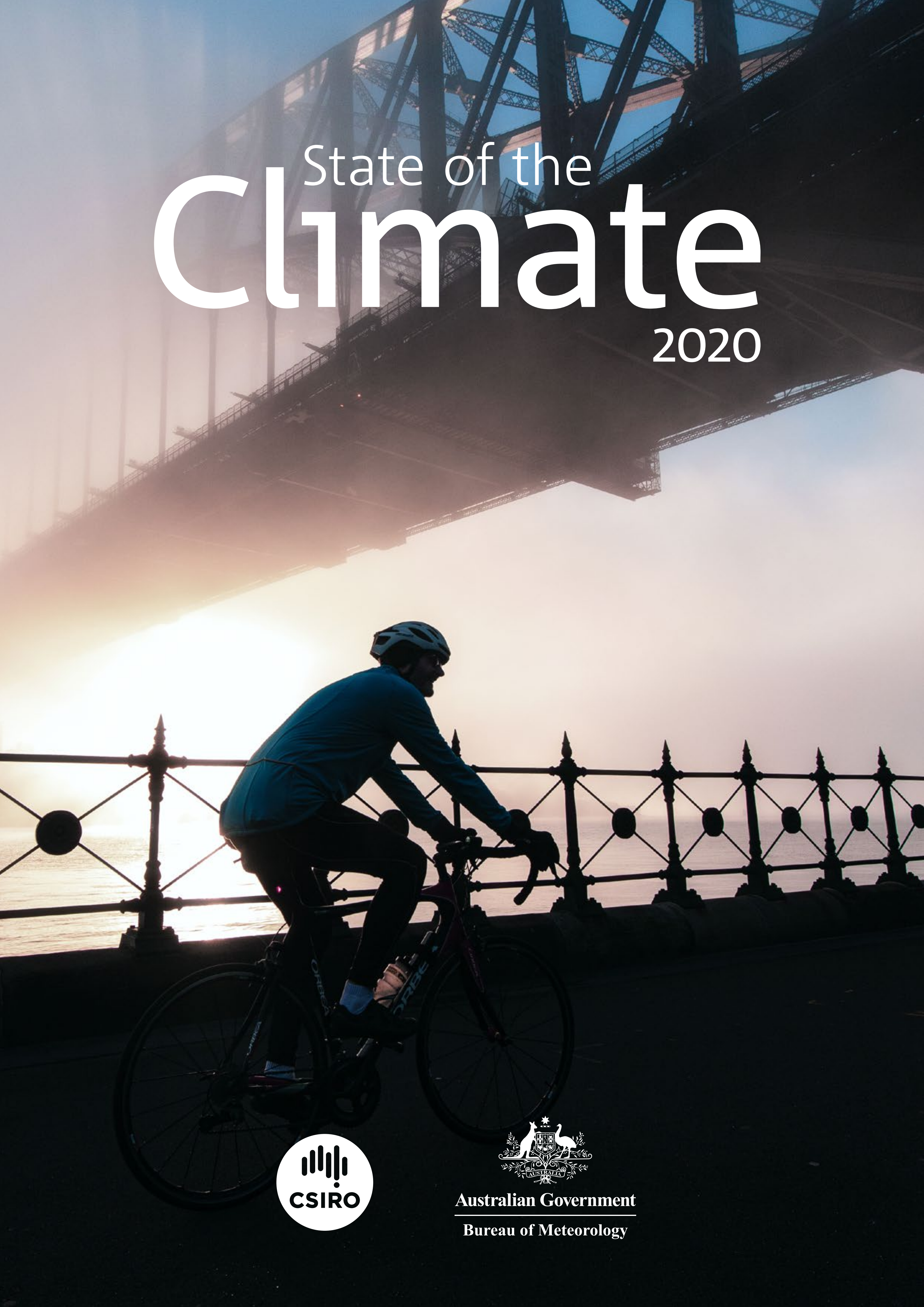


State of the Climate 2020

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 sixth biennial State of the Climate report draws on the latest climate research, encompassing observations, analyses and projections to describe year-to-year variability and longer-term changes in Australia's climate. The 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 informs a range of economic, environmental and social decision-making by governments, industries and communities.

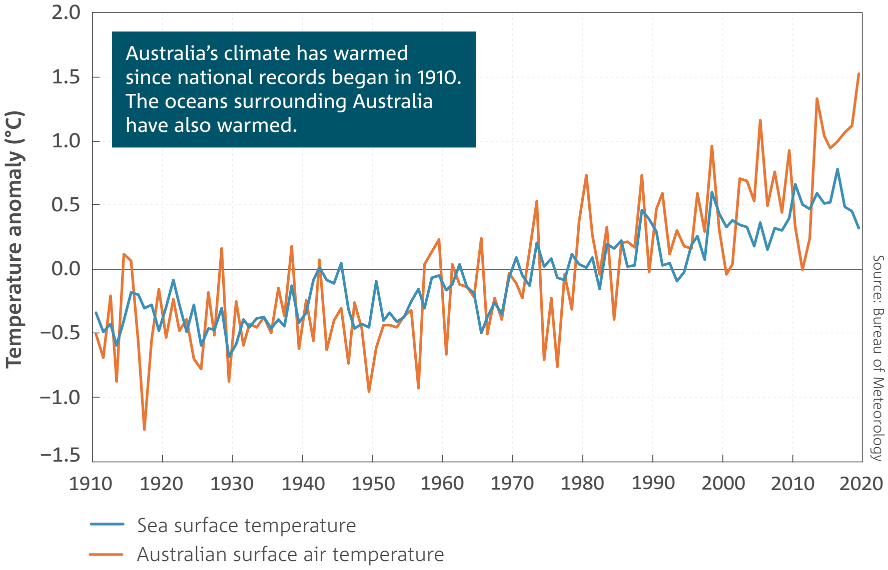
Observations, reconstructions and climate modelling paint a consistent picture of ongoing, long-term climate change interacting with underlying natural variability. Associated changes in weather and climate extremes—such as extreme heat, heavy rainfall and coastal inundation, fire weather and drought—have a large impact on the health and wellbeing of our communities and ecosystems. They affect the lives and livelihoods of all Australians.

Australia needs to plan for and adapt to the changing nature of climate risk now and in the decades ahead. Reducing global greenhouse gas emissions will lead to less warming and fewer impacts in the future.

Key points

Australia

- Australia's climate has warmed on average by 1.44 ± 0.24 °C since national records began in 1910, leading to an increase in the frequency of extreme heat events.
- There has been a decline of around 16 per cent in April to October rainfall in the southwest of Australia since 1970. Across the same region May–July rainfall has seen the largest decrease, by around 20 per cent since 1970.
- In the southeast of Australia there has been a decline of around 12 per cent in April to October rainfall since the late 1990s.
- There has been a decrease in streamflow at the majority of streamflow gauges across southern Australia since 1975.
- Rainfall and streamflow have increased across parts of northern Australia since the 1970s.
- There has been an increase in extreme fire weather, and in the length of the fire season, across large parts of the country since the 1950s, especially in southern Australia.

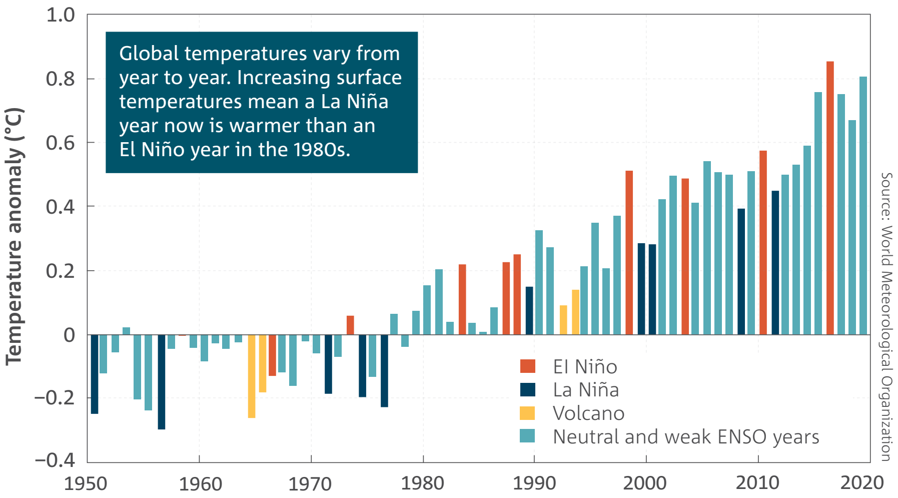


Anomalies in annual mean sea surface temperature, and temperature over land, in the Australian region. Anomalies are the departures from the 1961–1990 standard averaging period. Sea surface temperature values (data source: ERSST v5, www.esrl.noaa.gov/psd/) are provided for a region around Australia (4–46 °S and 94–174 °E).

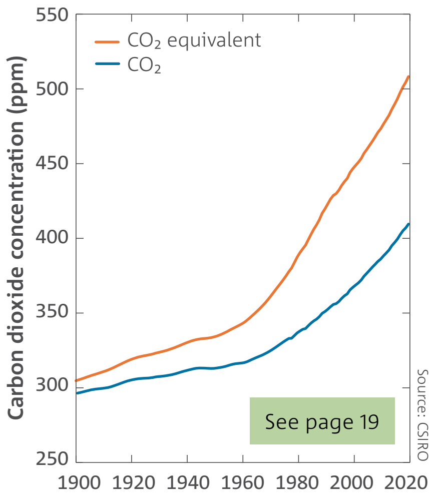
- There has been a decrease in the number of tropical cyclones observed in the Australian region since 1982.
- Oceans around Australia are acidifying and have warmed by around 1 °C since 1910, contributing to longer and more frequent marine heatwaves.
- Sea levels are rising around Australia, including more frequent extremes, that are increasing the risk of inundation and damage to coastal infrastructure and communities.

Global

- Concentrations of all the major long-lived greenhouse gases in the atmosphere continue to increase, with global annual mean carbon dioxide (CO_2) concentrations reaching 410 ppm in 2019 and the CO_2 equivalent (CO_2-e) of all greenhouse gases reaching 508 ppm. These are the highest levels seen on Earth in at least two million years.
- Despite a decline in global fossil fuel emissions of CO_2 in 2020 associated with the COVID-19 pandemic, this will have negligible impact in terms of climate change. Atmospheric CO_2 continues to rise, and fossil fuel emissions will remain the principal driver of this growth.
- Globally averaged air temperature at the Earth's surface has warmed by over 1 °C since reliable records began in 1850. Each decade since 1980 has been warmer than the last, with 2010–19 being around 0.2 °C warmer than 2000–09.
- The world's oceans, especially in the southern hemisphere, are taking up around 90 per cent of the extra energy resulting from enhanced greenhouse gas concentrations.
- More than half of all CO_2 emissions from human activities are being absorbed by land and ocean sinks, thus slowing the rate of increase in atmospheric CO_2.
- Global mean sea levels have risen by around 25 cm since 1880 and continue to rise at an accelerating rate.



Global surface temperature anomalies of the Earth (land and ocean) for 1950 to 2019. Anomalies are with respect to the 1961–1990 standard averaging period. Major tropical volcanic eruptions are associated with cooler global temperatures. Strong El Niño–Southern Oscillation (ENSO) years see a response in annual global temperatures, such that the year following the start year of an ENSO event is typically warmer than usual with an El Niño, and cooler with a La Niña. This is seen in 2016—the warmest year in this dataset—which followed the start year of the 2015–16 El Niño. Neutral years are those with no moderate or strong El Niño or La Niña events. Data from World Meteorological Organization.



Global mean CO_2 concentration and global mean of all greenhouse gas concentrations expressed as CO_2 equivalent.

Future

In the coming decades Australia will experience ongoing changes to its climate. Australia is projected to see:

- Continued increases in air temperatures, more heat extremes and fewer cold extremes.
- Continued decrease in cool season rainfall across many regions of southern and eastern Australia, likely leading to more time in drought, yet more intense, short duration heavy rainfall events.
- A consequential increase in the number of dangerous fire weather days and a longer fire season for southern and eastern Australia.
- Further sea level rise and continued warming and acidification of the oceans around Australia.
- Increased and longer-lasting marine heatwaves that will affect marine environments, such as kelp forests, and raise the likelihood of more frequent and severe bleaching events in coral reefs around Australia, including the Great Barrier and Ningaloo reefs.
- Fewer tropical cyclones, but a greater proportion projected to be of high intensity, with large variations from year to year.

Australia's changing climate

Temperature

- **Australia's climate has warmed on average by 1.44 ± 0.24 °C since national records began in 1910, leading to an increase in the frequency of extreme heat events.**

Australia's weather and climate are changing in response to a warming global climate. Australia has warmed on average by 1.44 ± 0.24 °C since national records began in 1910, with most warming occurring since 1950 and every decade since then being warmer than the ones before. Australia's warmest year on record was 2019, and the seven years from 2013 to 2019 all rank in the nine warmest years. This long-term warming trend means that most years are now warmer than almost any observed during the 20th century. When relatively cooler years do occur, it is because natural drivers that typically cool Australia's climate, such as La Niña, act to partially offset the background warming trend.

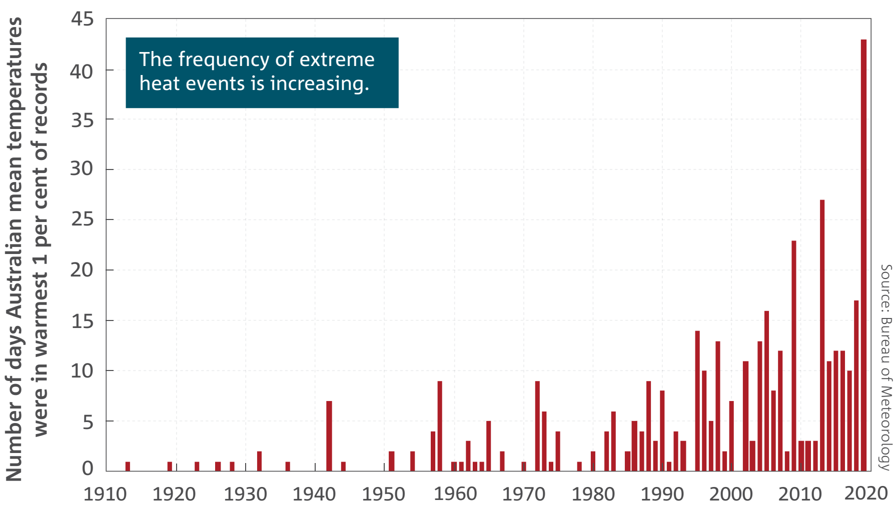
Warming is observed across Australia in all months with both day and night-time temperatures increasing. This shift is accompanied by more extreme nationally averaged daily heat events across all months. For example, 2019 experienced 43 extremely warm days, more than triple the number in any of the years prior to 2000. This increasing trend is observed at locations across all of Australia.

In summer we now see a greater frequency of very hot days compared to earlier decades. In terms of national daily average maximum temperatures, there were 33 days that exceeded 39 °C in 2019, more than the number observed from 1960 to 2018 combined, which totalled 24 days.

Australia's climate has warmed by over 1 °C since 1960, which has caused an increase in the frequency of months that are much warmer than usual. Very high monthly maximum temperatures that occurred nearly 2 per cent of the time in 1960–1989 and over 4 per cent of the time in 1990–2004, now occur over 12 per cent of the time (2005–2019). This is more than a sixfold increase over the sixty-year period. Very warm monthly night-time temperatures that occurred nearly 2 per cent of the time in 1960–1989 and over 5 per cent of the time in 1990–2004, now occur around 11 per cent of the time (2005–2019).

This shift in extremes has many impacts on human health, ecosystems and infrastructure and informs climate impact and risk assessments.

The frequency of extremely cold days and nights has declined across Australia. An exception to this is for extremely cold nights in those parts of southeast and southwest Australia which have seen significant cool season drying, and hence more clear winter nights. The frequency of frost in these parts is relatively unchanged since the 1980s.



Number of days each year where the Australian area-averaged daily mean temperature for each month is extreme. Extreme daily mean temperatures are the warmest 1 per cent of days for each month, calculated for the period from 1910 to 2019.

Fire weather

- There has been an increase in extreme fire weather, and in the length of the fire season, across large parts of Australia since the 1950s, especially in southern Australia.

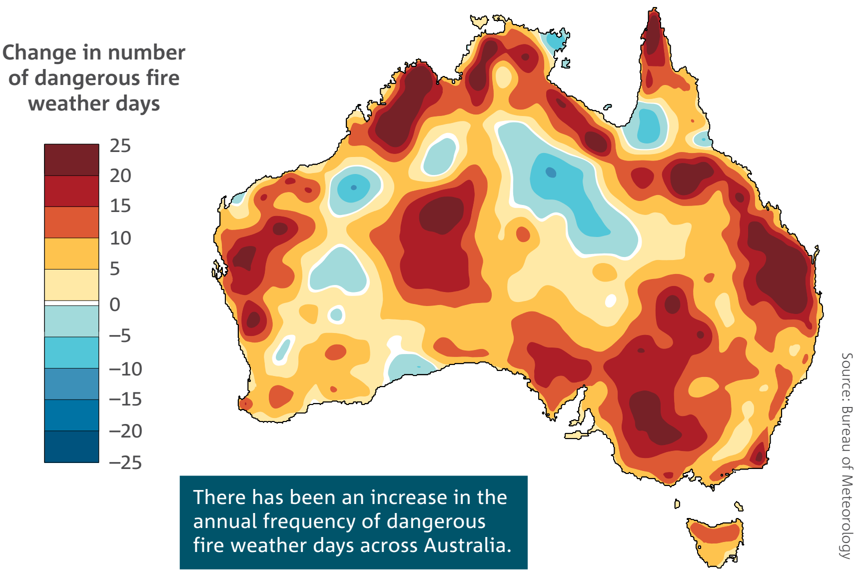
Fire weather is largely monitored in Australia using the Forest Fire Danger Index (FFDI). The FFDI indicates the fire danger on a given day based on observations of temperature, rainfall, humidity and wind speed. The frequency of the most dangerous 10 per cent of fire weather days has increased significantly in recent decades across many regions of Australia, especially in the south and east. These increases are particularly evident during spring and summer and are associated with an earlier start to the southern fire weather season. Climate change is contributing to these changes in fire weather including by affecting temperature, relative humidity and associated changes to the fuel moisture content. Considerable year-to-year variability in fire weather also occurs. La Niña years, for example 2010–11 and 1999–2000, are associated with wet and cool climate anomalies and a lower number of days with high FFDI values.

Dry lightning that occurs without significant rainfall is the primary source of natural ignition for bushfires. Understanding changes to bushfire ignition in Australia is a current area of active research, including the frequency of dry lightning.

There is a significant trend in some regions of southern Australia towards more days with weather conditions conducive to extreme bushfires that can generate thunderstorms within their smoke plumes. These fire-generated thunderstorms can lead to extremely dangerous fire conditions, as observed during the 2019–20 summer, and for the Canberra (2003) and Victorian Black Saturday (2009) fires. In some cases, the lightning strikes produced from the smoke plumes generate new fires.

Climate change influences long-term trends in some of the key risk factors for bushfires in Australia. While the influence of climate change on long-term trends is clear, the attribution of a single fire event to climate change is difficult and is the subject of current research.

Climate change affects the dryness and amount of fuel, through changes in rainfall and air temperature and atmospheric moisture content that exacerbate landscape drying. Furthermore, increased CO_2 can also alter the rate and amount of plant growth, which may also affect the fuel load. Increased frequency and intensity of extreme heat as a result of climate change can also worsen extreme fire weather risk.



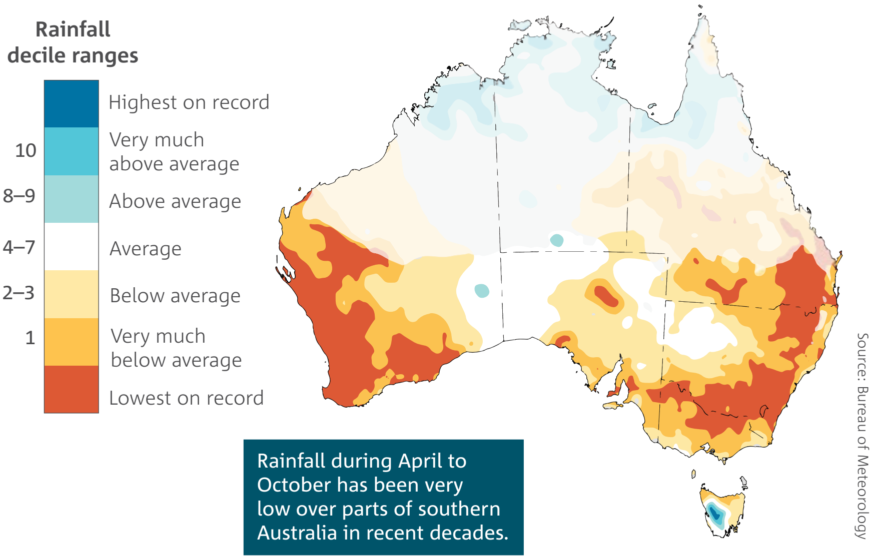
There has been an increase in the number of days with dangerous weather conditions for bushfires. This is based on the change in the annual (July to June) number of days between the two periods: July 1950 – June 1985 and July 1985 – June 2020 that the Forest Fire Danger Index exceeds its 90th percentile, which is an indicator of dangerous fire weather conditions for a given location.

Rainfall

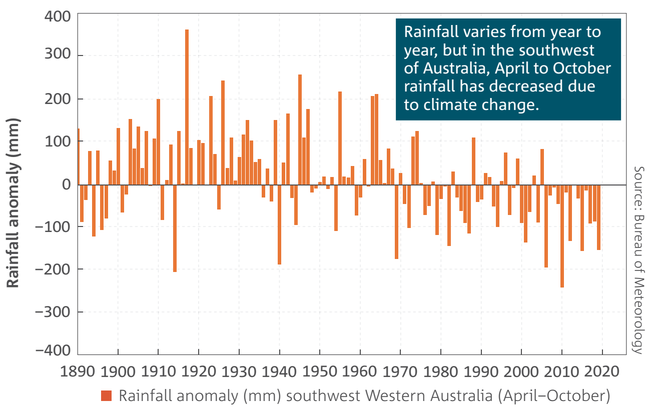
- There has been a decline of around 16 per cent in April to October rainfall in the southwest of Australia since 1970. Across the same region May to July rainfall has seen the largest decrease, by around 20 per cent since 1970.
- In the southeast of Australia there has been a decline of around 12 per cent in April to October rainfall since the late 1990s.
- Rainfall has increased across most of northern Australia since the 1970s.

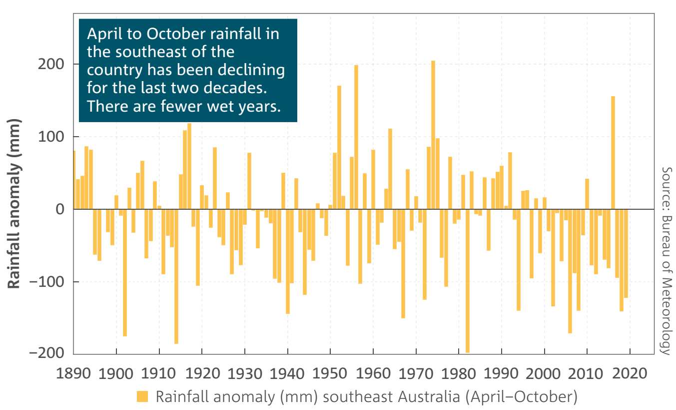
Australian rainfall is highly variable and is strongly influenced by drivers such as El Niño, La Niña, the Indian Ocean Dipole and the Southern Annular Mode. Despite this natural variability, long-term trends are evident in Australia's rainfall record. There has been a shift towards drier conditions across the southwest and southeast, with more frequent years of below average rainfall, especially for the cool season months of April to October. In 17 of the last 20 years, rainfall in southern Australia in these months has been below average. This is due to a combination of natural variability on decadal timescales and changes in large-scale circulation caused by increased greenhouse gas emissions.

Recent years with above-average rainfall in southern Australia were generally associated with drivers of higher than usual rainfall, such as a strong negative Indian Ocean Dipole in 2016, and La Niña in 2010–11. In contrast to southern mainland Australia, cool season rainfall has been above average in western Tasmania during recent decades.



April to October rainfall deciles for the last 20 years (2000–19). 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 are faded.



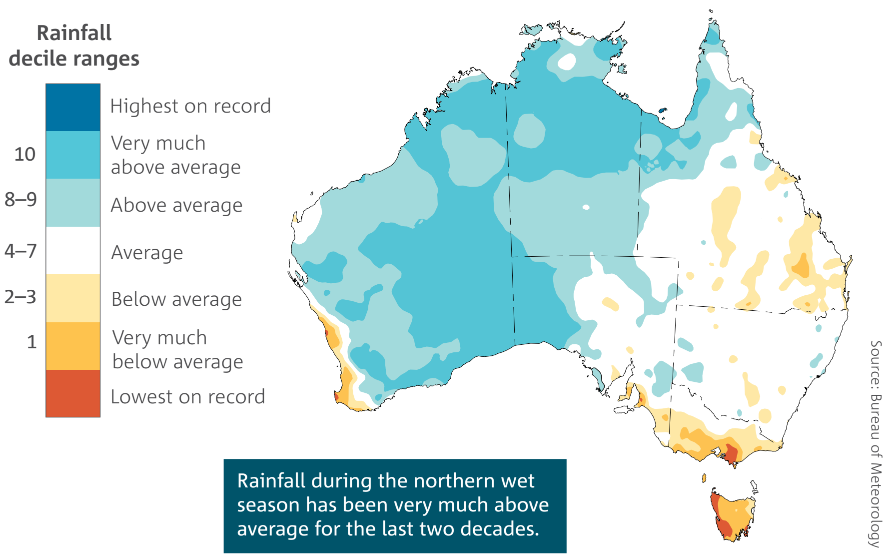


Anomalies of April to October rainfall for southwestern (southwest of the line joining the points 30° S, 115° E and 35° S, 120° E) and southeastern (south of 33° S, east of 135° E inclusive) Australia, with respect to 1961 to 1990 averages.

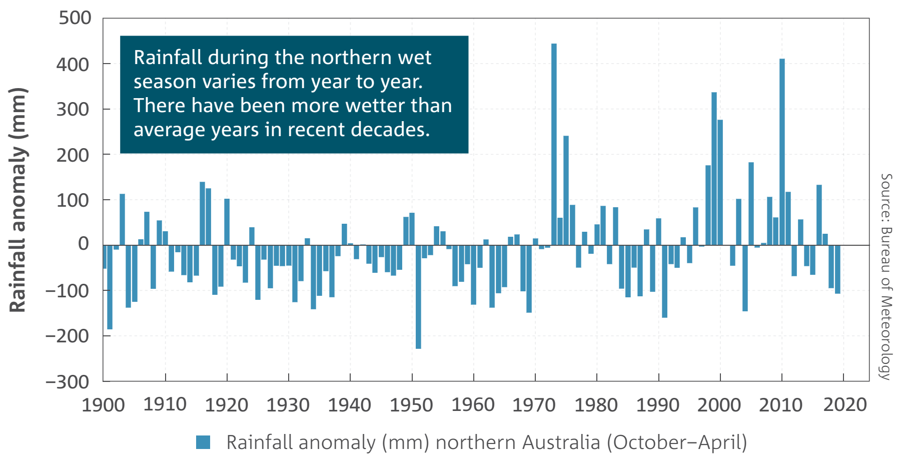
The drying trend in southern Australia has been most evident in the southwest and southeast of the country. Rainfall analyses in these regions can be extended back to around 1890 due to greater data coverage, enabling current droughts to be compared to historical droughts such as the Federation drought (1895 to 1902). The recent drying across these regions is the most sustained large-scale change in observed rainfall since the late 1880s. The trend is particularly strong for the period from May to July over southwest Western Australia, with rainfall since 1970 around 20 per cent less than the average from 1900 to 1969. Since 2000, this decline has increased to around 28 per cent. For the southeast of the continent, April to October rainfall for the period 2000 to 2019 has decreased by around 12 per cent when compared to 1900–1999. This period encompasses most of the Millennium drought, which saw low annual rainfall totals across the region from 1997 to 2009. However, cool season rainfall totals are still around 10 per cent below the 1900–1999 average in the years since the Millennium drought.

The cooler months between April and October are important hydrologically across southern Australia. The declining trend in rainfall during this period is associated with a trend towards higher surface pressure in the region and a shift in large-scale weather patterns—more highs and fewer lows. This increase in surface pressure across southern latitudes is a known response to climate change. There has been a reduction in the number of cold fronts and lows that produce rainfall in both southwest and southeast Australia, which are the most important weather systems for rainfall in these areas during the cool half of the year.

In contrast, northern Australia has been wetter across all seasons, but especially in the northwest during the northern wet season (October to April). However, rainfall variability remains high, with, for example, below average rainfall totals in northern Australia during both the 2018–19 and 2019–20 wet seasons.



Northern wet season (October–April) rainfall deciles for the last 20 years (2000–01 to 2019–20). 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

- Heavy rainfall events are becoming more intense.

Observations show that there has been an increase in the intensity of heavy rainfall events in Australia. The intensity of short-duration (hourly) extreme rainfall events has increased by around 10 per cent or more in some regions and in recent decades, with larger increases typically observed in the north of the country. Short-duration extreme rainfall events are often associated with flash flooding, and so these changes in intensity bring increased risk to communities. This is particularly so in urban environments where the large amount of impervious ground cover (e.g. concrete) leads to increased flooding during heavy downpours.

Heavy rainfall events are typically caused by weather systems such as thunderstorms, cyclones and east coast lows. Daily rainfall totals associated with thunderstorms have increased since 1979, particularly in northern Australia. This is due to an increase in the intensity of rainfall per storm, rather than an increase in the number of storms in general.

At the same time, the number of low-pressure systems that can bring heavy rainfall to heavily populated parts of southern Australia have declined in recent decades. This could have implications for recharging water storages and water resource management.

As the climate warms, heavy rainfall events are expected to continue to become more intense. A warmer atmosphere can hold more water vapour than a cooler atmosphere, and this relationship alone can increase moisture in the atmosphere by 7 per cent per degree of global warming. This can cause an increased likelihood of heavy rainfall events. Increased atmospheric moisture can also provide more energy for some processes that generate extreme rainfall events, which further increases the likelihood of heavy rainfall due to global warming.

Compound extreme events

Climate change influences the frequency, magnitude and impacts of many types of extreme weather and climate events. When extreme weather and climate events occur consecutively within a short timeframe of each other, or when multiple types of extreme events coincide, the impacts can compound in severity. For example, heatwaves can have a larger impact when combined with the stress of long-term drought.

Extreme events are more likely when natural climate variability acts to amplify the background influence of climate change. For example, record-breaking extreme heat and record-breaking fire weather are more likely when the El Niño–Southern Oscillation or the Indian Ocean Dipole favour warmer and drier conditions in Australia, since this reinforces warming and drying trends.

The spring and early summer of 2019 provides a good example of compounding extreme weather and climate conditions and illustrates the effect of background climate trends amplifying natural climate variability. In this period record-breaking low rainfall coincided with extreme heat, and both continued into early 2020. An extreme positive Indian Ocean Dipole and rare Antarctic stratospheric warming in 2019 provided the naturally occurring climate variability that exacerbated long-term climate trends. These combined influences led to severe drought, record-breaking heatwaves and fire weather.

Natural climate variability, which affects Australia's climate from one year to the next, means that not every year will see weather and climate that was as extreme as in 2019. However, the warming trend, primarily caused by climate change, increases the likelihood of extreme events that are beyond our historical experience. Multiple lines of evidence, including from observations and future climate change projections, point to a continuing trend of more frequent compound extreme events. Projecting the occurrence and severity of extreme events is therefore essential for current and future risk assessments, and for climate adaptation strategies and responses.

Streamflow

- **Three quarters of hydrologic reference stations around Australia show a declining trend in streamflow.**

The observed long-term reduction in rainfall across many parts of southern Australia has led to reduced streamflow. Declines in annual median streamflow have been observed in the Murray–Darling Basin, the South West Coast, the South Australian Gulf, the South East Coast (Victoria) and the South East Coast (New South Wales) drainage divisions. In each of these, between half and three quarters of gauges show a declining streamflow trend since 1975.

In the Tanami–Timor Sea Coast drainage division in northern Australia, which includes Darwin and much of the Northern Territory, there is an increasing trend in annual median flows at about 67 per cent of the gauges since 1975. This is consistent with the observed increase in rainfall since the 1970s in the region.

In the Murray–Darling Basin, more than three quarters of the long-term streamflow gauges show a declining trend since records began in 1970. This is more severe in the northern Basin where 94 per cent of the gauges show a declining trend in streamflow. In the northern Basin catchments, where these trends are strongly evident, there are statistically significant declining trends in the headwaters, including the Namoi, Condamine–Culgoa and Gwydir River catchments. In the Murrumbidgee, Lachlan, Goulburn and Loddon River catchments of the southern Basin, more than three quarters of the streamflow gauges show declining trends; these trends are statistically significant in one third of these gauging stations. In the Darling River region, declining trends were observed in all 19 streamflow gauges, of which half show a statistically significant declining trend.

Three quarters of Australia's hydrologic reference stations show a declining trend in streamflow, with a quarter of these showing a statistically significant declining trend. Hydrologic reference stations are an indicator of long-term impacts from climate change on streamflow, as they are gauges in catchments with little disturbance from human activities and with at least a 30-year record.

Tropical cyclones

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

Tropical cyclone activity in Australia's cyclone region varies substantially from year to year. This is partially due to the influence of large-scale climate drivers; the number of cyclones in our region generally declines with El Niño and increases with La Niña.

There has been a downward trend in the number of tropical cyclones observed in the Australian region since 1982. The trend in cyclone intensity is harder to quantify or estimate.

Snowfall

- **A downward trend in maximum snow depth has been observed for Australian alpine regions since the late 1950s, with large year-to-year variability.**

Downward trends in maximum snow depth have been observed for Australian alpine regions since the late 1950s, with the largest declines during spring and at lower altitudes. Downward trends in the temporal and spatial extent of snow cover and the number of snowfall days are also observed.

Snow depth is closely related to temperature, and the observed declines are associated with the observed warming trends. Maximum snow depth remains highly variable and is strongly influenced by rare heavy snowfall days, which have no observed trends in frequency. Several heavy snowfall events contributed to average to high maximum snow depths in the seasons from 2017 to 2019.

Oceans

Sea surface temperature

- Sea surface temperatures have risen around Australia; the ocean surface has warmed by over a degree since 1900.

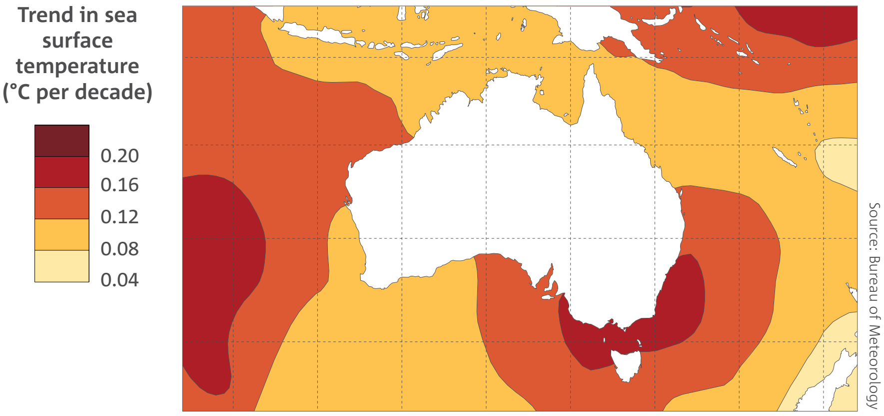
Average sea surface temperature in the Australian region has warmed by more than 1 °C since 1900, with eight of the ten warmest years on record occurring since 2010. The warmest year on record was 2016, associated with one of the strongest negative Indian Ocean Dipole events on record.

The greatest ocean warming in the Australian region since 1970 has occurred around southeastern Australia and Tasmania. The East Australian Current now extends further south, creating an area of more rapid warming in the Tasman Sea where the warming rate is now twice the global average. There has also been warming across large areas of the Indian Ocean region to the southwest of Australia.

Warming of the ocean has contributed to longer and more frequent marine heatwaves. Marine heatwaves are defined as periods when temperatures are in the upper range of historical baseline conditions for five days or more. Heatwaves in the ocean often persist much longer than heatwaves on land, sometimes spanning multiple months or even years.

The increasing frequency of marine heatwaves around Australia in recent years has caused permanent impacts on marine ecosystem health, marine habitats and species. These impacts include depleting kelp forests and sea grasses, a poleward shift in some marine species, and increased occurrence of disease. Recent marine heatwaves are the primary cause of mass coral bleaching and widespread damage to coral reefs around Australia, including the Great Barrier and Ningaloo reefs although other pressures such as tropical cyclones, nutrient runoff and disease also affect the health of some areas of the Great Barrier Reef.

The ocean surface around Australia has warmed, with more rapid warming in oceans to the southeast.



Trends in sea surface temperatures in the Australian region (4–46° S and 94–174° E) from 1950 to 2019.

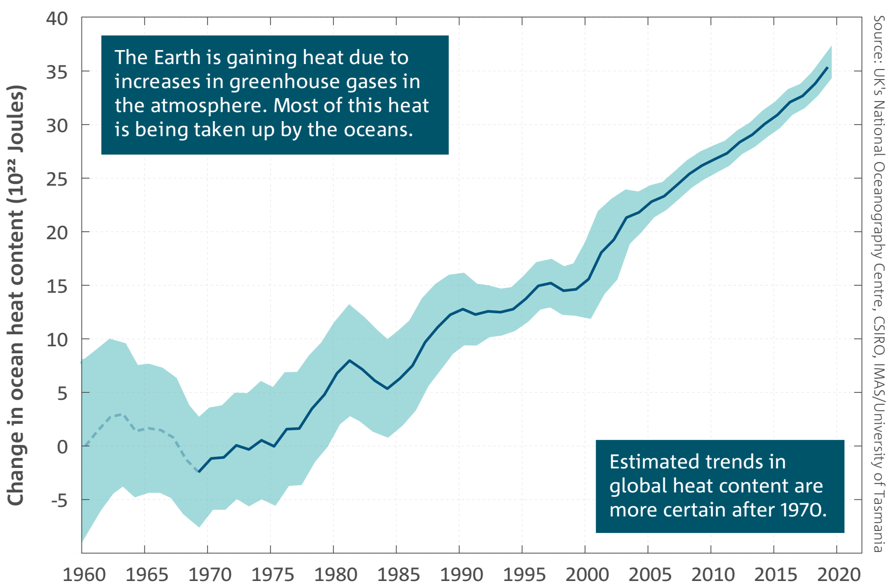
Ocean heat content

- The world's oceans are taking up around 90 per cent of the extra energy stored by the planet as a result of enhanced greenhouse gas concentrations. Measuring changes in ocean heat content is therefore an accurate way to monitor global warming.
- The rate at which the oceans are taking up heat has increased over recent decades.

The world's oceans are a major component of the Earth's climate system and have a profound effect on the climate by redistributing heat and influencing wind patterns.

Sea water stores about four times more heat for every degree of temperature rise than dry air of the same weight. The total weight of water in the ocean is about 280 times greater than the weight of the Earth's atmosphere, so the capacity for the ocean to store heat is vast. For example, if all the extra energy stored in the oceans was released to the atmosphere, the resulting temperature change in the atmosphere would be approximately 1000 times larger than the equivalent temperature change in the ocean.

While the absolute temperature changes over the whole ocean depth are small compared to those at the land and ocean surface, the ocean has taken up approximately 90 per cent of the extra energy from enhanced greenhouse gas concentrations. Oceans have therefore slowed the rate of warming near the Earth's land and ocean surface. Heat absorbed at the surface is redistributed both horizontally and vertically by ocean circulation. As a result, the ocean is warming both near the surface and at depth, with the rate of warming varying between regions and depths.

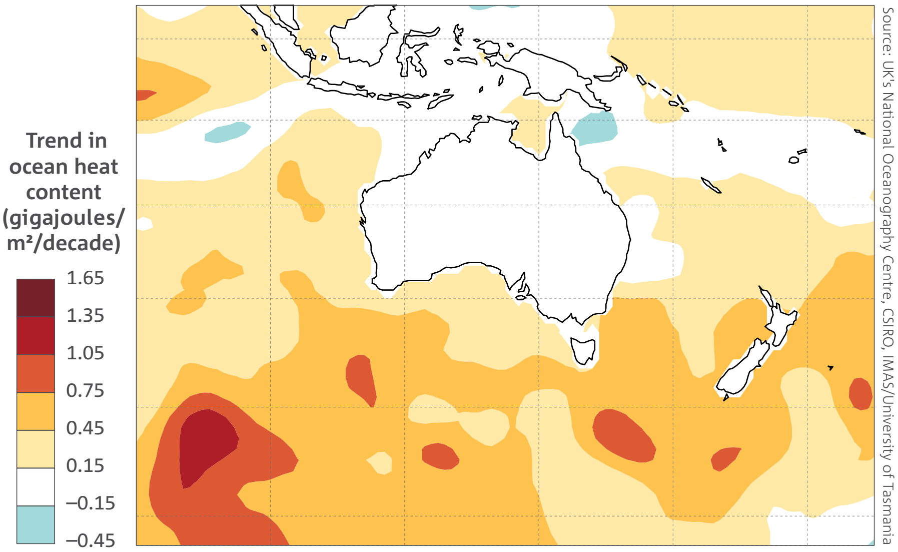


Estimated change in ocean heat content over the full ocean depth, from 1960 to 2019. Shading provides an indication of the confidence range of the estimates. The measurements contributing to the early part of the record, before 1970, are sparse and trends estimated over this period are small compared to the confidence range and hence are considered less reliable.

The rate at which oceans are taking up heat has increased in recent decades. Over its full depth, the global ocean gained 35 x 10^{22} joules of additional heat from 1960 to 2019. Southern hemisphere oceans take up much of the extra heat. This is because the Southern Ocean circulation takes heat from near the surface and transfers it into the deep ocean. A warming ocean affects the global ocean and atmospheric circulation, global and regional sea levels, uptake of anthropogenic CO_2, and causes losses in oxygen and impacts on marine ecosystems.

Long-term temperature trends in the deep ocean, below 2000 metres, show a slow but steady warming. However, there are currently far fewer observations below this depth compared to the upper ocean, so the magnitude of this warming is less certain.

Southern hemisphere oceans have taken up the majority of the extra heat from global warming.



Estimated linear decadal trend in ocean heat content between 1970 and 2019 in the upper 2000 m of the ocean, showing the highest uptake of heat in regions where the circulation draws heat into the deep ocean, such as the Southern Ocean.

Marine heatwaves and coral reefs

Warming oceans, together with an increase in the frequency, intensity and duration of marine heatwaves, pose a significant 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 1970s. Large-scale bleaching is a stress response of corals that occurs primarily in response to elevated ocean temperature. As waters warm, the symbiotic relationship between coral and its zooxanthellae (single-celled organisms that live within the corals) breaks down, eventually resulting in coral bleaching where the zooxanthellae are expelled. Without zooxanthellae, most corals struggle to survive. Recovery is possible, but mortality can occur if the thermal stress is too severe or prolonged.

Bleaching on the Great Barrier Reef has occurred with increased frequency in recent decades. Widespread bleaching occurred in 1998 and 2002, however over the last 10 years three mass coral bleaching events have occurred in 2016, 2017 and 2020. In 2016, bleaching was associated with some of the warmest sea surface temperatures ever recorded which, in turn, led to the largest recorded mass bleaching on the Great Barrier Reef. The impact of the mass bleaching in 2020 appears to be second only to 2016 and was associated with severely bleached coastal reefs along the entire 2300 km length of the Great Barrier Reef.

These three recent bleaching events are associated with marine heatwaves driven by anthropogenic climate change. Rapidly recurring bleaching events do not give the reef ecosystem time to recover from the damage caused by these events.

Climate models project more frequent, extensive, intense and longer-lasting marine heatwaves in the future. Coupled with a background warming of ocean temperatures, this implies more frequent and severe coral bleaching events are likely on the Great Barrier Reef and globally, leading to the potential loss of many types of coral throughout tropical reef systems worldwide. Along with ocean acidification and nutrient runoff, the increased severity and frequency of marine heatwaves are likely to reduce reef resilience and hinder coral recovery from future bleaching events.

Worsening impacts on coral reefs from marine heatwaves are expected in the future with continued warming but the intensification of marine heatwaves is much larger with higher global greenhouse gas emissions.

Sea level

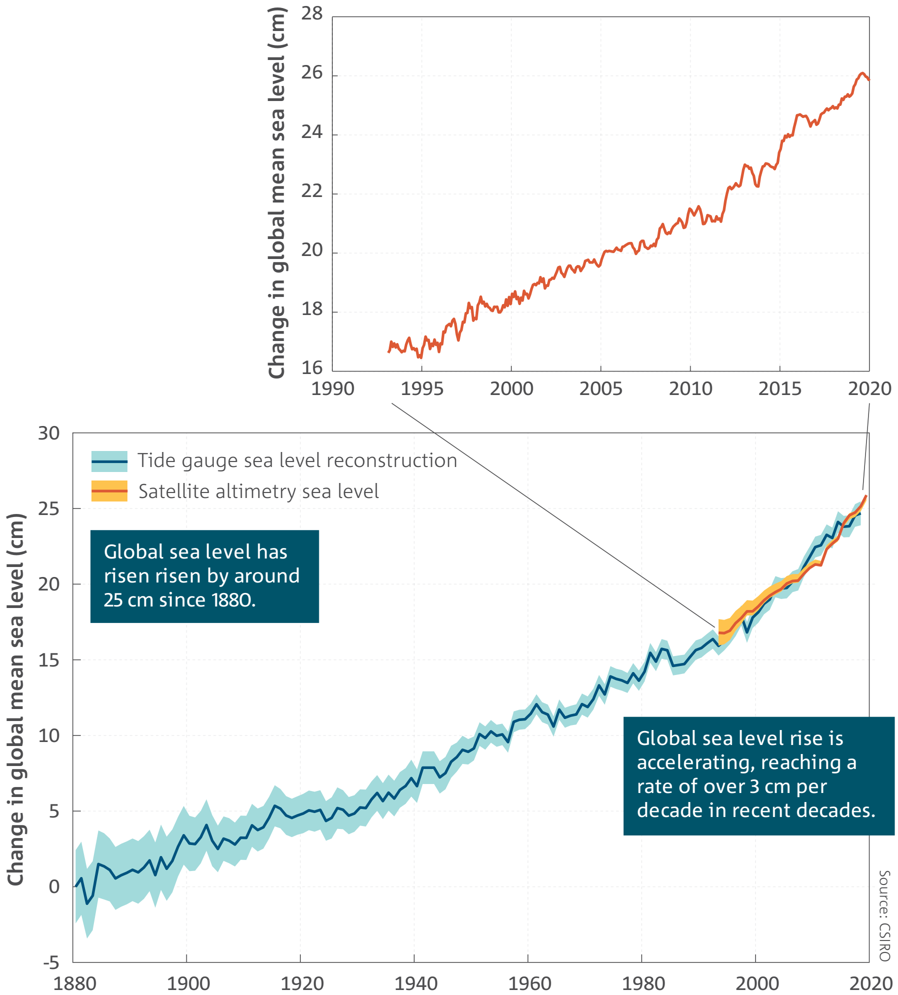
- Global mean sea level has risen by around 25 cm since 1880; half of this rise has occurred since 1970.
- Rates of sea level rise vary across the Australian region, with the largest increases to the north and southeast of the Australian continent.

As the ocean warms it expands and sea level rises. This thermal expansion has contributed about one third of the sea level rise observed globally, around 25 cm since the late 19th century. Ice loss from glaciers and polar ice sheets, together with changes in the amount of water stored on the land, contribute the remaining two thirds of the observed global sea level rise. Ice loss from Greenland, Antarctica and glaciers has been the dominant contributor to global sea level rise from 1993 to the present.

Global mean sea level rise is accelerating. Tide gauge and satellite altimetry observations show that the rate of global mean sea level rise increased from 1.5 ± 0.2 cm per decade (1901–2000) to 3.5 ± 0.4 cm per decade (1993–2019). The dominant cause of global mean sea level rise since 1970 is anthropogenic climate change.

Confidence in assessing changes in mean global sea level has continuously improved because there has been more analysis of satellite altimetry and longer records. Efforts to reliably quantify the various contributions to sea level rise have also led to greater confidence and process understanding.

Australia, like other nations, is already experiencing sea level rise. Sea level varies from year to year and from place to place, partly due to the natural variability of the climate system from the effect of climate drivers such as El Niño and La Niña. Based on satellite altimetry observations since 1993, the rates of sea level rise to the north and southeast of Australia have been significantly higher than the global average, whereas rates of sea level rise along the other coasts of the continent have been closer to the global average.

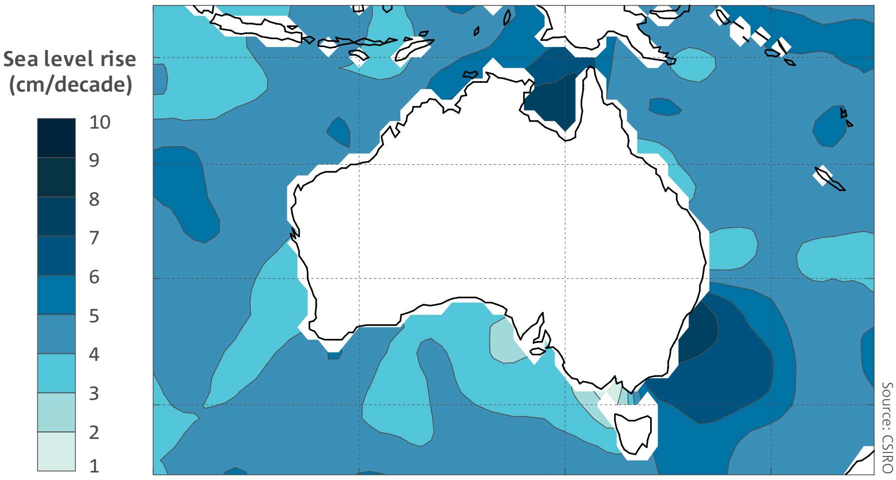


Annual global sea level change from 1880 in tide gauge data (1880–2019, blue line, shading indicates confidence range), and annual sea level change in satellite altimetry (1993–2019, orange line). The pull-out figure shows monthly sea level change from 1880, measured using satellite altimetry from 1993 to 2019.

The long-term altimetry sea level record is typically restricted to the offshore region, beyond 25–50 km, while changes closer to Australia's shoreline are estimated from tide gauge measurements at a limited number of locations. Local coastal processes, the effects of vertical land motion, and changes in site and/or reference levels affect local estimates of sea level change. For example, estimates from nearshore tide gauge measurements may differ from estimates derived from satellite altimetry tens of kilometres offshore. Nevertheless, tide gauges with good long-term records around Australia show overall changes in sea level rise consistent with offshore observations from satellite altimetry.

Rising sea levels pose a significant threat to coastal communities by amplifying the risks of coastal inundation, storm surge and erosion. Coastal communities in Australia are already experiencing some of these changes.

Sea levels have risen around Australia.



The rate of sea level rise around Australia measured using satellite altimetry, from 1993 to 2019.

Ocean acidification

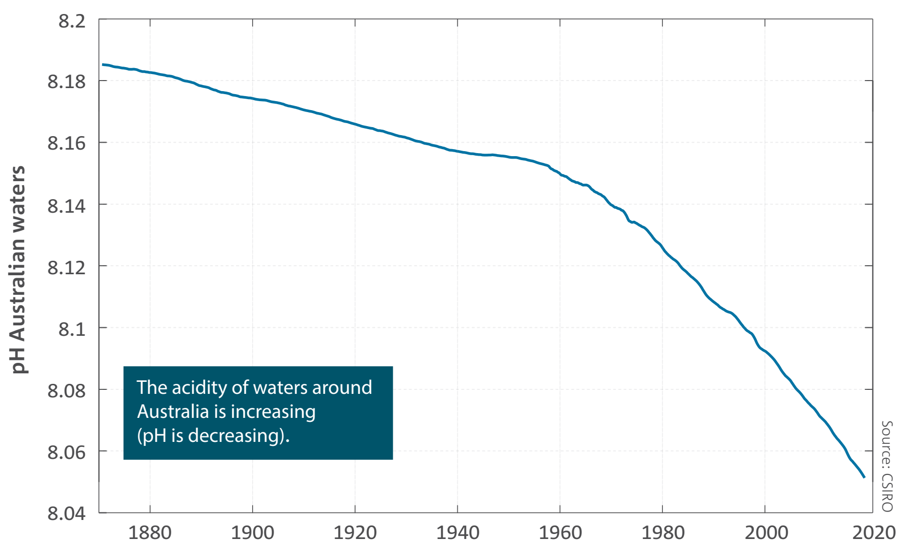
- The acidification of the oceans around Australia continues (pH is decreasing), and the impacts of these changes are detectable in areas such as the Great Barrier Reef.

Rising atmospheric CO_2 levels increase the uptake of CO_2 by the oceans, which affects their carbonate chemistry and decreases their pH; a process known as ocean acidification. In conjunction with other environmental changes, such as ocean warming and deoxygenation, ocean acidification brings additional pressures to the marine environment.

Impacts of ocean acidification to marine ecosystems include changes in reproduction, organism growth and physiology, species composition and distributions, food web structure, nutrient availability and reduced calcification rate. The last of these is particularly important for species that produce shells or skeletons of calcium carbonate, such as corals and shellfish.

Between 1880–1889 and 2010–2019, the average pH of surface waters around Australia is estimated to have decreased by about 0.12. This corresponds to a more than 30 per cent increase in acidity (and so the waters have become less alkaline). Due to latitudinal differences in ocean chemistry, the oceans to the south of Australia are acidifying faster than those to the north.

The rate of decrease in pH has accelerated to over 0.02 per decade, more than five times faster than from 1900 to 1960. This current rate of change is also 10 times faster than at any time in the past 300 million years. These changes have led to a significant reduction in coral calcification and growth rates on coral reefs such as the Great Barrier Reef, which affects their ability to recover from coral bleaching events.



The pH of surface waters around Australia. Top: change between 1880–1889 and 2010–2019, and 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.

Cryosphere

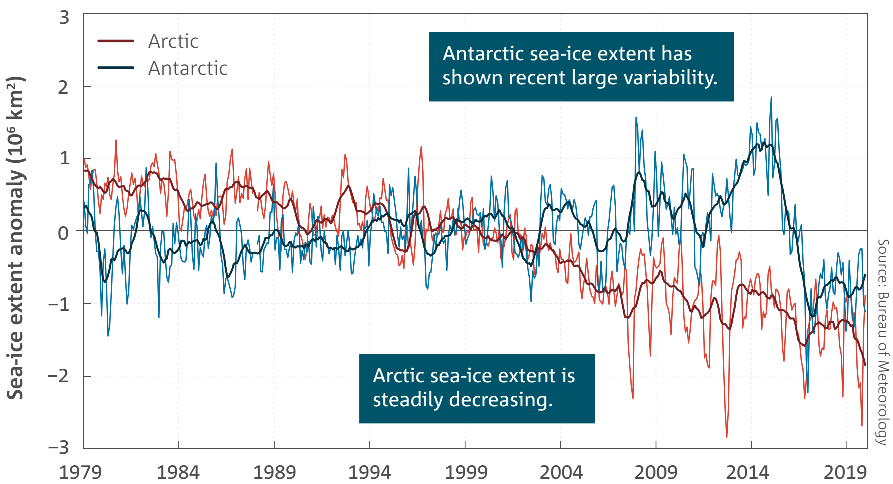
- The ice sheets and ice shelves of Antarctica and Greenland are losing ice and contributing to global sea level rise due to a warmer climate.
- The extent of sea ice in the Arctic has steadily reduced, while in the Antarctic there has been regional and seasonal variability in sea-ice cover.

The Earth's ice sheets—glacial ice that has accumulated from precipitation over land—and ice shelves, which are floating sheets of ice formed from glacial ice sheets, play crucial roles in our global climate system. Ice shelves help 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 several glaciers, increasing the Antarctic contribution to sea level rise. Atmospheric warming is also causing surface melting of ice sheets and ice shelves, particularly in Greenland and on the Antarctic Peninsula. From 2003 to 2019, melt from Greenland and Antarctica combined contributed around 1.4 cm of global sea level rise.

Changes in sea ice have little direct impact on sea level because sea ice is frozen sea water that floats. When it melts it returns the original volume of water to the sea. However, the presence or absence of sea ice influences the climate, including the rate of regional climate warming. Antarctic sea ice also acts as a protective buffer for ice shelves against destructive ocean swells. Changes in Antarctic sea-ice cover can also be an indicator of wider climate changes because it is an integrator of ocean, atmosphere and cryosphere components, from local change to the tropics.

Satellite monitoring of sea ice began in the late 1970s. Since then, Arctic sea-ice cover has consistently decreased, whereas net sea-ice cover changes within the Antarctic have been mixed. Overall, Antarctic sea-ice extent showed a small increase from 1979 to 2014, but with substantial regional variations. The largest daily recorded wintertime extent of approximately 20.2 million km^2 was in September 2014.

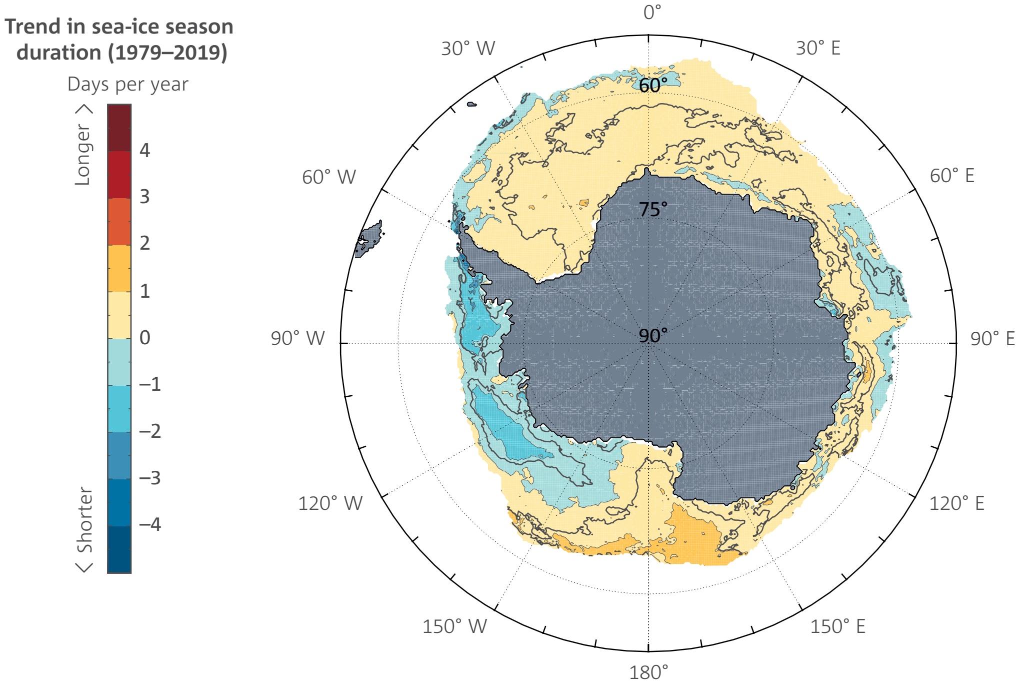
However, since then the sea-ice cover has decreased to below the long-term average, with the lowest recorded daily summertime extent of approximately 2.1 million km^2 occurring in 2017. The overall increase in Antarctic sea-ice extent during 1979–2014 has mostly been attributed to changes in westerly wind strength, whereas the marked decrease from 2015 to 2017 was predominantly related to warming in the uppermost layers of the ocean.



Antarctic and Arctic sea-ice extent (shown as the net anomaly from the 1981–2010 monthly averages in order to remove the seasonal variability) for the period January 1979 to December 2019 (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.

Observed changes in Antarctic sea-ice cover are also regionally variable, as depicted in the trends of yearly sea-ice duration. Statistically significant increases of up to two days per year in sea-ice duration have occurred in the Ross Sea, between 160° E and 150° W. Decreases in sea-ice duration of as much as four days per year are seen west of the Antarctic Peninsula and the Bellingshausen Sea offshore of West Antarctica. Recent sea-ice seasons (since 2015) have shown opposite regional responses to the long-term trend.

Changes in the Arctic sea-ice cover, since 1979, have been more seasonally and regionally uniform than those in the Antarctic, with decreasing trends in all months and virtually all regions. Sea-ice thickness in the Arctic has also decreased steadily over the last few decades, making it easier to break and melt in springtime.



Antarctic sea ice starts expanding in February and retreats from October.

The length of the sea-ice season has increased in some regions around Antarctica, but has decreased in others.

Source: Bureau of Meteorology

Trends in the length of the sea-ice season each year (in days per year) around Antarctica, from 1979–1980 to 2018–2019. Each year sea ice around Antarctica starts expanding in February and retreats from October. Duration is a measure of the number of days that a particular location is covered by sea ice.

Greenhouse gases

- Global average concentrations of all the major long-lived greenhouse gases continue to rise in the atmosphere, with the global annual mean carbon dioxide concentration reaching 410 ppm and CO_2 equivalent reaching 508 ppm in 2019.
- The rate of CO_2 accumulation in the atmosphere has increased with every passing decade since atmospheric measurements began.
- Despite the slow-down in global fossil fuel emissions of CO_2 from early 2020 associated with the COVID-19 pandemic, there will be negligible impacts in terms of climate change. Atmospheric CO_2 continues to rise, and fossil fuel emissions will remain the principal driver of this growth throughout 2020 and likely beyond.

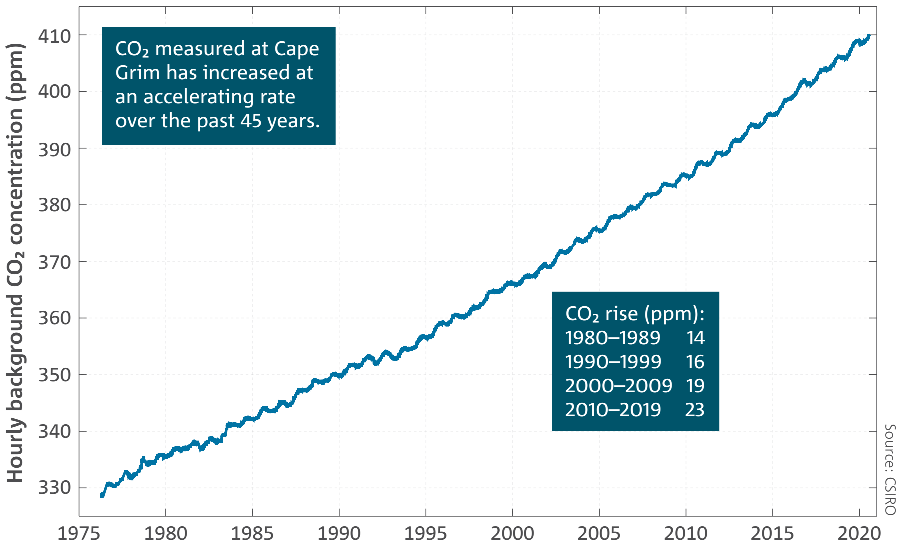
The global annual mean CO_2 level in 2019 was 410 parts per million (ppm), marking a 47 per cent increase from the pre-industrial concentration of 278 ppm in 1750. The rise in atmospheric CO_2 has been caused by emissions from fossil fuel use and land-use changes, leading to increased heat energy in the Earth's climate system.

Cumulative emissions of CO_2 will largely determine the speed and magnitude of global mean surface warming during this century and beyond. By 2019 human activities had already emitted 70 per cent of the cumulative emissions allowed to keep global temperatures below 2 °C warming (since 1850) with at least a 66 per cent chance. Because increased levels of CO_2 and other long-lived greenhouse gases, i.e. methane (CH_4), nitrous oxide (N_2O) and some synthetic gases such as the chlorofluorocarbons (CFCs), persist in the atmosphere for decades to centuries, further warming and sea level rise is inevitable.

The Cape Grim Baseline Air Pollution Station, located at the northwest tip of Tasmania, is a key site in the World Meteorological Organization's Global Atmosphere Watch program. Atmospheric concentrations of CO_2 measured at Cape Grim, like other stations around the world, show a persistent and accelerating upward trend. The annual average at Cape Grim reached 400 ppm in 2016 and climbed to 407 ppm in 2019, slightly lower than the global average.

Cape Grim CO_2 concentrations are generally lower than global averages because most CO_2 sources are in the northern hemisphere and it takes many months for this CO_2-rich air from the north to mix into the southern hemisphere and appear in the Cape Grim observations.

Two significant events from late 2019 and into 2020 have had subtle and opposing effects on the clean air CO_2 signal measured at Cape Grim. The extent and duration of the 2019–20 Australian bushfires burnt a large amount of biomass, making this an unusually large source of CO_2 from the Australian continent for that period. These bushfire emissions marginally accelerated growth in CO_2 concentrations at Cape Grim. Conversely, the impact of the COVID-19 pandemic has reduced fossil fuel CO_2 emissions in many countries, including Australia. Over the first three months of 2020, global CO_2 emissions declined by 8 per cent compared to the same three months in 2019, while global daily fossil fuel emissions were 17 per cent less in early April 2020 compared to the same period in 2019.



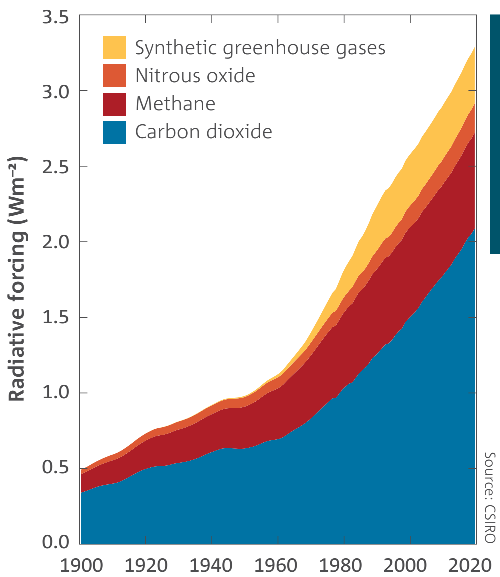
Background hourly clean-air CO_2 as measured at the Cape Grim Baseline Air Pollution Station from 1976 through to June 2020. The hourly data represent thousands of individual measurements. To obtain clean air measurements, the data are filtered to include only periods when air has come across the Southern Ocean and is thus free from local sources of pollution. The increase in CO_2 concentration for each decade from 1980 to 2019 (1 January for the start year and 31 December for the end year) is also shown.

However atmospheric CO_2 is still increasing and reduced emissions due to COVID-19 will likely reduce CO_2 accumulation in the atmosphere by only about 0.2 ppm throughout 2020. This is only about 10 per cent of the recent CO_2 growth rates of 2 to 3 ppm per year and, at most, 20 per cent of the year to year variability (~1 ppm) due to fluctuations in the natural carbon cycle. The effect on atmospheric greenhouse gas levels from COVID-19 related emissions reductions in 2020 will therefore be barely distinguishable from natural variability and negligible in terms of the mitigation needed to stabilise the climate.

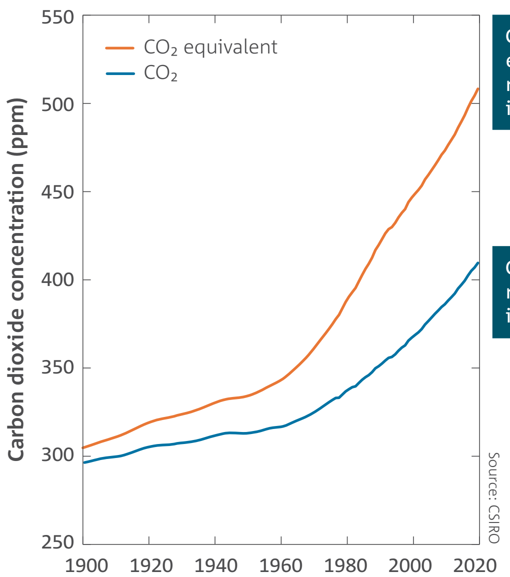
Globally averaged atmospheric concentrations of all major long-lived greenhouse gases and the radiative forcing of a group of synthetic (i.e. industry-made) greenhouse gases, continue to rise.

The climate effect of the changes in all the long-lived greenhouse gases in the atmosphere combined can be expressed as an enhancement of the net radiation, or radiative forcing. CO_2 is the largest contributor to this, but other gases also make substantial and increasing contributions.

The impact of all greenhouse gases can be converted to an equivalent CO_2 (CO_2-e) atmospheric concentration. The annual average CO_2-e measured at Cape Grim reached 503 ppm in 2019, which is almost twice the pre-industrial level of 278 ppm in 1750. Measurements of the carbon isotopic ratios in CO_2 (that is, carbon-13 and carbon-14, relative to carbon-12) confirm that the increased CO_2 originates primarily from fossil fuel and land clearing emissions.



The increase of energy into the climate system of 3.3 Wm^{-2}, compared to 1750, is due to long-lived greenhouse gases.



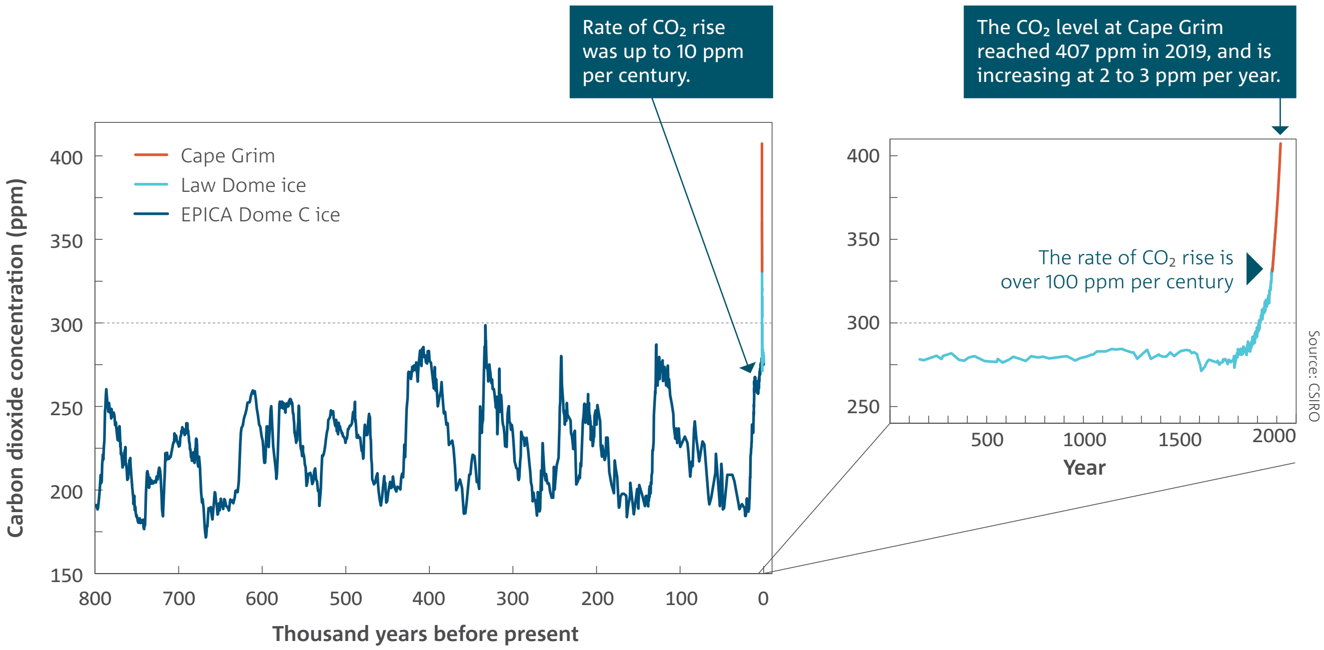
Global CO_2 equivalent reached 508 ppm in 2019.

Global mean CO_2 reached 410 ppm in 2019.

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 CO_2 equivalent (ppm). CO_2 equivalent 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 cores extend the atmospheric composition record back before direct observations. These measurements show that CO_2 concentrations were relatively stable and averaged around 280 ppm for most of the last 2000 years until recently increasing rapidly from about 1850 to present day concentrations.

Over the previous 800,000 years, CO_2 concentrations varied between about 170 ppm during colder glacial periods to nearly 300 ppm during warmer periods like today. Air extracted from Antarctic ice has recently enabled the record to be extended back to two million years ago, at discrete intervals, showing that CO_2 concentrations during the past century are higher than at any time in the ice core record. Even older atmospheric CO_2 concentrations can be inferred from ocean sediments and show that the last time that atmospheric CO_2 concentrations were the same or higher than today was the Pliocene epoch, over 2.6 million years ago, when mean global temperatures were 2–3 °C warmer than today.



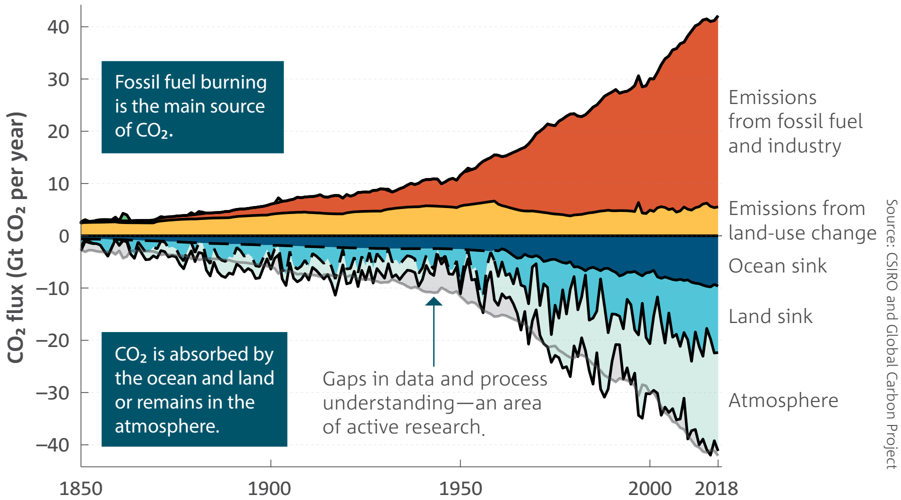
Atmospheric CO_2 concentrations, for the past 800,000 years (left), and for the past 2000 years (right). The time series, and information in the text boxes, are from measurements of air in Antarctic ice cores and at Cape Grim. Though there has been variability in the past, the rate of growth of CO_2 over the past century far exceeds (by a factor of 10 or more) the rate during the most rapid natural changes in the past (which occurred during de-glaciations).

Global carbon budget

Emissions of CO_2 from fossil fuel use and changes in land use have continued to increase. In the decade from 2009 to 2018, average global emissions were 41 ± 2.9 gigatonnes (Gt) of CO_2 per year (one gigatonne is equal to one billion tonnes). Around 85 per cent of global CO_2 emissions were from fossil fuels and 15 per cent from land-use change. Emissions reached an all-time high of 42.9 ± 2.8 Gt CO_2 in 2019. Emissions resulting from land-use change were higher in 2019 than the decadal average due to increased fire activity, particularly in Brazil.

The uptake of carbon into ocean and land sinks has grown in response to the accumulation of CO_2 in the atmosphere. In the decade from 2009 to 2018, the ocean and land sinks removed on average 9 ± 2 and 12 ± 2 Gt of CO_2 per year, respectively. Combined, these sinks are removing more than half of all CO_2 emissions from human activities and thus are slowing the rate of increase in atmospheric CO_2.

Despite this important uptake by the land and ocean sinks, atmospheric CO_2 has continued to increase, growing by 18 Gt CO_2 per year over the decade from 2009 to 2018.



Time series showing the input CO_2 fluxes per year (above zero on plot) from 1850 to 2018 due to emissions from fossil fuels and industry and land-use change; the amount of CO_2 taken up each year by the oceans and land; and the net CO_2 being added each year to the atmosphere.

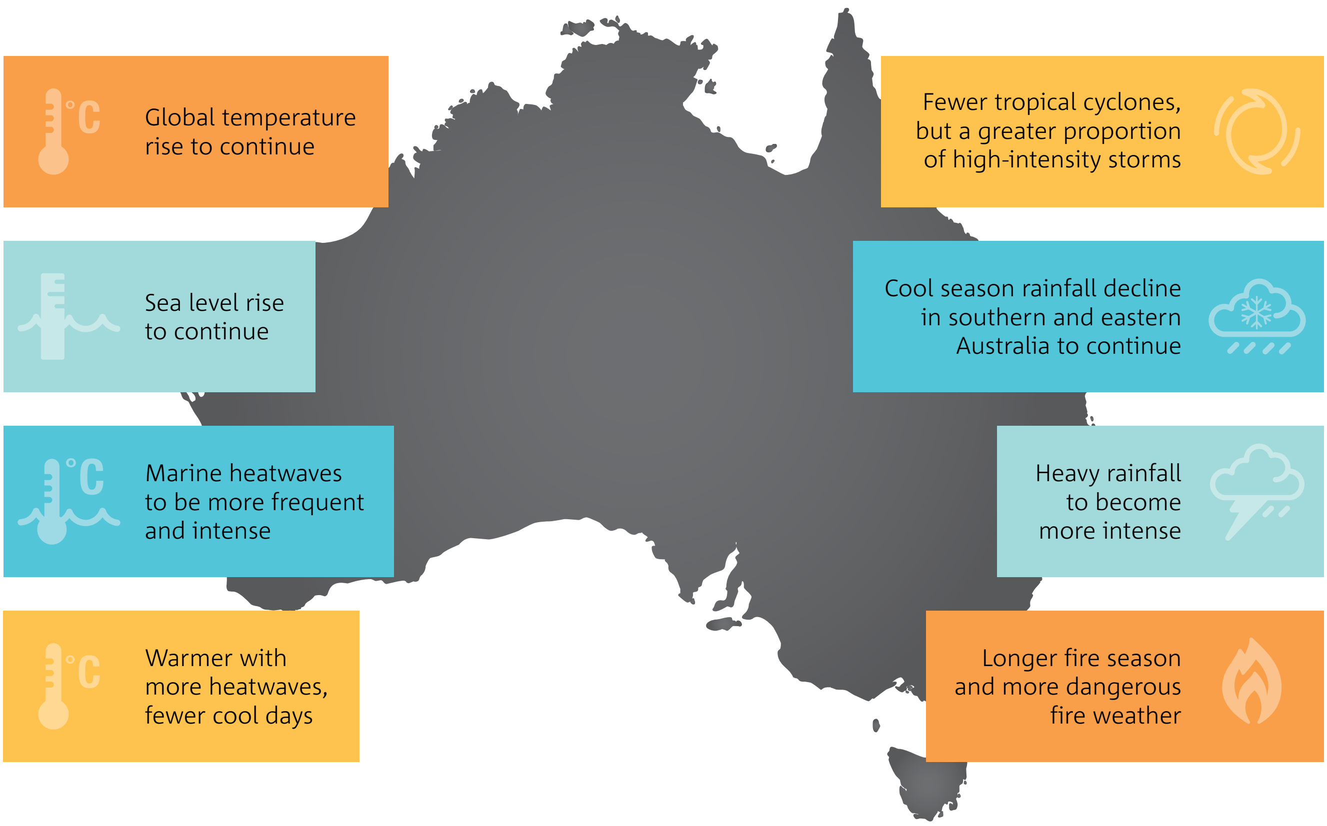
Future climate

A new set of simulations from the latest generation of global climate models are now available, including simulations from Australia's climate model, ACCESS. Analyses show that these new results are largely consistent with the existing projections for Australia at www.climatechangeinaustralia.gov.au, and add new insights. They show that over the coming decades, Australia is projected to experience:

- Continued warming, with more extremely hot days and fewer extremely cool days.
- A decrease in cool season rainfall across many regions of the south and east, likely leading to more time spent in drought.
- A longer fire season for the south and east and an increase in the number of dangerous fire weather days.
- More intense short-duration heavy rainfall events throughout the country.
- Fewer tropical cyclones, but a greater proportion projected to be of high intensity, with ongoing large variations from year to year.
- Fewer east coast lows particularly during the cooler months of the year. For events that do occur, sea level rise will increase the severity of some coastal impacts.
- More frequent, extensive, intense and longer-lasting marine heatwaves leading to increased risk of more frequent and severe bleaching events for coral reefs, including the Great Barrier and Ningaloo reefs.
- Continued warming and acidification of its surrounding oceans.
- Ongoing sea level rise. Recent research on potential ice loss from the Antarctic ice sheet suggests that the upper end of projected global mean sea level rise could be higher than previously assessed (as high as 0.61 to 1.10 m global average by the end of the century for a high emissions pathway, although these changes vary by location).
- More frequent extreme sea levels. For most of the Australian coast, extreme sea levels that had a probability of occurring once in a hundred years are projected to become an annual event by the end of this century with lower emissions, and by mid-century for higher emissions.

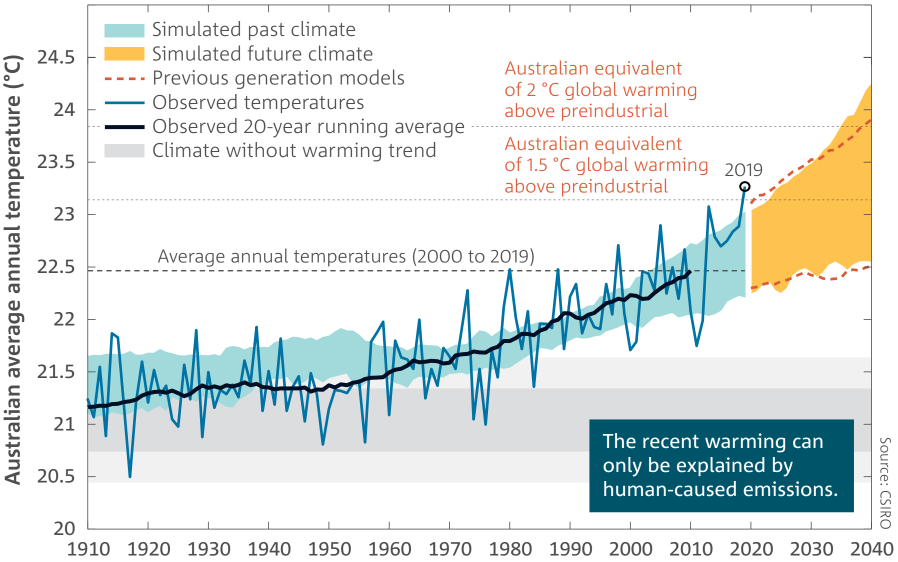
Projections of Australia's average temperature over the next two decades show:

- Every year is now warmer than the range it would have been in a world without human influence, known as climate change 'emergence'.
- The year 2019 was Australia's hottest year on record, due to the combination of climate variability and long-term warming. This is expected to be an average year in a world where the global mean temperature is 1.5 °C above the pre-industrial baseline period of 1850–1900.



Source:Bureau of Meteorology and CSIRO

- While the current decade is warmer than any other decade over the last century, it is also likely to be the coolest decade for the century ahead.
- The average temperature of the next 20 years is virtually certain to be warmer than the average of the last 20 years.
- The amount of climate change expected in the next decade is similar under all plausible global emissions scenarios. However, by the mid-21st century, higher ongoing emissions of greenhouse gases will lead to greater warming and associated impacts, while reducing emissions will lead to less warming and fewer impacts.

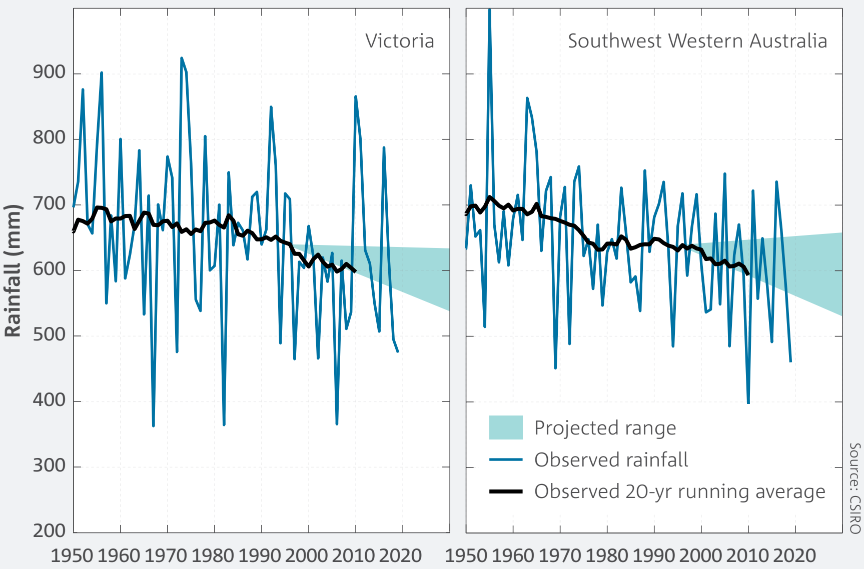


Australian average annual temperature observed and simulated from global climate models. Past and future bands show the range of 20-year running average of new generation climate model results, dashed lines show the equivalent from the previous generation of global climate models. Climate without warming trend shows both an inner and an outer band which are one and two standard deviations, respectively, from the 1850–1900 average, i.e. prior to the rapid growth in greenhouse gas emissions from human activities. The black dashed lines show the Australian equivalent of the global warming thresholds 1.5 °C and 2 °C above the pre-industrial baseline period 1850–1900, equating to warming levels of around +2.1 °C and +2.8 °C respectively, based on the observed ratio of Australian to global temperature of around 1.4.

Evaluation of average annual rainfall projections for Australia

Climate projections are given for a future climate period relative to a past baseline. Recent climate projections estimated changes in rainfall from 1986–2005 to 2020–2039. Now that it is 2020, we can see how the observed rainfall trend is tracking against these projections. This is an indication of their reliability thus far, noting that the projections can't be fully evaluated until the climate of 2020–2039 has emerged in its entirety.

Rainfall in southwest and southeast Australia has been declining in recent decades and is projected to likely decline further, especially in the cooler half of the year. The observed 20-year running average annual rainfall has been tracking the dry end of the projections (even though year-to-year values may fall outside the range), showing that the observed trends are consistent with these projected changes in rainfall. Importantly there is no evidence that the climate projections are overestimating the ongoing drying trend to date.



Evaluation of average annual rainfall projections for two example regions in Australia. Projected range starts at 1995 (mid-point of the 1986–2005 baseline).
Left: For Victoria, projection from the Victorian Climate Projections 2019 VCP19;
Right: Southwest Western Australia, projection from Climate Change in Australia, the national climate change projections for Australia. Southwest Western Australia is defined as a cluster of Natural Resource Management regions covering the southwest of the State; and differs from the area in the rainfall section.

About State of the Climate

The State of the Climate report draws on the latest monitoring, science and projection information to describe variability and changes in Australia's climate.

Changes to our climate affect all 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 climate change.

This is the sixth State of the Climate report. The report has been published every two years since the first report in 2010.

Further information

The Bureau of Meteorology

The Bureau of Meteorology is Australia's national weather, climate, ocean and water agency. Through regular forecasts, warnings, monitoring and advice spanning the Australian region and Antarctic territory, the Bureau provides one of the most fundamental and widely used services of government.

bom.gov.au/state-of-the-climate
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Further information about the content of this report, and a list of references is available online.

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