Electricity networks

A guide to climate change and its likely effects

Energy Networks Australia

scientell

Report prepared by Scientell Pty Ltd for Energy Networks Australia

Acknowledgement of Country

Scientell acknowledges the Traditional Custodians of country throughout Australia. We respect their scientific knowledge and traditions as the oldest living culture in the world. We acknowledge their continuing connection to land, sea and community, and we pay our respects to their Elders both past and present.

Acknowledgement

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Network Service Providers

ACT: Evoenergy
NSW: Ausgrid, TransGrid, Endeavour Energy, Essential Energy
NT: Power and Water Corporation
QLD: Energy Queensland, Powerlink
SA: ElectraNet, SA Power Networks
TAS: TasNetworks
VIC: AusNet Services, CitiPower & Powercor, Jemena, United Energy
WA: Western Power, Horizon Power

Disclaimer

Foreword

Weather changed my life, and climate has shaped it since.

On 28 September 2016, a series of severe thunderstorms struck South Australia with destructive wind gusts and at least seven tornadoes. Transmission lines went down, causing fault currents to surge through the network and trip the interconnector between South Australia and Victoria. The South Australian network collapsed and the state went into blackout.

A week later I was asked to chair a review of the National Electricity Market. On day one, I learnt about two fundamental characteristics of our electricity system: security and reliability.

We need system security to respond quickly and stabilise the frequency after unexpected events, like a lightning strike or generator failure. Then there's the challenge of having sufficient dispatchable generation and grid capacity to cope with more gradual disruptions, like a long spell of hot weather that increases demand. That's reliability.

What's more, the strains on our system are growing. Modelling predicts weather events, like the ones that caused the blackout in South Australia, will become more frequent and severe as a consequence of climate change. We'll need a third characteristic for our energy networks: resilience.

Resilience comes with careful planning for events that put additional demands on the system, like higher temperatures and more prolonged heat extremes, more frequent bushfires or the closure of coal-fired power stations. As we move to a zero emissions electricity system, with care and planning many of the required changes for a zero emissions grid can be implemented to increase resilience. These changes include building stronger towers for our new transmission lines, investing in long-duration storage and distributed generation.

When I got that call in 2016, I didn't expect the next six years of my life to be shaped by these concerns. Throughout, I've been guided by broad consultation, and expert reports like this one that educate us about what a changing climate means for the future of our electricity system.

There are lessons here for everyone. There are lessons for the transmission and distribution network operators, to help them plan for the impacts of climate change. There are lessons for engineers and researchers, to help them understand what those impacts will mean for their professions.

I encourage you to read on with intent. By working together and with careful planning, we can build a system that survives and adapts to extreme weather events in a changing climate.

Dr Alan Finkel AO
Chair, Technology Investment Advisory Council, Australian Government
Chief Scientist of Australia (2016-2020)

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Abbreviations

AEMO	Australian Energy Market Operator
APRA	Australian Prudential Regulation Authority
ASIC	Australian Securities and Investments Commission
CCIA	Climate Change in Australia
CMIP	Coupled Model Intercomparison Project
ENA	Energy Network Australia
ENSO	El Niño – Southern Oscillation
ESCC	Earth Systems and Climate Change Hub
ESCI	Electricity Sector Climate Information
FFDI	Forest Fire Danger Index
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
MJO	Madden-Julian Oscillation
NARCLiM	NSW and ACT Regional Climate Modelling
NEM	National Electricity Market
ppm	parts per million
RCP	representative concentration pathway
SAM	Southern Annular Mode
SSP	shared socioeconomic pathway
TCFD	Task Force on Climate-Related Financial Disclosures

Summary

Weather and climate extremes represent a major threat to Australia's electricity transmission and distribution system, henceforth referred to as 'electricity networks'. Human-induced climate change is making some of these extremes more frequent and severe. Parts of Australia, and regions worldwide, are experiencing increasing impacts from dangerous fire weather, extreme heat, sea-level rise, inundation and extreme rainfall events.

This report presents the latest authoritative information on climate change and its likely impacts on Australia's electricity networks, including the transmission towers, substations, poles and wires.

Information and projections come from a range of credible sources, including Australia's national climate change projections, the Earth Systems and Climate Change (ESCC) Hub, the Electricity Sector Climate Information (ESCI) project, the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, Energy Network Australia's (ENA) *Climate Risk and Resilience Industry Guidance Manual* and the Brattle Group's *Potential for Incorporating Climate-Related Risks into Transmission Network Planning*.

Scientists use sophisticated climate models to estimate future changes to climate and related variables, considering various possible future atmospheric greenhouse gas concentrations. This report summarises projections for temperature, bushfire weather, rainfall, drought, sea-level rise, lightning and storms, wind, east coast lows and tropical cyclones. Climate change is likely to affect the frequency and intensity of climate extremes, as well as affecting large-scale processes such as the El Niño – Southern Oscillation.

Australia's changing climate

Australia's climate is already changing. Extreme high temperatures are increasing, with extreme temperatures that occurred less than 2 per cent of the time in 1960–89 now occurring more than 12 per cent of the time. There has also been an increase in the intensity of extreme fire weather across much of the country.

Mean daily minimum and maximum temperatures will continue to increase throughout this century. Significantly greater warming is likely by 2090 if the world follows a high greenhouse gas emissions scenario than for an intermediate or low emissions scenario. Australia will experience more frequent, and more record-breaking, hot days and warm nights.

Southern and eastern Australia are likely to experience harsher fire weather and longer fire seasons. Across southern Australia, time in drought is projected to increase, with a greater frequency of severe droughts.

Winter rainfall is projected to decline in southern Australia. Extreme rain events are likely to become more intense.

Severe convective storms may increase in frequency and intensity. Tropical cyclones may occur less often, become more intense, and may reach further south.

The projected changes for Australia's climate are likely to affect Australia's electricity networks. Climate-related hazards such as extreme heat, flooding and storms can reduce network capacity; damage assets; increase outages and flashovers; increase operational, repair and maintenance costs; increase demand; and disrupt supply. These impacts pose risks to the sustainable and continuous supply of electricity to Australian households and businesses.

Particularly problematic for electricity networks are multiple extreme events that occur simultaneously or successively, such as extreme heat and drought followed by bushfire. Known as 'compound extreme events', they can amplify the impacts of individual climate-related hazards. A changing climate may bring more compound extreme events; however, such projections are made with low scientific confidence.

With knowledge of likely climate change, and an appreciation of community resilience, electricity networks can develop and implement adaptation actions to reduce some of the harmful impacts of climate change.

State and territory changes

Australian states and territories are all experiencing changes to their climate. Temperatures and sea level are rising. Many regions have recorded changes to rainfall, increased heatwave occurrence, and more days with dangerous weather conditions for bushfires.

Climate will continue to change in future. The appendices contain climate information and projections for each of the states and territories, and for selected cities. Where available, there are projections for temperature, precipitation, sea-level rise, lightning and storms, wind, and other climate-related hazards.

1 Introduction


Essential energy

Australia's electricity networks – the transmission towers, substations, poles and wires – link power generators with customers. Their reliable operation is critical to producers and consumers of electricity.

Weather-related events cause over half of all electricity outages and often cause prolonged outages. Extreme weather and associated events such as bushfires can cause significant damage to the networks. Climate change due to human-induced increases in atmospheric greenhouse gases is already exacerbating some of these threats – a trend that is likely to be more profound in future decades.

This report presents the latest authoritative information on climate change and its likely impacts on Australia's electricity networks. The primary audience includes sector executives, board members, asset owners and managers, network planners, engineers and risk managers. The report presents information about how weather and climate affect networks, how climate has changed in recent decades, and projections for the coming decades. The information is designed to help the sector better understand and assess the risks from climate change, conduct scenario planning, and communicate the impacts of climate change on networks with internal and external stakeholders, particularly the market bodies.

The report draws on information published by CSIRO, the Bureau of Meteorology, the Intergovernmental Panel on Climate Change, universities, the Earth Systems and Climate Change Hub, and state government agencies. The prime source of climate change projections is Climate Change in Australia, with updates included where available from peer-reviewed literature. The Electricity Sector Climate Information project is an important resource, as are various reports supplied and prepared by Energy Networks Australia.

Appendices contain climate-specific information and projections for each of the states and territories: New South Wales and the Australian Capital Territory, the Northern Territory, Queensland, South Australia, Tasmania, Victoria, and Western Australia.

1.1 Climate, weather and the electricity sector

Experiences in recent years with bushfires, flooding, heatwaves, drought and severe storms highlight the vulnerability of the power system to weather, climate and climate change. Climate-related risks affect all parts of the power system, including generators, transmission systems, distribution networks, operational staff, repair and maintenance and customers' usage patterns.

Climate- and weather-related variables of interest to the electricity sector include:

- temperature
- precipitation
- sea-level rise
- lightning and storms
- wind
- snow and ice
- hail
- humidity
- compound extreme events
- solar radiation.

The electricity sector is experienced at dealing with fluctuations and extremes in climate, such as hot weather, downpours, bushfires and drought. However, conditions in future will be different from those of the past due to ever-increasing atmospheric concentrations of heat-trapping greenhouse gases. Climate change will directly affect variables such as temperature – including maximum and minimum daily temperatures – as well many other climate variables, such as rainfall and sea-level rise.

Climate change also affects climate drivers that impact Australia's climate. Perhaps the best-known driver is the El Niño – Southern Oscillation (ENSO), which modulates the likelihood of drought, floods and tropical cyclones over large areas of Australia. Many other climate phenomena influence our weather, affecting many of the variables of interest to the electricity sector. This report includes information on the following:

- ENSO
- the Indian Ocean Dipole
- the subtropical ridge
- the Southern Annular Mode
- east coast lows
- tropical cyclones.

1.2 Climate versus weather

Climate and weather are related but different. Weather describes the brief, regularly changing atmospheric conditions at a particular place and time (from minutes to days). Climate, on the other hand, is a long-term average of the weather conditions over years to decades (often 30 years). Climate is an abstract concept, a generalisation; it does not physically exist, just as a cricketer's batting average is rarely hit during a match. Climate is what we expect, whereas weather is what we get.

Climate variability refers to the natural variation from year-to-year and decade-to-decade around the long-term average climate conditions.

1.3 Climate change

The natural greenhouse effect of Earth's atmosphere keeps the surface of our planet at a habitable temperature. Human activities are increasing atmospheric greenhouse gas concentrations (including carbon dioxide, methane and nitrous oxide), causing warming and changing the climate. Climate change over the past century due to human activities is superimposed on the climate variability caused by natural fluctuations such as ENSO.

The concentration of carbon dioxide in the atmosphere has increased by 48 per cent since pre-industrial times, rising from 277 parts per million (ppm) in 1750 to more than 410 ppm now. This is much higher than the natural range of 172 to 300 ppm that existed for hundreds of thousands of years. The Earth's average carbon dioxide level is now the highest in at least the past 2 million years.

We know the source of the extra carbon dioxide is human activities because analysis of the different types (or isotopes) of carbon shows where it comes from. Since 1750, the combustion of fossil fuels has contributed almost two-thirds of the extra carbon in the atmosphere that has led to climate change. Changes in land use, such as deforestation, have contributed about one-third.

Energy production (including burning fossil fuels to produce electricity, and manufacturing, mining, and residential and commercial fuel use) is the largest contributor to Australia's carbon emissions. This is followed by transport, agriculture and industrial processes.

In 2019–20, electricity generation was responsible for 48 per cent of Australia's direct emissions by industry, representing 157 million tonnes of carbon dioxide equivalent.

Climate of the recent past

The increase of greenhouse gases due to human activities coincides with a period of global warming and other changes to the climate. In 2021, the IPCC concluded that, 'it is indisputable that human activities are causing climate change, making extreme climate events, including heatwaves, heavy rainfall, and droughts, more frequent and severe.'

The world has warmed by 1.1 °C since 1850. There is no record of temperature having increased as rapidly as it has over the past century.

Similarly, Australia has warmed by around 1.4 °C since reliable national records began in 1910 (Figure 1, Figure 2) and by over 1 °C since 1960. All locations across Australia have warmed, and the frequency of extreme temperature events has increased.

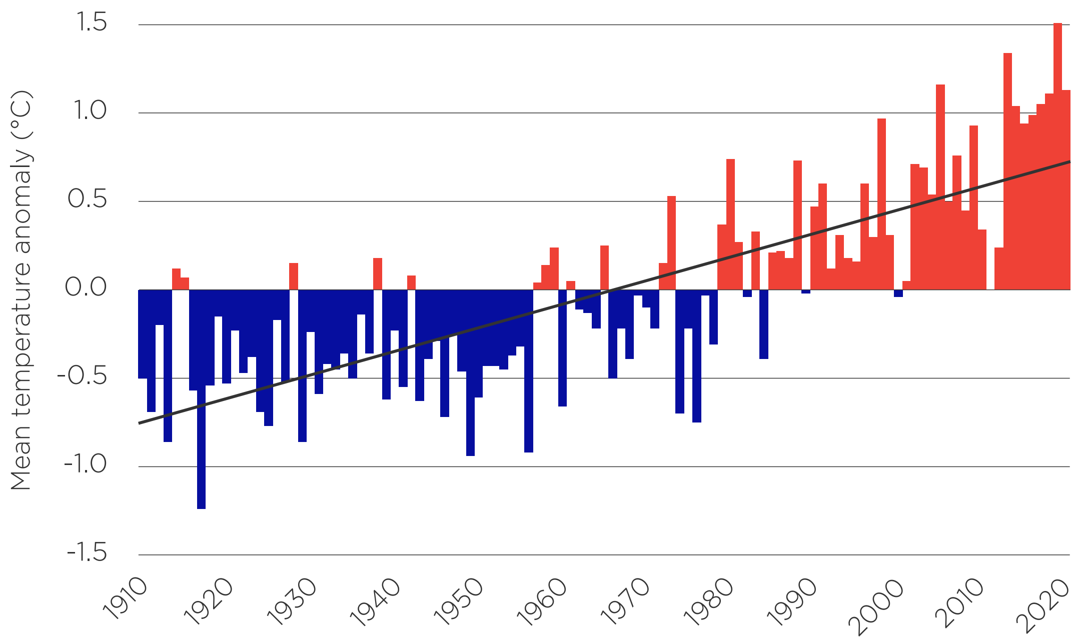

Figure 1 Australian annual mean temperature anomaly compared with the 1961–90 average, with linear trend (Bureau of Meteorology)

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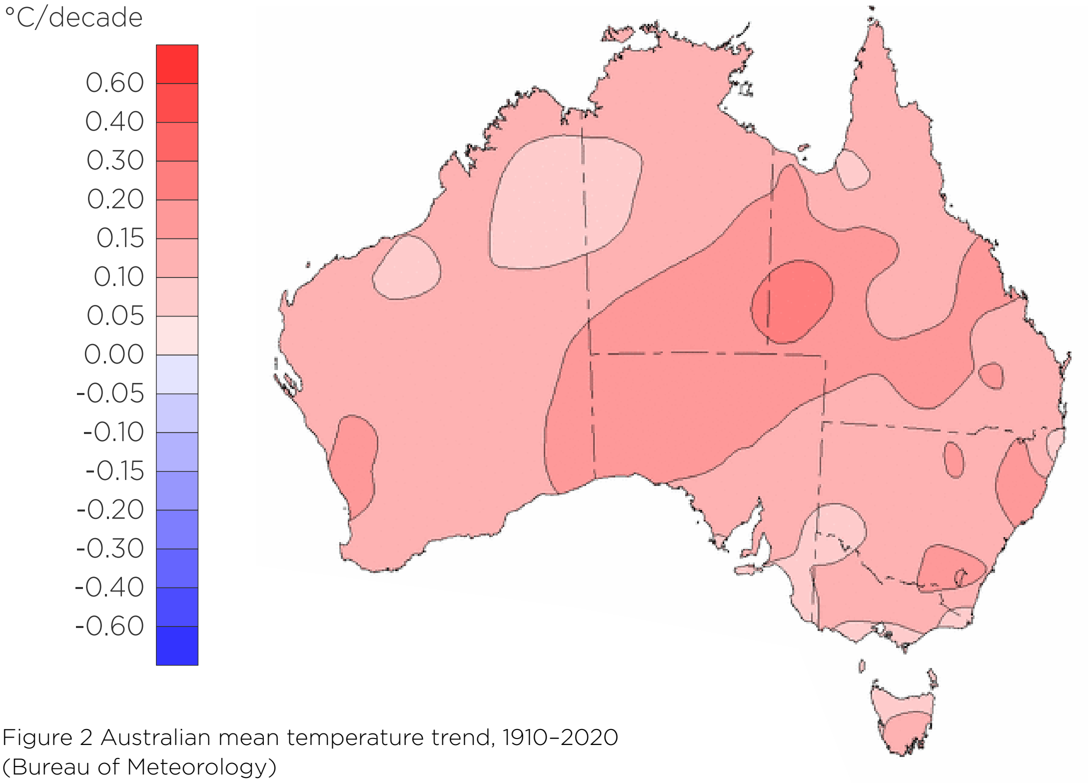

Figure 2 Australian mean temperature trend, 1910–2020 (Bureau of Meteorology)

Future climate

Climate will be strongly affected by the rate at which greenhouse gases accumulate in the atmosphere. The accumulation rate depends on many factors, including population growth, energy consumption, economics and the uptake of renewable energy sources.

To account for a range of future conditions, scientists have developed dozens of scenarios, covering a wide range of possible greenhouse gas emissions and concentrations. Some scenarios involve high greenhouse gas concentrations, some low, and some medium. The emission scenarios relate to different demographic, economic and technological factors that will influence emissions.

Today, the world is tracking along a path that is more like a medium to high emissions scenario. The Paris Agreement's global temperature goal is to hold the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C, recognising this would significantly reduce the risk of dangerous climate change.

The full range of emissions scenarios (from low to high) should be considered when undertaking climate risk assessments.

2 Weather and climate phenomena

Australia is affected by many different weather systems. These systems vary in their strength and impact, contributing to Australia's climate variability and to potential impacts on electricity networks.

As noted above, Australia is influenced by climate drivers, including ENSO, the Indian Ocean Dipole (IOD), the Australian monsoon, the Madden-Julian Oscillation (MJO) and the Southern Annular Mode (SAM) (Figure 3). These drivers have varying influences on rainfall, temperature and weather in Australia over different regions and seasons.

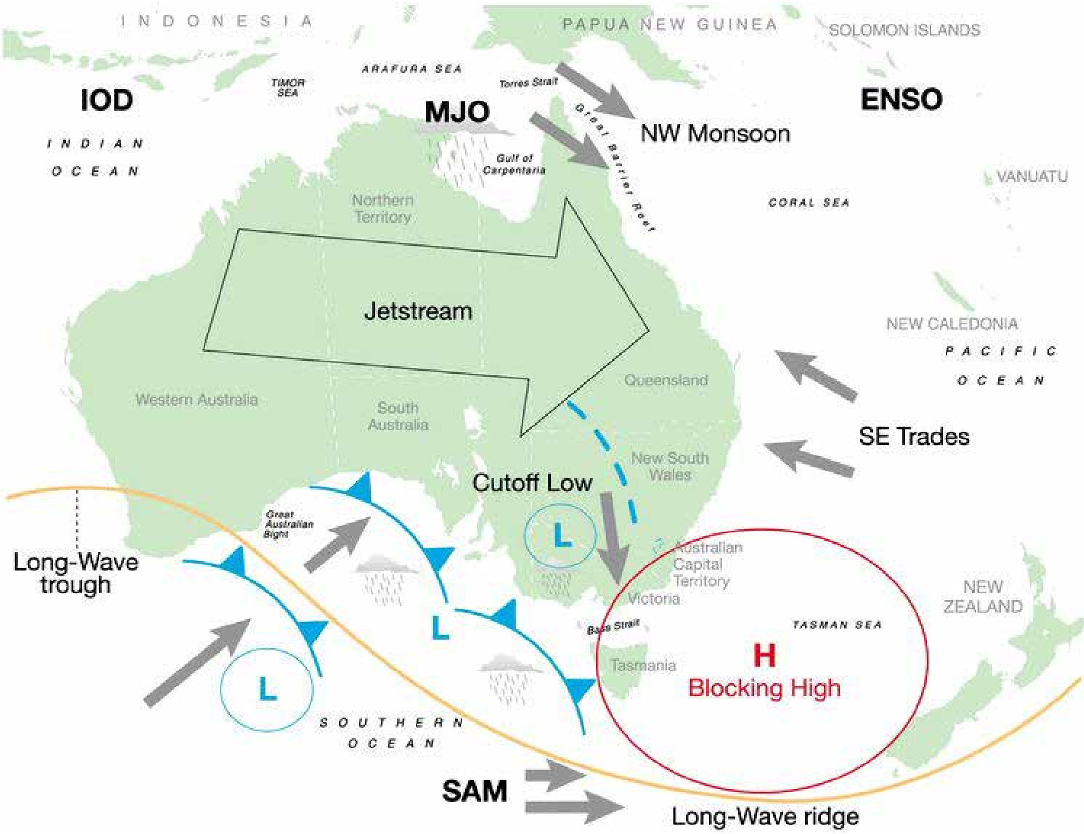

Figure 3 The main climate influences on Australia (Risbey JS, Pook MJ, McIntosh PC, Wheeler MC & Hendon HH (2009). On the remote drivers of rainfall variability in Australia, *Monthly Weather Review* 137, 3233-3253)

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The El Niño – Southern Oscillation

ENSO describes the irregular oscillation between the El Niño phase and the La Niña phase, with a neutral phase in between. El Niño conditions generally result in below-average rainfall over much of eastern Australia. La Niña conditions generally lead to above-average rainfall over much of Australia. ENSO has a profound impact on Australia's climate, contributing to changes in the likelihood of drought, flood, fire danger and severe weather.

The Indian Ocean Dipole

Changes in sea-surface temperature patterns in the northern Indian Ocean, known as the IOD, can affect Australia's rainfall. The positive phase of the IOD contributes to dry weather over Australia during winter and spring, while the negative phase brings wet weather.

The subtropical ridge

The subtropical ridge runs across a belt of high pressure that encircles the globe in the middle latitudes.

During the warmer part of the year, the ridge occurs to the south of the continent. During this time, the high-pressure systems along the ridge tend to suppress cold fronts. Therefore, summertime cold fronts tend to be weaker, and the weather (such as rainfall, temperature and wind) associated with these systems is generally less intense than during winter, when the ridge is further northward.

As winter approaches, the subtropical ridge moves northward over central Australia. Cold fronts associated with low-pressure systems begin to extend further into southern Australia. These wintertime cold fronts are associated with colder south-westerly winds and showery conditions.

The Southern Annular Mode

SAM is a north-south shift in the belt of strong westerly winds across the south of Australia, affecting cold fronts, storm activity and rainfall. The impact of SAM on rainfall during winter varies from place to place and from season to season. During winter, there is less rainfall during a positive SAM over south-west Western Australia (WA), Victoria, Tasmania and all regions in NSW, whereas rainfall tends to increase over much of central and northern NSW and many locations in Queensland. A negative SAM tends to cause the opposite in the same season. During summer, a positive SAM tends to increase rainfall in southern Queensland, most of NSW and Victoria and Tasmania, whereas it tends to reduce rainfall in parts of western Tasmania. The opposite impacts tend to occur in summer during negative SAM events.

East coast lows

East coast lows are intense low-pressure systems that occur off the eastern coast of Australia, in particular southern Queensland, NSW and eastern Victoria. East coast lows will often rapidly intensify overnight, making them one of the more dangerous weather systems to affect the south-east Australian coast. These systems occur, on average, about 22 times per year, with some events lasting longer than a day.

Intense east coast lows can cause extreme wind, ocean waves, rainfall and flooding, which can have severe impacts on coastal communities and businesses.

Tropical cyclones

Referred to in the United States as hurricanes, and in Asia as typhoons, tropical cyclones are intense low-pressure systems that form over warm tropical waters and produce heavy rainfall, destructive winds and damaging storm surges.

Severe convective storms

Severe convective storms, such as thunderstorms, are small-scale weather systems characterised by strong updrafts of warm, moist air. They can cause hazards such as lightning, hail, tornadoes, extreme winds, rainfall and flash flooding. Thunderstorms occur predominantly during the warmer months and are more common in Australia's north and east.

Compound extreme events

A compound extreme event is a simultaneous or sequential occurrence of multiple extremes at single or multiple locations. Compound extreme events can cause substantial disruption, which can be worsened by infrastructure failure and staff fatigue.

3 Australia's changing climate

Australia's climate is changing in response to a warming global climate. Most years in Australia are now warmer than almost any year during the 20th century.

Since the 1950s, each decade has been warmer than the one before. Australia's warmest year on record was 2019, followed by 2013, 2005, 2020, 2018 and 2017.

Some years have been relatively cool because of natural effects such as La Niña. This climate variability temporarily offsets the long-term warming trend but, overall, Australia is warming.

As expected with an increasing average temperature, the number of extreme temperature events has been increasing (Figure 4). Since 2001, extreme heat records in Australia have been broken more often than extreme cool records: three times as often for daytime maximum temperatures, and about five times as often for night-time minimum temperatures.

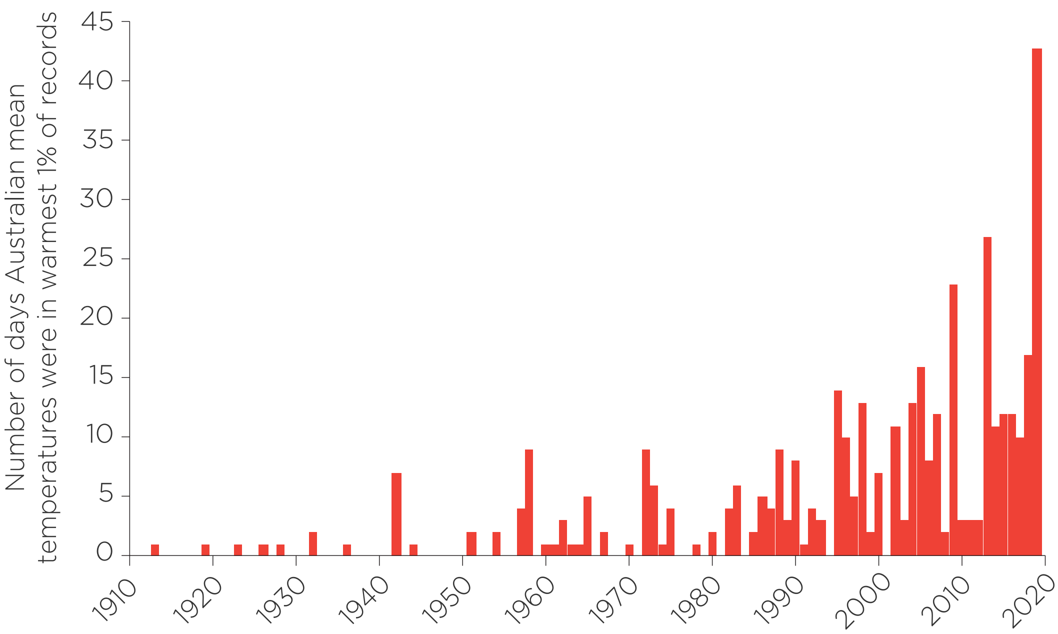

Figure 4 Number of days each year where the Australian area-averaged daily mean temperature for each month is extreme. Extreme daily mean temperatures are the warmest 1 per cent of days for each month, calculated for the period 1910 to 2019. (CSIRO and Bureau of Meteorology (2020). *State of the Climate 2020*)

Very high monthly maximum temperatures that occurred less than 2 per cent of the time in 1960–89 occur more than 12 per cent of the time now (2005–19). For example, 2019 experienced 43 extremely warm days, more than triple the number in any of the years before 2000.

The combined influences of climate, weather, vegetation and ignition sources cause bushfires in Australia. Increasing temperatures can influence fire danger through reduced humidity and decreased moisture content in vegetation. Since the 1950s, there has been an increase in the intensity of extreme fire weather, with an increase in the number of days with dangerous weather conditions for bushfires (Figure 5). There has also been an increase in the occurrence of extreme Forest Fire Danger Index (FFDI) days in south-east Australia from the late 1990s, with up to 24 more extreme days per year. The FFDI measures the risk of fire, considering the temperature, humidity, wind speed and a 'drought factor' based on daily rainfall and the time that has elapsed since the last rain. Australia now has an earlier-starting and longer fire season across much of the country, especially in southern Australia.

The average annual area of Australia burned has grown by 800 per cent in the past 32 years. Researchers state that this rise is consistent with increasingly more dangerous fire weather conditions, increased risk factors associated with pyroconvection (including fire-generated thunderstorms), and increased ignitions from dry lightning, all associated to varying degrees with climate change. There has been a correlation between the FFDI and the rise in area of forest burned since the 1930s.

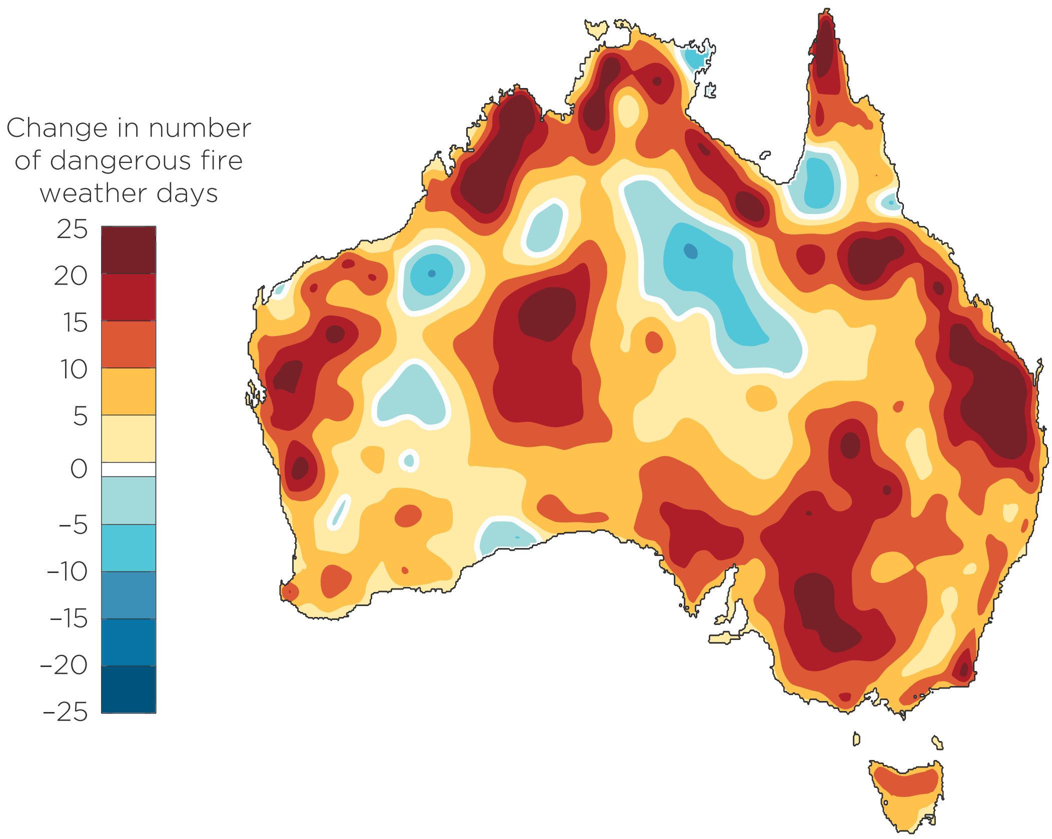

Figure 5 Change in the annual number of days between 1950–85 and 1985–2020 that the Forest Fire Danger Index exceeds its 90th percentile (considered dangerous fire weather) (CSIRO and Bureau of Meteorology (2020). *State of the Climate 2020*)

In the south-west of Australia since 1970, April to October rainfall has decreased by around 16 per cent, while May to July rainfall has decreased by around 20 per cent. In the south-east of Australia, April to October rainfall has decreased by around 12 per cent since the late 1990s.

Across most of northern Australia, rainfall has increased since the 1970s, with a general trend towards increased spring and summer monsoonal rainfall.

Across Australia, heavy rainfall events (often associated with flash flooding) have increased in intensity in recent decades, with a 10 per cent increase in the intensity of hourly extreme rainfall events in some regions.

About 11 tropical cyclones occur in the Australian region each year on average, with about four crossing the Australian coast. The number of tropical cyclones that occur in the Australian region has decreased since 1982, most likely due to a combination of natural variability and human-induced climate change. The number of severe tropical cyclones that make landfall over north-eastern Australia has significantly decreased since the late 19th century.

The number of east coast lows varies greatly from year to year. There is no clear increasing or decreasing trend.

Over the past 200 years, land use and land cover change have increased dust emissions in Australia.

Maximum snow depth, the number of days when it snows, the spatial extent of snow cover, and the length of the snow season are all decreasing, as would be expected with increasing temperatures.

Sea surface temperatures have increased around Australia faster than the global average, warming by more than 1 °C since 1900, with eight of the 10 warmest years on record for sea surface temperatures occurring since 2010.

Partly because of ocean warming, sea levels are rising around Australia. Over the past 30 years, sea level to the north and south-east of Australia has been rising at a significantly higher rate than the global average. The rates of sea-level rise on other coasts of Australia have been close to the global average. Combined with more frequent extreme events, rising sea levels increase the risk of flooding, causing damage to infrastructure and communities along the coast.

Image credit: Western Power

4 The science of projecting climate change

4.1 Global climate models

Scientists use computer-based, mathematical representations of the Earth system (called global climate models) to simulate likely future changes in the climate. These sophisticated climate simulations contain hundreds of thousands of lines of computer code and run on supercomputers that complete trillions of calculations every second. By changing the concentration of greenhouse gases in the simulation, the models can simulate what happens over years and decades into the future, to provide projections of the impacts on climate of various greenhouse gas emission scenarios.

Global climate models simulate all the important components of the climate system, including the atmosphere, land, oceans, ice, and the physical interactions between these. They can also simulate the response of plants to climate, and ocean biological and chemical interactions.

The simulations are tested rigorously by comparing simulations of past climate with historical observations. The World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) makes simulations from climate models around the world available to international researchers. CMIP allows model simulations to be checked and benchmarked against other models. This process adds to the confidence in using these models to determine future climate change.

4.2 Greenhouse gas emission scenarios

The IPCC Fifth Assessment Report introduced four scenarios for what might happen to future greenhouse gas emissions and climate warming. Known as representative concentration pathways (RCPs), the scenarios are characterised by the radiative forcing (the extra heat the lower atmosphere will retain due to additional greenhouse gases) by 2100, measured in watts per square metre.

RCP2.6 is the most ambitious pathway. It sees emissions peak early, then fall due to active removal of atmospheric carbon dioxide. In this scenario, global warming is kept well below 2 °C relative to pre-industrial temperatures, as nations have pledged to do under the 2015 Paris Agreement on climate change.

RCP8.5 represents a fossil-fuel intensive future with little effort to reduce emissions. This would lead to nearly 5 °C of global warming by the end of the century. RCP4.5 and RCP6.0 are intermediary pathways.

In 2021, the IPCC Sixth Assessment Report used new descriptions for future greenhouse gas emissions trajectories. The shared socioeconomic pathways (SSPs) are five socioeconomic and technological trajectories that the world could follow this century. The SSPs can be linked to climate change policies to generate different outcomes for the end of the century (analogous to RCPs), with radiative forcing of approximately 1.9, 2.6, 3.4, 4.5, 6.0, 7.0 or 8.5 watts per square metre in 2100.

4.3 Climate projections

The IPCC's Sixth Assessment Report stated that, 'it is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.'

The IPCC projects a global warming increase by 2100 of between 1 and 5.7 °C (relative to the climate baseline period of 1986 to 2005), depending on the emission scenario. Specifically, the planet is likely to warm by between 1 °C and 1.8 °C for a scenario where emissions of greenhouse gases are low following extensive global efforts to reduce emissions. Alternatively, global warming could be between 3.3 °C and 5.7 °C if there is little global action to reduce greenhouse gas emissions and the world follows the very high emission scenario.

The Earth's future climate will depend on whether the world's population manages to slow, or even reduce, greenhouse gas emissions. The IPCC noted in 2021 that, 'unless there are immediate, rapid, and large-scale reductions in greenhouse gas emissions, limiting warming to 1.5 °C will be beyond reach. However, some changes could be slowed, and others could be stopped by limiting warming.'

4.4 Assessing regional changes

The most useful information for many sectors, including electricity networks, to prepare for climate change is local and specific.

Downscaling is a method for producing higher-resolution climate information for local areas from large-scale models. The approach can better represent regional extreme events and the influence of small-scale features such as topography and urban heat islands. Downscaled regional climate projections can often provide information at scales better suited for decision-making purposes, such as location-specific risk assessments and adaptation activities.

Downscaled projections provide important additional information over the Australian Alps, Tasmania and near coastlines (Figure 6).

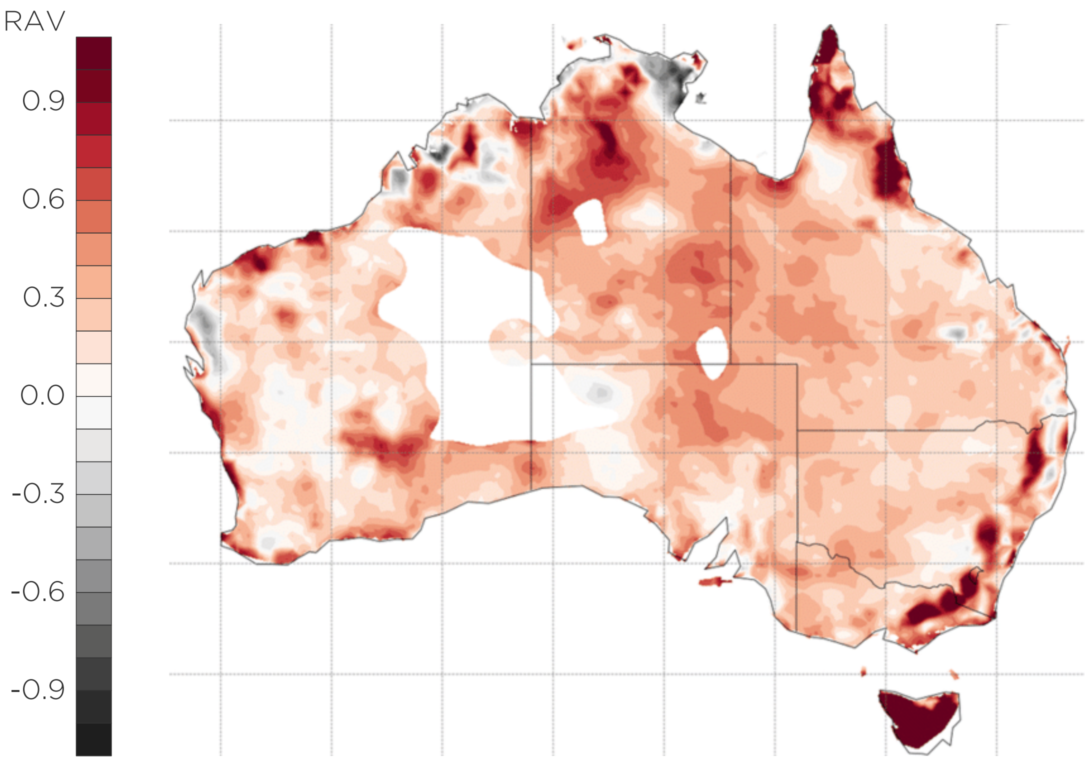

Figure 6 Red indicates where downscaling adds value to simulations from global climate models (Di Virgilio G, Evans J, Di Luca A, Grose M, Round V & Thatcher M (2020). Realised added value in dynamical downscaling of Australian climate change. *Climate Dynamics* 54, 4675–4692)

Many state and territory governments have produced downscaled climate projections for their region. These include the NSW and ACT Regional Climate Modelling (NARCLiM) in collaboration with the University of New South Wales, the Queensland Future Climate Dashboard by the Queensland Department of Environmental Science, SA Climate Ready in collaboration with the Goyder Institute for Water Research, Climate Futures for Tasmania in collaboration with the Antarctic Climate and Ecosystems Cooperative Research Centre, and the Victorian Climate Projections in partnership with CSIRO.

State and territory climate change projections resources

More information about regional climate change information and projections can be found via the following links:

- NSW and ACT Regional Climate Modelling (NARCLiM): https://www.climatechange.environment.nsw.gov.au/my-region
- Climate Change NT: https://climatechange.nt.gov.au/
- Queensland Future Climate Dashboard: https://www.longpaddock.qld.gov.au/qld-future-climate/
- SA Climate Ready: https://data.environment.sa.gov.au/Climate/SA-Climate-Ready/Pages/default.aspx
- Climate Futures for Tasmania: https://climatefutures.org.au/projects/climate-futures-tasmania/
- Victorian Climate Projections: https://www.climatechangeinaustralia.gov.au/en/projects/victorian-climate-projections-2019/
- WA Climate Science Initiative: https://www.wa.gov.au/service/environment/environment-information-services/climate-science-initiative

5 Climate change projections for the electricity sector

While there is certainty that climate change is already occurring and will continue to occur in future, there is uncertainty about the magnitude of future changes and their impacts.

The uncertainty stems from a lack of knowledge about how the world's climate will respond to greenhouse gas emissions, from future natural variability and from uncertainty about which future emissions pathway the world will follow.

Table 1 presents climate-related hazards in order from greatest to least confidence regarding the impacts of climate change. Scientists have high confidence in projections of sea-level rise and temperature change associated with emission scenarios. They have less confidence in how rainfall, tropical cyclones and thunderstorms will change in future. These projections can still be useful, but the uncertainty must be considered.

Table 1 Climate-related hazards and their likely changes due to climate change, listed in order from greatest to least confidence. (Based on ESCI (2021). *Electricity Sector Climate Information Project*)

Climate-related hazard	Observed and projected changes
Sea level	Increase
Temperature	Increase
Heatwaves and extreme heat events	Increased frequency of large-scale heatwaves and record high temperatures
Bushfire weather	Longer fire season with more extreme fire danger days
Extreme wind	Wind speeds are likely to decline overall, but the highest winds associated with local storms and tropical cyclones may increase
Rainfall	Reduced reliability of cool season rainfall; likely increase in heavy rainfall during the warm season
Tropical cyclones, east coast lows and storms	Decreased frequency but possible increase in intensity
Thunderstorms, lightning and hailstorms	Some evidence of increased frequency of thunderstorms for parts of eastern Australia

5.1 Projected Australian changes

Primary sources of information in this section, and the basis for confidence ratings, are Climate Change in Australia and IPCC's *Climate Change 2021: The Physical Science Basis*. 'High emissions scenario' refers to RCP8.5, 'intermediate emissions scenario' refers to RCP4.5, and 'low emissions scenario' refers to RCP2.6.

Confidence ratings for projections are based on physical theory and understanding of processes driving the change, agreement among climate model simulations, model evaluation, and consistency of global climate model results with downscaled high-resolution simulations.

Figure 7 presents a summary of the major changes expected for Australia.

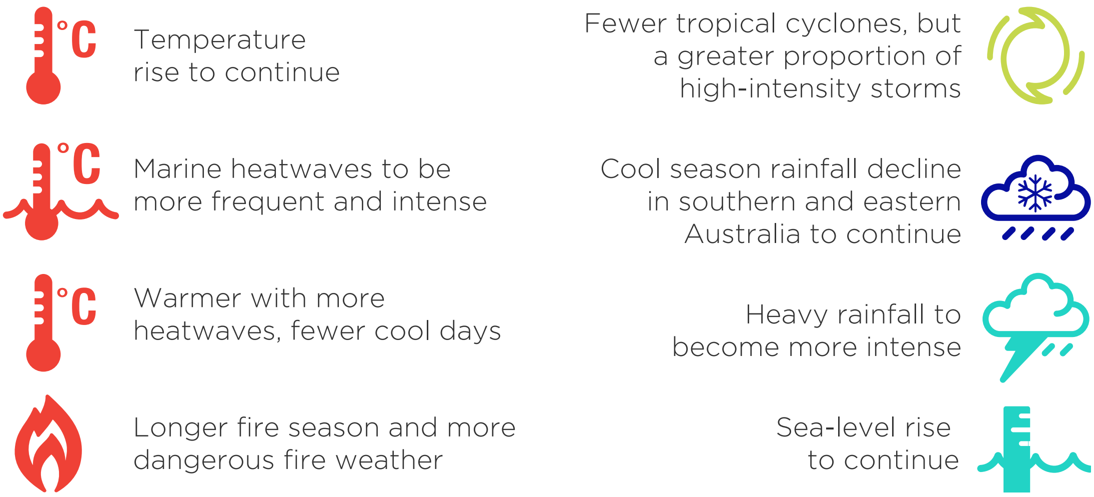

Figure 7 Overview of the key climate projections for Australia (CSIRO and Bureau of Meteorology (2020). *State of the Climate 2020*)

Temperature

Australia will warm substantially during the 21st century

There will be continued increases in mean, daily minimum and daily maximum temperatures throughout this century for all regions in Australia.

Scientists have very high confidence in these projections, which consider the observed warming trend, strong climate model agreement on the direction and magnitude of change, downscaling results and the robust understanding of the causes of warming. The magnitude of warming later in the century depends strongly on atmospheric greenhouse gas concentrations and, hence, the emissions scenario.

Natural variability means that average temperatures vary from year to year. The warming trend in the coming decades will be large compared with this natural variability and very large compared with natural variability late in the century (2090) under a high emissions scenario. Emissions scenario choice has little effect on warming in the next decade or so. However, significantly greater warming is likely by 2090 if the world follows a high emissions scenario.

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Australia's national projections (Climate Change in Australia) show that for a high emissions scenario, Australia is likely to experience warming of between 2.8 to 5.1 °C by 2090. Under an intermediate scenario, warming is likely to be between 1.4 to 2.7 °C, or under a low emissions scenario between 0.6 to 1.7 °C, by 2090.

However, the latest set of climate model results from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), produced and published during 2020 and 2021, projects higher likely warming for Australia beyond 2050 due to the increased climate sensitivity of some of the new models. For example, under the highest emission scenario, CMIP6 models project average annual temperatures in Australia to warm by 3.5 to 6.5 °C by the end of the century.

Under the high emissions scenarios described by both Australia's national projections and CMIP6, the projected warming for Australia will cause more frequent and hotter hot days and warmer cold extremes (very high confidence), resulting in more record hot days and warm nights. Inland Australia is projected to warm more than coastal areas.

Extreme heat events that occur on average once in 20 years are now projected to occur every year in central Australia and at least every five years across most of south-east Australia by the late 21st century. Capital cities across Australia can expect a substantial increase in the number of very hot days.

Bushfires

Longer fire seasons with more extreme fire danger days

More dangerous weather conditions for bushfires are projected throughout Australia. Southern and eastern Australia are likely to experience harsher fire weather and longer fire seasons, exacerbated by the increased occurrence of extreme heat events.

Climate models simulate a future increase in dangerous pyroconvection conditions for many parts of southern Australia. These conditions can lead to fire-generated thunderstorms that can produce extremely dangerous fire behaviour, including erratic changes in wind. They can also carry embers that can start new fires far ahead of the fire front. Fire-generated thunderstorms played a significant role in the devastating Australian fire season of 2019–20.

Image credit: Alex Ellinghausen

Precipitation

Cool-season rainfall is projected to decline in southern Australia, with extreme rain events projected to become more intense

In southern Australia, the southward movement of winter storm systems is likely to reduce winter and spring rainfall (high confidence), although increases are projected for Tasmania in winter (medium confidence). The winter decline may be as great as 50 per cent (compared with the 1986–2005 reference period) in south-western Australia under a high emissions scenario by 2090. The direction of change in summer and autumn rainfall in southern Australia cannot be reliably projected, but there is medium confidence in a decrease in south-western Victoria in autumn and in western Tasmania in summer.

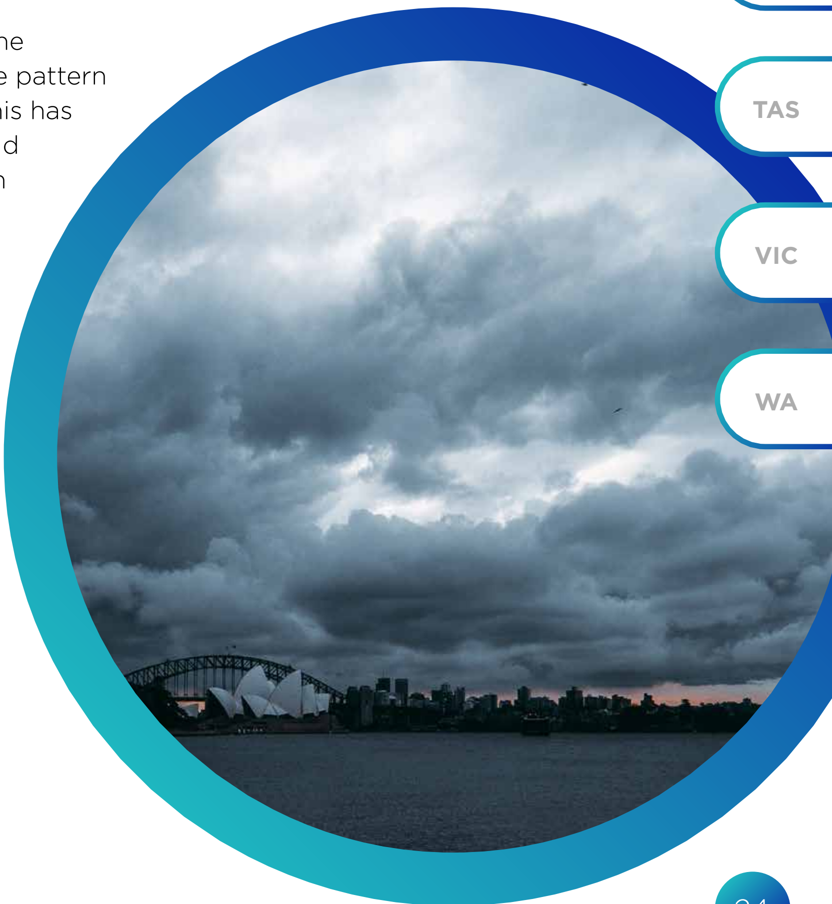
Late this century, eastern Australia is likely to experience winter rainfall decreases related to the southward movement and weakening of winter storm systems (medium confidence). Otherwise, there is low confidence in the direction of seasonal rainfall change due to strongly contrasting results from climate modelling. The large uncertainty in this region is also likely due to the range of influences on local rainfall and the impact of the Great Dividing Range.

In northern Australia, there is high confidence that, in the short-term, natural variability will predominate over trends due to greenhouse gas emissions. There is low confidence in the direction of future rainfall change by late in the century, but substantial changes to wet-season and annual rainfall are possible. Confidence in rainfall projections is low due to the lack of climate model agreement and limitations in their ability to reproduce smaller-scale features of observed rainfall.

The latest climate models (CMIP6) produce rainfall projections similar to those presented above.

Climate change has increased the intensity of the subtropical ridge, as well as a more summer-like pattern of pressure year-round in southern Australia. This has been associated with a reduced influence of cold fronts and low pressure systems compared with the climate of the mid-20th century.

Throughout most of Australia, extreme rainfall events (wettest day of the year and wettest day in 20 years) are projected to increase in intensity (high confidence). Increased rainfall intensity is projected for south-western Western Australia, but with medium confidence because of the large projected rainfall reductions in this region.



Drought

Time in drought is projected to increase in southern Australia, with a greater frequency of severe droughts

Under a warming climate, Australia will spend more time in drought, with longer and more intense drought conditions, particularly across southern and eastern Australia.

There is an increasing trend for all drought metrics (except drought frequency) across most of Australia. Regionally, the future periods considered (2030, 2050, 2070, 2090) experience significantly different conditions compared with the baseline period (1995), except for northern Australia and, to a lesser extent, inland regions. This indicates that there is strong climate model agreement in the projected changes.

There is more certainty in projections for the south-west of Australia, and to a lesser extent southern Australia, where all climate models show an increase in severe drought conditions.

ENSO is changing in response to human-induced increases in greenhouse gases. ENSO's impact on rainfall in the Pacific and beyond is expected to increase in response to a warming world.

ENSO and higher temperatures will likely lead to decreased rainfall year-round in south-western Australia and across large parts of eastern Australia, mostly during El Niño and neutral years. Northern Australia, the wet tropics and south-eastern Australia are likely to experience an increase in rainfall variability. As a result, approximately 60 per cent of future years are projected to be drought years in Perth, 35 per cent in Adelaide, 30 per cent in Melbourne, and 20–25 per cent of years in Sydney, Canberra and Brisbane.

The projections of change to the frequency and duration of drought presented here are consistent with assessments that ENSO events will intensify with climate change and may cause an intensification of El-Niño-driven drying in Australia. The frequency of extreme positive IOD events is projected to increase, leading to more occurrences of drought and bushfires.

Trends towards a more positive SAM have been linked to a reduction in rainfall in southern Australia.

Sea level

Sea levels will continue to rise throughout the 21st century and beyond, with extreme sea-level events increasing in frequency

In line with global mean sea level, Australian sea levels are projected to rise through the 21st century (very high confidence) and are very likely to rise at a faster rate during the 21st century than over the past four decades. Sea-level projections for the Australian coastline by 2090 are comparable to, or slightly larger than (by up to about 6 cm), the global mean sea-level projections of 26-55 cm for a low emissions scenario and 45-82 cm for a high emissions scenario (medium confidence).

A collapse in the marine-based sectors of the Antarctic ice sheet would result in sea levels increasing by up to several tenths of a metre by late this century.

Sea-level rise increases storm surge and coastal erosion risks. Projected increases in extreme rainfall intensity, coupled with sea-level rise, are likely to increase the frequency and magnitude of flooding in many coastal and estuarine regions, including during extreme weather events such as tropical cyclones. Most sandy coasts will experience shoreline retreat (erosion) throughout this century.

For most of the Australian coast, extreme sea-level events that had a probability of occurring once in 100 years are projected to become an annual event by the end of this century under lower emission scenarios, and by mid-century for higher emission scenarios.

Lightning and storms

Severe convective storms may increase in frequency and intensity, with mid-latitude weather systems projected to shift south in winter, and the tropics to expand

Climate models project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail and winds (high confidence).

The small scale of thunderstorms makes them difficult to model. However, some projections indicate an increase in the frequency of thunderstorms in parts of eastern Australia. Climate change may increase bushfire ignition risk from lightning, particularly for dry lightning, accompanied by little rainfall.

Climate change is likely to lead to an expansion of the tropics and a contraction of the mid-latitude storm tracks to higher southern latitudes.

The observed intensification of the subtropical ridge (the high-pressure belt over Australia) and expansion of the Hadley Cell (a circulation in the north-south direction connecting tropical and mid-latitude areas) are projected to continue throughout this century (high confidence). These changes have been linked to a reduction in rainfall in southern Australia.

In winter, mid-latitude weather systems are projected to shift south, with a decrease in the number of deep lows affecting south-west Western Australia and a decrease in the number of fronts in southern Australia.

Wind

Small changes in wind speed are projected

Under a high emission scenario, mean wind speeds are projected to decrease by 2090 in southern mainland Australia in winter (high confidence) and south-eastern mainland Australia in autumn and spring. Wind speed is projected to increase in winter in Tasmania. These changes are projected to be small.

Projected changes in extreme wind speeds are similar to those for mean wind. There is generally medium confidence in decreases in extreme wind speeds over the south of the continent and increases over Tasmania.

Throughout Australia, sand storms and dust storms may increase.

East coast lows

There may be fewer east coast lows, but those that do occur may bring more intense rainfall

Fewer east coast lows are likely to occur in the future due to increasing greenhouse gas emissions. However, other changes in our climate will affect the impacts of future east coast lows. For example, rising sea levels are likely to increase the impacts of large waves on coastal regions, and extreme rainfall is predicted to increase in intensity, increasing the risk of flooding. Intense east coast lows are also likely to bring damaging winds that can exacerbate the impacts experienced during these events.

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Image credit: AusNet

Tropical cyclones

Tropical cyclones may occur less often, become more intense, and may reach further south

Tropical cyclone numbers in the Australian region are likely to decrease this century, more so in the western Australian region than in eastern Australia.

There is likely to be a greater proportion of severe or intense tropical cyclones in future due to the increasing energy available to generate cyclones. Rainfall produced by tropical cyclones is expected to increase, particularly the intensity of extreme rainfall events which could increase by 10 per cent or more per degree of global warming (noting that about one degree of warming has already occurred). Damaging winds associated with more intense tropical cyclones would increase the risk to lives and property.

Scientists have only medium confidence in projections of tropical cyclone frequency and intensity. There is low confidence in results suggesting that tropical cyclones may reach further south under a warmer climate due to warmer oceans and changing large-scale wind patterns.

Snow, frost and hail

Snowfall in the Australian Alps is projected to decrease, especially at low elevations. Fewer frost days are projected but future changes in hail are uncertain

There is very high confidence that as warming progresses there will be a decrease in snowfall, an increase in snowmelt and thus reduced snow cover. These trends will be most evident at low elevations.

Places where frost now occurs only a few times a year are projected to become nearly frost-free by 2030. Under the high emissions scenario, coastal areas are projected to be frost-free by 2090, while frost is still projected to occur inland.

There is low confidence in projections of hail because competing physical processes may affect trends and current climate models are not able to simulate these. Hail is typically associated with smaller-scale convection systems, making it difficult to simulate in climate models.

Humidity

Relative humidity may decline, and evaporation rates are projected to increase

Relative humidity is projected to decline in inland regions and where rainfall is projected to decline. By 2090, there is high confidence that humidity will decrease in winter and spring as well as annually under a high emissions scenario. There is medium confidence in declining relative humidity in summer and autumn.

There is high confidence in increasing potential evapotranspiration (atmospheric moisture demand) closely related to local warming, although there is only medium confidence in the magnitude of change.

Compound extreme events

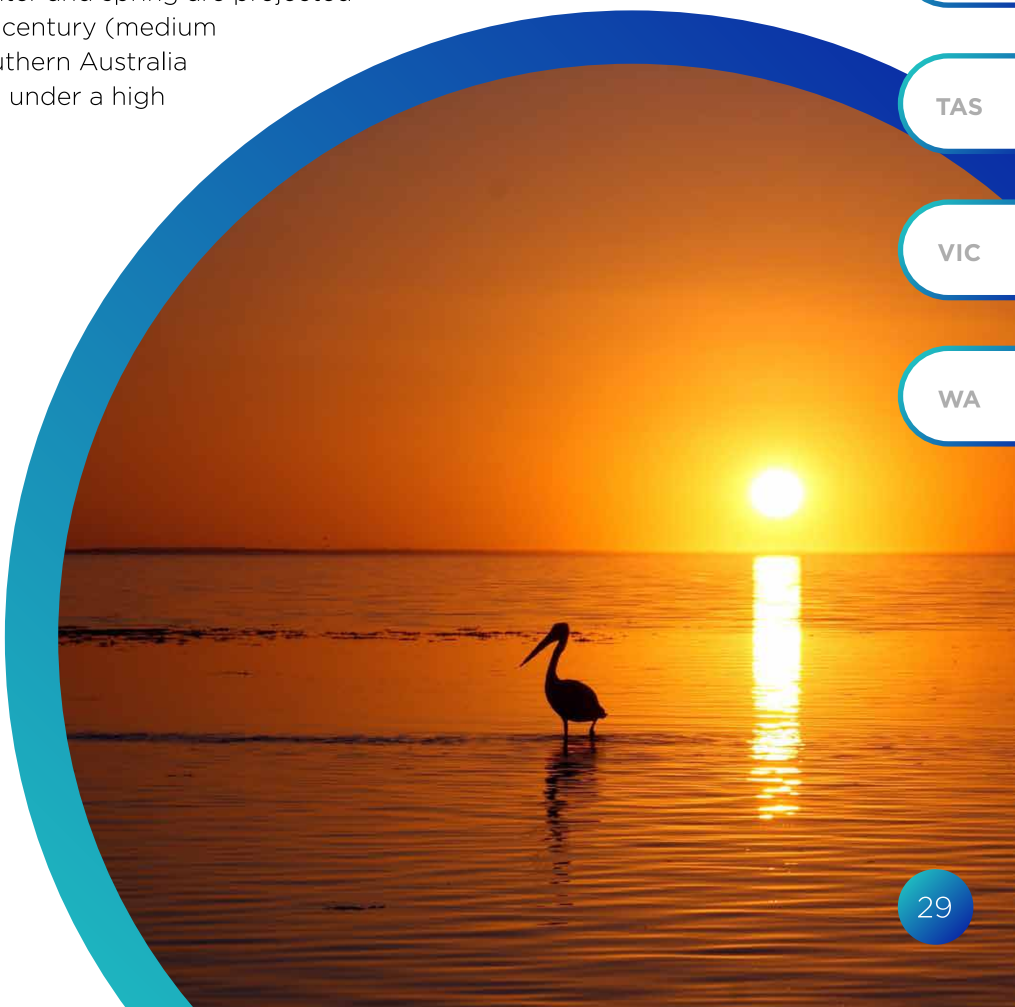
There may be more frequent compound extreme events under a changing climate

Climate change can have a significant influence on the frequency, magnitude and impact of some types of compound extreme events. As the climate warms, the warming trend increases the likelihood of extreme events that are beyond historical experience. A continuing trend of more frequent compound extreme events is likely, although confidence in these projections is low and projections of such events remains a significant scientific challenge.

Solar radiation

More sunshine is projected in winter and spring

Increases in solar radiation in winter and spring are projected for southern Australia late in the century (medium confidence). The increases in southern Australia may exceed 10 per cent by 2090 under a high emissions scenario.



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Soil moisture

Soil moisture is projected to decrease, and runoff will decline with decreasing rainfall

Changes in soil moisture and runoff vary from region to region over Australia.

There is high confidence in decreasing soil moisture in the southern regions (particularly in winter and spring) driven by the projected decrease in rainfall and higher evaporation. There is medium confidence in decreasing soil moisture elsewhere in Australia where evaporation is projected to increase, but the direction of rainfall change is uncertain.

Decreases in runoff are projected with high confidence only in south-west Western Australia and southern South Australia, and with medium confidence in far south-eastern Australia, where future rainfall is projected to decrease. Projected changes in runoff are generally two to three times larger than the relevant rainfall change.

The direction of change in runoff in the northern half of Australia cannot be reliably projected because of the uncertainty in the direction of projected rainfall change.

6 How climate-related hazards affect electricity networks

The National Electricity Market (NEM) is designed to respond to daily changes in temperature that affect demand and supply. However, the NEM is vulnerable to climate-related hazards such as heatwaves, drought, bushfires, floods and tropical cyclones.

Climate-related hazards present challenges to Australia's electricity distribution, particularly as temperatures rise and some extreme events become more frequent and intense. Degradation or damage to electricity distribution assets, such as overhead cables, and increased transmission losses due to high temperatures could result in system-wide impacts and create supply problems and financial implications for investors and customers.

6.1 Climate change impacts on electricity network staff and customers

More frequent and intense extreme events can affect network staff and customers, damaging the places they live and work, reducing the liveability of communities and affecting livelihoods.

Extreme hot days and heatwaves, as well as extreme events such as storms and flooding, pose risks to network staff, including contractors and accredited service providers. Heat stress and high dust and pollen days can affect people's health and their capacity to undertake work. Tropical cyclones, thunderstorms, hail, snow and extreme winds can make it difficult, or even unsafe, for staff to repair and maintain damaged assets and equipment, often leading to longer outages.

Weather extremes can disrupt services, often at times when people have an increased need for power – such as during heatwaves.

Extreme weather causing frequent damage to the United States electricity grid

Climate-related hazards affect electricity networks overseas, as well as in Australia. Climate Central, a non-profit news organisation that analyses climate science, reports that, 'hurricanes, wildfires, ice storms, flooding, heatwaves and other extreme weather events are growing in number or intensity with climate change. Extreme weather is causing frequent damage to our aging electrical grid, costing Americans and the economy tens of billions of dollars each year and impacting public health. Between 2003 and 2012, weather-related outages are estimated to have cost the United States economy an inflation-adjusted annual average of US$18 billion to US$33 billion.'

The analysis of national power outage data shows a 67 per cent increase in major power outages from weather-related events since 2000.

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6.2 Climate-related hazards

The main climate-related hazards that impact electricity networks include high temperatures, bushfire weather, intense precipitation, drought, sea-level rise, lightning and storms, wind, compound extreme events, vegetation growth, dust, snow, ice, hail, solar radiation and humidity.

The impacts of these hazards are described below and summarised in Table 2. Table 3 lists the energy network components affected by each of the identified climate hazards.

Table 2 Changes in climate-related hazards that can affect Australia's electricity networks. For each hazard, there is an indication of scientific confidence in the projected changes.

Climate type	Climate variable	Network risk and vulnerability
Temperature Projected increase in average and extreme temperatures and extreme bushfire weather *High confidence*	Extreme temperatures	Extreme temperature events may alter peak electricity demand and reduce the efficiency and capacity of overhead lines, cables and transformers. This may shorten the lifespan of assets.
	Mean temperature	Mean temperature changes may reduce the efficiency and capacity of overhead lines, cables and transformers. Hotter temperatures may also increase sag of overhead lines and cables.
	Bushfire weather	Dangerous bushfire weather may affect overhead lines and structures.
Precipitation Projected regional decrease in winter/ spring rainfall and increase in extreme rainfall events *Low-medium confidence*	Extreme rainfall	Extreme rainfall can cause floods, which may damage substations and indirectly damage overhead wires, underground cables and pipes. Extreme rainfall can also reduce access to repair assets.
	Mean rainfall	Mean and seasonal rainfall changes can cause maintenance and repair issues to underground cables and pipes.
	Drought	Drought can directly affect ground conductivity through underground cables and can damage overhead structures through ground movement.
Sea level Projected increase in sea levels and storm surge *High confidence*	Sea-level rise	Sea-level rise can cause an increased rate of inundation and erosion, damaging substations, transformers and circuit breakers.
	Storm surge	Storm surge can cause an increased rate of inundation and erosion damaging substations, transformers and circuit breakers.

Climate type	Climate variable	Network risk and vulnerability
Lightning and storms Lightning and storms may increase in frequency for tropical Australia. The trend for southern Australia is unclear. *Low confidence*	Lightning strikes	Lightning can disrupt energy supply and accelerate asset deterioration. Lightning can ignite bushfires.
	Storms	Storms may affect overhead lines and conductors and reduce access to repair assets.
Wind Projected decrease in high-wind events, and frequency of cyclones and east coast lows, but possible increase in the proportion of intense cyclones (Category 4–5) and east coast lows *Low-medium confidence*	Average wind speed	Average wind speed changes and high wind load events can damage overhead lines and conductors.
	Extreme wind e.g. tropical cyclones, east coast lows, downbursts	Extreme wind events can damage overhead transmission lines and reduce network capacity. Extreme winds can cause vegetation damage to lines, leading to outages.
Compound extreme events Projected possible increase in frequency or magnitude *Low confidence*	Multiple adverse impacts that occur concurrently or in quick succession	Depending on the extremes combined, compound extreme events can lead to physical damage to equipment and infrastructure, disruptions to supply, increased customer demand, de-rating of transmission and distribution lines, increased operational costs and network failures.
Other climate-related hazards	Vegetation growth patterns	Increased vegetation growth patterns can increase the maintenance of overhead lines.
	Dust	Dust storms can cause flashovers of overhead lines.
	Snow/ice/hail	Ice and hail storms can cause damage to exposed network assets. Snow can limit access to network assets for repair, causing supply restoration delays.
	Solar radiation	High solar radiation, combined with high temperatures and low winds, creates challenging conditions that can result in de-rating of equipment, such as cables.
	Airborne particles	Airborne particles such as salt spray can cause flashovers and a need for more maintenance of overhead lines.

Table 3 Components of Australian energy networks vulnerable to climate-related hazards. Red squares denote potential high or medium risk.

Climate-related hazard	Specific risk	Network component/function at risk: Substations	Transformers	Circuit breakers	Overhead lines	Wooden poles	Underground cables	Underground pipes
Sea level	Sea-level rise	■	■	■	■	■	■	■
Heatwaves and extreme heat events	Extreme temperatures	■	■	■	■	■	■	
	Mean temperature	■	■	■	■	■		
Bushfire weather risk	Bushfire weather	■	■	■	■	■	■	■
Extreme wind	Wind speed		■		■	■		
Rainfall	Extreme rainfall	■	■	■	■	■	■	■
	Mean rainfall				■	■	■	■
	Drought	■	■	■	■	■	■	■
Tropical cyclones and storms	Cyclones	■	■	■	■	■		
	Storms	■	■	■	■	■		
Thunderstorms, lightning and hailstorms	Lightning strikes	■	■	■	■	■		
	Hail	■	■	■	■	■		
Other	Vegetation growth patterns				■	■		
	Dust storms			■	■			
	Airborne particles			■	■	■		
	Interdependencies	■	■	■	■	■	■	■

Temperatures

Reduced network capacity | Increased demand | Increased operational costs | Accelerated asset damage | Productivity loss

Increased temperatures and extreme heat events can affect electricity distribution by damaging equipment and assets and by increasing transmission demand. These impacts place additional stress on networks, particularly older ones, and can accelerate asset degradation and shorten the life of infrastructure and equipment.

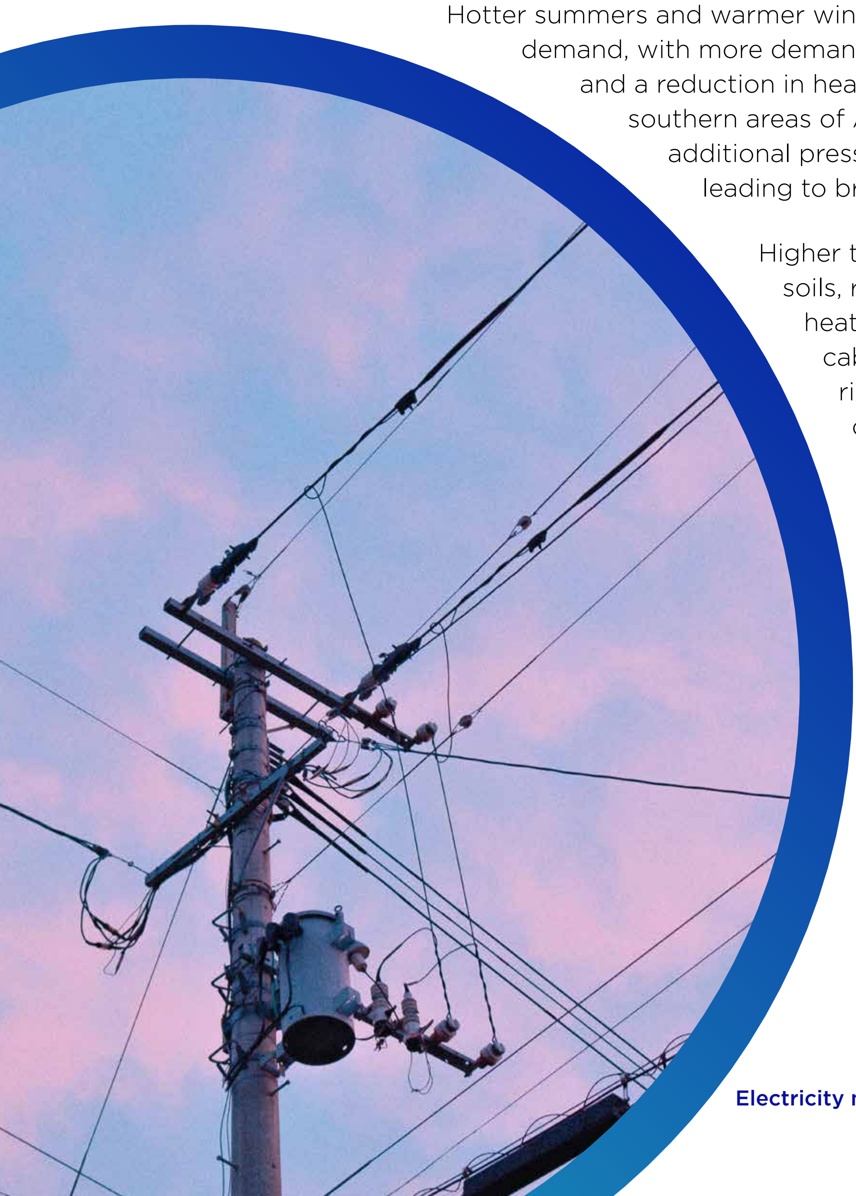
Extremely hot days and heatwaves can increase the risk of heat stress on network crew and subcontractors undertaking repair or maintenance work. This may result in health impacts on workers and a loss in productivity.

> Victoria experienced a heatwave in January 2019 that placed stress on electricity infrastructure and disrupted power supply to 200,000 homes and businesses, with people advised to reduce their power usage.

Increased temperatures can cause transmission lines to overheat and expand, leading to sagging. Operating at higher temperatures over a sustained period (such as during heatwaves) strains equipment and distribution infrastructure, reducing generator capacity and shortening the life of the equipment and assets. This can cause outages that affect customer supply and increase operational costs through patrol and repair of damaged transmission lines and equipment.

Hotter summers and warmer winters can change electricity demand, with more demand for cooling during summer and a reduction in heating during winter in some southern areas of Australia. This can place additional pressure on distribution elements, leading to brownouts and failures.

Higher temperatures can cause drier soils, reducing their ability to conduct heat away from underground cables. Dry soils increase the risk of ground movement that can damage cables and cable joints. Increasing air and soil temperatures can also result in de-rating of equipment for lines and substations, with the carrying capacity lowered to cope with the heat. Hot and dry weather can cause trees to shed branches, posing risks to overhead lines and cables.



Bushfire weather

Asset damage | Outages | Disrupted supply | Increased operational costs

Bushfires can cause widespread interruptions to electricity distribution and supply that can last for several weeks. Major bushfires can cause multiple simultaneous outages across wide areas.

Bushfire impacts include increased line sag, damage to infrastructure, the inability to access facilities for repair, increased operational costs because of a lack of time to complete pre-summer bushfire patrols and maintenance, and smoke and ash damage to equipment.

Distribution networks can sometimes ignite bushfires, with the risk of this increasing with the number of high fire danger days. Managing the risk of bushfire ignition often results in customer outages, as part of the network may need to be disconnected at times of high risk or during firefighting activities.

The 2019–20 bushfire season had a devastating impact on Australia's electricity distribution. The fires, ignited by lightning strikes, destroyed over 5,000 power poles across Victoria and NSW, with entire sections of electricity networks needing to be rebuilt.

From November 2019 to March 2020, the number of unplanned electricity outages in Australia was significantly higher than in the previous summer, particularly in NSW, with the increase mainly due to bushfires.

Precipitation

Damaged assets | Loss of supply | Maintenance and repair disruptions

Changes in rainfall patterns and increased extreme rainfall affect electricity distribution.

Extreme rainfall can lead to flooding or flash floods that can cause damage to substations and other infrastructure such as underground pipes and cables, resulting in extended electrical outages. Flooding and seasonal rainfall changes can disrupt access for maintenance and repair, resulting in increased operational costs and lengthy outages to supply.

Around 100,000 homes were without power in Sydney in February 2020 after the heaviest storm in 30 years lashed Australia's east coast, resulting in flash flooding.

Fallen trees due to wet and windy conditions can damage infrastructure. Extreme rainfall that causes flash flooding can result in mudslides and soil erosion, exposing buried pipelines and cables.

Drought

De-rating of equipment | Asset damage | Flashovers and outages

Dry, hot conditions accompanying drought can prevent the ground from conducting heat away from underground cables. This can result in the maximum current rating of cables being reduced. In addition, dry, hot and windy weather combined with dry vegetation can increase the probability of bushfires.

Dry soils can cause ground movement (subsidence and shrinkage) that can damage underground and overhead structures.

Sea-level rise

Increased outages | Asset damage | Increased maintenance costs

Sea-level rise and storm surge can increase the rate of inundation, causing damage to substations, transformers and circuit breakers in vulnerable coastal areas. As sea levels continue to rise, greater areas will be exposed to the risks of inundation, and access to structures for maintenance and repair will be reduced.

When Superstorm Sandy hit New York Harbour, over 4 metres of water above the average high tide flooded the electricity substations and left more than 8 million customers without power.

Low-lying network assets are likely to be increasingly at risk of inundation because of rising sea levels and storm surges, with some assets at risk of becoming inaccessible in the future.

Sea salt from encroaching oceans can corrode steel structures, fittings, conductors and earth wires. This can cause outages, often with longer periods required to restart transmission and distribution.

Coastal erosion caused by storm surge and sea-level rise can also damage and expose infrastructure and equipment in low-lying coastal areas.

Lightning and storms

Disrupted supply | Damaged assets | Sudden and lengthy outages

Lightning and storms can damage overhead lines and connection equipment, disrupt transmission and distribution, and accelerate asset deterioration.

Lightning strikes can damage structures and cause damaging electricity voltage spikes. Lightning strikes can also ignite bushfires, resulting in further risks and impacts to electricity equipment and infrastructure in the area.

Storms can cause widespread damage to overhead networks, particularly distribution networks, resulting in extended outages and lengthy repair times. Damage caused by fallen debris and tree branches during storms can create a short circuit between conductors.

Lightning and storms can lead to line outages due to equipment failure, including failure of insulators, earth wire and phase conductors, and associated line fittings. Lightning and storms can harm transformers due to lightning strikes and lightning-induced accelerated ageing.

In 2016, extreme winds, rain and multiple lightning strikes caused significant damage to South Australia's electricity transmission infrastructure. Almost the entire state lost electricity supply during the blackout, affecting 850,000 customers.

Downbursts associated with a thunderstorm severely damaged transmission lines and destroyed six 500 kV transmission towers in south-western Victoria in January 2020.

Wind

Disrupted supply | Damaged assets | Increased flashovers | Delayed repairs

Wind can damage transmission towers and lines. Extreme winds can cause transmission lines to swing between poles (referred to as conductor galloping) and contact the ground or other objects, leading to a short circuit that disrupts power flow. However, repairs can normally be carried out quickly in urban areas once conditions return to normal.

Extreme wind can lead to falling trees and vegetation, damaging transmission lines and cables and causing outages. Extreme wind can also increase salt aerosol deposits on assets and equipment, leading to flashovers and corrosion that result in reduced asset performance. More frequent de-energising of electricity networks may be required as a safety measure.

Strong winds and heavy rainfall in Victoria in October 2021 disrupted electricity supply to over 500,000 properties. Network crews faced challenging weather conditions and the risk of working near falling trees, with access to some properties delayed by blocked roads.

Tropical cyclones, tornadoes and east coast lows can devastate electricity infrastructure. Strong winds and flying debris can damage overhead lines and structures, causing outages. These severe weather systems are often accompanied by other climate-related hazards, such as flooding from extreme rainfall, amplifying their impact on electricity networks.

Windy and stormy conditions can slow repair and maintenance due to safety issues and difficulties accessing assets.

Compound extreme events

Disrupted supply | Damaged assets | Increased flashovers

Compound extreme events are multiple extreme events that occur simultaneously or successively, such as extreme heat and drought followed by bushfire. The combination of extreme events can amplify the impacts of climate-related hazards, affecting distribution and transmission assets.

Depending on the type of extremes that are combined, compound extreme events can damage equipment and infrastructure, disrupt supply, increase demand, lead to de-rating of transmission and distribution lines, increase operational costs and cause network failures.

In 2020, south-east NSW suffered extensive bushfires followed by torrential rains and associated flooding. This compound extreme event damaged electricity distribution to an unprecedented extent, causing 37,500 customers to lose power, damaging 2,165 power poles and 2,272 crossarms, and requiring repair and power restoration that took 49 days for some affected communities.

Other climate-related risks

Increased maintenance costs | Increased flashovers | Damaged assets | Productivity loss

Below are other risks to electricity networks that are directly or indirectly related to climate change.

Increased vegetation growth: can be caused by high rainfall followed by hot periods. This can increase the risk of vegetation growing close to overhead lines and interrupting electricity supply by touching exposed conductors or creating short circuits when blown onto lines. Preventing increased vegetation growth will increase vegetation management costs.

Large hail, lightning and heavy rains lashed parts of South Australia in October 2021 causing flash flooding and widespread damage. The wild weather cut power to more than 30,000 homes and businesses.

Dust: can rise from dry soils when rainfall is low. Dry conditions increase the risk of dust storms that disrupt electricity networks. Dust build-up can affect transmission lines, causing power outages and flashovers. Dust (and pollen) can impede staff, resulting in productivity loss.

Snow, ice and hail: can damage assets such as conductors and towers and reduce access to facilities for repair.

Airborne particles: can include salt spray and pollen, which can cause flashovers and increase the maintenance required for transmission lines.

Solar radiation: can combine with high temperatures and low winds to create challenging conditions that result in a minimum margin between the ambient temperature and the rated conductor design temperature. This can lead to de-rating of equipment, such as cables.

Humidity: can corrode equipment such as overhead lines and cable transformers, resulting in damage and increased maintenance costs.

7 Climate change risk assessments, disclosure and adaptation

7.1 Climate risk assessments

Energy Networks Australia published the *Climate Risk and Resilience: Industry Guidance Manual* to help network service providers plan for the impacts of climate change. The manual is designed to provide businesses with a consistent approach for undertaking a climate risk assessment, which can then be used to support climate change adaptation planning and decision-making by energy networks.

There are various approaches to climate risk assessments. ENA describes a risk framework consistent with the AS 5334-2013 Australian Standard – Climate Change Adaptation for Settlements and Infrastructure, and AS/NZS ISO 31000:2009 Risk Standard. The approach is based on these five steps:

- establish the context
- identify the risks (baseline and future)
- analyse the risks (evaluate changes)
- evaluate the risks (measure changes)
- treat the risks.

Inevitably, decisions will need to be made about which vulnerabilities to address. It would be reasonable to prioritise actions based on criteria such as the following:

- the probability that the vulnerability will result in significant disruption or damage without adaptation measures
- economic costs of the disruption or damage
- the timeframe over which the harmful impact is likely to occur
- adaptation potential, including the cost of measures that could significantly reduce harmful impacts.

7.2 Adaptation

Climate change adaptation entails adjusting to current or expected climate change to reduce or avoid climate impacts or exploit beneficial opportunities.

Electricity transmission and distribution infrastructure is often long-lived. Australia's future climate conditions must therefore be considered and incorporated into planning, risk assessments and adaptation decisions now to prepare, respond and appropriately manage the changing climate.

McKinsey & Company observes that, 'unless utilities become more resilient to extreme weather events, they put themselves at unnecessary risk, in both physical and financial terms. Repairing storm damage and upgrading infrastructure after the fact is expensive and traumatic.'

Adaptation in the United States – Consolidated Edison adaptation strategies

In response to increasing extreme events, some companies and jurisdictions in the United States have developed frameworks and approaches to identify the climate-related risks, their severity, and their impact, both physically and economically. The US energy company, Consolidated Edison, undertook a climate change vulnerability assessment that serves as an example of how to develop and implement recommended adaptation strategies. Consolidated Edison focused on how they could avoid future vulnerabilities and absorb, recover and advance from extreme events. Their adaptation strategies include updating design standards, specifications and ratings to account for likely changes in climate; replacing limiting wire sections with higher rated wire to reduce overhead transmission line sag during extreme heat events; retrofitting ventilation equipment with submersible equipment to prevent damage from inundation; using smart meters to implement targeted load shedding to restrict impacts to customers during extreme events by limiting the likelihood of large-scale outages; and ensuring replacement assets have increased resilience to the likely future climate.

The Multi-Hazard Mitigation Council in the United States reports that measures taken to reduce the impacts of natural hazards can result in significant savings in safety and preventing property loss and disruption. The council estimates that every dollar spent reducing risk before an event such as a flood, storm surge, wind extreme or wildfire saves up to 10 dollars that would otherwise need to be spent on recovery and response.

There are various ways for electricity networks to adapt to climate change. However, many of them are expensive and would need to be justified by risk and cost-benefit assessments. One approach is to reinforce infrastructure to prevent or reduce the damage from extreme weather events. This approach is known as 'hardening the grid'. Other options include decentralising generation, battery storage, microgrids (locally controlled loads and distributed-generation resources), smart grid technologies and managing the natural environment, such as preserving coastal wetlands.

In 2022, six Distribution Network Service Providers, including Ausgrid, Endeavour Energy, Essential Energy, Evoenergy, TasNetworks and NT Power & Water, released a consultation report and began community engagement on network resilience. The objective was to understand how service providers could define resilience, and identify how they could best support their local communities in adapting to a changing climate within the current regulatory framework. The figure from the report presents initial climate risks, impacts and adaptation options (Figure 8).

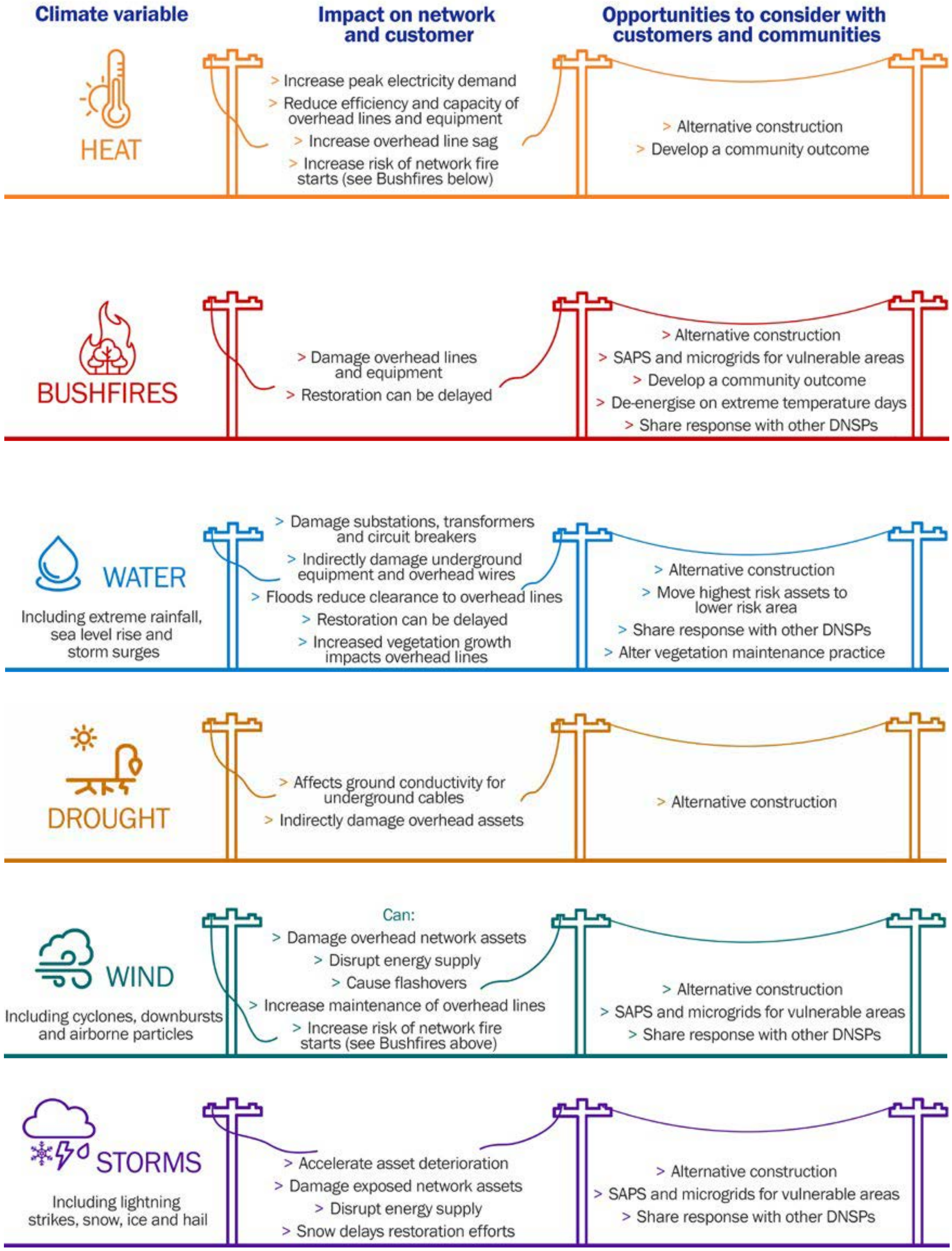


Figure 8 Examples of common climate risks, their impacts and selected adaptation options (NSW/ACT/TAS/NT Electricity Distributors (2022) Network Resilience: 2022 Collaboration Paper on Network Resilience)

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7.3 Task Force on Climate-related Financial Disclosures

In 2015, the Financial Stability Board created the Task Force on Climate-related Financial Disclosures (TCFD) to develop voluntary disclosure recommendations for use by companies in providing information to investors, lenders and insurance underwriters about the climate-related financial risks that companies face.

The TCFD sets out 11 recommended disclosures to help companies produce information that is useful for investors, including general and sector-specific guidance on implementation. The TCFD recommendations are now widely considered international best practice for climate-related financial reporting and, according to the Australian Institute of Company Directors, are already being used in Australia by 58 per cent of ASX100 companies.

The TCFD will form the basis of a new global disclosure standard by the International Sustainability Standards Board, against which companies will report climate change impacts.

While Australia is yet to mandate specific climate risk reporting, regulators including the Australian Prudential Regulation Authority (APRA) and the Australian Securities and Investments Commission (ASIC) have increased their focus on climate change risks. APRA expects financial institutions to report on the risks under existing prudential rules and has endorsed the use of the TCFD framework. ASIC has highlighted climate-related risk as a systemic risk in the Australian market and, like APRA, has recommended the TCFD framework to listed companies.

The TCFD recommendations on climate-related financial disclosures are widely adoptable and applicable to organisations across sectors and jurisdictions, including Australian electricity networks. Electricity network companies can benefit from considering and implementing recommendations from the TCFD, including integrating climate risk analysis (or climate-related scenario analysis) into strategic and financial planning processes, reporting on metrics that measure progress against emissions, water and energy targets and describing actions taken, or planned, to prevent and mitigate climate-related risks (or to take advantage of opportunities).

TCFD reporting may potentially create a competitive advantage as more customers and investors become aware of, and committed to, environmental sustainability and action on climate change. Consideration of the TCFD recommendations may also help companies to be well-positioned in the transition to a low-carbon economy. Some energy companies, such as AusNet Services, have already started reporting against the TCFD recommendations.

7.4 Electricity Sector Climate Information project

The Electricity Sector Climate Information (ESCI) project was initiated in response to the 2017 Finkel review into the future security of the NEM. The project, funded by the Commonwealth Department of Industry, Science, Energy and Resources, was undertaken by climate scientists from CSIRO and the Bureau of Meteorology in collaboration with the Australian Energy Market Operator (AEMO), and in partnership with electricity sector stakeholders.

ESCI aimed to improve and provide information for the electricity sector on likely future climate change scenarios to help the NEM be more resilient and the national grid more reliable. It delivered national climate datasets for the electricity sector, including maximum and minimum temperatures, wind speeds, bushfire conditions, solar radiation, rainfall and dam inflows. Data were produced at a scale of 1.5–12 kilometres across the NEM, at sub-daily intervals, to the year 2100.

The project also developed a climate risk assessment method to help the sector consider climate risk alongside other business risks. There is guidance to enable the electricity sector to assess climate risks and to plan with greater confidence, including case studies illustrating how the sector can apply the risk assessment method and ESCI data in their risk assessments.

More information is available via the Electricity Sector Climate Information project.

Image credit: Essential energy

8 Conclusion

Australian electricity networks have extensive experience in assessing and managing risks. Weather and climate extremes have presented threats to the sector since the first electrical installations in the 19th century. However, climate change is making some extremes more severe and/or more frequent. The impacts of climate change have been felt throughout Australia – and worldwide – for decades. The impacts will continue, and are likely to increase, throughout this century.

This report summarises the most authoritative and up-to-date projections of climate change for Australia and presents information about how the changes are likely to affect electricity networks. The projections represent defensible input into energy system risk assessments and adaptation plans.

In its Fifth Assessment Report, the IPCC stated that, 'climate change may influence the integrity and reliability of … electricity grids. Climate change may require changes in design standards for the construction and operation of … power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing … grids'.

The Energy Networks Association has produced resources to help energy network businesses and others assess the risks of climate change and develop adaptation plans. The ESCI project calls for a systematic assessment of sector vulnerability to climate change and a reassessment of engineering standards to include the influence of climate change. In its response to the Select Committee into the Resilience of Electricity Infrastructure in a Warming World, the Energy Networks Association noted that, 'resilience to climate change is likely to require modified approaches to network planning, risk analysis and contingency management.'

In addition to the physical risks of climate change to electricity network assets and infrastructure, climate change poses risks and impacts to network staff and customers. From the risk of heat stress for network repair and maintenance staff, to changing electricity demand of customers, to the inability of staff to access assets due to extreme weather conditions, the impact of climate change will be experienced at a personal level.

While there is extensive international literature on the likely future impacts of climate change, there is little information on recent trends in climate-related damage to electricity networks. Climate change is with us now and the projections for many of the changes are unequivocal; therefore evidence of actual sector impacts is a powerful force for justifying adaptation action.

Investments in increasing the resilience of electricity networks to climate change will always involve cost-benefit assessments. Networks are already developing innovative solutions to improve resilience, such as implementing stand-alone power systems, community batteries and pole-top batteries. These solutions are co-designed in collaboration with a wide range of stakeholders and customers. There is merit in assessing adaptation options and reporting on the likely costs and benefits.

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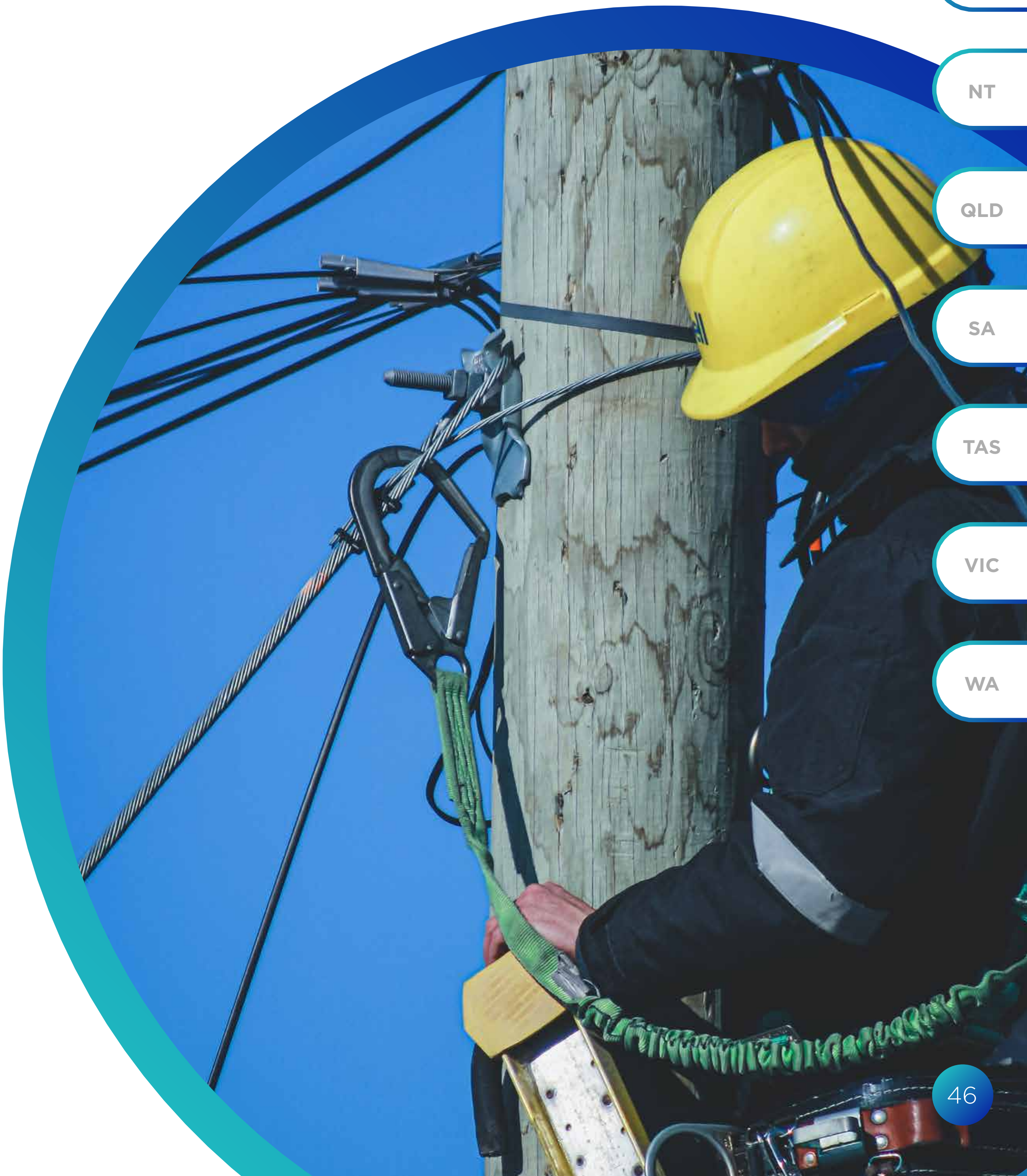
Severe convective downdrafts, thunderstorms, lightning and tornadoes are particularly destructive to the sector. However, the small spatial scale of these events means that they are poorly simulated by climate models. Further research into projections methods for these small-scale hazards, such as through climate model downscaling, is required.

As well as making decisions about optimum investments to protect the grid, Australia's electricity network, itself a major greenhouse gas emitter, can take steps to significantly reduce emissions.

The network is undergoing significant change as it seeks greater decentralisation and decarbonisation of energy generation. Energy Networks Australia and network operators are investing in organising and securing Australia's electricity grid, enabling the transition to a clean energy future. In 2020, the emissions across the National Electricity Market were 25 per cent below 2005 levels. This downward trend is expected to continue, representing a contribution to global emission reductions.



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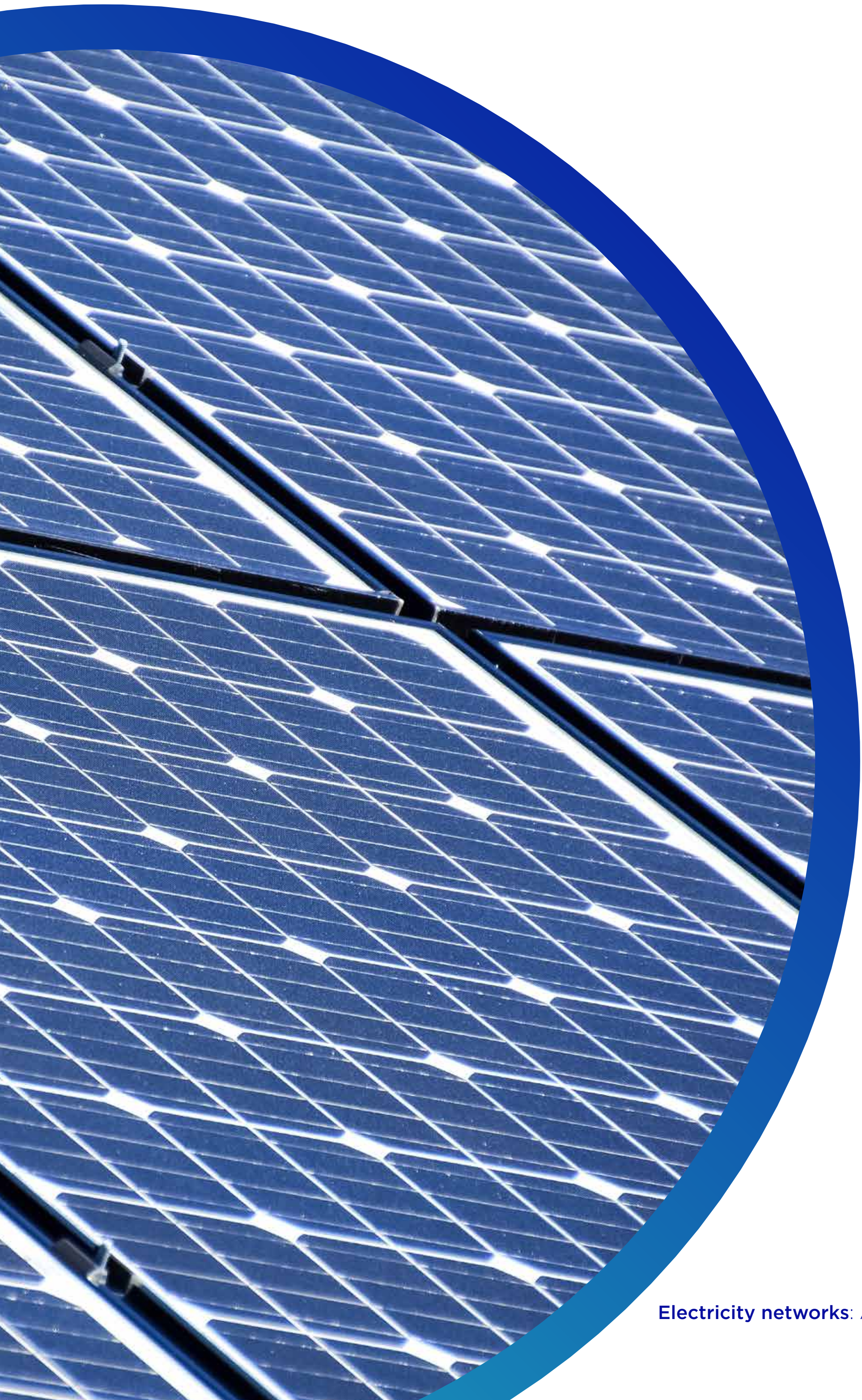

Appendix A. Climate change in New South Wales and the Australian Capital Territory

This appendix presents information about the past, current and likely future climate of New South Wales and the Australian Capital Territory.

The NSW and ACT region is already experiencing the impacts of climate change, with temperatures rising, heatwaves increasing in intensity, duration and frequency, and increases in both average and extreme fire weather in many places.

The climate of NSW and the ACT will continue to change in future. Included in this appendix are projections for temperature, precipitation, sea-level rise, wind and other climate-related hazards. There is information for the NSW and ACT, as well as specific projections for Sydney and Canberra.

Climate of NSW and the ACT

The climate of NSW and the ACT varies greatly among different regions and from year to year. The large variability in seasonal and regional climate brings heatwaves, storms, droughts, floods and bushfires, which can have devastating effects on the environment, human life and property.

Most of the region generally experiences mild temperatures. However, the arid north-west regularly records very high temperatures, and temperatures in the southern alpine regions are often below zero.

Annual average rainfall varies from less than 200 mm in the north-west to more than 1,800 mm along the coast. The north-east of the region experiences relatively wet summers and dry winters. The south depends on rainfall from winter cold fronts and receives less rain in summer. For most of the rest of the region, rainfall occurs intermittently through the year, although long-term monthly averages are more uniform.

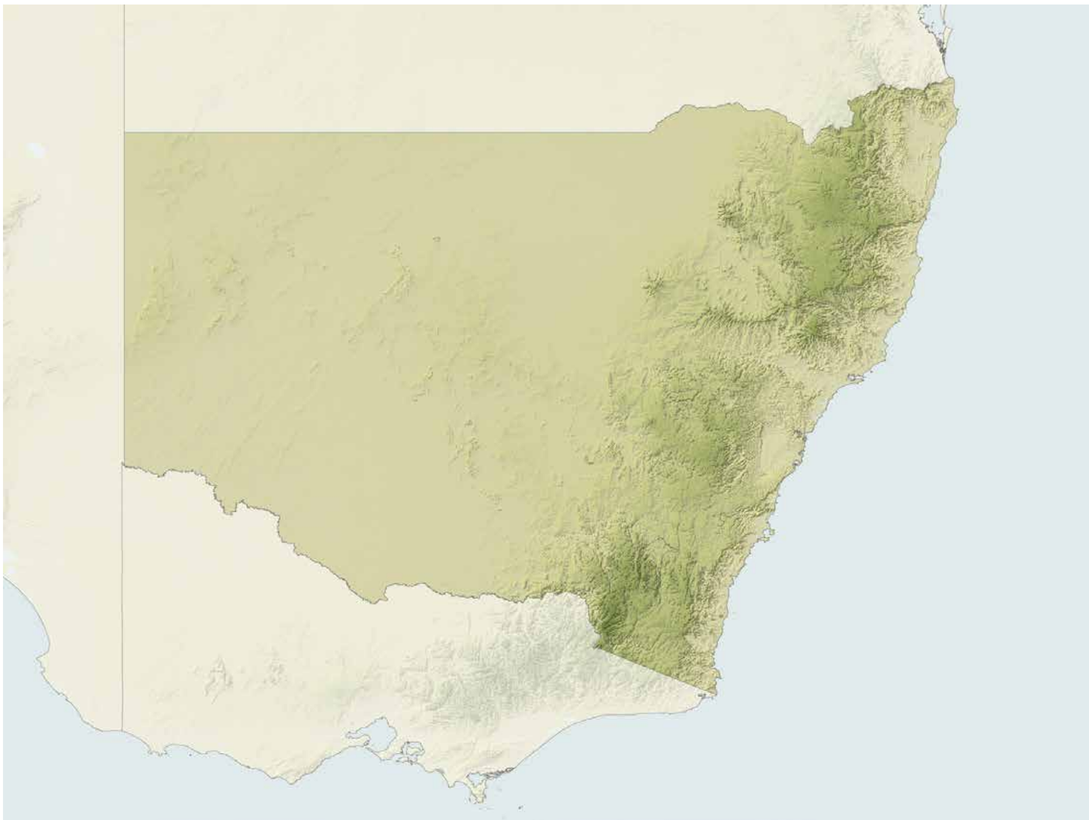

Figure 9 Topographic map of New South Wales and the ACT

The warm waters of the Tasman Sea moderate the temperature of the coast and help to generate abundant rain. The impact of the Great Dividing Range on moist air enhances rainfall near the coast, with a progressive decline in rainfall from east to west across NSW. The dry north-west of the state receives most of its highly variable rainfall in irregular, intense events, mostly in summer.

Occasionally, the heat from these arid north-west desert regions moves south and east ahead of summer cold fronts, producing very hot conditions in southern and coastal districts. High temperatures, strong winds and low humidity ahead of these fronts increase the risk of bushfire. In winter, cold snaps may lead to inland frosts and snowfall in the Australian Alps and Southern Tablelands.

While tropical cyclones do not affect NSW and the ACT very often, they have caused flooding, destructive winds, storm surges and loss of life. There are four likely ways for a tropical cyclone to affect the region:

1. making landfall in NSW from the east
2. making landfall in the Gulf of Carpentaria and moving overland towards the south-east over Queensland and then NSW
3. remaining offshore but generating huge coastal swells
4. affecting Lord Howe Island or Norfolk Island.

Climatic conditions can change greatly from year to year in response to large-scale phenomena (Figure 3) including:

- the subtropical ridge: the ridge allows cold fronts to pass over southern NSW in winter, pushing them southwards in summer.
- east coast lows: these intense low-pressure systems off the eastern coast bring strong and gusty winds, sustained heavy rainfall and high seas.
- El Niño – Southern Oscillation: El Niño events often lead to less rain in the region; its counterpart, La Niña, is associated with warm surface waters in the western Pacific and often brings above-average winter and spring rainfall over much of eastern Australia.
- the Indian Ocean Dipole: changes in sea-surface temperature patterns in the northern Indian Ocean can affect the region's rainfall; positive IOD conditions result in less rainfall, whereas negative conditions bring more rainfall, with the greatest impact experienced west of the Great Dividing Range.
- the Southern Annular Mode: this is a north-south shift in the belt of strong westerly winds across the south of Australia, affecting cold fronts, storm activity and rainfall. There tends to be less rainfall over central and northern NSW and more rainfall over a small region in southern NSW during a positive SAM in winter; a negative SAM tends to result in the opposite situation.

As well as their individual influence on the region's climate, ENSO, SAM and IOD can combine to create extreme conditions.

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Past and recent climate

Temperature

All of NSW and the ACT has warmed since 1910, with average annual temperature increasing by 1.4 °C since 1910 (Figure 10). The 2011–20 average temperature was around 1.1 °C above the 1961–90 average. Inland areas have warmed more than coastal areas.

The hottest year on record for the region was 2019. Daytime temperatures were especially warm, with Sydney and Canberra experiencing their highest annual mean maximum temperature on record.

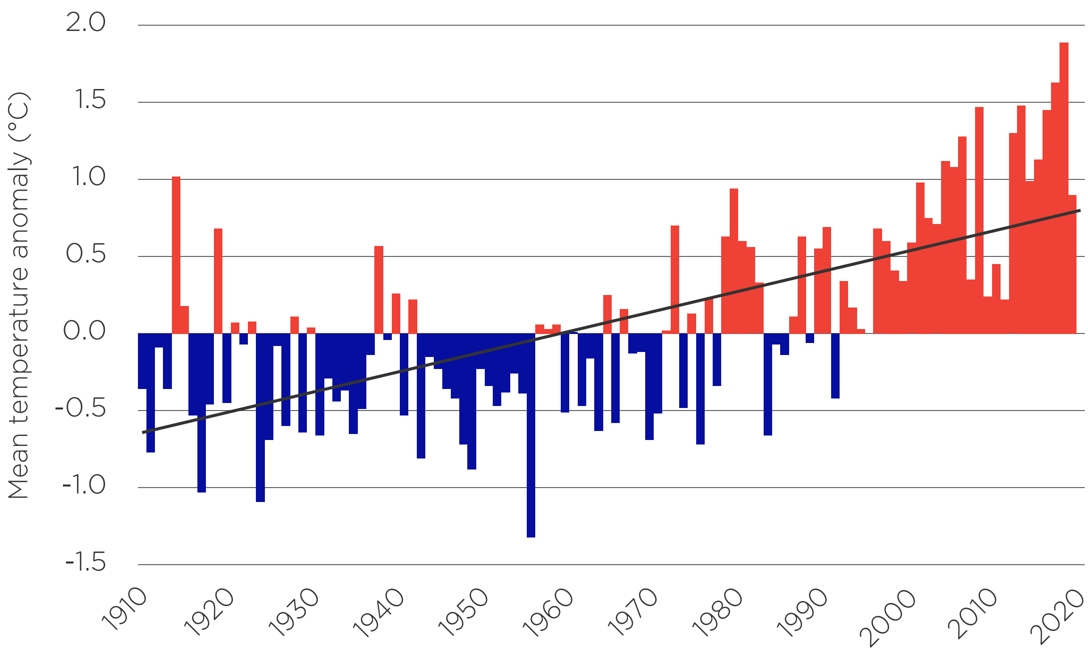

Figure 10 Annual mean temperature anomalies in NSW and the ACT compared with the 1961-90 average, with linear trend (0.13 °C per decade). Blue bars represent cooler-than-average years, while red bars are hotter-than-average years (Bureau of Meteorology)

A heatwave occurs when maximum and minimum temperatures remain unusually high for several days. They represent a significant hazard in Australia.

Heatwaves have increased in intensity, duration and frequency in parts of NSW and the ACT since 1911. The most significant increases in intensity have been along the Great Dividing Range and in parts of the state's far west. Almost the entire eastern seaboard and parts of the far west have experienced increases in the number of heatwaves each year and the annual frequency of heatwave days. There have been significant increases in the duration of heatwaves in southern coastal areas and parts of the far west.

With a variable climate, drought has been a constant and inevitable feature of the NSW landscape.

Rainfall

Since 1900, there have been large decadal variations in annual average rainfall, with an increasing trend of 5.27 mm per decade (Figure 11).

The region experienced drier conditions during much of the first half of the last century. Greater variability in annual rainfall occurred during the second half of the 1900s. The first decade of this century experienced below-average rainfall during the Millennium Drought period. The lowest rainfall total on record (251.5 mm) occurred in 2019.

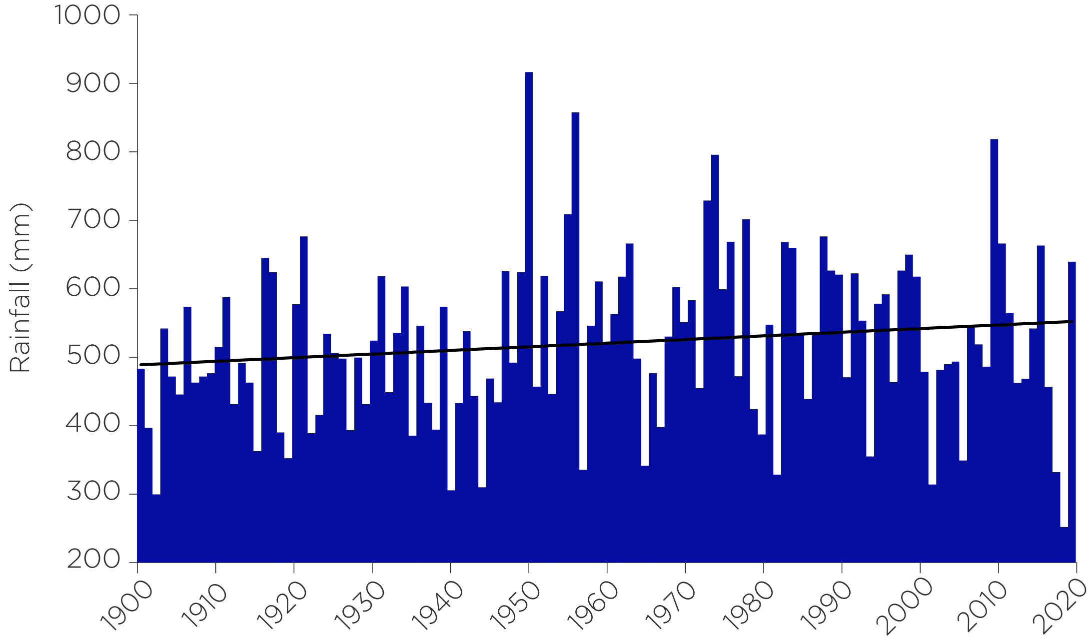

Figure 11 Annual rainfall for NSW and the ACT, 1900 to 2020, with linear trend (5.27 mm per decade) (Bureau of Meteorology)

Sea level

Sea level off Sydney rose prior to 1960, was quite stable between 1960 and 1990, and then began to rise at an increased rate.

Storm surge and king tides cause damage along the NSW coastline, exacerbated by higher sea levels.

Fire weather

Many areas across NSW and the ACT have experienced an increase in both average and extreme fire weather. Fire weather is classified as severe when the FFDI is above 50. Between 1973 and 2007, fire danger, as expressed by the annual sum of the FFDI, rose by between 10 and 40 per cent at many observation stations.

There has been a trend towards more dangerous conditions during summer and an earlier start to the fire season, particularly in parts of southern and eastern Australia. There has been an increase in the occurrence of extreme FFDI days in south-east Australia from the late 1990s, with up to 24 more extreme days per year. Researchers suggest that the increase in extreme FFDI days is contributing to potential increases in pyrocumulonimbus (thunderstorms that form in the convective plume of a fire).

The 2019–20 bushfire season was widespread and extreme. High temperatures and low moisture levels following several years of drought enabled devastating fires to burn across much of NSW, with intense bushfire weather conditions continuing through most of the fire season. The Black Summer bushfires caused 26 deaths, destroyed 2,448 homes and burnt 5.5 million hectares of land. The impact on communities, farmers, local businesses, wildlife and bushland was unprecedented.

Climate change projections

NSW and the ACT are experiencing climate change impacts, which vary across the region. The climate of NSW and the ACT is projected to continue to change in future.

In 2015, CSIRO and the Bureau of Meteorology released national projections of Australia's likely future climate through the Climate Change in Australia website. In addition, the NSW and ACT Governments, in conjunction with the University of New South Wales, have released state-based climate projections. The NSW and ACT Regional Climate Modelling (NARCLiM) project provides projections that are broadly consistent with the national projections, and at a higher resolution.

The projections presented here (Table 4) are largely based on the national projections, with some regional information from NARCLiM. The climate variables presented are those that are likely to affect Australia's electricity networks.

Scientific confidence in projections varies from variable to variable and, in some cases, from region to region.

Projections are typically for a range of years, such as 2040–59, referred to here as '2050'. Projections are relative to 1986–2005 (unless otherwise stated) and are provided for both a high emissions scenario (RCP8.5) and a low emissions scenario (RCP2.6) where available (Table 4).

Year by year and decade by decade, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall.

Figure 12 shows the likely change in the number of days with temperatures greater than 35 °C for the year 2070, for a range of emission scenarios. Figure 13 shows the likely change in the annual mean number of days with severe fire weather for 2070, for a range of emission scenarios.

Table 4 Climate change projections for NSW and the ACT.

Climate hazard	Projection
Temperature	**NSW and the ACT will continue to get hotter in future, with less warming on the coast and more warming inland.** • By 2050, under a high emissions scenario, the region can expect an average annual temperature increase of approximately 1.4 to 2.3 °C (central estimate of 1.9 °C). • By 2050, under a low emissions scenario, the region can expect an average annual temperature increase of approximately 0.7 to 1.4 °C (central estimate of 1.1 °C). **Heatwaves are projected to occur more often and last longer.** • NSW and the ACT are less likely to experience cold nights in the future. The decrease in the number of cold nights will occur across all seasons, with the largest decreases during winter and spring. **NSW and the ACT can expect longer fire seasons and more severe fire danger days.** • The increase in the number of days with severe fire danger is projected to occur primarily in summer and spring. • The increase in fire danger days is likely to lead to a corresponding increase in total fire ban days. • Severe fire weather is projected to increase across the region by 2070. The greatest increase in severe fire weather risk occurs in the far west of the region. The smallest increases occur along the coast and across the Great Dividing Range.
Precipitation	**Rainfall is expected to increase over most regions in autumn, with large regions experiencing decreases in rainfall during spring.** • Rainfall projections in NSW and the ACT vary by season and region. • Winter rainfall is projected to decrease across the ACT, with some NSW regions also experiencing decreased rainfall in winter, especially along the coast. • Extreme rain events are projected to become more intense across the region. **East Australia is likely to spend more time in drought under a high emissions scenario.** • An increase in frequency and duration of extreme drought under a high emissions scenario is possible.
Sea level	**By 2050, sea level is projected to rise by around 27 cm along the NSW coast.** • Sea-level rise can lead to higher storm surge and inundation levels.

Climate hazard	Projection
Lightning and storms	**The frequency and intensity of storms in NSW and the ACT are likely to be affected by climate change.** • NSW may experience increases in some thunderstorm hazards including convective rainfall extremes. • The ACT storm season is projected to extend from spring into autumn. • Uncertainties exist for future changes in lightning and storms in NSW and the ACT, although an increase in the intensity of storms is expected.
Wind	**By 2090, wind speeds are projected to decrease in southern mainland Australia in winter and south-eastern mainland Australia in autumn and spring.** • Winter decreases are not expected to exceed 10 per cent under a high emissions scenario. • Projected changes in extreme wind speeds are generally similar to those for mean wind. • By 2050, east coast lows are projected to decrease by up to 20 per cent under a high emissions scenario, primarily due to a reduction of events during winter. However, there are pockets of NSW where there may be increases. • In the warmer months, extreme east coast lows may increase in number. • Tropical cyclones are projected to become less frequent, but with a greater proportion of high-intensity storms, with stronger winds and greater rainfall.
Compound extreme events	**A changing climate may bring more compound extreme events.** • Multiple lines of evidence, including from observations and climate projections, point to a continuing trend of more frequent compound extreme events. • While there are no specific projections for future occurrences of compound extremes in NSW and the ACT, it would be prudent to plan for increases in some compound extreme events.
Other climate-related variables	**Snow and frost** • In alpine regions, an increase in snowmelt, especially at low latitudes, is projected along with a decline in snowfall. • There will be a large decrease in suitable temperatures for artificial snowmaking, especially later this century, in the NSW and ACT alpine region. • Possible reductions in frost days in the ACT are projected by mid-century under a high emissions scenario. **Solar radiation** • Possible increase in winter and spring sunshine is projected in southern Australia by 2090 under a high emissions scenario (low confidence), with little change in other seasons. **Humidity** • Humidity is likely to decline across inland regions and in areas where rainfall is projected to decline by 2090 under a high emissions scenario. Decreases are likely to be small.

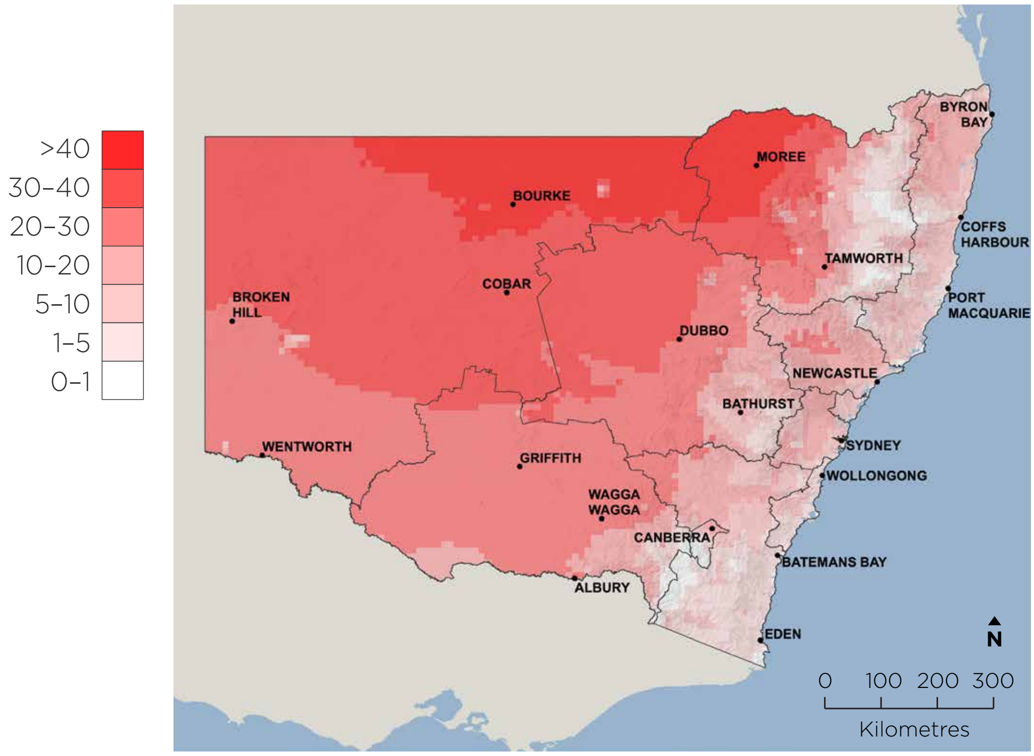

Figure 12 Change in the number of days with temperatures greater than 35 °C for around the year 2070, for a range of emission scenarios (NARCLIM (2014). *NSW and ACT Regional Climate Modelling*.).

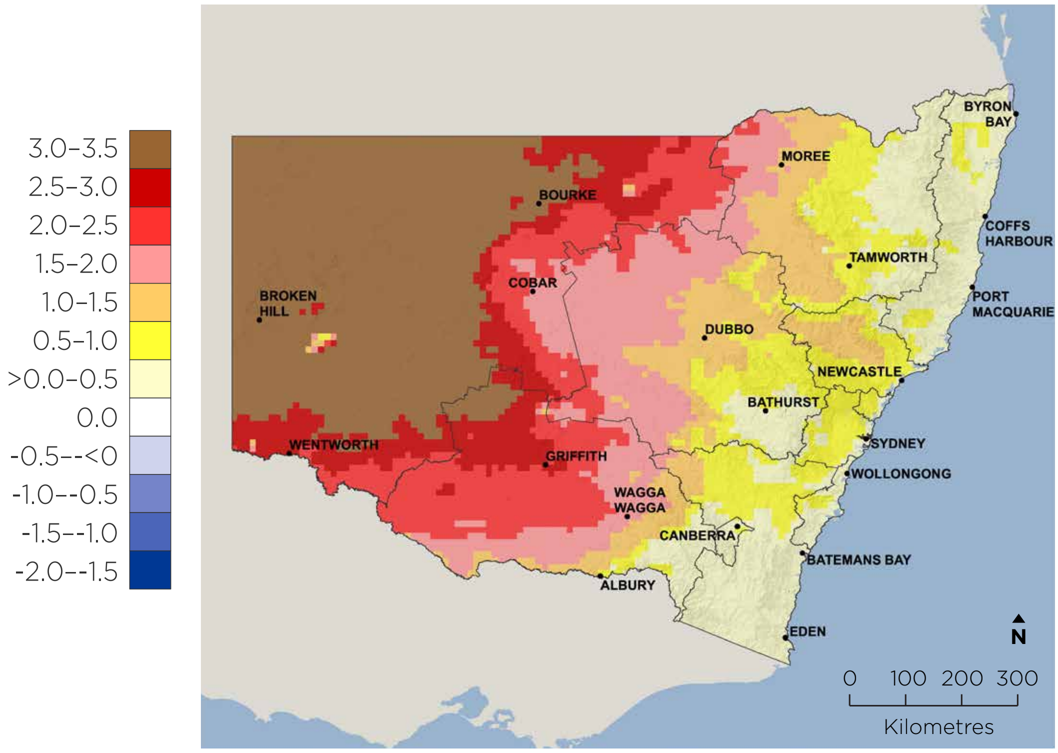

Figure 13 Change in annual mean number of severe fire weather days (i.e., days with an FFDI greater than 50) for around the year 2070, for a range of emission scenarios (NARCLIM (2014). *NSW and ACT Regional Climate Modelling*)

City projections

Sydney

Fringed by the Tasman Sea to the east, the Blue Mountains to the west, the Hawkesbury River to the north and the Woronora Plateau to the south, Sydney covers over 12,000 square kilometres. The complex topography of the region and its coastal setting create climatic variations across the city.

Average temperature in Sydney is projected to continue to increase in all seasons. Maximum temperatures are projected to increase by 0.3 to 1.0 °C around 2030 and by 1.6 to 2.5 °C around 2070, compared with the 1990–2009 average. There will be more hot days and warm spells, and fewer cold nights and frosts. Sydney is likely to experience more than double the number of days exceeding 35 °C by 2050, increasing from four to eight days per year.

Decreases in winter rainfall are likely, with increased intensity of extreme daily rainfall events.

Mean sea level will continue to rise and the height of extreme sea-level events will also increase.

Increased evapotranspiration is projected. Potential evapotranspiration can be regarded as the maximum possible evaporation rate that would occur under particular meteorological conditions if water sources were available.

Fire-weather climate is projected to become harsher.

By 2050, under a high emissions scenario, the climate of Sydney is projected to be more like the current climate of Grafton (about 600 km north of Sydney).

Canberra

Canberra, situated at the northern tip of the Australian Alps, has an elevation of approximately 580 metres above sea level.

Average temperature in Canberra is projected to continue to increase in all seasons. There will be more hot days and warm spells, and fewer cold nights and frosts. Canberra is likely to experience more than double the number of days exceeding 35 °C by 2050, increasing from six to 14 days per year.

By late in the century, rainfall is likely to decline during the winter and spring, with summer and autumn rainfall likely to remain unchanged. Extreme daily rainfall intensity is projected to increase.

Increased evapotranspiration is projected, and severe and average fire weather is projected to increase.

By 2050, under a high emissions scenario, the climate of Canberra is projected to be more like the current climate of Albury-Wodonga.

Projections for variables of interest

Figure 14 summarises the changes likely to occur across NSW and the ACT. These changes will be accompanied by year-to-year and decade-to-decade variability.

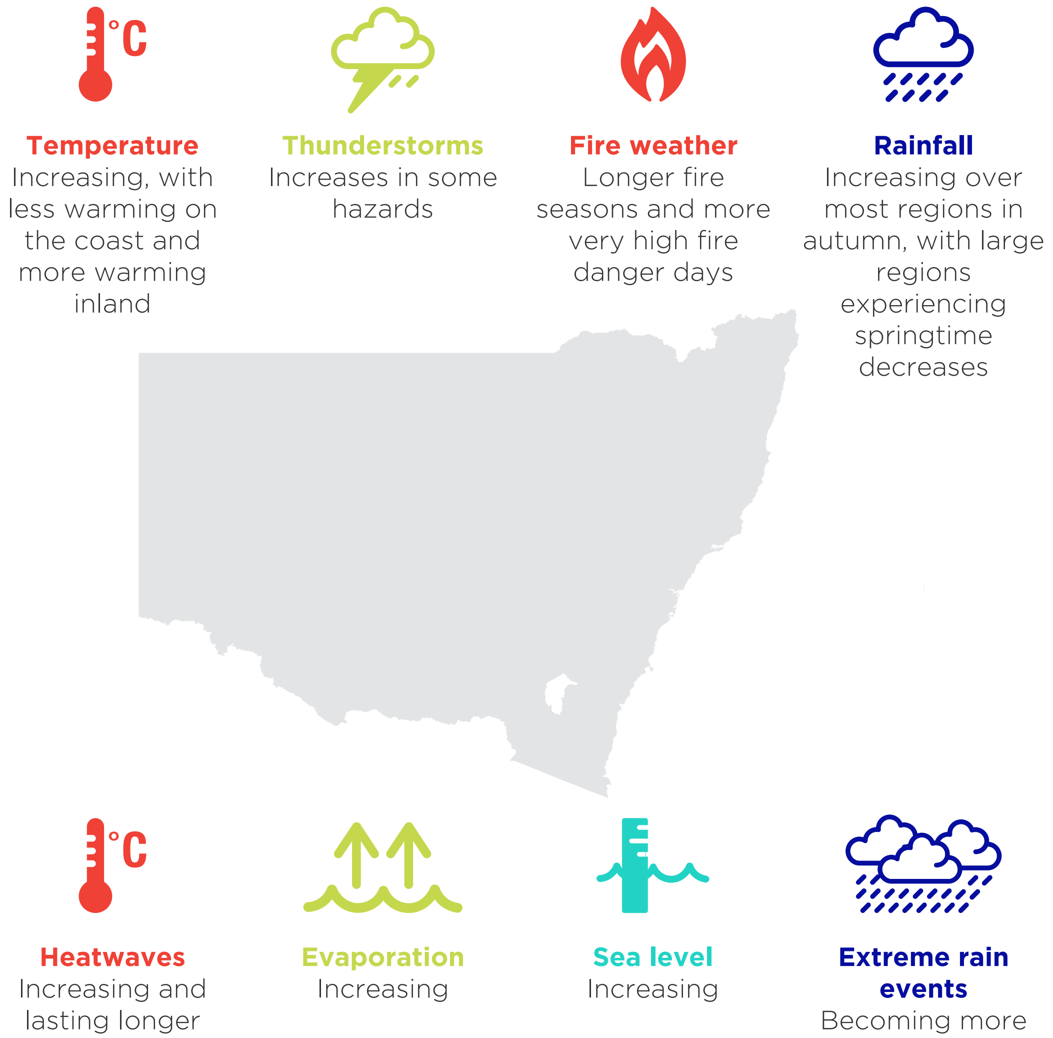

Figure 14 Projected changes across NSW and the ACT

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Appendix B. Climate change in the Northern Territory

This appendix presents information about the past, current and likely future climate of the Northern Territory.

The Northern Territory is already experiencing the impacts of climate change, with temperatures rising, an increase in annual average rainfall, more days with dangerous weather conditions for bushfires during the dry season, and fewer cold days.

The Northern Territory's climate will continue to change in future. Included in this appendix are projections for temperature, fire weather, precipitation, sea-level rise, tropical cyclones and other climate-related hazards. There is information for the Territory, as well as specific projections for Darwin and Alice Springs.

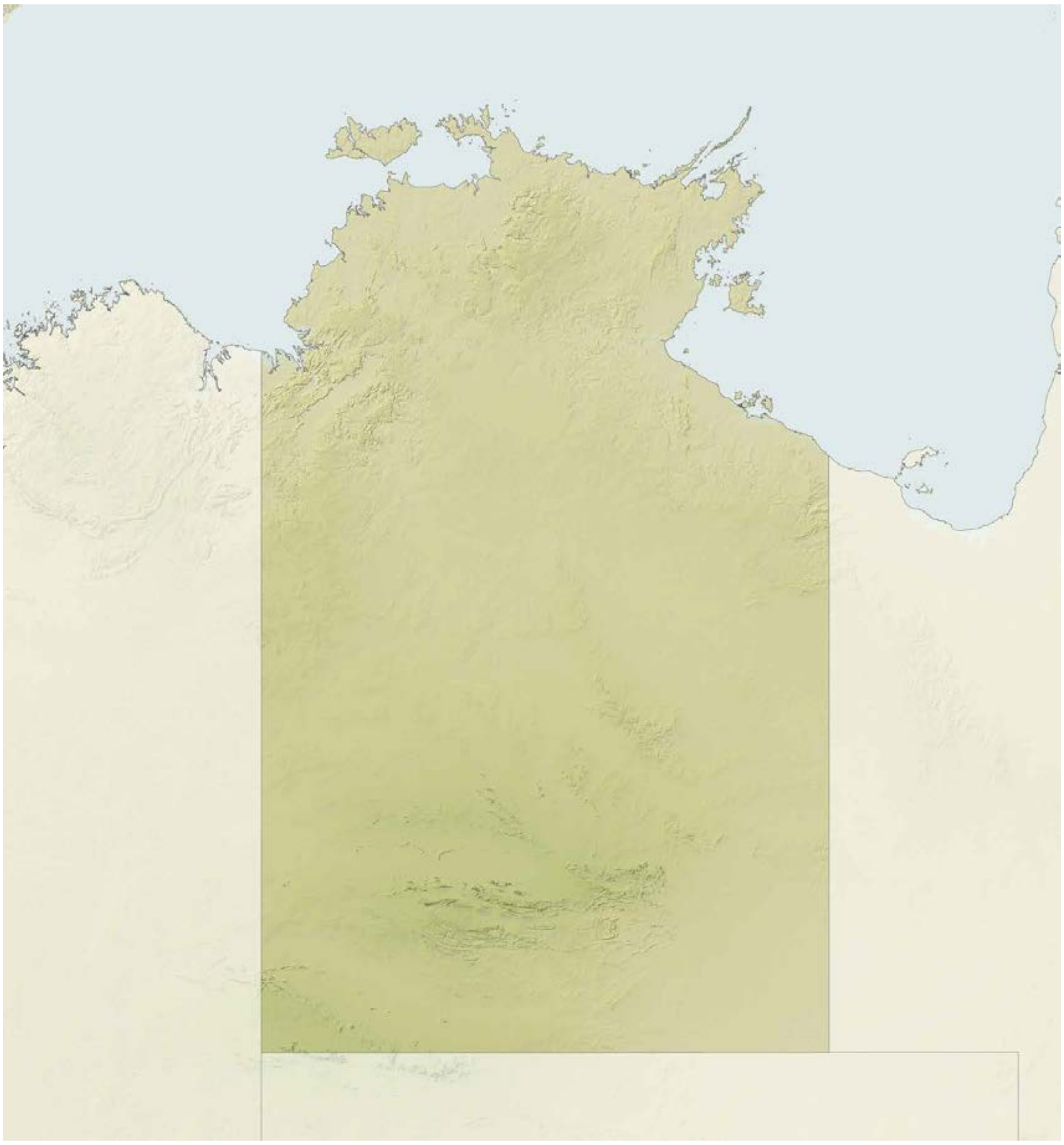


Figure 15 Topographic map of the Northern Territory

Climate of the Northern Territory

The Northern Territory has three distinct climate zones. The tropical north (the Top End) experiences a hot, humid wet season from November to April and a milder dry season from May to October. The central part of the Territory experiences hot, dry summers and mild winters. In the south, summers are also hot and dry, but winters can be cold.

In the north, average daily temperatures range from 15 to 33 °C in the dry season and 21 to 36 °C in the wet season. The central region of the Territory has average daily temperatures ranging from 21 to 39 °C in summer and 6 to 24 °C in winter. In the south of the Territory, average daily temperatures range from 18 to 39 °C in summer and 3 to 27 °C in winter.

On average, there are three tropical cyclones each wet season that affect the Northern Territory. Tropical cyclones contribute significantly to Top End rainfall. During the wet season, there are frequent thunderstorms in the Top End.

Rainfall varies significantly from year to year. The Top End receives 600 to 1800 mm of rain in the wet season, but only 100 to 400 mm in the dry season. Rain falls all year in the central and southern parts of the Territory, but winter is the driest season with an average of 50 to 100 mm rainfall in the central part of the Territory and 100 to 200 mm in the south. In summer, average daily rainfall in the central region ranges from 400 to 900 mm and 200 to 400 mm in the south. Figure 16 shows average annual rainfall over the Northern Territory.

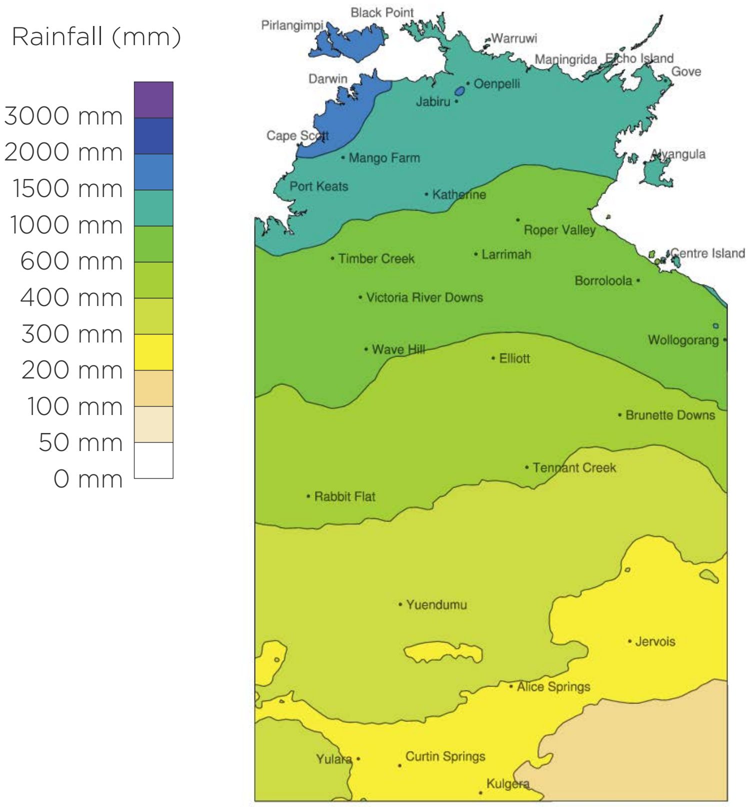


Figure 16 Average annual rainfall (mm) over the Northern Territory for 1981 to 2010 (Bureau of Meteorology)

The Northern Territory has experienced periods of extended dry conditions. Drought occurs all over the Territory, with the south more prone to drought than the north.

Bushfire occurrence relies on having an ignition source, fuel availability, fuel dryness and suitable fire weather. In the north, the most dangerous fire weather conditions occur in the dry season. In the central and southern regions, spring conditions are most conducive to bushfires.

Various weather systems and large-scale climate drivers (Figure 3) determine the Northern Territory's climate, including:

- the monsoon: the monsoon is responsible for much of the Top End's wet season rainfall. It typically lasts from late December to April, but this changes from year to year.
- the El Niño – Southern Oscillation: ENSO influences rainfall, temperatures and tropical cyclones. El Niño brings reduced rainfall in the monsoon build-up and fewer tropical cyclones. La Niña creates increased rainfall in the build-up months.
- the Indian Ocean Dipole: the positive phase of the IOD leads to dry build-up months in the Top End. In a negative IOD there is higher rainfall over the central Northern Territory in spring and higher rainfall in the north during the early wet season.

Past and recent climate

Temperature

The Northern Territory has warmed, with the average annual temperature increasing by 1.5 °C since 1910 (Figure 17). Annual maximum and minimum temperatures have also risen since 1910, and extreme temperatures have become more common. The 2011–20 average temperature was around 0.7 °C above the 1961–1990 average.

Most of the warmest years on record have occurred since 1979, and the two warmest years on record occurred in the past ten years. In contrast, most of the coolest years occurred before 1979. The two coolest years on record occurred before 1950.

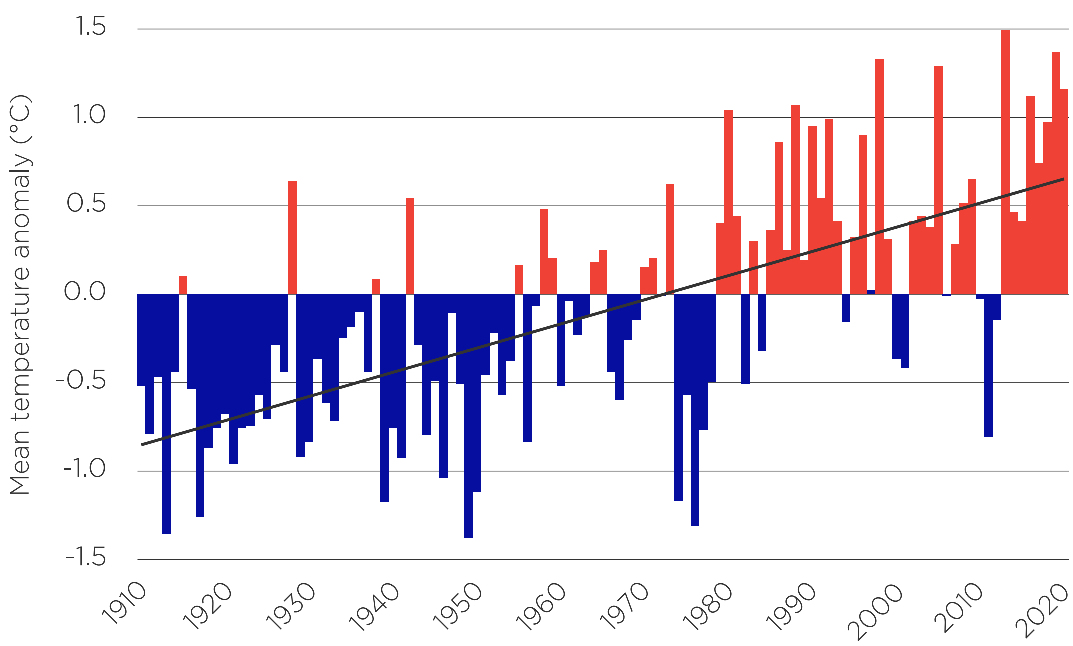


Figure 17 Annual mean temperature anomalies in the Northern Territory compared with the 1961-90 average, with linear trend (0.14 °C per decade). Blue bars represent cooler-than-average years, while red bars are hotter-than-average years (Bureau of Meteorology)

Rainfall

Rainfall across the Northern Territory increased by 26 per cent from 1900 to 2020. Figure 18 highlights the upward trend and the significant variability in annual rainfall.

There have been changes in seasonal rainfall. Wet season rainfall has increased over the Top End. The annual average amount of rainfall at Alice Springs remained relatively constant between 1959–1988 and 1989–2018, although the seasonal distribution has changed, with more summer rainfall and less in March and winter.

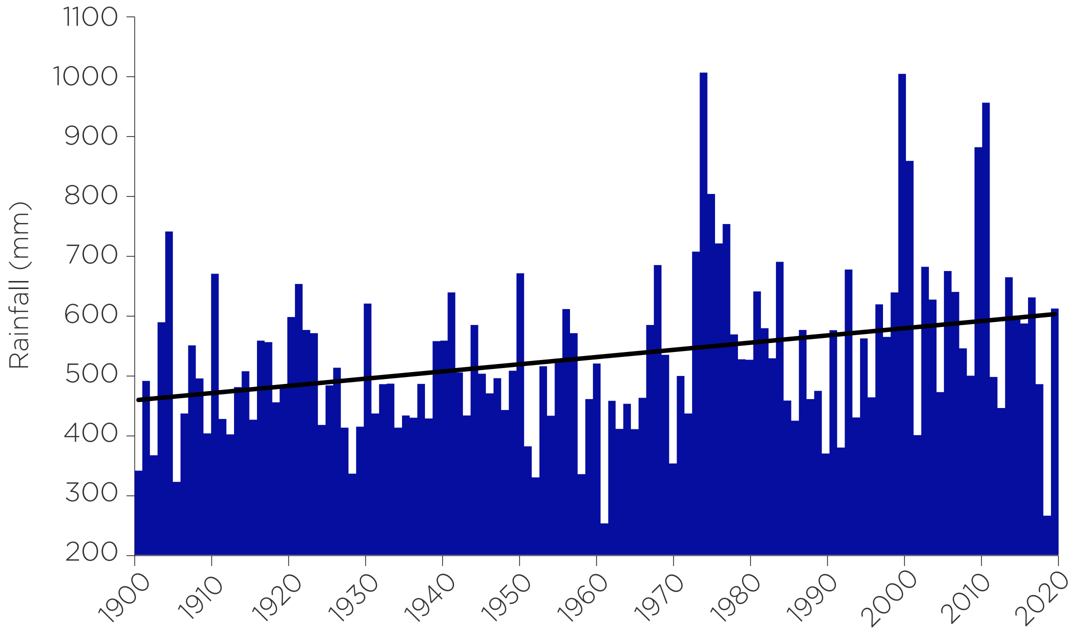


Figure 18 Annual rainfall for the Northern Territory, 1900 to 2020, with linear trend (11.97 mm per decade) (Bureau of Meteorology)

Sea level

The sea level around the Northern Territory coastline has risen at a higher rate since the early 1990s than much of the rest of the country, due to a combination of natural climate variability and climate change (Figure 19).

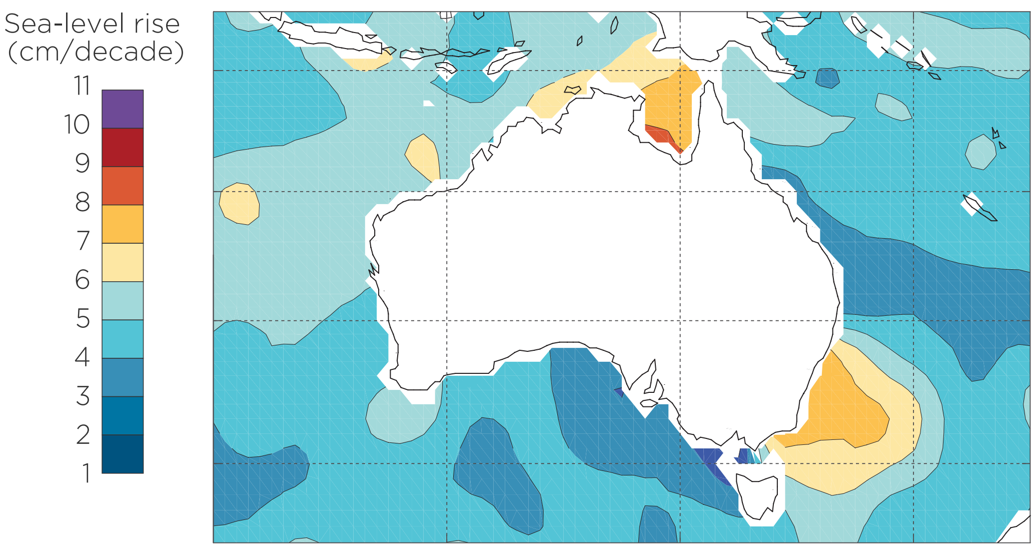


Figure 19 The rate of sea-level rise (cm per decade) around Australia based on satellite observations for 1993–2017 (ESCC Hub (2020). *Climate change in the Northern Territory: state of the science and climate change impacts*. NESP ESCC Hub)

Fire weather

Increases in monsoonal rainfall before the dry season have helped to increase fuel growth in recent decades. This is a key factor influencing fire danger in the region. Over the past 30 years or so, the number of days with severe fire weather has increased during the dry season (winter and spring) (Figure 20).

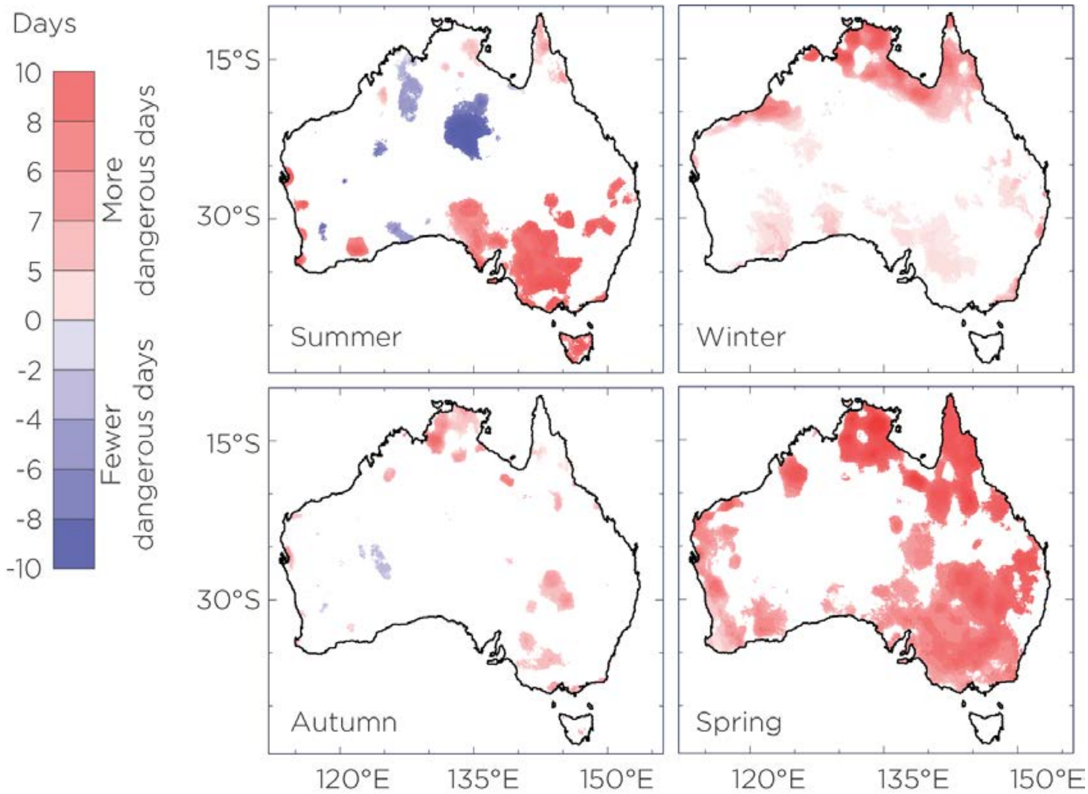


Figure 20 The number of fire weather days in the period 2000–2016 compared with 1983–1999 (ESCC Hub (2020). *Climate change in the Northern Territory: state of the science and climate change impacts*. NESP ESCC Hub)

Evaporation

Evaporation rates have largely remained unchanged in the Top End. In the central part of the Territory it has decreased, while spring and autumn potential evaporation rates at Alice Springs have increased by 10 to 20 mm for each month in the past 30 years (1989–2018) compared with the previous 30 years (1959–1988).

Tropical cyclones

The number of tropical cyclones across the Australian region has been declining since formal records began. However, over the Northern Territory there has been no discernible trend.

Climate change projections

The Northern Territory is already experiencing the impacts of climate change. The Territory's climate is projected to continue to change in future.

In 2015, CSIRO and the Bureau of Meteorology released national projections of Australia's likely future climate through the Climate Change in Australia website. In 2020, the National Environmental Science Program's Earth Systems and Climate Change Hub prepared a report for the Northern Territory Government on climate change in the Territory.

The projections presented here (Table 5) are largely based on the national projections, with some additional information from the Earth Systems and Climate Change Hub. The climate variables presented are those that are likely to affect Australia's electricity networks.

Scientific confidence in projections varies from variable to variable and, in some cases, from region to region.

Projections are typically for a range of years, such as 2040–59, referred to here as '2050'. Projections are relative to 1986–2005 (unless otherwise stated) and are provided for both a high emissions scenario (RCP8.5) and a low emissions scenario (RCP2.6), where available (Table 5).

Year by year and decade by decade, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall.

Table 5 Climate change projections for the Northern Territory.

Climate hazard	Projection
Temperature	**The Northern Territory will continue to get hotter in future.** • By 2050, under a high emissions scenario, the Northern Territory can expect an average annual temperature increase of approximately 1.5 to 2.5 °C (central estimate of 2.0 °C). • By 2050, under a low emissions scenario, the Northern Territory can expect an average annual temperature increase of approximately 0.8 to 1.7 °C (central estimate of 1.1 °C). • By 2090, Top End warming will range from 0.6 to 1.8 °C under low emissions and 2.8 to 5.1 °C under a high emissions scenario. **Extreme temperatures are becoming more common in the Northern Territory.** • The hottest days are projected to be hotter and more frequent. • Warm spells are projected to be longer. **The Northern Territory can expect a harsher fire weather climate in future.** • In the southern and central parts of the Territory, when bushfires occur, more extreme fire behaviour can be expected. • In the Top End, where abundant rainfall and bushfires are common, there is projected to be little change to fire frequency.
Precipitation	**Projected change in average annual rainfall for the Northern Territory is unclear, although significant change is possible.** • For the near future, natural variability is likely to cause greater year-to-year changes in rainfall than the effects of climate change. • Later in the century, both wetter and drier futures are plausible. Both wetter and drier futures should therefore be considered, especially in the monsoon region. • Heavy rainfall events are likely to become more intense. • The frequency and intensity of droughts may change, and time spent in drought may increase.
Sea level	**By 2050, sea levels are projected to rise by around 24 cm along the coast of the Northern Territory.** • The height of extreme sea-level events will increase. • Sea-level rise can also lead to higher projected storm surge and inundation levels. Combined with increased rainfall intensity, higher sea levels are likely to lead to an increase in the frequency and magnitude of flooding in many coastal and estuarine regions.
Lightning and storms	**The Northern Territory is likely to experience shifting storm patterns.** • Changes in storms and lightning are uncertain as scientists are unable to directly model thunderstorm activity due to its local and temporal scale.

Climate hazard	Projection
Wind	**Wind speed is projected to increase in tropical areas across northern Australia.** • Projections of extreme wind are generally consistent with those for mean winds. • Changes in wind speed are likely to be small.
Tropical cyclones	**The number of tropical cyclones is projected to decrease by about 10 per cent.** • Tropical cyclones may reach slightly further south. • Rainfall produced by tropical cyclones is expected to increase, particularly the intensity of extreme rainfall events. • The combination of sea-level rise, greater wind speeds and more intense rainfall may exacerbate coastal impacts due to tropical cyclones.
Compound extreme events	**A changing climate may bring more compound extreme events.** • Multiple lines of evidence, including from observations and climate projections, point to a continuing trend of more frequent compound extreme events. • While there are no specific projections for future occurrences of compound extremes in the Northern Territory, it would be prudent to plan for increases in some compound extreme events.
Other climate-related variables	**Evaporation** • Evaporation is likely to increase. **Humidity** • By the end of the century, relative humidity is likely to decrease. **Frost** • Frost risk days will decrease over time. • The number of frost risk days in Alice Springs is expected to be halved by the middle of the century under a high emissions scenario.

City and town projections

Darwin

Darwin is situated on a low peninsula north-east of the entrance to Port Darwin.

Average temperature in Darwin is projected to continue to increase in all seasons, and there will be more hot days and warm spells.

Changes to annual and seasonal rainfall are possible, but unclear. Heavy rainfall events are likely to become more intense. Increased evapotranspiration is projected.

Mean sea level will continue to rise, as will the height of extreme sea-level events.

Fewer, but more intense, tropical cyclones are projected by the end of the century, with notable year-to-year and decadal variability.

By 2050, under a high emissions scenario, Darwin's climate is projected to be more like the current climate of Jabiru.

Alice Springs

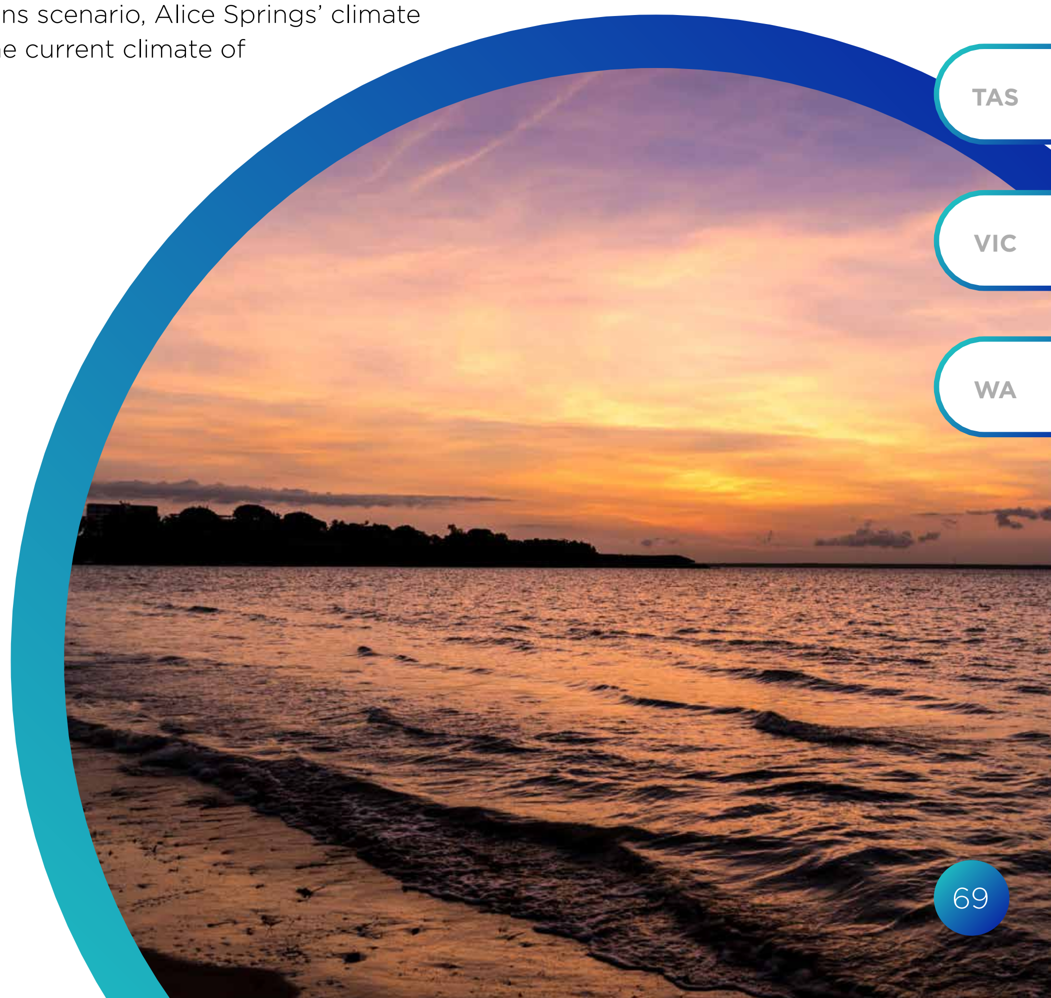
Alice Springs is 1,500 kilometres to the south of Darwin, in the interior desert region.

Average temperatures will continue to increase across all seasons, and there will be more hot days and warm spells.

Changes to annual and seasonal rainfall are possible but unclear. Heavy rainfall events are likely to become more intense. Increased evapotranspiration is projected.

By 2050, under a high emission scenario, the number of very hot days (days over 40 °C) is projected to increase from approximately 14 to 48 days per year.

By 2050 under a high emissions scenario, Alice Springs' climate is projected to be more like the current climate of Warburton, WA.



Projections for variables of interest

Figure 21 summarises the changes likely to occur across the Northern Territory. These changes will be accompanied by year-to-year and decade-to-decade variability.

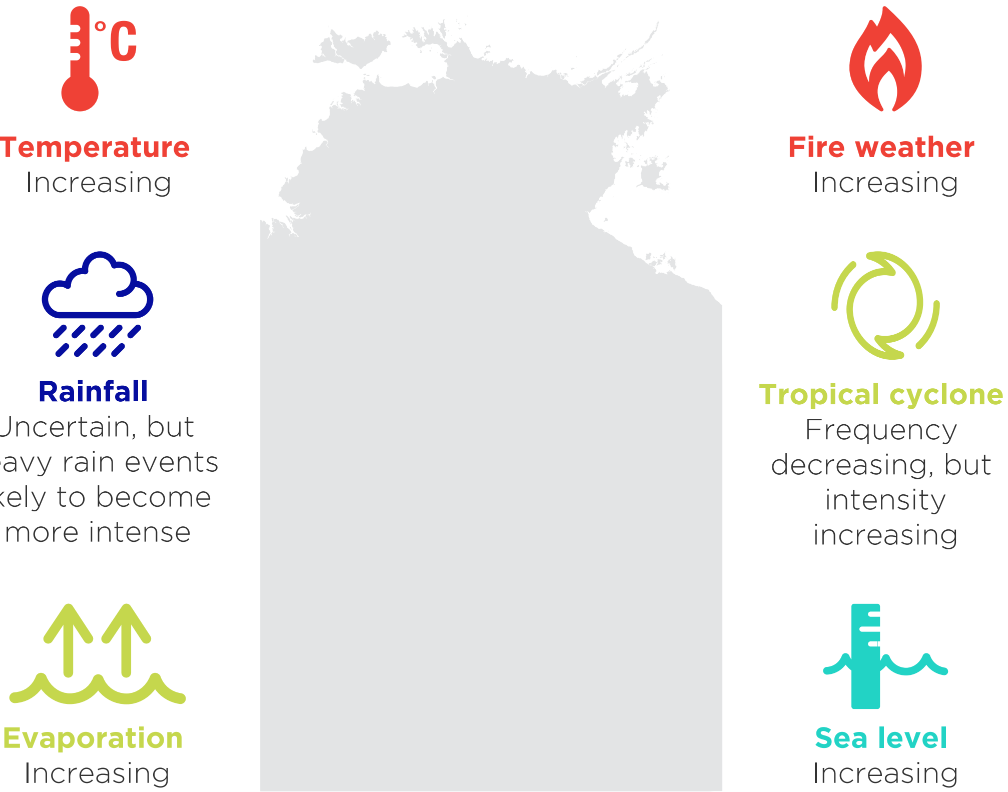


Figure 21 Projected changes across the Northern Territory

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Appendix C. Climate change in Queensland

This appendix presents information about the past, current and likely future climate of Queensland.

Queensland is already experiencing the impacts of climate change, with temperatures rising, heatwaves increasing in frequency, and increases in the number of days with dangerous bushfire weather conditions.

The climate of Queensland will continue to change in future. Included in this appendix are projections for temperature, precipitation, sea-level rise, fire weather, wind and other climate-related hazards. There is information for the state, as well as specific projections for Brisbane and Cairns.

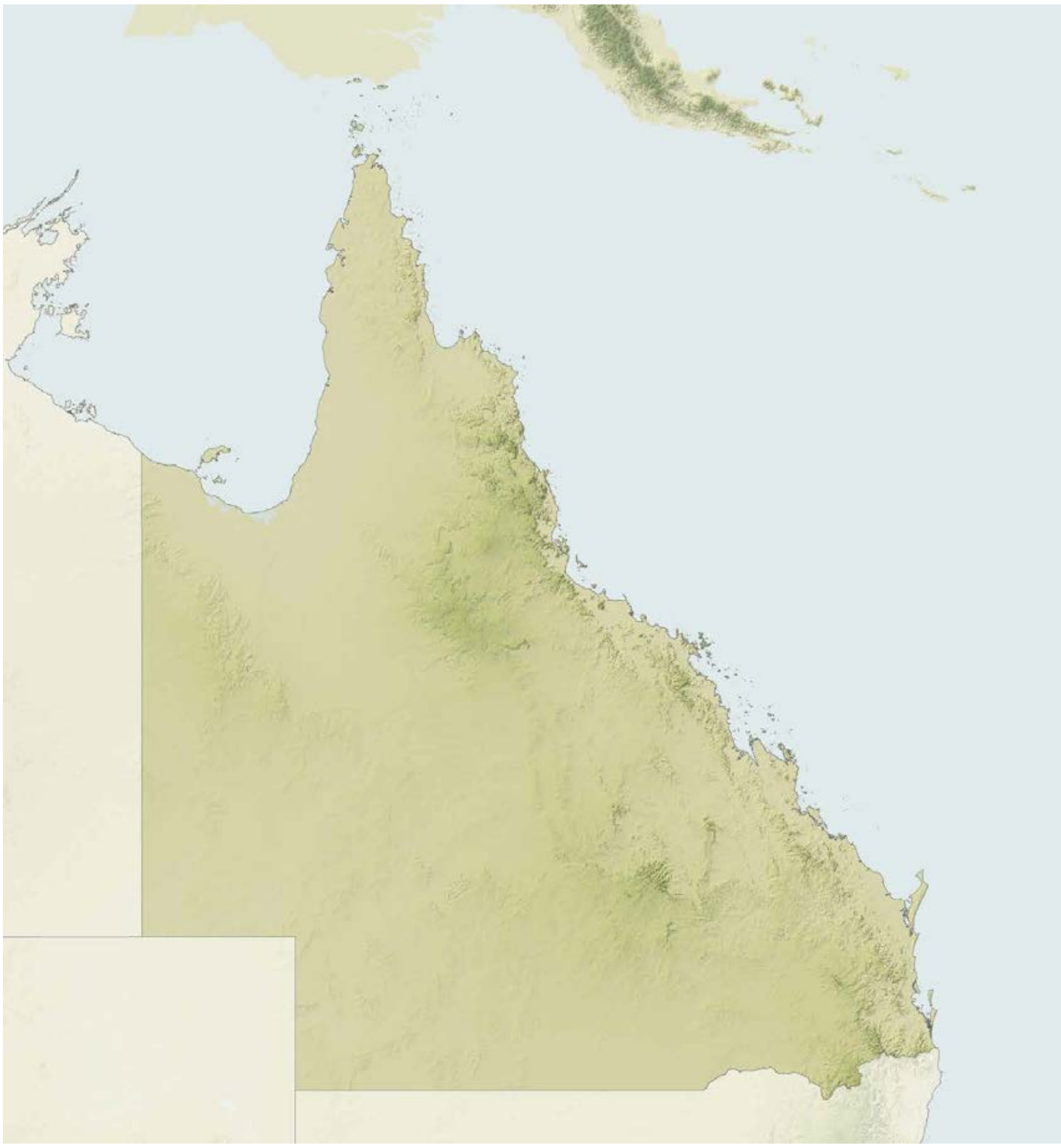

Figure 22 Topographic map of Queensland

Climate of Queensland

Queensland experiences great variations in climate, from the temperate south to the tropical north and the arid west.

South-east Queensland, which includes Brisbane and the Gold and Sunshine Coasts, experiences warm summers. The climate of the Cape York region is tropical, with high to very high temperatures throughout the year. Western Queensland has a semi-arid to arid climate with very hot summers and warm, dry winters.

Annual and seasonal average rainfall are variable, affected by local factors such as topography and vegetation, and broader scale weather patterns, such as the El Niño – Southern Oscillation.

Most of Queensland's rainfall occurs in summer. The total summer rainfall in southern Queensland often exceeds 500 mm. The north is much wetter, with annual rainfall of over 1,000 mm. Arid areas in the west have annual rainfall below 400 mm.

Pacific south-easterly trade winds produce rainfall along the eastern coast throughout the year. Tropical cyclones bring significant rainfall to the north.

Climatic conditions can change greatly from year to year in response to large-scale phenomena (Figure 3), including:

- the subtropical ridge: this extensive area of high pressure moves north in winter, resulting in drier conditions over Queensland.
- east coast lows: these intense low-pressure systems off the eastern coast bring strong and gusty winds, sustained heavy rainfall and high seas.
- the El Niño – Southern Oscillation: El Niño events often lead to less rainfall in the region; its counterpart, La Niña, is associated with warm surface waters in the western Pacific and often brings above-average winter and spring rainfall over much of Australia.
- the Indian Ocean Dipole: changes in sea-surface temperature patterns in the northern Indian Ocean and waters to the north of Australia can affect Australia's rainfall; positive IOD conditions can result in lower rainfall in much of Queensland.
- the Madden-Julian Oscillation: a large-scale slow-moving band of increased wind, cloudiness and rainfall that travels eastwards in the tropics. The MJO can occur at any time of the year but influences northern Australia mostly during the wet season. It can drive bursts and breaks in monsoon, and it can also influence the timing of the onset of the monsoon.

Past and recent climate

Temperature

All of Queensland has warmed since 1910. Average annual temperature has increased by 1.5 °C since 1910 (Figure 23). The 2011–2020 average temperature was around 1.1 °C above the 1961–1990 average. The hottest year on record for the region was 2017.

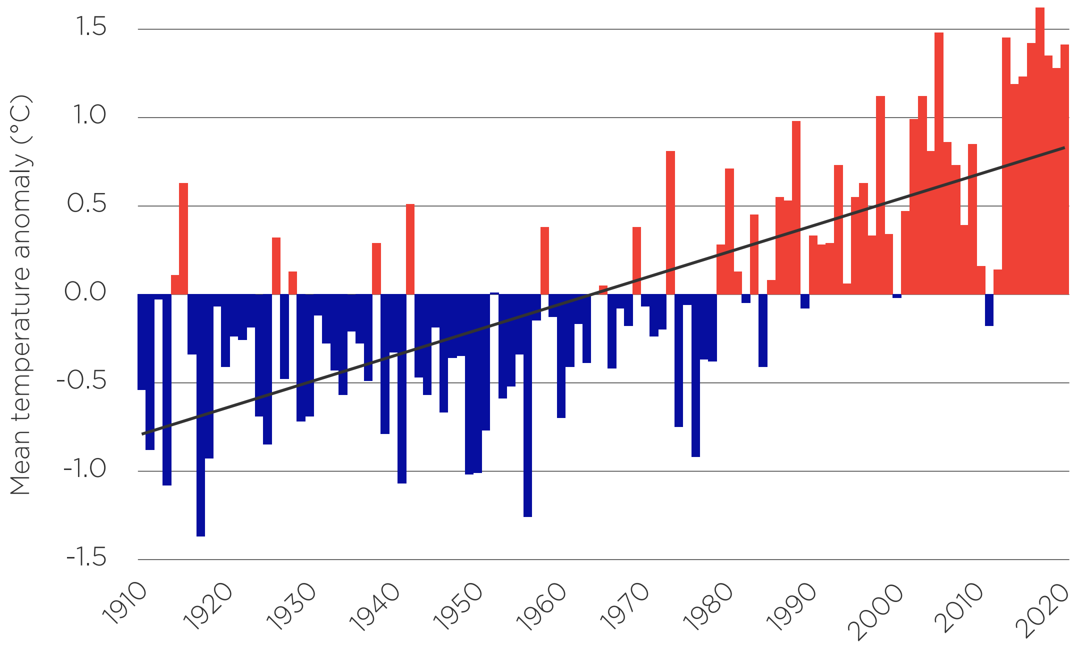

Figure 23 Annual mean temperature anomalies in Queensland compared with the 1961-90 average, with linear trend (0.15 °C per decade). Blue bars represent cooler-than-average years, while red bars are hotter-than-average years (Bureau of Meteorology)

A heatwave occurs when maximum and minimum temperatures remain unusually high for several days. They represent a significant hazard in Australia.

Since 1958, there has been an increase in the occurrence of heatwaves in Queensland. Between 1986 and 2015, a substantial proportion of the state has experienced an average of three heatwaves per year.

Rainfall

There have been large decadal variations in annual average rainfall since 1900 (Figure 24). During this period, wet season rainfall has increased over most of Queensland, while dry season rainfall has declined.

Drier than normal conditions prevailed in many inland and southern parts of Queensland between 2013 and 2019.

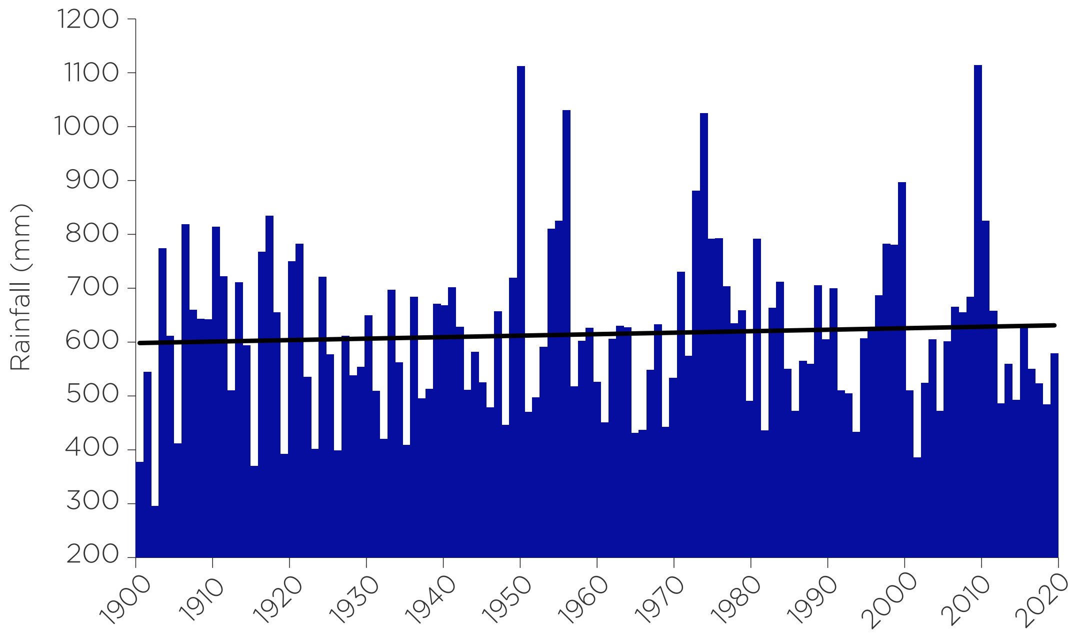

Figure 24 Annual rainfall for Queensland, 1900 to 2021, with linear trend (2.9 mm per decade) (Bureau of Meteorology)

Tropical cyclones

During La Niña, there are typically more tropical cyclones in the Australian region, with twice as many making landfall than during El Niño years on average. The only years with multiple severe tropical cyclone landfalls in Queensland have been La Niña years.

The number of tropical cyclones recorded in the Australian region has decreased significantly in recent decades. The number of severe tropical cyclones making landfall over north-eastern Australia, from near Cairns to northern NSW approximately 1,500 km further south, has declined since the late 19th century.

Ex-tropical cyclones can also cause severe damage. In January 2022, ex-Tropical Cyclone Seth caused heavy rain and flooding along the Wide Bay and Fraser Coast regions, also affecting inland centres, causing damage to buildings and equipment.

Fire weather

The number of days with dangerous weather conditions for bushfires has increased in nearly all locations across the state.

The 2019 bushfire season in Queensland was catastrophic. Bushfires affected over 7.7 million hectares in Queensland between September and December 2019, destroying homes and businesses, and causing disastrous consequences for residents, primary producers, agriculture and the environment. At the height of the season, Queensland Fire and Emergency Services dealt with more than 90 bushfires.

Sea level

Sea level has been measured at Queensland ports since around 1890.

Rates of sea-level rise vary across the Australian region. Based on satellite altimetry observations since 1993, the rates of sea-level rise to the north of Australia have been significantly higher than the global average. Global average sea-level rise increased from 1.5 ± 0.2 cm per decade (1901–2000) to 3.5 ± 0.4 cm per decade (1993–2019).

Climate change projections

Queensland is already experiencing the impacts of climate change, which vary across the state. Queensland's climate is projected to continue to change in future.

In 2015, CSIRO and the Bureau of Meteorology released national projections of Australia's likely future climate through the Climate Change in Australia website. In addition, the Queensland Department of Environment and Science provides state-based climate projections through the Long Paddock portal. These state-based projections are provided at a higher resolution than the national projections and may better represent regional climate. While the methodologies for producing the national and state-based projections differ, the resulting information about the changing climate is broadly consistent, but with some regional differences.

Within the Long Paddock portal, the Queensland Future Climate Dashboard provides climate projection, heatwave and rainfall information. The dashboard allows users to explore, visualise and download the latest high-resolution climate modelling data for specific regions, catchments, disaster areas, local government areas and model grid squares.

The projections presented here (Table 6) are based on the national projections and those from the Queensland Future Climate Dashboard. The climate variables presented are those that are likely to affect Australia's electricity networks.

Scientific confidence in projections varies from variable to variable and, in some cases, from region to region.

Projections are typically for a range of years, such as 2040–59, referred to here as '2050'. Projections are relative to 1986–2005 (unless otherwise stated) and are provided for both a high emissions scenario (RCP8.5) and a low emissions scenario (RCP2.6) where available (Table 6).

Year by year and decade by decade, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall.

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Table 6 Climate change projections for Queensland.

Climate hazard	Projection
Temperature	**Queensland will continue to get hotter.** • By 2050, under a high emissions scenario, the region can expect an average annual temperature increase of approximately 1.3 to 2.5 °C (central estimate of 1.9 °C). • By 2050, under a low emissions scenario, the region can expect an average annual temperature increase of approximately 0.7 to 1.7 °C (central estimate of 1.2 °C). • Maximum, minimum and average temperatures are likely to continue to rise. **An increase in hot spells is projected.** • There is likely to be an increase in the temperature reached on the hottest days, and an increase in the frequency of hot days. **Queensland can expect longer fire seasons and more severe fire danger days.**
Precipitation	**South-east Queensland is likely to become drier during winter-spring.** • Average annual rainfall change is unclear in the monsoon region, with significant change possible. Both wetter and drier futures should be considered. • Extreme rain events are projected to become more intense. **By late this century, under a high emissions scenario, it is likely that the south of the state will experience more time in drought.**
Sea level	**By 2050, sea levels are projected to rise by around 26 cm along the Queensland coast.** • Sea-level rise can lead to higher storm surge and inundation levels.
Tropical cyclones	**Tropical cyclones are projected to become less frequent, but the proportion of the most intense storms is projected to increase.** • The number of tropical cyclones is projected to decrease by about 8 per cent by 2050.
Lightning and storms	**Projections of storms and lightning are uncertain.** • Some projections indicate an increase in the frequency of severe thunderstorm environments for parts of eastern Australia. • Lightning and storms may increase in frequency for tropical Australia. • Changes in storms and lightning are uncertain as researchers are unable to directly model thunderstorm activity due to its local and temporal scale.
Wind	**Wind speeds are projected to slightly increase.** • East coast lows, which occur in southern Queensland, are projected to decrease by up to 20 per cent by 2050 under a high emissions scenario, primarily due to a reduction during winter.

Climate hazard	Projection
Compound extreme events	**A changing climate may bring more compound extreme events.** • Multiple lines of evidence, including from observations and climate projections, point to a continuing trend of more frequent compound extreme events. • While there are no specific projections for future occurrences of compound extremes in Queensland, it would be prudent to plan for increases in some compound extreme events.
Other climate-related variables	**Frost** • A substantial decrease in the frequency of frost risk days is projected by 2070. **Evaporation** • By 2050, the median value of annual potential evaporation is projected to increase by 5 per cent under both medium and high emissions scenarios. **Humidity** • Humidity is expected to decline by 2050. Decreases are likely to be small. **Solar radiation** • Possible small increases in solar radiation across all seasons are projected in Queensland by 2050 under both medium and high emissions scenarios.

City projections

Brisbane

Brisbane extends from the hilly floodplain of the Brisbane River Valley between Moreton Bay and the Taylor and D'Aguilar mountain ranges.

Average temperature in Brisbane is projected to continue to increase in all seasons. Brisbane is likely to experience more hot days and warm spells, and fewer frosts. By 2050, the number of hot days (with temperatures exceeding 35 °C) will increase from approximately two to eight days per year.

Annual and seasonal-average rainfall changes are possible but unclear. Extreme daily rainfall events are likely to become more intense, and evapotranspiration is projected to increase.

Mean sea level will continue to rise and the height of extreme sea-level events will also increase.

Fire-weather climate is projected to become harsher.

By 2050, under a high emissions scenario, the climate of Brisbane is projected to be more like the current climate of Mareeba (about 1,400 km north of Brisbane).

Cairns

Cairns is located on the east coast of Cape York Peninsula on a long, narrow coastal strip between the Coral Sea and the Great Dividing Range.

Average temperature in Cairns is projected to continue to increase in all seasons. Cairns is likely to experience more hot days and warm spells. By 2050, the number of hot days (with temperatures exceeding 35 °C) will increase from approximately four to up to 18 days per year.

Annual and seasonal-average rainfall changes are possible but unclear. Extreme daily rainfall events are likely to become more intense, and evapotranspiration is projected to increase.

Mean sea level will continue to rise and the height of extreme sea-level events will also increase.

By the end of the century, there are likely to be fewer but more intense tropical cyclones.

By 2050, under a high emissions scenario, the climate of Cairns is projected to be more like the current climate of Cooktown (about 170 km north of Cairns).

Projections for variables of interest

Figure 25 summarises the changes likely to occur across Queensland. These changes will be accompanied by year-to-year and decade-to-decade variability

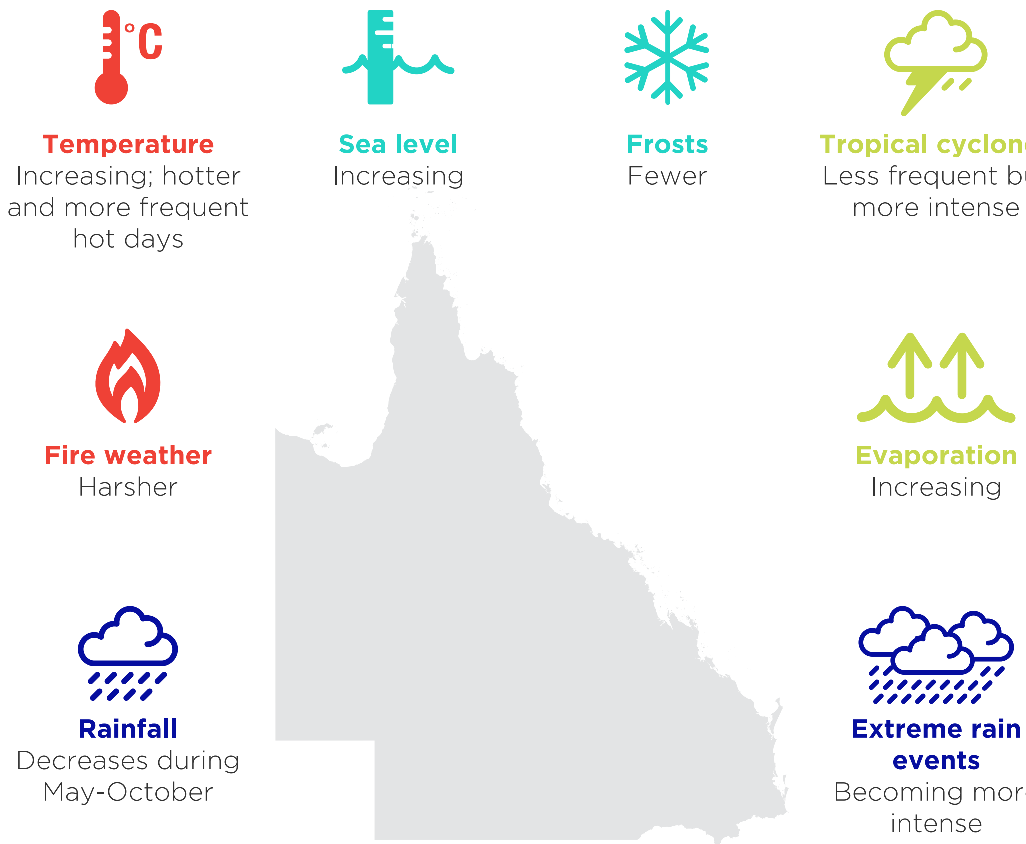

Figure 25 Projected changes across Queensland

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Appendix D. Climate change in South Australia

This appendix presents information about the past, current and likely future climate of South Australia (SA).

SA is already experiencing the impacts of climate change, with temperatures rising, a greater frequency of very hot days and an increase in the number of days with dangerous weather conditions for bushfires.

The climate of SA will continue to change in future. Included in this appendix are projections for temperature, precipitation, sea-level rise, fire weather, wind and other climate-related hazards. There is information for the state, as well as specific projections for Adelaide.

Climate of South Australia

SA is the driest state in Australia. It has a Mediterranean climate with warm, dry summers and mild winters. It is hotter in the north and cooler further south, such as on Kangaroo Island.

Figure 26 Topographic map of South Australia

The winter months bring most of the state's rainfall. Rainfall in the arid interior of SA is highly erratic. The average annual rainfall in the southern coastal areas is between 400 and 1,000 mm per year, while the central areas of the state generally receive only between 100 and 300 mm per year (Figure 27).

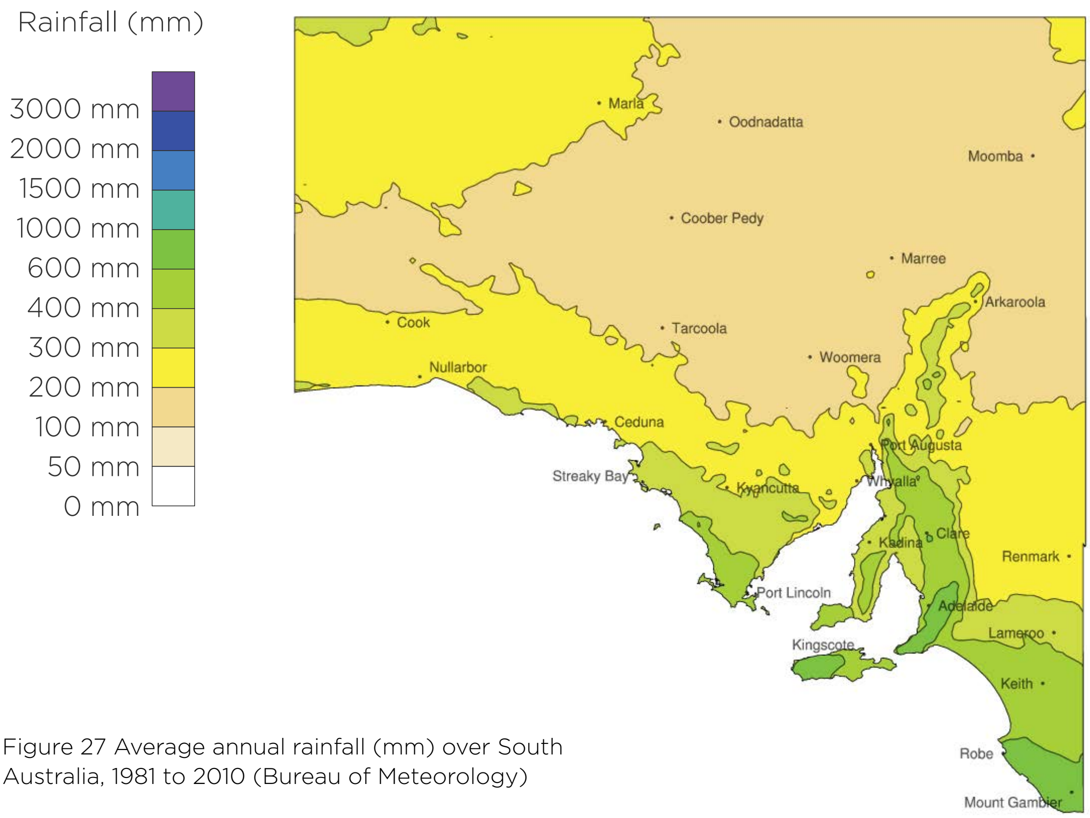

Figure 27 Average annual rainfall (mm) over South Australia, 1981 to 2010 (Bureau of Meteorology)

Climatic conditions can change greatly from year to year in response to large-scale phenomena (Figure 3), including:

- the subtropical ridge: the ridge is a belt of high-pressure systems across southern parts of Australia. It blocks rain-bearing fronts during summer, bringing fine and dry weather to SA, but allows cold fronts to pass over the state in winter.
- the El Niño – Southern Oscillation: has less effect over much of SA than for more eastern parts of Australia. However, during an El Niño, there is less moisture over the state during the cooler seasons, whereas La Niña results in greater amounts of moist tropical air being driven across Australia, resulting in lower temperatures.
- the Indian Ocean Dipole: changes in sea-surface temperature patterns in the northern Indian Ocean and waters to the north of Australia can affect the state's rainfall. A positive IOD tends to result in less rainfall for SA, while a negative IOD results in increased rainfall.
- the Southern Annular Mode: moves cold fronts and weather events from the Southern Ocean, mainly affecting southern areas during the cooler months of the year. SAM can affect rainfall in SA, with the strongest effect occurring along the south-eastern coastal fringe. A positive SAM causes weaker-than-normal westerly winds and high pressure over southern Australia, resulting in reduced rainfall.
- Madden-Julian Oscillation: is an eastward-moving pulse of wind, cloud and rainfall near the equator that typically recurs every 30 to 60 days. The MJO can sometimes influence rainfall in SA.

Blocking highs and cut off lows also affect the climate of SA. Blocking highs are strong high-pressure systems that form further south than usual and remain near-stationary for an extended period. They block the west-to-east progression of weather systems across southern Australia. A blocking high can produce hot and dry conditions for SA and can contribute to fog and frost occurrences.

Cut-off lows are low-pressure systems that break away from the main belt of low-pressure that lies across the Southern Ocean. They are associated with sustained rainfall and can produce strong, gusty winds and high seas in the region.

Past and recent climate

Temperature

All of SA has warmed, with average temperature increasing by 1.6 °C since 1910 (Figure 28). The highest rates of increase have occurred in the north of the state. The 2011–2020 average temperature in SA was more than 1 °C above the 1961–1990 average. Since 1990, SA has experienced only one year with a mean temperature below the mean annual temperature of the 20th century.

2019 was a particularly hot year for SA, with records broken across the state, including Adelaide's hottest day on record on 24 January 2019, when the temperature reached 46.6 °C.

Maximum and minimum temperatures have increased across the state, although with considerable year-to-year variability. This has resulted in fewer cold days and nights, and more hot days and nights.

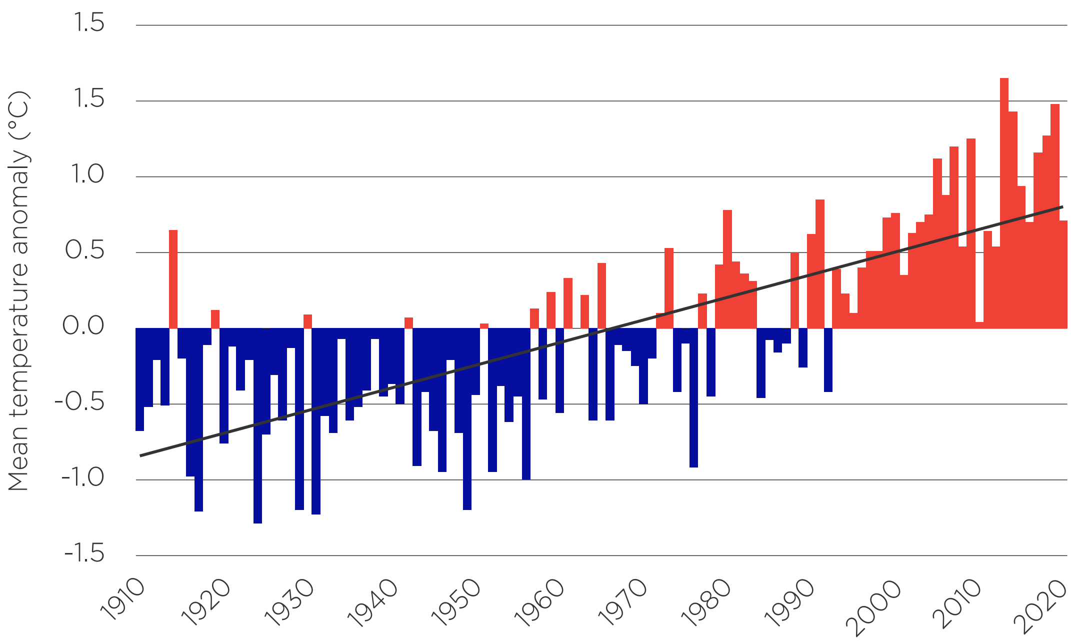

Figure 28 Annual mean temperature anomalies in South Australia compared with the 1961–90 average, with linear trend (0.15 °C per decade). Blue bars represent cooler-than-average years, while red bars are hotter-than-average years (Bureau of Meteorology)

The peak temperature, frequency, duration and number of heatwaves in SA have increased since 1950. Heatwaves are now lasting longer, especially over inland parts of the state.

Droughts have intensified in SA over the 1960–2010 period. This intensification is more prominent for long-term drought. Coastal and near inland regions experience a higher frequency of drought than the arid inland, but they are usually less intense, and shorter.

Rainfall

SA experiences significant regional variations in seasonal rainfall, with summer rainfall increasing in the north of the state and winter rainfall decreasing in the south.

Overall, SA has experienced a slight increasing rainfall trend since 1900 (Figure 29). However, there has been a persistent decline in rainfall in the state's southern agriculture areas, with a 20 per cent decrease in autumn and spring rainfall in some areas. Should it continue, this drying trend has the potential to affect future water security, reduce agricultural yields and increase fire risk.

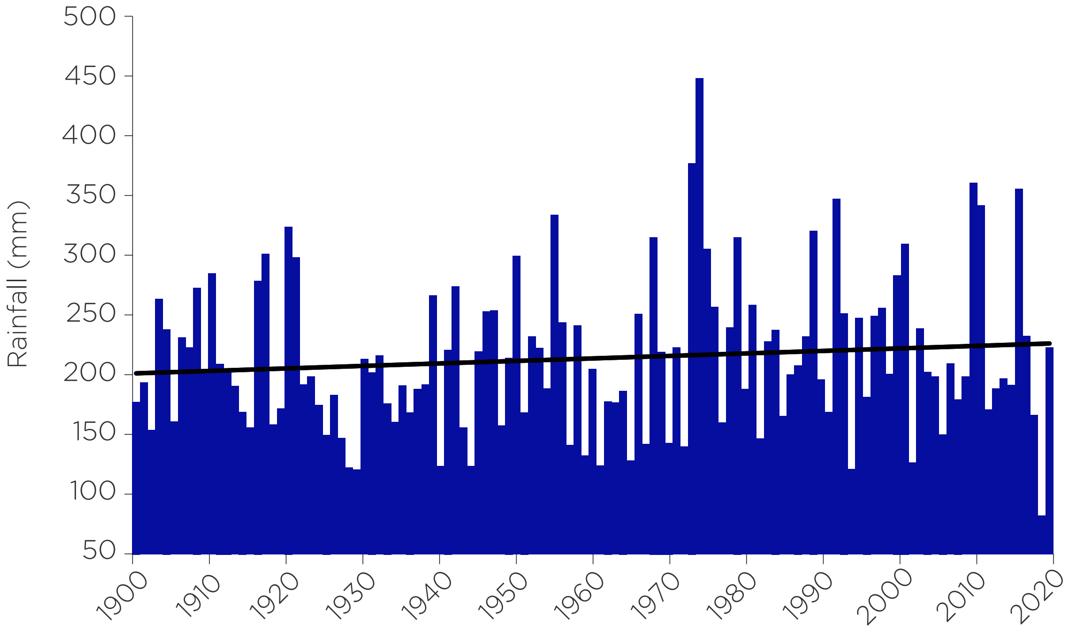

Figure 29 Annual rainfall for South Australia, 1900 to 2021, with linear trend (2.05 mm per decade) (Bureau of Meteorology)

Sea level

Sea levels along the state's coast rose by 1.5–4 mm per year between 1965 and 2018.

Fire weather

Fire danger weather has increased in frequency and severity across the state since the 1970s. The highest rates of increase have occurred in the mid-north, south-east and far north-east of SA.

Low rainfall and high temperatures have exacerbated spring and summer fire weather conditions in recent years. During 2018 and 2019, the persistence of below-average rainfall led to increasingly high forest fire danger index (FFDI) values across much of the state. From December 2019 into early January 2020, hot conditions combined with a dry landscape and strong winds to produce particularly dangerous fire weather conditions. In December 2019 this resulted in area-averaged accumulated FFDI values 24 per cent higher than the previous highest December on record, in 1972.

Climate change projections

SA is already experiencing climate change impacts, which vary across the region. The state's climate is projected to continue to change in future.

In 2015, CSIRO and the Bureau of Meteorology released national projections of Australia's likely future climate through the Climate Change in Australia website. In addition, the South Australian Department of Environment and Water (DEW), through the SA Climate Ready initiative, has released state-based projections. These projections are broadly consistent with the national projections and are presented at a higher resolution.

The projections presented here (Table 7) are largely based on the national projections, with some regional information from the SA Climate Ready initiative. The climate variables presented are those that are likely to affect Australia's electricity networks.

Scientific confidence in projections varies from variable to variable and, in some cases, from region to region.

Projections are typically for a range of years, such as 2040–59, referred to here as '2050'. Projections are relative to 1986–2005 (unless otherwise stated) and are provided for both a high emissions scenario (RCP8.5) and a low emissions scenario (RCP2.6), where available (Table 7).

Year by year and decade by decade, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall.

Figure 30 shows the projected average number of days per year with a Forest Fire Danger Index rating of greater than 50 (severe) under a high emissions scenario.

Table 7 Climate change projections for South Australia.

Climate hazard	Projection
Temperature	**SA will continue to get hotter in future.** • By 2050, under a high emissions scenario, SA can expect an average annual temperature increase of approximately 1.3 to 2.2 °C (central estimate of 1.9 °C). • By 2050, under a low emissions scenario, SA can expect an average annual temperature increase of approximately 0.7 to 1.4 °C (central estimate of 1.0 °C). • Maximum, minimum and average temperatures are likely to continue to rise. • Warming in spring is likely to be greater than in any other season. **The frequency of very hot days will continue to increase.** • Heatwaves are projected to be longer and hotter in future. **SA can expect longer fire seasons.** • Harsher fire weather is likely and there will be more days of severe and extreme fire danger. • Projected warming and drying across the state is likely to lead to fuels that are drier and more ready-to-burn. • By 2050, there are likely to be around 40 per cent more very high fire danger days. The increase in fire danger days is likely to lead to a corresponding increase in total fire ban days.
Precipitation	**Rainfall across SA is likely to decline, however large variability exists.** • By 2050, annual rainfall in SA is projected to decline by 6.6 to 15 per cent. • Spring rainfall declines are projected to be greater than in any other season. • The number and intensity of heavy rainfall events in SA are projected to rise, increasing the risk of flooding. **Extreme rainfall is projected to become even more extreme.** • By 2050 the amount of rain falling in extreme rainfall events is projected to increase in all SA regions and the frequency of extreme rainfall events is expected to increase. **More time in drought is projected.** • By 2050, time spent in drought is projected to more than double in regions around Adelaide, Kangaroo Island and Yorke Peninsula. By 2050, these regions could be in drought by up to 70 per cent of the time.
Sea level	**By 2050, sea levels are projected to rise by around 24 cm along the coast of SA.** • Rising sea levels are likely to increase coastal erosion and flooding. • Sea-level rise can also lead to higher storm surge and inundation levels. • The height of extreme sea-level events is projected to increase.

Climate hazard	Projection
Lightning and storms	**Projections of storms and lightning are uncertain.** • Possible reductions in storminess are projected over southern Australia. • Projected changes in storms and lightning are uncertain as scientists are unable to directly model future thunderstorm activity due to its local and temporal scale.
Wind	**Average wind speed is projected to remain unchanged until 2030, but a decrease in wind speed in the longer-term is likely.** • Projections are for relatively small changes in mean annual wind speed. • Longer-term decreases in wind speed are most likely to occur in the southern parts of SA.
Compound extreme events	**A changing climate may bring more compound extreme events.** • Multiple lines of evidence, including from observations and climate projections, point to a continuing trend of more frequent compound extreme events. • While there are no specific projections for future occurrences of compound extremes in SA, it would be prudent to plan for increases in some compound extreme events.
Other climate-related variables	**Frost** • The frequency of frosts between August and November is likely to remain unchanged until the early 2030s. • In the longer-term, frosts are expected to decrease as the climate warms. Locations where frost now occurs only a few times a year are projected to become nearly frost-free. **Solar radiation** • Little change in solar radiation is projected. • However, by 2090 there may be an increase in solar radiation in winter and spring in southern Australia. The increase may exceed 10 per cent by 2090 under a high emissions scenario. **Humidity** • Relative humidity is projected to decline in inland regions and where rainfall is projected to decline. By 2090, humidity is likely to decrease in winter and spring as well as annually. **Potential evaporation** • Potential evapotranspiration is projected to increase across all seasons and regions in SA.

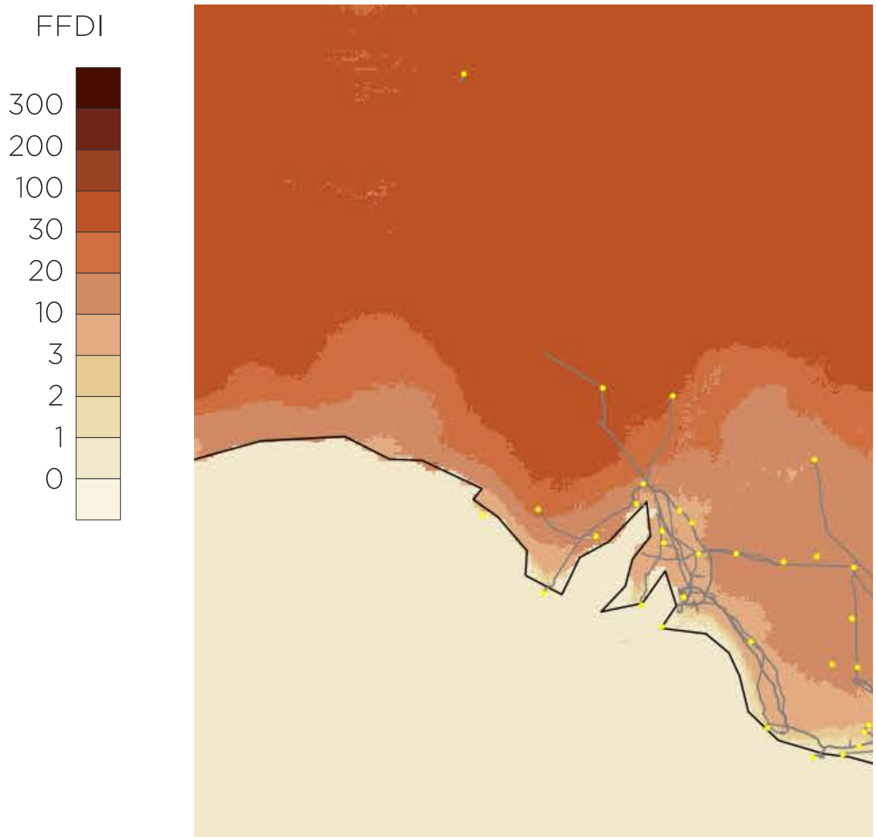

Figure 30 Projected average number of days per year with a Forest Fire Danger Index rating of greater than 50 (severe) under a high emissions scenario for the period 2040-2059 (ESCI Climate Data)

City projections

Adelaide

The coastal city of Adelaide is in the south-east of SA on the Adelaide Plains north of the Fleurieu Peninsula, between the Gulf St Vincent in the west and the low-lying Mount Lofty Ranges in the east.

Average temperature in Adelaide is projected to continue to increase across all seasons. Projected temperature increases by 2090 range from 1.5 °C under a medium emissions scenario to 2.9 °C under a high emissions scenario (relative to the 1986–2005 average).

There will be more hot days and heatwaves. The number of very hot days (maximum temperatures exceeding 40 °C) in Adelaide is projected to increase from approximately two to six days per year by 2050.

A continuation of the trend of decreasing winter and spring rainfall in Adelaide is projected. The intensity of extreme daily rainfall events is projected to increase.

There will be increased evapotranspiration, fewer frosts after the 2030s and a harsher fire-weather climate. Mean sea level will continue to rise and the height of extreme sea-level events will also increase.

By 2050, under a high emissions scenario, Adelaide's climate is projected to be more like the current climate of Kadina (about 150 km north-west of Adelaide).

Projections for variables of interest

Figure 31 summarises the projected changes likely to occur across South Australia. These changes will be accompanied by year-to-year and decade-to-decade variability.

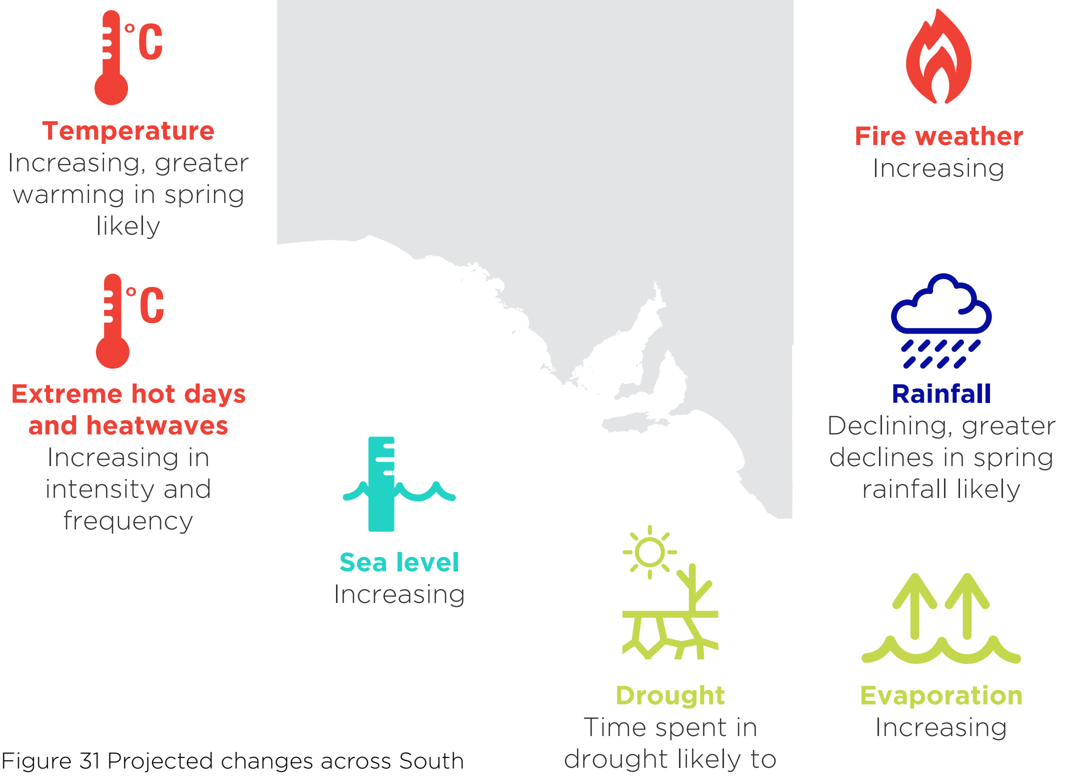

Figure 31 Projected changes across South Australia

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Appendix E. Climate change in Tasmania

This appendix presents information about the past, current and likely future climate of Tasmania.

Tasmania is already experiencing the impacts of climate change, with temperatures rising, a decrease in annual average rainfall, more days with dangerous weather conditions for bushfires and fewer very cold days.

Tasmania's climate will continue to change in future. Included in this appendix are projections for temperature, fire weather, precipitation, sea-level rise, wind, and other climate-related hazards. There is information for the state, as well as specific projections for Hobart.

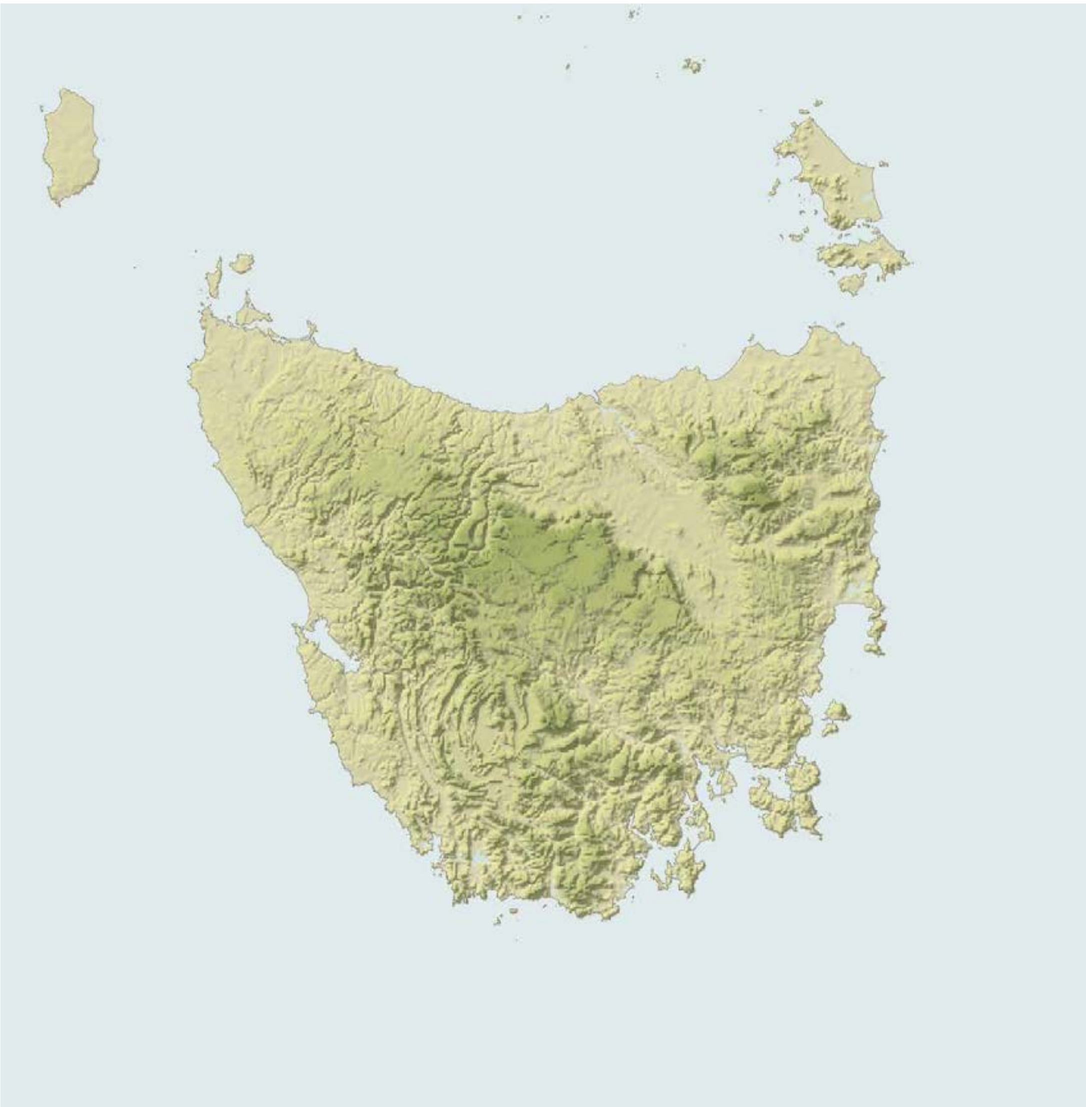

Figure 32 Topographic map of Tasmania

Climate of Tasmania

Tasmania has a temperate maritime climate, with temperatures moderated by the surrounding seas. The seasonal temperature range is small, with mean maximum temperatures of 18 °C to 23 °C in summer and 9 °C to 14 °C in winter. Mountains in the west, central and north-east regions affect rainfall distribution.

Mean annual rainfall varies from less than 600 mm in the central midlands to more than 3,000 mm near the west coast (Figure 33).

Tasmania lies in the 'Roaring 40s' belt of westerly airflow. The westerlies are strongest in winter and spring. Variations in the strength and persistence of the westerly wind contribute to the seasonal rainfall pattern, especially in the western and central regions of the state.

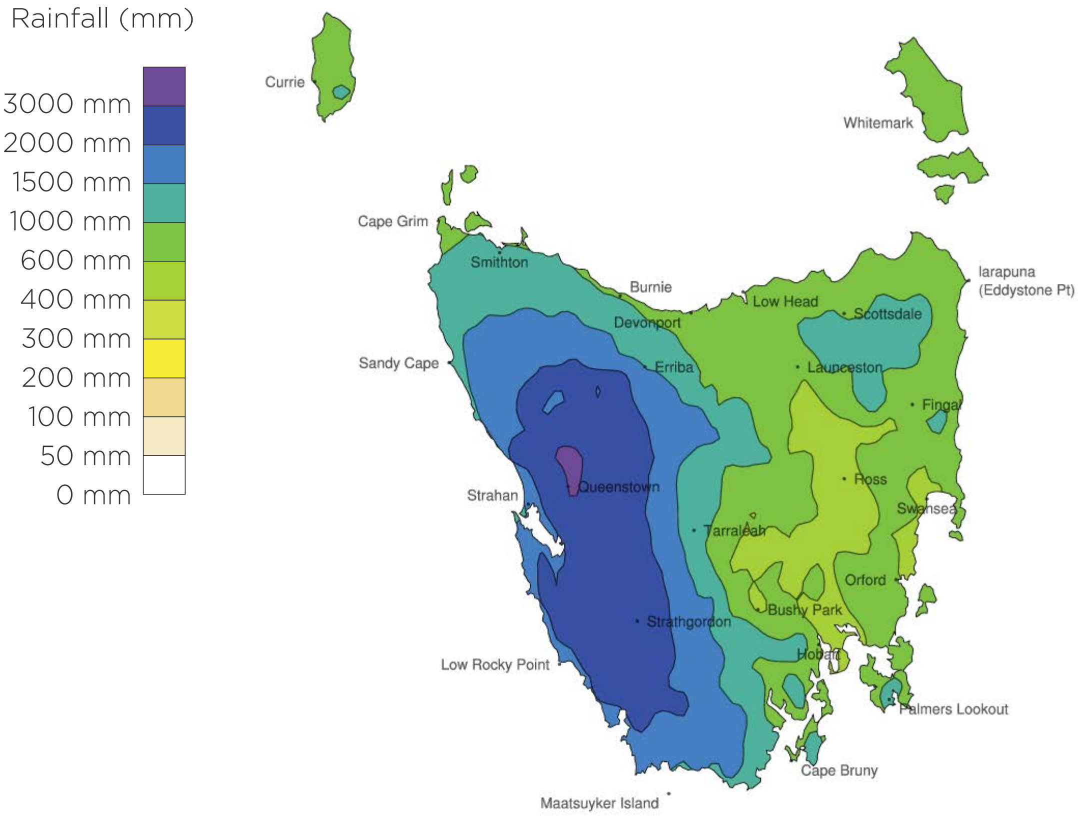

Figure 33 Average annual rainfall (mm) over Tasmania for 1981 to 2010 (Bureau of Meteorology)

Slow-moving high-pressure systems (anticyclones) can interrupt the westerly systems. These 'blocking highs' can persist for several days or even weeks and can block the approach of rain-bearing cold fronts. They can occur year-round but reach a maximum in the transition from summer to winter as the westerlies weaken.

In winter, a persistent set of storm tracks passes from the Great Australian Bight over Bass Strait and into the Tasman Sea. The strength of these systems and their proximity to Tasmania greatly affect rainfall. On occasion, these low-pressure systems become cut off from the westerly flow. These infrequent slow moving cut-off lows can affect the rainfall of northern, central and eastern regions.

The combination of mountainous topography, prevailing westerly winds, the annual pressure cycle, winter storm tracks, blocking highs, east coast lows and cut-off lows results in a large spatial variation in rainfall across Tasmania.

NSW/ACT
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Climate is naturally variable, with short-term changes occurring over months, seasons and years (Figure 3). Large-scale climate influences that affect Tasmania include:

- the subtropical ridge: the ridge is a belt of high-pressure systems and normally lies to the north of Tasmania. While the wind is predominantly westerly at Tasmanian latitudes, there are year to year changes in the position and strength of the ridge.
- El Niño – Southern Oscillation: northern and eastern Tasmania often receive higher winter and spring rainfall during La Niña events, while northern and eastern Tasmania often experience below-average winter and spring rainfall during El Niño events.
- the Indian Ocean Dipole: changes in sea-surface temperature patterns in the northern Indian Ocean during negative IOD conditions can bring more rain in winter and spring (except in parts of south-west Tasmania). Positive IOD conditions can result in less rainfall in these seasons.

Past and recent climate

Temperature

Tasmania experienced milder, though variable, mean temperatures during the first half of the 20th century, followed by an increase in mean temperature. This rise has been less than for mainland Australia. Daily minimum temperatures in Tasmania have risen more than daily maximum temperatures.

Since 1910, average annual temperature averaged over Tasmania has increased by 1.1 °C. The 2011–20 average temperature was around 0.5 °C above the 1961–1990 average.

2016 was a very warm – and very wet – year, with strong winds and warm oceans leading to persistently mild nights (Figure 34). Several sites (including Hobart, Launceston and Devonport) experienced their highest annual mean temperature on record. The state is experiencing more 35 and 40-degree days than in the past.

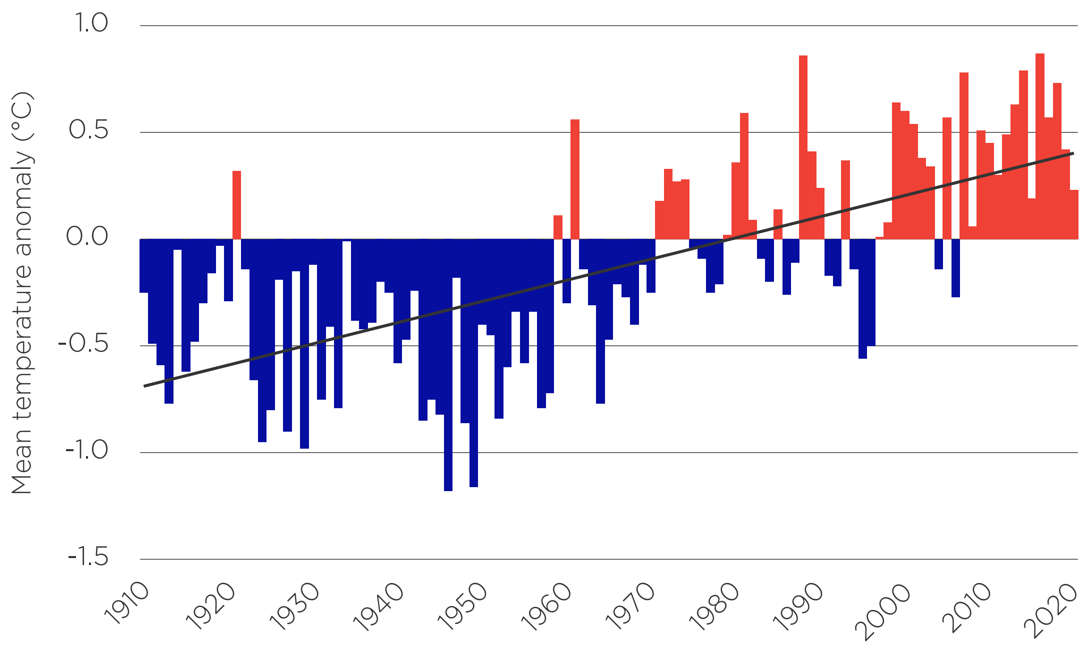

Figure 34 Annual mean temperature anomalies in Tasmania compared with the 1961-90 average, with linear trend (0.1 °C per decade). Blue bars represent cooler-than-average years, while red bars are hotter-than-average years (Bureau of Meteorology)

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Rainfall

Annual average rainfall has decreased over most of Tasmania since 1900. In the south-west, Bass Strait islands and central Tasmania there has been little change or an increase over this period.

Wet years have become less common and dry years more common (Figure 35). The decline has been greatest in late autumn and early winter.

Rainfall changes appear to be at least partly linked to shifts in large-scale climate influences over Tasmania since around 1960. The subtropical ridge has moved slightly southward and intensified. There has been an increase in the frequency of El Niño events and a strengthening of the Southern Annular Mode (a north–south shift in the belt of strong westerly winds across the south of Australia). Additionally, there has been an increase in blocking highs in summer, with rain-bearing cold fronts approaching Tasmania being pushed to the south-east.

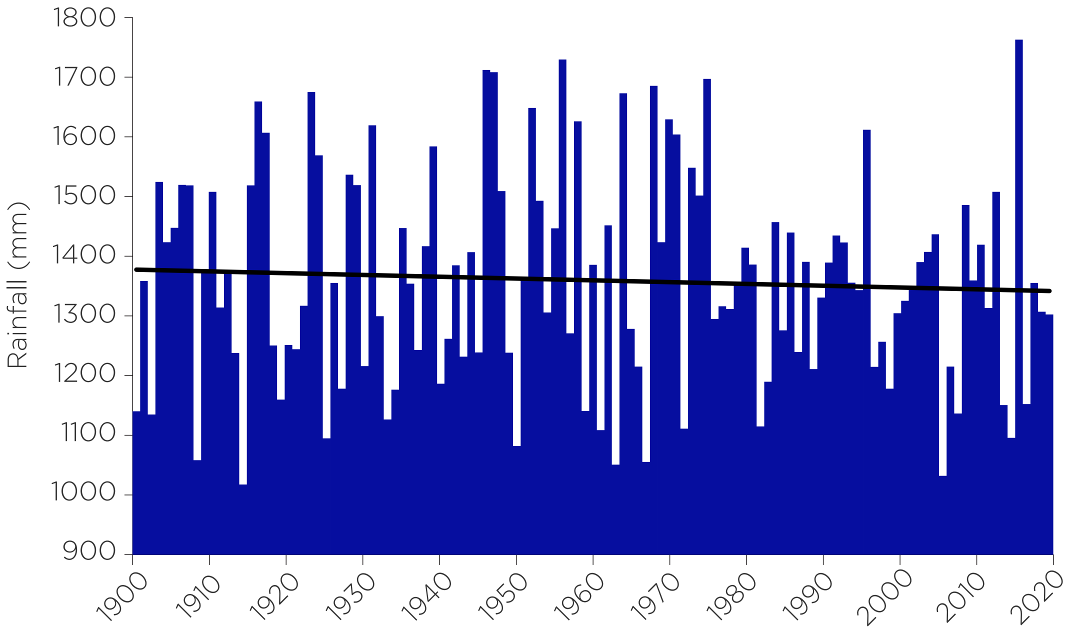

Figure 35 Annual rainfall for Tasmania, 1900 to 2020, with linear trend (-2.96 mm per decade) (Bureau of Meteorology)

Sea level

Globally averaged sea levels rose by 21 cm during the 20th century in Tasmania.

Relative sea level around Australia rose at an average rate of 1.4 mm per year between 1966 and 2009, and 1.6 mm per year after the fluctuating influence of ENSO on sea level was removed.

Fire weather

The number of days with dangerous weather conditions for bushfires has increased across the region.

During the 2019–20 bushfire season, almost all of Tasmania recorded accumulated monthly forest fire danger indices in the highest 10 per cent of historical values for December. During that bushfire season, an estimated 36,000 hectares were burnt across Tasmania.

Climate change projections

Tasmania is already experiencing the impacts of climate change. The state's climate is projected to continue to change in future.

In 2015, CSIRO and the Bureau of Meteorology released national projections of Australia's likely future climate through the Climate Change in Australia website. In addition, in 2010, the Tasmanian Government released state-based climate projections through the Climate Futures for Tasmania project. These state-based projections were produced at a higher resolution than the national projections, providing local-scale information that may better represent regional climate. While the methodologies for producing the national and state-based projections differ, the resulting information about the changing climate is broadly consistent, with some regional differences.

The projections presented here (Table 8) are largely based on the national projections, with some regional information from Climate Futures for Tasmania. The climate variables presented are those that are likely to affect Australia's electricity networks.

Scientific confidence in projections varies from variable to variable and, in some cases, from region to region.

Projections are typically for a range of years, such as 2040–59, referred to here as '2050'. Projections are relative to 1986–2005 (unless otherwise stated) and are provided for both a high emissions scenario (RCP8.5) and a low emission scenario (RCP2.6), where available (Table 8). (The medium emissions scenario is IPCC SRES B1.)

Year by year and decade by decade, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall.

The projected temperature changes in Tasmania for both high and low emissions scenarios are less than those for the Australian mainland and for global average changes for the periods quoted. These smaller projected changes for Tasmania are largely due to the moderating influence of the surrounding oceans.

Figure 36 shows projected increases in daily maximum temperatures under high and low greenhouse gas emissions scenarios. Temperature changes are similar in the coming decades under both scenarios, diverging significantly later in the century.

Table 8 Climate change projections for Tasmania.

Climate hazard	Projection
Temperature	**Tasmania will continue to get hotter in future.** • By 2050, under a high emissions scenario, Tasmania can expect an average annual temperature increase of approximately 0.9 to 1.7 °C (central estimate of 1.2 °C). • By 2050, under a low emissions scenario, Tasmania can expect an average annual temperature increase of approximately 0.3 to 1.1 °C (central estimate of 0.7 °C). • By the end of the century, under a high emissions scenario, Tasmania can expect an average annual temperature increase of approximately 2.6 to 3.3 °C (central estimate of 2.9 °C). • By the end of the century, under a medium emissions scenario, Tasmania can expect an average annual temperature increase of approximately 1.3 to 2.0 °C (central estimate of 1.6 °C). • Daily minimum temperature is projected to increase more than daily maximum temperature. **Extreme temperatures are projected to increase at a similar rate to mean temperature.** • A substantial increase in the temperature reached on hot days and the frequency of hot days are projected. • The duration of warm spells is also projected to increase. **Tasmania can expect a harsher fire weather climate in future.** • While Tasmania will experience large year-to-year changes in fire danger throughout the century, there will be an underlying increasing trend. This trend will increase the length of the fire season and increase the number of days at the highest range of fire danger. • By the end of this century, scientists expect an eight-fold increase in fire risk.
Precipitation	**It is likely that Tasmania will experience less annual rainfall.** • Approximately three-quarters of climate models project decreased rainfall. The projected decrease in rainfall is greatest in spring, with greater changes possible under the higher emissions scenarios. • Notable differences across the state are plausible, including a difference in the direction of change between east and west in some seasons. • An increase in the intensity of extreme rainfall events is likely, however, the magnitude cannot be confidently projected. **Time spent in drought is projected to increase.** • The episodic and regional nature of drought events will continue. The east coast of Tasmania will stay especially drought prone. • The duration and frequency of extreme droughts are projected to increase.

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Climate hazard	Projection
Sea level	**By 2050, sea levels are projected to rise by around 26 cm along the Tasmanian coast.** • The height of extreme sea-level events will increase. • Sea-level rise can also lead to higher projected storm surge and inundation levels. • 1-in-100-year coastal inundation events in exposed locations are projected to occur almost every year (during the annual high tide).
Lightning and storms	**An increase in storms is possible. This may result in increased coastal erosion and inundation.** • As climate change creates a drier landscape, dry lightning (which is an ignition risk for bushfires) is projected to increase. • Projected changes in storms and lightning are uncertain as scientists are unable to directly model future thunderstorm activity due to its local and temporal scale.
Wind	**Increases are projected for mean wind speed in winter.** • Wind speeds and projected changes are greater over the oceans surrounding Tasmania than over the land. • By 2090, stronger average wind speeds are projected during winter, primarily in western Tasmania. • Under a high emissions scenario, decreases in summer mean wind speeds are expected. The projected changes in other seasons are smaller. • By 2090, under a high emission scenario, the annual maximum one-day wind speed and the 20-year return value for one-day wind speed are projected to increase, in line with an increase in mean wind speed. **Fewer but more intense east coast lows are possible.** • A reduction of about 30 per cent of east coast low formation is projected for the late 21st century compared with the late 20th century. • An increase in the intensity of east coast lows would affect mean rainfall and heavy rain events.
Compound extreme events	**A changing climate may bring more compound extreme events.** • Multiple lines of evidence, including from observations and climate projections, point to a continuing trend of more frequent compound extreme events. • While there are no specific projections for future occurrences of compound extremes in Tasmania, it would be prudent to plan for increases in some compound extreme events. • The Tasmanian bushfires in 2015-16 were accompanied by floods and an intense marine heatwave. This example of compound extremes caused fire damage to Tasmania’s World Heritage Area, stretched emergency resources, shut businesses and stressed the state’s energy supply and connection to the national electricity grid.

Climate hazard	Projection
Other climate-related variables	**Frost** • By 2100, the incidence of frost is projected to halve. **Solar radiation** • An increase in solar radiation is projected in the cool season throughout the century. **Evaporation** • There are likely to be increased evaporation rates and an increase in potential evapotranspiration. **Humidity** • Reduced relative humidity is projected across all seasons by 2090.

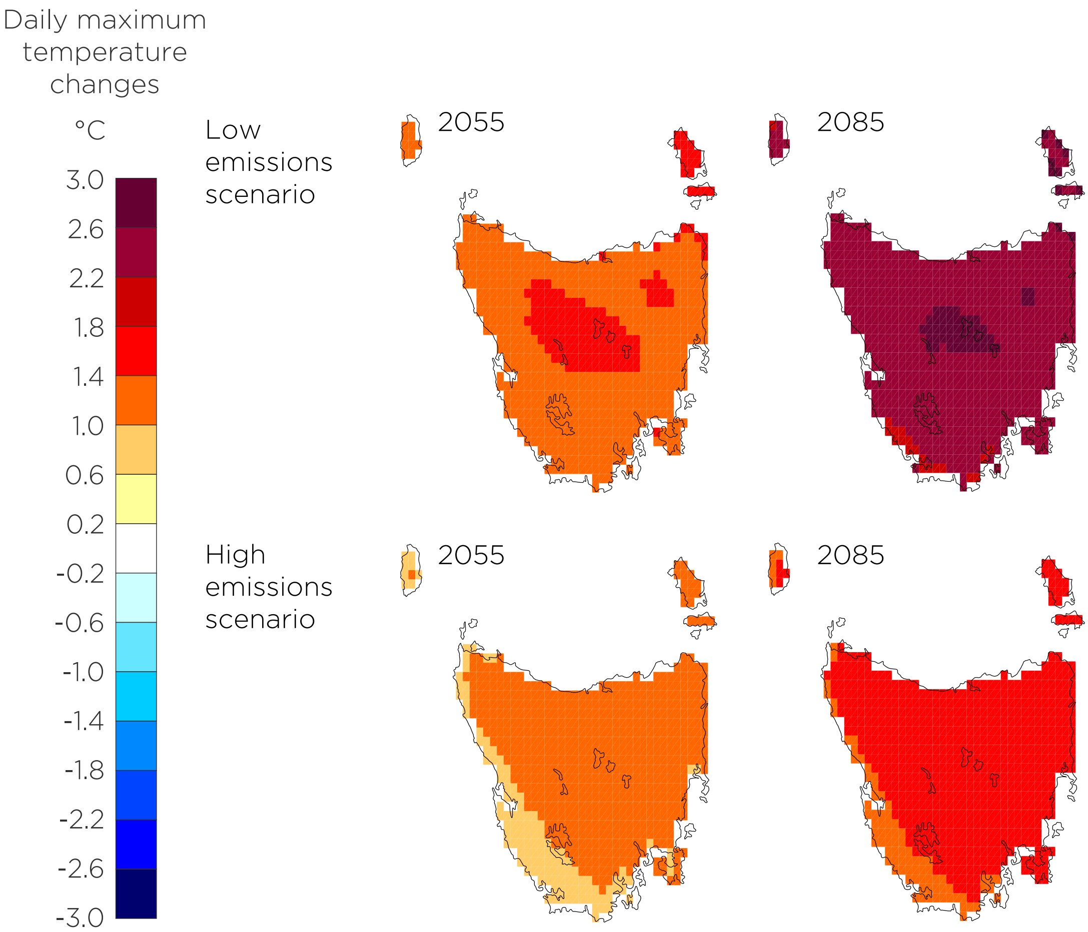

Figure 36 Projected average daily maximum temperature around the year 2055 (left maps) and 2085 (right maps) under a high (upper maps) and low (lower maps) greenhouse gas emissions scenario (Grose et al. (2010) Climate Futures for Tasmania: general climate impacts technical report. Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart, Tasmania)

City projections

Hobart

Australia's most southerly city, Hobart is in Tasmania's south-east on the banks of the River Derwent estuary. The city is located along the steep foothills of Mount Wellington.

Average temperature in Hobart is projected to continue to increase year-round. There will be more hot days and warm spells. The number of hot days (with maximum temperature exceeding 30 °C) in Hobart will increase from four or five days per year to eight days per year. Similarly, the number of hot days in Launceston will increase from approximately three to eight days per year.

More rainfall in winter is projected for Hobart, with a decrease in spring. Changes to summer and autumn rainfall are possible but trends are less clear. Regardless of rainfall changes, extreme daily rainfall events will become more intense.

There will be increased evapotranspiration, and a harsher fire-weather climate in Hobart.

Mean sea level will continue to rise and the height of extreme sea-level events will also increase.

By 2050, under a high emissions scenario, Hobart's climate is projected to be more like the current climate of Geelong, Victoria, and Launceston's climate is projected to be more like the current climate of Bathurst, NSW.

Projections for variables of interest

Figure 37 summarises the changes likely to occur across Tasmania. These changes will be accompanied by year-to-year and decade-to-decade variability.

Figure 37 Projected changes across Tasmania

NSW/ACT
NT
QLD
SA
TAS
VIC
WA

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Appendix F. Climate change in Victoria

This appendix presents information about the past, current and likely future climate of Victoria.

Victoria is already experiencing the impacts of climate change, with temperatures rising, more hot days and fewer very cold days. The number of days with very high fire danger days occurring in spring has increased across the state, and the state has experienced a decline in cool season rainfall over the past 30 years.

The climate of Victoria is projected to continue to change in future. Included in this appendix are projections for temperature, precipitation, sea-level rise, storms, wind and other climate-related hazards. There is information for the state, as well as specific projections for Melbourne.

Climate of Victoria

Victoria has a temperate climate. It ranges from the hot, dry conditions in the north-west to the wet elevated areas of Gippsland, with alpine conditions in the mountains. Cooler seasons bring widespread frost and snow at high altitudes (Figure 38).

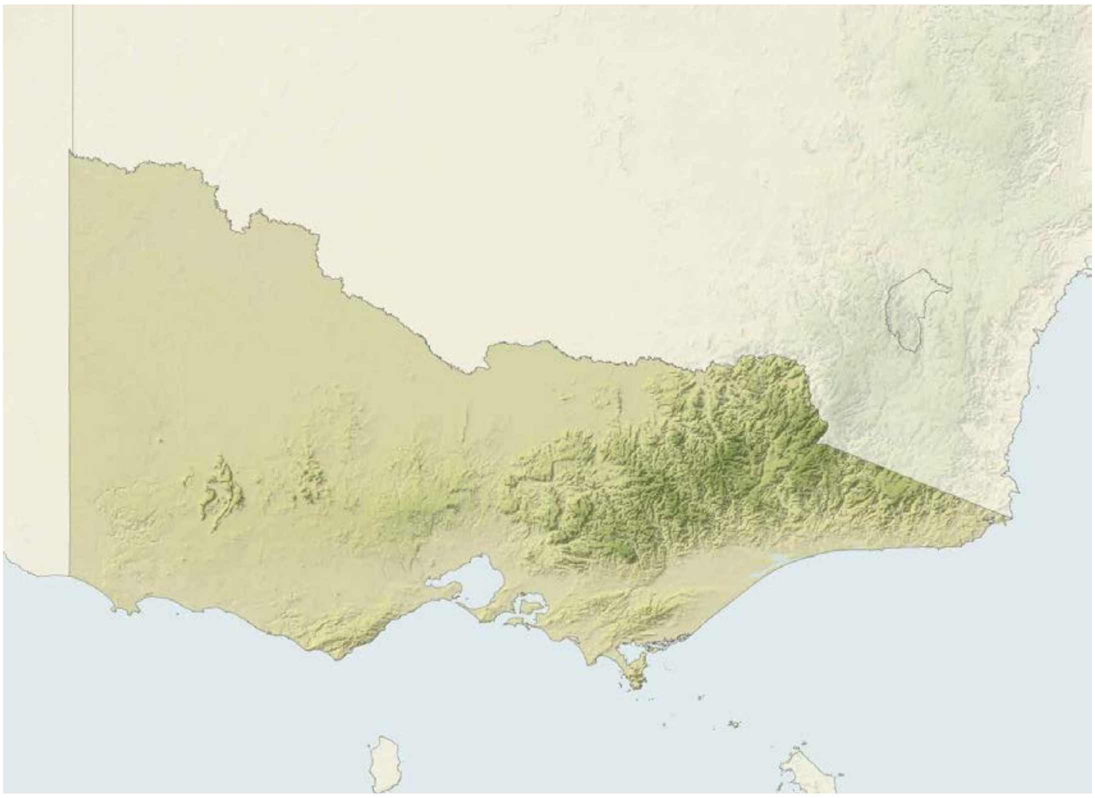

Figure 38 Topographic map of Victoria

Most rainfall occurs from April to October. Rainfall totals vary, from 917 mm per year in the south-east to 730 mm per year in the south-west, to 562 mm per year in the drier area north of the Great Dividing Range (Figure 39).

Most of western Victoria's rain comes from the cold fronts and troughs embedded within the predominant westerly air flow. In eastern Victoria, east coast lows can cause heavy and widespread rainfall, particularly in autumn and winter. Thunderstorms also bring much rainfall to this region.

Climate is naturally variable, with short-term changes occurring over months, seasons and years. Large-scale climate influences (Figure 3) that affect Victoria include:

- the subtropical ridge: the ridge is a belt of high-pressure systems across southern parts of Australia. It influences the passage of rain-bearing weather systems over Victoria. In winter, the sub-tropical ridge typically moves north allowing fronts to bring rain to Victoria. In summer, it moves south limiting the passage of fronts and associated rain.
- the El Niño – Southern Oscillation: during its El Niño phase, Victoria tends to experience hotter and drier conditions, especially in winter and spring. During a La Niña, Victoria tends to experience cooler and wetter conditions in winter, spring and summer.
- the Indian Ocean Dipole: changes in sea-surface temperature patterns in the northern Indian Ocean during negative IOD conditions can bring above-average rainfall, with positive IOD conditions often resulting in low rainfall.
- the Southern Annular Mode: in winter, a positive SAM typically indicates lower rainfall, and in spring and summer, enhanced rainfall in Victoria.

When occurring together, ENSO and the IOD events may reinforce or work counter to each other. For example, a combination of an El Niño event and a positive IOD has contributed to some of the driest June to October periods in Victoria.

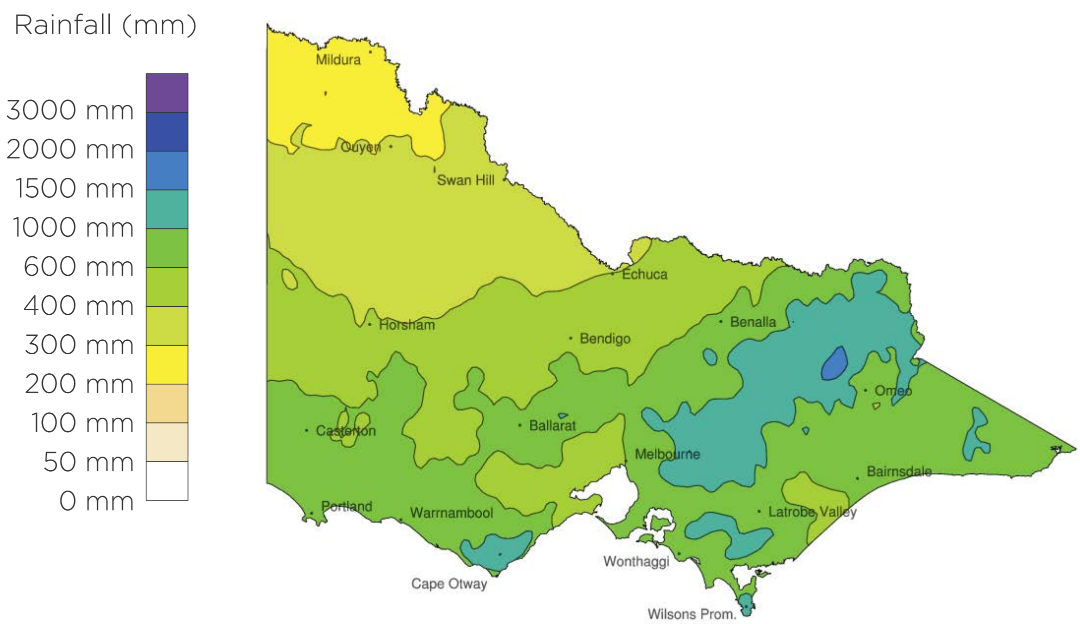

Figure 39 Average annual rainfall (mm) over Victoria, 1981 to 2010 (Bureau of Meteorology)

Past and recent climate

Temperature

All of Victoria has warmed since 1910. Victoria's average annual temperature has increased by 1.2 °C since 1910. The rate of temperature change across Victoria has accelerated in recent decades, at least partly due to human-induced greenhouse gas emissions, but also with a contribution from natural variability. The 2011–2020 average temperature was almost 0.9 °C above the 1961–1990 average.

There have been many more warm years than cool years this century (Figure 40). There has been an increase in the frequency of unusually hot days (days with maximum temperature above the 99th percentile of each month from 1910 to 2019).

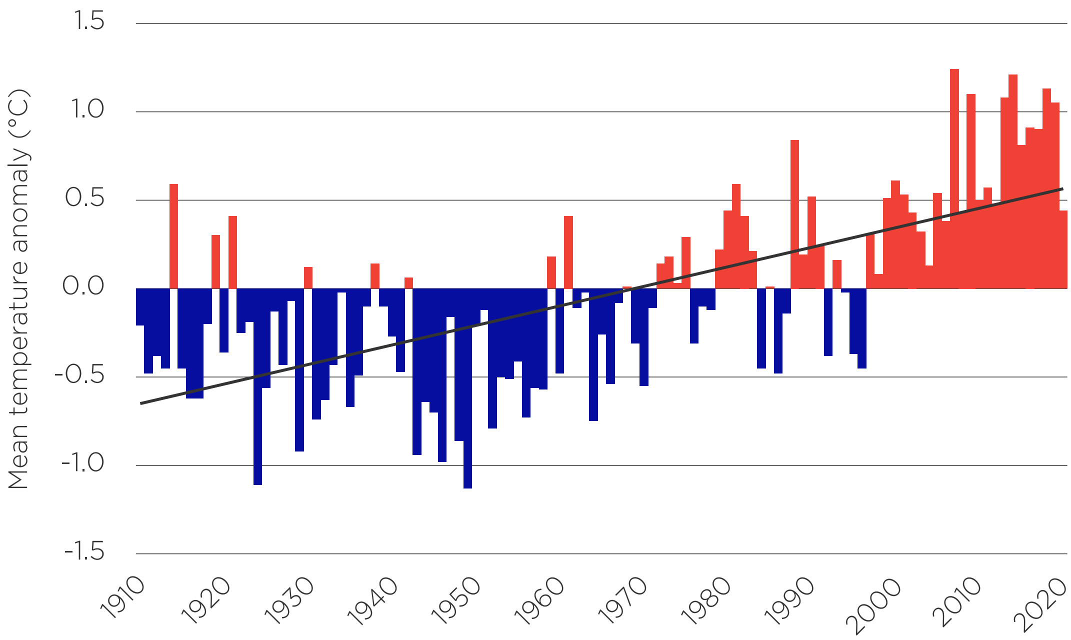

Figure 40 Annual mean temperatures anomalies in Victoria compared with the 1961-90 average, with linear trend (0.11 °C per decade). Blue bars represent cooler-than-average years, while red bars are hotter-than-average years (Bureau of Meteorology)

The frequency of heatwaves and the highest temperature experienced during heat waves have increased over most of Victoria since 1950. In January 2019, an extreme heatwave swept across northern Victoria, and Albury-Wodonga had its highest ever recorded temperature of 45.3 °C. In January 2018, Bendigo experienced 12 consecutive days over 35 °C, breaking the previous record of eight days, set in 2014.

Rainfall

Victoria's annual rainfall has declined since 1900 (Figure 41). Trends vary from region to region and season to season. For example, nearly all locations have experienced declines during autumn, and most locations have experienced declines during winter and increases during summer (Figure 42).

Victoria has experienced significant reductions in streamflow. The declines have varied from about 25 to 75 per cent (1997–2014 compared with 1975–1997) and have been larger in western Victoria and smaller in the alpine areas.

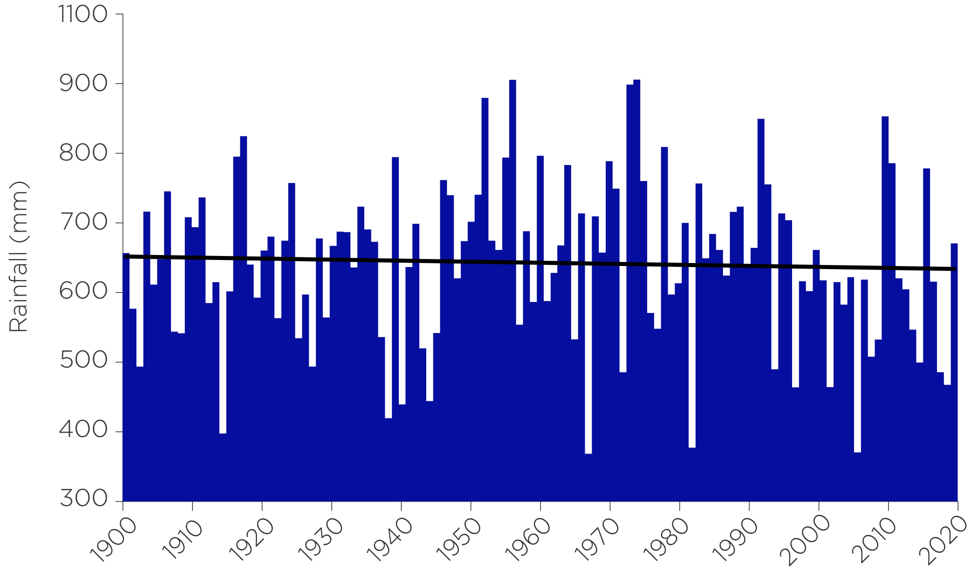

Figure 41 Annual rainfall for Victoria, 1900 to 2021, with linear trend (-1.22 mm per decade) (Bureau of Meteorology)

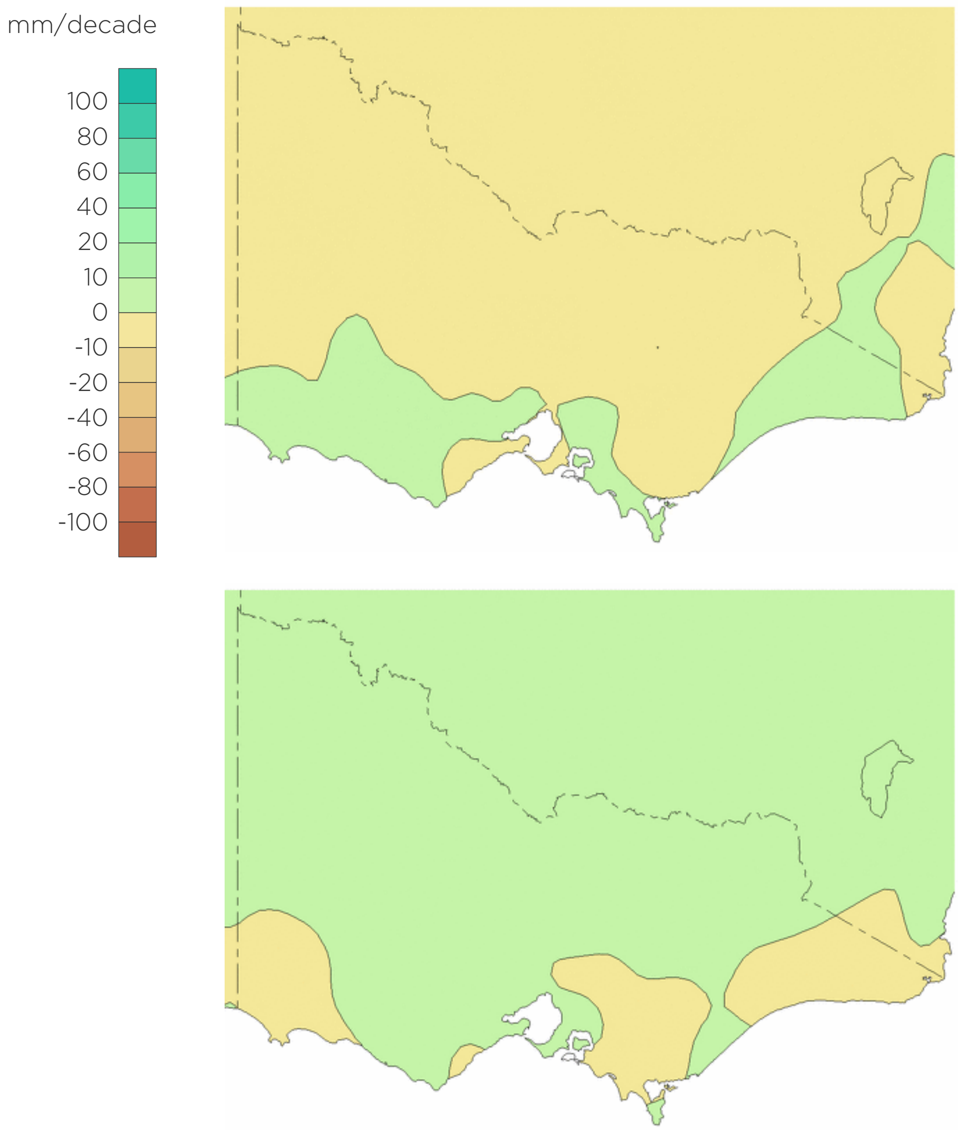

Figure 42 Winter (top; June–August) and summer (bottom; December–February) total rainfall trends since 1900 (Bureau of Meteorology)

Sea level

Victoria's mean sea level has been increasing, with average increases between 1.57 cm and 5.31 cm per decade between 1993 and 2017. Melbourne (recorded at Williamstown) has the longest continuous record of sea level observations in Victoria and has reported an average increase in mean sea level of approximately 2 mm per year since 1966.

Fire weather

The number of days with dangerous weather conditions for bushfires has increased across Victoria (Figure 43).

There has been a trend towards more dangerous fire weather conditions during summer and an earlier start to the fire season, particularly in parts of southern and eastern Australia. There has been an increase in the occurrence of extreme Forest Fire Danger Index days from the late 1990s, with up to 24 more extreme days per year. In Victoria's south-west, there have been associated increases in temperature and wind speed and decreases in relative humidity.

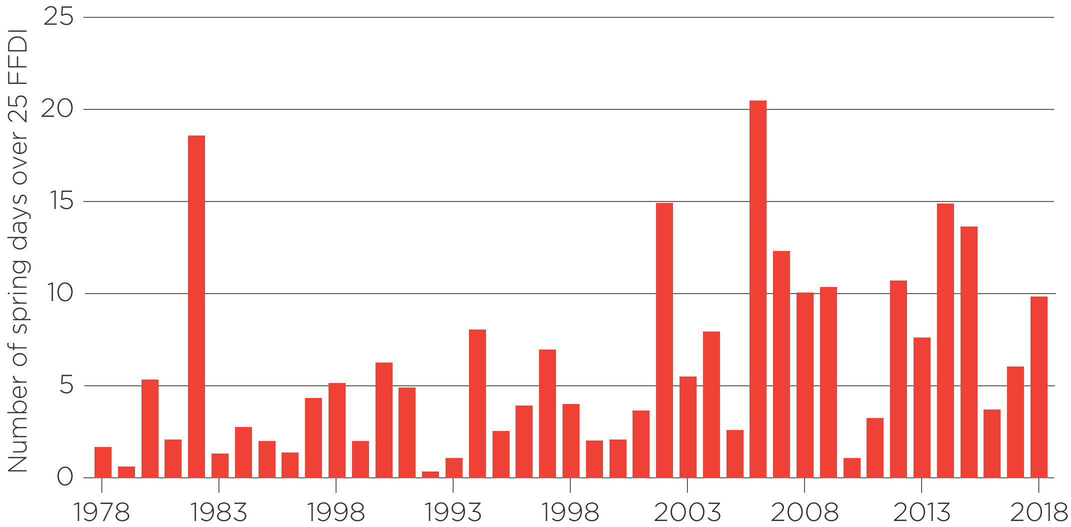

Figure 43 The number of days with Forest Fire Danger Index (FFDI) greater than 25 (very-high fire danger) in Victoria in spring from 1978 to 2018 (Department of Environment, Land, Water and Planning (DELWP))

Climate change projections

Victoria is already experiencing the impacts of climate change, becoming warmer and, in many places, drier. The climate of Victoria is projected to continue to change.

In 2015, CSIRO and the Bureau of Meteorology released national projections of Australia's likely future climate through the Climate Change in Australia website. In addition, the Victorian Department of Environment, Land, Water and Planning (DELWP) through the Victorian Climate Projections 2019 project has released state-based projections. These projections are broadly consistent with the national projections and are presented at a higher resolution.

The projections presented here (Table 9) are largely based on the national projections, with some regional information from the Victorian Climate Projections. The climate variables presented are those that are likely to affect Australia's electricity networks.

Scientific confidence in projections varies from variable to variable and, in some cases, from region to region.

Projections are typically for a range of years, such as 2040–59, referred to here as ‘2050’. Projections are relative to 1986–2005 (unless otherwise stated) and are provided for both a high emissions scenario (RCP8.5) and a low emissions scenario (RCP2.6), where available (Table 9).

Year by year and decade by decade, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall.

Figure 44 shows past temperatures for Victoria, with projected warming under high and low emission scenarios. Victoria’s observed temperatures are tracking towards the upper limit of projections.

Table 9 Climate change projections for Victoria.

Climate hazard	Projection
Temperature	**Victoria will continue to get hotter in future.** • By 2050, under a high emissions scenario, Victoria can expect an average annual temperature increase of approximately 1.3 to 2.0 °C (central estimate of 1.6 °C). Separate regional-scale modelling suggests that warming could be as high as 1.4 to 2.4 °C), with enhanced warming under the driest future. • By 2050, under a low emissions scenario, the region can expect an average annual temperature increase of approximately 0.6 to 1.2 °C (central estimate of 0.9 °C). • There are likely to be increases in daily maximum and minimum temperatures. **Extreme temperatures are projected to increase.** • Hotter and more frequent hot days are projected, with fewer cold days and extreme cold nights. • More frequent and more intense heatwaves are likely. • By the 2050s, Victorian towns could experience around double the number of very hot days each year compared with the 1986–2005 average. **Victoria can expect longer fire seasons.** • By 2050, there are likely to be around 40 per cent more very high fire danger days. • The increase in fire danger days is likely to lead to a corresponding increase in total fire ban days. • Alpine regions could experience roughly double the increase in fire days projected for non-alpine regions of Victoria. • By the 2050s under a high emissions scenario, Bendigo, Ballarat, and Shepparton could experience a 60 per cent increase in the number of high fire danger days compared with 1986–2005. • The risk of pyroconvection – where heat and moisture generated by bushfires creates clouds and thunderstorms – is projected to increase in some regions of southern Australia.

Climate hazard	Projection
Precipitation	**Rainfall variability is high in Victoria. Overall, rainfall is expected to decrease, with larger decreases expected for winter and spring.** • Enhanced drying on the western slopes of the Alps in autumn through to spring is projected. • Extreme rain events are projected to become more intense. • Even in places where average rainfall is projected to decrease slightly, the rainfall from wet days, heavy rainfall and extreme daily rainfall are still projected to increase under a high emissions scenario. • This projected increase in daily extremes is likely to result in unprecedented events of heavy rainfall and flash flooding. **More time in drought is projected.** • Southern and eastern Australia are likely to spend more time in drought under a high emissions scenario. • Longer and more intense drought conditions are projected under a warming climate. • Evaporation is projected to increase across Victoria, with the greatest increases in spring and summer.
Sea level	**By 2050, sea levels are projected to rise by around 24 cm along the Victorian coast.** • Sea-level rise contributes to extreme events, which are caused by a combination of mean sea level, tides, storm surge, surface waves and coastal geometry. • Sea-level rise can also lead to higher storm surge and inundation levels.
Lightning and storms	**Projections of storms and lightning are uncertain.** • There may be an increase in conditions favourable for thunderstorm formation.
Wind	**By 2090, wind speeds are projected to decrease in southern mainland Australia in winter and south-eastern mainland Australia in autumn and spring.** • Winter decreases are not expected to exceed 10 per cent under a high emissions scenario. • Projected changes in extreme wind speeds are generally similar to those for mean wind. **Fewer but more intense east coast lows and tropical cyclones are possible.** • By 2050, the frequency of east coast lows is projected to decrease by up to 20 per cent under a high emissions scenario, primarily due to a reduction of events during winter. • Tropical cyclones are projected to become less frequent, but with a greater proportion of high-intensity storms, with stronger winds and greater rainfall.

Climate hazard	Projection
Compound extreme events	**A changing climate may bring more compound extreme events.** • Multiple lines of evidence, including from observations and climate projections, point to a continuing trend of more frequent compound extreme events. • While there are no specific projections for future occurrences of compound extremes in Victoria, it would be prudent to plan for increases in some compound extreme events.
Other climate-related variables	**Snow and frost** • In alpine regions, snow depths and snow extent are projected to decrease due to reductions in snowfall and increases in snow melt. • Victorian alpine areas are projected to continue to experience declining snowfall of between 35–75 per cent by the 2050s, under a high emissions scenario. • An increased risk of frost is possible in some regions and seasons, such as spring, due to an increase in cold clear nights, at least in the short to medium-term. In the long-term, higher temperatures will tend to prevent frosts, even on clear nights, leading to an overall decrease in their occurrence. **Solar radiation** • A projected increase (may exceed 10 per cent) in solar radiation in winter and spring in southern Australia is possible by 2090 under a high emissions scenario. **Humidity** • Humidity is likely to decline in Victoria, with only minor changes projected even under a high emissions scenario.

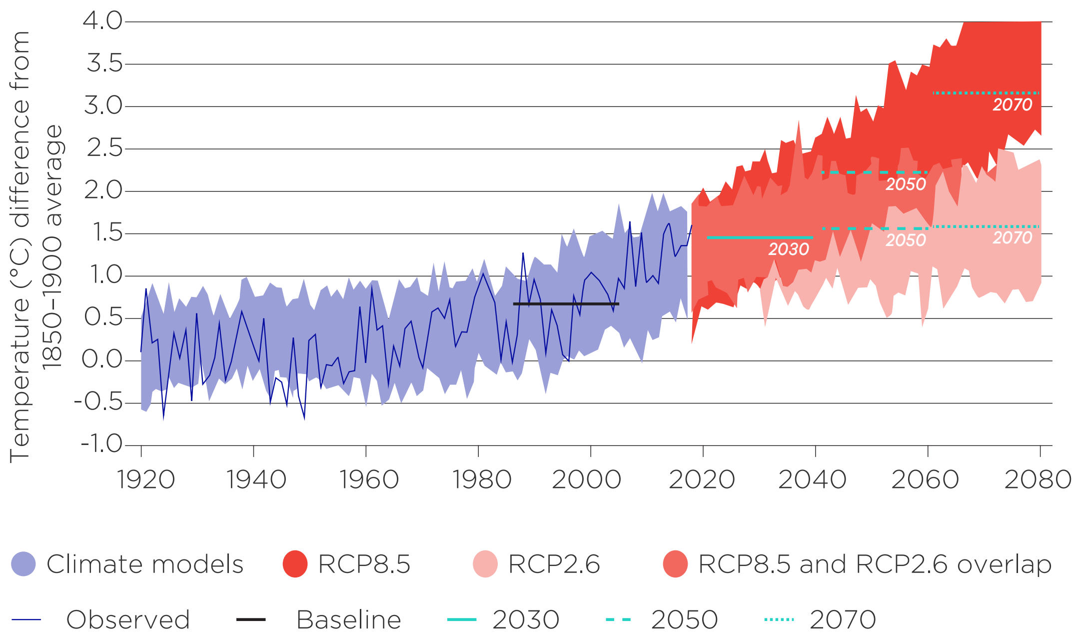

Figure 44 Average annual temperature of Victoria in observations for the past (thin black line) and models for the future (shading) relative to the pre-industrial era. Warming for the highest emissions scenario (RCP 8.5) and the lowest (RCP 2.6) are shown separately. The thicker horizontal lines show the 20-year average temperature from the average of all models for each period (Department of Environment, Land, Water and Planning (DELWP))

City projections

Greater Melbourne

The Greater Melbourne region extends from the coastlines of Port Phillip Bay, Western Port Bay and Bass Strait to the south; the Yarra Ranges in the east; and the Great Dividing Range to the north and west.

Average temperature in Melbourne is projected to continue to increase year-round. Under a high emissions scenario, maximum temperatures are projected to increase by 1.2 °C around 2030 and by 1.9 °C around 2070, compared with 1986-2005.

There will be more hot days and warm spells, and fewer cold nights and frosts. Melbourne is likely to experience more than double the number of days exceeding 40 °C by 2050, increasing from 0.8 to 2.7 days per year.

Decreases in winter and spring rainfall are likely, with increased intensity of extreme daily rainfall events.

Mean sea level will continue to rise and the height of extreme sea-level events will also increase.

There will be increased evapotranspiration, and a harsher fire-weather climate.

By 2050, under a high emissions scenario, Melbourne's climate is projected to be more like the current climate of Wodonga (about 250 km north east of Melbourne).

Projections for variables of interest

Figure 45 summarises the projected changes likely to occur across Victoria. These changes will be accompanied by year-to-year and decade-to-decade variability.

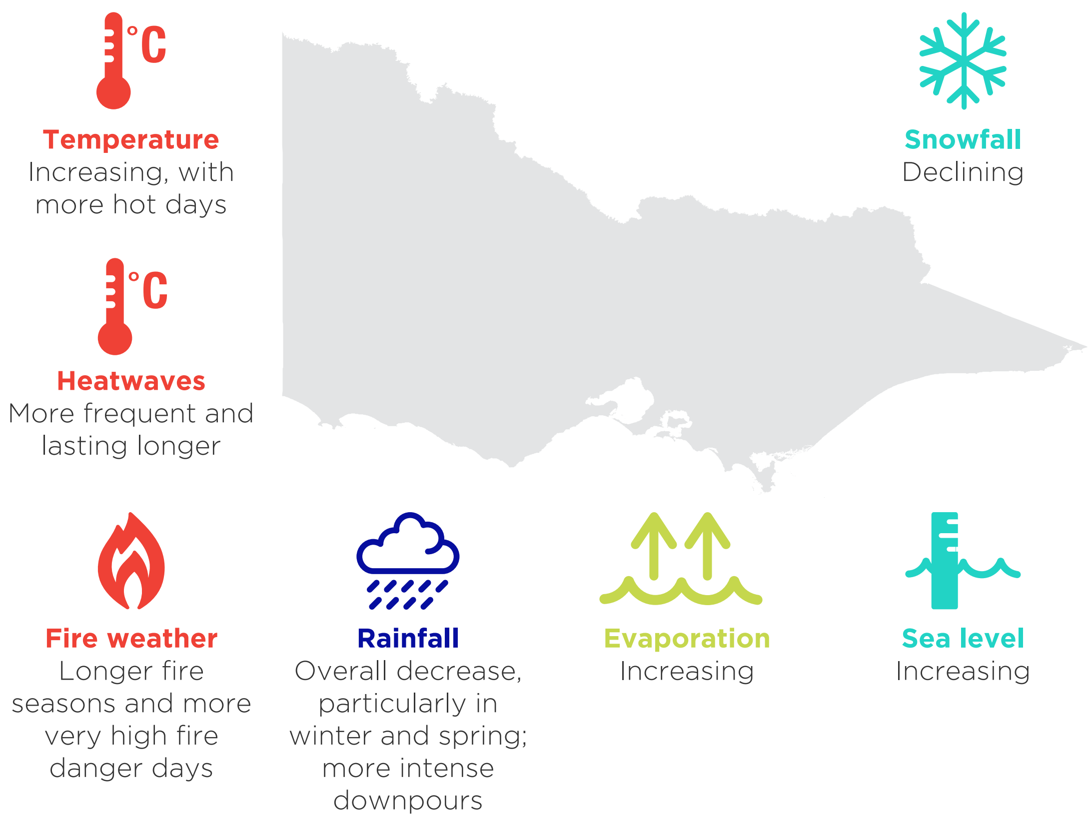

Figure 45 Projected changes across Victoria

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Appendix G. Climate change in Western Australia

This appendix presents information about the past, current and likely future climate of Western Australia (WA).

WA is already experiencing the impacts of climate change, with temperatures rising, heatwaves increasing in frequency and an increase in the number of days with dangerous bushfire weather conditions across the state.

The climate of WA will continue to change in future. Included in this appendix are projections for temperature, precipitation, sea-level rise, tropical cyclones, wind and other climate-related hazards. There is information for the state, as well as specific projections for Perth.

Climate of Western Australia

As the largest state in Australia, WA has one of the most diverse climates in the country. The state extends about 2,400 km from the monsoonal tropical north to the windswept coastal heaths of the far south (Figure 46).

In the south-west, the climate is temperate, with winter rainfall (June–August) and four distinct seasons. To the north, the climate is more tropical, with a wet and dry season. Much of the rest of the state is arid or semi-arid. Away from the coast, rainfall decreases and the differences in temperature between day and night increase.

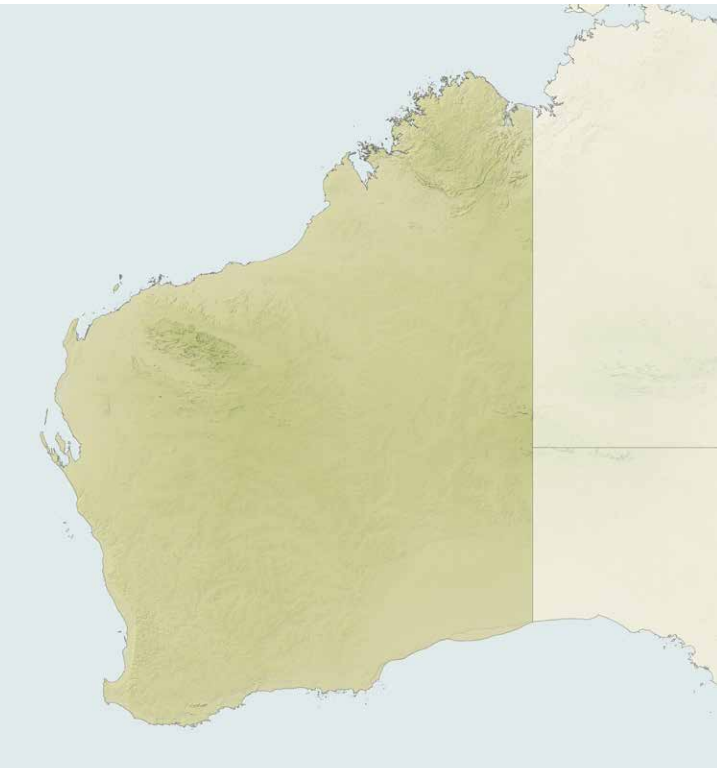

Figure 46 Topographic map of Western Australia

NSW/ ACT
NT
QLD
SA
TAS
VIC
WA

The highest annual precipitation in WA occurs in the far north, on the Mitchell Plateau in the Kimberley, and in the far south-west, between Pemberton and Walpole. Precipitation decreases south and north from both locations and with increasing distance inland from the coast (Figure 47).

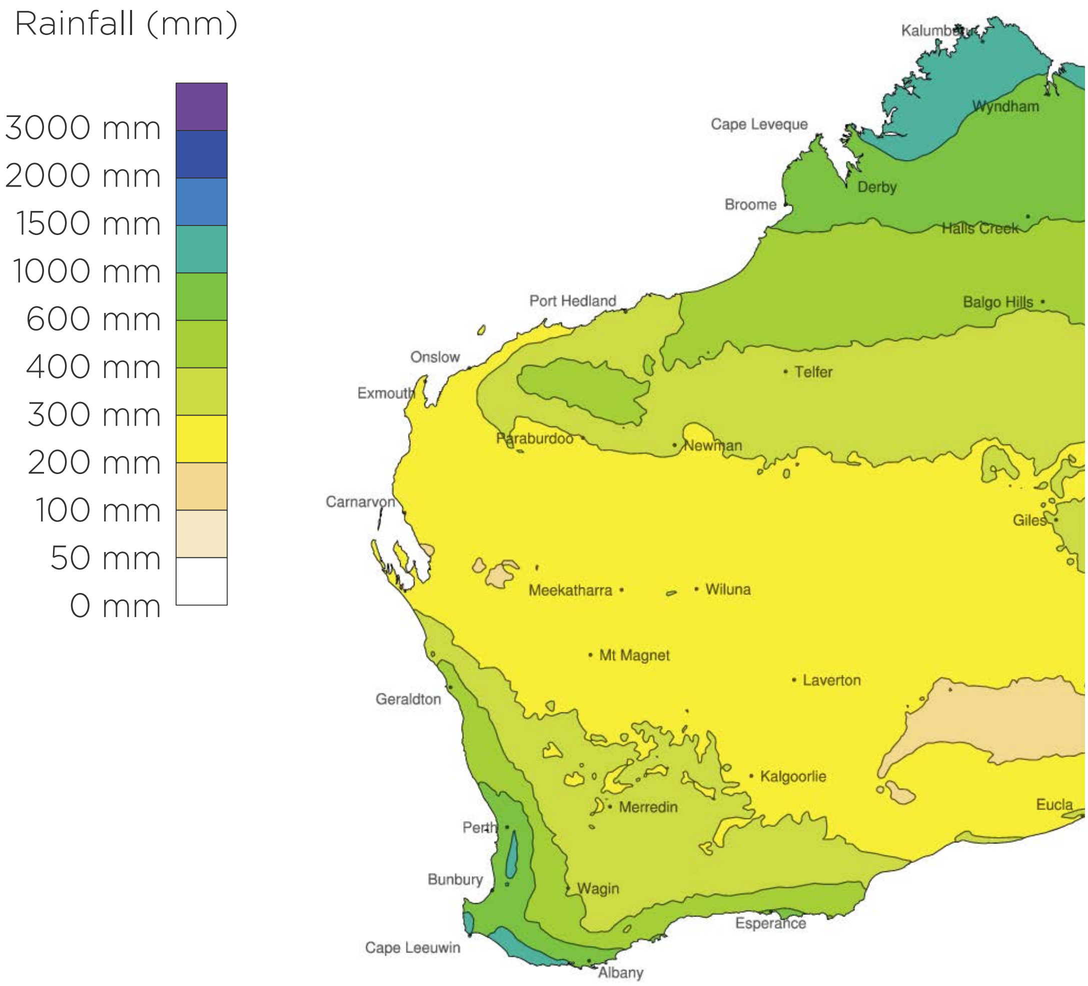

Figure 47 Average annual rainfall (mm) over Western Australia for 1981 to 2010 (Bureau of Meteorology)

Tropical cyclones develop offshore during the northern wet season, which lasts from about December to March. They frequently move inland between Broome and Onslow, although occasionally they have travelled south of Perth before curving inland. Tropical cyclones can be highly destructive, but they are also beneficial, bringing widespread rain to otherwise parched inland areas.

The weather of WA is affected by the movement of an anticyclonic system (large wind system that rotates about a centre of high atmospheric pressure) that produces winds in an east–west direction across Australia for about half the year. In winter, this system moves to the north and is responsible for clear skies, sunny days and easterly winds in the tropics.

To the south of the anticyclonic system, westerly winds and a procession of cold fronts associated with the 'roaring forties' (strong westerly winds occurring between 40 °S and 50 °S) bring cool, cloudy weather and rain and westerly gales along the southern coast. By summer, the anticyclonic belt has moved so far south that its axis is off the southern coast. Easterly winds prevail over most of WA, but in the far north a depression develops, bringing westerly monsoon wind patterns to the coastal districts northeast of Onslow and into parts of the Kimberley.

Climatic conditions can change greatly from year to year in response to large-scale phenomena (Figure 3), including:

- the west coast trough: a semi-permanent feature of the synoptic pressure pattern near the west coast of Australia during the warmer months. It is the dominant influence on west coast weather at that time of the year. Depending on the location of the trough, areas to the east of it can experience hot days, with temperatures above 40 °C and the possibility of thunderstorms. To the west of the trough, there are milder conditions with sea breezes.
- the subtropical ridge: the ridge is a belt of high-pressure systems across the mid-latitudes, which moves north in winter and south in summer. From November to April it can block cold fronts for days or weeks. In winter it moves north, allowing cold moist air to create rain.
- the El Niño – Southern Oscillation: ENSO has a limited influence in WA compared with the east coast. However, during an El Niño, winter and spring rainfall can be lower than average and fewer tropical cyclones occur. During a La Niña, the northern regions of WA are likely to be wetter than normal, and more tropical cyclones may occur.
- the Indian Ocean Dipole: changes in sea-surface temperature between the western and eastern Indian Ocean and to the north of Australia from May to October affect rainfall in WA. In its positive phase, the IOD can bring less rain to parts of WA, while in its negative phase it can bring more.
- the Southern Annular Mode: a north-south movement of the westerly wind belt that circles Antarctica and drives cold front movement in the south of the region, influencing rainfall throughout the year. In winter, a positive SAM results in a reduction of rainfall for the south-west tip and more rainfall along the remainder of the southern coast of WA, whereas during a negative phase the impacts tend to be reversed. SAM does not have an impact on WA rainfall during summer.

Past and recent climate

Temperature

All of WA has warmed, with average temperature increasing by 1.3 °C since 1910 (Figure 48). The 2011–2020 average temperature in WA was around 0.9 °C above the 1961–1990 average.

The hottest year on record for WA was 2019, followed by 2020 as the second hottest year.

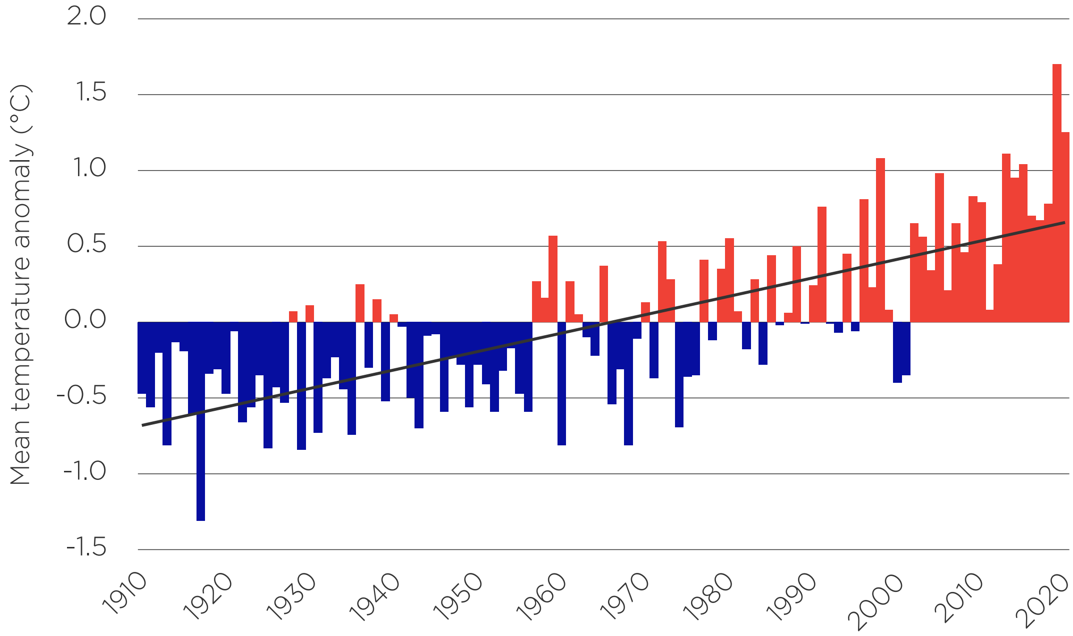

Figure 48 Annual mean temperature anomalies in Western Australia compared with the 1961–90 average, with linear trend (0.12 °C per decade). Blue bars represent cooler-than-average years, while red bars are hotter-than-average years (Bureau of Meteorology)

Since the 1950s, the frequency of hot spells has increased across WA. The intensity and duration of hot spells have also increased, except along parts of the south coast.

The south-west region of WA has experienced an increase in various drought-related variables, including an increase in the frequency of exceptionally low rainfall totals covering large areas, particularly in winter.

Rainfall

Since 1900, rainfall has increased over most of WA, apart from the far west and south-west where it has declined. At the state level, the significant rainfall in the Kimberly and Pilbara regions has masked the large decrease in rainfall experienced in south-west WA (Figure 49). With approximately 90 per cent of the population of WA based in the south-west, this continuing drying rainfall trend will have a significant impact on water supply and water-dependant industries, such as agriculture, in the region.

Since 1999, annual rainfall in south-west WA has been 20 per cent lower than the long-term average, with the greatest declines experienced during the growing season. The decline in rainfall in the south-west has been larger than anywhere else in Australia and is consistent with increasing greenhouse gas concentrations. While heavy rainfall events still occur in this region, they are often interspersed by longer dry periods.

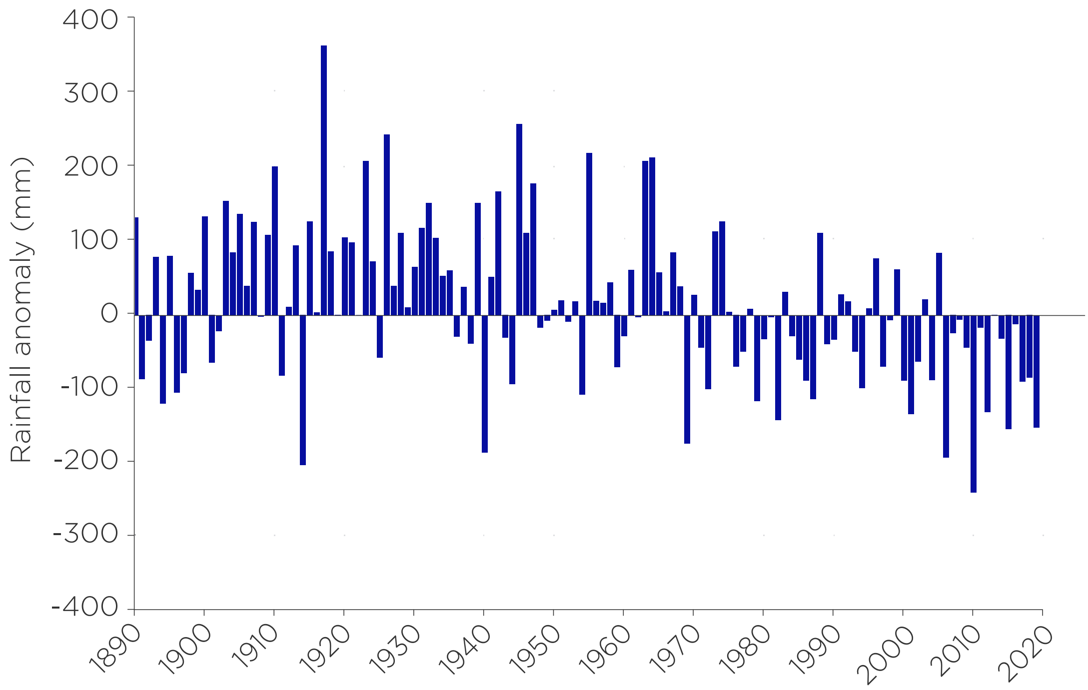

Figure 49 Rainfall anomaly (mm) for south-west Western Australia, April-October (CSIRO and Bureau of Meteorology (2020). State of the Climate 2020)

Rainfall has increased in most areas of the Kimberley and Pilbara, with five of the 10 wettest years in the past 210 years in the Pilbara occurring in the past two decades. Tropical cyclones are responsible for most of the extreme rainfall events across north-west WA and generate up to 30 per cent of the total annual rainfall near the Pilbara coast. Over the past 40 years, the frequency of tropical cyclones has not changed significantly in WA, but there is some evidence that the frequency of the most intense cyclones has increased.

Sea level

Between 1966 and 2019, mean sea levels rose by a total of 8–13 cm along the WA coastline, at an average rate of approximately 2–3 mm per year. This is comparable with the global mean rate of sea-level rise over the same period.

Extreme sea-level events affect the coastline of WA, resulting in inundation, erosion and coastal flooding. Mean sea-level rise is an increasingly important contribution to extreme sea-level events in the region, especially along the coast between Fremantle and Esperance. For example, in 2019 sea-level rise represented about a 20 per cent contribution to extreme sea-level events at Fremantle.

Fire weather

The number of days with dangerous weather conditions for bushfires has increased in nearly all locations of the state, with significant increases in Perth, Kalgoorlie and Broome. Fire weather danger has increased more in winter and spring than in summer and autumn.

Bushfire conditions in many parts of the state, especially the northern and interior regions, depend highly on fuel availability, which is governed largely by rainfall. In the Kimberley, where abundant rainfall and bushfires are common, climate change is not expected to change the frequency of fire. However, when fire does occur, fire behaviour is likely to be more extreme.

During the 2019–20 bushfire season, the bushfire activity across WA, and other regions of Australia, was unprecedented in area burned in densely populated regions, and its impacts were disastrous.

Climate change projections

WA is already experiencing climate change impacts, which vary across the region. The state's climate is projected to continue to change in future.

In 2015, CSIRO and the Bureau of Meteorology released national projections of Australia's likely future climate through the Climate Change in Australia website. The projections presented here (Table 10) are largely based on these national projections, with some regional information from WA Government websites and summary reports. The climate variables presented are those that are likely to affect Australia's electricity networks.

New regional climate change projections, downscaled to higher resolutions, for priority regions in Western Australia are under development through the 'Climate Science Initiative', as part of the Western Australian Climate Policy (2020).

Scientific confidence in projections varies from variable to variable and, in some cases, from region to region.

Projections are typically for a range of years, such as 2040–59, referred to here as '2050'. Projections are relative to 1986–2005 (unless otherwise stated) and are provided for both a high emissions scenario (RCP8.5) and a low emissions scenario (RCP2.6), where available (Table 10).

Year by year and decade by decade, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years and for rainfall.

Figure 50 provides a comparison of the current mean number of hot days (greater than 35 °C) per year across key locations in WA and hot days projected in the 2090s under a high emissions scenario.

Table 10 Climate change projections for Western Australia.

Climate hazard	Projection
Temperature	**WA will continue to get hotter in future, with greater warming expected in the interior.** • By 2050, under a high emissions scenario, WA can expect an average annual temperature increase of approximately 1.5 to 2.4 °C (central estimate of 2.0 °C). • By 2050, under a low emissions scenario, WA can expect an average annual temperature increase of approximately 0.8 to 1.6 °C (central estimate of 1.2 °C). • Mean, maximum and minimum temperatures are projected to increase by similar amounts. **Extreme temperatures are projected to increase in line with projected mean temperatures.** • The temperature and frequency of very hot days are expected to increase. • Heatwaves will get longer and more intense. • The frequency of hot spells will generally increase in the southern half of the state and the duration will increase in northern coastal areas. **WA can expect longer fire seasons.** • The number of days with severe fire danger rating is likely to increase over most of WA in response to increased temperatures and decreased rainfall. • The greatest projected increases in severe fire days are in the Pilbara and northern rangelands. • In the Kimberley and northern parts of the region, where rainfall is projected to remain unchanged, changes in fire risk are less certain and may stay about the same. However, fire behaviour is projected to be more extreme.

Climate hazard	Projection
Precipitation	**WA is likely to experience a drying trend, apart from the monsoonal north where projected rainfall changes remain unclear.** • The drying trend in the south-west will continue under climate change. • The decline in winter rainfall in the south-west of the state may be as great as 50 per cent under a high emissions scenario by 2090. • By 2090, under a high emissions scenario, every year's winter rainfall in the south-west is projected to be lower than the current average. • Rainfall is projected to decline in the Pilbara region and be relatively unchanged in northern and central parts of WA. • An increase in the intensity of heavy rainfall events is projected, although with less confidence in south-west WA due to the large projected reduction in rainfall there. • Rainfall variability is projected to become more intense, leading to more very wet and very dry years. • Decreases in runoff are projected for south-west WA. **Time spent in drought is projected to increase.** • The number of dry days is likely to increase over all of WA. • Drier and hotter conditions are likely to lead to decreases in soil moisture and runoff because of increased water loss from plants and soils (evapotranspiration). This could further exacerbate drought conditions. • Agricultural drought months (extremely low soil moisture) are projected to increase by up to 20 per cent over most of Australia by 2030 and up to 80 per cent in the south-west by 2070. • The duration and frequency of droughts over the south-west are projected to increase for all emissions scenarios.
Sea level	**Higher sea levels and more frequent sea-level extremes are projected.** • By 2050, sea levels are projected to rise by approximately 24 cm along the WA coast. • Under future climate conditions, extreme sea levels are expected to change due to increases in regional sea level and changes in climate and meteorological events. • Sea-level rise can also lead to higher projected storm surge and inundation levels.
Lightning and storms	**Projections of storms and lightning are uncertain.** • A reduced likelihood of the formation of storms that bring rainfall to south-west WA is projected. • Projected changes in storms and lightning are uncertain as scientists are unable to directly model future thunderstorm activity due to its local and temporal scale.
Wind	**Average wind speed is projected to remain unchanged.** • Projections are for relatively small changes in mean annual wind speed. • Wind speed will likely decrease in winter in the south-west, but no change is expected to occur in the Kimberly and interior of the state.

Climate hazard	Projection
Tropical cyclones	**Tropical cyclones are projected to become less frequent, but the proportion of the most intense storms is projected to increase.** • The number of tropical cyclones is projected to decrease by about 12 per cent for this region of Australia.
Compound extreme events	**A changing climate may bring more compound extreme events.** • Multiple lines of evidence, including from observations and climate projections, point to a continuing trend of more frequent compound extreme events. • While there are no specific projections for future occurrences of compound extremes in WA, it would be prudent to plan for increases in some compound extreme events.
Other climate-related variables	**Frost** • Frost frequency is expected to decrease as temperatures increase. However, in agricultural areas, generally drier winter conditions and reduced cloudiness may cause frost risk to persist for longer than expected. **Solar radiation** • Little change in solar radiation is projected. **Humidity** • Relative humidity is projected to decline in inland regions and in areas where rainfall is projected to decline. By 2090, humidity is likely to decrease in winter and spring as well as annually. **Evaporation** • Evaporation is projected to increase after 2030, especially in the far north and south. Potential evapotranspiration is also projected to increase over WA.

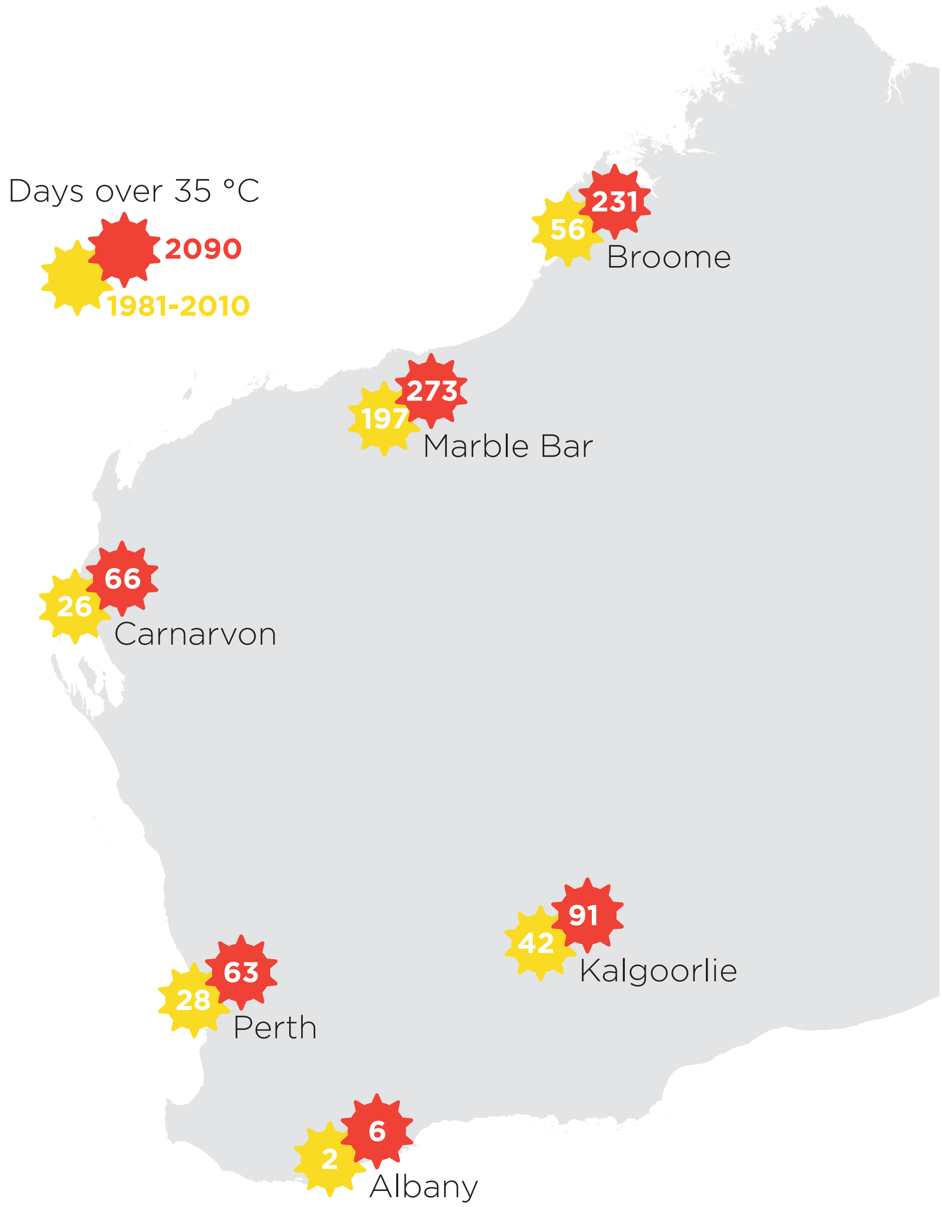

Figure 50 Comparison of the average number of hot days (greater than 35 °C) per year currently (between 1981 and 2010) and in the 2090s under a high emissions scenario (RCP8.5) (WA Department of Water and Environmental Regulation (DWER))

City projections

Perth

Perth is situated between the Darling Ranges and the Indian Ocean, and along the banks of the Swan River.

Average temperature in Perth is projected to continue to increase year-round. Projected temperature increases by 2090 range from 1.7 °C under a medium emissions scenario to 3.5 °C under a high emissions scenario (relative to the 1986–2005 average).

There will be more hot days and warm spells in Perth. Under a high emissions scenario, the number of hot days (maximum temperatures exceeding 35 °C) per year in Perth is projected to increase from 28 to 63, while the number of very hot days (exceeding 40 °C) per year is projected to increase from four to up to 20 by 2090.

A continuation of the trend of decreasing winter and spring rainfall in Perth is projected. Rainfall changes in other seasons are unclear. Extreme daily rainfall events are expected to increase in Perth in future.

There will be increased evapotranspiration, fewer frosts and a harsher fire-weather climate.

Mean sea level will continue to rise and the height of extreme sea-level events will also increase.

By 2050, under a high emissions scenario, Perth's climate is projected to be more like the current climate of Jurien Bay, which is about 220 km north of Perth.

Projections for variables of interest

Figure 51 summarises the changes likely to occur across Western Australia. These changes will be accompanied by year-to-year and decade-to-decade variability.

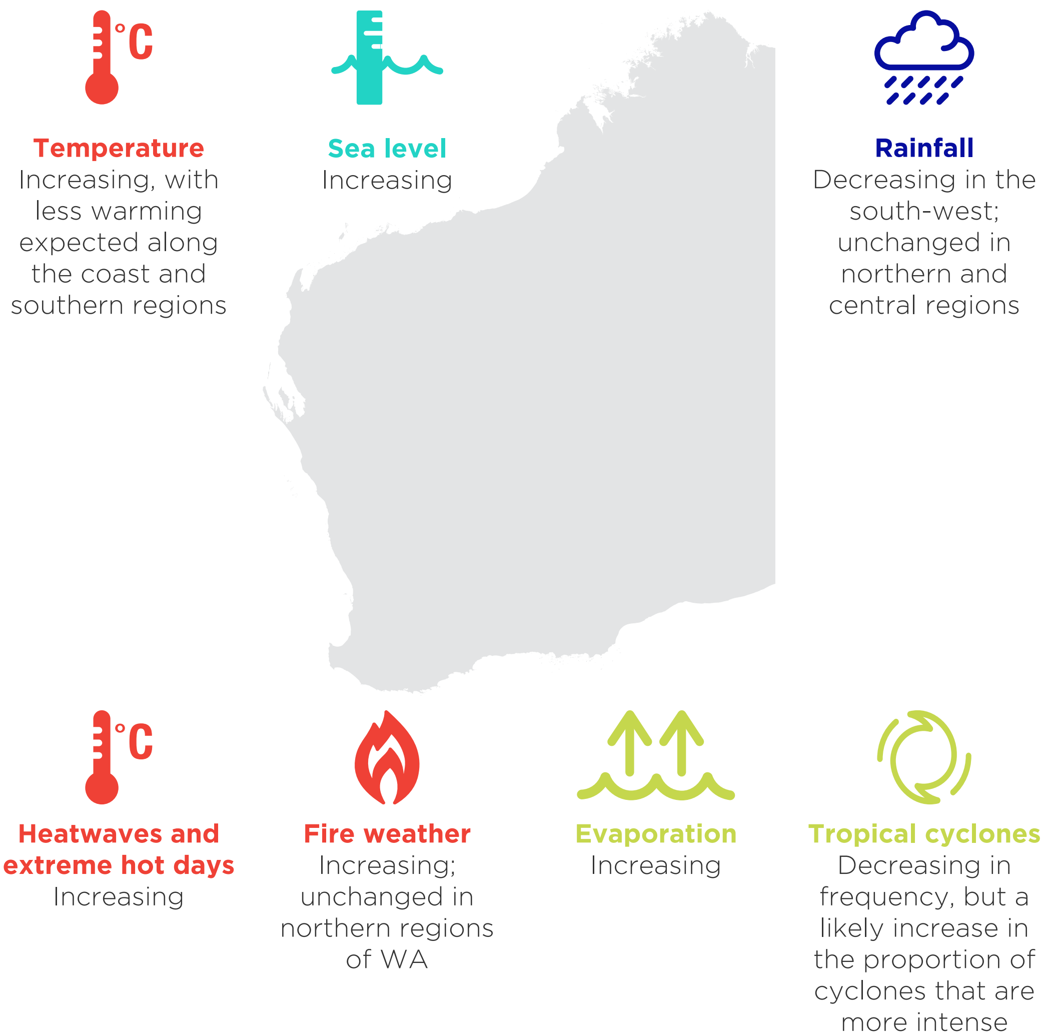

Figure 51 Projected changes across Western Australia

NSW/ACT
NT
QLD
SA
TAS
VIC
WA

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