Australian Government
Australian Research Council

climate extremes
ARC centre of excellence

The State of Weather and Climate Extremes 2022

Contents

About this report

Climate extremes already affect many facets of Australian society including health, soil and water, agriculture, infrastructure, energy security and financial security, posing significant risks to the global and Australian economy.

Our region will face more and more intense extremes in the future, even with rapid and deep cuts in greenhouse gas emissions.

This report provides a summary of the significant extreme weather and climate events which occurred in 2022 across Australia and Antarctica. The report provides a description of each event and an explanation which reflects our understanding of the causes. Our research continues to learn more about these events.

This document has been prepared to assist policy makers and the general public understand the complexity and nature of the climate extremes we are experiencing.

Australian Research Council Centre of Excellence for Climate Extremes

The State of Weather and Climate Extremes 2022
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Acknowledgments

Acknowledgment of the Traditional Owners

The ARC Centre of Excellence for Climate Extremes respectfully acknowledges the Traditional Owners of the Land throughout Australia. We pay our respects to their Elders past, present and emerging, and recognise their continuous connection to country.

This scientific assessment and research has been conducted by the following researchers across the ARC Centre of Excellence for Climate Extremes: Dr Zoe Gillett, Dr Yawen Shao, Dr Tess Parker, Dr Michael Barnes, Dr Kim Reid, Dr Dongxia Yang, Dr Tim Raupach, Mr Andrew Lawrence Brown, Dr Stacey Hitchcock, Dr Moutassem El Rafei, Dr Amelie Meyer, Professor Julie Arblaster, Professor Andy Pitman.

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The ARC Centre of Excellence for Climate Extremes

The **ARC Centre of Excellence for Climate Extremes** is Australia's leading climate science centre consisting of five partner universities - The University of New South Wales, Monash University, The Australian National University, The University of Melbourne and The University of Tasmania as well as multiple international partner organisations including the NASA Goddard Space Flight Centre, the Max Planck Institute of Meteorology and the Met Office UK.

The Centre, established in August 2017, is funded by the Australian Research Council as a Centre of Excellence with investment from the New South Wales Government's Research Attraction and Acceleration Program and the New South Wales Department of Planning and Environment.

The Centre represents over one hundred researchers contributing to the science of climate extremes through developing fundamental climate science and improving models to analyse the extremes of the past and predict the extremes of the future. The Centre reduces Australia's economic, social and environmental vulnerability to climate extremes.

Our research focuses on the processes underlying extremes across four principal areas: weather and climate interactions, drought, ocean extremes and the attribution (whether climate change may be responsible for an event) and risk of extremes. The research considers underlying processes including the background climate, variability on multiple timescales (climate variability), connections with meteorological or environmental events over a distance (teleconnections) and changes in global mean surface temperature and issues associated with climate sensitivity.

The research is necessarily quantitative, understanding the physics, dynamics and biology of climate extremes and describing them in the Australian Community Climate and Earth-System Simulator (ACCESS). Central to our research is the high-performance computers and data environment provided by the National Computational Infrastructure (NCI) and the software engineering provided by the ACCESS National Research Infrastructure.

The goal of the **ARC Centre of Excellence for Climate Extremes** is to transform the understanding and modelling of climate extremes, including their dependence on climate change and variability; to advance scientific understanding; and to assist decision-makers.

The 2022 year in review

A third consecutive La Niña contributed to severe rainfall and flooding across Eastern Australia.

Australia's hottest temperature was recorded in the coastal town of Onslow, Western Australia.

Weather and climate extremes had disastrous impacts on socioeconomic systems.

Summary of events

1.1 Introduction

Australia experienced a year of record-breaking extreme events in 2022 (Figure 1) with extreme rain and flooding overshadowing all other events. Second and third consecutive La Niña events dominated the weather and climate across eastern Australia. The three successive phases in La Niña contributed to persistent, heavy rainfall breaking multiple daily, monthly and yearly flood and rainfall records.

While La Niña promoted cooler and damper conditions in the east of the country, Australia still equalled its highest temperature ever in Western Australia. Regionally records also fell for extreme heat in the Antarctic which had a significant year of ice melt.

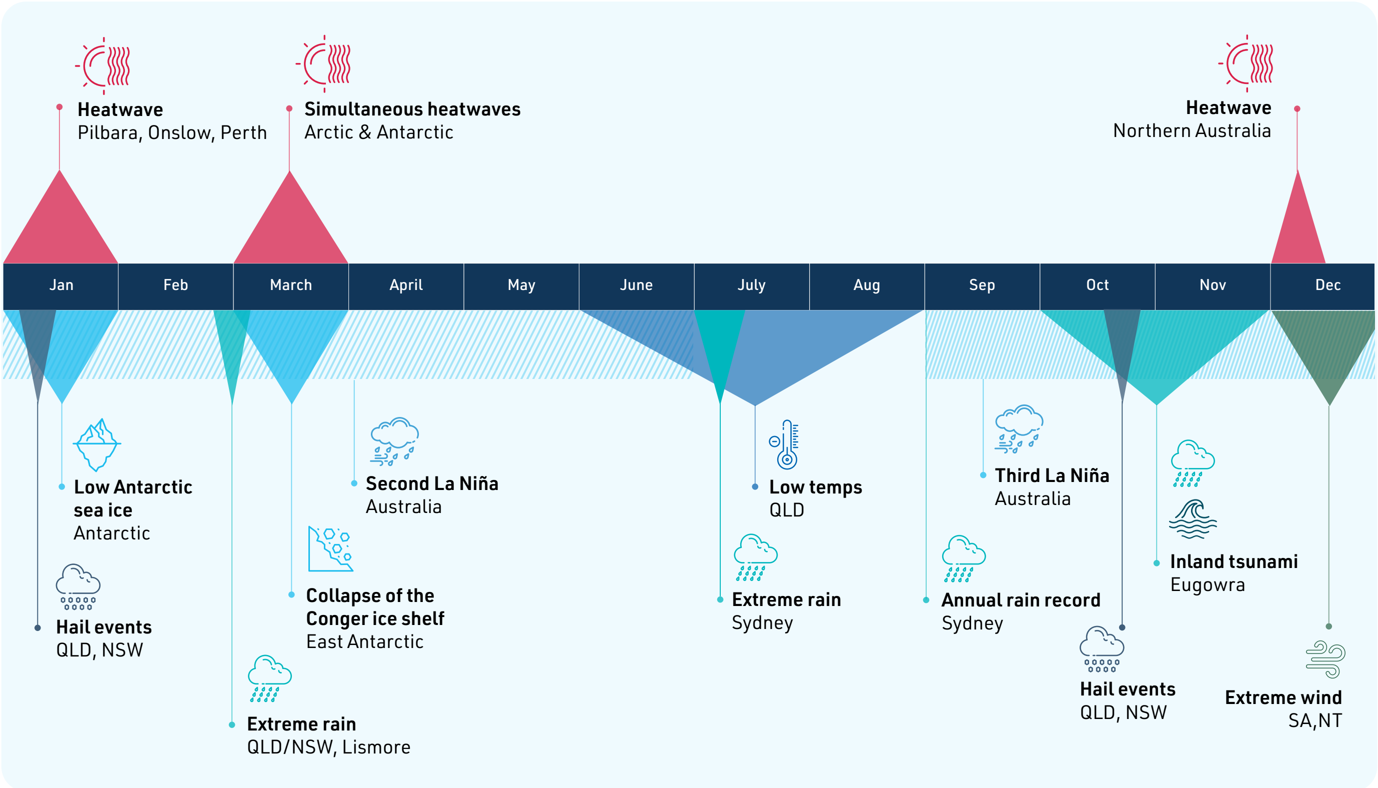

Figure 1: Timeline of the major extreme events in 2022.

1.2 Rainfall

Much of Australia experienced above average rainfall for 2022 (Figure 2), as the second La Niña transitioned to a third consecutive La Niña accompanied by wet phase climate drivers: a negative Indian Ocean Dipole (IOD) and a predominantly positive Southern Annular Mode (SAM). The occurrence of three consecutive La Niña events is rare, but not unprecedented, having occurred previously in 1973-1976 and 1998-2001.

A second La Niña peaked at the beginning of 2022, with flooding returning and affecting south-eastern Queensland and eastern New South Wales from late February 2022. Storms saw areas of south-eastern Queensland and eastern New South Wales receive rainfall over 5 times the February average. The extreme rain brought floods to many areas, with Lismore recording flood levels 2m higher than previous records.

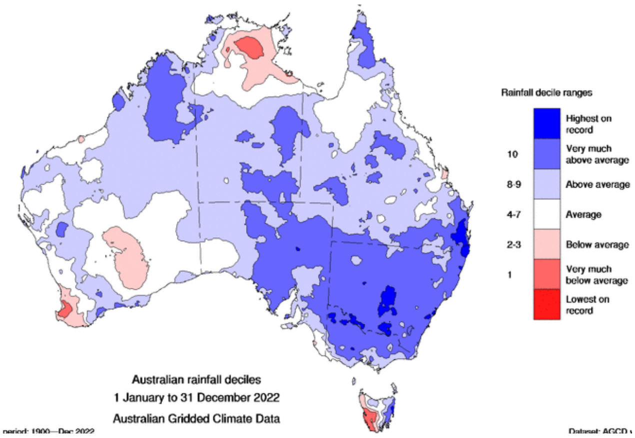

Figure 2: Australia's above average rain in 2022. Australian rainfall deciles since 1900. Source: Bureau of Meteorology.

By the end of the first week of March, both Queensland and New South Wales had received more than a year's worth of rain in a month. Further storms continued to hit these regions over following months, causing repeated flooding.

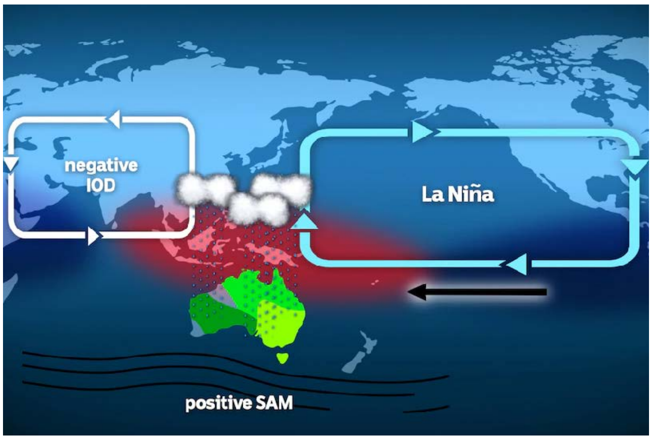

Figure 3: Multiple climate drivers including La Nina BOM declares La Niña, increasing flood risk for third year in a row. Source: Australian Broadcasting Corporation.

By autumn, La Niña weakened returning to a neutral phase, although four out of seven forecasting models were predicting La Niña would return in late spring or summer of 2022.

The heavy rain continued in winter. For Greater Sydney, July was the wettest on record with areas receiving up to 8 times their average rainfall for the month. This caused major flooding and the evacuation of 85,000 people. July was also very wet for Queensland with many sites in the east of the state recording their wettest July.

From late winter until the end of spring, the Indian Ocean Dipole was in its negative phase. In September, the Bureau of Meteorology declared a third La Niña in a row. This was coupled with a positive Southern Annular Mode for much of spring making an extremely wet spring.

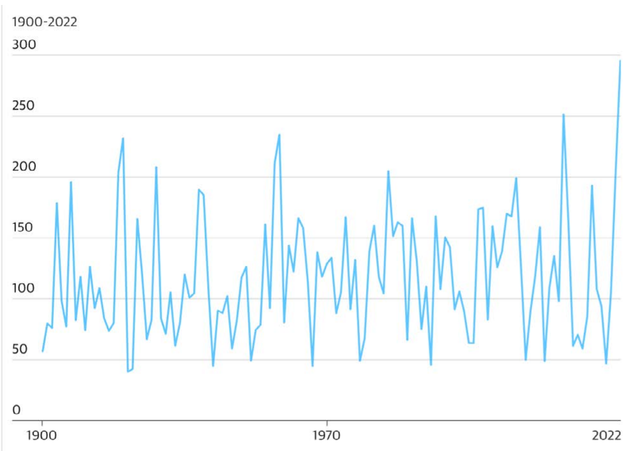

Figure 4: Spring yearly rainfall in mm in the Murray-Darling Basin. Australia's record-breaking weather in 2022: a very wet and sometimes very hot year. Image: The Guardian. Source: Bureau of Meteorology.

1.2 Rainfall

Spring rainfall in 2022 was 112% above average for Australia, the second wettest spring on record. The Murray-Darling Basin saw its wettest spring on record breaking the previous spring record of 251mm with just over 295mm (Figure 4). The Murray-Darling Basin October record was also broken(Figure 5). The Hume Dam, in southern New South Wales, which supplies a large amount of water to the Murray-Darling Basin, had its largest rainfall on record.

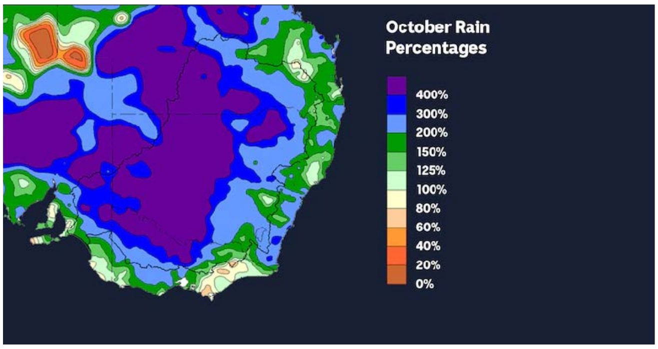

Figure 5: The Murray-Darling Basin broke its October record in 2022. Murray-Darling Basin experiencing its wettest October on record after latest deluge. Source: Australian Broadcasting Corporation.

October was the second wettest on record for Australia as a whole. Many rain gauge stations in New South Wales, Victoria and Tasmania had their wettest October on record. In Echuca, the Murray River reached 94.98m in October, the highest level in 29 years. Many regions in northern Tasmania, including Sheffield and Deloraine had their wettest October on record. Heavy rainfall from the 12th-14th of October, brought flooding to parts of northern Tasmania. By early October, Sydney had broken its record for wettest year ever, with a total of 2522.8mm of rainfall for 2022 (Figure 6). This beats the previous annual record of 2194 mm from 1950 and was double the city's annual average of 1213.4 mm.

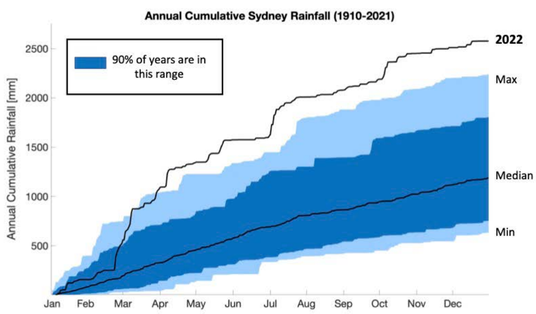

Figure 6: Sydney Rainfall from 1859 – 2021 showing how 2022 exceeded the 99th percentile. Source: Kim Reid.

November in south-eastern Australia was amongst the top 3 wettest Novembers on record. On the 13th of November in northern Victoria, Seymour flood levels exceeded the record of 7.64m set in 1974 to 8.37m. A day later on the 14th of November, the town of Eugowra in the central west of New South Wales experienced flash flooding or an 'inland tsunami'. Water levels in Eugowra peaked at 11.2 m, shattering the previous record of 10.01m in 1950 (Figure 7).

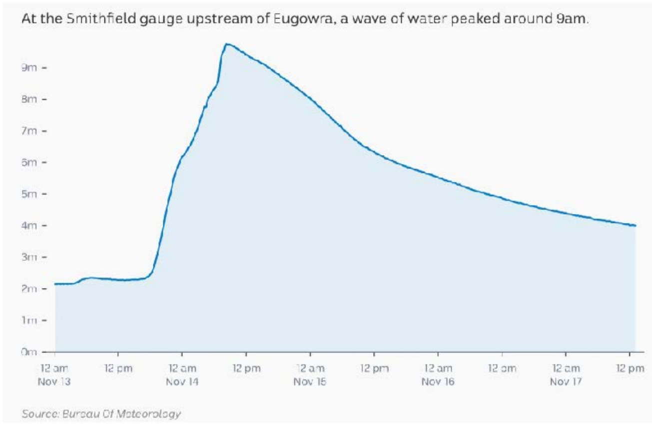

Figure 7: Smithfield gauge water levels, upstream of Eugowra on the 13th and 14th of November 2022. Image: Australian Broadcasting Corporation. Source: Bureau of Meteorology.

As of December 26, Brisbane was just 26mm away from exceeding its 1972 record. The Alderley rain gauge, in Brisbane's north, received more than 45 per cent of its total 2022 rainfall in just one week at the end of February.

1.3 Temperature

As the rainfall records were surpassed in 2022, so too were the extreme heat records. The average temperature over Australia has warmed by 1.47± 0.24°C since 1910. Despite the cooling influence that is usually associated with La Niña events, 2022 was 0.50°C above the 1961–1990 average.

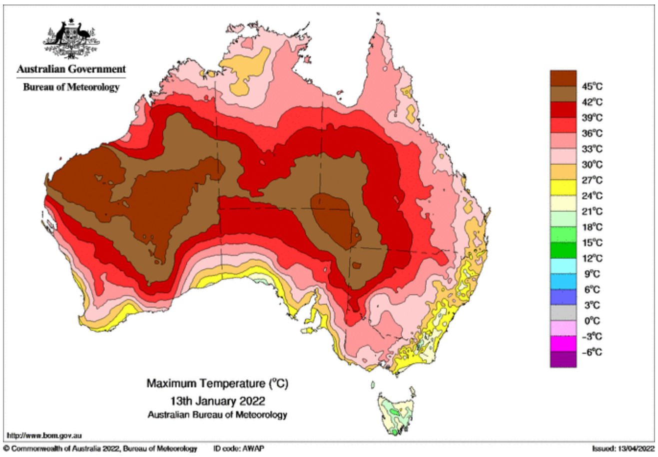

Figure 8: Mean daily maximum temperatures in January 2022. Onslow, WA equalled Australia's hottest day on the 13th of January 2022. Source: Bureau of Meteorology.

In January, the Pilbara region in Western Australia experienced a record-breaking heatwave, during which the coastal town of Onslow equalled Australia's highest ever temperature of 50.7°C (Figure 8).

For Victoria and Tasmania as a whole, the January mean minimum temperature was the warmest on record for both states. A very large number of sites across Victoria, Tasmania, and south-east South Australia observed their warmest mean minimum temperature on record for January, with some setting records for their warmest mean minimum temperature on record for any month of the year. Macquarie Island, halfway between New Zealand and Antarctica, had a previous record summer temperature set in 1984 of 14.4 °C. This was surpassed on the 8th and 9th of February 2022 when it reached 17.0 °C and 14.6 °C respectively.

Australia had its third warmest Autumn on record. The Northern Territory experienced the second hottest March and third warmest April on record for average temperature. Maximum temperatures in March were also the warmest on record for areas of the Central Coast and surrounds. July in Queensland was 1.02 °C below the average maximum temperature with many areas in Queensland experiencing their coldest July day on record.

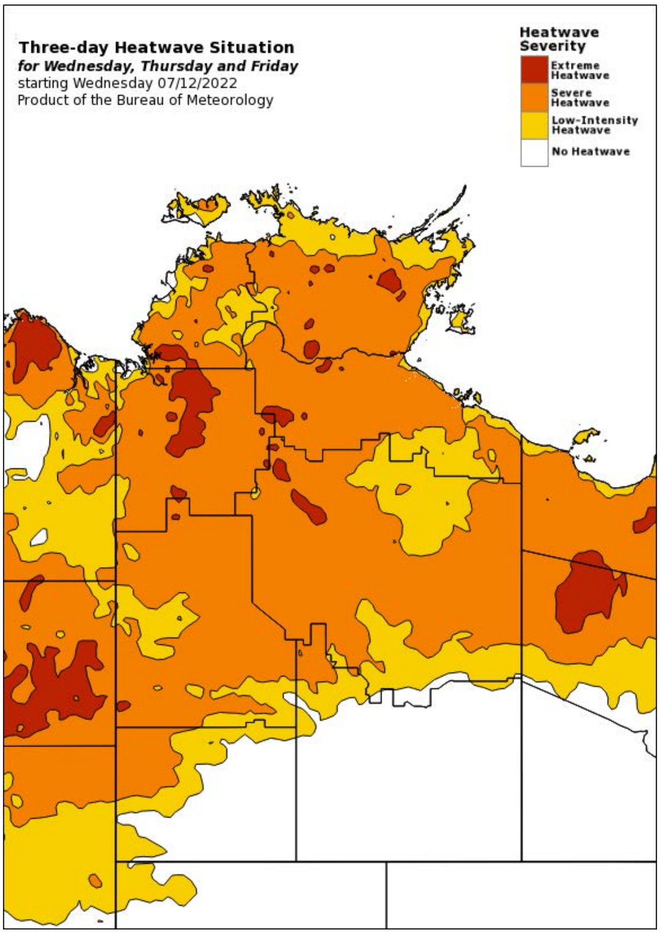

Figure 9: Extreme heatwave conditions in December 2022. Source: Bureau of Meteorology.

After a year of extreme rain, the year overall ended cooler than average with both mean maximum and mean minimum temperatures below or much lower than average in the eastern states. At the beginning of December, the north of Australia experienced a period of extreme heat with maximum temperature records broken across the Top End (Figure 9). Record highs were recorded In Nhulunbuy, with a high of 38.7°C, Groote Eylandt with a high of 39.8°C and Borroloola, which experienced a high of 44.6°C.

1.4 Large-scale climate drivers

A lingering La Niña influenced Australian rainfall for much of 2022. La Niña is an ocean temperature and wind pattern across the Pacific Ocean which pushes warm and moist air towards Australia[1]. It therefore has an important influence on Australian rainfall, promoting increased winter-spring rainfall in eastern Australia and increased late summer-autumn rainfall along the east coast.

La Niña conditions first began in spring 2020 and continued until early autumn 2021. A second La Niña developed in spring 2021 and persisted through early winter 2022. Known as a "double-dip" La Niña, back-to-back Australian summers with La Niña conditions are not uncommon and have occurred in about 50% of all past La Niña events (Figure 10). Southeast Queensland and northeast New South Wales experienced extreme rainfall and widespread flooding in February and March 2022 towards the end of this second La Niña event. A third consecutive La Niña was declared in spring 2022 and persisted through to early 2023. "Triple-dip" La Niña events are rare and have only happened twice since 1950, with previous events occurring in 1973-1976 and 1998-2001. Multi-year La Niña events can be associated with an increased risk of flooding due to the possibility of more rain falling on already saturated catchments.

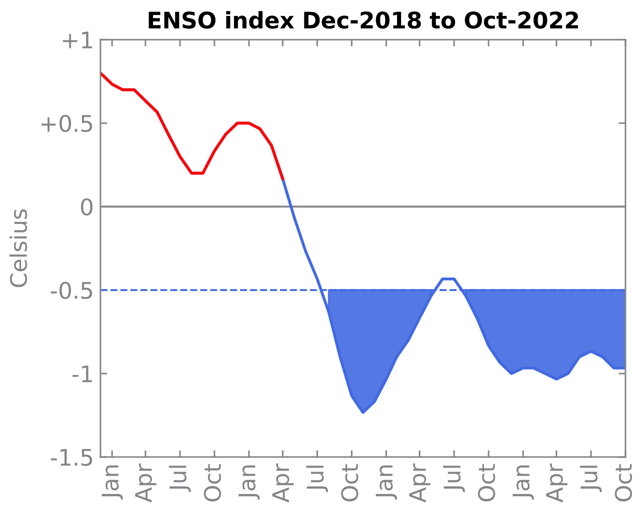

Figure 10: The recent Triple-dip La Niña event. The blue line shows the La Niña phase of ENSO, and the red line shows the El Niño phase (note reversed y-axis for easier visualisation of La Niña). The dashed blue line indicates the threshold used to define La Niña events (shaded blue). The ENSO index from NOAA uses a threshold of -0.5°C. Source: Dr Zoe Gillett.

La Niña was not the only climate driver acting to promote rain across eastern Australia in 2022, particularly in spring 2022. The combined influence of a trio of rain-promoting climate drivers, La Niña, the negative phase of the Indian Ocean Dipole (IOD) and the positive phase of the Southern Annular Mode (SAM), contributed to Australia's second wettest spring in 123 years of records[2].

A negative IOD is like the Indian Ocean's version of La Niña and is associated with warmer waters around northern Australia[3]. It promotes increased rainfall in southern and eastern Australia during winter and spring. A negative IOD event occurred from late winter to the end of spring 2022. Interestingly, this was also part of a multi-year event, after a negative IOD also occurred a year earlier in 2021.

The SAM was in its positive phase for much of spring 2022. In the positive phase of the SAM, the belt of westerly winds over the Southern Ocean moves further away from Australia[4]. This enables more easterly winds from the Pacific Ocean to move across eastern Australia and promote increased rainfall in spring and summer.

The positive phase of the SAM also promotes reduced rainfall in parts of southern Australia, including in western Tasmania. While record-breaking rainfall in mainland eastern Australia dominated the news in 2022, in 2021/22, Tasmania had its driest summer in 41 years[5] because the SAM was largely in its positive phase, promoting high-pressure over the state and blocking rain-producing weather systems.

The negative IOD and positive SAM tend to co-occur with La Niña and the combination of these climate drivers further increases the chances of above-average rainfall in eastern Australia.

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1.5 Weather and climate extremes in Antarctica

The Antarctic saw a series of extreme events over 2022: simultaneous heatwaves in Antarctic and Arctic, a major collapse of the Conger ice shelf in East Antarctica and record low Antarctic sea ice observations.

In March 2022, the Antarctic experienced a heatwave. Warm moist air became trapped over East Antarctica by a blocking high pressure system resulting in temperatures over 50°C above average in some areas. A new record March maximum temperature was set with some locations warm enough for the surface of the ice and coastal ice shelves to melt.

At the same time, in March 2022, a large area of the East Antarctic ice shelf, the size of New York City, collapsed. The extreme heat in 2022 contributed to the rapid destabilisation and collapse of the Conger ice shelf, and it remains to be seen if the ice shelf will reform over coming years or if it will remain lost like some collapsed ice shelves in other regions of Antarctica.

Rapid declines in sea ice from spring 2021 continued, leading to record low extent in late summer 2021-22.

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2.0 Social impacts of climate extremes

The extremes throughout 2022 were disastrous for local communities. At least 23 people died from the flooding in south-eastern Queensland and eastern New South Wales in early 2022. The State Emergency Service considered over 3,600 homes across the New South Wales northern rivers region as uninhabitable. The New South Wales State Emergency Service responded to 31,400 calls for help in the six-week period.

The floods between February and March were the costliest in Australia's history totalling $5.56 billion in insured losses across Queensland and New South Wales. Parts of Australia's food growing regions were affected, with damage to infrastructure (Figure 12), crops and loss of livestock. Supply chains were impacted, challenging food supply and increasing the price of some fruit and vegetables. These economic costs do not include the psychosocial effects associated with traumatic extreme weather events such as displacement of people from their homes, community impacts, stresses from loss of financial security or the threat of repeated events.

In Eugowra, 2 people died and more than 150 people were airlifted from building rooftops or evacuated by boats when the flash floods occurred. Most homes in the town were affected by the flood waters causing water damage to belongings, instability caused by dislodged footings, windows smashed and many items to washed away. Rebuilding is likely to take years. The cost of weather-related disasters in Australia is increasing every decade (Figure 11). Whether this trend of increasing costs is related to climate change, or increased exposure to weather related disasters is not easy to disentangle.

Attributing climate change to events

Climate extremes such as heatwaves and short-duration heavy rainfall have already increased in frequency and intensity in Australia and the risk of these events increases with every fraction of a degree of warming.

Demonstrating that some major extremes are, or are not, strongly influenced by climate change can take several years to accomplish. Therefore, while these extremes are increasing that does not mean we can clearly attribute all the extreme events that occurred in 2022 to climate change.

- Some, including regional heatwaves are extremely likely to have been influenced by climate change,
- Some, such as the short-duration intense rainfall may have been,
- Some are most likely simply reflecting natural variability.

It is also possible that what we call "natural variability" is itself being influenced by climate change.

In Section 4, which looks at specific events, explaining events through natural mechanisms does not imply that climate change does not play a role.

The ARC Centre of Excellence for Climate Extremes is reducing Australia's vulnerability to these climate events by improving our understanding of how these events occur and how they will change in the future.

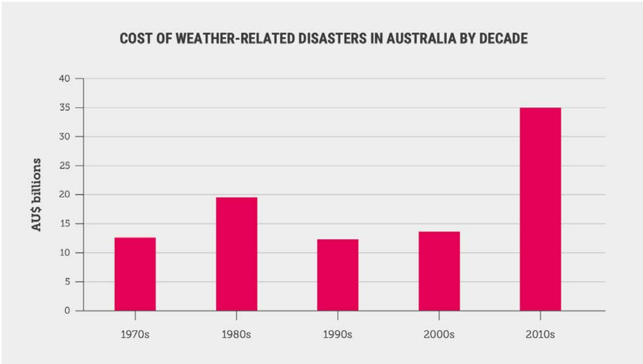

Figure 9: Cost of weather-related disasters in Australia by decade.[1] Based on data from EM-DAT, the International Disaster Database: https://www.emdat.be/ (See Appendix 1 for more details).

Figure 11: 2022 Australian Flooding - Source: Center for Disaster Philanthropy.

Figure 12: How an extreme flash flood wiped out Eugowra in NSW. Source: Australian Broadcasting Corporation.

3.0 International extreme events

Looking beyond Australia, a range of extreme events took place globally with 2022 the sixth warmest year on record (Figure 13), since 1880.

It was the warmest La Niña year on record globally[10].

While Australia experienced record breaking flooding; heat waves, wildfires and drought swept across the Northern Hemisphere. India and Pakistan experienced record-breaking heat waves in late April and May. Parts of India reached temperatures over 47.0°C, according to the India Meteorological Department. Jacobabad in Pakistan exceeded its previous record for maximum temperature by over 1.0°C, reaching 49.0°C on April 30th[1]. China experienced a particularly severe heatwave; their most severe summer heatwave in six decades. It persisted for 70 days with many regions experiencing sustained temperatures in excess of 40°C, affecting over 900 million people[2]. The heat was accompanied with low rainfall which exacerbated drought conditions in China. Parts of the Yangtze River reached their lowest level since 1865.

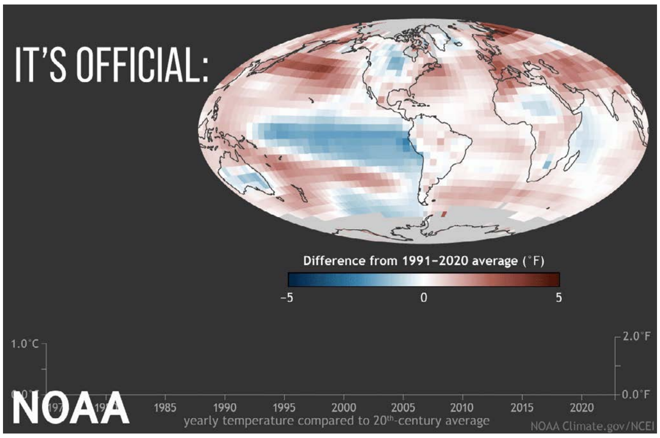

Figure 13: 2022 was the sixth warmest year on record (2022 was world's 6th-warmest year on record | Source: National Oceanic and Atmospheric Administration

Summer in Europe and the UK was the warmest on record, bringing intense and persistent heatwaves[3,4]. The highest temperature of 47°C was recorded in Pinhão, Portugal on 14th July (Figure 14). The United Kingdom experienced temperatures greater than 40°C for the first time on the 19th of July. The heatwaves put further pressure on already strained energy systems, with increased demand for cooling and hot temperatures reducing the capacity for energy supply.

The heat coincided with wildfires and severe drought across the region[5]. The wildfires were particularly severe in Spain, Portugal, Romania and France[6].

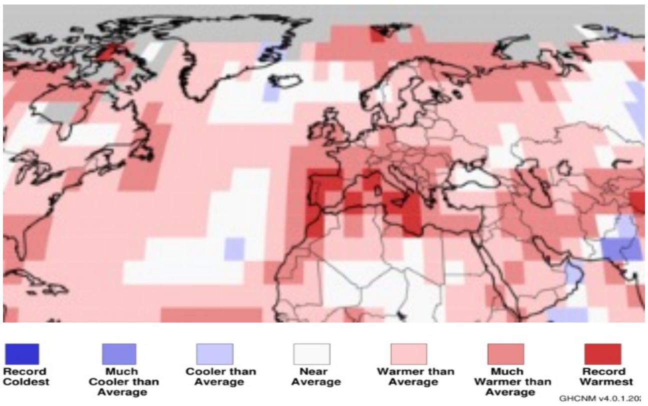

Figure 14: July 2022 blended land and sea surface temperature percentiles. Land & Ocean Centers Environmental Information Data source: NOAAGlobal Temp v5.0.0-20220808. July 2022 Global Climate Report. Source: National Centers for Environmental Information.

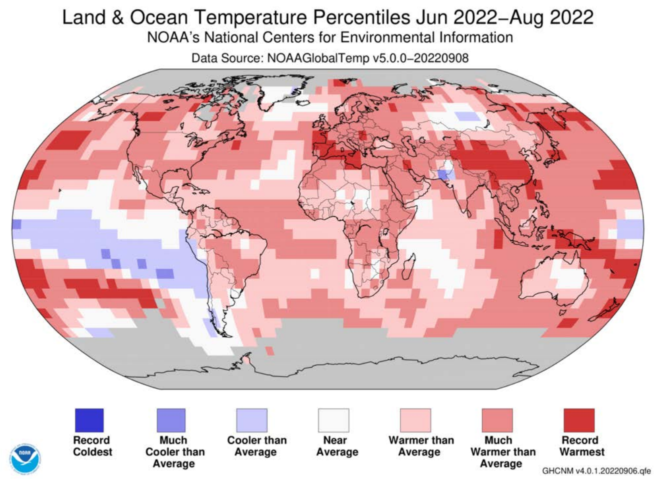

Figure 15: The global land and ocean surface temperatures for June - August 2022 was 0.89°C above the 20th century average. It tied with 2015 and 2017 as the fifth warmest in the 143-year temperature record. Source: National Oceanic and Atmospheric Administration.

Catastrophic floods and storms were a feature of global weather in 2022. Pakistan endured record-breaking floods during the monsoon season (June to October), which impacted approximately 33 million people and killed over 1,700 people[7]. In the United States, there were 10 severe storms and two tropical cyclones where losses were over $1 billion for each event. The most severe of these was Hurricane Ian, where sustained winds over 240 km/hr hit Florida on the 28th of September. Hurricane Ian caused over 140 deaths and billions in damages[8].

Note: This text has been updated to correct an error in the warmest years on record.

3.1 Record high levels of carbon dioxide in 2022

In May 2022, atmospheric carbon dioxide hit the highest level in over 4 million years, reaching 421 parts per million[9]. Greenhouse gas data from Kennaook / Cape Grim shows the latest CO_2 data from one of the cleanest air sources in the world (Figure 16, 17).

It is unequivocal that the increased CO_2 in the atmosphere is warming our climate. Every incremental degree of warming heightens the risk of climate extremes such as heatwaves on land and in the ocean, heavy rainfall events and drought. These extreme events have already increased in frequency and intensity in Australia and many other regions around the world.

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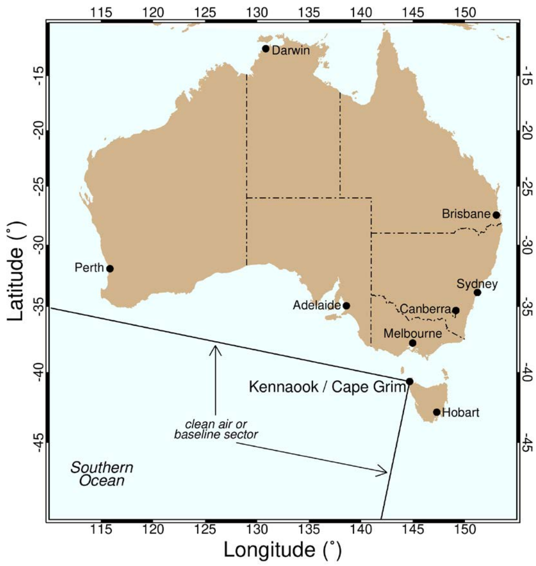

Figure 16: The Kennaook / Cape Grim station is positioned just south of the isolated north-west tip (Woolnorth Point) of Tasmania.

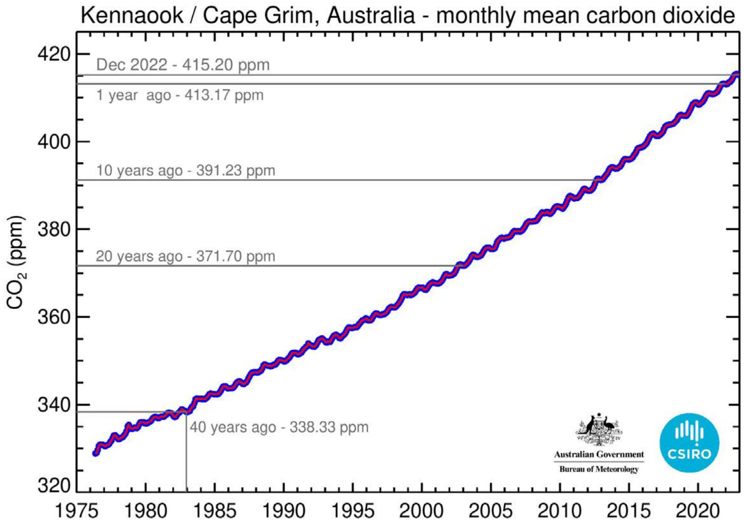

Figure 17: Carbon dioxide December 2022 415.22 ppm (parts per million). Source: Bureau of Meteorology/CSIRO.

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4. Description of events

4.1 Heatwaves in Western Australia

- Western Australia experienced a series of heatwaves in December 2021 - January 2022.
- The coastal town of Onslow, Western Australia, equalled Australia's hottest day at 50.7°C.

Western Australia experienced a series of heatwaves over the 2021-2022 summer period, starting on 17th December and 12th January, and in the south-west, starting on 23rd December and 18th January of the Pilbara region.

These led to several records, including the equal hottest day in Australia of 50.7°C, at Onslow on 13th January, and Perth recording six days in a row above 40°C between 18th and 23rd January – the longest run of such days for any month in 123 years of observations.

This marked Perth's 11th day over 40°C for the 2021-22 summer and exceeded the previous record of 7 summer days over 40°C, set in the 2015-16 summer. For Marble Bar, a total of 16 days of maximum temperatures above 45°C in December is the highest count for that month on record, and the second highest for any month.

During this heatwave, a strong high-pressure system over the Great Australian Bight created easterly winds that brought hot and dry weather from the desert to Perth (see Figure 18). Additionally, a west coast trough - an extended region of low atmospheric pressure - was situated either just along the west coast, or slightly offshore.

The combination of the high over the Bight and the coastal trough resulted in easterly to north easterly winds, which acted to block the afternoon sea breeze, causing it to weaken and form later, allowing heat to build up over the land for most of the day.

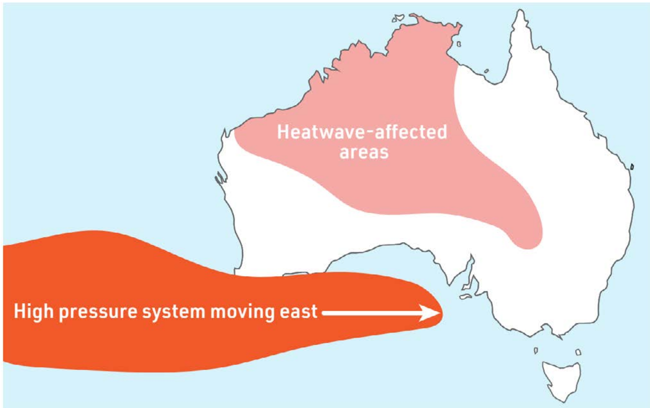

Figure 18: Schematic of the Pilbara heatwave of November-December 2021. Source: ARC Centre of Excellence for Climate Extremes.

Heatwaves are one of the most significant natural hazards in Australia in terms of loss of life. They can negatively impact infrastructure, agriculture, ecosystems as well as health. Heatwave conditions are expected to continue to worsen as the climate warms. The ARC Centre of Excellence for Climate Extremes is continuing to research links between heatwaves and weather systems[1], soil moisture[2] and climate change[3].

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4.2 Extreme rainfall and flooding in Queensland and New South Wales February-March 2022

- Rainfall was 5 times the February monthly average for some areas of south-eastern Queensland and eastern New South Wales.
- Over 500 millimetres of rain fell during a two-week period in March 2022.
- The flooding caused loss of life and an estimated AU$3.35 billion in insured losses.

South-eastern Queensland and eastern New South Wales experienced a series of storms which caused persistent and heavy rainfall during the first half of 2022. The rainfall events broke multi-day rainfall records in many locations, with some regions experiencing over five times their monthly average rainfall[1].

Lismore, in north-eastern New South Wales, saw record breaking floods with flood levels 2 meters higher than the previous record set in 1954. The flooding between February and May 2022[2] was the costliest flooding event in Australia's history, totalling an estimated AU$3.35 billion[3] in insured losses across Queensland and New South Wales. They caused major disruptions to food supplies, fuel, transport, significant damage to infrastructure and the loss of over 20 lives.

This high impact flooding was a compound event, an event caused by multiple hazards or drivers. In this case, a combination of meteorological phenomena caused persistent, heavy rain[4] to fall on catchments that were already sodden and primed for flooding due to a second consecutive La Niña event.

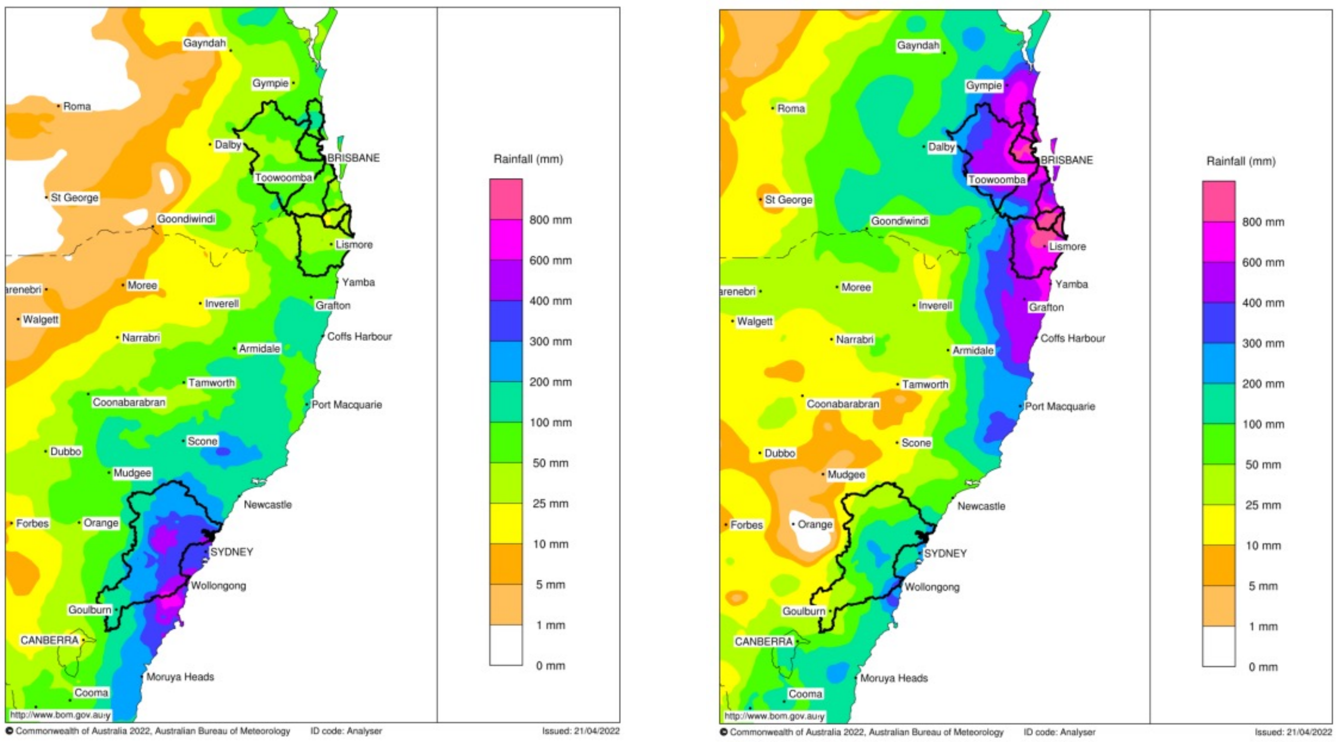
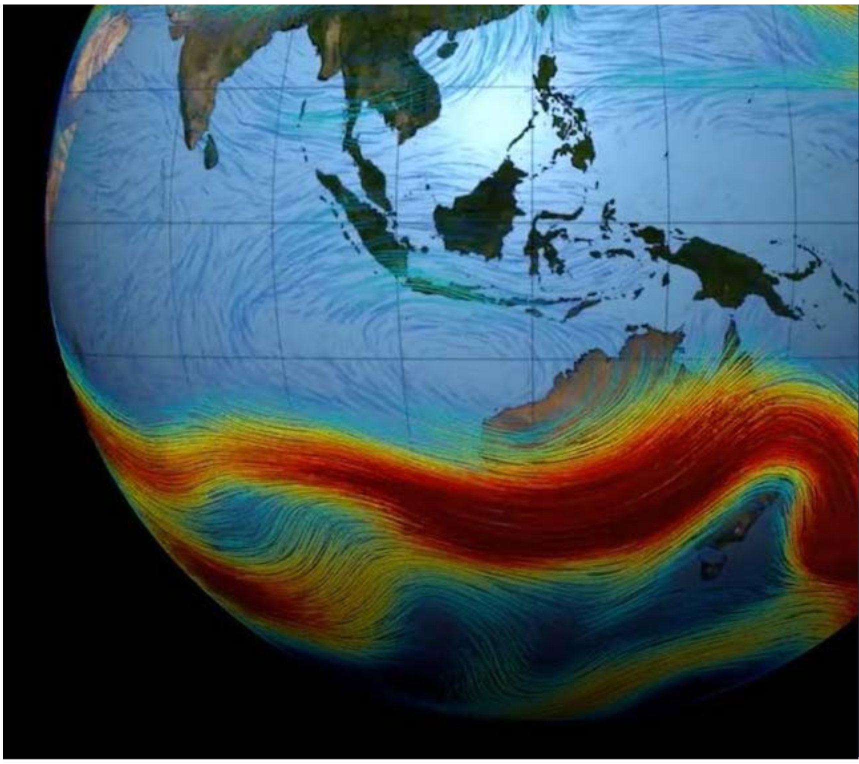


Figure 19: Weekly rainfall (mm) for south-eastern QLD and north-eastern NSW for weeks ending 2nd March and 9th March 2022. The black outline shows areas where 7-day catchment-average records were broken during this flooding. Some regions in pink received over 1m of rain in a week. Source: Bureau of Meteorology.



Event Explainer:
What are Rossby waves

Rossby wave breaking was one of the main drivers of the weather experienced along the New South Wales and Queensland coastlines over much of February and March 2022. Rossby waves are building blocks of weather and are high-altitude, planetary-scale waves that are largely responsible for a variety of weather experienced at the surface. Rossby waves are distrubances in planetary waves such as the jet stream over Australia. As the waves get bigger, they may break just like those at the beach.

Wiggles in the jet stream are what climate scientists call Rossby waves. Source: NASA

In late February 2022, the development of multiple rain producing weather systems was triggered by a Rossby wave (See: Event Explainer: What are Rossby waves?) breaking event south of Australia. The combination of a high-pressure system located to the southeast of Australia and a low-pressure system along the east coast transported moist air from the Coral Sea over Australia, while a slow-moving cut-off low provided the uplift necessary for rainfall. The persistence of these systems produced a prolonged spell of rainfall over the region, beginning in QLD and moving south to NSW (Figure 19). This resulted in flooding over south-eastern QLD (including Brisbane) and the Northern Rivers (including Lismore).

Similar Rossby wave breaking events and associated weather systems reoccurred several times throughout March and April resulting in multiple flooding events over eastern Australia including a second event in Lismore and Sydney.

As a new pressure system developed the conditions continued. On the 7th of April another heavy rain event caused more flooding over Sydney and southern New South Wales. There was record breaking rainfall across eastern and northern Queensland, as well as areas of New South Wales, into May 2022. The rain continued to the end of June.

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4.3 Record low Antarctic sea ice extent in 2022

- Record low values of sea ice extent in Antarctic in 2022.
- Implications for local marine life, the food chain and ice sheet melt.

Antarctic sea ice affects global climate by reflecting sunlight, influencing air-sea interactions and ocean circulation. Sea ice also provides habitat for krill, a keystone species in the Southern Ocean food web.

Despite global warming, Antarctic sea ice coverage slowly increased from 1979 until the mid-2010s. Then, in 2016, an unprecedented decline in sea ice occurred during spring, leading to sustained record low sea ice coverage[1,2,3]. Since then, sea ice had somewhat rebounded.

However, in spring 2021 sea ice once again decreased rapidly (Figure 20), with total coverage at its third-lowest level for spring.

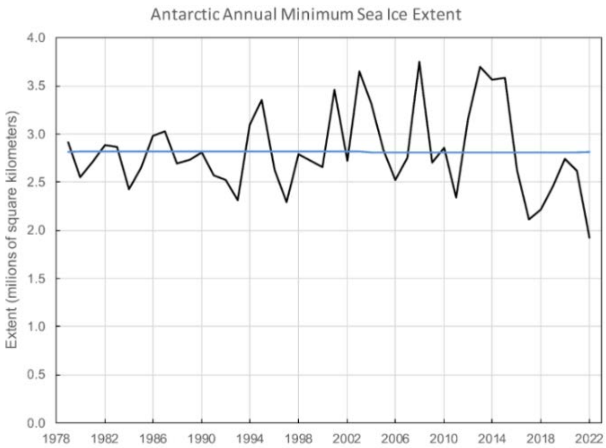

Figure 20: Annual Antarctic minimum sea ice extent for 1979 to 2022 (black) and the 1979-2022 trend line (blue). Source: National Snow and Ice Data Center.

Continued rapid loss has led to record low extent in late summer 2021-22, the first time that the ice was observed to shrink below 2 million square kilometres (Figure 21). This was followed by a series of much below-average extents observed since February 2022, including record low values for the time of year in June and July 2022. This led to a new record low in summer 2022-23, when sea ice reached its lowest extent ever observed since the start of the satellite record in 1979.

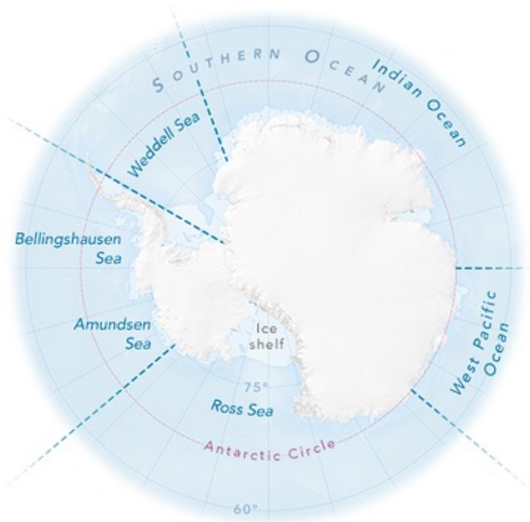

Figure 21: Antarctic region showing Weddell and Amundsen Sea. Source: NASA.

4.3 Record low Antarctic Sea ice extent in 2022

These extreme sea ice events represent an increase in Antarctic sea ice variability which has been linked to changes in the balance of sea ice trends across different Antarctic regions: the relative decrease of the role of the Amundsen-Bellingshausen region and increased role of the Weddell region (Figure 21) for total Antarctic Sea ice (Figure 22)[4].

The ARC Centre of Excellence for Climate Extremes is continuing to research and understand the drivers of these sea ice extreme events and sea ice predictability[5]. Whether the changes in Antarctic sea ice variability over the past decade are due to multidecadal variability (natural climate cycles) or a response to climate change is yet to be established. However, recent work shows that warming in the Amundsen-Bellingshausen region is unequivocally due to anthropogenic greenhouse gasses.

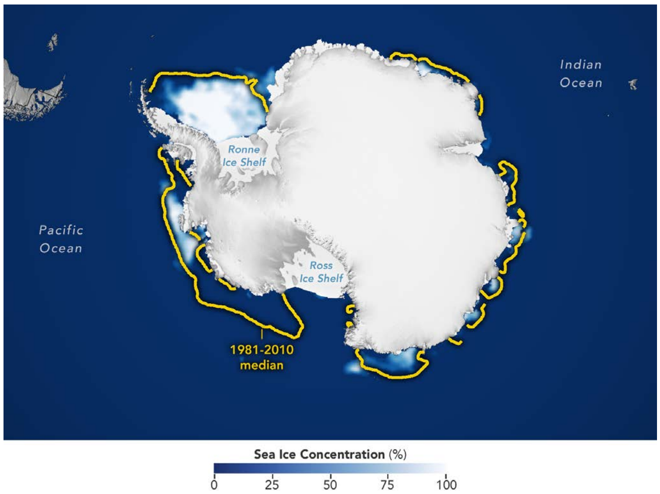

Figure 22: Antarctic Sea Ice Reaches Record Low. Source: NASA

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4.4 Simultaneous Antarctic and Arctic heatwaves

- Two record-breaking heatwaves occurred simultaneously in the Antarctic and Arctic.
- Temperatures reached about 40°C above normal.

Beginning on the 15th of March 2022, two record breaking heatwaves occurred simultaneously in the Antarctic and Arctic. For both poles to display such heating at the same time was both unprecedented and unexpected.

The two heatwaves were not synoptically linked but both were related to similar weather patterns involving warm and moist air being transported surprisingly close to the poles.

In the Southern Hemisphere, a band of westerly winds around Antarctica usually isolates the continent from other weather systems. During the heatwave event, a strong atmospheric river of warm and moist air originating in the mid-latitudes was pumped from near Tasmania and South Australia, breaching the westerly winds (Figure 24). The warm air became trapped over East Antarctica by a blocking high pressure system for a few days. Cloud cover over the Antarctic ice plateau also reduced the amount of heat radiating away from the land. In East Antarctica, temperatures during this heatwave reached ~40°C above normal over large areas of the plateau for a few days (Figure 23).

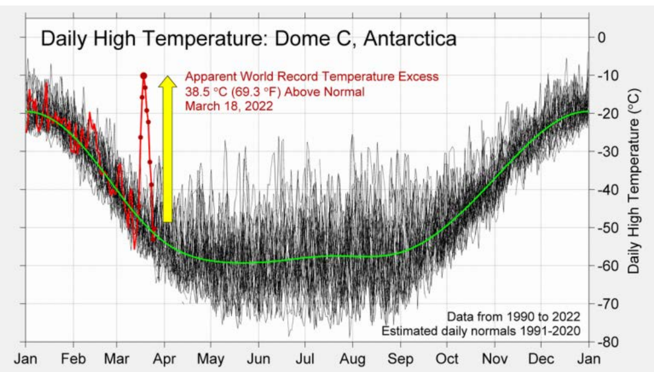

Figure 23: Daily high temperature (°C) at Dome C, Antarctica. Red dots show the March heatwave temperatures. Source: Climate Reanalyzer, University of Maine.

On March 16th, the Australian coastal station Casey[1] reached 5.6°C, marking a new March maximum temperature that was warm enough to melt ice.

The East Antarctic heatwave drove the overall Antarctic continental average temperature to about 5°C warmer than normal on the 17th of March. The Italian French research station Concordia[2] reached its highest observed temperature for any month of -11.8°C on March 18th, in stark contrast to the usual -50°C March temperatures there.

We cannot yet attribute this heatwave in Antarctica to climate change This does not mean that this heatwave was not linked to climate change. Rather, it means that we will need a longer time record to be able to identify a climate change signal in Antarctic extreme events.

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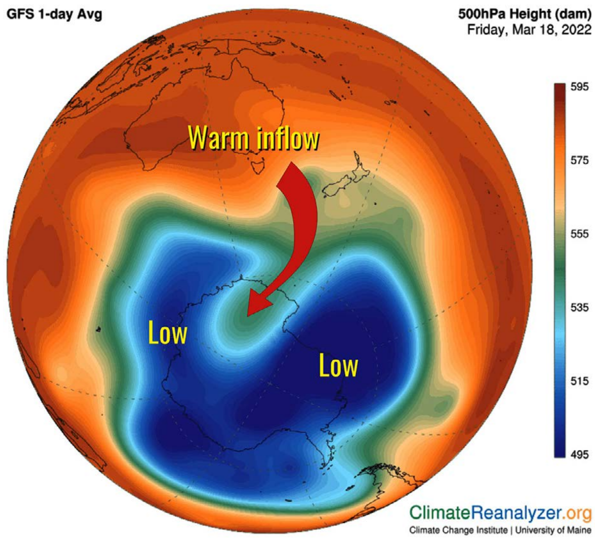

Figure 24: Diagram showing the warm inflow of air that moved over East Antarctica on the 18th of March 2022 temperatures. Source: Climate Reanalyzer.org Climate Change Institute, University of Maine.

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4.5 Collapse of East Antarctic Conger ice shelf

- The 1200 square km Conger ice shelf collapsed in March 2022.
- The collapse of an ice shelf is a rare event.

On the 15th of March 2022, the complete collapse of the Conger ice shelf[1] in East Antarctica occurred (Figure 25). The Conger ice shelf was a 1200 square kilometre expanse of land-formed ice, the size of Rome, floating on the ocean but still attached to land-fast ice. Antarctica is divided into east and west antarctica and separated by the Transantarctic Mountain Range. Whilst the west has experienced instability and collapsing ice, with the ice shelves there losing iceberg chunks for decades, the east experiences ice collapse rarely. However, in March 2022, the Eastern Antarctic ice shelf collapsed, breaking off from Antarctica completely (Figure 26).

Ice shelves are already floating in the ocean so this collapse on its own will not add to sea level rise. However, the loss of ice shelves can accelerate the flow of the land-based ice behind them into the ocean. It is not clear yet what led to the collapse of the Conger ice shelf but fortunately it will have only a minor impact on global sea level rise as there is little ice in the valley behind it.

The collapse of ice shelves are rare events. Collapse have historically occurred due to natural processes, however the number of ice shelves that have collapsed in recent decades is concerning. As the climate continues to warm, more and more ice shelf collapses are forecast to occur, potentially leading to an acceleration of sea level rise.

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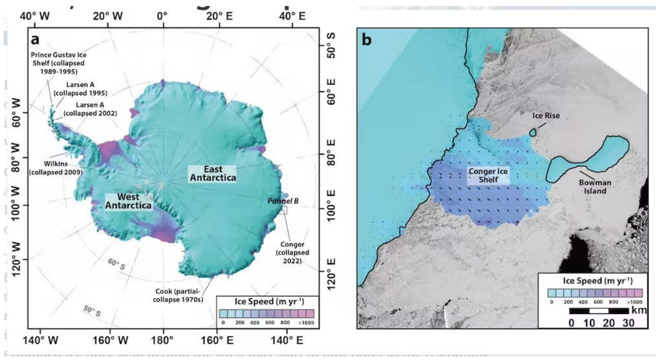

Figure 25: The Conger ice shelf (outlined in blue) before (left) and after (right) the collapse. Source: Bertie Miles/US Geological Survey/ European Space Agency.

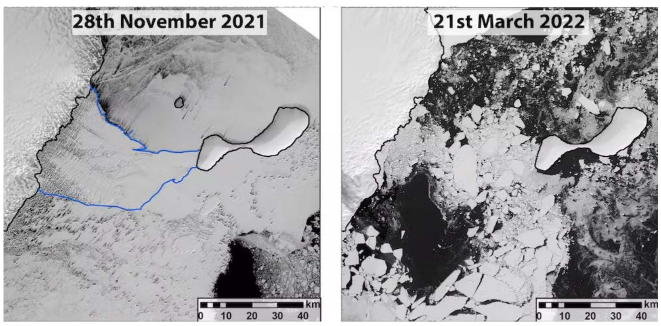

Figure 26: Source: The European Space Agency.

4.6 Coldsnap in Queensland

- Many regions in Queensland recorded the lowest ever maximum temperature for July.
- Toowoomba in southern Queensland had its coldest July day on record reaching 7.6°C on the 4th.

Queensland endured an unusual cold snap on the 4th and 5th of July 2022 (Figure 27)[1]. Toowoomba in southern Queensland reached a maximum temperature of 7.6°C on the 4th of July which was the lowest ever daily maximum temperature for this month. During the cold snap daily maximum temperatures were 8-12°C below the monthly average for Queensland, with many sites including Mackay, Townsville, Emerald and Sunshine Coast airport reporting their coldest July day on record. The cold days were accompanied by widespread rainfall pouring down the east coast.

As with many climate extremes during 2022, record cold daytime temperatures resulted from the prolonged presence of a cut-off low pressure system (Figure 28).

In this event, a pool of cold air broke off from a cold airmass in the mid-latitudes and moved over Australia. The cold pool of air was extremely slow moving and was situated over southern Queensland for several days. It extended close to the land surface, allowing for the cold, mid-latitude airmass to penetrate towards the surface resulting in cold day time temperatures over the region. Persistent cloud cover over the Queensland coast (Figure 28) further contributed to these cold temperatures and brought widespread rainfall during this period.

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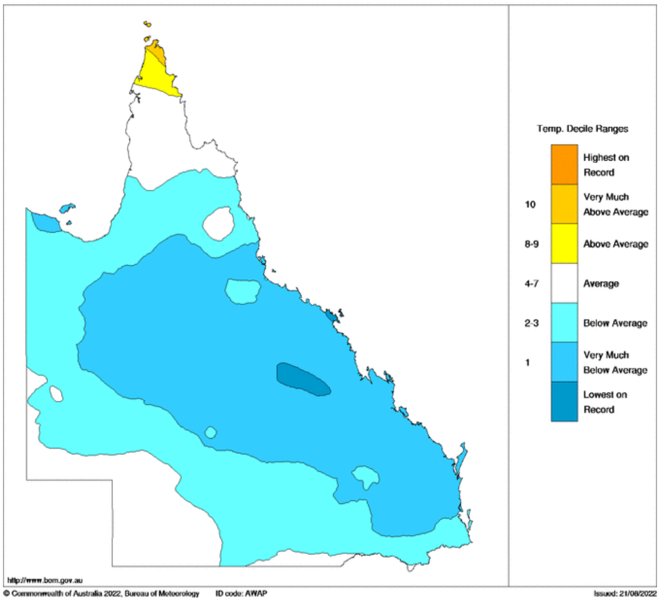

Figure 27: Daily maximum during July 2022. Source: Bureau of Meteorology.

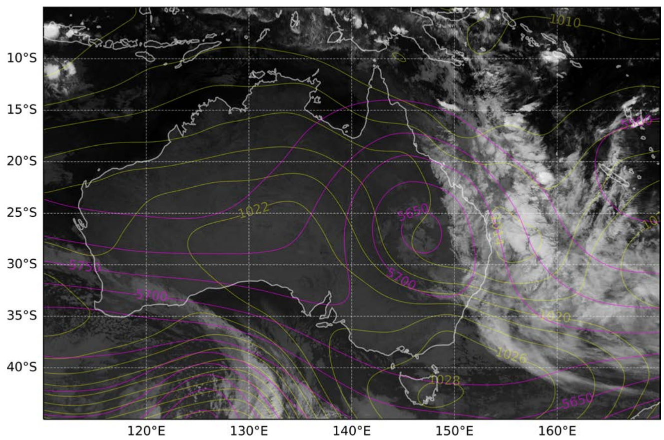

Figure 28: Himawari-8 satellite image on 5 July 2022 from the Bureau of Meteorology retrieved from the National Computational Infrastructure. Mean sea level pressure (yellow contours) and 500hPa geopotential height (magenta contours) from ERA5 reanalysis data are overlaid. Source: National Computational Infrastructure.

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4.7 Sydney's wettest year on record

- Sydney experienced its wettest year on record in 2022.
- Three weather events were responsible for 40% of the total rainfall in 2022.

Sydney experienced its wettest year on record in 2022 (Figure 29). This record-breaking year was a result of just three main rainfall events in February - March, July and October. Sydney (Observatory Hill) received 2530 mm of rainfall in 2022 which is more than double the average Sydney rainfall (1213 mm).

Atmospheric rivers played an important role in these heavy rainfall events, providing the large source of moisture which was dumped over Sydney. Atmospheric rivers are narrow regions of enhanced water vapour transport in the lower atmosphere and are often associated with extreme rainfall over Eastern Australia[1]. Atmospheric rivers feed huge amounts of water into other weather features such as low-pressure systems and cold fronts, which then convert the water vapour into rainfall via uplift - the process of forcing air to rise and cool where it can then condense into rainfall. During the February - March heavy rainfall, an atmospheric river from the warm Coral Sea fed moisture into an east coast low, which dumped this moisture over Sydney.

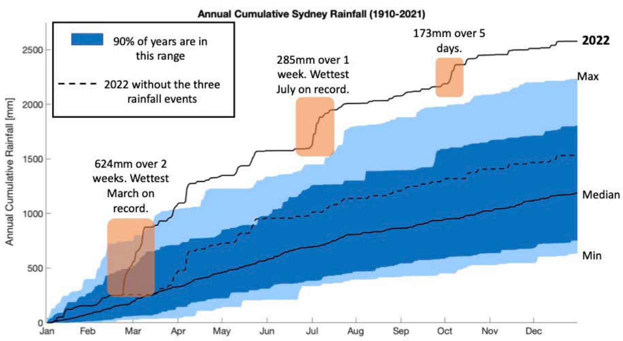

Figure 29: Annual cumulative rainfall in Sydney from 1910-2021. Areas in blue show the range of previously observed rainfall. The orange boxes highlight three extreme rainfall events that contributed to the record rainfall in 2022. The dotted black line shows the rainfall that would have occurred without these three rainfall events. Source: Kim Reid.

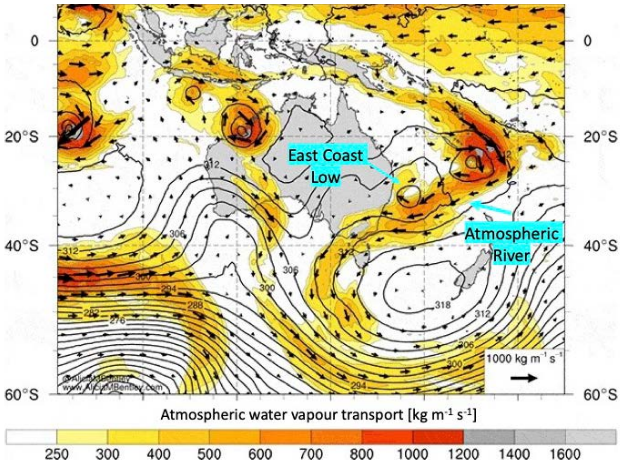

Figure 30: Atmospheric water vapour transport on the 2nd March 2022. Source: Alicia M. Bentley.

East coast lows are strong low-pressure systems that move along the east coast of Australia powered by the warm East Australian Current that runs parallel to the coast. Similarly, in July, a Low became cut-off from the steering westerly winds to the south of Australia and sat over NSW. This Low was also fed by an atmospheric river over the Coral Sea and dumped 285mm over Sydney in one week (Figure 30). In October, the rainfall came from the west with the passage of multiple fronts and associated atmospheric rivers. Atmospheric rivers over the Coral Sea are more likely during La Niña periods while east coast lows have a weak relationship with El Niño and La Niña[2,3].

4.7 Sydney's wettest year on record

The heavy rainfall events in February-March and July caused flash flooding across Sydney and significant flooding of the Hawkesbury-Nepean catchment. During the July storms, millions of people in the Greater Sydney region were advised to stay home and avoid any non-essential travel due to trains being significantly impacted. Fifty thousand people were affected by evacuation orders and warnings and the State Emergency Service received more than 5,300 requests for assistance, of which over 250 were flood rescues[4].

Recent research at the ARC Centre of Excellence for Climate Extremes indicates that the intensity of short duration (sub-hourly) rainfall events have already intensified over the past two decades[5], at least over the Sydney Basin. However, how longer duration rainfall events will change in the future is still an active topic of research.

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4.8 An "inland tsunami" hits Eugowra

- River levels peaked at a record breaking 11.2 metres after 120mm of rain on 13 November 2022.
- On November 14th 2022, Eugowra in New South Wales was hit by a devastating one-in-5000-year flash flooding event.

Eugowra, a small town in the central west of New South Wales, experienced a severe flash flood in the early morning of the 14th of November. The flash flooding was caused by intense rainfall the day before, with 120mm of rain falling across the catchment on the 13th of November. This event was preceded by months of above average rainfall over south-eastern Australia. As a result, the ground was already saturated and prone to flooding.

Eugowra sits on the banks of Mandagery Creek. As floodwaters made their way downstream, the intense flash flooding occurred. The creek levels peaked at 11.2 metres, smashing the previous record of 10.01m observed in 1950. This level was higher than the town's estimate of a one-in-5000-year flood[1] . The flooding was so fast and large that it was called an "inland tsunami" by residents[1].

The heavy rainfall was caused by a deep low-pressure system which developed over Western Australia during the 11th of November. The low-pressure system intensified and affected the south-eastern parts of Australia during the 12th - 13th of November. The system caused moisture rich air to flow from tropical Australia to the southeast. When combined with uplift caused by the system, this led to heavy rainfall over southeast Australia (Figure 31).

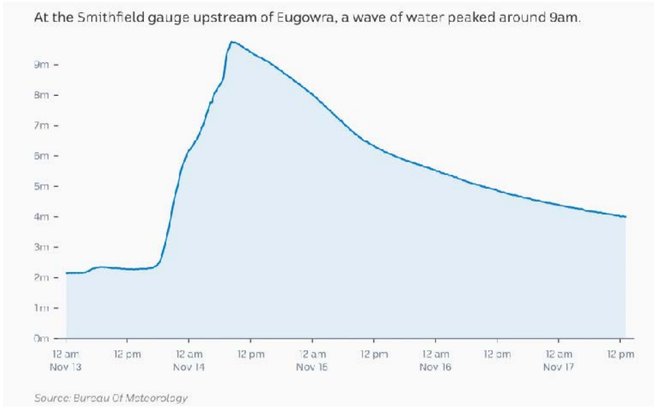

Figure 31: The water level of Mandagery Creek near Eugowra. How an extreme flash flood wiped out Eugowra in NSW. Image: Australian Broadcasting Corporation. Source: Bureau of Meteorology.

This extreme flooding caused devastating consequences and enormous economic losses to the residents of Eugowra. During the flooding, 159 people were evacuated in boats and helicopters and two people lost their lives. Up to 80% of homes in the town were damaged, with some homes floating several blocks away[2]. According to the Insurance Council of Australia[3], 412 insurance claims have been lodged across the region since the floods hit. The estimated cost of insured losses for Eugowra and its nearby region is at least $150m.

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4.9 Hailstorms in Queensland, Victoria and New South Wales

- Victoria, Queensland, and New South Wales all experienced damaging hail events in the 2022 storm seasons.
- Reported damage included potato, citrus, and grape crops with some growers losing 30-50% of their crops.

There were numerous damaging hailstorm events in Australia in 2022. On January 5, severe storms that included marble-sized hail damaged most potato crops in the Ballarat agricultural district in Victoria[1]. Citrus and grape crops near Griffith, New South Wales were also damaged by hail in severe storms on January 6 and 14, with some grape growers losing 30-50% of their crops[2,3]. On January 6, a severe storm with giant hail in Portland, Victoria led to more than 100 calls to the State Emergency Service (Figure 32)[4].

Later in the year, large hail, some cricket-ball sized, fell near Rockhampton, Queensland on 24 October[5]. In late November, hailstorms across the Mallee region of Victoria caused millions of dollars in crop losses and damaged cars and houses[6], while in New South Wales a hailstorm in Port Macquarie on November 28 caused property damage and prompted more than 120 calls for assistance from the New South Wales State Emergency Service[7].

Figure 32: Giant hail in Portland, Victoria, on 6 January 2022.
Source: Jessica Laws.

Climate change affects atmospheric properties of relevance to hailstorms in ways that lead to expectations of reduced hailstorm frequency but increased hailstorm severity[8]. However, there is large geographic variation in observed and modelled changes, so hailstorm responses to climate change remain highly uncertain in Australia and across the world[9]. The ARC Centre of Excellence for Climate Extremes is conducting research into how climate change is affecting severe convective storms including hailstorms, as well as links between large-scale atmospheric conditions and hail occurrence[9].

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4.10 Northern Australia heatwave

- Northern Australia experienced extreme temperatures during December, with mid to high 40s in many locations.
- The extreme temperatures are unusual for tropical regions.

The northern parts of Western Australia, the Northern Territory and Queensland experienced a prolonged heatwave during the first fortnight of December 2022 (Figure 33). At the same time, south-eastern Australia was recording cold and wet conditions, with a series of cold fronts bringing showers, winds and snow in some alpine areas. A record low summer temperature of -7°C was recorded at Perisher in the early hours of the 9th of December.

On the 7th of December, Marble Bar in Western Australia's Pilbara region was the hottest place in the world, reaching 46.2°C. The preceding three days had seen temperatures in excess of 45°C at this location. Several other locations in the Northern Territory and Queensland were in the top 20 hottest temperatures in the world on that day.

The heatwave was fuelled by a lack of weather conditions which have a "cooling" effect in this region. A period of suppressed tropical activity, resulting in dry air and clear skies, allowed the heat to build. During this "monsoon break", the usual north-westerly winds, which help to keep temperatures down, did not arrive over northern Australia. The negative Indian Ocean Dipole, which increases cloud across northern Australia, returned to neutral conditions with the index showing neutral values for five consecutive weeks. The reduced cloud cover allowed more heat from the sun to reach the land surface. The sea breeze was also weakened due to extremely warm sea surface temperatures, particularly around the Gulf of Carpentaria and Coral Sea, where spring ocean temperatures were the warmest on record.

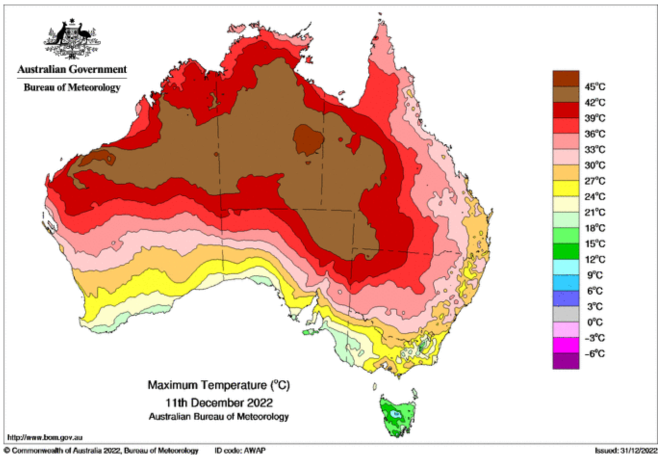

Figure 33: Mean maximum temperatures on 11 December 2022, showing the extent of the heatwave across northern Australia. Source: Bureau of Meteorology.

The heatwave followed a cooler, wetter period over eastern Australia. People take time to acclimatise to the heat, and so health impacts from extreme heat are worse early in the warm season. Heatwaves are one of the most significant natural hazards in Australia in terms of loss of life. For this reason, the Bureau of Meteorology considers recent temperatures in heatwave alerts. Heatwave conditions are expected to continue to worsen as the climate warms. The ARC Centre of Excellence for Climate Extremes is continuing to research links between heatwaves and weather systems[1], soil moisture[2] and climate change[3].

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4.11 Damaging wind gusts in South Australia and the Northern Territory

- Severe winds impacted parts of South Australia and the Northern Territory On the 12th of November 2022.
- Damage included failure of transmission lines in South Australia and damage to buildings, including the removal of a roof off of a school in the Northern Territory.

On the 12th of November 2022, severe thunderstorms impacted parts of South Australia and the Northern Territory, producing strong winds causing significant damage near Adelaide and Alice Springs (Figure 34). These thunderstorms were part of a broader region of severe weather that developed along a trough of low pressure extending through central Australia. These types of strong wind events generally begin by the evaporation and melting of water and ice in thunderstorm clouds. This produces cold, dense air that sinks, leading to "downdrafts" that can rapidly descend towards the surface and cause gusty conditions on the ground.

Storms began near Adelaide at around 12:00 pm Australian Central Standard Time(ACST) in the Spencer Gulf and travelled eastwards before reaching Adelaide at around 3:00 pm ACST. At that time, the storms were organised in a line around 140 km long. These types of 'linear' systems often impact southern Australia, sometimes bringing heavy and extreme rainfall[1]. The system also included a curved or 'bowing' segment, indicating strong winds at the surface[2].

The winds produced by this system caused widespread damage to the electricity network, with nearly 500 reports of downed overhead wires, services to 163,000 electricity customers affected, and the failure of high-voltage transmission infrastructure causing an isolation of South Australia from the National Energy Market[3,4,5]. A weather station at Parafield airport recorded a maximum gust of 106 km/h at around 3:00 pm ACST. However, the transmission line failure suggests even stronger gusts occurred. Weather stations only represent winds at a single point, so they may not always capture a thunderstorm's strongest gust.

The thunderstorm in Alice Springs was very different to those in the Adelaide region. The storm was around 10 km across when it impacted the town at approximately 5:30 pm ACST. The small size and strong winds associated with this thunderstorm suggest that it was a "microburst" event. Microbursts occur when thunderstorms begin over regions where there is a deep layer of hot, dry air near the surface, such as in central Australia. This hot, dry air encourages rain to evaporate as it falls out of the cloud, leading to more cooling, stronger downdrafts, and intense surface winds. The gust produced by this microburst was brief, but caused damage to several buildings, including removing the roof of a local school. The strongest gust recorded at Alice Springs Airport during this event was 76 km/h, but the structural damage indicates gusts were at least 100 km/h! (Figure 35)

Figure 34: Trees and powerlines down in Adelaide. Source: Andrew Hough

4.11 Damaging wind gusts in South Australia and the Northern Territory

Winds from thunderstorms are challenging to observe and predict because of the short-lived and localised nature of severe thunderstorm impacts. Although we expect an increase in the energy available for thunderstorms under climate change, there are significant uncertainties in explaining how locally damaging winds might vary[6]. Within the Centre, researchers are currently trying to understand the characteristics and types of locally damaging wind events that have occurred using historical data and simulations from computer models, with the aim of improving climate predictions, and providing better information for designing infrastructure[7,8].

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Figure 35: Microburst over Alice Springs. Source: Kaira Palupe

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