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The State of Weather and Climate Extremes 2023

Australian Research Council Centre of Excellence for Climate Extremes

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Acknowledgments

Acknowledgment of the Traditional Owners

The Australian Research Council (ARC) Centre of Excellence for Climate Extremes respectfully acknowledges the Traditional Owners of Country throughout Australia. We pay our respects to their Elders past, present and emerging, and recognise their continuous connection to Country and the contributions and sophistication of traditional knowledge.

Contributors

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Contents

About this report

This report provides a summary of selected significant extreme weather and climate events which occurred across Australia in 2023. The report provides a description of each event and an explanation which reflects our understanding of the causes. The report also provides an overview of selected international events including Antarctica. 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.

Defining extreme weather and climate

The Intergovernmental Panel on Climate Change defines[1] an extreme weather or climate event as:

'The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classified as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., high temperature, drought or heavy rainfall over a season). For simplicity, both extreme weather events and extreme climate events are referred to collectively as climate extremes.'

About the ARC Centre of Excellence for Climate Extremes

As Australia's leading climate science centre, the **ARC Centre of Excellence for Climate Extremes (the Centre)** recognises the risks of climate change for all Australians. The Centre consists 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 UK Meteorological Office.

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.

Our research focuses on the processes underlying extremes across four principal areas: weather and climate interactions, drought, ocean extremes, attribution (whether climate change may be responsible for an event) and risk of extremes.

The research uses the Australian Community Climate and Earth-System Simulator (ACCESS). Central to our research are high-performance computers and a data environment provided by the National Computational Infrastructure (NCI) and the software engineering provided by the ACCESS National Research Infrastructure.

The Centre's work improves Australia's national capacity to understand the processes underlying climate extremes and how these may change and affect us into the future.

A message from our Director

Professor Andrew Pitman

The year 2023 was the hottest year on record[1]. July was the hottest month on record [2], global sea surface temperatures were the highest on record[3], and Antarctic sea ice extent reached a record low[4]. There were days during 2023 where the average global temperature exceeded the 1.5°C target set by the Paris agreement[5]. Although increasing temperatures align with warming projections, soaring global temperatures have been described as "absolutely gobsmackingly bananas"[6].

The year saw another record set for the highest monthly atmospheric carbon dioxide in May, reaching 424 parts per million at Mauna Loa in Hawaii[7]. It is established that there is a direct and unambiguous link between these record levels of atmospheric carbon dioxide and the record temperatures. Even relatively small increases in temperature cause changes in extreme events[8]. Despite this, global carbon dioxide emissions from fossil fuels continue to increase and have now reached 36.8 billion tonnes in 2023, up 1.1% from 2022[9].

We know how to fix the problem of global warming. We need to reduce the concentrations of atmospheric carbon dioxide and other greenhouse gases in the atmosphere. Decision makers have all the evidence they need to urgently work towards net zero emissions. Reducing greenhouse gas emissions reduces the risk of extreme events for all Australians.

The good news is that emissions are plateauing[9]. The bad news is emissions are not declining rapidly enough as coal, oil and gas exploration, licensing, investment, extraction and use continues to expand around the world. This report provides details on a broad range of record-breaking extremes which impacted Australia in 2023. Many of these events are unlikely to be considered as 'extreme' in future years, without very deep reductions in global emissions.

Professor Andrew Pitman, AO, FAA,

Director, ARC Centre of Excellence for Climate Extremes

1.0 Review of 2023

1. Globally, 2023 was the warmest year in recorded history.

2. Australia experienced a broad range of record-breaking extremes.

3. Impacts from extreme events had economy-wide effects.

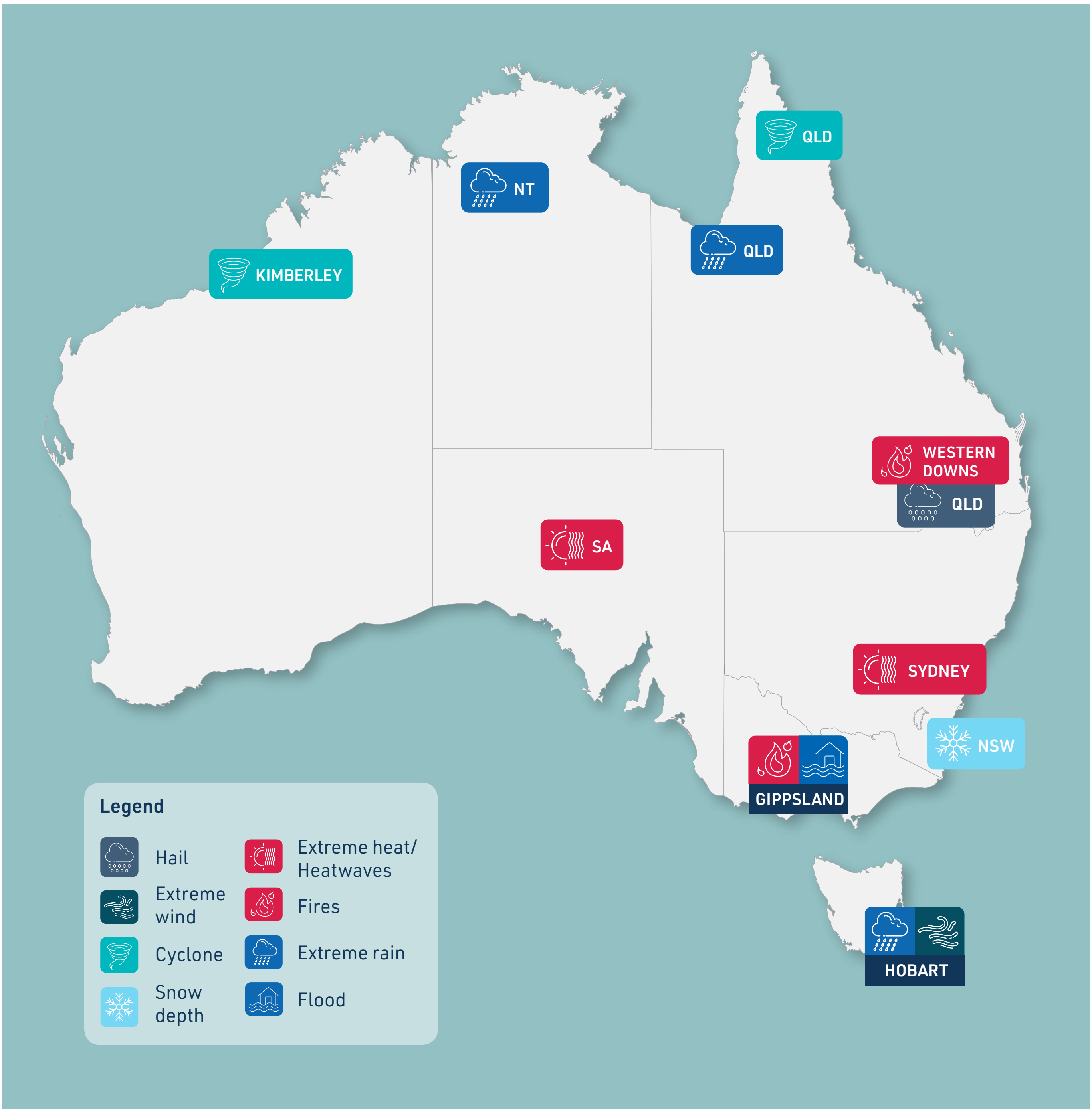


Figure 1: Location of major extreme events in 2023. Source: ARC Centre of Excellence for Climate Extremes.

1.1 Introduction

Above-average rainfall in northern Australia characterised the start of 2023, progressing to increasingly dry conditions in southern and eastern Australia as the year continued. After a multi-year La Niña, conditions returned to neutral in March; however, there were signs of an El Niño forming in the Pacific, which eventually resulted in the Bureau of Meteorology declaring an El Niño in September[1].

Multiple extreme events occurred across Australia (Figure 1, 2), ranging from a compound fire and flood event in eastern Victoria to significant heat in eastern Australia including a record-breaking heatwave during September around the Eyre Peninsula in South Australia. Sydney and New South Wales experienced their warmest winter on record. The year concluded with Queensland bearing the brunt of multiple extreme rain events, with Cyclone Jasper and compounding severe storms causing damage and loss of life.

This report presents a summary of major extreme events from 2023.

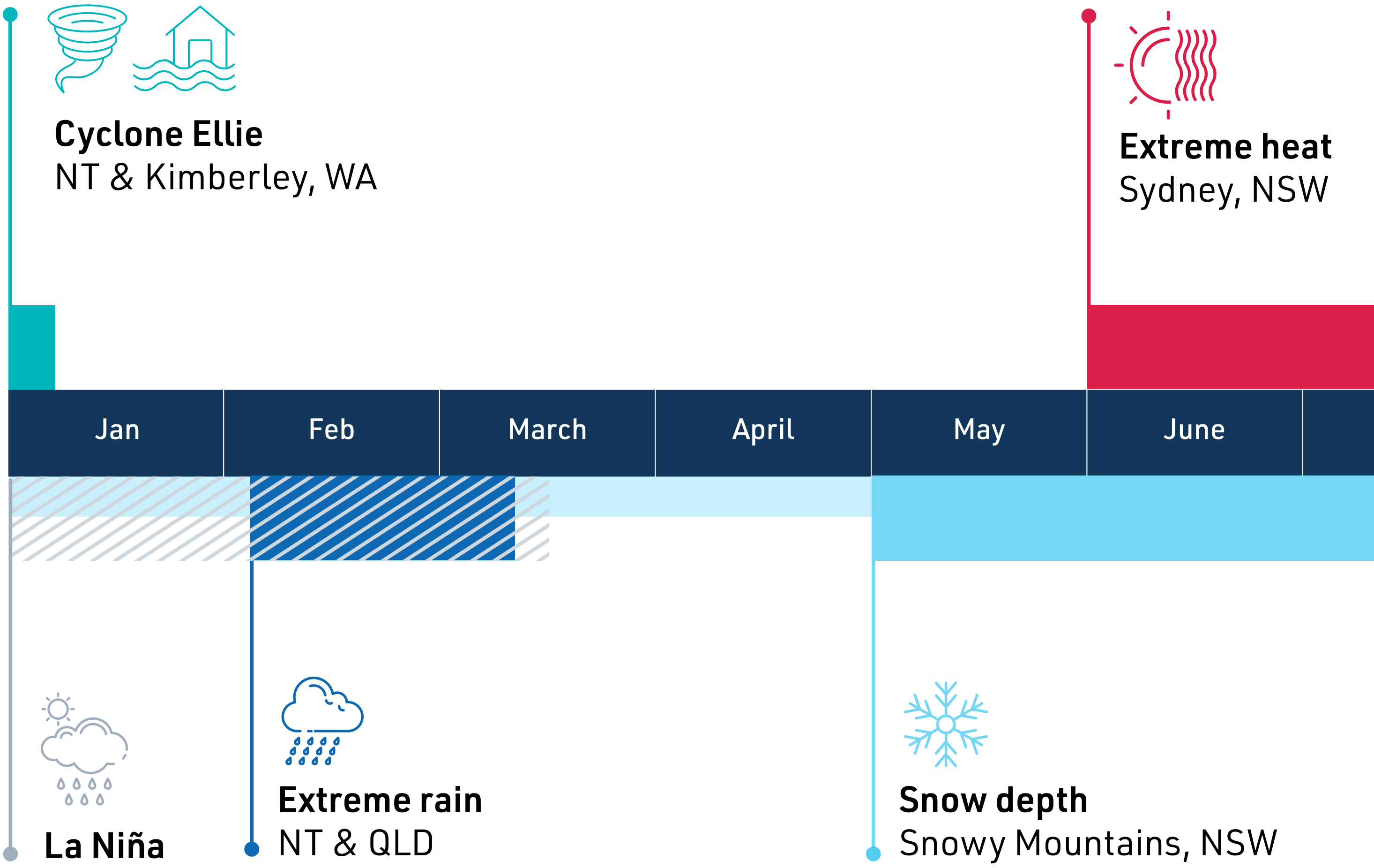
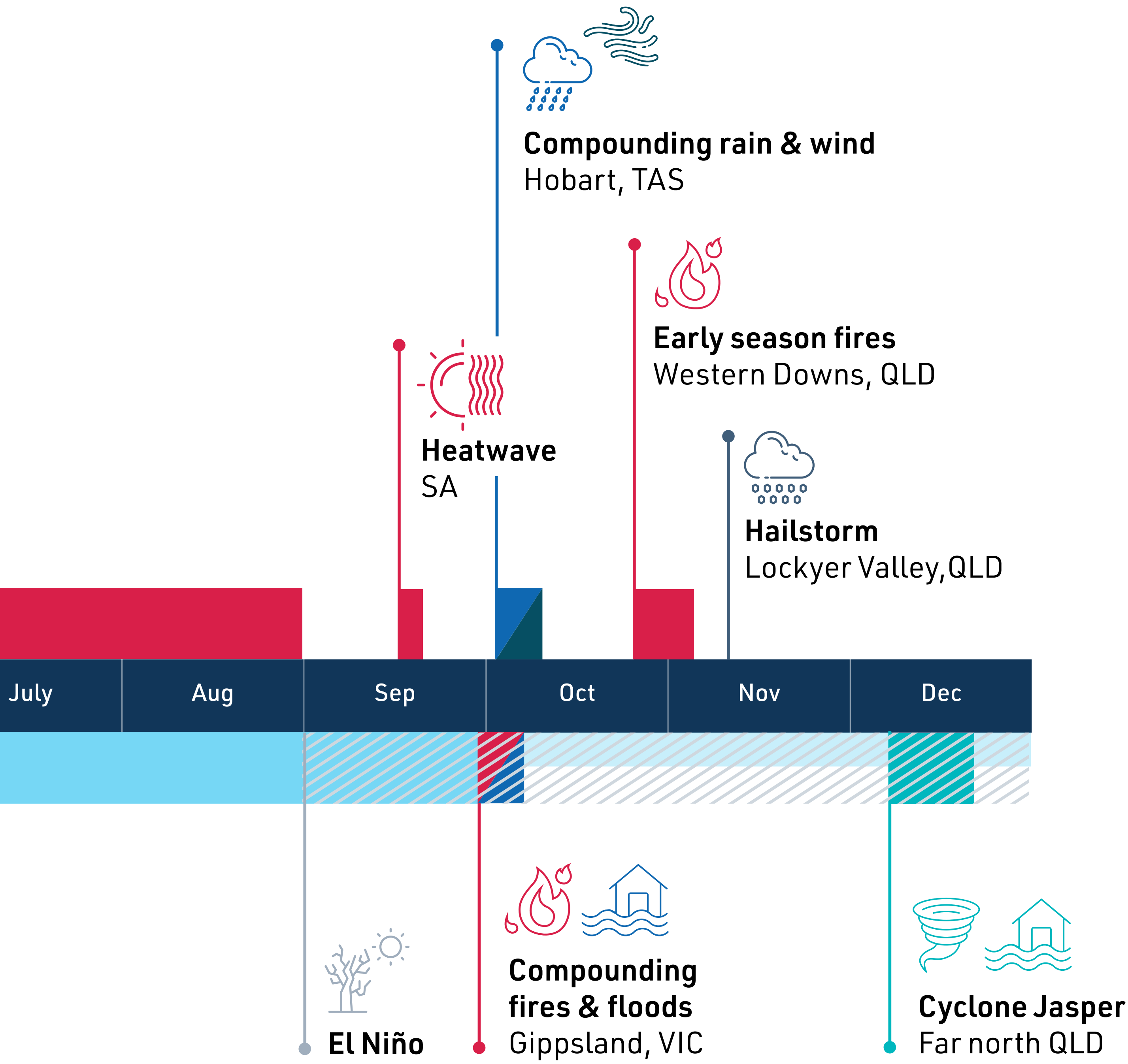


Figure 2: Timeline of major extreme events in 2023. Source: ARC Centre of Excellence for Climate Extremes.


Compounding rain & wind
Hobart, TAS
Early season fires
Western Downs, QLD
Heatwave
SA
Hailstorm
Lockyer Valley,QLD
July
Aug
Sep
Oct
Nov
Dec
El Niño
Compounding
fires & floods
Gippsland, VIC
Cyclone Jasper
Far north QLD

1.2 Climate drivers

After dominating the last three consecutive years[1], La Niña weakened in the tropical Pacific Ocean at the beginning of 2023 and officially ended in March. Neutral conditions returned; however, there were early signs that an El Niño could form later in the year. El Niño is characterised by unusually warm ocean temperatures in the central and eastern equatorial Pacific Ocean. An El Niño was announced at the beginning of July by the World Meteorological Organization[2] after sea surface temperatures in the tropical Pacific warmed and exceeded El Niño thresholds.

By mid-September, the onset of El Niño was declared by the Australian Bureau of Meteorology (BoM)[3] (Figure 1). The BoM uses different thresholds and metrics to define an El Niño, including the atmospheric components of wind and pressure. El Niño is typically associated with drier and warmer conditions over much of Australia in spring and early summer, and increases the risk of heatwaves, droughts, and bushfires[4].

The positive Indian Ocean Dipole (IOD), a phenomenon similar to El Niño but located in the tropical Indian Ocean[5], was announced[3] during this time. The positive IOD gained strength quickly and became the second strongest positive IOD event since BoM began recording IOD events in 2001, approaching the record-breaking positive IOD event of 2019. A positive IOD typically promotes below-average rain and increased daytime temperatures over central and south-eastern Australia during winter and spring.

The combined influence of El Niño and the positive IOD is associated with a higher chance of a warm and dry Australia, particularly during spring. Spring 2023 was Australia's fifth warmest spring on record since observations began in 1900. Overall, Australia's rainfall was below average in spring 2023. September was the driest on record, and October was the fifth driest on record[6]. This is in clear contrast to spring 2022, which was Australia's second wettest on record[7]. However, late spring thunderstorms and showers meant that Australia's November rainfall was above-average. This is an important reminder: El Niño and the positive IOD do not guarantee that eastern Australia will be hot and dry, rather it increases the likelihood of hotter and drier conditions.

In addition to the impacts of these climate drivers, the impact of global warming is also notable. Australia's climate has warmed by about 1.48 ± 0.23°C since national records began in 1910[8]. There has been a tendency towards more extreme rainfall, especially in northern and eastern Australia, and a reduction in cool-season rainfall in southern Australia[9].

Given the probability of warm and dry weather is influenced by the natural climate drivers and temperature changes are affected by an increase in greenhouse gas emissions, the increased impact on fire danger metrics was evident across most states and territories as spring turned into summer[10].

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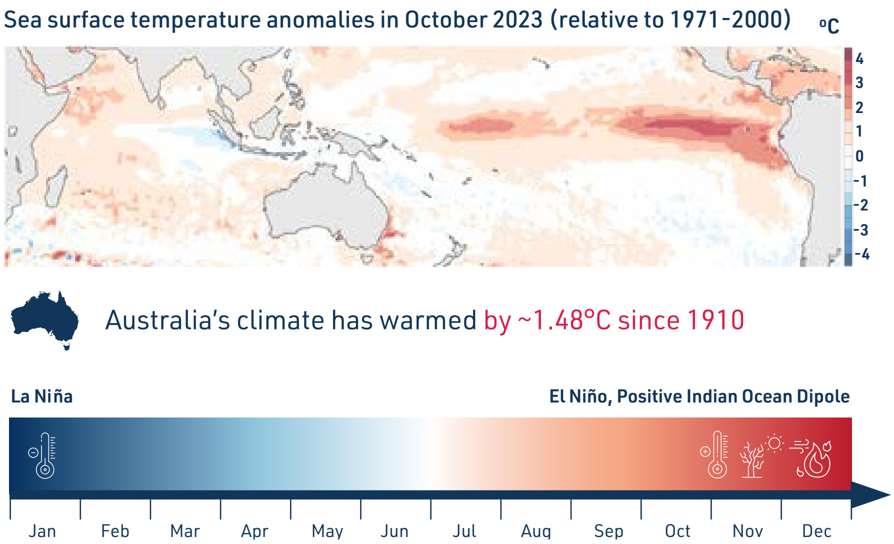

Figure 1: (top) Map showing the sea surface temperature anomalies in October 2023 relative to 1971-2000. Dark orange shows higher than normal sea surface temperature while dark blue shows lower than normal. The map shows El Niño conditions with warmer sea surface temperatures in the central-eastern Pacific and positive IOD with colder sea surface temperatures around northern Australia. Source: National Oceanic and Atmospheric Administration (NOAA). (bottom) Timeline of the El Niño-Southern Oscillation and IOD in 2023.

1.3 Temperature

Temperatures in Australia during 2023 were 0.98°C above the 1961-1990 average, making it the eighth hottest year on record. The year began relatively cooler than average, during the tail end of a "triple-dip" La Niña. In January and February 2023, several stations across Queensland and New South Wales observed their coldest summer day on record. However, summer mean temperatures around Australia were still higher than the 1961-1990 average, due to above average maximum temperatures over Western Australia, South Australia and Tasmania.

This cooler weather continued from summer into the autumn months, resulting in the coldest autumn nationally since 2012. Despite an overall cooler autumn, occasional events of very high temperatures were seen in several regions. Some sites in New South Wales, South Australia, Victoria and Queensland recorded their highest March temperatures on record between 17-21 March, when high temperatures hit most of the country. The highest were observed in north-western New South Wales with White Cliffs and Wilcannia reaching 43.8°C on 19th March. Strong cold fronts across south-eastern Australia in May caused several stations across the country to record their lowest nighttime temperature for autumn, with Canberra Airport experiencing -5.4°C on the 28th, the coldest May morning since 2015.

A major shift was observed moving into the winter months. Winter was the warmest on record for Australia since observations began in 1910, about 1.5°C higher than average (Figure 1). Almost all states and territories had records broken during this time. Queensland, New South Wales and South Australia observed their warmest winter, where mean and maximum temperatures were the highest on record. Tasmania had its highest recorded mean minimum temperature, about 20% higher than the previous record in 1988.

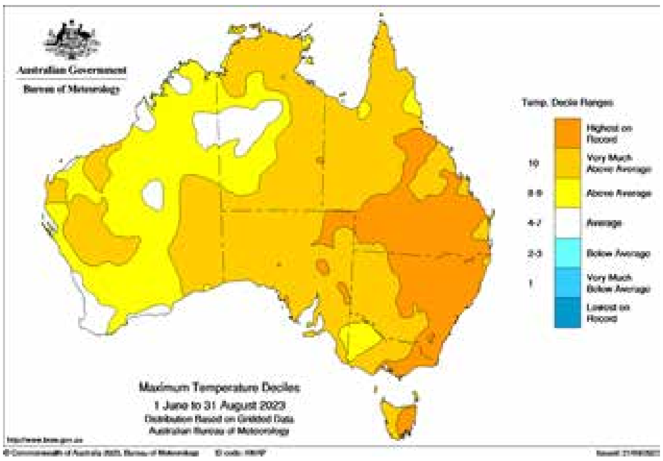

Figure 1: Deciles of maximum temperature over the winter season from 1961-1990 average records (1st June to 31st August 2023). Deciles are the ranking of temperatures compared to past observations, with 1 being in the lowest 10% on record and 9 being in the highest 10% on record. Source: Bureau of Meteorology.

September and October brought a very warm start to spring, with the mean temperatures exceeding about 1°C of the 1961-1990 average. Western Australia had its third warmest October and November on record and its hottest spring season ever. November was among the 10th warmest for Tasmania and Queensland. Daytime temperatures were also well above average for almost all of Australia. Warmest spring maximum temperatures were recorded around Western Australia, New South Wales and parts of eastern Victoria. The very warm start to the spring season likely contributed to the heatwaves in September and primed conditions for the October bushfires in Gippsland, Victoria and south-east Queensland.

December started off with a severe heatwave that affected most of the mainland from 2-10 December 2023. Sydney Airport recorded its highest December daytime temperature of 43.5°C in 85 years. Daytime temperatures were about 10-15°C above average over most of the country while nighttime temperatures were the fifth highest on record. The month of December in 2023 was Australia's fourth warmest December since 1910.

Overall, temperatures were above to very much above average for most of Australia in 2023 (yellow and orange parts, Figure 2), excluding certain parts in the north. These warm temperatures contributed to the several unseasonal extreme events, especially in winter and spring.

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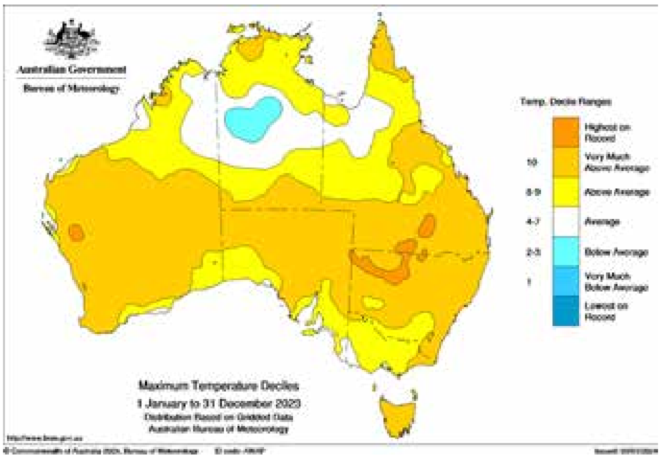

Figure 2: Deciles of maximum temperature for the year 2023 (1st Jan to 31st December 2023). Source: Bureau of Meteorology.

1.4 Rainfall

Australia's overall rainfall for 2023 was close to the 1961-1990 average. The year was marked by above-average rainfall in northern Australia, while the south-eastern quarter of Queensland, significant portions of New South Wales, Tasmania and southern Western Australia experienced drier than average conditions (Figure 1).

The year began with above-average rainfall across Australia, influenced by the "triple-dip" La Niña phase. Summer rainfall was 27% above average, with some parts of the country experiencing record-breaking rainfall. From late December 2022 to early January 2023, Cyclone Ellie contributed to significant rainfall and flooding over the northern areas of Western Australia, the Northern Territory and Queensland, causing major flooding of the Fitzroy River and substantial damage.

By autumn the La Niña conditions had dissipated but parts of the country continued to experience wet conditions. Significant flooding affected large parts of the eastern Northern Territory and north-western Queensland due to heavy rainfall in early March associated with a monsoon trough and a slow-moving tropical low. Ten-day rainfall totals between 400 and 800 mm were observed in some areas. During mid-April, Tropical Cyclone Ilsa brought high daily rainfall totals and flooding to parts of north-western Western Australia.

Late autumn and winter saw increasingly dry conditions develop, possibly influenced by an emergence of El Niño conditions. May was the second driest on record, with rainfall 70% below average. The winter was particularly dry in coastal Victoria, New South Wales and south-east Queensland. Pockets of Victoria experienced their driest July on record. However, some stations in Western Australia, Northern Territory, large parts of Queensland and an area spanning the border between South Australia and New South Wales, experienced significant unseasonal rainfall during late June and early July.

The dry conditions intensified in late winter and spring with August-October marking the driest three-month period on record in Australia. South-east Queensland and north-east New South Wales experienced a particularly dry spring, with record dry conditions leading to widespread agricultural impacts. The dry conditions also contributed to early season bushfires in the Gippsland region of Victoria beginning in late September and fires in Western Downs, Queensland in late October. November brought some relief to the dry conditions, with widespread thunderstorms and showers crossing the country.

December rainfall was above average for Queensland, New South Wales, Victoria and South Australia, but below average for Tasmania, much of Western Australia and the Northern Territory. Tropical Cyclone Jasper brought heavy rainfall to northern Queensland, leading to severe flooding in far north Queensland. Many stations in this region saw record rainfall totals for December, with some areas recording over 2000 mm during a seven-day period.

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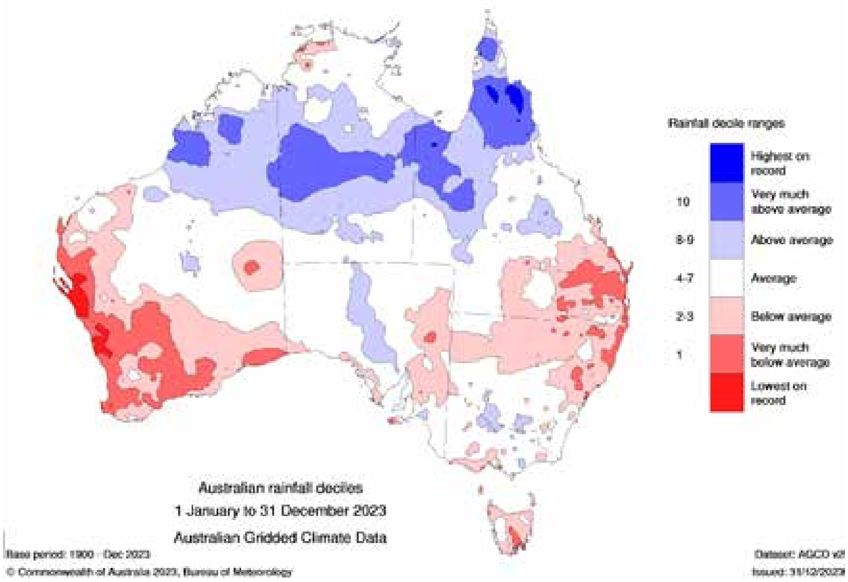

Figure 1: Australian rainfall deciles in 2023. Source: Bureau of Meteorology.

1.5 Ocean

Throughout 2023 ocean temperatures were unusually hot in Australian waters. Each month of the year was ranked within the top 60% for ocean temperature. March, in particular, was the fourth hottest ever for Australian waters, with ocean temperatures being on average 0.5°C higher than a normal March. Autumn water temperatures were especially high in Queensland, reaching up to 0.8°C hotter than normal.

The high ocean temperatures have meant that 2023 has witnessed a concerning number of "marine heatwaves" – discrete and prolonged events of extremely warm ocean temperatures. Just like a heatwave on land, these extended periods of unusually warm ocean temperatures tend to have negative impacts on marine ecosystems, and can also negatively impact aquaculture and fisheries.

In 2023, there were some marine heatwaves around Australia that persisted for over three months. A marine heatwave off eastern Tasmania, between December 2022 and May 2023, saw ocean temperatures remain more than 2°C above average over an area greater in size than 17 Tasmanias. It was the fourth most intense marine heatwave seen since satellite records began.

Two extreme marine heatwaves occurred in Queensland, with temperatures up to 1.5°C hotter than normal persisting for five months. The first, from March to August in north-east Queensland, was the second-longest duration for this region. The second, which occurred from 9th March to 5th August in south-east Queensland, is recognised as the third longest on record.

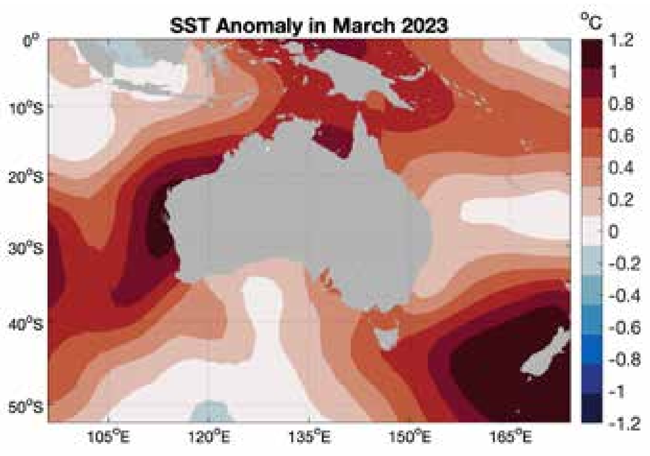

Figure 1. Sea surface temperature anomaly in March 2023 around Australia using the baseline during 1961-2023. Source: Dr Zijie Zhao.

These marine heatwaves off the coasts of Tasmania and Queensland are especially concerning for Tasmania's kelp habitats, and for Queensland's coral ecosystems in the Great Barrier Reef – two "foundational" marine species that provide habitats for the rest of the marine ecosystem. The detrimental impact of heat stress upon these vitally important habitat-forming species is well documented.

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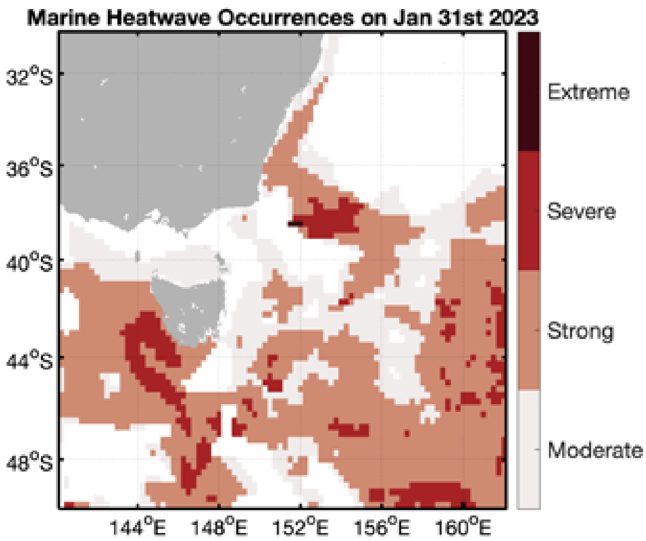

Figure 2. Marine Heatwave Occurrences on January 31st 2023 around south-eastern Australia. Source: Dr Zijie Zhao.

2.0 Attributing extreme events to climate change

"Human-caused climate change is already affecting many weather and climate extremes in every region across the globe[1]"

Australian surface air temperatures have risen by around 1.5°C[2], and will continue to rise until at least 2050 under all plausible emission scenarios, making further increases in some climate extremes inevitable[3].

Our ability to detect changes in our climate, and attribute these to human-caused climate change is very high for global scale changes in quantities like temperature, rainfall and atmospheric pressure. Detecting changes in the frequency or intensity of individual extreme events, and attributing these to human-caused climate change, is much harder and needs to be approached hazard by hazard.

At the global scale, it is virtually certain that hot extremes have been increasing due to climate change, it is likely that high intensity rainfall events are increasing, and there is medium confidence that climate change will result in an increase in drought and fire weather[1]. However, considering specific events that impacted Australia in 2023, it typically takes several years of research before clear statements can be made as to whether (or to what extent) climate change played a role.

In Australia, the frequency and intensity of heatwaves has increased across most of the continent since the 1950s[4]. The number of annual marine heatwave days has more than doubled over the last century[5]. Short duration rainfall events have been seen to be intensifying in some regions of Australia, including Sydney which has observed a 40% increase over the last 20 years[6]. For south-western and parts of eastern Australia, increases in drought occurrence are showing an emerging link to climate change[7]. Considering bushfires, research suggests the character of fire events may continue to worsen in the future[8].

While general statements about the increase in extremes can be made robustly, Section 3 of this report describes a selection of extreme events from 2023. These events are associated with natural processes, potentially modified by climate change. Robust event attribution requires extensive analysis, and our ability for attribution varies substantially depending on the type of event and our ability to observe and model the event[9].

The Centre is continuing to explore the impacts of local, regional and global scale processes in shaping extreme events, and how these are changing. Briefing notes are available for further details on Detection and Attribution and Event Attribution.

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3.0 Extreme events in Australia

3.1 Kimberley flooding from Cyclone Ellie

- Ex-tropical Cyclone Ellie spent more than two weeks moving over the Northern Territory and Kimberley region of Western Australia.
- Ellie brought substantial rainfall and flooding to the region, with the Fitzroy River flood level exceeding the previous record by almost two metres.
- Dimond Gorge and Napier Downs received weekly rainfall totals of 830.2mm and 701.2 mm.

Over the 2022 Christmas and New Year period, ex-Tropical Cyclone Ellie spent over two weeks moving slowly across the Northern Territory and the Kimberley region of Western Australia. Ellie brought heavy rainfall and record-breaking river flooding to multiple locations[1].

Ellie made landfall near the mouth of the Daly River in the Northern Territory on 22nd December 2022 as a category 1 tropical cyclone. Ellie weakened to a tropical low as it travelled southeast over land, and brought substantial rainfall to many areas including Timber Creek, which saw over 200 mm fall during 23rd December and overnight[1].

The system continued moving south-east, but on 27th December began to track westwards into Western Australia. Between 30th December and 3rd January Ellie stalled over the Kimberley, bringing several days of heavy rainfall[1]. In Dimond Gorge, north of Fitzroy Crossing, 838.8 mm of rainfall was recorded in the 10 days to 6th January, nearly equivalent to the annual average rainfall (Figure 1). Elsewhere in the Kimberley, multiple sites saw rainfall accumulations over the same period exceeding between 300 mm and 600 mm[2].

These totals resulted in a one-in-100 year flooding of the Fitzroy River, which recorded a peak river level of 15.8 metres on 4th January, beating the previous record by 1.8 metres[2].

Ellie then tracked westwards towards Broome, with more than 400 mm rainfall recorded at Broome airport between 4th and 6th January, flooding the Roebuck Plain and cutting off the town by road. The low then tracked southeast, weakening and eventually dissipating on 8th January.

Over 200 people were evacuated by the military from the Fitzroy Valley, and many settlements including Indigenous communities were left isolated[3]. The Fitzroy River Bridge, a vital piece of infrastructure in the Kimberley, was irreparably damaged. A new bridge is under construction with an estimated cost of $200 million. Because of the damage to critical transport infrastructure, trucks were unable to access the region, causing supermarket food shortages[3]. A $6 million tourism package was announced to alleviate the cost of flights into the region. As of May 2023, the total cost of Cyclone Ellie was estimated at $322 million[4].

We have not attributed this tropical cyclone to climate change, but that does not mean climate change has not played a role. The science implies climate change could result in fewer occurrences of tropical cyclones in Australia, but the proportion of intense cyclones such as Ellie may increase[5].

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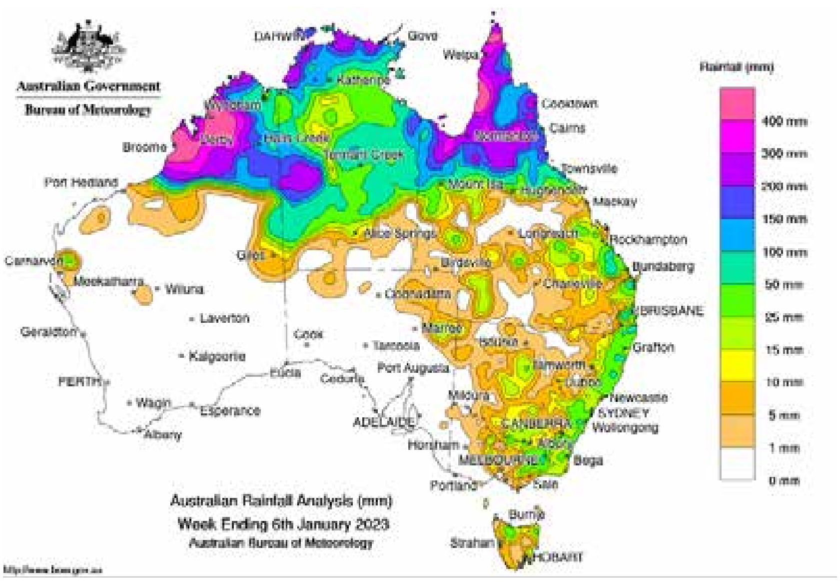

Figure 1: Rainfall totals in the week ending 6 January 2023. Source: Bureau of Meteorology.

3.2 Flooding in Northern Territory and north-west Queensland

- A persistent low-pressure system brought extensive rainfall across wide areas of the Northern Territory and Queensland.
- Flooding occurred in remote communities, presenting a challenge for emergency services.

From late February to early March 2023, a persistent and slow-moving monsoon low produced extensive rainfall over wide areas of northern Australia, including the Northern Territory and north-west Queensland.

While the low-pressure system was much weaker than a tropical cyclone, barely dropping below 1000 hPa (hectopascals), its long-lived and slow-moving nature led to spectacular accumulated rainfall totals over several days (Figure 1).

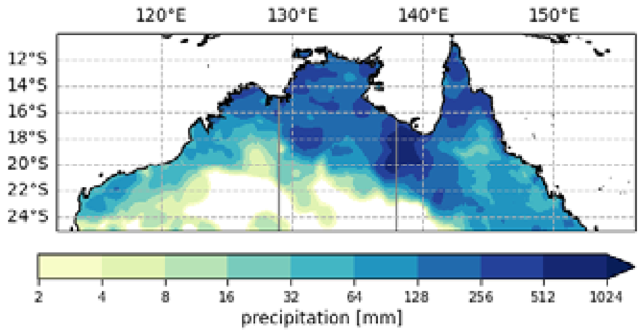

Figure 1: The Bureau of Meteorology's analysis of accumulated rainfall from 24th February to 12th March 2023. Source: Bureau of Meteorology.

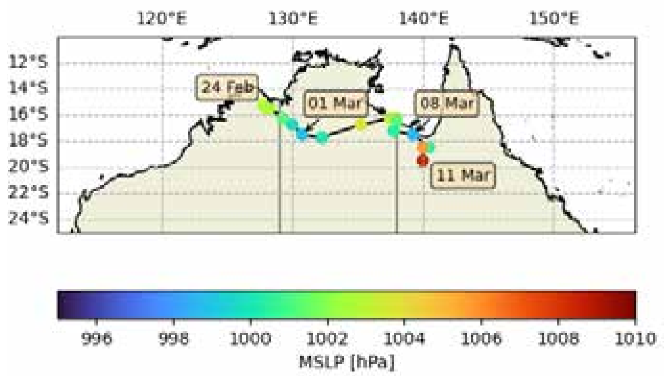

Figure 2: Track of the monsoon low using ERA5 data. The minimum mean sea level pressure is shown in colours. Source: European Centre for Medium-Range Weather Forecasts.

The monsoon low initially formed around the 24th February over north-western Western Australia, situated within a prominent monsoon trough (Figure 2). From here it strengthened and slowly tracked south-eastwards into the Northern Territory, where widespread weekly rainfall values of more than 200 mm were recorded[1].

From the start of March, the low weakened slightly, continuing its slow eastward movement. A second pulse of development began on 3rd March as it moved towards the Queensland border. In the 24 hours to 8th March, Century Mine (located north of Mount Isa) received a record 315 mm of rainfall[2].

The low began to weaken from 8th March. In its final stages, a midlatitude trough (a band of low pressure) from southern Australia interacted with the weak low-pressure system, bringing moderate rainfall to central and southeast Queensland.

The remote location of the flooding provided a considerable logistical challenge to emergency services supporting isolated communities. In the Northern Territory, people in three Indigenous communities, Kalkarindji, Daguragu and Pigeon Hole, were evacuated and relocated to Darwin. They were temporarily housed in shelters until they could safely return to their community up to three months later[3].

The Northern Territory flooding impacted transport routes as floodwaters cut off rail access to South Australia and increased the reliance on one road to connect the states. This resulted in widespread food shortages and some grocery stores flying in food[4], placing further strain on affected communities, such as Lajamanu, which were trapped by the waters.

Flooding in northern Queensland also resulted in major transport disruption to the supply of essential food products. Re-routing food transport increased costs for suppliers and transport time, with some regions waiting for over a week for food supplies to arrive[5].

Persistent monsoon lows like these are uncommon but not unheard of in Australia. We have seen numerous recent events of a similar nature, such as the 2019 northern Queensland floods and ex-Tropical Cyclone Ellie in early 2023.

Centre researchers are working to understand how these slow-moving and high-impact weather systems work and what role they may have in the future. While there are some theoretical grounds to believe they will worsen in a warmer climate, it is still an active topic of research today.

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3.3 New South Wales winter heat

- Sydney and the state of New South Wales experienced the warmest winter on record.
- Large scale synoptic weather patterns and anthropogenic greenhouse warming were major driving factors.
- The heat and rainfall deficits during winter accelerated the early onset of the bushfire season in the state.

Against the backdrop of the warmest winter on record in Australia, the state of New South Wales and the city of Sydney experienced their warmest recorded winters.

The state of New South Wales experienced daily maximum temperatures 2.23°C above the 1961-1990 average[1]. In addition, there was below average rainfall along the NSW coastline[1] (Figure 1). The Bureau of Meteorology reported that more than 10 sites across Sydney (with active weather stations) had their highest winter-average daily maximum temperature on record[2]. One of the sites, Sydney Observatory Hill (Figure 2a) experienced a winter-average daytime temperature approximately 2.43°C above the climatological mean. The temperature in the month of July was around 3.5°C higher than the long-term average.

Persistent high-pressure systems sat over Australia's south-east coast (Figure 2b), preventing easterly winds that often bring showers and rain. This led to clearer skies, allowing more heat from incoming solar radiation.

Moreover, the unusual westerly and north-westerly winds over the state of New South Wales brought warm and dry air, contributing to the heat. This warming, as a result of the large-scale weather patterns on top of the background warming from anthropogenic greenhouse gas emissions[3], resulted in the record-breaking temperatures.

Warm winters are often considered pleasant. However, unusually warm winters can have a significant impact on ecology and agriculture and bring an early onset of the bushfire season. Elevated temperatures, or prevailing dry conditions, can often damage crops such as rice, canola, wheat, barley, and lead to lower crop yields[4]. New South Wales Rural Fire Service announced an early start to the fire danger season in the north of the state, with over 70 blazes already active by August[5].

As warming continues, winters in south-east Australia will continue to warm and cool-season heat events will become more frequent and intense[3].

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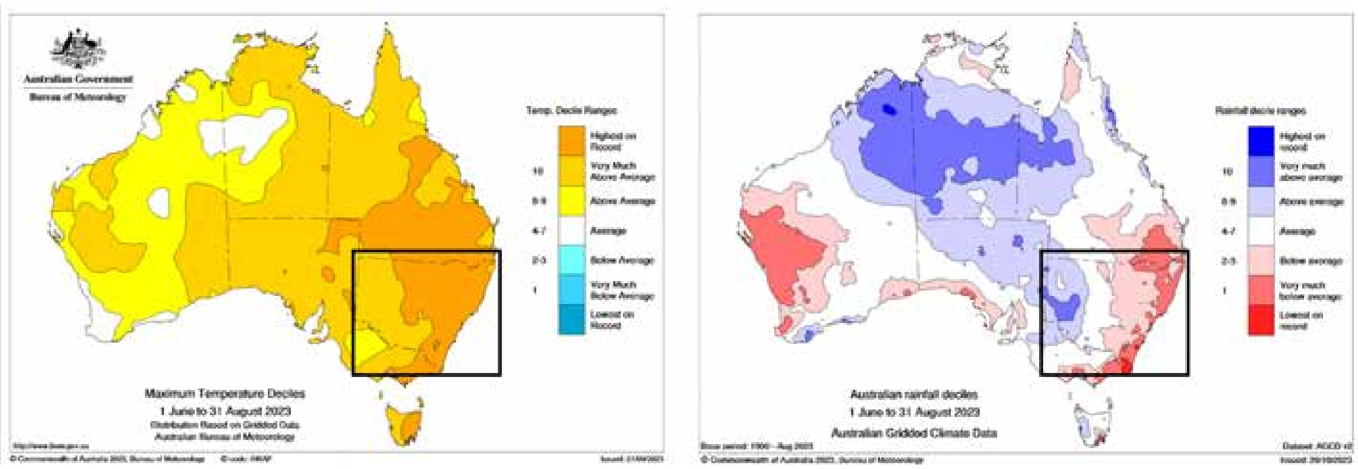

Figure 1: Maximum temperature (left) and mean rainfall (right) decile ranks for winter 2023 (1st June - 31st August). The state of New South Wales is highlighted in the black box. Source: Bureau of Meteorology.

3.3 New South Wales winter heat

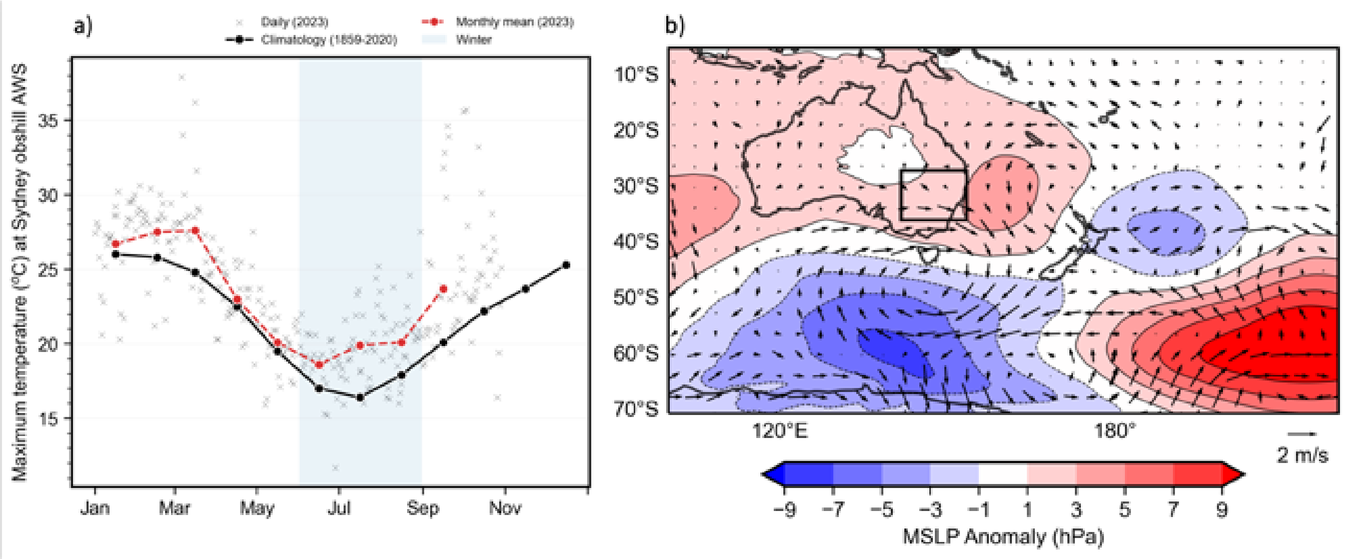

Figure 2: a) Daily maximum temperature during 2023 (grey markers), monthly averaged maximum temperature during 2023 (in red) and monthly averaged maximum temperature during 1859-2020 (in black) at the Sydney Observatory Hill weather station. b) Winter (1st June - 31st August) Mean Sea Level Pressure (MSLP) anomaly and wind (10m above ground) anomaly with respect to 1961-1990 baseline. The state of New South Wales is highlighted in the black box. Source: Aditya Sengupta.

3.4 Early end to snow season

- The Australian Alps experienced rapid and early loss of snow cover in September of the 2023 snowsports season.
- The unusually warm and dry weather from June to September contributed to the snow loss.

After a strong start, Australia's snowsports season came to an early finish, with Australia's warmest winter on record contributing to rapid snow decline in the alps. As well as being popular for winter sports, the Australian Alps are important for renewable energy generation, hosting the Snowy Mountains Hydro-Electric Scheme.

In the Australian Alps, cold weather and snow are generally associated with cold fronts[1]. During the 2023 winter, a combination of continued human-caused global warming and natural weather systems meant that far fewer cold fronts arrived to bring snow to the region. Instead, high-pressure systems that promote warmer, drier weather were widespread across south-eastern Australia.

The warm, dry winter culminated in a September that was both extremely dry, and the hottest September on record in the Australian Alps[2]. The long-term average September temperature in Perisher Valley is 2.25°C. The 2023 September temperature was 5.85°C, which is 3.6°C hotter than average. September 2023 was also 1.45°C hotter than the next-warmest September on record for Perisher Valley (2013). This hot weather caused a very rapid and early loss of snow cover across the alps.

The rapid snow decline did not only impact snowsports. Water storages in the Snowy Mountains Hydro-Electric Scheme are used to generate renewable energy, and to capture, store and divert water for downstream users in New South Wales and Victoria.

'The low frequency of cold fronts and warmer-than-average temperatures this winter impacted both natural snowfall, as well as the opportunities for snowfall enhancement via our Cloud Seeding Program,' says Dr Johanna Speirs, Senior Climate Scientist at Snowy Hydro.

'Snowmelt and runoff into the Snowy Scheme for June to November were about 60% of the long-term average.'

Fortunately, the Snowy Scheme was designed to operate within a variable climate, and reservoir storages had recently been boosted by the three-year wet period associated with La Niña and negative Indian Ocean Dipole.

We cannot yet attribute this year's poor snow season to climate change. However, this does not mean that climate change did not play a part – in fact, snow depths have been steadily declining over the past decades, while alpine temperatures have been rising.

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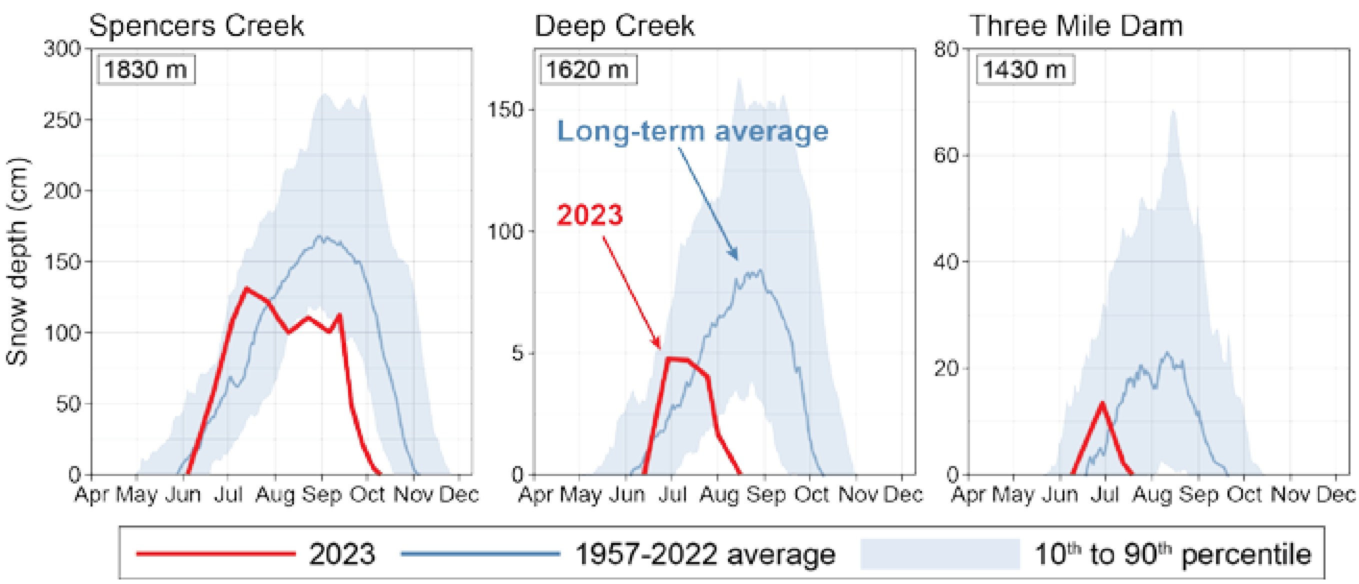

Figure 1. Average snow depths at three Snowy Hydro monitoring sites within the Snowy Mountains. Sites arranged by decreasing elevation from left to right. Blue line shows 1957-2022 average snow depth, ribbon shows snow depths in the 10th to 90th percentile, red line shows 2023 snow depth. Source data: Snowy Hydro.

3.5 South Australia September heatwave

- A record-breaking heatwave occurred throughout mid-September around the Eyre Peninsula.
- Some areas reached temperatures over 18°C above average.

Extreme temperatures 10°C to 20°C above average occurred over large parts of South Australia from 16th to 19th September 2023. At Ceduna, the temperature reached 39.8°C on 17th September, which is the highest recorded September temperature in Ceduna since records began. This temperature was 18.2°C above the September average temperature. The maximum September temperature record was also broken at Port Augusta, where the temperature reached 38.4°C.

Winds coming from the north resulted in dry and warm air blowing in from the northern parts of Australia into south-east Australia. These northerly winds were in part due to a stationary high-pressure system off the east coast of the country. This hot air from the central Australian desert then drove the already warm landscape into the extreme heatwave conditions that occurred during this event. The hot weather in South Australia also extended to New South Wales and Victoria. For example, on 17th September the Sydney marathon took place in over 30°C heat, with 40 people requiring treatment by paramedics[2].

Such unseasonably high temperatures are part of a larger trend in south-east Australia, where heatwave events are becoming more frequent, more intense, and occurring earlier than usual as a result of human-caused climate change[3].

Although South Australians are well adapted to hot weather, these events are concerning due to their negative impacts on agriculture, human health as well as natural and urban environments[4].

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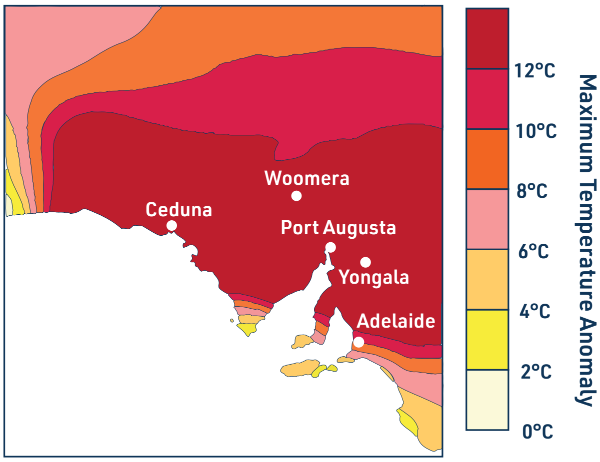

Figure 1: Maximum temperature anomaly for 17th September 2023. The temperatures were over 12 degrees above September averages. Source: Bureau of Meteorology.

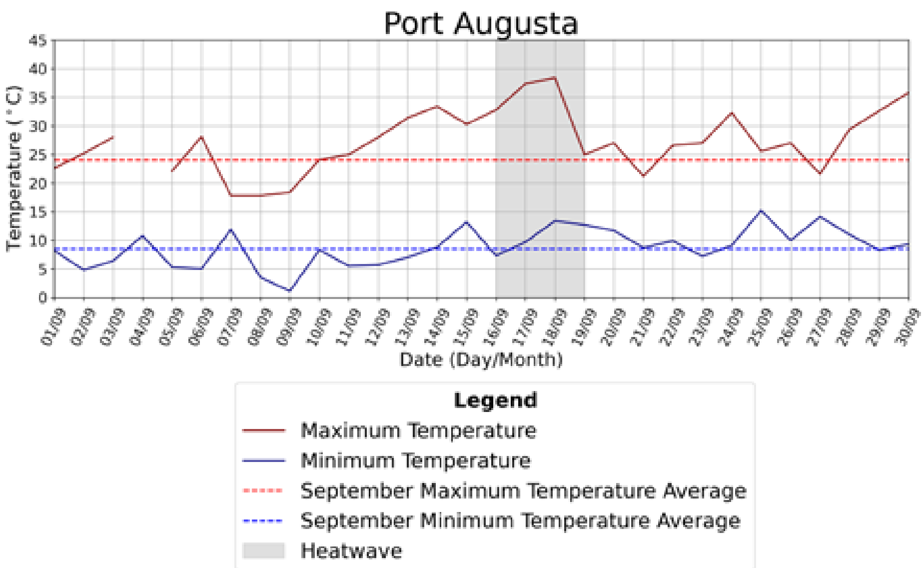

Figure 2: Daily maximum and minimum temperatures recorded by the Port Augusta airport weather station throughout September 2023[1]. Note that there was no data on the 4th of September. Source: Bureau of Meteorology.

3.6 Gippsland fires and floods

- Gippsland experienced unseasonably early spring bushfires.
- A strong cut-off low extinguished the fires but caused widespread flooding.
- Centre research is trying to understand how these weather features may behave in the future.

The Gippsland region of eastern Victoria experienced compounding fires and floods[1] during the first week of October 2023 (Figure 1).

Gippsland receives the bulk of its rainfall between late autumn and early spring. Temperatures during winter were above average while rainfall was below average, producing a dry landscape. September 2023 received less than 40% of the typical September rainfall. Dried vegetation is a critical ingredient for runaway wildfires, providing the fuel required for the unseasonably early bushfires.

On 30th September, the warm, dry, gusty north-westerly winds ahead of a cold front fanned the fires over the dry landscape. The fires spread, becoming out of control in the Briagolong, Loch Sport and Walhalla regions.

Figure 1: Simultaneous fire and flood warnings on 3rd October over a large region of Victoria. Source: Victorian Emergency[4].

A second, much more intense, cold front affected the region from 2nd October (Figure 3). The intense frontal system was again associated with warm and gusty north-westerly winds ahead of it, fanning fires further. As the cold front moved over Victoria, the atmospheric waves (Rossby waves) supporting the weather system broke. The result was the generation of a cut-off low that broke away from the strong winds to the south, and further intensification of the cold front. The weather system's intensity and northward extent promoted the transport of enhanced moisture from tropical Australia – known as an atmospheric river[2]. The moisture fed into the slow-moving weather system and produced prolonged, widespread rainfall over eastern Victoria.

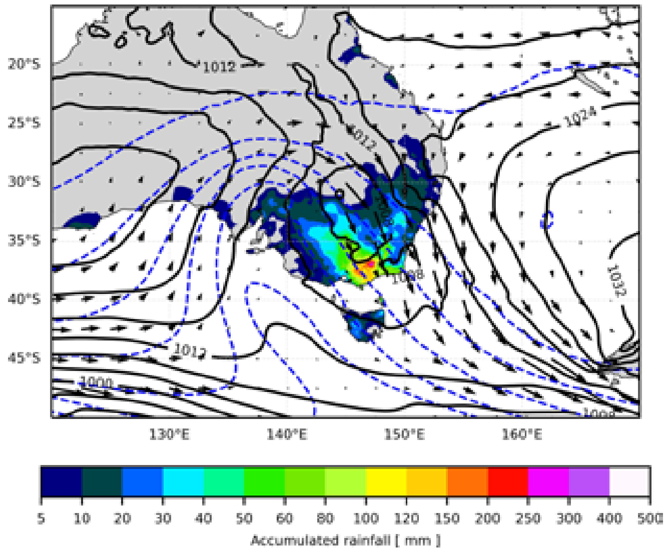

Figure 2: Map showing the dominant weather systems associated with heavy rainfall over Victoria on 3-4 October 2023. Mean sea level pressure (black contours), 500hPa geopotential height (blue dashed contours), integrated vapour transport (arrows) and accumulated rainfall between 1-5 October 2023 (shading) are shown. Source: Bureau of Meteorology.

Over 200 mm of rain fell over the region in under 48 hours[3]. Although this terminated the fires, the rainfall caused substantial flooding and destruction over the region. About 130 properties were flooded and the SES[1] received 300 calls in 24 hours on 3-4 October.

Hot and dry winters make Australia more prone to early season fires. Additionally, a warmer atmosphere can hold more moisture, making heavier falls more likely when rain does occur. However, future changes to the intensity and frequency of weather features that produce fire and flooding extremes are uncertain. Ongoing work within the ARC Centre of Excellence for Climate Extremes aims to understand compound events[5], atmospheric rivers, Rossby wave breaking and lows to guide our understanding of future extremes.

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3.7 Early season Queensland bushfires

- Queensland experienced over 1000 bushfires in late October 2023.
- The Western Downs region in south-east Queensland was significantly impacted, with the town of Tara losing more than 20,000 hectares of land to the fires.

In late October 2023, the state of Queensland experienced a series of bushfires, marking one of the earliest fire seasons since satellite records began in 2001. Over 1000 fires burned across the state, with significant fires occurring in the Western Downs region, located approximately 300 km west of Brisbane.

On 23rd October, multiple fires started in the Western Downs region and were rapidly pushed toward the town of Tara due to changing winds. These fires maintained their intensity over the following days resulting in Tara losing more than 20,000 ha of land by 29th October[1]. On 31st October strong westerly winds and temperatures approaching 40°C further intensified the fires. The situation eased on 3rd November with the passage of several storms across the region and the arrival of much-needed rainfall.

The fires were unusual in two ways: they began early in the season and a greater number than usual continued to burn through the night[2]. This atypical behaviour was caused by exceptionally hot and dry conditions, which are made more likely with climate change. These fires also coincided with the return of El Niño, which typically results in reduced springtime rainfall in eastern Australia[3]. This was the case in 2023, which saw the driest September since 1900. These exceptionally dry conditions allowed plant regrowth from three consecutive La Niña years to dry out and become fuel for the fires.

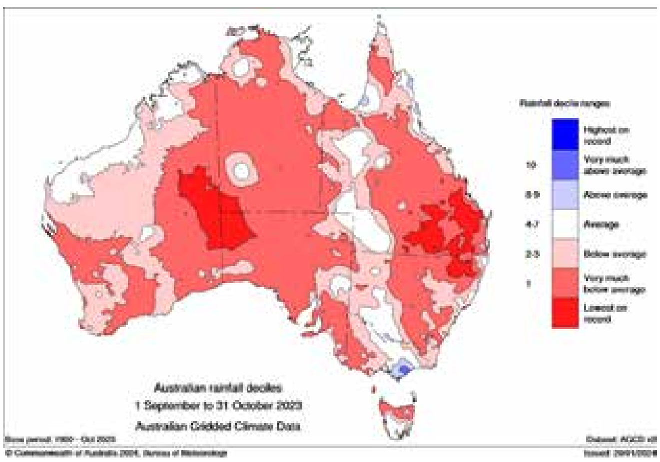

Figure 1: Rainfall deciles for September and October. Parts of southeast Queensland experienced the driest September-October on record. Source: Bureau of Meteorology.

The fires had devastating impacts, with 58 homes destroyed in Tara, surpassing the toll of the Black Summer fires of 2019 across the whole of Queensland[4]. Nearly 300 people were forced to evacuate their homes and two people died. Queensland's firefighters received substantial support, with more than 80 firefighters arriving from Victoria and 27 crews coming from New Zealand.

In the future, south-east Queensland is expected to face harsher fire conditions due to global warming. Modelling conducted by CSIRO and the Bureau of Meteorology shows that the region is likely to experience large declines in rainfall in the coming decades[5]. These projected drier and hotter conditions may result in higher fire risks for the area.

The ARC Centre of Excellence for Climate Extremes is researching how different atmospheric processes, such as the transport of dry air, contribute to fire events.

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3.8 Compound rain-wind event in Hobart

- A slow-moving low-pressure system brought heavy rain to Tasmania, dumping a month's worth of rain over a large part of the island.
- This was followed by another low-pressure system associated with extreme winds two days later.
- The rain loosened the soil, which meant that trees blew over more easily, wreaking havoc across the state's south, including Hobart.

Throughout 21st and 22nd October, a slow-moving low-pressure system spent two days over Tasmania, bringing the heaviest rain day on the 22nd for over a year to many regions, including Hobart. This was followed by another system, which brought strong winds to the state on the 24th. The combination of these two systems brought down trees and caused widespread damage.

A low-pressure system developed over the Great Australian Bight on 20th October and tracked south-eastwards towards Tasmania. On the 21st, the intensifying system was located off the west coast of Tasmania leading to heavy rain, thunderstorms and showers. More than 40,000 lightning strikes were recorded[1] as a line of thunderstorms moved across the state on the 21st, reaching Hobart just before midnight. Many sites in southern Tasmania recorded their highest daily rainfall for over a year, with Hobart reaching a total of 40 mm by 9am on the 22nd, recording 11 mm in just 10 minutes from 11:40 to 11:50 pm. The Huon River reached minor flood levels, however substantial widespread flooding did not occur. The associated wind was strong in places but not significant.

Figure 1: Tree fell on a car in South Hobart. Source: Australian Broadcasting Corporation.

As the remnants of this slow-moving system were leaving the south-east of Tasmania on 23rd October, a subsequent system was forming south of the Western Australian coast. This system developed, deepened and moved eastward, rapidly moving across Tasmania throughout the 24th. Winds reached speeds of 98 km/h in Hobart and 159 km/h on kunanyi/Mt Wellington, which are extreme but not uncommon for south-east Tasmania. However, with saturated soil, from the previous system, the effect of these gusts was compounded.

When the soil is saturated in windy conditions, the movement of the trees causes the wet soil to begin to act more like a fluid. Subsequently, some tree roots are no longer held firmly by the soil, but are moving through it, leading to trees falling more easily. This occurred in south-east Tasmania on 24th October, leading to widespread damage.

More than 7000 properties across the state lost power and several southern Tasmanian schools were closed for the day due to power outages[2]. Properties, power lines, cars and other infrastructure were destroyed by falling trees[2]. Damage to Hobart Show equipment meant delays to events[2]. Many roads and paths in state parks had to be cleared of fallen trees.

If just one of these events occurred without the other, then the impacts would have been far less severe. Centre researchers have found that extreme winds-and-rain compound events will occur more frequently in many regions in the future, particularly if we do not reduce greenhouse gas emissions[3].

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3.9 Lockyer Valley hailstorm

- A severe thunderstorm brought hail and extreme wind gusts to south-east Queensland's Lockyer Valley on 10th November 2023.
- The storm resulted in one fatality and destroyed crops and farm equipment with an estimated loss of $50 million.

On the afternoon of 10th November 2023, a severe thunderstorm passed through the Lockyer Valley west of Brisbane. A large volume of hail fell, and damaging winds were also observed[1]. A high-pressure system over New Zealand and an associated ridge over the coast of south-east Queensland resulted in moisture from the ocean being transported into the region on 10th November[2]. Strong surface heating and hot afternoon temperatures, coupled with the high moisture availability, created an atmospheric environment favourable for thunderstorms.

Thunderstorms formed to the north-west of the affected area at around 2 pm local time and moved south-east towards Brisbane and the surrounding regions. One relatively isolated storm developed into a supercell thunderstorm and tracked through the Lockyer Valley, bringing isolated large and giant hailstones and a large volume of smaller hail[3] that accumulated on the ground in layers several cm deep[4]. Wind gusts up to 87 km/h and localised flooding from heavy rainfall compounded the property damage[1,5].

Figure 1: Hail in the Lockyer Valley on 10th November 2023. Source: Ben McBurney.

The hailstorm resulted in destruction of agricultural property in the Lockyer Valley, with damage to crops and farming infrastructure estimated at $30 million and $20 million respectively[1]. The 35-40 farmers impacted, along with the workers they employ, face loss of income for multiple months[1]. These impacts are also compounded by continuing difficulties after the flooding events in 2022[1].

Sadly, there was one fatality from a falling tree during the storms[1,5]. Due to the multiple storms that affected south-east Queensland, the SES received 19 calls for help and the south-east Queensland-based provider Energex reported loss of power to more than 2000 customers in the region[5].
As of 15th November, 18 farmers had reported damage, with three reporting catastrophic damage and 12 reporting major damage[6]. This hail event demonstrates that hail volume as well as hailstone size influences the resulting damage.

Severe thunderstorms are expected to be affected by climate change, but thunderstorms are difficult to observe and model, and observed and projected changes for hail vary by region, partly owing to variations in atmospheric circulations[7]. A broad expectation with warming is for fewer hailstorms overall, but larger hailstones when surface hail does occur, however a range of outcomes is possible[7]. Scientists at the Centre undertake research to understand, observe and project climate-related changes to severe thunderstorms and their associated hazards and impacts.

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Figure 2: Supercell thunderstorm that hit the Lockyer Valley on 10th November 2023. Source: Ben McBurney.

3.10 Cyclone Jasper hits far north Queensland

- Tropical Cyclone Jasper made landfall north of Cairns on 13th December bringing strong winds, significant rainfall and flooding.
- Jasper stalled as a weak tropical low over Cape York, contributing further rainfall and flooding over far north Queensland.
- Jasper caused evacuations, power outages, disruption of supply chains and damage to tourism and agriculture.

In mid-December, Tropical Cyclone Jasper hit tropical north Queensland, unleashing formidable winds, torrential rainfall and flooding. Following landfall, the cyclone stalled as a tropical low over Cape York, contributing to a week of continuous torrential rainfall. The prolonged deluge inflicted extensive damage across eastern parts of Cape York contributing to a week of continuous torrential rainfall.

Tropical Cyclone Jasper developed in the northern Coral Sea on 5th December 2023. It made landfall as a category 2 tropical cyclone near Bloomfield on the north Queensland coast on 13th December 2023.

Strong winds felled trees, damaged crops and infrastructure and caused power cuts. Between 150-350 mm of rain fell over the coastal areas between Cooktown and Innisfall over a 36-hour period. This resulted in flooding in the Mossman and Daintree River catchments.

The worst of the destruction was yet to come. The cyclone was downgraded to a tropical low as it headed towards the Gulf of Carpentaria. The tropical low slowed and stalled over the Cape York Peninsula. The location of the stalled weather system produced persistent, northerly winds bringing moisture to the region from the Coral Sea. The moist northerlies collided with south-easterly trade winds over the Peninsula, producing torrential rainfall over the region for several days. A large region of far north Queensland received over 400 mm of rainfall. Isolated areas received particularly heavy rainfall with some stations recording over 2 metres of rainfall over the course of the event.

The persistence and intensity of the rainfall flooded multiple catchments in the region. Widespread damage to roads, buildings, crops and loss of power was experienced[1]. Cairns airport was closed for several days with rising floodwaters halting both incoming and outgoing flights. The Barron Gorge hydro plant near Cairns was damaged, taking 66MW off the grid. The event occurred before a busy Christmas tourism period, hurting the hugely important local tourism economy with multiple cancelled holidays.

Jasper caused arguably more damage in the days after its landfall (as a weak tropical low) rather than during its approach and landfall as a category 2 tropical cyclone. This is primarily the result of the system stalling.

Far north Queensland has experienced stalled tropical lows in the past, most notably during February 2019 when a stalled tropical low produced heavy rainfall and flooding over Townsville. Recent work by the ARC Centre of Excellence for Climate Extremes researchers has shown that this was the result of weak winds in the mid-troposphere that allowed the tropical low to remain stationary[2]. Other research themes such as tropical lows, tropical convergence lines and stalled weather systems[3] are also being addressed within the Centre to further enhance our understanding of tropical rainfall extremes.

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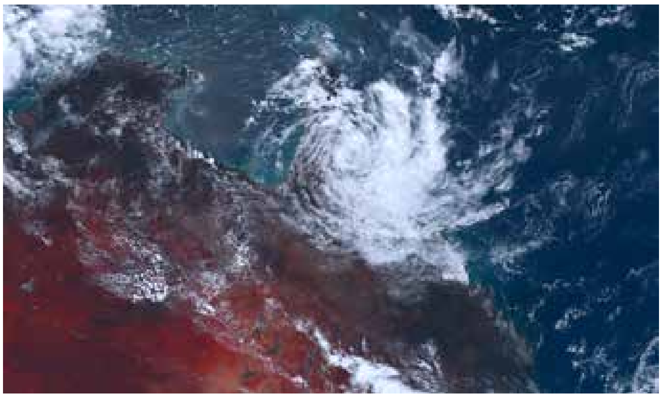

Figure 1: Himawari-8 satellite image (valid 14/12/2023 12h00) of Tropical Cyclone Jasper after making Landfall over Far North Queensland. Source: Japan Meteorological Agency, Himawari-8.

Figure 2: Prime Minister Anthony Albanese posts pictures of the damage caused by Tropical Cyclone Jasper on his official X site on 17th December 2023. Source: X (formerly Twitter).

3.11 Record low Antarctic sea ice

- Both the southern hemisphere summer (2022/23) and winter (2023) sea ice extent were at a record low.
- The winter sea ice maximum extent was over 1 million square kilometres less than the previous record.
- The very low Antarctic sea ice extent throughout 2023 is unmatched in historical observations.

Antarctic sea ice extent has a large seasonal cycle: it grows steadily from March to September and rapidly declines from October to February. Satellite records for sea ice extent began in 1979 with Antarctic sea ice extent relatively stable and with a small significant increasing trend from 2006 onward. Between 2007-2015 Antarctic sea ice extent was mostly above average throughout the year. From 2016, Antarctic sea ice extent shifted to below average, setting summer minimum extent record lows while the winter maximum extent remained close or within past records. The shift to below average sea ice extent after 2016 is consistent with climate change projections and aligns with warmer ocean temperatures.

The year 2023 stands out as significantly below average sea ice extent for almost the entire year, setting new summer and winter minimum extent records. Sea ice still grew in the cooler months but much slower than in previous years.

Most sectors of Antarctica had below average sea ice in 2023, with record low monthly anomalies in June totalling an area comparable to the size of Western Australia.

The largest loss of sea ice was observed in the Ross Sea region and large parts of the Indian Ocean. Only the Amundsen Sea region had above average sea ice extent.

Sea ice extent anomalies prior to 2016 responded mostly to changes in atmospheric circulation patterns. However, the relationship broke down in recent years resulting in a regime shift where the ocean now plays a larger role, with atmospheric circulation influencing the regional structure of the anomalies but not the magnitude[1].

The recent decline of Antarctic sea ice extent has implications within the global climate system that have negative consequences for Earth's heat budget, global circulation and sea level rise. Impacts in Antarctica include habitat loss for penguins, seals and smaller creatures, decreasing primary production in the ocean, exposing ice shelves and hindering Antarctic operations.

The Australian and international scientific community closely follows the development of Antarctic sea ice and collaborates to better understand the drivers for these changes and their implications.

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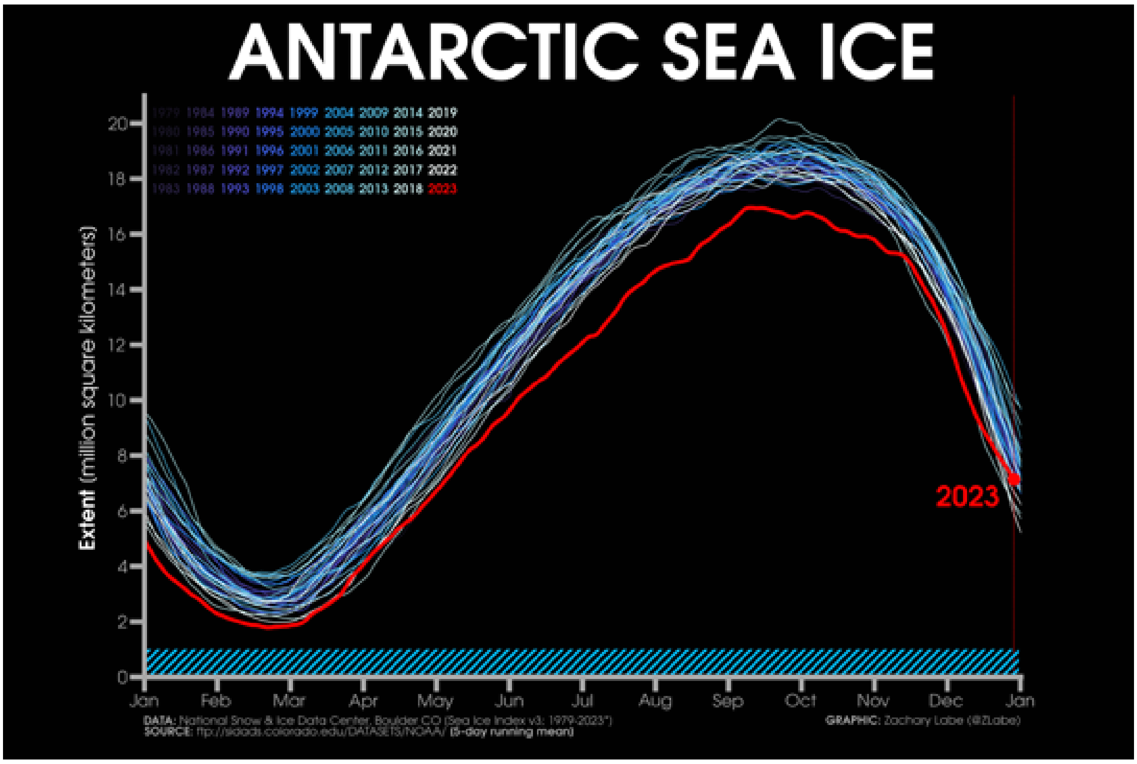


Figure 1: Annual Antarctic sea ice extent since the start of the satellite records in 1979. The anomalous record of 2023 is highlighted in red. Source: https://zacklabe.com/antarctic-sea-ice-extentconcentration/ Dr Zachary Labe.

4.0 Extreme events around the world

Globally, 2023 was a year of extremes. Here we present a selection of extreme events from around the world.

January

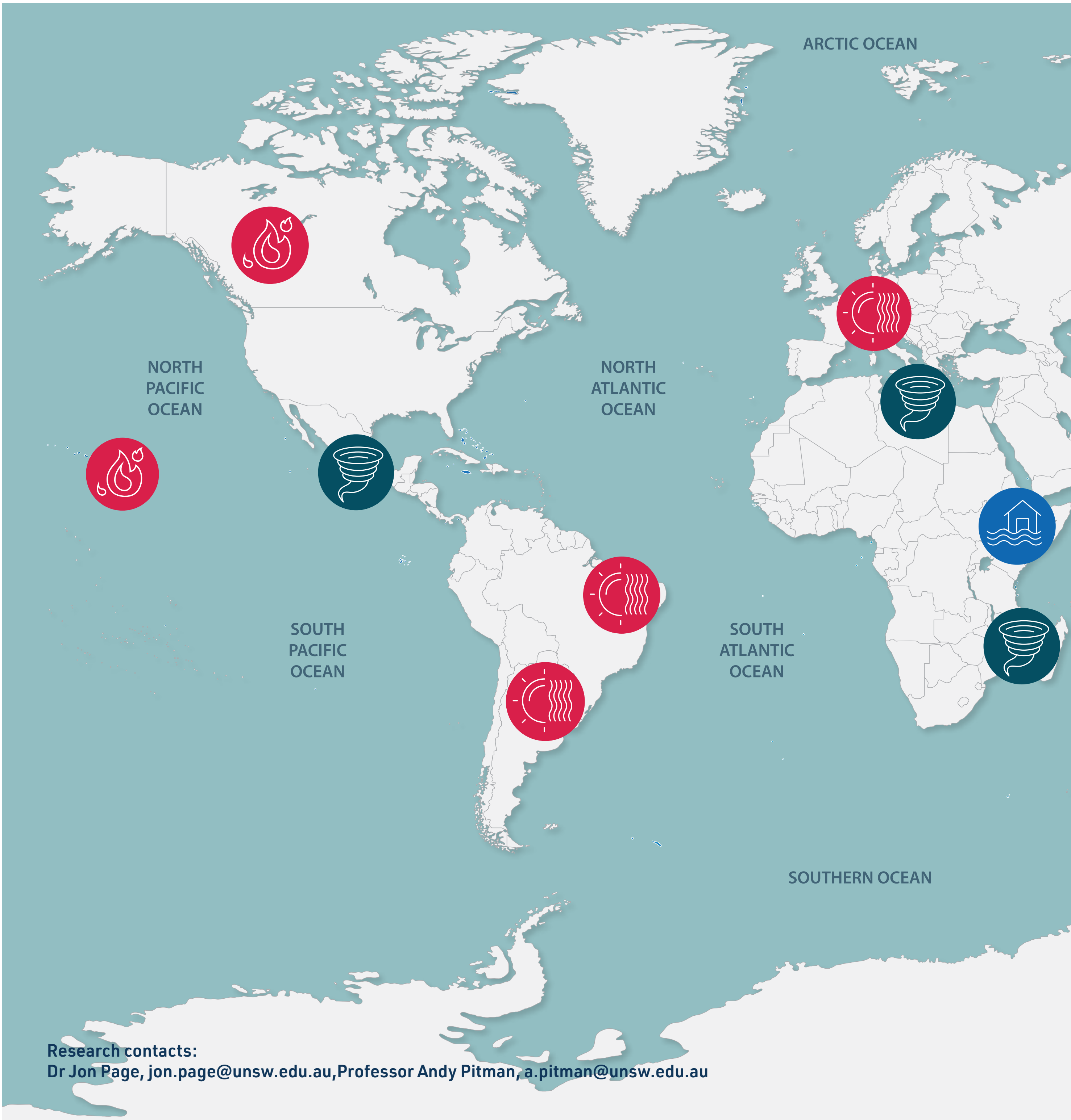
January in Auckland, New Zealand was its wettest month recorded with 27th January its wettest day on record causing catastrophic flooding, as an atmospheric river lay stationary over the region[1,2].

February

Tropical Cyclone Freddy was declared the longest lasting and most energetic tropical cyclone ever seen, resulting in over 1400 deaths in Madagascar, Malawi and Mozambique[3,4].

March

A heatwave over South America resulted in record-breaking March temperatures for locations in Argentina and Uruguay, with the region already in the grip of the worst drought seen in 60 years[5,6].



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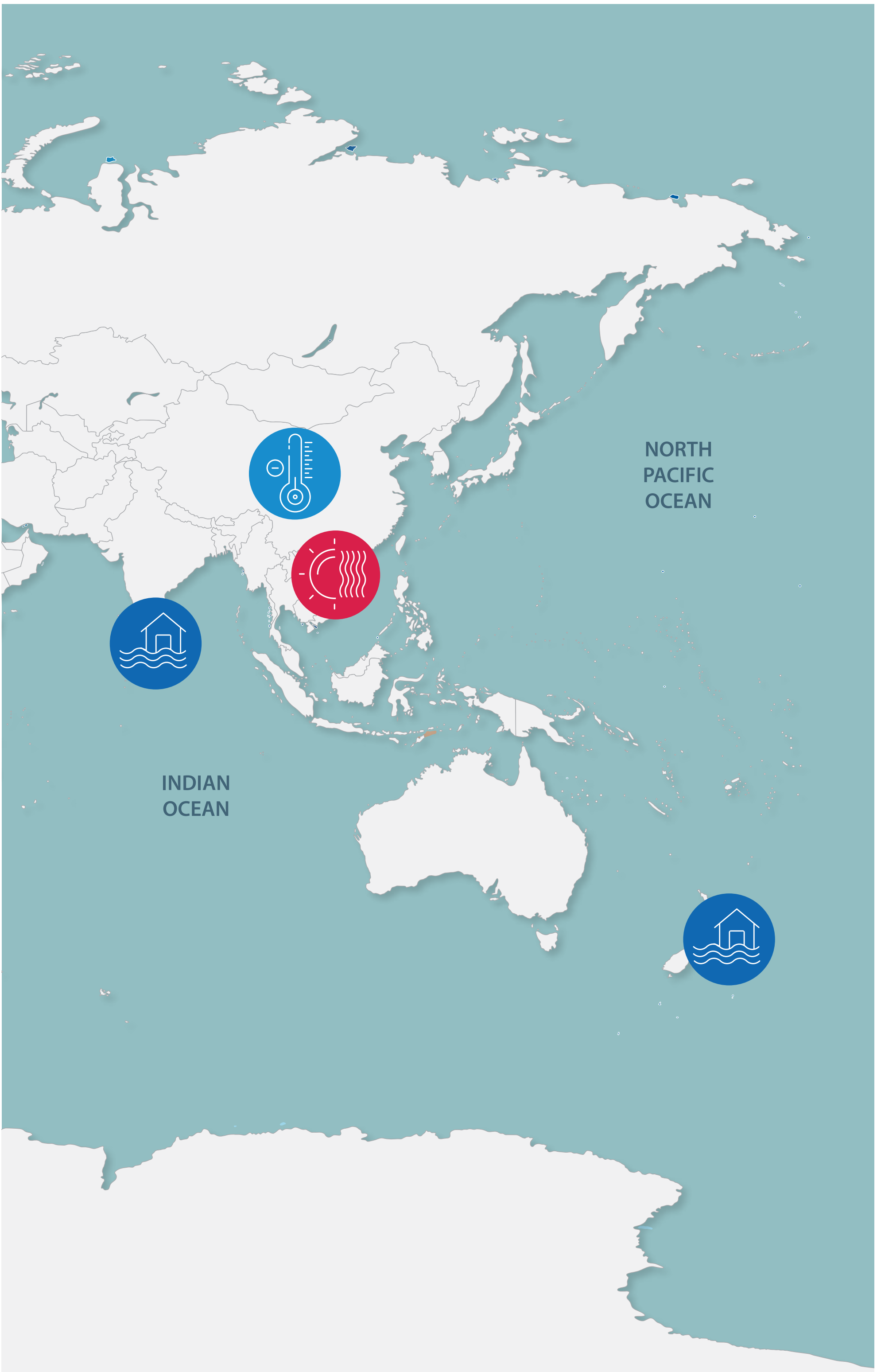
April

Multiple Southeast Asian countries including China, Thailand, Vietnam and Laos broke all-time temperature records in an April heatwave that affected 30% of the global population and that was made 30 times more likely by climate change according to World Weather Attribution[7,8].

May

After five failed rainy seasons, May saw flash flooding across Somalia and Ethiopia displacing over 250,000 people. Remarkably, the devastating rains were not sufficient to break the prolonged drought. Two-and-a-half million people were affected as flooding continued throughout the year, with significant impacts also seen in October[9,10,11].



June

Canada's wildfire season was unprecedented with 18.4 million hectares burnt, the largest area burned in the country's history and more than 2.5 times the previous record[12]. Over 75 million people were subjected to poor air quality due to the record emissions from the fires[13,14].

July

The Cerberus heatwave over Europe contributed to many national and global temperature records tumbling in July, the hottest month ever recorded on Earth, with marine heatwaves experienced in both the Mediterranean and the Atlantic[15,16,17].

August

In August, abnormally dry conditions and strong winds contributed to significant wildfires across large parts of Maui in Hawaii, which with nearly 100 casualties became the deadliest US wildfire since 1918[18,19].

September

Over 4000 people died when the deadliest Mediterranean tropical-like cyclone in history, Storm Daniel, brought heavy rains, dam collapses and flooding to Libya[20,21].

October

Hurricane Otis was the strongest Pacific hurricane to ever make landfall when it devastated Acapulco, Mexico in October[22]. Meanwhile, the lowest October rainfall on record contributed to 2023 being the second driest year since records began over the Panama Canal. Reductions in shipping capacity through this critical trade route have been necessary[23,24].

November

November saw Brazil record its hottest ever temperature during an intense heatwave that placed record pressure on the energy grid[25]. High temperatures, combined with high humidity, resulted in "feels like" temperatures of nearly 60°C[26].

December

Minimum temperature records were set throughout China in December as a cold wave swept the country[27]. Meanwhile, southern India suffered through severe flooding as heavy rain lashed the state of Tamil Nadu[28].

5.0 Trends over Australia

Climate extremes are changing fast and it's hard to keep on top of those changes. Developed by the ARC Centre of Excellence for Climate Extremes, a new climate dashboard provides the ability to examine trends of climate extremes using additional indicators of extremes. The climate dashboard (https://www.climdex.org/dashboard/) enables easy and reliable access to data. Examining temperature and rainfall extremes can be challenging. Here we highlight temperature extremes. Figure 1 shows two temperature measures – trends in the hottest day and coldest night of the year.

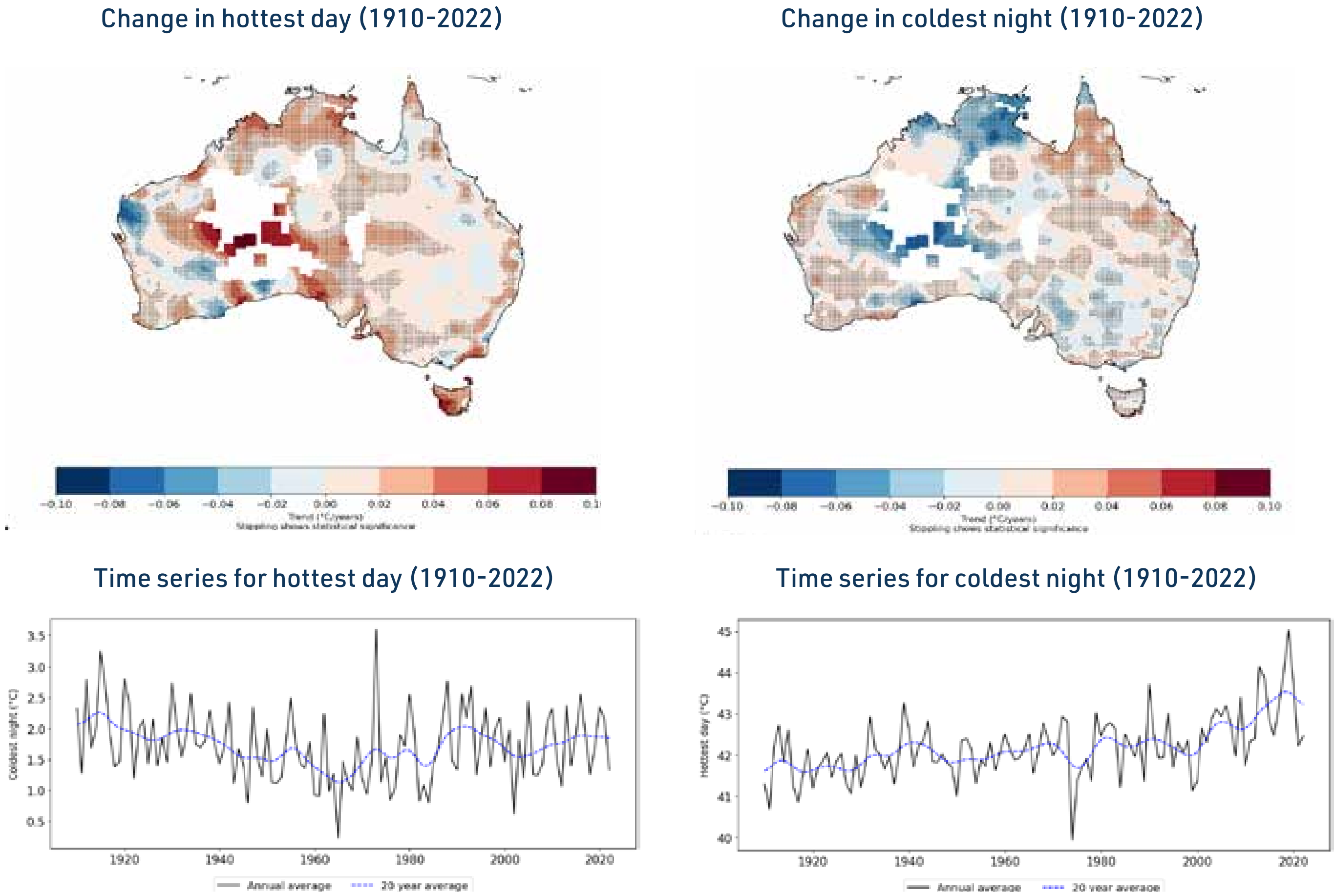


Figure 1: Maps show trends (°C/year) in the hottest day and coldest night of the year. Time series represent the Australian average each year from 1910-2022. Source: Professor Lisa Alexander, using the BoM's Australian Gridded Climate Dataset (AGCD).

Figure 1 shows that the trend in the hottest day of the year is increasing almost everywhere, with strong warming over parts of Tasmania and in the far north of Australia. When viewed over time it shows variability but with an increasing trend since the 1940s. Increases in temperature extremes in Australia have been shown to be caused by anthropogenic emissions of greenhouse gases.

The trend in the coldest night of the year is more complex, with areas where the coldest nights are trending colder and areas where they are trending warmer. This is often associated with changes in the atmospheric humidity and cloud cover that strongly influences nighttime minimum temperature.

The ARC Centre of Excellence for Climate Extremes is developing additional metrics to help provide robust data for the analysis of extremes in 2024. For more information contact Professor Lisa Alexander or go to https://www.climdex.org/dashboard/

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