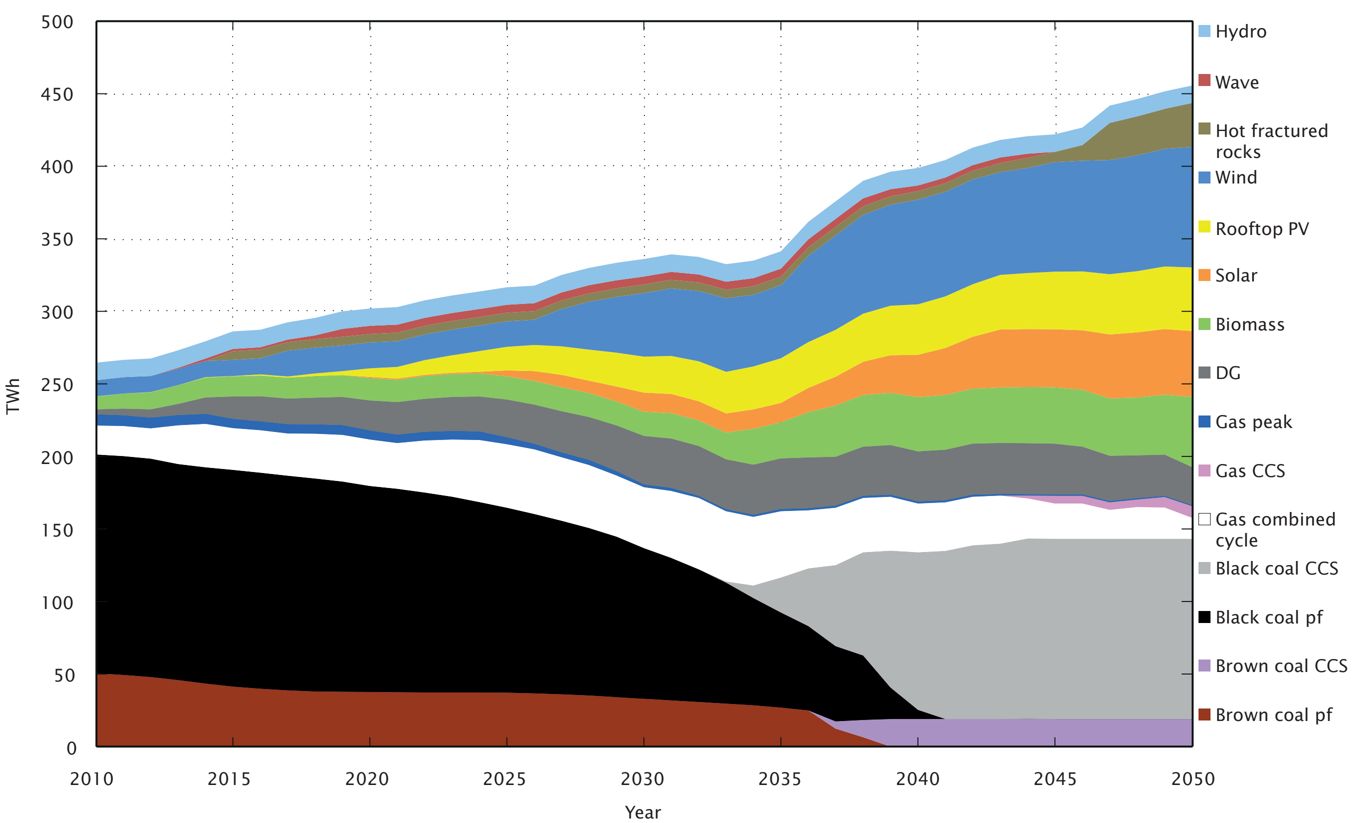
Complicating the picture is a consistent trend in public opinion favouring renewables over coal or nuclear energy. Meanwhile, due to strong worldwide interest in demand for energy and improved energy technologies generally, the cost of all forms of energy generation has risen. This combination of factors may cause hesitation and impose further delays on decisions in Australia to invest in base-load power generation. Unless plant costs fall – or electricity prices rise – to reduce the level of investment risk, it is plausible that investment in base-load power generation will be delayed for one to two decades, with consequent energy shortages.

Oil prices, rather than pressure to reduce emissions, are likely to be the main influence on the evolution of Australian transport technology in the foreseeable future. The impact at the pump of an oil price above US$200 a barrel – as anticipated by the US Energy Information Administration (US EIA) in one of its higher-range scenarios – is some 10 times larger for motorists and transport operators than a carbon levy, which may add no more than 10–25 cents a litre (depending on the carbon price), and even this would be over three to four decades. High world oil prices, driven by resuming economic growth and concerns about global peak oil and energy efficiency regulation, will be the main signals to shift to fuel and transport alternatives, and these signals are likely to occur within the next two decades.

There remains significant uncertainty about the future price of oil, which is volatile on both daily and multi-year scales. Although current oil prices are high enough to encourage significant investment in new oil field production, it is unclear how long new oil production will be able to offset the decline in production from existing oil fields. If a global production peak occurs in the near term, and alternative fuels are unable to fill the gap sufficiently rapidly, fuel prices may at times increase by several dollars a litre in order to curtail global demand.

The role of innovation

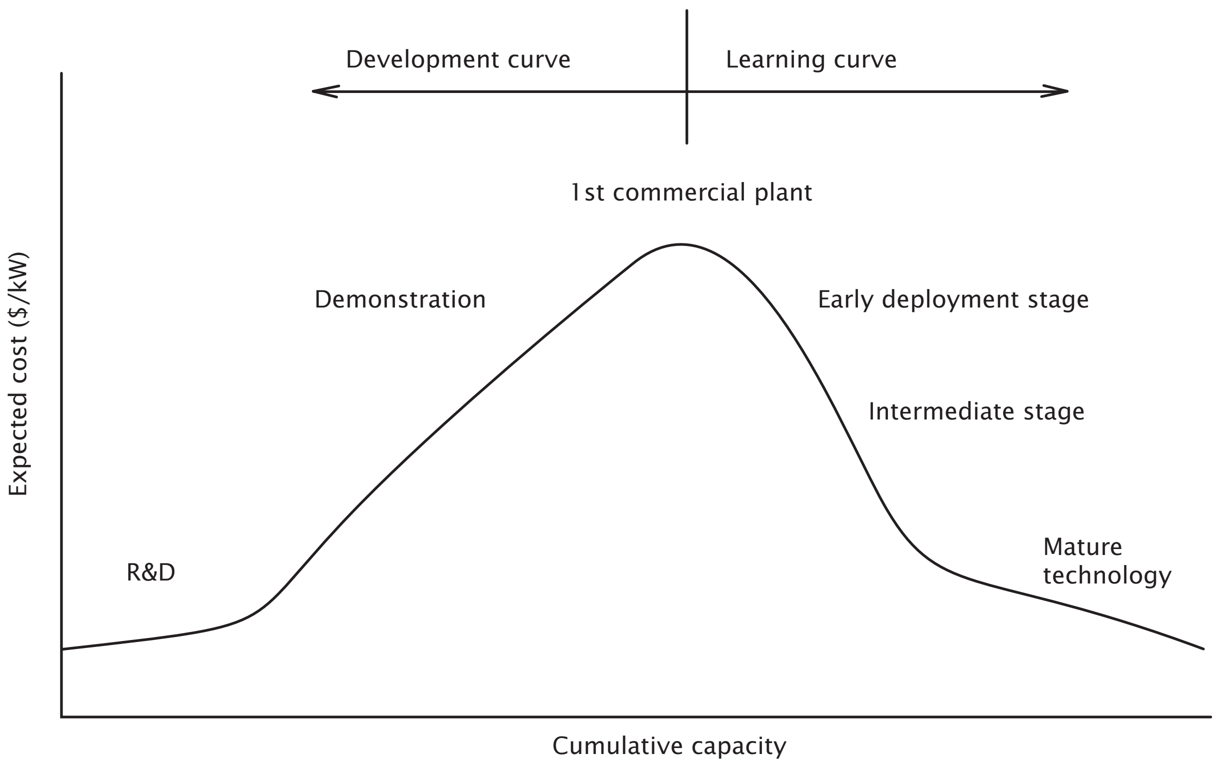
Australia has an abundance of clean energy opportunities, many of which must feature in our diverse energy future. Figure 9.3 illustrates the result of modelling by CSIRO, which shows one possible (but not the only) scenario of the adoption of a number of the electricity generation technologies most commonly considered.



▲ ***Figure 9.3***: *CSIRO projection of potential mix of Australian clean energy sources for electricity production out to 2050 showing the changes in technology mix to achieve emissions reduction. (CCS = carbon capture and storage, pf = pulverised fuel, DG = distributed generation)*

Each of these technologies faces obstacles to its continued use and/or future deployment – including cost, state of development, environmental issues, government policy, the need for storage technologies, and public acceptability. The energy mix we achieve by the mid-century will thus depend on which technologies are best able to overcome the various barriers facing them and prove to be most adaptable to the Australian policy environment.

As they progress through R&D to development, demonstration, and adoption, most new technologies follow a similar path. Figure 9.4 shows how cost estimates rise as a technology approaches its first deployment, then fall as it begins to be more widely adopted and costs stabilise. However, there is no guarantee that the cost declines demonstrated by one technology will be replicated by all technologies.



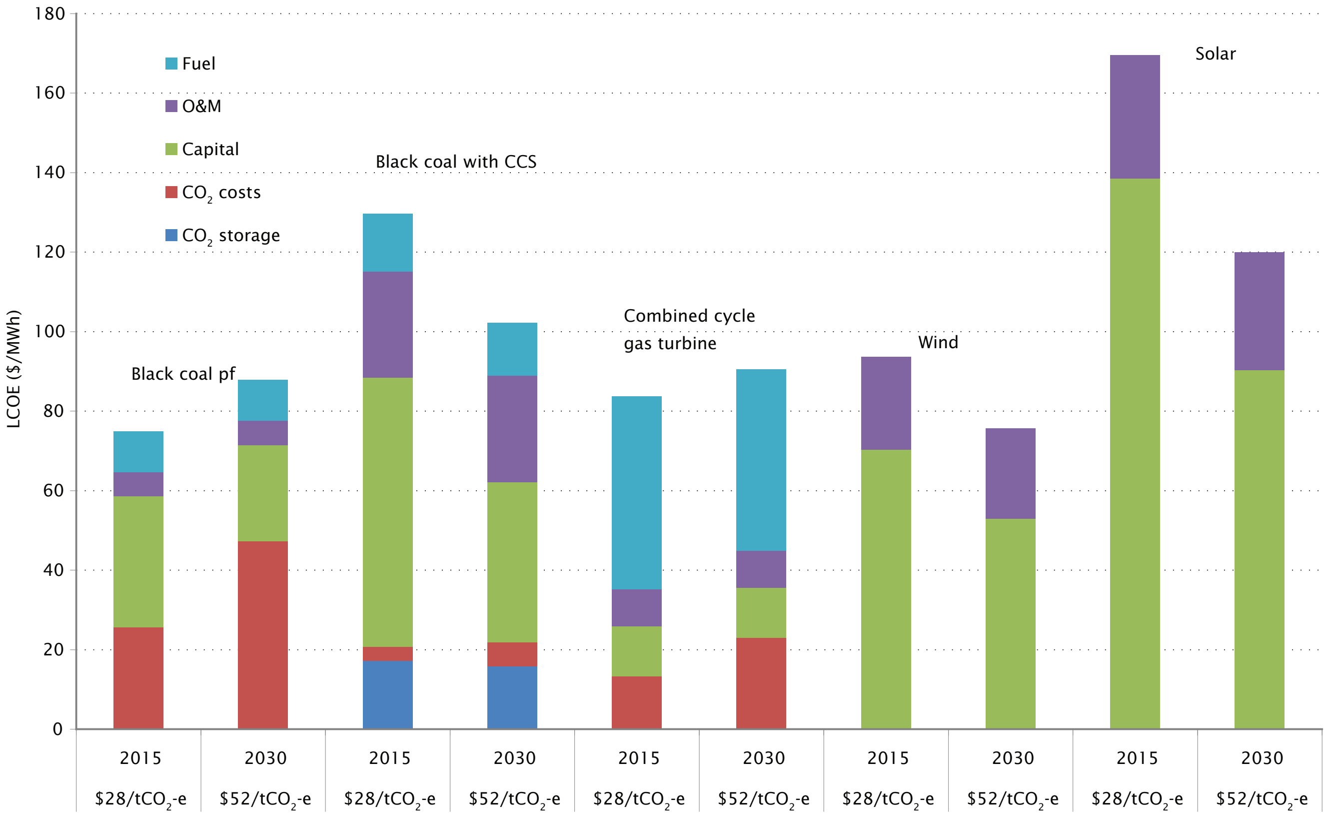
▲ ***Figure 9.4***: *Generalised curve showing the rising cost of technology as it is developed from the research and development phase, then the fall in cost as it is deployed.*

Basically, learning curves indicate that the more of a particular technology that is built and used, the cheaper it becomes. However, many factors can alter the shape of the curve – for example, when demand for a technology exceeds supply, it temporarily drives up prices (as has happened with wind power in recent years). Government policies – such as Australia's 20% Mandatory Renewable Energy Target – can also drive the adoption of technologies faster along the learning curve nationally and internationally. Technologies can be accelerated down the learning curve when they share components or have components that interlink, and learning also can be accelerated by technology diffusion between countries. A technology may also undergo a step-wise change due to a new research discovery that drops the price – as thin film solar photovoltaic (PV) technology is expected to do.[5]

Figure 9.5 shows CSIRO's near- and longer term projections of the electricity generation costs of different energy options when a carbon price is added, and the learning curve methodology applied, to an economic model of electricity generation. The model shows investment in capital when required to meet demand and generate electricity at the lowest price, up to the year 2050. Investing in capital pushes technologies 'down' the learning curve so they become cheaper (Figure 9.4). This then encourages further investment in the now-cheaper technology. In the model, technologies compete in terms of price, and the cheaper technologies will then generate the most electricity.[6] In this particular scenario, by 2030 – and with a carbon dioxide price of AU$52 per tonne – wind could be more competitive than the fossil fuel technologies, even though its capital cost is still relatively high.

Figure 9.5 shows the need to balance decisions about capital costs for plant, fuel cost, and carbon dioxide storage costs on a comparative basis. Renewable technologies have high capital cost but no fuel costs, while gas turbine technologies have the lowest capital cost but high fuel cost.

Companies planning investment in generation assets, which may have a useable life of decades, also need to model specific site costs, market behaviour, capital service costs, fuel contracts, and the impact of policy options in specific locations.



▲ ***Figure 9.5****: CSIRO simulations of the cost of electricity (represented as levelised cost of electricity LCOE) for different technologies for two* CO_2*-e prices. (CCS = carbon capture and storage, pf = pulverised fuel, O&M = operations and maintenance)*

Energy and transport technologies

The following section summarises the state of development and role of key electricity and transport technologies and processes important to reduce CO_2 emissions.

1. Efficiency, demand reduction, and distributed power generation

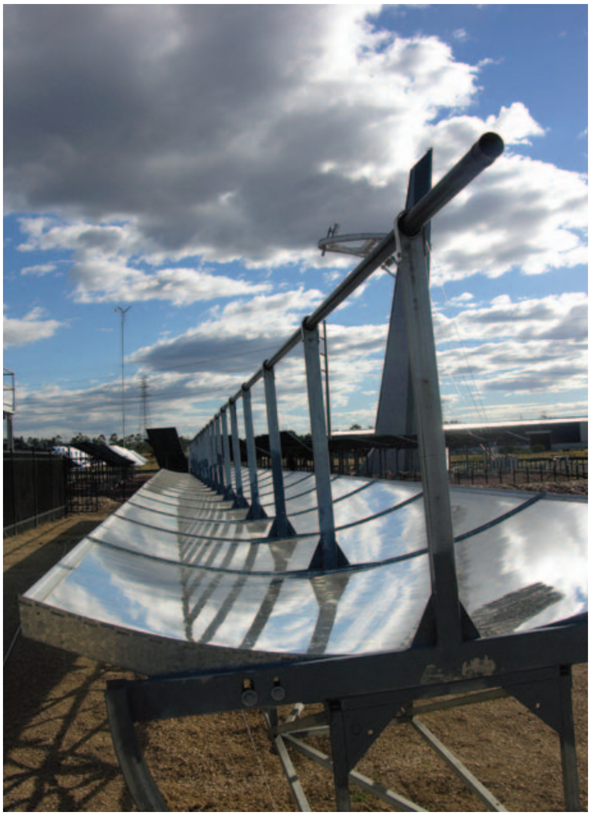
Energy efficiency gains can come from all sectors. The *First Opportunities* report for the Federal Energy Efficiency Opportunities Program[7] reported that 199 large companies have identified energy saving opportunities equivalent to 1.1% of Australia's greenhouse gas emissions, with savings to boilers, furnaces, kilns, chemical processes, and electrical equipment and mobile equipment. Other savings may come from non-industrial sectors, where there have been low incentives for improvements in the past. Prospective areas for improvement include the building sector, commercial air-conditioning, residential water heating, improved insulation, and commercial and domestic lighting, with a more complete breakdown provided in the *IPCC Fourth Assessment Report*.[8] These will save energy, and so reduce costs for businesses and households, if non-financial barriers to the implementation of energy investments can provide win–win opportunities. However, they may have disadvantages such as loss of function, convenience, and performance. Furthermore, the uptake of energy-efficiency opportunities may be hindered by lacking or misaligned incentives and market failures.

Demand reduction can be achieved in many ways, such as the use of 'smart agents' and 'intelligent grids'. Here, sensors monitor and report information about energy use that can be used to manage supply and demand to a central controller. For example, systems that sense whether rooms are occupied – and that can regulate lighting, heating, and cooling accordingly – can reduce overall demand for power.

Many modern buildings are designed with considerations of reduced energy use in mind, such as natural lighting, thermal load management via the use of appropriate building materials, siting of buildings, and the use of shading, breezes, and vegetation. Demand reduction can be stimulated by government incentives and regulation, and is very often another case of win–win: making sense for both the economy and climate.

Distributed power generation seeks to achieve energy savings by generating electricity close to the point of use – even inside the actual building that uses the energy. Small generators that burn fossil fuels are more efficient overall and are less greenhouse gas intensive if their waste heat is captured and used locally for heating and cooling. Combining heating, cooling, and power production can potentially double the efficiency of fuel use. Small-scale generation is more responsive to local demand and, in some circumstances, can achieve greater cost savings overall when the network costs are considered.

Although distributed generation achieves even greater greenhouse gas reductions when the source of energy is renewable, such as solar, wind, or geothermal power, there is another aspect that must be considered. The current Australian electricity grid was designed to supply power to consumers from a small number of large centralised power stations. In order to achieve a reliable and stable supply from a significant number of distributed generators along with the current large centralised power stations, the electricity grid will require significant augmentation and capital investment.



CSIRO

2. Renewables and nuclear

Solar power holds great promise as the energy source of the future. There are two categories of solar power that may play a role in future electricity generation: photovoltaics and solar thermal.

Photovoltaic (PV) technologies convert sunlight directly to electricity through the properties of photoactive materials. The main challenge for PV developers is to find the ideal combination of low production cost, optimum conversion efficiency and output, the cost of greenhouse gases emitted in making the materials, and the longevity of the cells in the environment. Silicon-based PV technology has developed over the past three decades, with significant gains in efficiency, and units have been commercially available for some time. However, the cost per kilowatt hour and the need to store electricity for night-time use remain barriers. Second-generation thin-film PV technologies such as CdTe have been introduced, with higher efficiencies and lower costs for large-scale PV power plants, while third-generation PVs, such as organic solar cells (PV or dye), are early stage technologies that promise rapid and cheap production, but their efficiency is still significantly lower than for silicon units.

Solar thermal technologies concentrate the Sun's rays to produce heat that can then be used to heat water, induce chemical reactions, or drive other energy processes. The main technologies include:

- domestic solar hot water systems
- 'trough' collectors that focus the Sun's rays along a single axis where the receiver is

located and which tracks with the Sun. They are cheap to make and produce steam at up to 300ºC, which can be used to produce electricity or heat for industry.

- linear Fresnel technology in which the linear receiver is stationary and is heated by tracking mirrors to provide outputs similar to the 'trough' collectors
- dish collectors that track the Sun and focus the Sun's rays on a receiver
- 'heliostat' and tower collectors that focus the Sun's rays to a single point to produce very high temperatures (of the order of 1000ºC) to drive chemical processes, and make steam or hot air to run electrical turbines.

Although solar technologies are still expensive, the technology is improving constantly, energy prices are changing, and the 'learning curve' promises more competitive solar thermal technologies within a decade or so.

Wind power is currently the most adoptable of the renewable energies and is being deployed on quite a large scale across Australia. Obstacles to its use include the high capital cost of the generators (driven by strong global demand), its intermittency, power fluctuations, the need to store power during calm conditions, and varying levels of local public acceptance. Many of the best wind sites in Australia are already taken. Those that remain may be more distant from the grid, have less favourable wind conditions, and may be less profitable for investors; these factors will eventually slow adoption, increasing the opportunities for other technologies.

Nick Pitsas/CSIRO

Both solar and wind power require the development of cost-effective energy storage facilities to be able to mitigate power fluctuations, to provide energy at night-time for solar, or during periods of calm for wind power.

Biomass energy – for electricity or fuels – is seen as having considerable potential if sustainable use can be established and costs reduced through new technologies. CSIRO's assessment of bioenergy prospects is based on zero competition with food for agricultural resources. The best prospects occur when the biomass source is close to the place where the energy is consumed: for example, when the bagasse produced by the sugar cane industry is burned to produce heat and electricity used for sugar refining.

Hydro power has limited large-scale expansion opportunities in Australia due to public aversion to the large-scale impacts on river systems, limited accessible sites, and declining rainfall in the south.

Source: Adriana Downie, Pacific Pyrolysis

CSIRO

Hot fractured rocks are still being developed as a potential base-load energy source for the future. Obstacles include current high drilling costs, geological uncertainty, low relative power efficiencies, the amount of water needed to access the heat which is lost in the process, and the proximity of the grid. If these can be overcome, hot fractured rocks could emerge as a reliable, low-cost source of base-load power.

Ocean energy – Australia has access to vast ocean resources: some of the best in the world for wave, current, and tidal energy, especially along the WA, Victorian and Tasmanian coasts. However, the technologies are still at an early stage in their development and, like some other renewables, suffer from intermittency, distance from the grid, and uncertainty about long-term maintenance and operational costs. Australia's ample resources of solar and wind energy mean that these may be fully developed before ocean power can become financially competitive.

Nuclear energy may become an economic option for power generation in Australia, but the main barriers to its adoption include high capital costs, long lead times, lack of a trained workforce, and current lack of public support.

3. Fossil fuel energy and carbon capture and storage

Although energy efficiency and renewable energy hold out great promise for a low-carbon economy, the world is heavily committed to the use of fossil fuels through its existing generation infrastructure, which will continue to provide the bulk of electricity generated for some time. In addition, many developing economies see coal use as the lowest-cost option to provide electricity for the growth of their economies and to increase the living standard of their people.

Carbon capture and storage (CCS) is the pathway for reducing greenhouse gas emissions from fossil fuels used for large-scale electricity generation. The aim is to capture the CO_2 released when coal is burned and then store it in stable geological formations, deep underground. It is worth noting that oil, natural gas, and CO_2 have been stored naturally in such formations for many millions of years.

The three most promising CCS technologies are gasification, oxyfuel combustion, and post-combustion capture.

- **Gasification** involves reacting coal with controlled amounts of oxygen and water at high temperature and pressure to produce raw syngas. When combined with syngas processing, the ultimate products are CO_2 and hydrogen. The pressurised CO_2 can be separated for storage and the hydrogen burned in special turbines to produce electricity, with water as the only emission.
- **Oxyfuel combustion** burns coal in a CO_2/oxygen mixture with recycled flue gas (instead of nitrogen/oxygen when air is used). The flue gas is predominantly CO_2. Some is removed, cleaned, dried, and pressurised for geological storage. Gasification and oxyfuel combustion are termed pre-combustion low-emissions coal technologies.
- **Post-combustion capture** involves reacting the flue gas from a conventional combustion power station with a chemical solvent to capture the CO_2 before the flue gas is emitted. The chemicals are regenerated and reused. The CO_2, now in concentrated form, can be cleaned, dried, and pressurised for storage. The potential advantage of post-combustion capture is that it can be retrofitted to existing coal plants.

Implementation of CCS in a timely and secure way faces a number of challenges. The principal challenge is that, although elements of the technology chain currently exist, there has as yet been no demonstration of an integrated process at a commercial large-scale power station. However, there are numerous programs worldwide, including in Australia, that aim to demonstrate CCS technology on a commercial scale.

Besides CCS, other ways to process bulk CO_2 so that it is 'locked up', or achieves savings elsewhere, are being investigated:

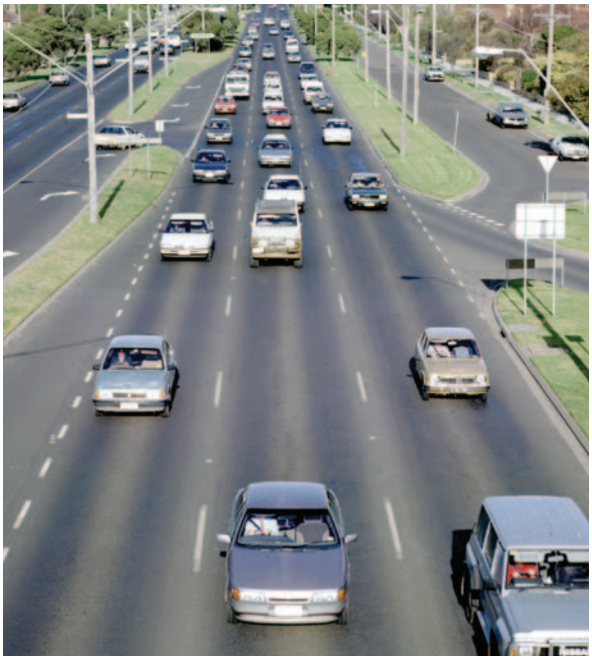
- **Mineralisation**, where CO_2 is reacted with naturally occurring minerals to form very stable carbonate rocks that can be stored in mines, or even used in building materials.
- **Algal cultures**, where the CO_2 and added nutrients are used to grow algae with a high lipid content for the production of biodiesel for transport fuels and thus displace petroleum fuels, with consequent greenhouse gas savings.

Other developments based on fossil fuels aiming to reduce CO_2 emissions include:

- **Gas**, which is seen largely as a 'transitional fuel' for peak power generation, bridging between today's systems and CCS or renewables in future. However, natural gas is in high demand worldwide and the power generators that use it are exposed to fluctuations in supply, demand, and price. There is also rapid development of coal seam gas in Australia which provides another source of this valuable resource.
- **Hybrid technologies** that combine fossil fuels, CCS, and renewables are also promising. These include: coal-fired power supplemented by solar thermal energy to reduce the amount of coal burned, reduce emissions, and boost efficiency; and solar/gas systems.
- The development of much more efficient ways of converting the chemical energy in coal to electricity. Two such promising technologies are large diesel engines fired with specially prepared slurries of fine coal and the direct carbon fuel cell.

4. Transport sector

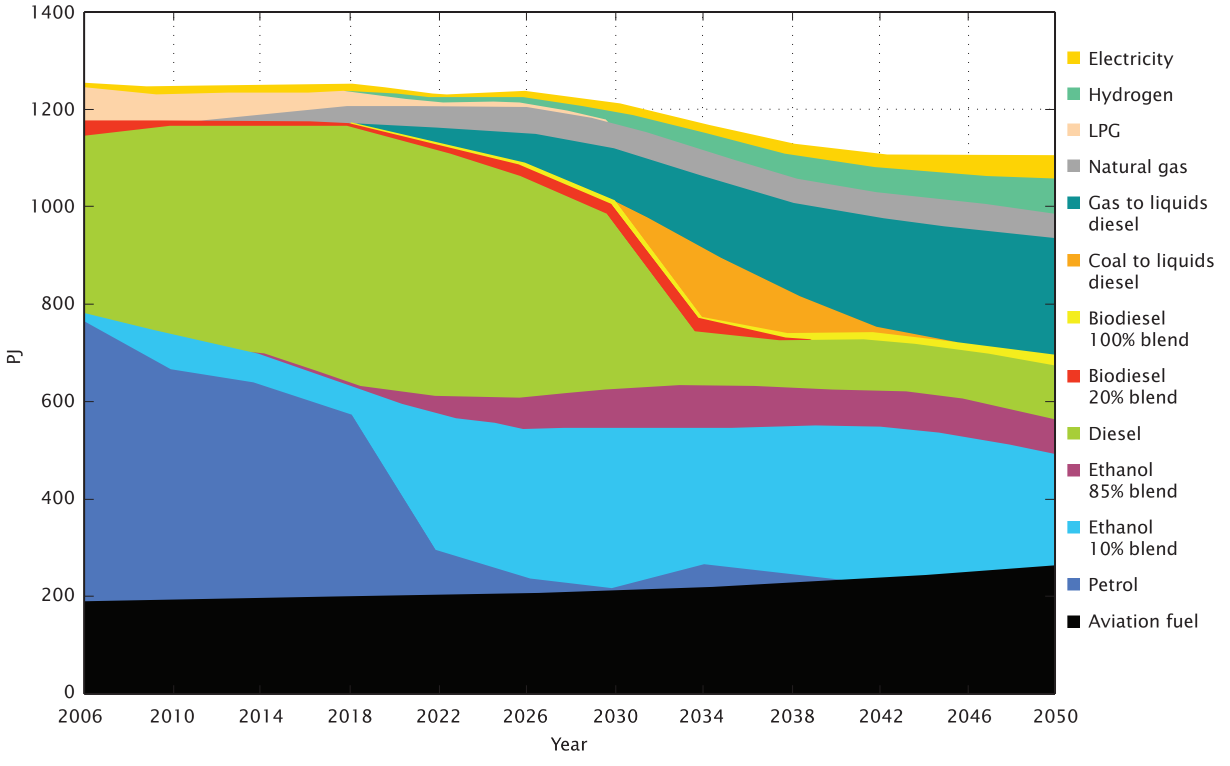
Over the next 10 years, and allowing for a cost for carbon, CSIRO modelling[9, 10] projects that diesel, electricity, liquefied petroleum gas (LPG), and natural gas (particularly in freight) will all increase their share of the transport fuel market (Figure 9.6). These fuels all have some existing production and distribution infrastructure, but will require more to make them readily accessible.



Tracey Nicholls/CSIRO

In the longer term, beyond 2020, advanced biofuels that do not compete directly with food production, and synthetic fuels derived from gas and coal, are also expected to come into wider use once production infrastructure has had time to scale up. How widely they are adopted will depend on primary fuel prices and greenhouse gas emission targets.

Realistically, only four additional transport fuel options are capable of being produced in large enough volumes to satisfy a significant part of the needs of the transport sector in the next two decades and supplement traditional fossil transport fuels – biofuels, liquefied natural gas (LNG), compressed natural gas (CNG), and electricity.

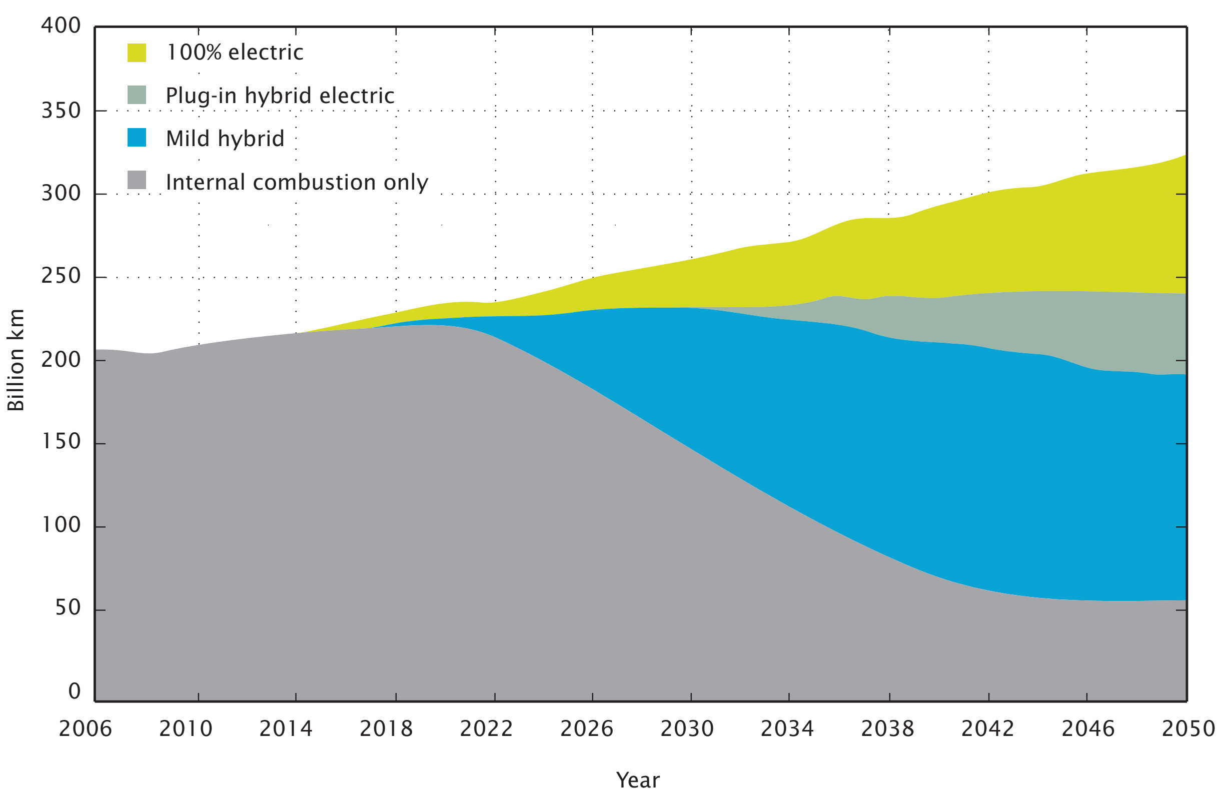


▲ ***Figure 9.6**: Likely changes in share of different transport fuels under a high oil price scenario.*

Biofuels could, in theory, supply around one-quarter of transport needs without having a significant impact on food production or soil nutrient quality. In the short term, ethanol and biodiesel blends will continue to be available, using crop wastes, tallow, and cooking oil. However, from around 2020–25, the principal future sources of biofuels will be lignocelluloses and plant oils (from crop stubble and forestry residues or special energy crops such as algae), thereby improving both Australia's balance of trade and greenhouse gas emissions. Biofuels are not completely emission-free because, among other inputs, they use fossil fuels in the biomass feedstock production process. However, in the long run, agriculture will probably move to lignocellulose-based biofuels and algal biodiesel for its motive energy.

LNG is a niche fuel more likely to suit long-distance transport operators, because the cost of converting vehicles is high and can only be re-couped by significant fuel savings. LNG is cheaper than diesel at present. However, in the longer term its costs are likely to follow those of oil as Australia's domestic gas industry becomes increasingly exposed to rising international oil and gas prices.

Electricity may emerge as the Australian transport fuel of choice for the majority of motorists and transport operators in the longer term. It is expected that the share of vehicles drawing electricity from the grid will increase from a handful today (excluding rail, which currently draws 8 petajoules) to at least 10% by 2030 (Figure 9.7). As hybrid vehicle technology matures, it will enable drivers to achieve 80% of their (city) mileage using electricity: using fossil fuel only for the 20% of trips that are outside battery range. The rate of electrification will depend critically on world oil prices relative to electricity prices and battery costs.



▲ ***Figure 9.7***: *Projected increasing electrification of road transport vehicles, based on mid range oil prices and a carbon price.*

A challenge for electrification of the transport fleet will be the source of electricity. If this is provided by coal-fired power stations, a large increase in CO_2 emissions will ensue. Therefore electrification of the transport fleet in response to rising petroleum prices may constitute another driver for the commercial introduction of CCS and/or renewables.

Although synthetic fuels made from coal and natural gas are among Australia's possible transport energy options, the fact that they involve large greenhouse gas emissions means they are not likely to attract large-scale investment in the medium term: certainly not before carbon capture and storage (CCS) has been fully demonstrated. Synthetic fuel plants also suffer from the same investment risks as large-scale coal power generation, being multi-billion-dollar investment projects dependent on uncertain revenue drivers (in this case, the international oil price, rather than carbon prices).

Hydrogen is a clean fuel that can be made from fossil fuels or by splitting water into its constituents, hydrogen and oxygen. However, the development of a cost-effective vehicle fuel cell to convert hydrogen into electrical power is lagging behind other sources of power for electric and hybrid vehicles: as of 2010, there were no hydrogen-fuelled cars commercially available anywhere in the world, and only a very few demonstration models. The fuel cell's acceptance as a technology will depend on its price relative to competing sources, consumer preferences for the range of hydrogen vehicles compared with electric vehicles, and the lead/lag time of the roll-out of refuelling infrastructure. In the medium term, however, the option exists to replace the batteries in an electric vehicle with a hydrogen fuel cell. The availability of hydrogen fuel could be fairly easily achieved by locating small units that use electricity to split water into hydrogen and oxygen at service stations, car parks, and elsewhere.

Conclusion

Making the right energy choices for Australia's future from among our abundant resources and technologies is profoundly complex. Often it will be an issue of which energy source, or combination of sources, best suits a particular context – rather than trying to pick a single 'winner'. Australia's greatest need is for low-emissions technologies that are competitively priced, resilient, and flexible enough to cope with a range of possible future energy challenges and demands. Technologies whose costs fall quickest will tend to predominate, even though they may be more expensive at present. All options are still in the mix for a future energy system, with many niches and opportunities. Rather than advocating a single solution, it will be important for us to have the skills to identify the most advantageous combinations of solutions.

Australia has more energy options than almost any other country – and the systems we develop ought logically to reflect that diversity. The technologies we choose will not necessarily be invented or developed here: instead we can become a leading-edge user of the best the world has to offer.

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Reducing energy demand: the imperative for behavioural change

By Peta Ashworth

Key messages

- The Australian public will have a powerful influence over the pace and extent of climate change mitigation and adaptation strategies and actions adopted by the nation. Deep cuts in Australia's greenhouse gas emissions will depend on a combination of technological innovation, economic reform, and societal change, achieved with public consent.
- There is considerable scope for individuals to reduce their own carbon footprint, and there is growing public support for a transition to a 'green economy'.
- Face-to-face communication and knowledge sharing to overcome the gaps in knowledge are critical.

Mitigation is not an activity for the agriculture, forestry, energy, and transport sectors alone. The Australian public will have a powerful influence over the pace and extent of national climate change mitigation strategies. Deep cuts in Australia's greenhouse gas emissions will only emerge through a combination of technological innovation, economic reform, and societal change: all achieved with public consent. This applies especially to two areas. First, there are the many things individuals can do, in their own lives and work, to reduce the burden of greenhouse gas emissions that future Australians will have to bear. To date, however, the actions of the majority of Australians to reduce their personal greenhouse gas emissions have been minimal. To achieve a significantly greater rate of change will require a major alteration in public attitudes. The second calls for broad public understanding, not only of the issues surrounding climate change itself, but especially of the range of low-emission energy technologies and smart energy-saving methods that will emerge over the coming years. It is here that public preference, consumer choice, and community sanction will play a critical role in determining the eventual mix of technologies adopted by Australia. This mix will cover the full spectrum, ranging from low-emission coal-fired electricity to solar thermal and photovoltaic, wind, geothermal, nuclear, hydroelectricity, biofuels, cogeneration, and demand management, through to energy efficiency and other energy approaches.[1] Public familiarity with these alternatives, their technical pros and cons, and their associated costs, will have an important bearing on the national debate and the extent to which politicians feel empowered to make far-reaching decisions for Australia to transition to a low carbon economy.

Chris Taylor/CSIRO

Australian attitudes to energy technologies

Recognising that knowledge and understanding will be critical to support the transition to a low carbon economy, CSIRO has been researching public attitudes to climate change and energy technologies for several years.[2–5] This has established that the Australian public:

- agrees that climate change is an important issue to Australia, particularly the 18–25 age group (82% of respondents agreed that global warming has been established as a serious problem and immediate action is necessary, or that there is enough evidence that global warming is taking place and some action should be taken[6])
- still has limited knowledge about the causes of climate change and what can be done to mitigate it (in a survey of more than 2000 Australians, the average response to a quiz on energy and environmental issues was *equivalent to guessing*, and many people didn't see the link between their own energy consumption and greenhouse gas emissions[7])
- can be quite concerned and depressed about the enormity of the problem
- recognises there is a role for government, industry, and themselves in responding to climate change
- is willing to pay for necessary changes.

Nick Pitsas/CSIRO

CSIRO research[8] has found that the highest level of public support was for solar and wind technologies, followed by other renewable forms of energy. When asked to rank the priority they would give to funding for the deployment of various energy options, participants ranked solar highest, followed by wind, wave/tidal then geothermal. Carbon dioxide capture and storage (CCS) ranked marginally better than coal-fired power, but it remains the technology least familiar to the general public. Opinion on nuclear power, although it has warmed somewhat, remains sharply polarised.

The public is also realistic in appreciating that new technologies mean higher energy costs. Most participants in the study indicated that they would be prepared to pay up to AU$50 more a quarter for electricity. A significant number already subscribe to green power, ranging from 49% in Brisbane to 13% in Perth. Participants were also quick to identify the need for transparency in pricing and support for low-income families if electricity prices were to increase.

Changing individual behaviour

It is known from the remarkable shift in public behaviour towards water during the droughts of the early 21st century, that profound changes in individual attitudes and practices are possible in relatively short spans of time. The scope for individuals to reduce their carbon footprint is, if anything, even greater than is the case for water, owing to the array of opportunities available. These include electricity use, transport habits, food choices, waste disposal, consumption patterns, house design, home heating and cooling, and so on. However, one of the main challenges is to make the issue of energy consumption sufficiently potent so that individuals are motivated to implement personal strategies to reduce their own impact on the climate. The public claim to be put off taking action because of a lack of technical knowledge or understanding of climate science and the issues surrounding it.[9] Education would seem, therefore, to be an essential component of attitudinal change.

CSIRO

One of the most important findings from CSIRO's research with members of the public is the importance of face-to-face communication and knowledge sharing to overcome the gaps in knowledge about the issue and technologies. In response CSIRO has developed Energymark, a process based on the well-established Watermark (http://www.watermark.org.au/) concept for grassroots action on water saving.[10] Energymark works by engaging those citizens who are determined to do something to reduce their own personal carbon footprint, to work with CSIRO to convene a group of friends, family, or work colleagues to contemplate the topic of climate and energy over an 8- to 12-month period.

In the first 12-month trial carried out by CSIRO in the city of Newcastle, New South Wales, 172 citizens managed to reduce their collective greenhouse gas emissions by 27%. In the process, average household electricity consumption in the group fell from 14 420 to 9029 kilowatt hours, with participants managing to cut their power use by 35% through the use of energy-saving appliances and the way they used appliances in the home. They also cut their transport emissions by 27% by using more public transport and walking rather than taking the car, their household waste by 16%, and their beef consumption by 28.5%. The Newcastle City Council has asked to become a world testing ground for the approach.[11]

Opportunities for the individual to save energy in daily life, such as those trialled in Newcastle, are set out in *The CSIRO Home Energy Saving Handbook*, which explains 'how to save energy, save money and reduce your carbon footprint'.[12] The book explains that the first step is understanding your own carbon footprint. To help the public understand this, they are asked to think of it in terms of domestic garbage bags, each holding 100 g of CO_2 (or its equivalent). Thus a household of three typically fills 500 000 bags a year with CO_2 from all its activities: the aim is to eliminate as many of these 'bags' as possible by energy savings and other measures. The book provides examples of practical things that Australians can do in their daily lives to reduce their greenhouse emissions, rating the effectiveness of these actions by the number of 'garbage bags of CO_2 avoided' and according to ease and affordability. For example:

Small steps with a big impact:	**Bags avoided**
✻ Improve heating and cooling of home	up to 12 000
✻ Change to cold water clothes washing	8000
✻ Turn off spare fridge	4000
✻ Dry clothes on a line	3000
✻ Replace incandescent lights with low-energy bulbs	7000
✻ Eat foods with lower carbon content	10 000
✻ Reduce purchases by 10%	14 000
✻ Grow your own vegetables and compost waste	17 000
✻ Car pooling and cycling.	20 000
Smart investments:	**Bags avoided**
✻ Adopt passive heating and cooling	up to 24 000
✻ Replace electric heaters with natural gas	up to 80 000
✻ Use solar, gas, or heat pump for hot water	up to 34 000
✻ Buy an energy efficient fridge or washing machine	6000
✻ Go for low-wattage lighting	10 000
✻ 75% of your journeys by bike or public transport.	20 000
Giant leaps:	**Bags avoided**
✻ Base house design on the surrounding environment	up to 37 000
✻ Install solar, wind power, or micro-hydro for domestic electricity	50 000
✻ Buy a hybrid car.	19 000

Target audiences and processes

CSIRO has developed a range of social processes for engaging communities on issues around climate mitigation. The choice of process depends on the audience and topic. With climate change mitigation, the four main audience groups are:

- influential stakeholders, such as politicians, media, NGOs, chief executives, and so on.
- the general community.
- the education sector – not only schools and universities, but also through museums, science centres, and so on.
- communities or groups affected by particular energy projects.[13]

In modern society there is little time to learn about and attend to issues, such as climate change, that seem to many as having little effect on their immediate day-to-day tasks. CSIRO's work to engage public groups through various processes, such as Energymark, underlines the importance of working face-to-face to create the interest, discussion, and dissonance that allow people to grow their understanding, change attitudes, and take action. People are strongly motivated by the idea of being good citizens and often enjoy working in groups of like-minded individuals. However, they are also looking for leadership and for reliable, objective information from trusted sources such as CSIRO and universities. Trust is a critical element, and having multiple sources of reliable advice can help to overcome the confusion that arises when competing arguments over climate change are aired.

Apart from the Energymark concept, another process for raising awareness and changing behaviour is 'Carbon Kids', an educational program developed by CSIRO Education to enable primary and secondary school classes to work together to achieve reductions in their carbon footprint.

Despite some limitations, citizens' panels provide an excellent framework for tackling complex issues that can be applied in various contexts at the local, national, or international level. CSIRO has found that the rich deliberation that participants enjoyed is well received and it is clear that shifts in attitudes take place as a result of the interactions with trusted experts, as well as from hearing the views of fellow citizens. This has led many participants to question the underlying assumptions they hold about the various technology solutions. This work provides a strong foundation for helping the Australian public to understand more about climate change and the range of energy technologies required to achieve a low-carbon economy.

Conclusion

The next few years will be critical in deciding whether or not Australia – and the world – is successful in mitigating greenhouse gas emissions sufficiently to avoid 'dangerous' climate change as described in reports by the IPCC, Nicholas Stern, Ross Garnaut and others.[14, 15] However, effective mitigation will require the united forces of government, industry, and the community to make it happen. The public has made it clear in numerous polls that it wants action, but it is also looking to others in positions of influence to lead it in what to do and which technologies to support. At the same time, the public is an important driver in the whole process – and its expectations will have a powerful influence over the actions of government and industry. Studies concluding that the public is willing to pay for the changes strongly suggest Australia should be doing more. Many Australians are taking climate change seriously, as best evidenced by a range of personal mitigation actions: for example, through small steps such as changing light bulbs, cold water washing, and walking instead of driving the car, to installing various distributed energy options, including solar hot water systems, solar photovoltaic systems, or purchasing green power. Action on climate change will only be successful through the combined efforts of government, industry, and the public at large.

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Responding to a changing climate

By Helen Cleugh, Mark Stafford Smith, Michael Battaglia, and Paul Graham

Key messages

- Evidence from many different sources shows human activities are contributing to the Earth's changing climate.
- The impacts of climate change on Australia, its industries, and people over the coming decades and centuries will be significant, with some of these impacts already apparent.
- The Earth is committed to some degree of climate change as a result of past greenhouse gas emissions, so we will need to adapt to this change.
- Adaptation on a scale far more extensive than is currently occurring will be essential in all walks of life if we are to limit the social, economic, and environmental impacts of climate change.
- Action within the next decade to lower greenhouse gas emissions will reduce the probability and severity of climate change impacts.
- Agriculture and forestry hold great potential for mitigating greenhouse gas emissions through afforestation, soil carbon management, and better management of livestock and cropping emissions.
- Making the right energy choices for Australia's future from among our abundant options will often be a matter of choosing the energy source, or combination of sources, for a particular context.
- Practical and sometimes beneficial or low cost actions can make significant progress in tackling climate change.

The evidence amassed by CSIRO, the Australian Bureau of Meteorology, universities, and other scientific institutions around the world shows overwhelmingly that human activities are contributing to the Earth's changing climate. Even if there were mechanisms in place to halt and eventually reverse the growth in net greenhouse gas emissions, their long life in the atmosphere means some climate change is already 'locked-in' as a result of past emissions. We will need to adapt to this committed change, which will challenge us with rising temperatures and sea levels, increasing storm intensity, and greater risk of fire, flood, and drought. Evidence shows that proactive adaptation to these challenges can create future opportunities for growth, development, and sustainability.

While some impacts of climate change will take many decades to unfold, it is increasingly likely that the level of global warming will exceed the 2ºC threshold of 'dangerous' climate change. There is a limited window of opportunity before thresholds for largely irreversible environmental impacts are reached. Action within the next decade to lower greenhouse gas emissions will reduce the probability and severity of climate change impacts.

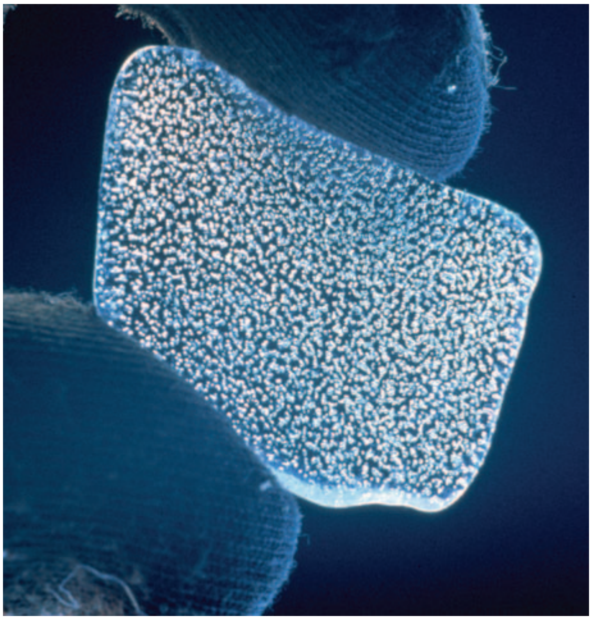
Australia has a significant task ahead if the nation chooses to make large reductions in its greenhouse gas emissions. We have a relatively high per capita emissions intensity and energy use per unit of GDP. This is a function of the structure of our economy, which includes low-cost fossil fuel and mineral resource extraction and processing industries. On the other hand, Australia is endowed with a very wide array of low-carbon energy resources. Exploiting these resources would create new industries, and may have other co-benefits such as improved energy security.

Our choices will have different sets of impacts over time on the economy, environment, and society. Many global economies are leading Australia in their responses to climate change and are using these responses to create new economic opportunities. In partnership with industry, government, and the community CSIRO continues to work to understand the range of responses, solutions, and opportunities available to Australia.

The following central messages of this book summarise the conclusions drawn from many years of research carried out by CSIRO, the Bureau of Meteorology, universities, and many other organisations.

The science of climate change, and the role of humans, is clear

Observations on land and in the oceans, of ocean level, acidity, and salinity, and of other aspects of the climate system give us a picture of our climate over time. There is a great deal of evidence from many different sources that the Earth's climate has warmed over the last century. It is very likely that the primary cause of this warming is the emission of greenhouse gases (carbon dioxide and others) by human activities.



CSIRO

Australia is highly vulnerable to climate change

Projections of future climates from mathematical representations of the Earth's climate system indicate that it is very likely that warming and other climate changes will continue and also accelerate through the coming century if emissions of greenhouse gases continue to increase. The impacts of climate change on Australia, its industries, and people over the coming decades and centuries will be significant, and changes can now be clearly seen in stresses on our water supplies and farming, changed natural ecosystems, reduced seasonal snow cover, and extreme events.

Gregory Heath/CSIRO

Adaptation can reduce the impacts of climate change that are already locked-in

Significant climate change impacts are unavoidable due to the greenhouse gases that are already in the atmosphere, as well as likely future emissions. The impacts of climate change will pose a large risk to human wellbeing in the future, and will require the drawing up of action plans at national, state, regional, and local levels to adapt to the most likely changes. Adaptation on a scale far more extensive than is currently occurring will be essential in all walks of life if we are to limit the social, economic, and environmental impacts of climate change.

Willem van Aken/CSIRO

Reducing greenhouse gas emissions can limit the impact of climate change

Adaptation alone cannot absorb all the projected impacts of climate change, especially over the long term. Some of these can be further avoided, reduced, or delayed by effective reduction in global net greenhouse gas emissions. Agriculture and forestry hold great potential for mitigating greenhouse gas emissions through afforestation, soil carbon management, and better management of livestock and cropping emissions. Making the right energy choices for Australia's future from among our abundant resources and technologies will often be an issue of which energy source, or combination of sources, best suits a particular context. Australia's greatest need is for low-emissions technologies that are competitively priced, resilient, and flexible enough to cope with a range of possible future energy challenges and demands. All options are still in the mix for a future energy system with many niches and opportunities.

In summary, the work of CSIRO and others shows that human-driven climate change is real, that it is already happening, and that its impact on our society, economy, and environment will be far-reaching. The timeframe for choosing the form and level of response to reduce these impacts is limited. While the choices are challenging, research shows that there continues to be support within the Australian community and industry for addressing climate change and capturing the opportunities. Through practical and sometimes beneficial or low-cost actions, we can make significant progress in tackling climate change.

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