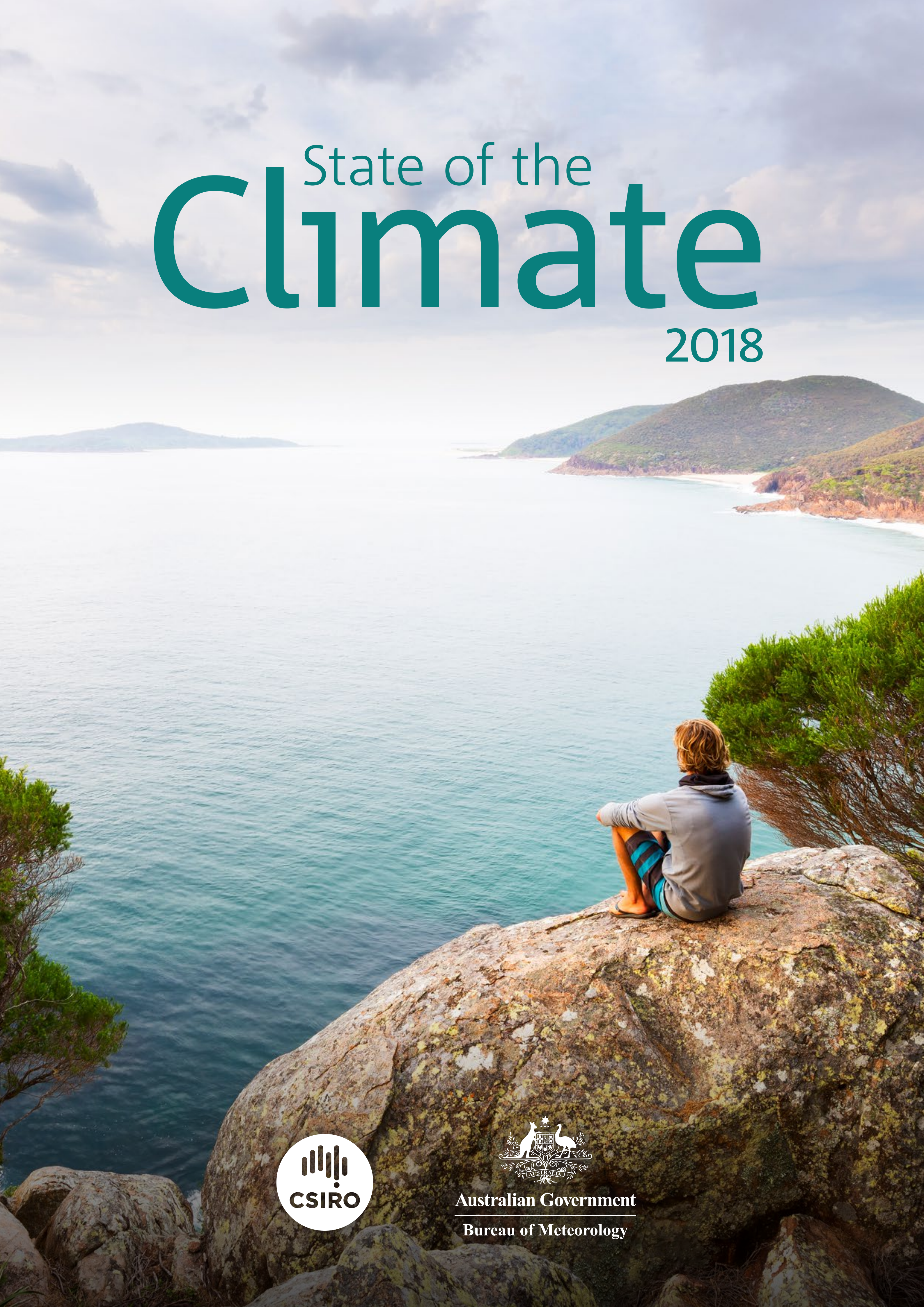
State of the Climate 2018



CSIRO

Australian Government
Bureau of Meteorology

Report at a glance

The Bureau of Meteorology and CSIRO play an important role in monitoring, analysing and communicating observed and future changes in Australia's climate.

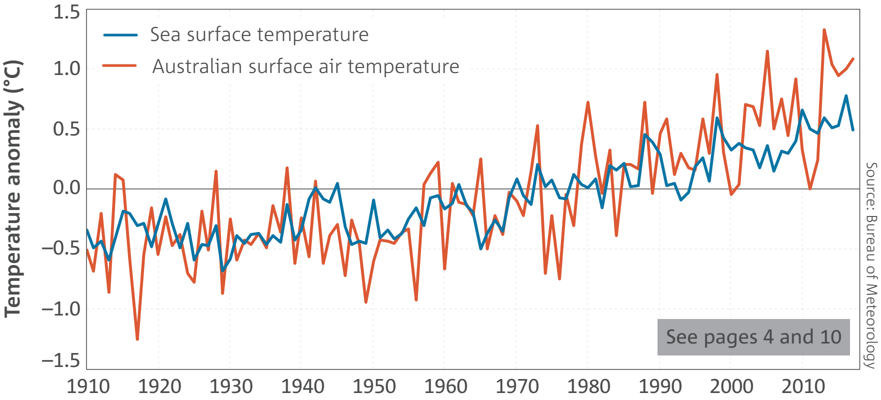
This fifth, biennial State of the Climate report draws on the latest monitoring, science and projection information to describe variability and changes in Australia's climate. Observations and climate modelling paint a consistent picture of ongoing, long-term climate change interacting with underlying natural variability.

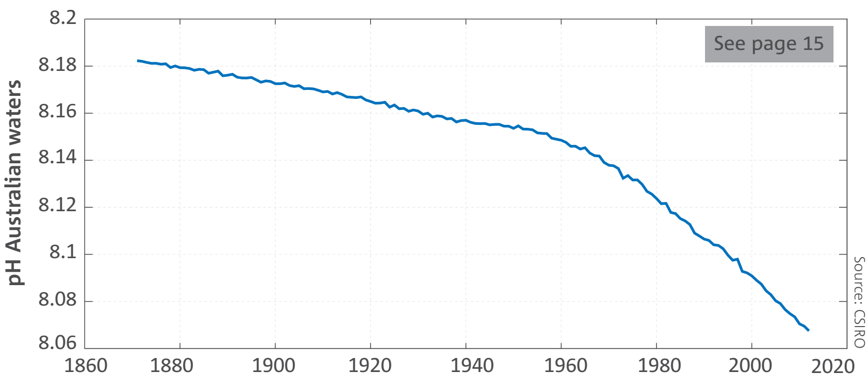
These changes affect many Australians, particularly the changes associated with increases in the frequency or intensity of heat events, fire weather and drought. Australia will need to plan for and adapt to some level of climate change. This report is a synthesis of the science informing our understanding of climate in Australia and includes new information about Australia's climate of the past, present and future. The science underpinning this report will help inform a range of economic, environmental and social decision-making and local vulnerability assessments, by government, industry and communities.

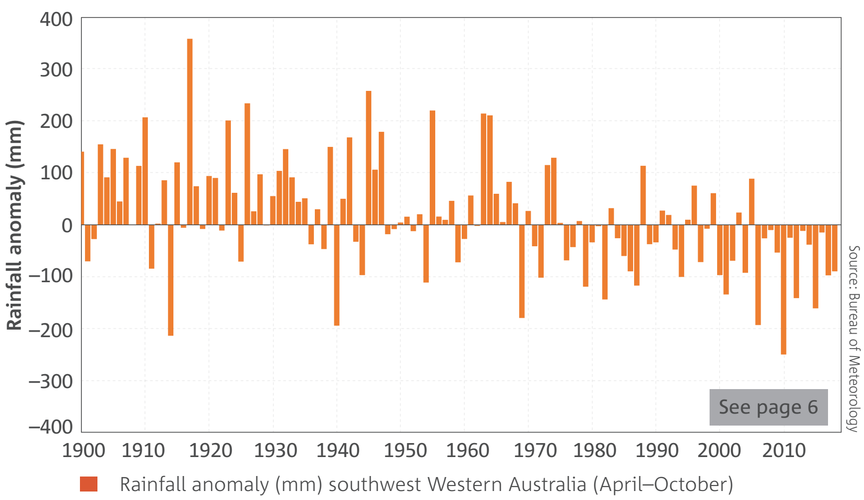
Key points

Australia

- Australia's climate has warmed by just over 1 °C since 1910, leading to an increase in the frequency of extreme heat events.
- Oceans around Australia have warmed by around 1 °C since 1910, contributing to longer and more frequent marine heatwaves.
- Sea levels are rising around Australia, increasing the risk of inundation.
- The oceans around Australia are acidifying (the pH is decreasing).
- April to October rainfall has decreased in the southwest of Australia. Across the same region May–July rainfall has seen the largest decrease, by around 20 per cent since 1970.
- There has been a decline of around 11 per cent in April–October rainfall in the southeast of Australia since the late 1990s.
- Rainfall has increased across parts of northern Australia since the 1970s.
- Streamflow has decreased across southern Australia. Streamflow has increased in northern Australia where rainfall has increased.
- There has been a long-term increase in extreme fire weather, and in the length of the fire season, across large parts of Australia.

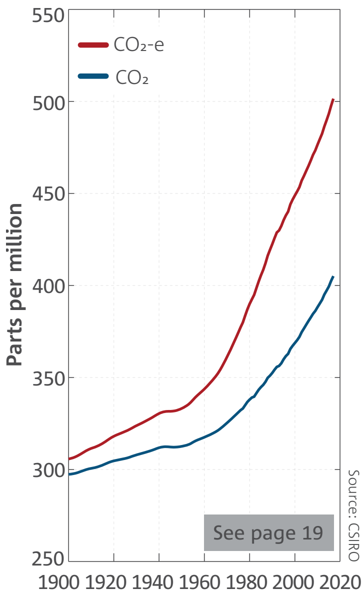


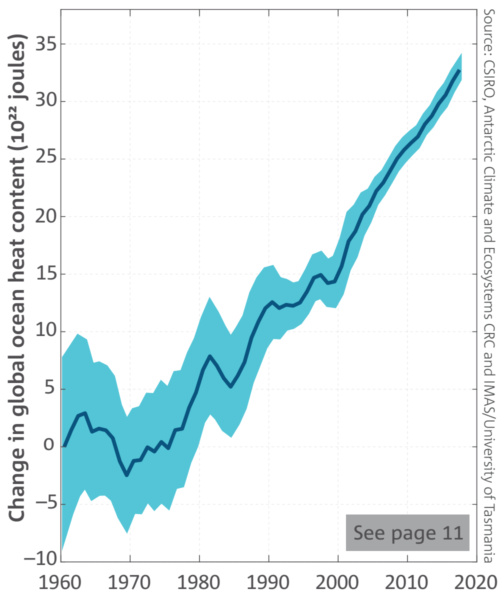


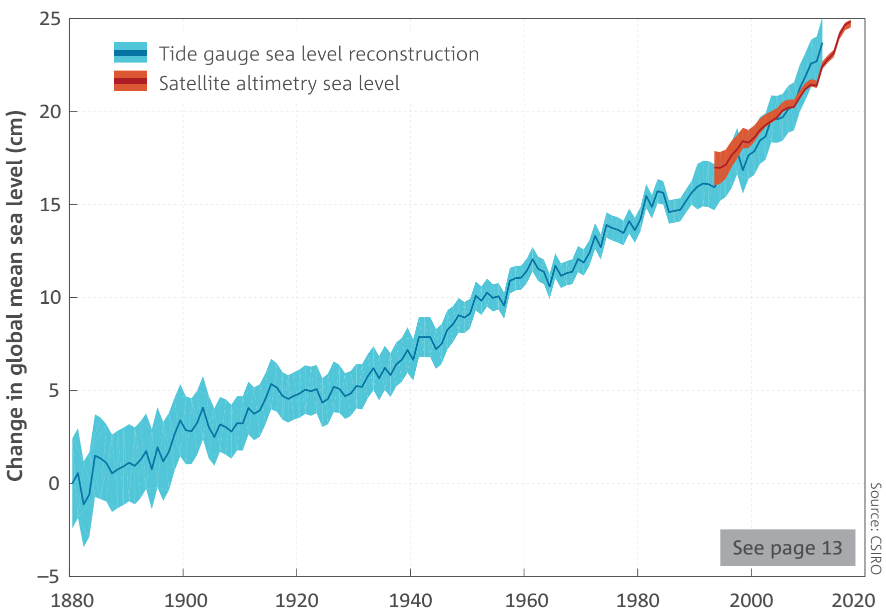


Global

- Concentrations of all the major long-lived greenhouse gases in the atmosphere continue to increase, with carbon dioxide (CO_2) concentrations rising above 400 ppm since 2016 and the CO_2 equivalent (CO_2-e) of all gases reaching 500 ppm for the first time in at least 800,000 years.
- Emissions from fossil fuels continue to increase and are the main contributor to the observed growth in atmospheric CO_2.
- The world's oceans, especially in the southern hemisphere, are taking up more than 90 per cent of the extra energy stored by the planet as a result of enhanced greenhouse gas concentrations.
- Global sea level has risen by over 20 cm since 1880, and the rate has been accelerating in recent decades.
- Globally averaged air temperature has warmed by over 1 °C since records began in 1850, and each of the last four decades has been warmer than the previous one.







Future

Australia is projected to experience:

- Further increases in sea and air temperatures, with more hot days and marine heatwaves, and fewer cool extremes.
- Further sea level rise and ocean acidification.
- Decreases in rainfall across southern Australia with more time in drought, but an increase in intense heavy rainfall throughout Australia.

Australia's changing climate

Temperature

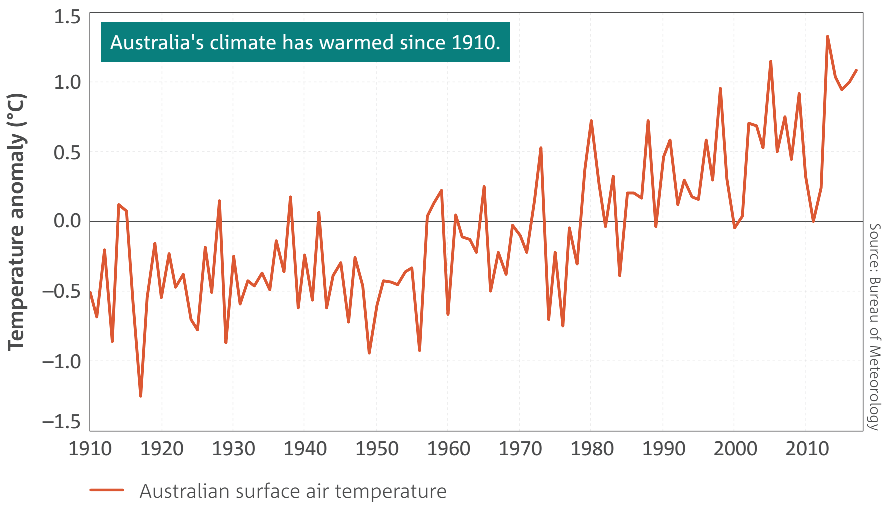
- Australia's climate has warmed by just over 1 °C since 1910, leading to an increase in the frequency of extreme heat events.

Australia's weather and climate continues to change in response to a warming global climate. Australia has warmed by just over 1 °C since 1910, with most warming since 1950. This warming has seen an increase in the frequency of extreme heat events and increased the severity of drought conditions during periods of below-average rainfall. Eight of Australia's top ten warmest years on record have occurred since 2005.

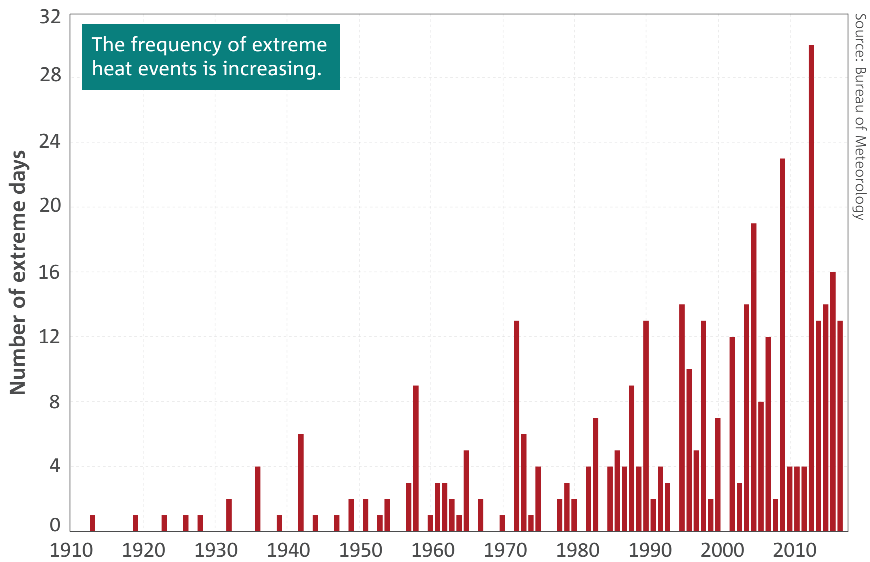
The year-to-year changes in Australia's climate are mostly associated with natural climate variability such as El Niño and La Niña in the tropical Pacific Ocean and phases of the Indian Ocean Dipole in the Indian Ocean. This natural variability now occurs on top of the warming trend, which can modify the impact of these natural drivers on the Australian climate.

Increases in temperature are observed across Australia in all seasons with both day and night-time temperatures showing warming. The shift to a warmer climate in Australia is accompanied by more extreme daily heat events. Record-warm monthly and seasonal temperatures have been observed in recent years, made more likely by climate change.

Examining the shift in the distributions of monthly day and night-time temperature shows that very high monthly maximum temperatures that occurred around 2 per cent of the time in the past (1951–1980) now occur around 12 per cent of the time (2003–2017). Very warm monthly minimum, or night-time, temperatures that occurred around 2 per cent of the time in the past (1951–1980) now also occur around 12 per cent of the time (2003–2017). This upward shift in the distributions of temperature has occurred across all seasons, with the largest change in spring.



Anomalies in annual temperature over land in the Australian region. Anomalies are the departures from the 1961–1990 standard averaging period.

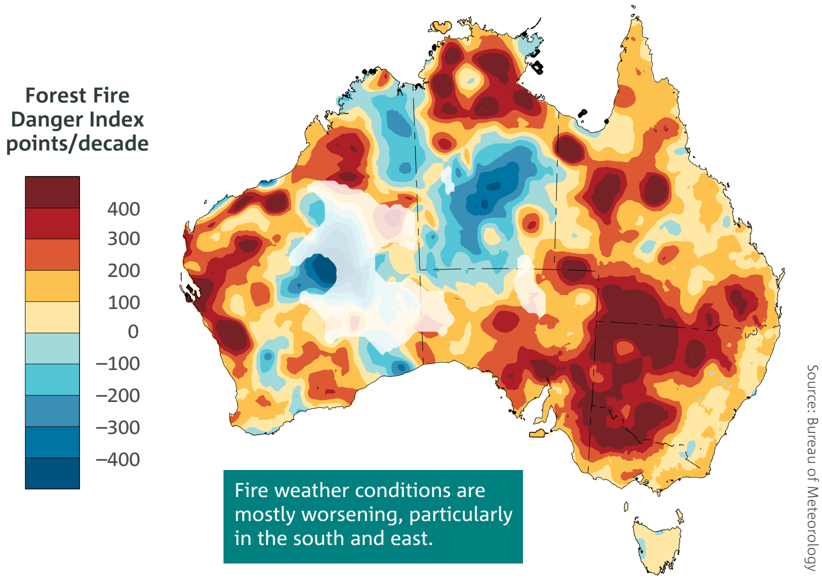


Number of days each year where the Australian area-averaged daily mean temperature is extreme. Extreme days are those above the 99th percentile of each month from the years 1910–2017. These extreme daily events typically occur over a large area, with generally more than 40 per cent of Australia experiencing temperatures in the warmest 10 per cent for that month.

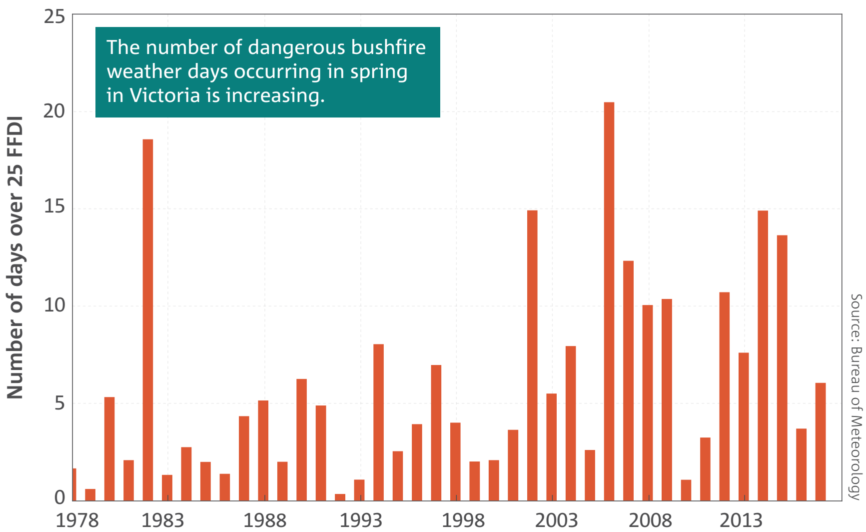
Fire weather

- There has been a long-term increase in extreme fire weather and in the length of the fire season across large parts of Australia since the 1950s.

Fire weather is largely monitored in Australia using the Forest Fire Danger Index (FFDI). This index estimates the fire danger on a given day based on observations of temperature, rainfall, humidity and wind speed. The annual 90th percentile of daily FFDI (i.e., the most extreme 10 per cent of fire weather days) has increased in recent decades across many regions of Australia, especially in southern and eastern Australia. There has been an associated increase in the length of the fire weather season. Climate change, including increasing temperatures, is contributing to these changes. Considerable year-to-year variability also occurs, with La Niña years, for example 2010–2011 and 1999–2000, generally associated with a lower number of days with high FFDI values.



Trends from 1978 to 2017 in the annual (July to June) sum of the daily Forest Fire Danger Index—an indicator of the severity of fire weather conditions. Positive trends, shown in the yellow to red colours, are indicative of an increasing length and intensity of the fire weather season. A trend of 300 FFDI points per decade is equivalent to an average trend of 30 FFDI points per year. Areas where there are sparse data coverage such as central parts of Western Australia are faded.



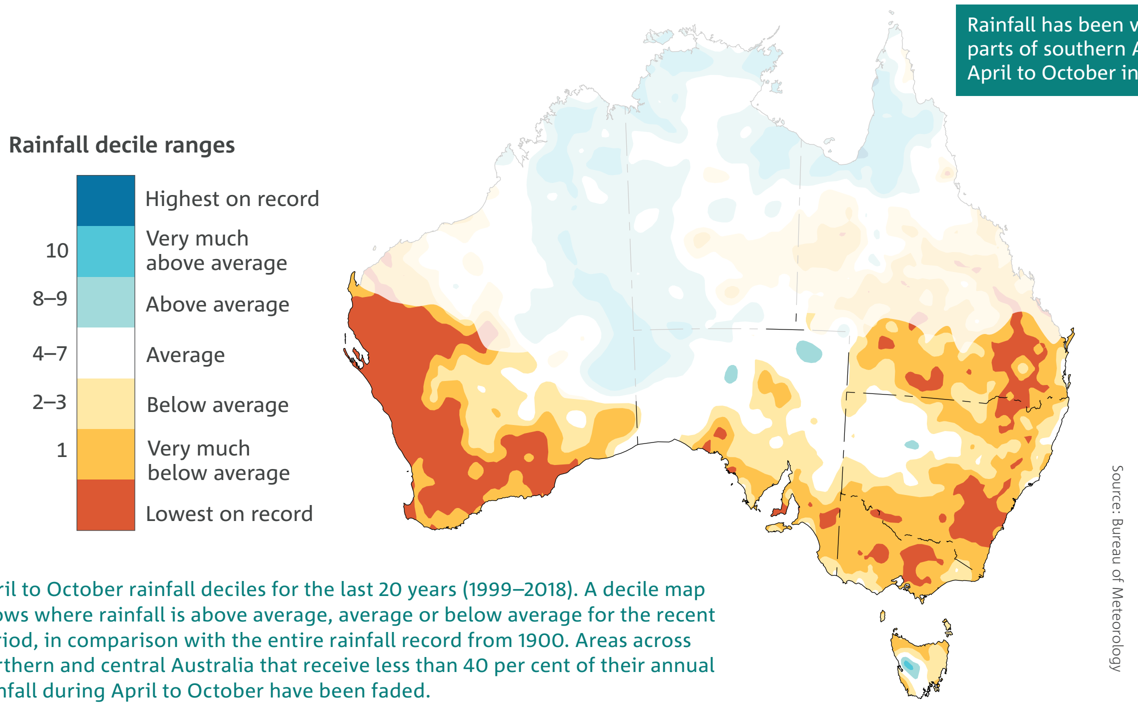
Area average of the number of days with FFDI greater than 25 (very high fire danger) in Victoria in spring for the years starting in July (1978–2017). Although there is considerable interannual variability in the index, there is also a clear trend in more recent decades towards a greater number of very high fire weather days in spring.

Rainfall

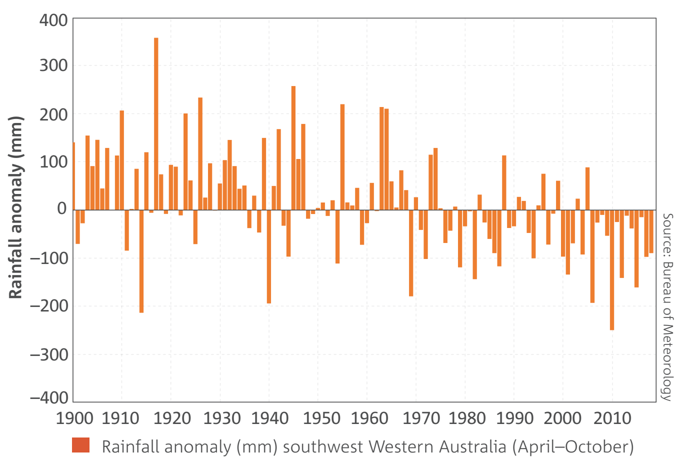
- April to October rainfall across southeastern and southwestern Australia has declined.
- Rainfall has increased across parts of northern Australia since the 1970s.

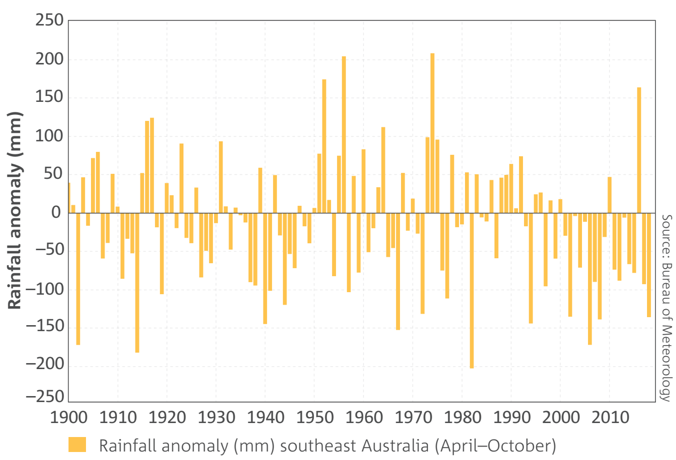
Australian rainfall is highly variable and is strongly influenced by phenomena such as El Niño, La Niña, and the Indian Ocean Dipole. Despite this large natural variability, underlying long-term trends are evident in some regions. There has been a shift towards drier conditions across southwestern and southeastern Australia during April to October. Northern Australia has been wetter across all seasons, but especially in the northwest during the tropical wet season.

Rainfall has been very low over parts of southern Australia during April to October in recent decades.



April to October rainfall deciles for the last 20 years (1999–2018). A decile map shows where rainfall is above average, average or below average for the recent period, in comparison with the entire rainfall record from 1900. Areas across northern and central Australia that receive less than 40 per cent of their annual rainfall during April to October have been faded.





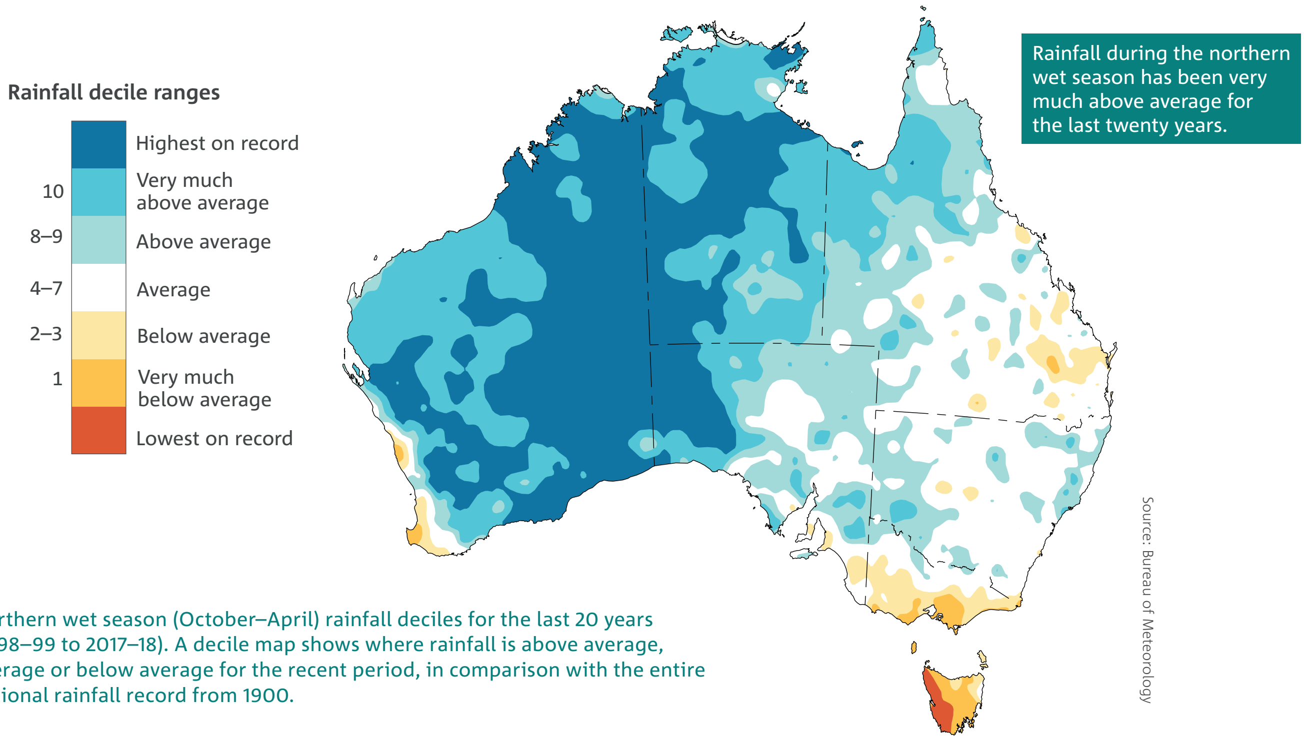
Anomalies of April to October rainfall for southwestern (southwest of the line joining the points 30° S, 115° E and 35° S, 120° E) and southeastern (south of 33° S, east of 135° E inclusive) Australia. Anomalies are calculated with respect to 1961 to 1990 averages.

Year-to-year variability occurs against the background drying trend across much of the southern half of Australia (south of 26° S). In 17 of the last 20 April to October periods since 1999, southern Australia has had below-average rainfall. Recent years with above-average rainfall in this region were generally associated with drivers of higher than usual rainfall across Australia, such as a strong negative Indian Ocean Dipole in 2016, and La Niña in 2010.

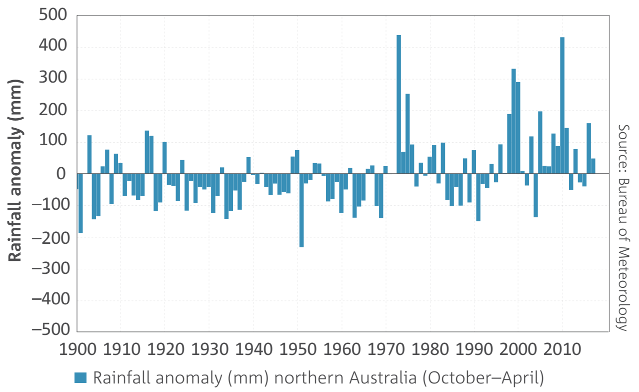
The drying in recent decades across southern Australia is the most sustained large-scale change in rainfall since national records began in 1900.

The drying trend has been most evident in the southwestern and southeastern corners of the country. The drying trend is particularly strong between May to July over southwest Western Australia, with rainfall since 1970 around 20 per cent less than the average from 1900 to 1969. Since 1999, this reduction has increased to around 26 per cent. For the southeast of the continent, April to October rainfall for the period 1999 to 2018 has decreased by around 11 per cent when compared to the 1900 to 1998 period. This period encompasses the Millennium Drought, which saw low annual rainfall totals across the region from 1997 to 2010.

This decrease, at an agriculturally and hydrologically important time of the year, is linked with a trend towards higher mean sea level pressure in the region and a shift in large-scale weather patterns—more highs and fewer lows. This increase in mean sea level pressure across southern latitudes is a known response to global warming. There has been a reduction in the number of cold fronts impacting the southwest, and a decrease in the incidence and intensity of weather systems known as cut-off lows in the southeast regions of Australia. Cut-off lows bring the majority of rainfall and the most intense rainfalls in some regions of eastern Victoria and Tasmania.



Northern wet season (October–April) rainfall deciles for the last 20 years (1998–99 to 2017–18). A decile map shows where rainfall is above average, average or below average for the recent period, in comparison with the entire national rainfall record from 1900.



Anomalies of October to April rainfall for northern Australia (north of 26° S inclusive). Anomalies are calculated with respect to the 1961 to 1990 average.

Heavy rainfall

- There is evidence that some rainfall extremes are becoming more intense.

Although the range of natural variability in heavy rainfall is very large, there is evidence from observed weather station records that a higher proportion of total annual rainfall in recent decades has come from heavy rain days.

As the climate warms, heavy rainfall is expected to become more intense, based on the physical relationship between temperature and the water-holding capacity of the atmosphere. For heavy rain days, total rainfall is expected to increase by around 7 per cent per degree of warming. For short-duration, hourly, extreme rainfall events, observations in Australia generally show a larger than 7 per cent increase. Short-duration rain extremes are often associated with flash flooding.

Compound events

While scientists often report on changes in individual climate variables, such as rainfall, historically significant weather and climate events are often the result of the combined influence of extremes in multiple variables occurring simultaneously. These events are commonly the most impactful and hazardous, and planning for such events is a major component of disaster risk reduction and resilience.

Compound extreme events can occur in various ways. This includes an extreme storm surge, combined with extreme rainfall, leading to extreme coastal inundation. Similarly, extreme rainfall and extreme high wind events along the New South Wales coast are often associated with the simultaneous occurrence of an intense low pressure system, cold front and thunderstorms.

Compound extreme events can also describe the confluence of climate and weather extremes of varying timescales, such as a drought period intersecting with a prolonged heatwave, or record high daily temperatures—an occurrence which typically results in large impacts on agriculture, human health, fire weather and infrastructure.

Climate change can have a significant influence on the frequency, magnitude and impact of some types of compound events.

For example, the confluence of background warming trends, background drying trends and natural variability saw extreme heat and low rainfall across Tasmania during the spring, summer and autumn of 2015–2016. October 2015 saw the third highest mean monthly maximum temperature on record for the State, record low monthly rainfall and record high fire danger. These conditions rapidly transitioned to record atmospheric moisture and heavy rainfall in June. Tasmania experienced significant impacts from these events, including drought and fires, followed by flooding.

There is also a trend in some regions towards an increasing number of days when high fire danger ratings are combined with conditions that allow bushfires to generate thunderstorms. This can lead to extremely dangerous fire conditions as observed for the Canberra (2003) and Black Saturday (2009) fires, including generating additional fires from lightning strikes.

As climate change continues, the combination of increases in heavy rainfall and rising sea levels means that coastal and estuarine environments may have an increase in flood risk from multiple causes.

Projecting the occurrence and severity of future compound extreme events is a significant scientific challenge, as well as a very important one for future climate adaptation.

Streamflow

- Streamflow has decreased across southern Australia since the 1970s.
- Streamflow has increased in northern Australia, since the 1970s, in places where rainfall has increased.

The observed long-term reduction in rainfall across southern Australia has led to even greater reductions in streamflows. For example, the mean annual streamflow into Perth water storages has dropped from 338 GL during the period 1911–1974 to 134 GL during the subsequent years from 1975–2017. During this latter period there is a continuing decline to a mean annual inflow of 47 GL during the last six years.

Declines in streamflow have also been observed in four drainage divisions: the Murray–Darling Basin, South East Coast (Victoria) and South East Coast (New South Wales) (which include Sydney and Melbourne), and the South Australian Gulf (which includes Adelaide). In each of these drainage divisions between two thirds and three quarters of streamflow records show a declining trend since the 1970s.

In the Tanami–Timor Sea Coast drainage division in Northern Australia, which includes Darwin and covers much of the Northern Territory, there is an increasing trend in mean annual flows at more than half of the gauging stations, following an increase in rainfall since the 1970s.

Tropical cyclones

- There has been a decrease in the number of tropical cyclones observed in the Australian region since 1982.

Tropical cyclone activity in the Australian region, which is specified as the ocean and land areas from 90° E to 160° E in the southern hemisphere, has large variability from year-to-year, due to the influence of naturally occurring climate drivers. For example, the number of tropical cyclones in the Australian region generally declines with El Niño and increases with La Niña.

Observations since 1982 indicate a downward trend in the number of tropical cyclones in the Australian region.

In contrast to the number of tropical cyclones, cyclone intensity is harder to observe, so it is not currently possible to quantify any trends with a substantial degree of confidence.

Snow

- A downward trend in snow depth has been widely observed for Australian alpine regions since the late 1950s.

Downward trends in snow depth have been observed for Australian alpine regions since the late 1950s, with largest declines observed during spring. Downward trends in the spatial extent of snow cover in Australia have also been observed. Snow depth is closely related to maximum temperatures, and the observed declines are associated with the long-term trend of increasing temperatures.

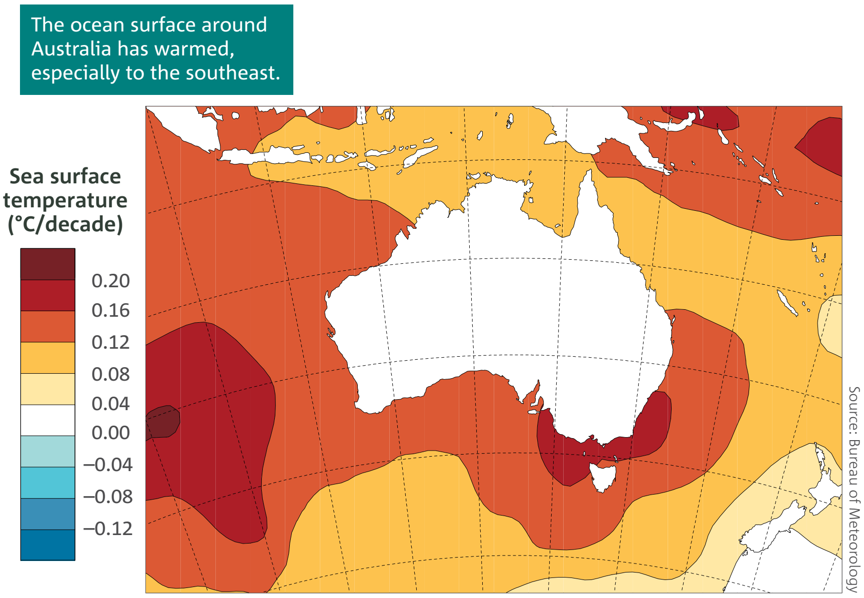
Oceans

Sea surface temperature

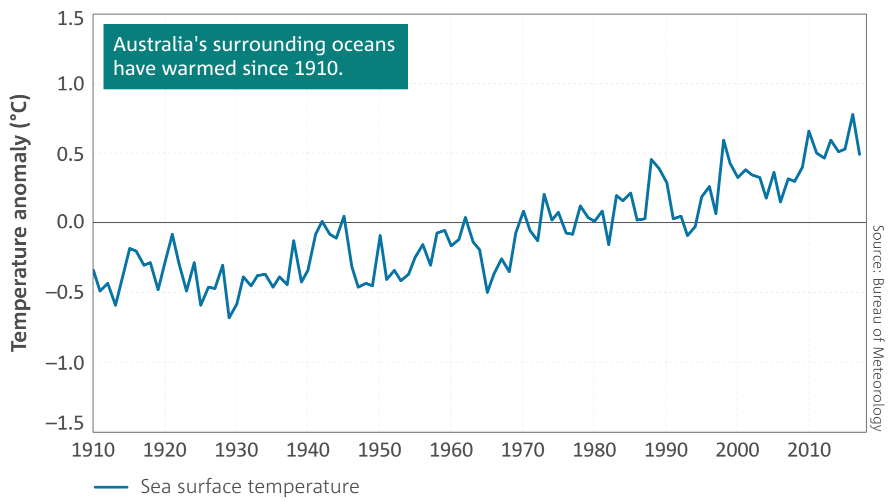
- The ocean surface around Australia has warmed, contributing to longer and more frequent marine heatwaves.

The ocean surface around Australia has warmed over recent decades at a similar rate to the air temperature. Sea surface temperature in the Australian region has warmed by around 1 °C since 1910, with eight of the ten warmest years on record occurring since 2010. Part of the East Australian Current now extends further south, creating an area of more rapid warming in the Tasman Sea. This extension is having numerous impacts on marine ecosystems, including many marine species extending their habitat range further south.

Warming of the ocean has contributed to longer and more frequent periods when the sea surface temperature is in the upper range of historical baseline conditions for five days or more, known as marine heatwaves. There were long and intense marine heatwaves in the Tasman Sea and around southeast Australia and Tasmania from September 2015 to May 2016 and from November 2017 to March 2018. Scientific analysis shows that the severity of both events can be attributed to anthropogenic climate change. Recent marine heatwaves are linked to coral bleaching in the Great Barrier Reef (see box on page 12).



Trends in sea surface temperatures in the Australian region from 1950 to 2017 (data source: ERSST v5, www.esrl.noaa.gov/psd/).



Anomalies in annual sea surface temperature in the Australian region. Anomalies are the departures from the 1961–1990 standard averaging period. Sea surface temperatures are for the Australian region (4–46° S and 94–174° E).

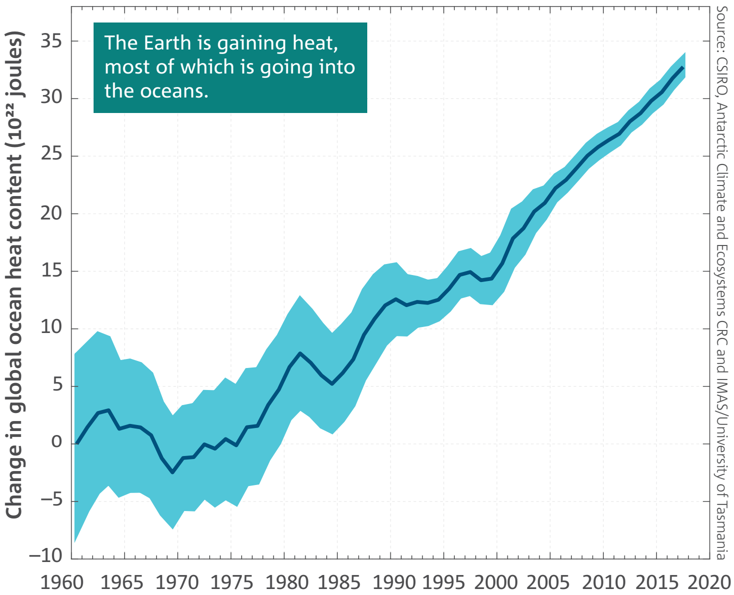
Ocean heat content

- The world's oceans are taking up more than 90 per cent of the extra energy stored by the planet as a result of enhanced greenhouse gas concentrations, and the southern hemisphere oceans have taken up the majority of this heat.

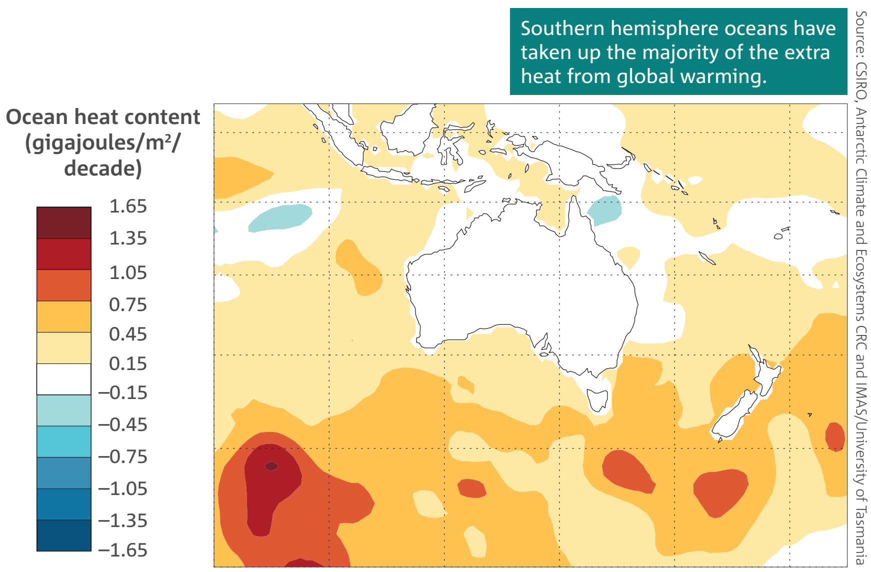
The world's oceans play a critical role in the climate system. More than 90 per cent of the additional energy arising from the enhanced greenhouse effect is taken up by the ocean, slowing down the rate of warming at the Earth's surface. Heat is absorbed at the surface and then moves to the deep ocean in those regions where currents move water vertically. As a result, the ocean is warming both near the surface and at depth, with the rate varying between regions and depths.

The upper ocean is more extensively measured than the deep ocean. Between 1960 and 2017 the global ocean between the surface and a depth of 700 m gained 24 x 10^{22} joules of additional heat. This is more than 60 per cent of the heat accumulated over the full depth of the ocean. Due to the location of currents that move water vertically, the southern hemisphere oceans have taken up the majority of the heat, including the Southern Ocean to the south of Australia.

The rate at which the deep ocean below 700 m is warming is slow but steady, compared to the more variable rate of change in the upper ocean. Long-term trends in the deep ocean show a clear warming, however there are far fewer observations below 2000 m than near the surface, so the magnitude of this warming is less certain. The observation coverage in the deep ocean will dramatically increase in coming years as the newest generation of observing technology becomes operational, including the automated samplers known as ARGO floats with an extended depth range down to 6000 m.



Estimated change in ocean heat content over the full ocean depth, from 1960 to 2017. Shading provides an indication of the confidence range of the estimate. Note that data contributing to the early part of the record are sparse and trends estimated over this period are small compared to the error bars, hence considered unreliable.



Estimated linear trend in ocean heat content between 1970 and 2017 in the top 700 m of the ocean, showing the highest uptake of heat in regions where ocean currents move heat to the deep ocean such as the Southern Ocean south of Australia.

Ocean heat and coral reefs

Warming ocean temperatures and an increase in the frequency and intensity of marine heatwaves pose a major threat to the long-term health and resilience of coral reef ecosystems. Globally, large-scale mass coral bleaching events have occurred with increasing frequency and extent since the latter decades of the 20th Century. Bleaching is a stress response of corals, as the water warms the symbiotic relationship between the coral and its zooxanthellae breaks down, turning corals pale. Without these zooxanthellae, most corals struggle to survive, and can ultimately die if the thermal stress is too severe or prolonged.

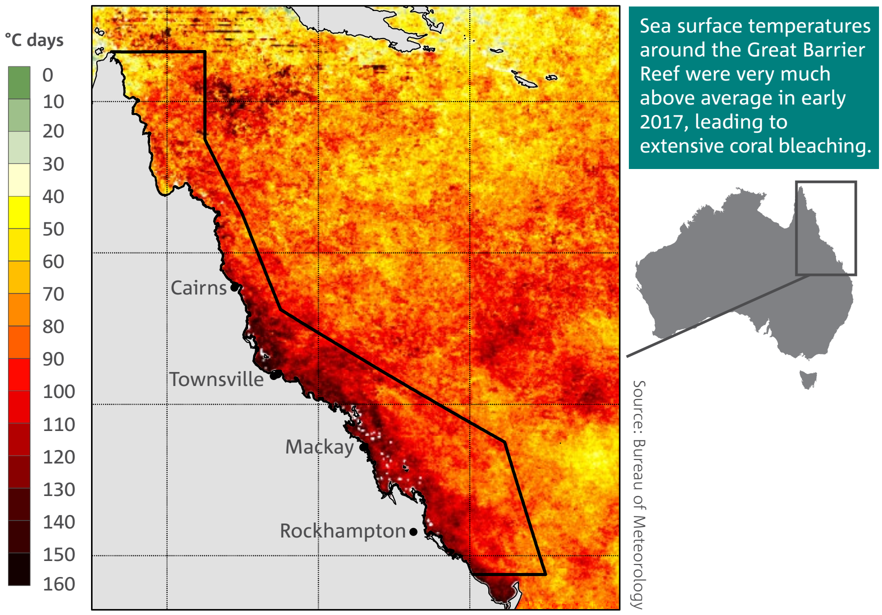
Bleaching on the Great Barrier Reef has occurred in the past, but with increased frequency and extent in recent decades. Widespread bleaching was observed in 1998, driven by higher summer temperatures associated with a strong El Niño combined with long-term warming trends. The last two years (2016 and 2017) have seen mass bleaching over parts of the Reef in consecutive years for the first time, with the northern Great Barrier Reef experiencing bleaching in both summers.

In February to May 2016, the bleaching was associated with some of the warmest sea surface temperatures ever recorded, with temperatures well above the long-term monthly averages in February, March and April. As a result, 30 per cent of all coral cover across the entire Great Barrier Reef was lost, and 50 per cent in the northern third was lost between March and November 2016. This was four times greater than previous mass-bleaching events in 2002 and 1998.

A second mass bleaching occurred in 2017 linked to another marine heatwave, with temperatures again well above the long-term mean.

Both events could have been more extensive in the Southern Great Barrier Reef if it were not for cooling winds associated with distant tropical cyclones *Winston* and *Tatiana* in 2016 and tropical cyclone *Debbie* in 2017.

The primary cause of both marine heatwaves and mass bleaching events was very likely due to warming oceans as a result of anthropogenic climate change, compounded in early 2016 by a very strong El Niño event.



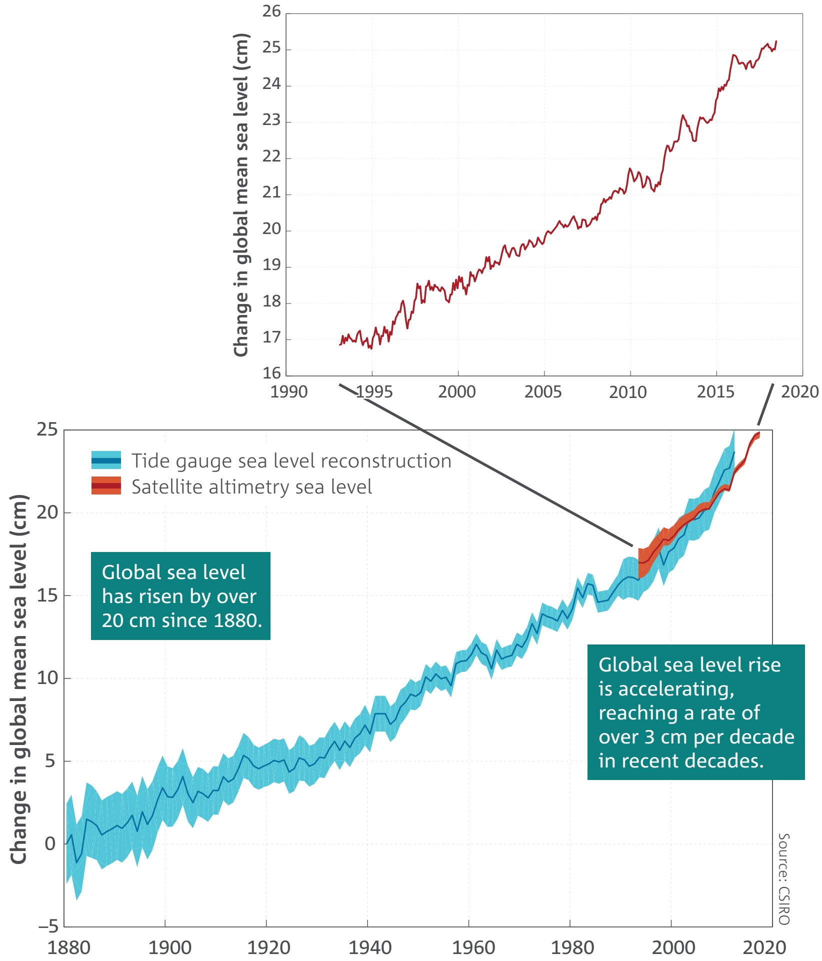
Great Barrier Reef coral bleaching risk map, shown as Degree Heating Days: the accumulated (sum) of positive sea surface temperature anomalies with respect to the long-term average of 2002–2011 each day over the reef for December 2016 to March 2017. Green = OK. Yellow = watch. Orange = coral bleaching risk. Red = coral mortality risk.

Sea level

- Global sea level has risen by over 20 cm since 1880, and the rate has been accelerating in recent decades.
- Rates of sea level rise vary around Australia.

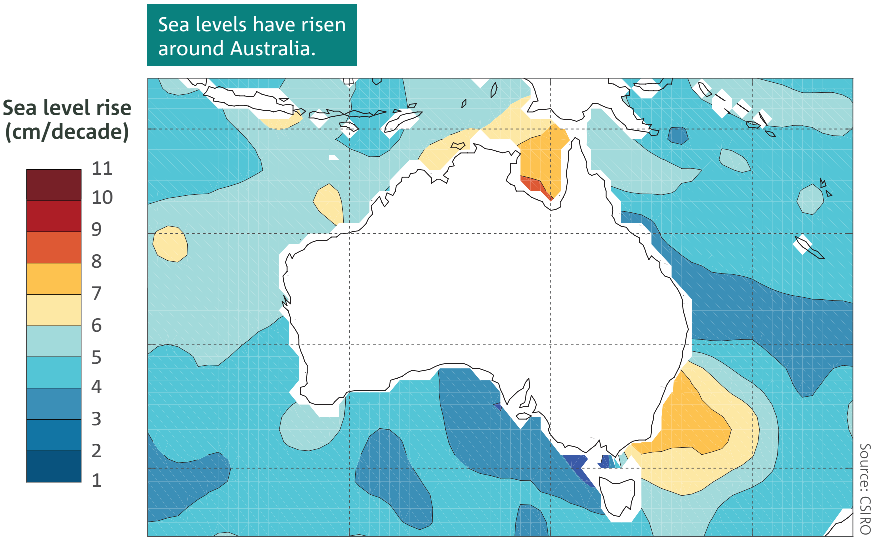
As the ocean warms it expands and sea level rises. This has contributed about a third of the observed global sea level rise of over 20 cm since the late 19th Century. The remainder comes from the loss of ice from glaciers and polar ice sheets, and changes in the amount of water stored on the land. The confidence range of global sea level change has continuously improved because there has been more analysis of satellite altimetry, the time series has lengthened, and the various contributions to sea level have now all been reliably quantified and accounted for. Since 1993 sea level has been rising at 3.2 cm per decade.

Sea level has been rising around Australia. Sea level rise varies from year to year and from place to place. This is partly due to the natural variability of the climate system from influences such as El Niño, La Niña and the Pacific Decadal Oscillation. Based on the satellite altimetry observations since 1993, the rates of sea level rise to the northwest, north and southeast of Australia have been higher than the global average, while rates of sea level rise along the south and northeast coasts of the continent have been close to or slightly less than the global average.



High-quality global sea level measurements showing annual sea level change from 1880 in tide gauge data (1880–2014 blue line, light blue shading indicates confidence range), and annual sea level change in satellite altimetry (1993–2017, red line). The pull out figure shows monthly sea level change from 1880 in satellite altimetry from 1993 to July 2018 (updated from Church and White 2011). https://research.csiro.au/slrwavescoast/sea-level/.

The longer-term satellite record is restricted to offshore (at least 25 km off the coast) and does not include estimates of sea level rise along Australia's coasts, where changes are instead measured from tide gauge data. Changes in sea level measured by tide gauges may be different from those measured by satellites due to coastal processes, vertical land motion or changes to the surveyed reference level of the tide records (e.g. a site change). These factors introduce some uncertainty to rates of change in sea level experienced at the coast. Nevertheless, tide gauges with good long-term records around Australia show consistent sea level rise over time.

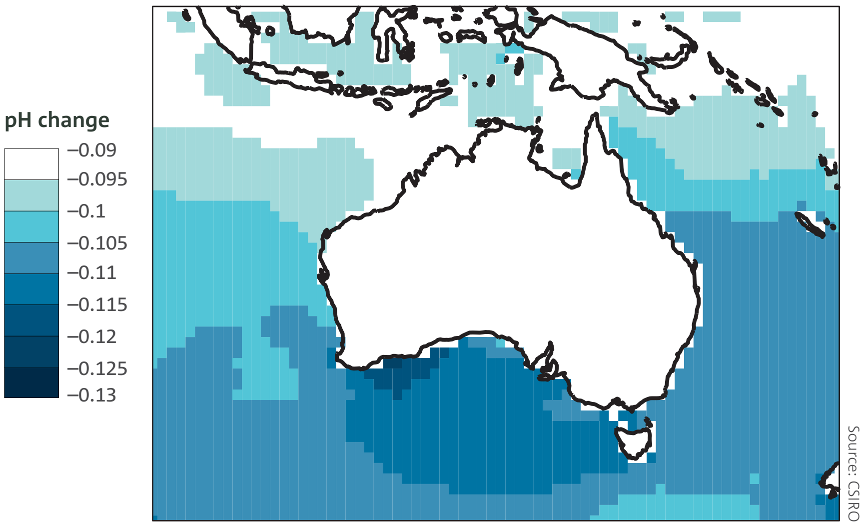


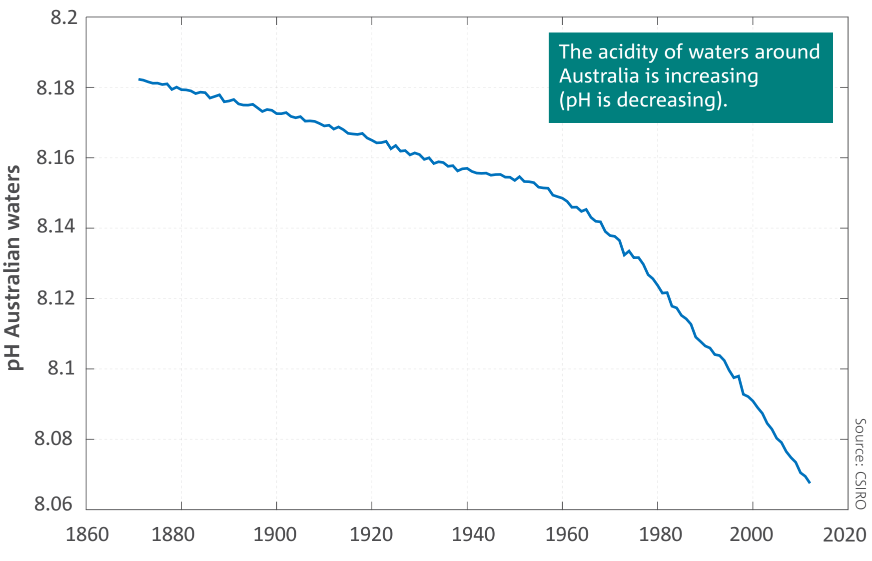
The rate of sea level rise around Australia by satellite observations from 1993 to 2017. Source: CSIRO, update from White et al. (2014).

Ocean acidification

- The oceans around Australia are acidifying (the pH is decreasing).
- The changes in ocean acidification have led to detectable impacts in areas such as the Great Barrier Reef.

The uptake of atmospheric CO_2 by the oceans affects the carbonate chemistry and decreases pH, a process known as ocean acidification. Ocean acidification is the consequence of rising atmospheric CO_2 levels and impacts the entire marine ecosystem—from plankton at the base through to the top of the food chain. Impacts include changes in reproduction, organism growth and physiology, species composition and distributions, food web structure, nutrient availability and calcification. The latter is particularly important for species that produce shells, or skeletons of calcium carbonate, such as corals and shellfish. The average pH of surface waters around Australia is estimated to have decreased since the 1880s by about 0.1, corresponding to a more than 30 per cent increase in acidity (the waters have become less alkaline). These changes have led to a reduction in coral calcification and growth rates on the Great Barrier Reef, with implications for recovery from coral bleaching events. The current rate of change is ten times faster than at any time in the past 300 million years. Due to the differences in ocean chemistry by latitude, the oceans to the south of Australia are acidifying faster than those to the north.





The pH of surface waters around Australia, top: change between 1880–1889 and 2003–2012, bottom: the average pH of water surrounding Australia. Calculations are based on present-day data on the carbonate chemistry of surface seawater around Australia from the Integrated Marine Observing System and other programs, and extrapolation of atmospheric carbon dioxide concentration changes since the 1880s. Source: CSIRO, Lenton et al. (2016).

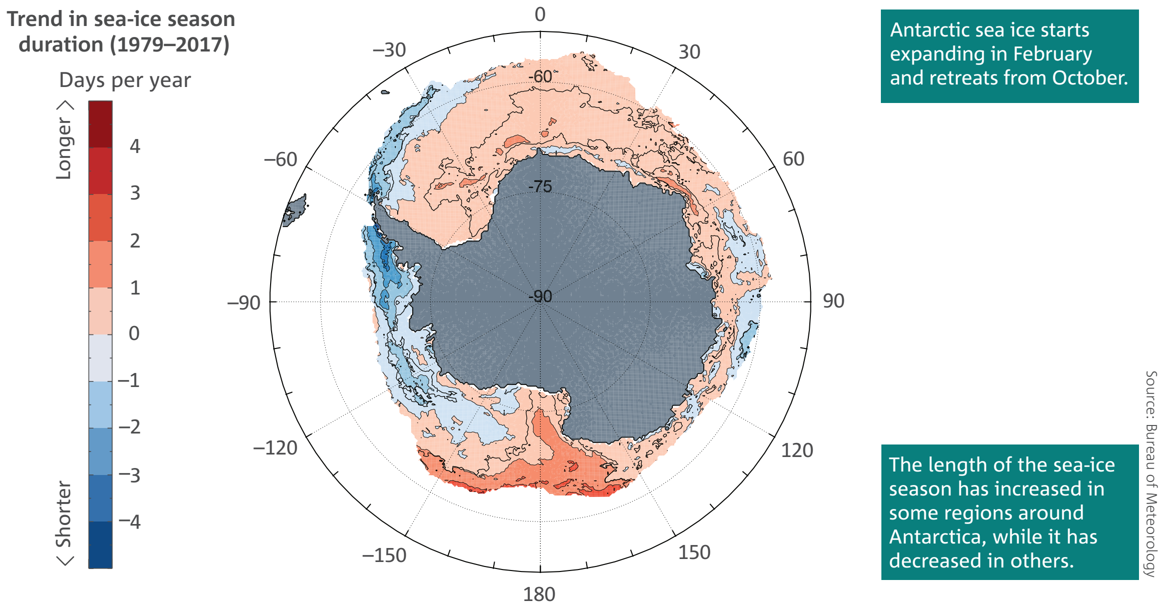
Cryosphere

- The ice sheets and ice shelves of Antarctica and Greenland are losing ice due to a warmer climate; sea-ice extent has reduced in the Arctic.

Changes have been observed in the ice sheets and ice shelves around Antarctica, with glaciers retreating in West Antarctica and melting of the underside of ice shelves to the west of the Antarctic Peninsula. Floating ice shelves help to stabilise the Antarctic ice sheet, by restricting the flow of glacial ice from the continent to the ocean. Warm ocean water penetrating below the ice shelves of the West Antarctic ice sheet is destabilising a number of glaciers, increasing the Antarctic contribution to sea level rise. Latest estimates for the Antarctic ice sheet show a loss of 2720 ± 1390 billion tonnes from 1992 to 2017, corresponding to an increase in global mean sea level of 7.6 ± 3.9 mm (approximately 10 per cent of the total). Melting of the Greenland ice sheet has increased dramatically, from an average of 34 billion tonnes (Gt) per year during 1992–2001 to 215 Gt per year over 2002–2011.

Changes in sea ice have little direct impact on sea level because sea ice is frozen sea water that floats and when it melts it returns the original volume of water to the sea. However, the presence or absence of sea ice can influence the climate and can also be an indicator of wider climate changes.

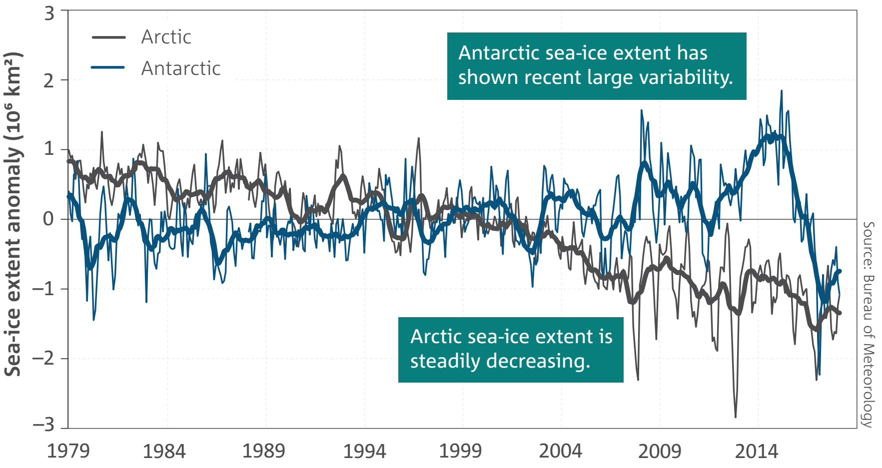
Changes in Antarctic sea ice are complex, with statistically significant increases in extent and seasonal duration in some regions—particularly in the Ross Sea, between 160° E and 150° W—and decreases in others—particularly to the west of the Antarctic Peninsula in the Bellingshausen Sea. The duration of the sea-ice season has changed by up to four months over the 38 years of record in these regions. Sea-ice extent around Antarctica has significant inter-annual variability.



Trends in the length of the sea-ice season each year (in days per year) around Antarctica, 1979–2017. The Antarctic land-mass is shaded grey. Each year sea ice around Antarctica expands (or advances) from a minimum extent in February to a maximum extent in September. Duration is a measure of the number of days that a particular location contains sea ice.

Between 1979 and 2014 the net sea-ice extent showed a positive trend, with substantial regional variations, however since then sea-ice coverage has been predominantly below average. Over the long term, sea-ice coverage responds to large-scale atmospheric and oceanic changes. The overall increase in sea-ice extent since 1979 has mostly been attributed to changes in westerly wind strength. The largest recorded wintertime extent of approximately 20.2 million km^2 was recorded on 20 September 2014, closely followed by the lowest recorded summertime extent of approximately 2.1 million km^2 on 1 March 2017. These trends and the large variability are due to many factors including changes in winds over the Southern Ocean and near the Antarctic continent, and changes in ocean surface temperature and salinity. More observations are needed to determine if the recent decrease in sea-ice extent is the start of a long-term trend or a short-term change.

The sea-ice extent in the Arctic Ocean has decreased 3.5–4.1 per cent per decade since satellite records began in 1979. The four lowest wintertime maximum Arctic sea-ice extents in the satellite record have all occurred in the past four years. The record low minimum Arctic sea-ice extent occurred in September 2012.



Antarctic and Arctic sea-ice extent (shown as the net anomaly from the 1981–2010 average) for the period January 1979 to May 2018 (10^6 km^2). Thin lines are monthly averages and indicate the variability at shorter time-scales, and thick lines are eleven-month running averages.

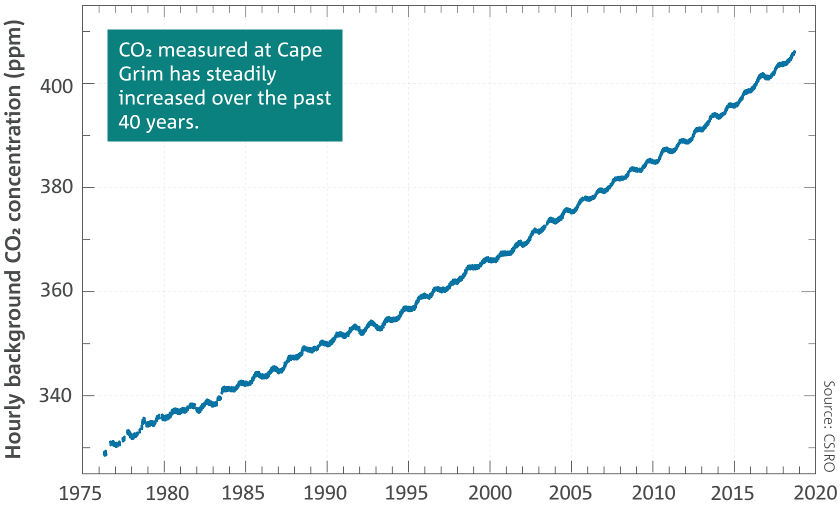
Why are Australia and the Earth warming?

Energy comes from the Sun. To maintain stable temperatures at the Earth's surface this incoming energy must be balanced in the longer-term by an equal amount of heat radiated back to space. Greenhouse gases in the atmosphere, such as carbon dioxide and methane, make it harder for the Earth to radiate this heat, so increase the temperature of the Earth's surface, ocean and atmosphere. This is called the greenhouse effect. Without any greenhouse gases, the Earth's surface would be much colder, with an average temperature of about –18 °C. For centuries prior to industrialisation the incoming sunlight and outgoing heat were balanced, and global average temperatures were relatively steady, at a little under 15 °C. Now, mostly because of the burning of fossil fuels and changes in land use, the concentrations of greenhouse gases in the atmosphere are rising and causing surface temperatures to increase, leading to an 'enhanced' greenhouse effect. There is now an energy imbalance at the Earth's surface of around 0.7–0.8 Wm^{-2} (averaged globally). The atmosphere and oceans will continue to warm until enough extra heat can escape to space to allow the Earth to return to balance. Because increased levels of carbon dioxide persist in the atmosphere for hundreds of years, further warming and sea level rise is inevitable.

Greenhouse gases

- Global average concentrations of all the major long-lived greenhouse gases continue to rise in the atmosphere, with carbon dioxide concentrations rising above 400 ppm since 2016 and the CO_2 equivalent of all gases reaching 500 ppm in 2017.
- Emissions from burning fossil fuels continue to increase and are the dominant contributor to the observed growth in atmospheric CO_2.

The global annual mean CO_2 level in 2017 was 405 ppm—a 46 per cent increase from the concentration of 278 ppm around the year 1750, and likely the highest level in at least the past two million years. Cape Grim, located at the northwest tip of Tasmania, is one of three key global greenhouse gas monitoring stations in the World Meteorological Organization's Global Atmosphere Watch program, and has been running continuously for 42 years. Atmospheric concentration of CO_2 measured at the Cape Grim Baseline Air Pollution Station shows a steady upward trend, passing 400 ppm in May 2016 and remaining above this level since. The annual average CO_2 concentration at Cape Grim in 2017 was 402 ppm.

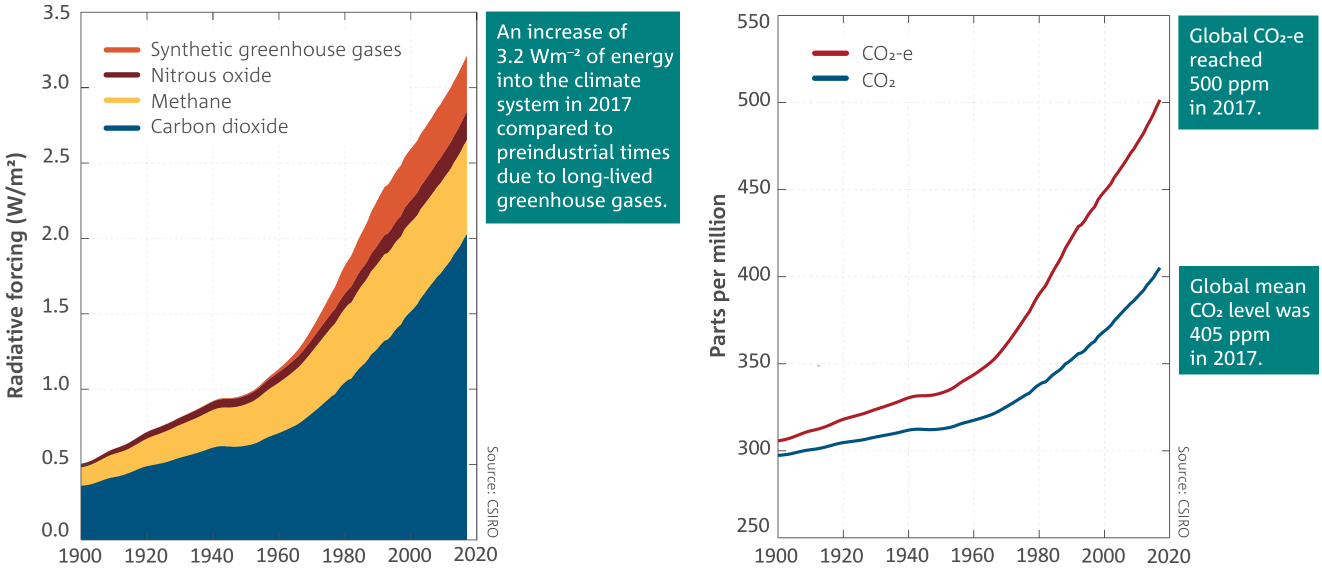


Background hourly clean-air CO_2 as measured at the Cape Grim Baseline Air Pollution Station through to September 2018. The blue hourly data represent thousands of individual measurements. To obtain clean air measurements, the data are filtered to only include times when weather systems come across the Southern Ocean, and thus the air is not influenced by local sources of pollution.

Globally averaged atmospheric concentrations of all major long-lived greenhouse gases, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and a group of synthetic greenhouse gases, continue to rise. The amounts of CO_2, CH_4 and N_2O in the atmosphere show significant seasonal and year-to-year variabilities, but all show ongoing upward trends.

The impact of all the long-lived greenhouse gases in the atmosphere combined can be expressed as an enhancement of the net radiation, or 'radiative forcing', in watts per metre squared. CO_2 is the largest contributor to this enhancement, but other gases make a significant contribution.

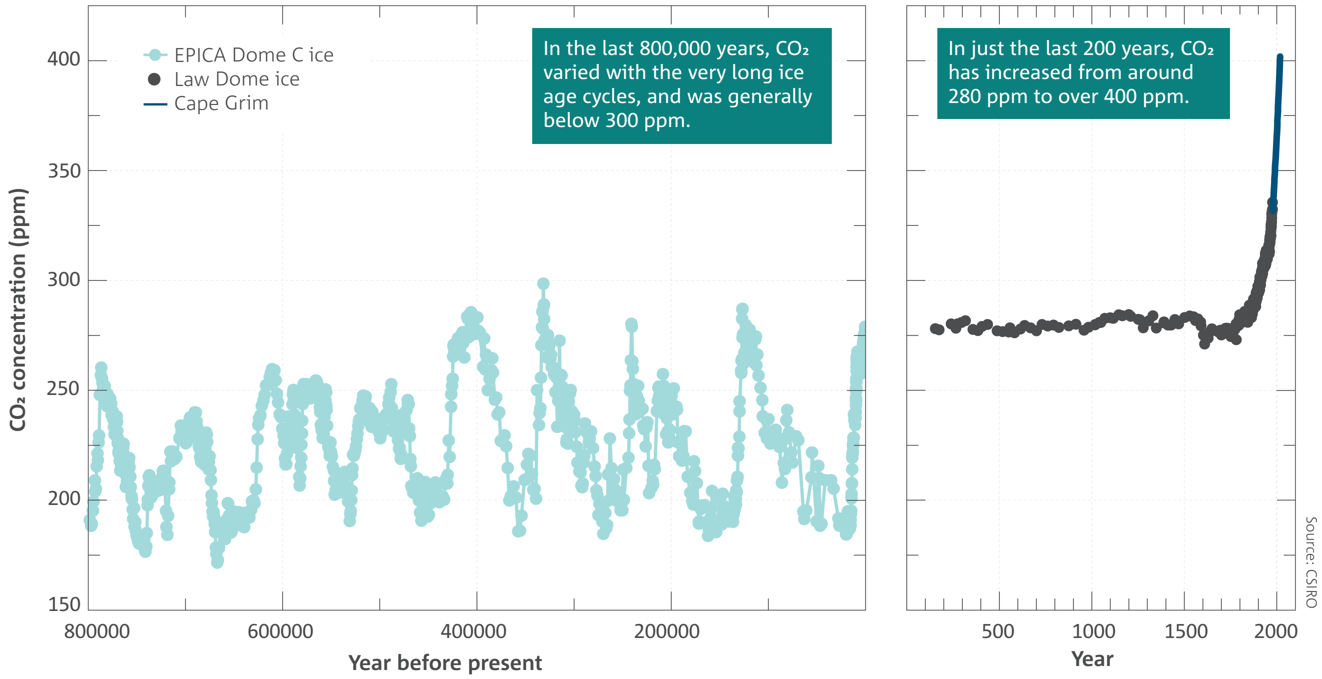
The impact of all greenhouse gases can be converted to an 'equivalent CO_2 (CO_2-e)' atmospheric concentration. The global annual average CO_2-e reached 501.5 ppm in 2017, and the CO_2-e value at Cape Grim reached the 500 ppm milestone in mid-2018.



Left: Radiative forcing relative to 1750 due to the long-lived greenhouse gases carbon dioxide, methane, nitrous oxide and the synthetic greenhouse gases, expressed as watts per metre squared. Right: Global mean CO_2 concentration and global mean greenhouse gas concentrations expressed as equivalent CO_2 (ppm: parts per million). Data in both panels are from *in situ* monitoring by CSIRO and the Bureau of Meteorology (commencing Cape Grim, Tasmania, 1976) and the Advanced Global Atmospheric Gases Experiment (global, including Cape Grim, commencing 1978) and from measurements of flask air samples (global, including Cape Grim, commencing 1992), the Cape Grim Air Archive (1978–2017) at the CSIRO GASLAB (Aspendale, Melbourne) laboratory, and air from Antarctic firn (compact snow) and ice cores measured at CSIRO GASLAB and ICELAB (Aspendale, Melbourne). Equivalent CO_2 is calculated from the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and the suite of synthetic greenhouse gases.

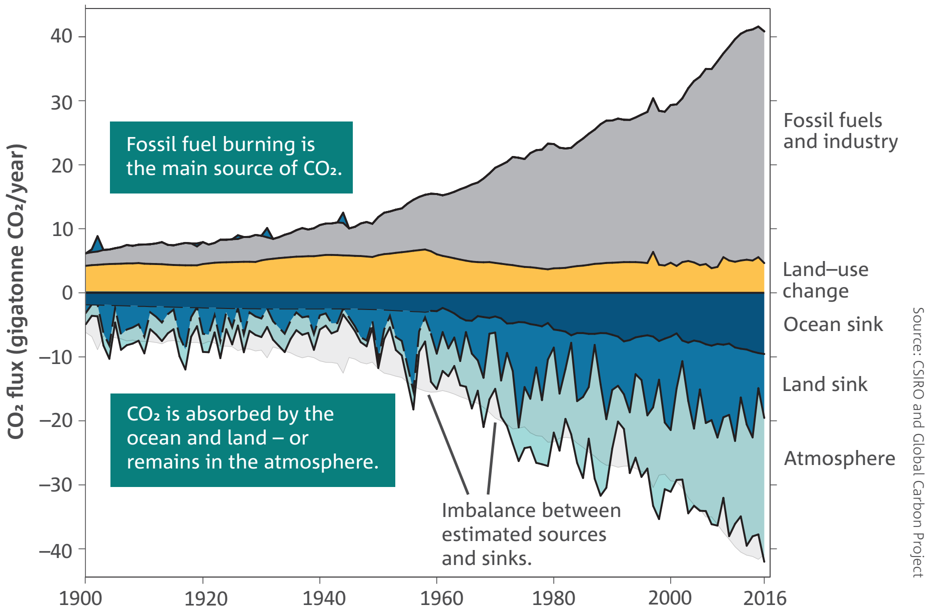
Measurements of air extracted from Antarctic ice extend the record of measured atmospheric CO_2 concentrations to 800,000 years ago. Over the past 2000 years, concentrations were around 280 ppm with only small changes until the start of the industrial era, before rapidly increasing. Over the previous 800,000 years, CO_2 concentrations varied between regular warm periods and colder glacial periods but were always lower than those of the past century. The last time atmospheric CO_2 concentrations were the same or higher than present day was the Pliocene epoch, more than 2.3 million years ago, as determined from isotopes and organic molecule tracers in ocean sediments.

Analysis of the ratio of carbon types, or isotopes, in measured CO_2 confirms that the observed increase in atmospheric CO_2 is the result of CO_2 emissions from human activities such as the combustion of fossil fuels and industrial processes, and changes in land use and land cover.

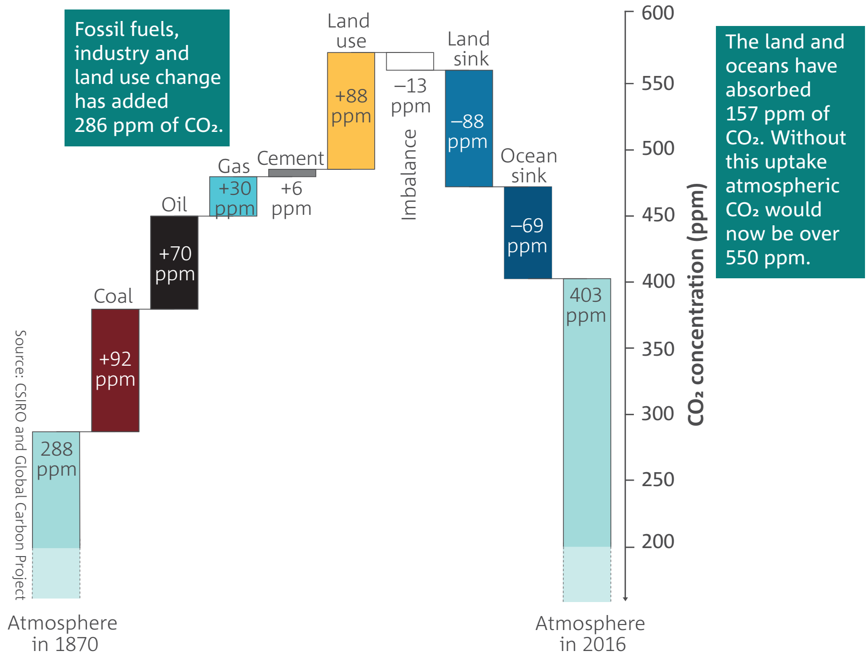


Atmospheric CO_2 concentrations from 800,000 years ago to around year 0, and for the last 2017 years, from measurements of air in Antarctic ice cores and at Cape Grim.

An analysis of the carbon sources and sinks shows that of the 600 ± 65 GtC (1 Gt = 1 billion tonnes = 10^{15} grams, 1 GtC = 3.664 $GtCO_2$) of historical cumulative emissions from human activities during the industrial era, 420 ± 20 GtC were from the combustion of fossil fuels and 180 GtC from land-use change. Emissions from fossil fuels continue to increase, despite relatively little change during 2014–2016. Emissions from land-use change are complex to measure but are estimated to have been stable over the past decade. On the uptake side, about 25 per cent of the CO_2 emissions from human activities have been taken up by the ocean through diffusion, and over 30 per cent by the vegetation on land, and the remaining emissions have remained in the atmosphere and led to the observed increase in the concentration of atmospheric CO_2.



The CO_2 fluxes in the global carbon budget over the period 1900–2016.



The cumulative contributions to the global carbon budget from 1870 to 2016. Visualising the difference between the year 1870 and 2016, the cumulative drivers of increase (sources) on one side, and the drivers of decrease (sinks) on the other side explains the increase in atmospheric concentration of CO_2. The small remaining carbon imbalance represents the gap in the current understanding and estimates of sources and sinks.

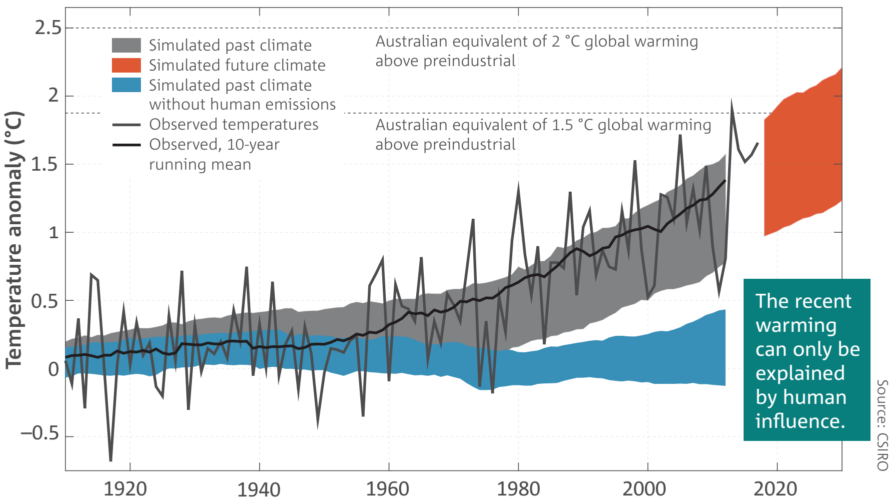
Future climate

Australia's national climate projections at www.climatechangeinaustralia.gov.au indicate that over coming decades Australia will experience:

- Further increase in temperatures, with more extremely hot days and fewer extremely cool days.
- Ongoing sea level rise.
- Further warming and acidification of the oceans around Australia.
- More frequent, extensive, intense and longer-lasting marine heatwaves, suggesting in turn more frequent and severe bleaching events on the Great Barrier Reef, and potentially the loss of many types of coral throughout the tropical reef systems of Australia and globally.
- A decrease in cool-season rainfall across many regions of southern Australia, with more time spent in drought.
- More intense heavy rainfall throughout Australia, particularly for short-duration extreme rainfall events.
- An increase in the number of high fire weather danger days and a longer fire season for southern and eastern Australia.
- Fewer tropical cyclones, but a greater proportion of high-intensity storms, with ongoing large variations from year to year.

Climate change will continue in the decades ahead, superimposed on natural variability. Changes in the climate, particularly in weather and climate extremes, can have a very significant impact on our environment and wellbeing, including on ecosystems, agriculture and the built environment.

Using our scientific understanding of the climate system, and advanced computer simulations, we can analyse the causes of past climate changes and explore projected future climate under differing scenarios of human emissions of greenhouse gases and aerosols. The amount of climate change expected in the next decade or so is similar under all plausible global emissions pathways. However, by the mid-21st Century, higher ongoing emissions of greenhouse gases will lead to greater warming and associated impacts, and reducing emissions will lead to less warming and fewer associated impacts.

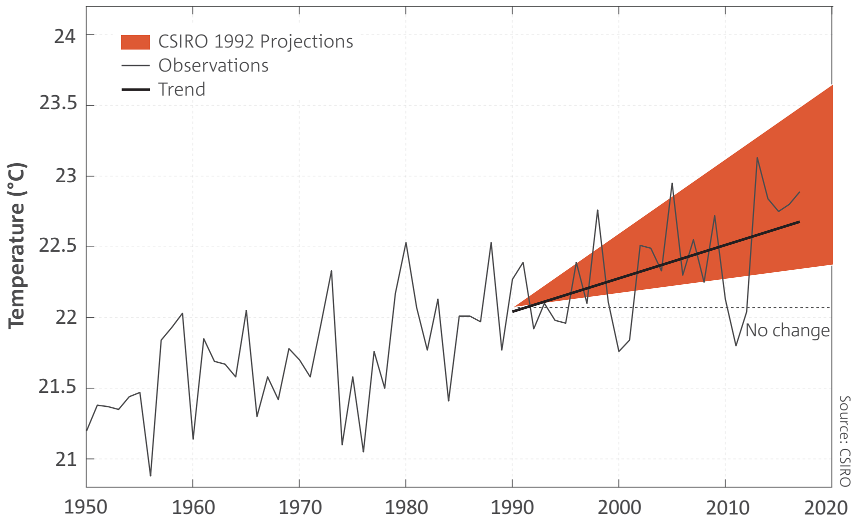


Australia's average annual temperature relative to the 1861–1900 period. The grey line represents Australian temperature observations since 1910, with the black line the ten-year running mean. The shaded bands are the 10–90% range of the 20-year running mean temperatures simulated from the latest generation of Global Climate Models. The grey band shows simulations that include observed conditions of greenhouse gases, aerosols, solar input and volcanoes; the blue band shows simulations of observed conditions but not including human emissions of greenhouse gases or aerosols; the red band shows simulations projecting forward into the future (all emissions scenarios are included). Warming over Australia is expected to be slightly higher than the global average. The dotted lines represent the Australian equivalent of the global warming thresholds of 1.5 °C and 2 °C above preindustrial levels, which are used to inform possible risks and responses for coming decades.

Evaluation of previous temperature projections for Australia

It has now been almost 30 years since the first sets of climate model projections were published, providing the opportunity to compare those projections to observations of the actual climate. CSIRO (1992) produced projections of Australian temperature from 1990 to 2030 for Australia divided into three regions. Drawing the projections together as an Australian average, the linear trend in observed temperature has been tracking within this published range, and above 'no change'. The fact that observations have been tracking within the envelope of projections builds confidence that climate models represent the key processes responsible for the warming trend and therefore these projections were a useful resource for future planning when they were released.

It should be noted that factors such as unforeseeable changes to the atmospheric composition and variability from influences such as specific El Niño and La Niña events mean that we can never make a forecast of the exact time series of Australian temperature, and that the projections will differ from observations over short to medium periods.



Further information

The Bureau of Meteorology and CSIRO monitor, archive, analyse, model, interpret and communicate Australia's observed and future weather and climate.

Collaboratively we contribute to research that underpins the health, security and prosperity of Australia in areas such as weather and ocean prediction, hazard prediction and warnings, climate variability and climate change, water supply and management, and adaptation to climate impacts.

Further information about the content of this report, and a list of references is online.

Bureau of Meteorology
www.bom.gov.au/state-of-the-climate
e helpdesk.climate@bom.gov.au

CSIRO
www.csiro.au/state-of-the-climate
e csiroenquiries@csiro.au
t 1300 363 400

Additional information about climate change and projections for Australia can be found at: www.climatechangeinaustralia.gov.au

ISBN: 978-1-925315-97-4