State of the Climate 2024

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 eighth biennial State of the Climate report draws on the latest national and international climate research, encompassing observations, analyses and future projections to describe year-to-year variability and longer-term changes in Australia's climate. The report is a synthesis of the science that underpins our understanding of Australia's climate. It is intended to inform economic, environmental and social decision-making by governments, industries and communities.

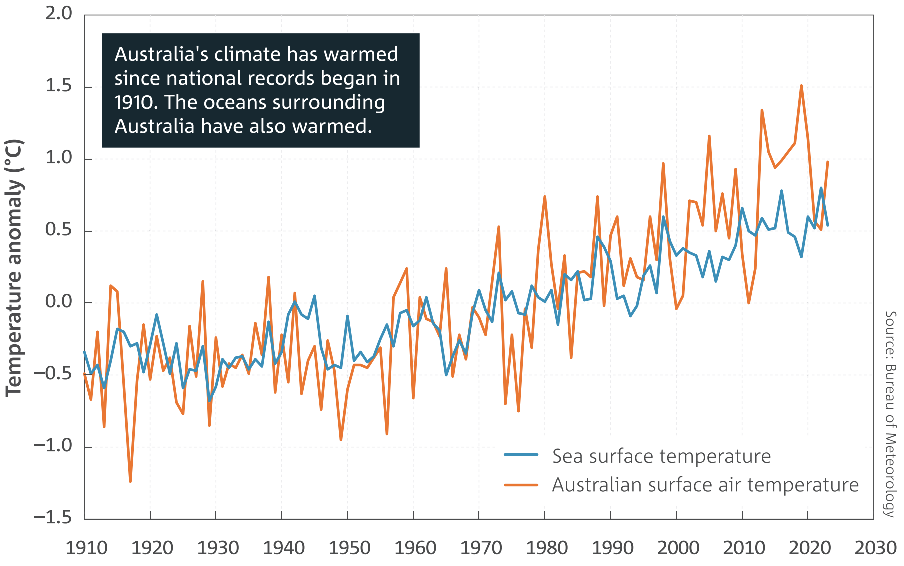
Observations, reconstructions of past climate and climate modelling continue to provide a consistent picture of ongoing, long-term climate change interacting with underlying natural variability. Associated changes in weather and climate extremes—such as extreme heat, heavy rainfall, coastal inundation, fire weather and drought—exacerbate existing pressures on the health and wellbeing of our communities and ecosystems. These changes in the weather and climate are happening at an increasing pace; the past decade has seen record-breaking extremes contributing to natural disasters that are exacerbated by anthropogenic (human-caused) climate change, including 'compound events', where multiple hazards and/or drivers occur together or in a close sequence, which intensifies their impacts.

These changes have a growing effect on the lives and livelihoods of all Australians. Australia must plan for, and adapt to, the changing nature of climate risk now and in the decades ahead. The severity of impacts on Australians and our environment will depend on the speed at which global greenhouse gas emissions can be reduced.

Key points

Australia

- Australia's climate has warmed by an average of 1.51 ± 0.23 °C since national records began in 1910.
- Sea surface temperatures have increased by an average of 1.08 °C since 1900.
- The warming has led to an increase in the frequency of extreme heat events over land and in the oceans.
- In the south-west of Australia there has been a decrease of around 16% in April to October rainfall since 1970. Across the same region, May to July rainfall has seen the largest reduction, by around 20% since 1970.
- In the south-east of Australia, there has been a decrease of around 9% in April to October rainfall since 1994.
- Heavy short-term rainfall events are becoming more intense.
- There has been a decrease in streamflow at most gauges across Australia since 1970.
- There has been an increase in rainfall and streamflow across parts of northern Australia since the 1970s.
- There has been an increase in extreme fire weather, and a longer fire season, across large parts of the country since the 1950s.



Australia's climate has warmed since national records began in 1910. The oceans surrounding Australia have also warmed.

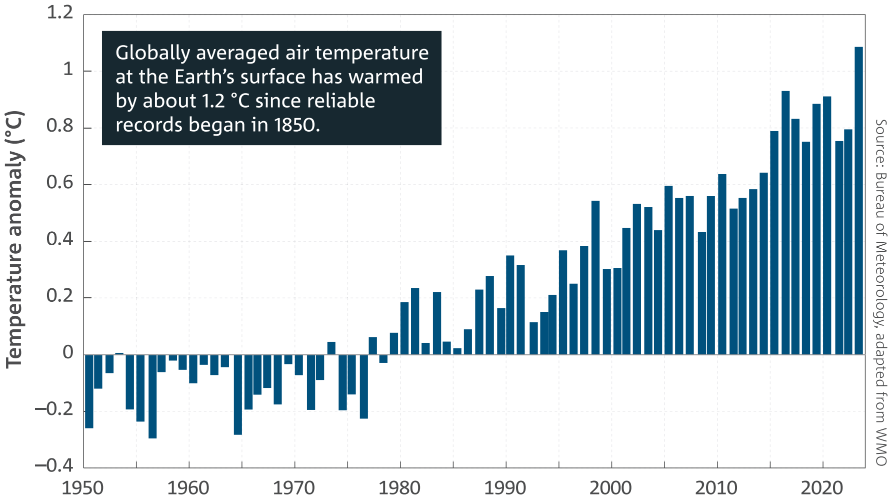
Source: Bureau of Meteorology

Anomalies (departures from the mean for the 1961–1990 standard averaging period) in annual mean sea surface temperature, and temperature over land, in the Australian region. 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 at least 1982.
- Snow depth, snow cover and number of snow days have decreased in alpine regions since the late 1950s.
- Oceans around Australia are becoming more acidic, with changes happening faster in recent decades.
- Sea levels are rising around Australia, including more frequent extreme high levels that increase the risk of inundation and damage to coastal infrastructure and communities.

Global

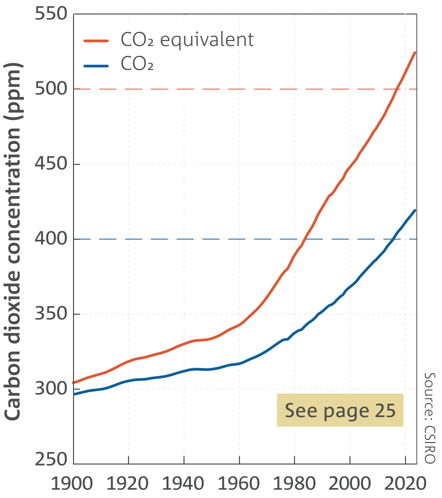
- Concentrations of all major long-lived greenhouse gases in the atmosphere continue to increase. Global annual mean carbon dioxide (CO_2) concentrations reached 419.2 parts per million (ppm) in 2023 and the CO_2 equivalent (CO_2-e) of all greenhouse gases reached 524 ppm. These are the highest levels on Earth in at least 2 million years.
- Global fossil fuel CO_2 emissions, the principal driver of the growth in CO_2 concentrations, are continuing to increase. Overall anthropogenic CO_2 emissions, including fossil fuel and land-use change emissions, have levelled off over the last decade after increasing for more than a century prior to the 2010s.
- In 2022 and 2023, the amounts of methane (CH_4) and nitrous oxide (N_2O), both greenhouse gases, in the atmosphere increased rapidly.
- Globally averaged air temperature at the Earth's surface has warmed by about 1.2 °C since reliable records began in 1850. Each decade since 1980 has been warmer than the last, with 2011–2020 being around 0.2 °C warmer than 2001–2010. 2023 was the warmest year on record globally.
- The world's oceans, especially in the Southern Hemisphere, have taken up more than 90% of the extra energy stored by the planet (as heat) arising from enhanced greenhouse gas concentrations.
- The ice sheets and ice shelves of Antarctica and Greenland are losing ice due to a warmer climate, and contributing to global sea level rise.
- There has been an abrupt decrease in Antarctic sea-ice extent since 2015, after a small increase over the period from 1979 to 2014.
- Around half of all CO_2 emissions from human activities are absorbed by land and ocean sinks, which act to slow the rate of increase in atmospheric CO_2.
- Global mean sea levels have risen by over 22 cm since 1900; half of this has occurred since 1970.



Globally averaged air temperature at the Earth's surface has warmed by about 1.2 °C since reliable records began in 1850.

Source: Bureau of Meteorology, adapted from WMO

Annual global surface temperature anomalies of the Earth (land and ocean), 1950–2023. Anomalies are relative to the 1961–1990 standard averaging period. Based on data from the World Meteorological Organization.



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Source: CSIRO

Global mean CO_2 concentrations and global mean of all greenhouse gas concentrations expressed as CO_2-e.

Future

In the coming decades, Australia will experience ongoing changes to its weather and climate. The changes are projected to include:

- Continued increase in air temperatures, with more heat extremes and fewer cold extremes.
- Continued decrease, on average, in cool season rainfall across many regions of southern and eastern Australia, which will likely lead to more time in drought.
- More intense short-duration heavy rainfall events even in regions where the average rainfall decreases or stays the same.
- Continued increase in the number of dangerous fire weather days and a longer fire season for much of 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 increase the likelihood of more frequent and severe bleaching events in coral reefs around Australia, including the Great Barrier Reef and Ningaloo Reef.
- Fewer tropical cyclones, but with higher intensity on average, and greater impacts when they occur through higher rain rates and higher sea level.
- Reduced average snow depth in alpine regions, but with variations from year to year.

Source: unsplash.com

Changes in weather systems and climate influences

Australia's weather systems are changing. Southern Australia receives much of its rainfall during the cooler months of the year from low-pressure systems and cold fronts to the south of the subtropical high-pressure ridge. During recent decades, these systems have become less common over southern Australia, and are less likely to produce rainfall when they do occur, contributing to declines in cool season rainfall. Mean sea level atmospheric pressure is increasing over Australia, and there has been an increase in the number of high-pressure systems over southern Australia, which bring dry, clear weather and little rainfall. This increase in atmospheric pressure across southern latitudes is a response to climate change. There is large variability in the frequency of individual weather systems between individual months and years. Many of these trends are consistent with simulations from climate models, which demonstrate that increased greenhouse gas levels lead to fewer low-pressure systems in southern Australia and a stronger subtropical ridge, but an increase in the intensity of heavy rainfall, including from thunderstorms.

Australia's climate is also influenced from year to year by various broadscale climate influences, such as the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM). SAM shows a sustained trend towards more positive conditions from 1950 to the present day, particularly in summer. The level of ENSO activity over the past 50 years is higher, with more significant El Niño and La Niña events than in the years between 1920 and 1970. However, there is no clear indication that recent activity levels are outside the long-term range of variability, with evidence of high levels of ENSO activity in the late 19th and early 20th centuries. There is low confidence in the long-term trends in the IOD, particularly prior to the 1960s, although paleoclimate data indicate that the recent frequency of strong positive IOD events is high in the context of multi-century variability.

Australia's changing climate

Temperature

- Australia, on average, has warmed by 1.51 ± 0.23 °C since national records began in 1910.
- There has been an increase in extreme heat events associated with the warming.

Australia, on average, has warmed by 1.51 ± 0.23 °C since national records began in 1910, with most warming occurring since 1950. Every decade since 1950 has been warmer than preceding decades. The warming in Australia is consistent with global trends, with the degree of warming similar to the overall average across the world's land areas.

Australia's warmest year on record was 2019, and 8 of the 9 warmest years on record have occurred since 2013. The long-term warming trend means that most years are now warmer than almost any observed during the 20th century. 2021 and 2022 were less warm than most of the preceding decade, reflecting the cooling that typically occurs during La Niña years, but were still warmer than most years prior to 2000.

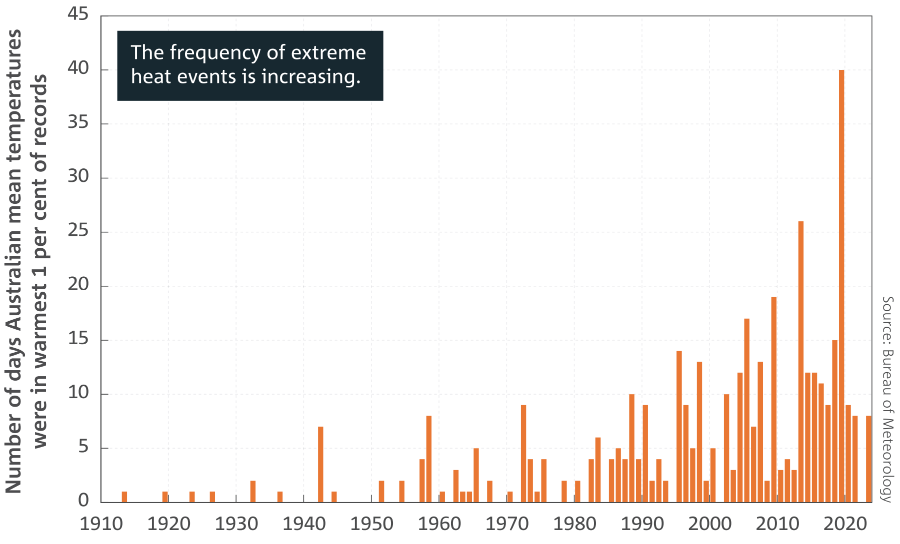
Warming is observed across Australia in all months with both day- and night-time temperatures increasing. This shift is accompanied by an increased number of extreme heat events across all months, including a greater frequency of very hot days in summer. In the record warm year of 2019 there were 40 days with extremely high nationally-averaged mean temperatures (those in the warmest 1% of days for each month), about 3 times more extreme heat days than any year prior to 2000. Also in 2019, there were 33 days when national daily average maximum temperatures exceeded 39 °C, a larger number than seen in the 59 years from 1960 to 2018 combined.

There were fewer extremes in the period from 2020 to 2023, which was dominated by La Niña conditions, although the number of extreme heat days in those years (except 2022) was still high compared with most years prior to 2000. Extreme heat has caused more deaths in Australia than any other natural hazard and has major impacts on ecosystems and infrastructure.

The very high monthly maximum temperatures that were recorded under 2% of the time in 1960–1989, are occurring 11% of the time in 2009–2023. That is about 6 times as often.

Similarly, the very high night time temperatures, which are also a major contributor to heat stress, and occurred 2% of the time in 1960–1989, now occur about 10% of the time – 5 times as often.

The occurrence of very cold days and nights has declined across Australia. An exception is for extremely cold nights in parts of south-east and south-west Australia, where the frequency of frost in these parts has been relatively unchanged since the 1980s. In this region, there has been significant cool season drying, and hence more clear winter nights. This results in colder nights due to increased heat loss from the ground.



The frequency of extreme heat events is increasing.

Source: Bureau of Meteorology

Number of days each year where the Australian area-averaged daily mean temperature for each month is extreme. Extreme days are defined as those where daily mean temperatures are the warmest 1% of days for each month, calculated for the period 1910–2023.

Australian temperatures and global warming

Australian temperatures have warmed by 1.51 °C from 1910 to 2023. An increase of 1.5 °C is a threshold that is widely referenced in global climate change assessments, and it is important to understand how the values being reported here for Australia relate to broader global warming levels.

The Paris Agreement commits signatories to pursue efforts to limit the increase in the global average temperature to 1.5 °C above pre-industrial levels. The Agreement does not define how this is measured, but the Intergovernmental Panel on Climate Change (IPCC) in their Sixth Assessment Report defines the time of crossing a given warming level based on the first period when the 20-year average crosses that level. The first individual months with global temperatures above the 1.5 °C threshold occurred during the 2015–2016 El Niño. 2023 was the world's warmest year since instrumental records began, with global temperatures 1.45 °C above the 1850–1900 average. In most major data sets, global temperatures averaged over the 12-month period from June 2023 to May 2024 were more than 1.5 °C above the pre-industrial level. Individual months or years above the threshold, however, do not mean that the threshold has yet been crossed on a sustained basis.

Over most of the world, land areas are warming faster than the ocean. This is also the case for Australia, where land areas are warming about 40% faster than the surrounding oceans. The observed rate of warming in Australia is very close to the global average for land areas, while the rate of warming for sea surface temperatures in the Australian region also closely matches the global average for oceans. Evidence available from the 19th century, which is more limited than after 1910, indicates that Australian land temperatures warmed by 1.6 ± 0.2 °C from 1850–1900 to 2011–2020. This compares to the global land average of 1.59 °C over the same period. Global temperature measurements include both land and oceans, so when a global warming level of 1.5 °C is reached, most land areas will have warmed by considerably more than 1.5 °C. In parallel, temperature extremes on land are also projected to continue to warm faster than the global average, with extreme heat days in mid-latitudes globally expected to warm by an average of about 3 °C at 1.5 °C of global warming.

In addition to extreme heat, many other climate hazards are expected to be more significant at 2 °C or higher global warming levels than at 1.5 °C or at present-day levels. These include increased coastal inundation as a result of rising sea levels, increased heavy precipitation, increases in human health risks, water stress, and impacts on biodiversity and ecosystems on land and in the oceans.

Source: pexels.com

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. This has led to larger and more frequent fires, especially in southern Australia.

The influence of climate change on bushfires varies across Australia, depending largely on the kinds of vegetation (fuel) which grow in each region. Climate change is driving changes in temperature, rainfall, and relative humidity, all of which influence fuel availability, fuel dryness, fire weather, and ignition sources. Fire weather (often hot, dry and windy) is a significant contributor to fire risk in forest fuel areas of southern and eastern Australia. Conversely, wetter conditions in northern and central regions results in abundant grassy fuel loads, which is a key contributing factor to fire risk in those regions.

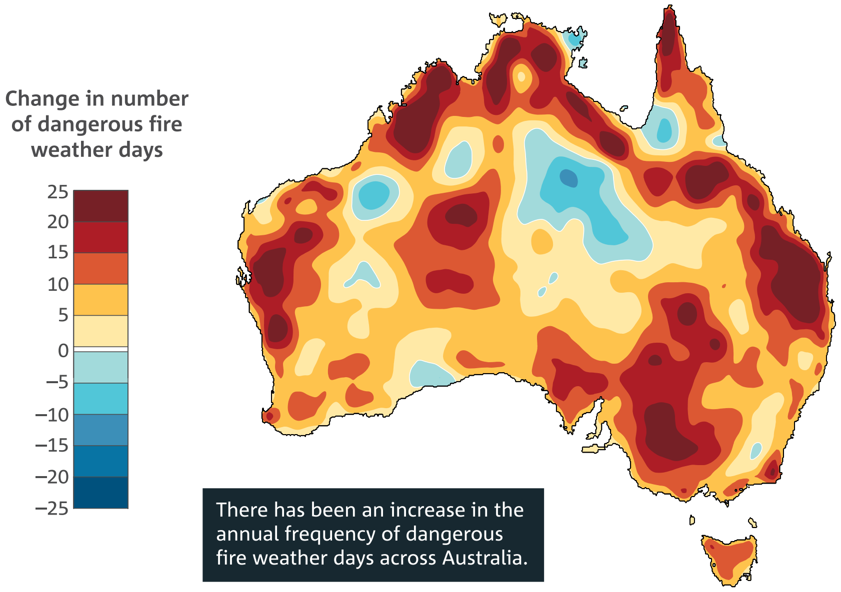
The Forest Fire Danger Index (FFDI) is a measure of fire weather calculated from observations of temperature, rainfall, humidity, and wind speed. There has been an increase in the frequency of dangerous fire weather days (those with an FFDI above the 90th percentile) across most regions over the last 75 years, although with substantial differences between regions. These changes are particularly evident during spring and summer, and are associated with an earlier start to the southern fire weather season.

There is a notable trend in some regions of southern Australia towards more days with weather that is conducive to generating thunderstorms within smoke plumes. These fire-generated thunderstorms can lead to extremely dangerous fire behaviour, such as during the Black Summer fires (2019–2020), the Victorian Black Saturday fires (2009), and the Canberra fires (2003). New fires can be ignited from lightning strikes produced by these thunderstorms.

Year-to-year climate variability influences how much fuel is available and its dryness. During a La Niña event, wet and cool climate anomalies are generally observed through central and south-eastern Australia. The cooler and wetter conditions which occurred, for example, during the southern fire seasons 2020–2021, 2021–2022, and 2022–2023, mean fewer days with high FFDI values, and a reduced risk of fire in forest fuels in the south-east. Conversely, increased rainfall in inland areas leads to higher grassy fuel loads, which increases risk of fire in those regions when the vegetation dries. High rainfall in 2022 and early 2023 across northern Australia resulted in high fuel loads in spinifex and savanna regions and made 2023 one of Australia's most extensive bushfire seasons in terms of area burned. In the interior of Australia, parts of which have seen relatively little change in FFDI, changes in fuel availability are a major driver of changes in fire risk with fire weather being less significant as a risk factor than in the east and south.

The type and amount of fuel in a region is strongly associated with the local climate. Changes in climate can change a region's susceptibility to fire by increasing the amount of fuel (stimulating vegetation growth), by making fuel more available (through drying), or by changing the dominant vegetation type. As the climate has changed, so has the distribution of Australia's ecosystems which in turn has altered the distribution of areas prone to dangerous fire conditions.

Lightning that occurs without significant rainfall (known as 'dry lightning') is a major source of natural ignition for bushfires. Understanding changes to bushfire ignition in Australia, including the frequency of dry lightning, is a current area of active research.



There has been an increase in the annual frequency of dangerous fire weather days across Australia.

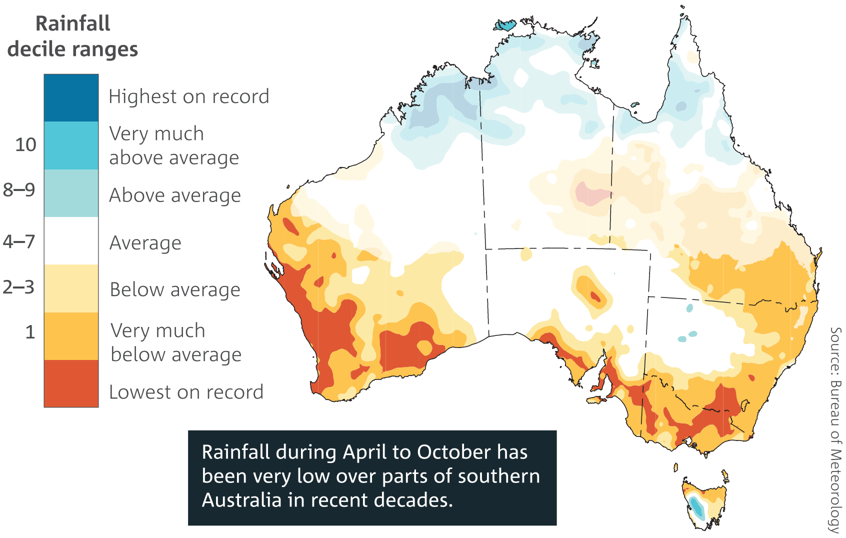
Source: Bureau of Meteorology

There has been an increase in the number of days with dangerous weather conditions for bushfires. The map shows the change in the number of days per year (July to June) that the FFDI exceeds its 90th percentile of conditions observed from 1950–2024, between 2 periods: July 1950 to June 1987 and July 1987 to June 2024. The FFDI is an indicator of dangerous fire weather conditions for a given location.

Rainfall

- In the south-west of Australia, there has been a decline of around 16% in April to October (cool season) rainfall since 1970. Across the same region, May to July rainfall has seen the largest decrease, of around 20% since 1970.
- In the south-east of Australia, there has been a decrease of around 9% in April to October rainfall since 1994.
- October to April (wet season) rainfall in northern Australia has increased by around 20% since 1994.

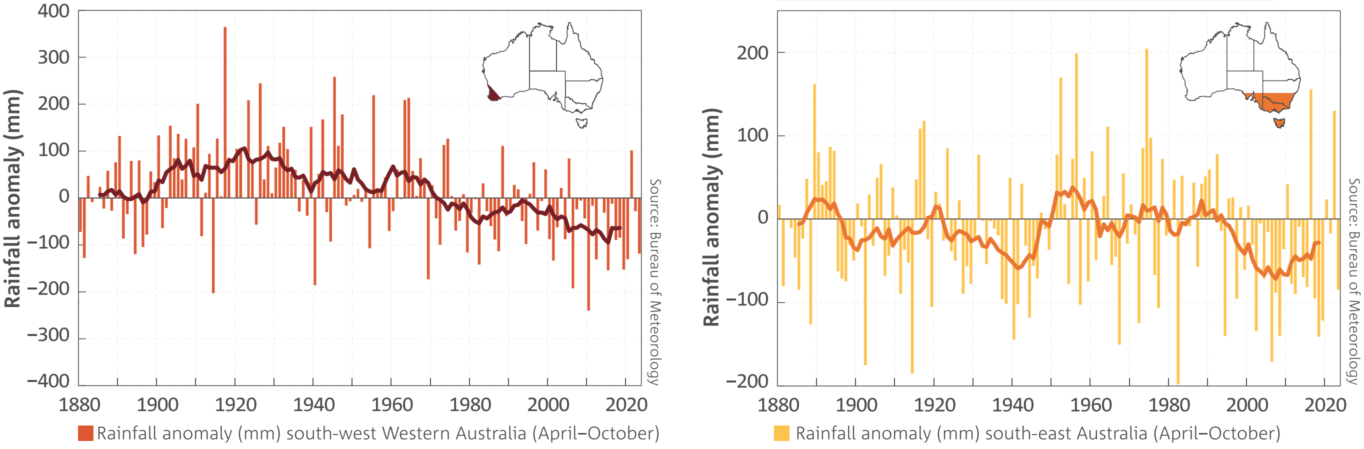
Australian rainfall is highly variable and is strongly influenced by seasonal climate influences such as El Niño, La Niña, the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM). Despite this natural variability, long-term trends are evident in Australia's rainfall records. There has been a shift towards drier conditions across the south-west and south-east of Australia, with more frequent periods of below-average rainfall, especially for the cool season months from April to October. Cool season rainfall in southern Australia has been above the 1961–1990 average in only 6 of the 30 years from 1994–2023, a 30-year period which includes the Millennium Drought (1997–2009). This is due to a combination of natural variability on decadal timescales and changes in large-scale circulation largely driven by an increase in greenhouse gas emissions. Cool season rainfall is particularly important for southern Australia, as it is the main growing season for many crops. It is when peak streamflow occurs in most catchments in the region, as cool season rainfall is generally more effective than warm-season rainfall in generating runoff, and is also when groundwater recharge is most likely to occur.



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

Source: Bureau of Meteorology

April to October rainfall deciles for the 30 years from 1994 to 2023. A decile map shows where rainfall is above average, average, or below average for this period compared to all years from 1900 (when reliable national rainfall records began) to 1993. Areas across northern and central Australia that receive less than 40% of their annual rainfall from April to October are faded.



Rainfall varies from year to year, but in the south-west of Australia, April to October rainfall has decreased due to climate change from the 1960s onwards.

April to October rainfall in the south-east of the country has been declining for the last two decades. There are fewer wet years now than during the 20th century.

Source: Bureau of Meteorology

Source: Bureau of Meteorology

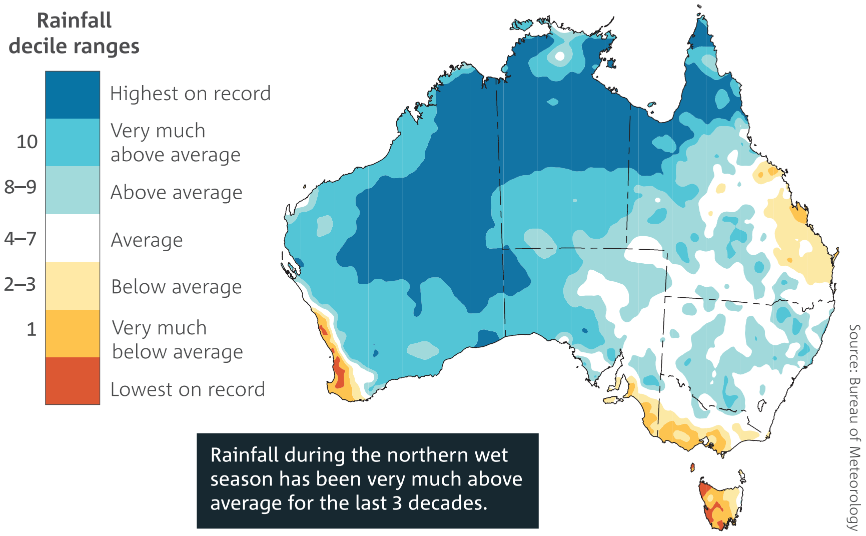
April to October rainfall anomalies for south-western Australia (south-west of the line joining the points 30° S, 115° E and 35° S, 120° E) and south-eastern Australia (south of 33° S, east of 135° E inclusive), with respect to 1961–1990 averages. The line shows the 11-year running mean.

The drying trend in southern Australia is most evident in the south-west and south-east of the country. The recent drying across these regions is the most sustained large-scale change in observed rainfall since widespread observations became available in the late 1880s. The trend is particularly strong for the period from May to July, in the earlier part of the cool season, over south-west Western Australia, with average rainfall since 1970 around 20% less than the average from 1900 to 1969. Over the full cool season from April to October, the decline in rainfall over the same period is around 16%. In the last 30 years since 1994, the decline in May to July has further strengthened to around 24%, despite relatively high cool season rainfall during 2021. It is highly unlikely that a decline of this magnitude could have occurred due to natural variability alone.

Since 1994, average cool season rainfall in the south-east has been around 9% lower than it was in the 1900–1993 period. The Millennium Drought was a major influence on this, affecting rainfall totals across the region from 1997–2009. However, cool season rainfall has remained below average after the Millennium Drought, with mean rainfall during 2010–2023 remaining 5% below the 1900–1993 average. In the years since 2010 cool season rainfall above the 1961–1990 average has only been recorded for south-eastern Australia in 4 out of 14 years, during the La Niña events of 2010–2012 and 2020–2022 and the strong negative IOD event of 2016. The declining trend in rainfall is associated with a trend towards higher surface atmospheric pressure in the region and a shift in large-scale weather patterns-more highs, fewer lows and a reduction in the number of rain-producing lows and cold fronts.

Conversely, northern Australia has been wetter than average over the last 30 years across all seasons, especially in the north-west during the northern wet season from October to April. Since 1994, wet season rainfall in northern Australia (from 26 °S, the latitude of the South Australia-Northern Territory border, northwards) has been 20% above the 1900–1993 average. Seven of the 10 wettest northern Australia wet seasons have occurred since 1998, including during the recent La Niña periods 1998–2001, 2010–2011, and 2022–2023. Rainfall variability remains high, however, with rainfall during the last decade being closer to the long-term average than in the previous 2 decades. In parts of eastern Queensland south of the tropics, there has been a trend towards lower rainfall throughout the year, particularly during the past decade.

Warm season rainfall has been below average in parts of Tasmania, and the south-east and south-west coasts of mainland Australia in recent decades.

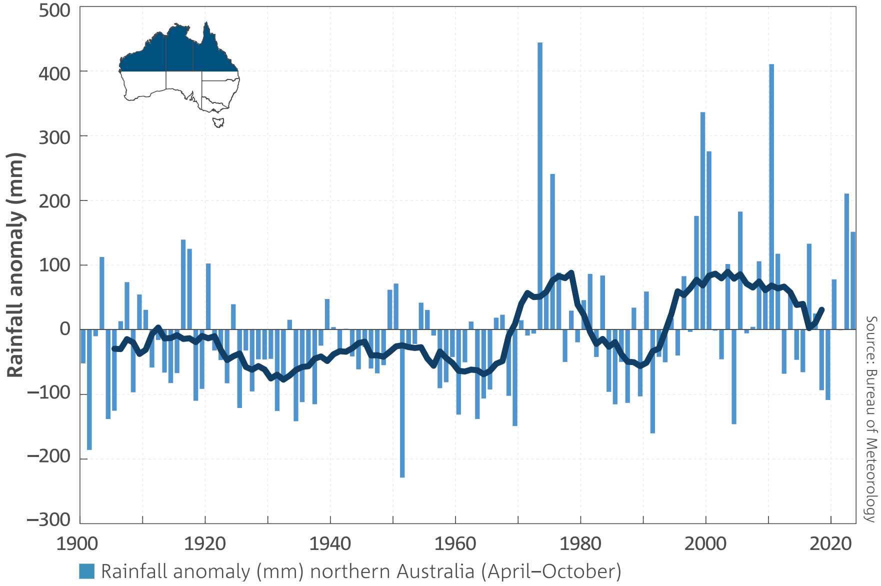


Rainfall during the northern wet season has been very much above average for the last 3 decades.

Source: Bureau of Meteorology

Northern wet season (October–April) rainfall deciles for the past 30 years (1994–2024). A decile map shows where rainfall is above average, average or below average for this period compared to all years from 1900 to 1993.

Rainfall during the northern wet season varies from year to year. Wetter than average years have been more common in recent decades.



Source: Bureau of Meteorology

Anomalies of October to April rainfall for northern Australia (from 26° S northwards). Anomalies are calculated with respect to the 1961–1990 average. The line shows the 11-year running mean.

Heavy rainfall

- Heavy short-term rainfall events are becoming more intense.

Observations show an increase in the intensity of heavy rainfall events in Australia. The intensity of short-duration extreme rainfall events has increased by around 10% or more in some regions and in recent decades, with the largest increases typically observed in the north of the country. Short-duration extreme rainfall events (such as high hourly total rainfalls) are often associated with flash flooding, which brings increased risk to communities. This is particularly the case in urban environments, where the prevalence of impervious ground cover (e.g. concrete) leads to increased flooding during heavy downpours.

Heavy short-term rainfall events are usually caused by weather systems such as thunderstorms, tropical cyclones, and monsoon and east coast lows. Widespread heavy rainfall at a range of timescales can also be linked to other types of systems, including extratropical lows and fronts.

Daily rainfall totals associated with thunderstorms have increased since 1979, particularly in northern Australia. This is primarily due to an increase in the intensity of rainfall per storm. Conversely, the number of low-pressure systems that can bring sustained heavy rainfall to highly populated parts of southern Australia has declined in recent decades. This has implications for recharging surface water storages and groundwater, and water resource management.

Source: unsplash.com

Heavy rainfall, climate change and flood risk

The intensity of heavy rainfall events in Australia is increasing as the climate warms. Warmer air can hold more water vapour than cooler air, and moisture in the atmosphere can increase by 7% per degree of warming, all other things being equal. This can cause an increased likelihood of heavy rainfall events, even in areas where average rainfall is likely to decrease such as some regions of southern Australia.

Observational data indicate that daily rainfall extremes that happen once per year or less often are likely to intensify by an average of about 8% for each degree of global warming, although this varies with region. Hourly extreme rainfall is also likely to increase by around 15% per degree of warming, well above the 7% that would arise from increased moisture content in a warmer atmosphere alone.

While the role of climate change in recent extreme heat in Australia is very well established, attributing individual heavy rainfall events to climate change is more challenging. Interannual variability in heavy rainfall in Australia is high compared with most other parts of the world, which is linked to major climate influences including La Niña and the Indian Ocean Dipole (IOD). A potential increase in rainfall intensity of 10% relative to pre-industrial climate is small relative to the typical difference in heavy rainfall between El Niño and La Niña years in much of Australia, making any potential climate change signal difficult to detect in observations of any individual event.

Climate model simulations project that heavy rainfall events will further intensify during the 21st century, with the rate of intensification proportional to the rate of global warming. Changes in heavy rainfall in particular locations are also influenced by changes in weather systems, such as east coast lows and tropical cyclones, both of which are expected to become less frequent. This may lead to some regions experiencing trends in heavy rainfall that differ from typical values at the national or global scale, particularly for rainfall events that occur multiple times per year as opposed to rarer events. Increased atmospheric moisture can also provide more energy for some processes, such as enhanced updrafts in thunderstorms, that generate heavy rainfall events, which can further increase the intensity of heavy rainfall due to global warming. In addition, although widespread heavy rainfall typically occurs when very high atmospheric moisture coincides with unusually severe or persistent synoptic systems, localised heavy rainfall from thunderstorms may not as be well simulated by climate models as larger-scale systems are.

Climate change may also affect the drivers of, and processes involved in, multi-day rainfall extremes. These include atmospheric rivers which are responsible for the transport of large quantities of moisture, the behaviour of El Niño and La Niña, and persistent blocking highs (strong high-pressure systems that remain almost stationary for an extended period of time, blocking the eastward progression of weather systems across southern Australia) in the Tasman Sea. The details of these effects are subject to ongoing research.

Heavy rainfall is one of the major drivers of flood risk, which is one of the major natural hazards facing Australia. Multiple factors contribute to flood risk. The most important weather-related factors include how extreme a rainfall event is and how wet catchments are prior to the rain event. In estuarine and coastal environments, tides and sea levels can also be important. Flood risk can also change over time as a result of changes in land use and land cover, and through changes in the extent to which streams in the catchment area are regulated. Flood risk is influenced by rainfall at a range of timescales, depending on the catchment. Flash flooding is driven by intense rainfall in localised regions on timescales of minutes to hours, while flooding in larger catchments responds to rainfall on timescales of days to weeks.

Sustained heavy rainfall and associated flooding in much of Australia, particularly the east, is most common during La Niña, as illustrated by the multiple floods that occurred in eastern Australia in 2022. The 11 wettest years on record in eastern Australia were all influenced by La Niña, and many of eastern Australia's most significant flood years, such as 1974, 2010–2011 and 2021–2022, have occurred during strong La Niña events, although significant flooding can sometimes occur in non-La Niña years. For a given flow level, larger floods occur when soil moisture levels are high. The impact of multiple flood events is particularly pronounced when La Niña events occur in multiple successive years, as occurred in 2020–2022, and previously in periods such as 1954–1956 and 1973–1976.

Streamflow

- More than 28% of hydrologic reference stations around Australia show significant decreases in streamflow since 1970 while only 4% of gauges have shown significant increases.
- The significant decreases in streamflow are concentrated in southern Australia, while the increases are almost all in the north.

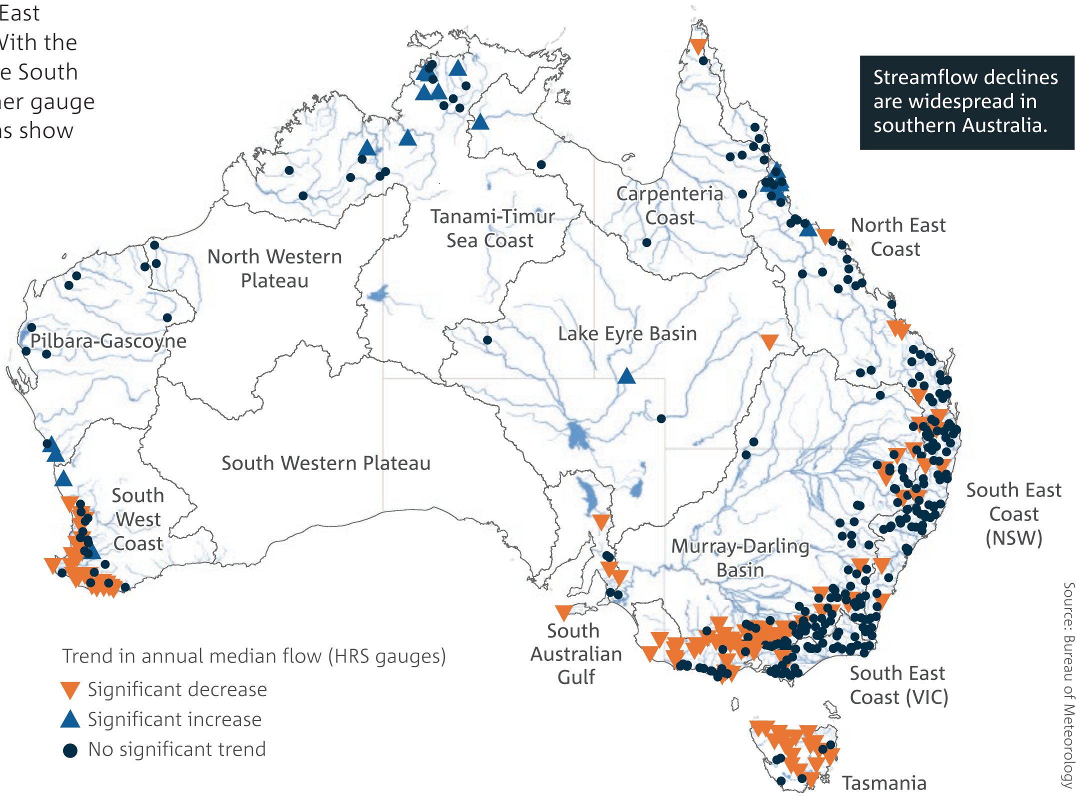
The observed long-term reduction in rainfall across many parts of southern Australia has led to reduced streamflow, although with considerable interannual variability. More than 28% of Australia's Hydrologic Reference Stations (HRS) gauges show a significantly declining trend in annual median streamflow since 1970. HRS are gauges in catchments with little disturbance from human activities and with at least a 30-year record, and are an indicator of long-term impacts from climate change on streamflow. Across the HRS gauges, the drainage divisions with the highest proportion of stations with significant declines are Tasmania (19 out of 25), South West Coast (30 out of 50), Murray-Darling Basin (40 out of 129), South Australian Gulf (4 out of 7) and South East Coast (VIC) (19 out of 66). With the exception of 2 gauges in the South West Coast division, no other gauge in these 5 drainage divisions show any increasing trend.

Significant increases in streamflow have been observed at only 4% of the 459 assessed gauges. Increases are almost exclusively in the northern half of the country, in the Tanami-Timor Sea Coast, North East Coast, Carpentaria Coast and Pilbara-Gascoyne drainage divisions where wet season rainfall has generally increased.

The North East Coast drainage division exhibits mixed trends, with increases in the north and decreases in the south. Increases in the other northern Australian divisions are prominent and no gauges show significant declines.

Nearly one third of the HRS gauges in the Murray-Darling Basin show significantly declining streamflow trends, with the highest proportion in the southern Basin including the Avoca, Broken, Campaspe, Loddon, Wimmera and Goulburn catchments. In the northern Basin, the Border Rivers, Namoi and Gwydir catchments have the highest number of gauges with significant declines.

Declining trends are also observed in the magnitude of annual high and low flows, with more reductions observed in high flows, and reduced flow duration including fewer days with high flows. In more than half of the gauges in the Murray-Darling Basin, North East Coast, South Australian Gulf, South East Coast (VIC), South West Coast and Tasmania divisions, the number of days at or above high flow thresholds has been reduced. At gauges in the Tasmania, South Australian Gulf and South East Coast (VIC) divisions, low flow days have increased and high flow days have decreased, which indicates a general reduction of water availability in the streams at those locations.



Streamflow declines are widespread in southern Australia.

Source: Bureau of Meteorology

Trends in annual median streamflow from available data in the 1970–2023 period at Hydrological Reference Stations. Significance is indicated at a 95% probability level.

Tropical cyclones

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

Tropical cyclone activity in the Australian 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. Intense tropical cyclones can cause serious impacts associated with catastrophic winds, storm surges and heavy rainfall and flooding.

There has been a downward trend in the number of tropical cyclones observed in the Australian region since reliable satellite observations began in 1982. Additional non-satellite observations suggest there has also been a longer-term reduction in the number of tropical cyclones since 1900.

The trend in cyclone intensity in the Australian region is harder to quantify than cyclone frequency, due to uncertainties in estimating the intensity of individual cyclones and the relatively small number of intense cyclones.

Snowfall

- Maximum snow depth, snow cover and number of snow days have all decreased in Australian alpine regions since the late 1950s.

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 have also been observed. The number of snowfall days has also decreased. Years with persistent deep snow cover have become rare.

Snow depth is closely related to temperature, and the observed declines are associated with global warming trends. Decreasing trends in snow depth are greater in the late-season month of September than during winter. Maximum snow depth remains highly variable and is strongly influenced by rare heavy snowfall days, which have no observed trends in frequency.

Source: pexels.com

Oceans

Sea surface temperature

- Sea surface temperatures around Australia have warmed by over 1 °C since 1900.

Average sea surface temperature in the Australian region has warmed by 1.08 °C since 1900, with 9 of the 10 warmest years on record occurring since 2010. This rate of warming is close to that of the global mean sea surface temperature. The year with the highest average sea surface temperature on record was 2022, which was associated with a strong negative Indian Ocean Dipole event and mass coral bleaching in the Great Barrier Reef, which had never previously occurred in a La Niña event. Extremely high Australian region sea surface temperatures have previously been associated with the end of significant El Niño events.

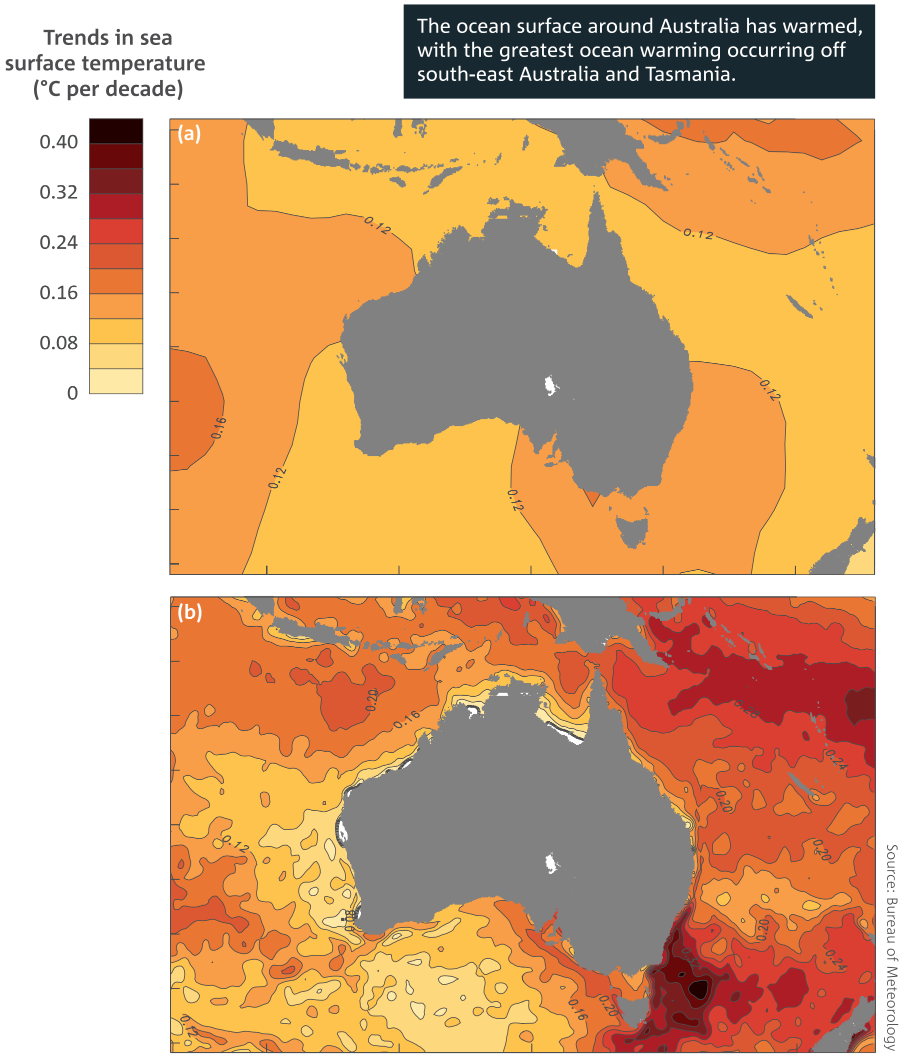
The greatest ocean warming in the Australian region has occurred in the Coral Sea, and off south-east Australia and Tasmania where more rapid warming trends have occurred over the past 4 decades. The East Australian Current now extends further south, creating an area of more rapid warming in the Tasman 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 west coast of Australia.

Warming of the ocean has contributed to longer and more frequent marine heatwaves. Marine heatwaves are periods when temperatures are in the upper range of historical baseline conditions for at least 5 days. 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 contributed to permanent impacts on marine ecosystem health, marine habitats, and species.

These impacts include depleting kelp forests and seagrasses, a poleward shift in marine species, and increased occurrence of disease.

The ocean surface around Australia has warmed, with the greatest ocean warming occurring off south-east Australia and Tasmania.



Source: Bureau of Meteorology

Trends in sea surface temperature in the Australian region (4–46° S and 94–174° E) (a) over 1950–2023 based on the NOAA Extended Reconstructed SST (ERSST) v5 product, and (b) over 1981–2023 based on the Optimum Interpolation SST (OISST) product derived from various in-situ and satellite observation platforms.

Ocean heat content

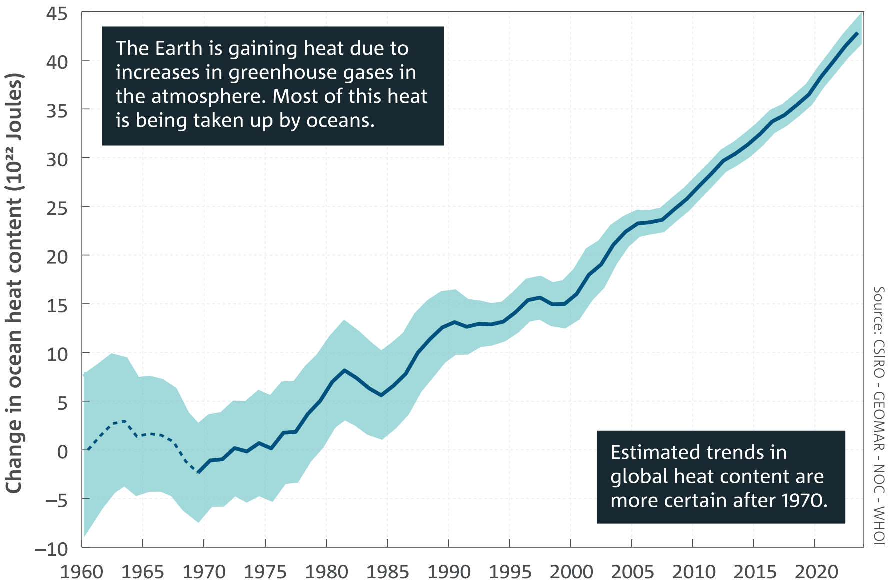
- The world’s oceans have taken up more than 90% of the extra energy stored by the planet as a result of enhanced greenhouse gas concentrations. Measuring changes in ocean heat content is therefore an effective way to monitor global warming.
- The ocean does not warm evenly. Some regions, including some around Australia, show increases in ocean heat several times faster than the global mean.
- 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, taking up vast quantities of heat from the atmosphere and redistributing it. Seawater stores about 4 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. The way the ocean redistributes this heat influences our weather patterns and the climate change signal we see in temperature and rainfall.

While the temperature changes over the whole ocean depth are small compared to those at the land and ocean surface, the ocean has taken up more than 90% of the excess energy in the Earth system arising 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.

Ocean warming has accelerated since the early 2000s. In 2023, the global ocean heat content was the highest on record, with an estimated additional 42.8 ±1 x 10^{22} joules of energy relative to 1960. The Southern Ocean has taken up more than half of that excess heat, as its circulation takes heat from near the surface and transfers it into the deep ocean. A warming ocean affects the global ocean and atmospheric circulation, the cryosphere, global and regional sea levels, oceanic uptake of anthropogenic CO_2, and causes losses in dissolved oxygen and impacts on marine ecosystems.

Regionally, ocean warming can vary substantially from year to year due to climate phenomena such as the El Niño-Southern Oscillation. In areas of strong warming, changes in heat content can be several times larger than the global mean change. This is the case in the oceans around Australia, where strong warming results from a redistribution of heat due to changes in the structure of the East Australian Current, and enhanced heat uptake in the subantarctic region south of Australia.



The Earth is gaining heat due to increases in greenhouse gases in the atmosphere. Most of this heat is being taken up by oceans.

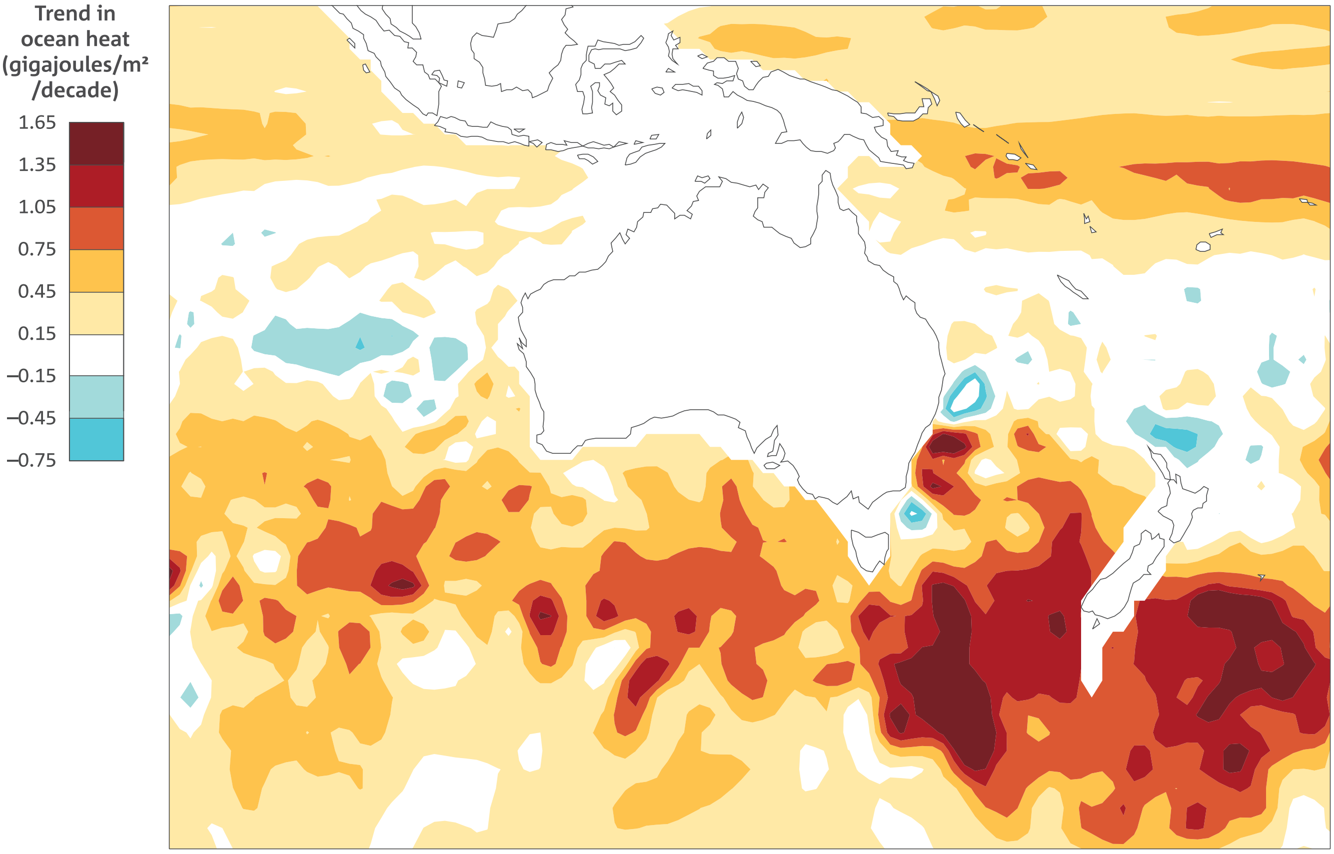
Estimated trends in global heat content are more certain after 1970.

Source: CSIRO - GEOMAR - NOC - WHOI

Estimated change in ocean heat content globally averaged over the full ocean depth, from 1960–2023. Shading indicates 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. Source: CSIRO, GEOMAR (Germany) and National Oceanographic Centre (UK), Woods Hole Oceanographic Institute (USA)

Year-to-year changes in ocean heat content associated with interannual climate variability are large in the top 300 metres of the ocean but have little impact on the waters below. On long-term timescales, the deep waters below 2,000 metres have also warmed throughout most of the global ocean, but there are far fewer observations of the deep ocean and the magnitude of this warming is less certain. Maintaining the global ocean observing system and expanding its coverage in the deep ocean, the polar oceans, and continental shelves will be critical to prepare for, and adapt to, a changing climate.

Southern Hemisphere oceans have taken up the majority of the extra heat from global warming. Since 2005, Argo floats have provided unprecedented resolution of the ocean. Trends derived over this period are consistent with the long-term record.



Source: SIO (USA) and CSIRO

Estimated trend in ocean heat content in the upper 2,000 metres between 2005 and 2023. The highest uptake of heat occurred in regions where the circulation draws heat into the deep ocean, such as the Southern Ocean (data source Scripps Institute of Oceanography, Roemmich and Gilson Argo climatology).

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. Mass coral bleaching events have occurred with increasing frequency and extent around the world since the 1970s, including on the Great Barrier Reef. Mass bleaching is a stress response of corals that occurs primarily due to elevated ocean temperature. Recovery is possible, but mortality can occur if the thermal stress is too severe or prolonged. Ocean acidification places further stress on corals.

Five mass coral bleaching events have occurred on the Great Barrier Reef over the past 10 years: in 2016, 2017, 2020, 2022 and 2024. In 2016, bleaching was associated with then record high sea surface temperatures, which in turn led to the largest recorded mass bleaching to date on the Great Barrier Reef. The impact of the 2020 mass bleaching event was associated with severely bleached coastal reefs along the entire 2,300 km length of the Great Barrier Reef. The 2022 event was the first time that mass bleaching occurred on the Reef during a La Niña year. Accumulated thermal stress during the 2024 event was higher than in 2016, although the full impact in terms of bleaching is still being assessed.

These 5 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 fully recover.

In 2022 bleaching was also observed on some reefs on Australia's west coast, including Ningaloo Reef. This was due to warm ocean temperatures, driven by the 2021–2022 La Niña. The region's previous severe marine heatwave was driven by the 2010–2011 La Niña, which resulted in bleaching being recorded for the first time on Ningaloo and the closure of several Western Australian fisheries.

Climate models project more frequent, extensive, intense and longer-lasting marine heatwaves in future. Worsening impacts on coral reefs from marine heatwaves are expected in the future with continued warming. The intensification of marine heatwaves is much greater under high greenhouse gas emission scenarios. More frequent and severe coral bleaching events are likely, potentially leading to the loss of many types of coral and impacts on reef fisheries. 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.

Source: unsplash.com

Sea level

- Global mean sea level has risen by over 22 cm since 1900. Half of this rise has occurred since 1970.
- Rates of sea level rise since 1993 vary across the Australian region, with the largest increases to the north and south-east of the Australian continent.

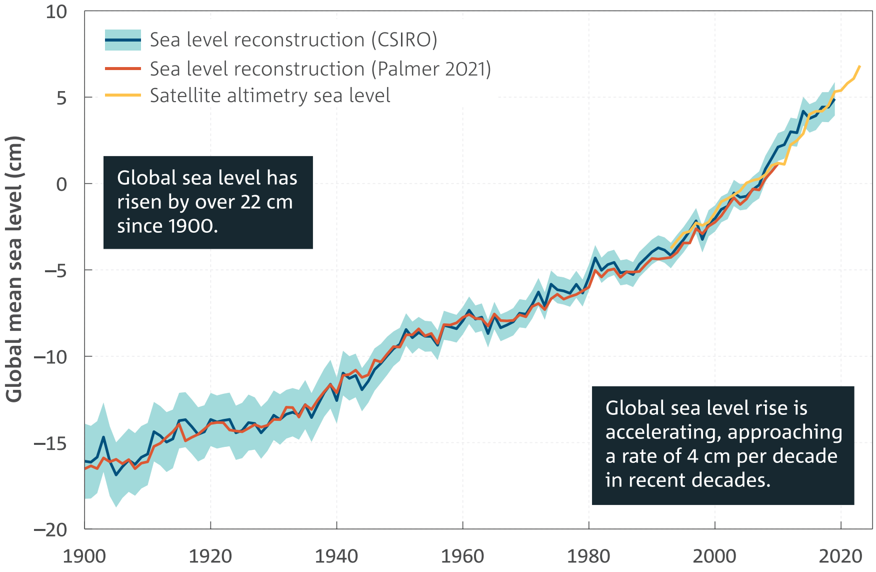
Global mean sea level has risen by over 22 cm since 1900, with half of this rise occurring since 1970. Rising sea levels pose a significant threat to coastal communities and coastal ecosystems by amplifying the risks of coastal inundation, storm surge, erosion and saltwater intrusion into groundwater systems. Coastal communities in Australia are already experiencing some of these changes.

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 cm (± 0.2 cm) per decade from 1901 to 2000, and is now approaching 4 cm (± 0.4 cm) per decade from 1993 to 2023. The dominant cause of global mean sea level rise since 1970 is anthropogenic climate change.

As the ocean warms it expands, causing sea levels to rise. This thermal expansion has contributed about one-third of the sea level rise observed globally. 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.

Confidence in assessing changes in global mean sea level has continuously improved because there has been more analysis of satellite altimetry data, and because the data record becomes longer over time. Ongoing research has also resulted in increased confidence in quantifying the various contributions to sea level rise, and a greater understanding of the processes involved.

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. Satellite altimetry observations since 1993 show that the rates of sea level rise to the north and south-east 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, or lower than, the global average. Altimetry data show higher sea level rise near Australia's south-east coast than near the south coast, which may indicate the emergence of climate change impacts from a poleward shifting and strengthening of the subtropical ocean gyre circulation, of which the East Australian Current is a part.



Global sea level has risen by over 22 cm since 1900.

Global sea level rise is accelerating, approaching a rate of 4 cm per decade in recent decades.

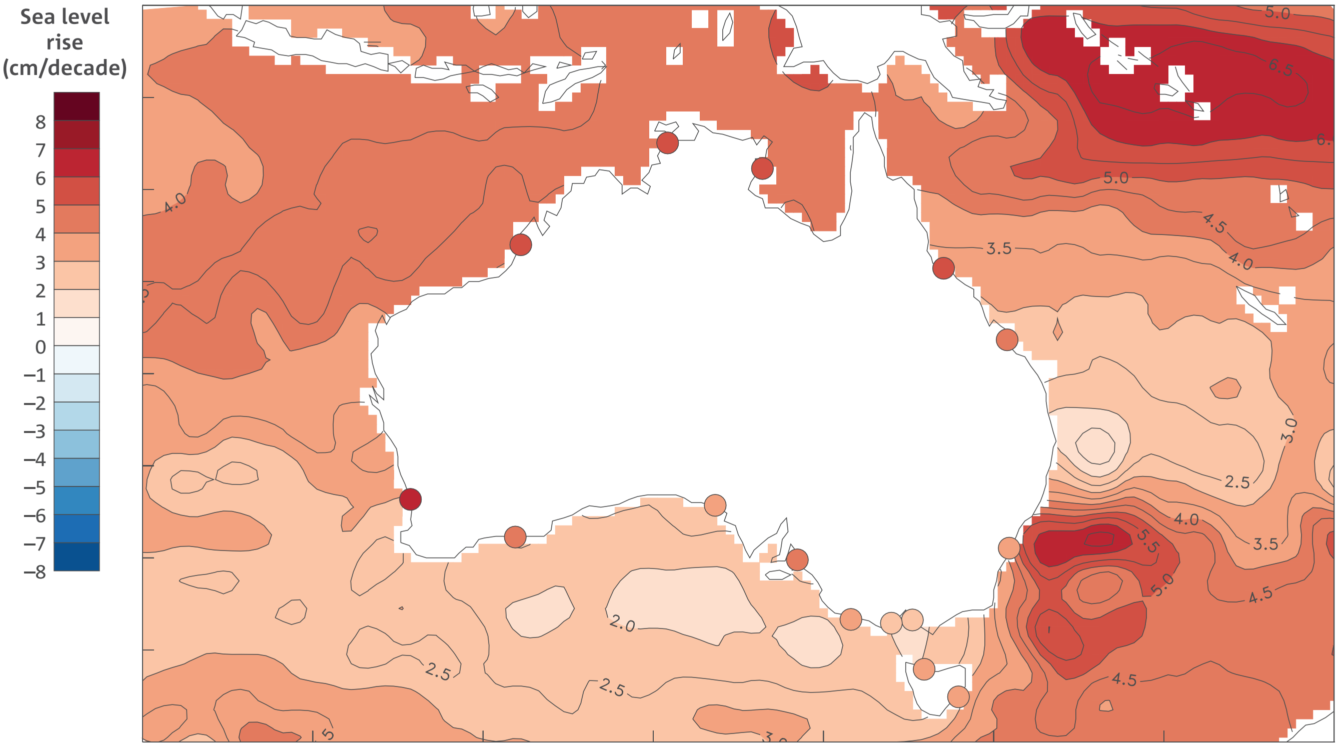
Source: CSIRO

Global mean sea level change (in cm) from 1900 to 2019 reconstructed with tide gauges from CSIRO (blue line), Palmer et al. (2021; red line) and global mean sea level based on satellite altimetry between 1993 and 2023 (yellow line). Shading indicates the confidence range of the estimates.

The long-term satellite altimetry sea level record is typically restricted to the offshore region, beyond 25–50 km from the coast, while changes closer to Australia’s shoreline are estimated from tide gauge measurements at a limited number of locations. Tide gauges with reliable long-term records around Australia show overall changes in sea level rise that are consistent with offshore observations from satellite altimetry. Where local differences exist between coastal and offshore data, they may be influenced by factors such as local coastal processes and the effects of vertical land motion.


Source: CSIRO

Sea levels have risen around Australia.



Source: Bureau of Meterology and NOAA

The rate of offshore sea level rise (in cm per decade) around Australia measured using satellite altimetry from 1993 to 2023, and onshore sea level rise (coastal points) from the multi-decadal tide gauge dataset from the Australian Baseline Sea Level Monitoring Project. The colour scale applies to both the altimetry and tide gauge observations.

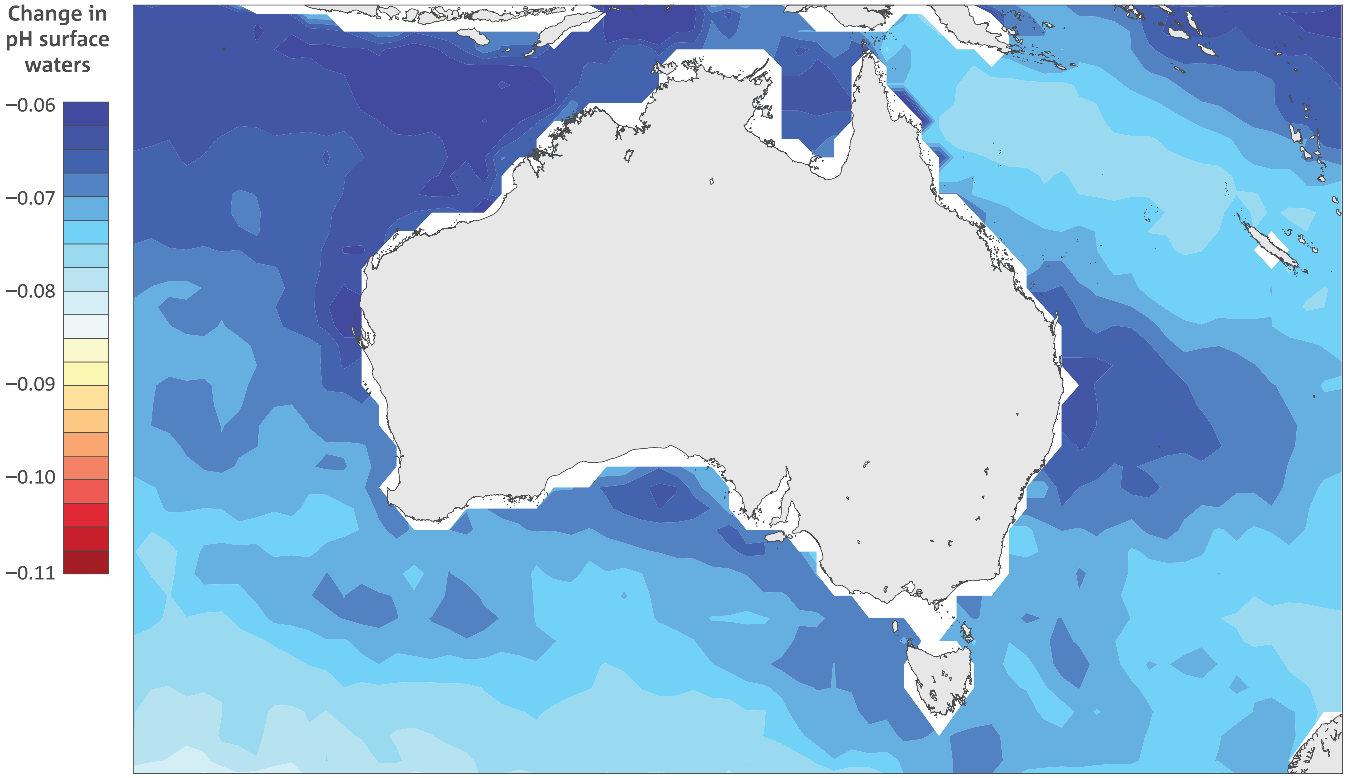
Ocean acidification

- The acidification of the oceans around Australia continues (pH is decreasing), with changes happening faster in recent decades.
- Increasing CO_2 in the atmosphere will continue to drive ocean acidification, with the greatest changes in acidity occurring south of Australia.

Rising atmospheric CO_2 levels increase the uptake of CO_2 by the oceans, which absorb 26% of annual global emissions. This affects the oceans' carbonate chemistry and decreases their pH, a process known as ocean acidification. The pH changes in surface waters are primarily driven by increasing CO_2 in the atmosphere, causing the uptake of CO_2 which reacts with water producing hydrogen ions and a pH decrease. Impacts of ocean acidification on marine ecosystems include changes in reproduction, organism growth and physiology, species composition and distributions, food web structure, nutrient availability, and reduced calcification rate. The latter is particularly important for species that produce shells or skeletons of calcium carbonate, such as corals and shellfish. Ocean acidification is occurring along with changes in ocean warming and deoxygenation, resulting in compounding pressures on the marine environment.

Since the decade of 1880–1889 the average pH of surface waters around Australia and globally is estimated to have decreased by about 0.12, corresponding to about a 30% increase in acidity. There are regional variations in acidity increases; between 1982 and 2022 the greatest acidity increases have occurred in the Southern Ocean (21%) and in the Coral Sea (19%), with the smallest increases to the north-west of Australia (15%).

The acidity of waters around Australia is increasing (pH is decreasing).



Source: OceanSODA-ETHZ

The pH change of surface waters around Australia between 1982 and 2022 (data sourced from the OceanSODA-ETHZ dataset). Calculations are based on data from the Integrated Marine Observing System and other programs.

The pH changes tend to be greater at higher latitudes where there is more total dissolved CO_2 in the surface waters, which reduces their capacity to buffer against pH change. The major boundary currents that transport surface waters poleward along the Australian coast also influence patterns of pH changes along with regional temperature and precipitation trends.

The current rate of change of pH in open ocean surface waters is about 10 times faster than at any time in the past 65 million years, and the rate of acidification has grown in recent decades. Some ecosystems are now exposed to conditions outside the pH ranges experienced in the pre-industrial era before 1850. The changes are expected to reduce the capacity of coral reefs, including those of the Great Barrier Reef, to survive and grow. The growth of many carbonate producing organisms along the southern Australian shelf including commercially important shellfish are also likely to be impacted in future as acidification continues with rising atmospheric CO_2.

Source: unsplash.com

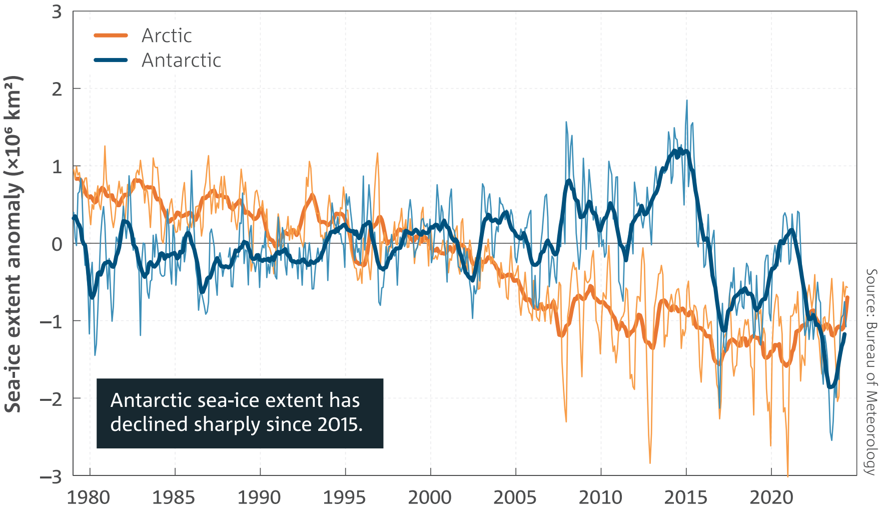
Cryosphere

- The ice sheets and ice shelves of Antarctica and Greenland are losing ice due to a warmer climate, which is contributing to global sea level rise.
- There has been an abrupt decrease in Antarctic sea-ice extent since 2015, after a small increase over the period from 1979 to 2014.

The cryosphere is the part of Earth's surface characterised by frozen water. The cryosphere includes the ice sheets (glacial ice that has accumulated from precipitation over land) and ice shelves (floating sheets of ice formed from glacial ice sheets). Together the ice sheets of Antarctica and Greenland contain about 99% of the Earth's fresh water, which is the equivalent of over 60 metres of sea level rise.

Ice shelves around Antarctica help stabilise the ice sheet there 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, along with increased iceberg calving, is now destabilising several glaciers, increasing the Antarctic contribution to sea level rise. Surface melt, particularly over Greenland and the Antarctic Peninsula, is also contributing to sea level rise. Partially offsetting this is increased precipitation (snowfall) over Antarctica, due to increased evaporation of moisture from nearby oceans as a result of reduced sea-ice extent. Over the last few decades, the Amundsen Sea sector contributed most to the net mass loss of the Antarctic ice sheet. Between January and November 2023, the net mass loss over the Antarctic ice sheet is estimated to be about 170 Gt. This is in contrast to the net mass gain observed in 2022 which was the highest on record (since 1980), driven by enhanced snowfall.

Unlike the continental ice sheets, changes in sea ice shelves have a negligible direct impact on sea level, though sea ice influences the rate of regional climate warming and ocean/atmosphere moisture fluxes. Since the commencement of satellite monitoring of sea ice in the late 1970s, Arctic sea-ice cover has consistently decreased, whereas the Antarctic has shown a more complex pattern of changes. Overall, Antarctic sea-ice extent increased slightly from 1979 to 2014, but with substantial regional and seasonal variations. The largest daily recorded wintertime sea ice extent since satellite monitoring began, of approximately 20.2 million km^2, was in September 2014. Since 2014, there has been a marked, abrupt and relatively persistent decrease in net sea ice extent, which in early 2022 dropped below 2.0 million km^2 for the first time since satellite observations began. Extraordinarily low net Antarctic sea-ice extents occurred throughout 2023, with new record low observations in 7 months. Unusually, negative anomalies in sea-ice extent almost surrounded the continent, with only the Bellingshausen and Amundsen Seas showing positive ice extent anomalies. Regional negative anomalies were coincident with above average upper ocean and surface temperatures.



Antarctic sea-ice extent has declined sharply since 2015.

Source: Bureau of Meteorology

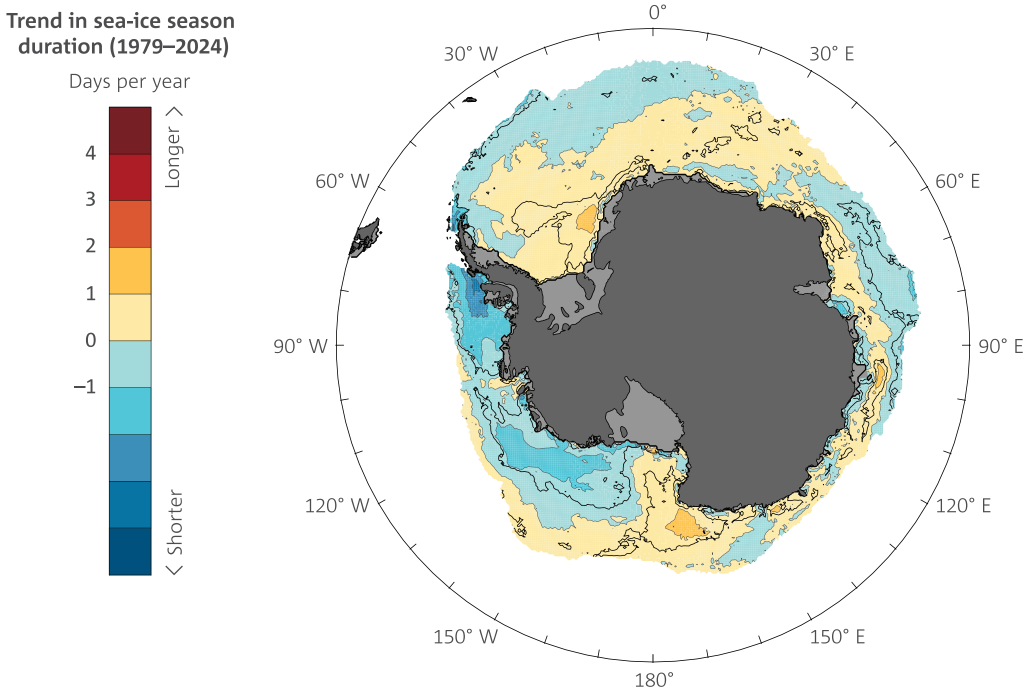
Antarctic and Arctic sea-ice extent (shown as the anomaly relative to 1981–2010) for January 1979 to April 2024 (10^6 km^2). Thin lines are monthly averages and indicate the variability at shorter timescales, while thick lines are 11-month moving averages (centred).

Regionally the trend in sea-ice cover has been variable. Statistically significant trends over the 1979–2023 period show reduced sea-ice duration, by as much as 4 days per year, to the west of the Antarctic Peninsula, offshore of West Antarctica and within the Bellingshausen Sea. These are in contrast to increased sea-ice duration within the western Ross Sea and the southern region of the Weddell Sea, although these increases are smaller, only locally reaching 1 to 2 days per year.

The overall increase in Antarctic sea-ice extent from 1979 to 2014 has largely been attributed to changes in westerly wind strength, whereas the marked decrease since 2015 has been attributed to a combination of atmospheric and oceanic anomalies. The primary influence on low sea-ice growth in recent years, particularly in 2023 and 2024, has been abnormally warm subsurface temperatures in the Southern Ocean, with additional impacts from anomalies caused by large-scale weather patterns across the region.

Reduced Antarctic sea-ice coverage and growth can have significant impact on the global climate, including changes in the ocean circulation. Increased glacial melt has been shown to slow the sinking of dense cold water around the Antarctic margin, causing warming and deoxygenation of the deep ocean. Slowing of the ocean overturning circulation (the network of ocean currents that circles the globe and connects the upper and lower layers of the ocean) would impact climate by reducing how much heat and carbon the ocean can absorb from the atmosphere and transfer to the deep ocean. Slowing of the overturning would also reduce oxygen levels in the deep ocean and the cycling of nutrients and carbon between the upper and lower layers of the ocean.

Further, the reduced presence of sea ice around the continental edge removes the barrier between ocean swell and waves and the ice shelves, potentially destabilising ice shelves and inducing sudden collapse. Since 2022 there has been anomalously high Antarctic coastal exposure (regions of coastline not protected by a sea-ice buffer), with 154 days of record high coastal exposure during 2023.



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 2023–2024. 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 major long-lived greenhouse gases continue to rise in the atmosphere, driving further climate change.
- The rate of CO_2 accumulation in the atmosphere has increased every decade since atmospheric measurements began. Global average annual mean CO_2 concentration reached 419.2 ppm in 2023. Adding all greenhouse gases together, concentrations reached 524 ppm of CO_2-equivalent.
- Over the past 2 years, the amounts of atmospheric methane and nitrous oxide have increased rapidly.

The primary and unequivocal driver of climate change since the 1850–1900 period is the accumulation of greenhouse gases in the atmosphere. Global mean surface warming throughout the 21st century will be largely determined by cumulative emissions of carbon dioxide (CO_2) and the other long-lived greenhouse gases, and what proportion of those emissions persist in the atmosphere.

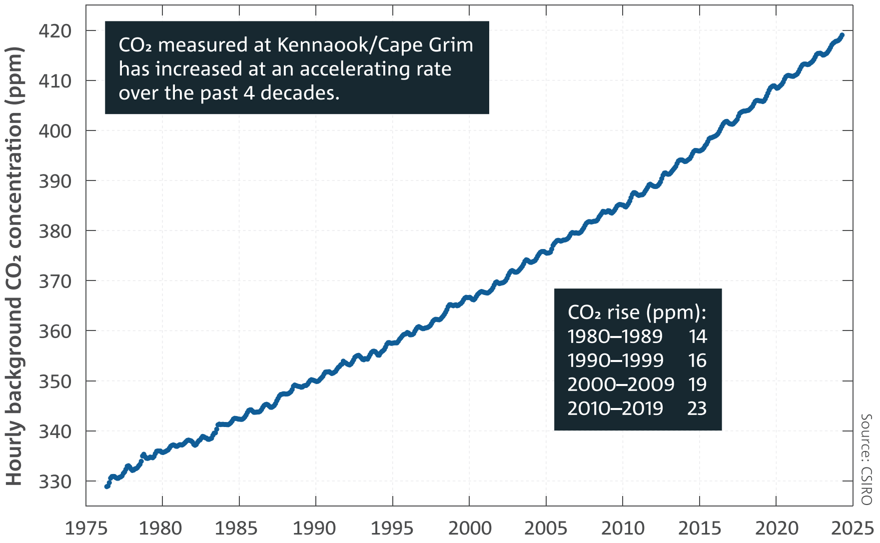
Globally averaged atmospheric concentrations of all major long-lived greenhouse gases, and a group of synthetic greenhouse gases industrially produced for uses such as refrigeration, continue to rise.

The global annual mean CO_2 concentration in 2023 was 419.2 ppm—a 51% increase from the concentration of 277 ppm in 1750 found from air trapped in Antarctic ice.

Other long-lived greenhouse gases also contribute to global warming. The most significant of the non-CO_2 greenhouse gases are methane and nitrous oxide. In 2023, the global annual mean concentration of methane was 1,919 parts per billion (ppb), while for nitrous oxide it was 337 ppb. Respectively, these are rises of 162% and 23% above their 1750 levels of 731 ppb and 273 ppb measured in Antarctic and Greenland ice.

Methane (CH_4) is the second most important greenhouse gas in terms of radiative forcing and is emitted from a wide range of sources. Natural microbial decomposition of organic matter in wetlands is the largest single source of methane emissions. However, human activities are responsible for emissions from fossil fuel extraction and use (including natural gas), farming of livestock, rice cultivation and waste from landfills and agriculture. Together, these sources account for about 65% of global methane emissions. Methane has a global warming potential 81 times that of CO_2 when measured over a 20-year timeframe. However, it persists in the atmosphere for only around a decade, so efforts to reduce methane emissions will have a large impact on reducing warming on a short timescale. Therefore, reducing atmospheric methane is an important component of pathways to manage climate change. However, since 2020, atmospheric methane concentration has increased rapidly, by more than 10 ppb per year, with rises of 13 and 10 ppb in 2022 and 2023 respectively.

Nitrous oxide (N_2O) has a global warming potential 273 times that of CO_2 when measured over a 20-year timeframe. It is emitted naturally from the land and oceans. Use of nitrogenous fertilisers is the largest anthropogenic source, and it has been rising steadily in recent decades, leading to accelerating atmospheric growth rates. Throughout 2022 and 2023, nitrous oxide has grown in the atmosphere by more than 1 ppb per year. The growth rate of nitrous oxide, measured directly or through Antarctic ice and compressed snow (firn), has been less than 1 ppb per year for at least the past 2000 years, until the last decade when it has been greater than 1 ppb per year 7 years out of 10.



Background monthly mean CO_2 in clean air as measured at the Kennaook/Cape Grim Baseline Air Pollution Station from 1976 to June 2024. The monthly means are computed from hourly data and represent thousands of individual measurements. To obtain clean air measurements, the data are filtered to include only periods when weather systems have travelled across the Southern Ocean and the sampled air is thus free from local sources of pollution (Steele, 2014). The increase in CO_2 concentration for each decade (1 January for the start year and 31 December for the end year) is also shown.

Kennaook/Cape Grim Baseline Air Pollution Station

The Kennaook/Cape Grim Baseline Air Pollution Station, located at the north-west tip of Tasmania, is the Southern Hemisphere's key greenhouse gas monitoring station in the World Meteorological Organization's Global Atmosphere Watch program. It has been running continuously for 48 years.

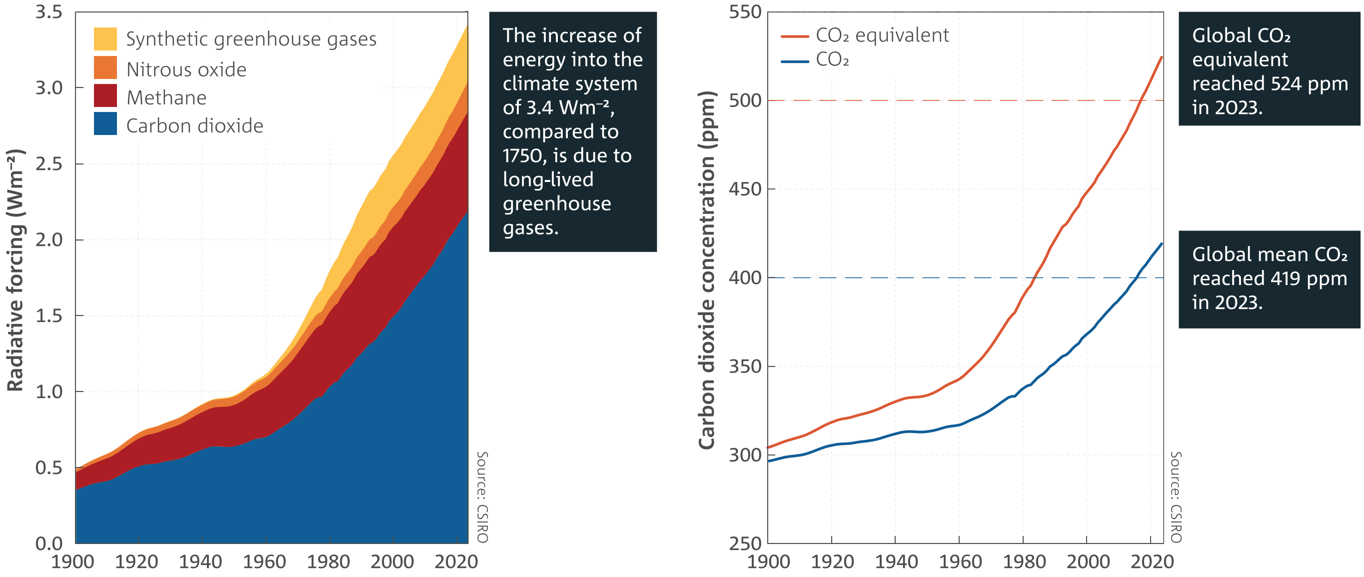
Atmospheric concentrations of CO_2 measured at Kennaook/Cape Grim continue to show an upward trend with the decadal growth rates accelerating since measurements began. This is consistent with other stations globally. The annual average CO_2 at Kennaook/Cape Grim reached 416.4 ppm in 2023, slightly lower than the global average of 419.2 ppm.

Kennaook/Cape Grim greenhouse gas concentrations are typically lower than the global averages because most emissions originate in the Northern Hemisphere. It takes many months for Northern Hemisphere air, with higher greenhouse gas concentrations, to mix into the Southern Hemisphere and appear in the Kennaook/Cape Grim observations.

Global anthropogenic CO_2 emissions have levelled off over the last decade after having increased almost continuously for more than a century prior to the early 2010s. Relatively stable emissions from ongoing fossil fuel use and land-use change mean that CO_2 has continued to grow in the atmosphere throughout 2022 and 2023 at a rate of more than 2 ppm per year. This growth rate is similar to averages for the past decade and higher than typical rates in the decades prior to the 2010s.

Substantial global emissions reductions, sustained over a period of 5–10 years, will be required before there is an attributable decline in the atmospheric growth rate of CO_2. To abate climate change requires greenhouse gases to stop accumulating in the atmosphere. This requires the world to reach global net zero emissions; a state in which any residual greenhouse gas emissions are balanced by removal of an equivalent amount of greenhouse gases from the atmosphere.

The combined impact of all greenhouse gases can be converted to a CO_2-e atmospheric concentration by considering the global warming potential (ability to trap heat in the atmosphere) of each gas and its concentration. The annual average CO_2-e measured at Kennaook/Cape Grim reached 518 ppm in 2023, and 524 ppm globally.



The increase of energy into the climate system of 3.4 Wm^{-2}, compared to 1750, is due to long-lived greenhouse gases.

Global CO_2 equivalent reached 524 ppm in 2023.

Global mean CO_2 reached 419 ppm in 2023.

Source: CSIRO

Source: CSIRO

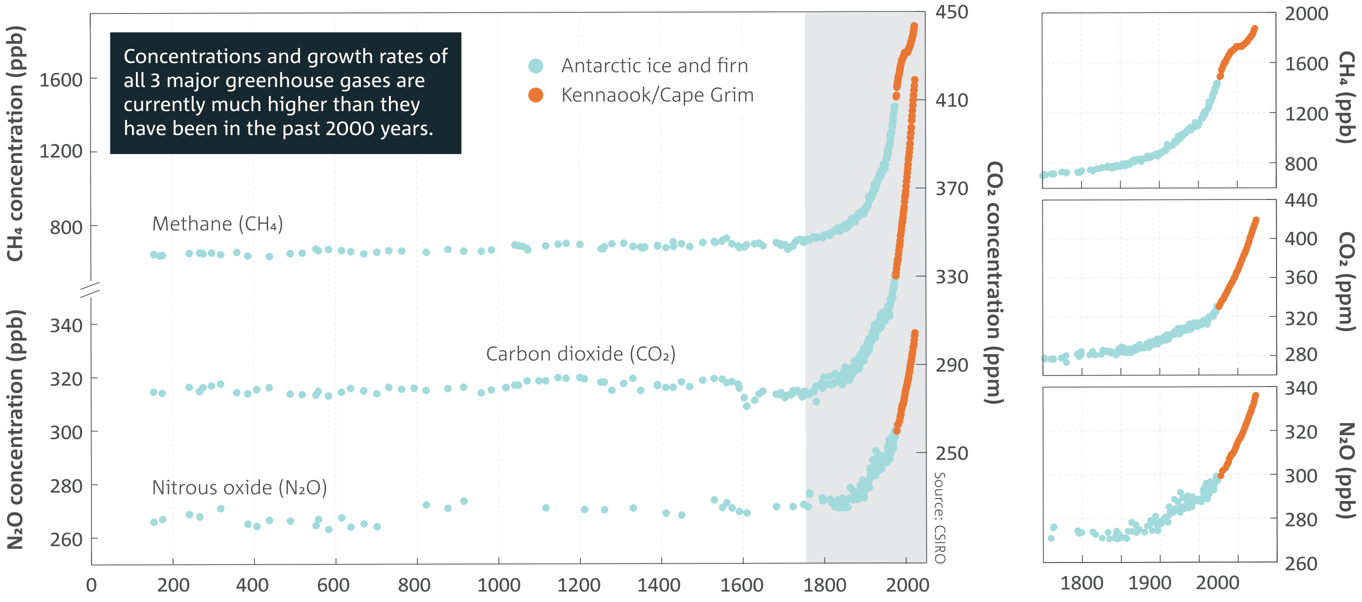
Left: Radiative forcing relative to 1750 due to the long-lived greenhouse gases CO_2, methane, nitrous oxide and the synthetic greenhouse gases, expressed as watts per metre squared. Right: Global mean CO_2 concentration and global mean greenhouse gas concentrations expressed as CO_2-e (ppm). CO_2-e is calculated from the atmospheric concentrations of CO_2, methane, nitrous oxide and the suite of synthetic greenhouse gases.

The cumulative climate effect of all the long-lived greenhouse gases (CO_2, CH_4, N_2O and the synthetic greenhouse gases) in the atmosphere can be expressed as radiative forcing. Radiative forcing is the enhancement of the net radiation, through the additional trapping of energy within the atmosphere. It quantifies the increase in energy in the climate system due to the accumulation of long-lived greenhouse gases into the atmosphere relative to 1750. Because it is the most abundant greenhouse gas, CO_2 is the largest contributor to radiative forcing, but other gases make substantial and growing contributions.

Other changes to the earth system since 1750, including short-lived gases, aerosols (airborne particles), albedo (surface reflectivity) and solar variability have made much smaller contributions to radiative forcing.

Measurements of air extracted from Antarctic ice cores and firn extend the atmospheric composition record back before direct observations commenced. These measurements show that all 3 major greenhouse gases (CO_2, CH_4 and N_2O) were relatively stable for most of the past 2000 years, before beginning to rise in the late 18th century, coincident with industrialisation and the expansion of agriculture. All 3 major greenhouse gases have been increasing at an accelerating pace since around 1850 and are now rising at historically unprecedented rates.

The increase in CO_2 concentration since 1800 originates principally from fossil fuel and land clearing emissions. This is determined by using the isotopes of carbon in atmospheric CO_2 to identify its different sources, with measurements of carbon-13 and carbon-14 relative to carbon-12.



Concentrations and growth rates of all 3 major greenhouse gases are currently much higher than they have been in the past 2000 years.

Source: CSIRO

Concentrations of the major greenhouse gases (CO_2, methane and nitrous oxide) in the atmosphere over the past 2000 years. Blue data are measured from air extracted from Antarctic ice cores and the overlying compressed snow (firn) layer. Orange data show the modern in situ record measured at Kennaook/Cape Grim Baseline Air Pollution Station. Note the different scales used for the concentration of each gas.

Global carbon budget

- Total anthropogenic CO_2 emissions – the sum of fossil and land-use change emissions – levelled off over the past decade after a century-long increase, with a small growth in fossil emissions closely matching a small but uncertain decline in land-use change emissions.
- At current (2023) total annual anthropogenic CO_2 emissions of 40.9 $GtCO_2$, the remaining carbon budget for a 50% chance of limiting warming to 1.5 °C will be exceeded in 7 years. The carbon budget is the amount of allowable emissions for limiting warming to a given global mean temperature.

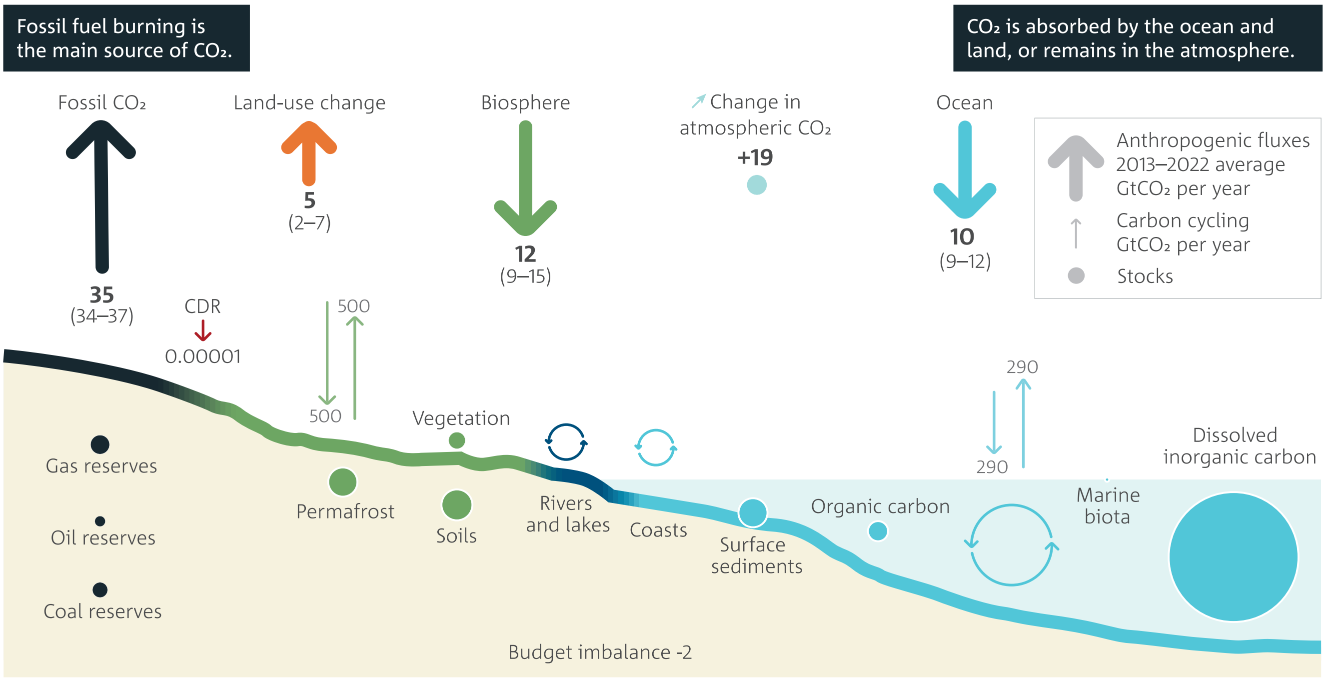
Global emissions from fossil fuel use increased by 1.1 ±1.1% in 2023 from 2022, reaching 36.8±2 billion tonnes of carbon dioxide ($GtCO_2$), compared to 35±2 $GtCO_2$ as the decadal mean of 2013–2022. Emissions from all fuel types (coal, oil, natural gas) increased. Emissions are declining in 26 countries, representing 28% of global emissions, and emissions growth is slowing in other countries. Importantly, these efforts remain insufficient to reverse the growth in global fossil fuel emissions.

Global CO_2 emissions from land-use change, the second largest source of CO_2 emissions, were 4.1±2.6 $GtCO_2$ in 2023, continuing an estimated small decline (with high uncertainty) over the past 2 decades. Global land-use change emissions from permanent forest loss through deforestation are larger than CO_2 removals from reforestation and afforestation.

Total CO_2 emissions – the sum of fossil and land-use change emissions have levelled off over the past decade, with a small growth in fossil emissions closely matching a small but uncertain decline in land-use change emissions. Total emissions were 40.9±3.2 $GtCO_2$ in 2023 leading to a further increase in atmospheric CO_2. The levelling off over the last decade follows emissions increasing almost continuously for more than a century prior to the 2010s.

If current CO_2 emissions levels persist, the remaining carbon budget for a 50% chance to limit warming to 1.5°C above pre-industrial levels will be exceeded in 7 years. Within 15 years, the remaining budget for 1.7°C would be exceeded. Returning global temperatures below these thresholds after they have been crossed would require a huge increase in carbon dioxide removal after global net zero emission has been reached.

The land and ocean CO_2 sinks continue to take up around half of global CO_2 emissions, despite the negative impact of climate change on the land and ocean sinks.



Source: Global Carbon Project

Perturbation of the global carbon budget caused by anthropogenic activities, global annual average for the decade 2013–2022 ($GtCO_2$ per year). Vertical arrows indicate CO_2 fluxes in or out of the atmosphere; the sum of all sources does not match the sum of all sinks because of estimate uncertainties and number rounding. Circle arrows indicate lateral transport or redistribution without an earth component. Solid circles indicate the size of the carbon stocks in GtC. Figure adapted from Friedlingstein et al. (2023).

The Australian carbon budget

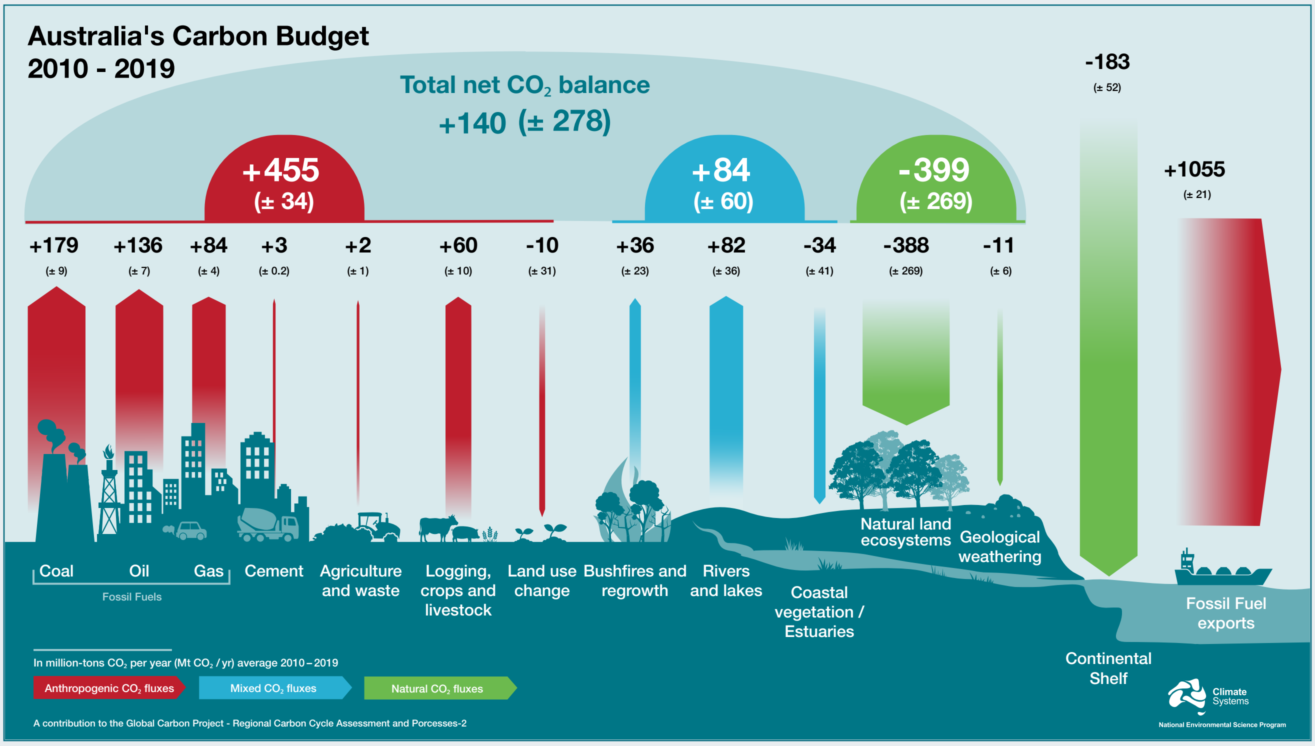
Australia's carbon sources are dominated by human emissions from the extraction and use of fossil fuels – coal, oil, and gas. Logging, crops, and other agriculture add additional CO_2 to the atmosphere. Together these anthropogenic sources averaged a total of 455 $MtCO_2$ emissions per year between 2010 and 2019.

Forests, rangelands, and coastal ecosystems remove a significant portion of anthropogenic emissions, with coastal shelves and open oceans also being a sink for CO_2.

CO_2 emissions from wildfires and prescribed burns are large sources of CO_2 and can be as high as or higher than all fossil fuel emissions in extreme fire years such as during the Black Summer fires. However, post-fire regeneration over the following years to decades offsets a large portion of the emissions, with an average net emissions of 36 $MtCO_2$ per year during the last decade.

When we combine all the land-based CO_2 sources and sinks with the fossil fuel emissions, Australia was a net source to the atmosphere of 200 million tonnes of CO_2 per year between 2010 and 2019. If we count the CO_2 sinks from coastal ecosystems, the contribution to the atmosphere is smaller. This means CO_2 sinks partially offset fossil fuel emissions, albeit with large uncertainties. Australia also transfers large amounts of carbon embedded in its fossil fuel exports, the emissions of which are accounted for in the country where the combustion occurs.

This new assessment of the Australian carbon budget shows that the net annual carbon balance of the entire continent is highly variable from year to year, owing to changes in the behaviour of natural CO_2 sinks. Australia can be a large net source of CO_2 in one year, to carbon neutral the next, to a large net CO_2 sink in the next year. This 'boom and bust' dynamics of Australia's carbon budget, largely driven by the responses of the land CO_2 sinks to rainfall and fire, underscores the potential large impacts of future climate change on Australia's net carbon balance.



Future climate

Research in Australia and around the world, together with the IPCC's Sixth Assessment Report, enhances understanding of the state of Australia's future climate. The changes are projected to include:

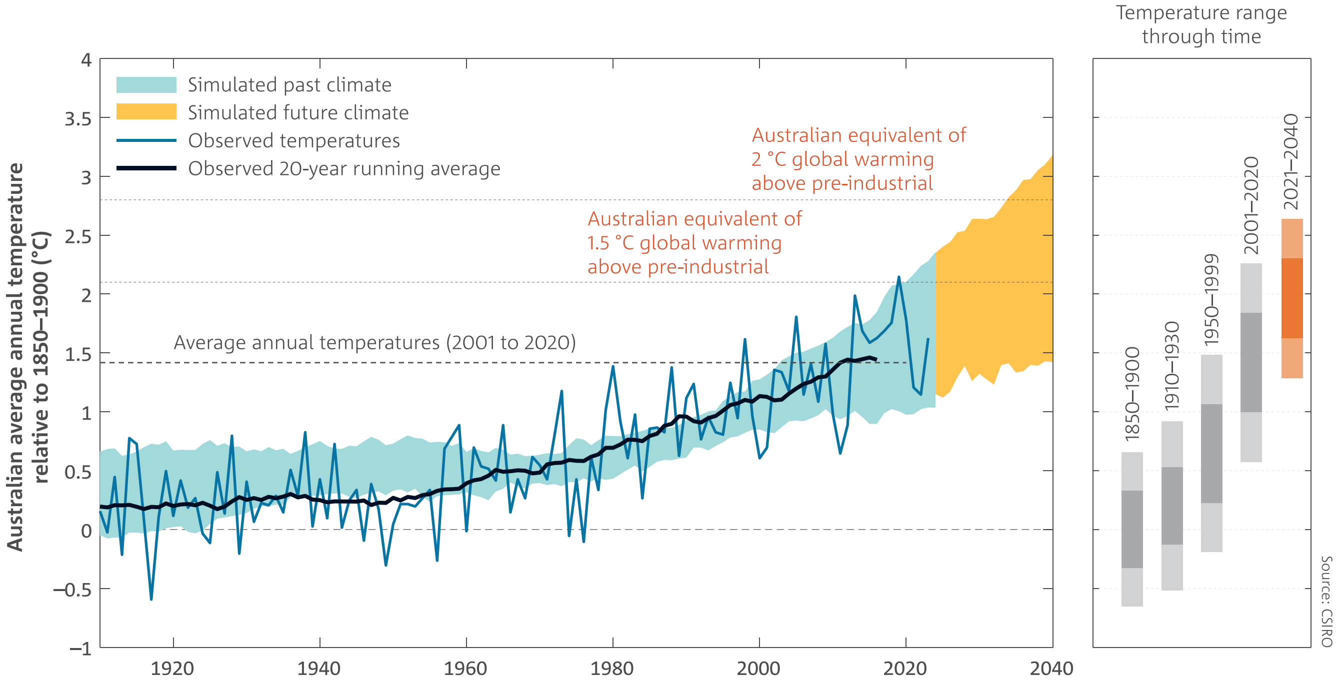
- Continued warming, with more extremely hot days and fewer extremely cool days.
- A further decrease in cool season rainfall across many regions of the south and east.
- Continued drying in the south-west of Western Australia, especially during winter and spring.
- Likely increases in the average duration of drought and aridity in regions within the south and east.
- A longer fire season for much of the south and east, and an increase in the number of dangerous fire weather days for many regions.
- More intense short-duration heavy rainfall events, even in regions where the average rainfall decreases or stays the same.
- Fewer tropical cyclones, but a greater proportion projected to be of high intensity, with ongoing large variations from year to year. The intensity of rainfall associated with tropical cyclones is also expected to increase and, combined with higher sea levels, is likely to amplify the impacts from those tropical cyclones that do occur.
- Fewer east coast lows on average, particularly during the cooler months of the year, but a likely greater impact from those that occur due to heavier rainfall and higher sea levels.
- Ongoing sea level rise through this century and beyond, at a rate that varies by region but roughly follows the global average. Recent research on potential ice loss from the Antarctic ice sheet suggests that a scenario of larger and more rapid sea level rise this century or beyond can't be ruled out.
- More frequent extreme sea levels linked to coastal inundation and coastal erosion. For most of Australia, coastal floods that currently occur occasionally will become chronic later this century. 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 greenhouse gas emissions, and by the mid-21st century for higher emissions.
- Continued warming and acidification of surrounding oceans with consequent impacts on biodiversity and ecosystems.
- Increased and longer-lasting marine heatwaves, which will further stress marine environments such as kelp forests and increase the likelihood of more frequent and severe bleaching events in coral reefs around Australia, including the Great Barrier Reef and Ningaloo Reef.
- An increase in the risk of disasters from extreme weather, including 'compound events', where multiple hazards and/or drivers occur together or in sequence, thus compounding their impacts.

Source: Bureau of Meteorology and CSIRO

Projections of Australia's future climate conditions

Projections of Australia's average temperature over the next 2 decades show:

- The average temperature of each future year is now expected to be warmer than any year prior to the commencement of human-caused climate change.
- Ongoing climate variability means each year will not necessarily be hotter than the last, but the underlying probabilities are changing. This leads to less chance of cool years and a greater chance of repeatedly breaking Australia's record annual average temperature (e.g. record set in 2005 was subsequently broken in 2013 and then again in 2019).
- While the previous decade was warmer than any other decade in the 20th century, it is likely to be the coolest decade for the 21st century.
- The average temperature of the next 20 years is virtually certain to be warmer than the average of the past 20 years.
- The amount of temperature 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 lower emissions will lead to less warming and fewer impacts.
- Temperature increases are generally expected to be greater in the interior of Australia than near the coast.



Source: CSIRO

Australian average annual temperature in observations and global climate models shown relative to the 1850–1900 baseline approximating the pre-industrial era. Past and future coloured bands show the 20-year running average from models for historical conditions and plausible future scenarios to 2040. Black dashed lines show the average warming expected for Australia when the global average temperature reaches 1.5 and 2.0 °C above the pre-industrial era. The panel to the right shows the range of temperatures (one and 2 standard deviations) in various epochs from observations and the 2021–2040 period as simulated by one climate model (the results from which are close to the mean of all models).

Why are Australia and the world warming?

Energy comes from the Sun. In order to maintain stable temperatures at the Earth's surface, in the long run this incoming energy must be balanced by an equal amount of heat radiated back to space. Greenhouse gases in the atmosphere, such as CO_2, act to increase the temperature of the Earth's surface, ocean and atmosphere, by making it harder for the Earth to radiate this heat. 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, due to the radiation balance alone (even colder when feedback mechanisms are considered). 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. This increase in greenhouse gases, along with an increase in aerosol particles in the air and the flow-on effects to clouds, has created an 'effective radiative forcing' of 2.72 $W\ m^{-2}$ (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 CO_2 persists in the atmosphere for hundreds of years, further warming and sea level rise are locked in. This well-established theory, together with observations of the air, water, land and ice, as well as paleoclimate records and climate models, allows us to understand climate changes and make projections of the future climate.

Source: unsplash.com

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 eighth State of the Climate report. The report has been published every 2 years since the first report in 2010.

About Kennaook/Cape Grim

The 48 years of uninterrupted measurement at the Cape Grim Baseline Air Pollution Station, Tasmania, is a source of great pride for the Bureau of Meteorology and CSIRO. In 2021, the dual name of Kennaook/Cape Grim Baseline Air Pollution Station was formally adopted for Australia's globally important atmospheric observatory, in recognition of the deep history and continuing presence and participation of the Peerapper people in the custodianship of the Kennaook area.

This area has been a site of historical violence and dispossession of its First Peoples, the Peerapper, perpetrated by British colonists. Both the Bureau of Meteorology and CSIRO are committed to taking action towards reconciliation with Australia's First Nations people. We acknowledge the Peerapper people as the traditional custodians of the lands, waters and skies of the area traditionally known as Kennaook, which encompasses the site of the Kennaook/Cape Grim observatory, and pay our respect to Elders past and present.

Further information

The Bureau of Meteorology

The Bureau of Meteorology is Australia's national weather, climate, ocean, water and space weather 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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CSIRO

CSIRO is Australia's national science agency, solving the greatest challenges through innovative science and technology. CSIRO uses collaborative research to turn science into solutions for food security and quality; clean energy and resources; health and wellbeing; resilient and valuable environments; innovative industries; and a secure Australia and region.

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

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