Victoria's Climate Science Report 2024

VICTORIA State Government | Energy, Environment and Climate Action

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We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it.

We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

DEECA is committed to genuinely partnering with Victorian Traditional Owners and Victoria's Aboriginal community to progress their aspirations.

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Minister's foreword

Victoria's Climate Science Report 2024 is founded on state-of-the-art climate science. To manage the risks of climate change across the state, the *Climate Change Act 2017* requires the government to develop a climate science report every 5 years. This report builds upon Victoria's Climate Science Report 2019 and provides a summary of how Victoria's climate has changed and will continue to change under a warming climate. Investment in this report includes commissioning updated climate projections for Victoria and reviews by leading academic institutions and experts on climate hazards, such as droughts, bushfires, floods, heatwaves and sea-level rise.

Over the past few decades, Victoria has become hotter, drier during the cool season, and has experienced more extreme weather events. These changes are expected to continue under a warming climate. Increasing average temperatures, shifting rainfall patterns, rising sea levels and increasing intensity and frequency of extreme events, such as heatwaves, droughts, bushfires and floods, will continue to pose significant risks to the state's communities, ecosystems, coasts, industries and infrastructure.

The Victorian Government is leading efforts to reduce greenhouse gas emissions, with some of the most ambitious emissions reduction targets in the world. With these enshrined in legislation, we are working towards halving our emissions by 2030 and reaching net zero by 2045.

Victoria's Climate Science Report 2024 builds upon an evidence base that enables the Victorian Government to deliver a range of 5-yearly legislated requirements. These include adaptation action plans across 7 systems used by local governments, businesses and communities. Together with the community-led regional climate change adaptation strategies, these plans are a major step forward in ensuring we are ready to respond to the changing climate.

The Victorian Government is committed to working with the scientific community to provide robust and up-to-date data to strengthen our understanding of how the climate is changing and what that means for our state both now and in the future. We will continue to proactively engage with leading experts and the latest science as we work towards net zero emissions and a climate-resilient state.

The Hon. Lily D'Ambrosio MP
Minister for Climate Action
Minister for Energy and Resources
Minister for the State Electricity Commission

First Peoples and climate change

The Victorian Government acknowledges and respects Victorian Traditional Owners as the original custodians of Victoria's lands and waters. In the face of colonisation and dispossession, Victoria's Aboriginal communities remain diverse and resilient, with deep and ongoing connections to Country.

The Victorian Government acknowledges the nuance and sophistication of traditional knowledge systems developed and maintained by Aboriginal communities to sustainably manage the long-term and multi-layered relationships with their land, waters and air. The concept of holding both Aboriginal and western world views can enable a dialogue between Traditional Owners and government that does not exclude one or the other world view. The Statewide Caring for Country Partnership Forum, established under Pupangarli Marnmarnepu 'Owning Our Future' Aboriginal Self-Determination Strategy 2020–2025, recognises this approach as 'two ways of knowing'.

The Victorian Government acknowledges that climate change is occurring at its current pace and scale due to global industrialisation and the associated burning of fossil fuels. Colonisation has led to the combustion of fossil fuels on an industrial but inequitable scale around the world and in Victoria, and the resulting climate change has led to the destruction and damage of previously sustainable natural systems in Victoria. In contrast, practices established by Aboriginal communities over thousands of generations have laid the foundation of a culture designed to sustainably care for Country.

The Victorian Government acknowledges that the impact and structures of colonisation still exist today (Department of Environment, Land, Water and Planning, 2019). Colonisation has created disparities in health and wellbeing through the dispossession of traditional land and waters, suppression of traditional knowledge and structural racism (HEAL Network & CRE-STRIDE, 2021). Given this colonial legacy, Aboriginal people are subject to higher rates of socio-economic disadvantage, which in turn exacerbates the impact of climate change on the health of these populations (Commonwealth of Australia (Department of Health and Aged Care), 2023).

Climate change imposes additional disproportionate impacts on Aboriginal communities by compounding the loss of traditional connections to Country and by posing a risk to cultural heritage, including traditional laws, customs and practices. Climate change impacts on Country include sea-level rise, the presence or absence of water, changes in plant and animal behaviour, and increased intensity and frequency of bushfires and extreme weather events.

The Victorian Government recognises that only Traditional Owners can speak for Country and the knowledge, know-how, skills and practices of traditional knowledge systems. In accordance with the Victorian Aboriginal Affairs Framework 2018–2023, the Victorian Government is committed to embedding self-determination as the guiding principle in Aboriginal affairs (State of Victoria, 2018). We acknowledge our obligation to ensure that intellectual property rights and data sovereignty are maintained and protected and that supporting self-determination involves transferring decision-making control and resources to Aboriginal communities on matters affecting their lives.

Aboriginal communities have cared for Country for millennia and continue to draw on traditional knowledge systems to achieve climate change mitigation, adaptation, hazard preparedness and disaster response. Cultural burning is one form of land management practised by Aboriginal people that can reduce risk while mitigating greenhouse gas emissions by reducing the number, scale and severity of bushfires (Commonwealth of Australia (Department of Health and Aged Care), 2023). Aboriginal peoples have expressed that they know what is best for their Country, and there is an urgent need to centre and strengthen the role of Aboriginal knowledges in the fight against climate change (HEAL Network & CRE-STRIDE, 2021).

Victoria's Climate Science Report 2024 draws on traditions of western science to understand Victoria's past, present and future climate.

The Victorian Government is committed to working in partnership to support Traditional Owner rights to restore traditional knowledge systems and return resources and decision-making powers to Traditional Owners. This will begin the complex task of healing Country and community while ensuring Victoria's First Peoples benefit from the transition to a climate-resilient and net zero economy.

As we look towards future Victorian climate science reports, we commit to working with the Statewide Caring for Country Partnership Forum to better recognise two ways of knowing in science and policy across the climate action portfolio.

About this report

Victoria's Climate Science Report 2024 (VCSR24) is a statutory requirement under the *Climate Change Act 2017*. A report is required every 5 years, with the first report released in 2019.

VCSR24 summarises the best available scientific evidence on climate for our state. It builds on Victoria's Climate Science Report 2019 (VCSR19), which remains a relevant component of our evidence base. Our understanding of the past and future climate is continually improving based on new observations, updated science on climate processes, and improvements in climate modelling. VCSR24 synthesises:

- information on the changing climate within the global and Victorian context
- the methodology and findings from the latest climate projections for Victoria
- the science of climate hazards relevant to Victoria and the effects of climate change on these hazards
- how climate science can be applied in decision-making processes using case studies.

Investment in this report includes commissioning updated climate projections for Victoria and reviews from leading academic institutions and experts on climate hazards, such as droughts, bushfires, floods, heatwaves and sea-level rise. This report sets a framework for considering climate science information, including plausible futures in decision-making processes. This is a notable difference from VCSR19.

Since the release of VCSR19, the Intergovernmental Panel on Climate Change (IPCC) has released its Sixth Assessment Report (AR6), which contains the latest global scientific, technical and socio-economic assessments of climate change.

Climate modelling is a key source of the evolving evidence base on our likely future climate. Based on the best climate science practically available at the time, VCSR19 used the fifth generation of global climate modelling from the internationally recognised World Climate Research Programme's Coupled Model Intercomparison Project (CMIP5). VCSR24 adds to the suite of climate projections for Victoria based on the sixth generation of global climate modelling (CMIP6).

CMIP6 models describe future greenhouse gas emissions scenarios using Shared Socio-economic Pathways (SSPs) consistent with the IPCC's AR6. The models provide more global simulations at a higher resolution than were previously available, and are based on the latest understanding of ocean, atmospheric and terrestrial processes.

Projections in the VCSR24 report include:

- 34 global climate models at 80 to 250 km resolution
- more detailed nationwide modelling from the Australian Climate Service and Queensland Government at 10 to 17 km resolution
- regional modelling sourced from the New South Wales and Australian Climate Modelling 2.0 project (NARCliM2.0) at approximately 4 km resolution over Victoria.

These downscaled models provide climate information at more regional and local levels that are useful for decision-making and planning in Victoria.

Climate science will continue to evolve and advance. Over the next 5 years, the Victorian Government will continue to collaborate with commonwealth, state and territory governments and key partners to access the latest science and develop updated , and improved national and regional climate projections. This will ensure that the Victorian Government provides robust and up-to-date data to support decisions and risk management related to climate change.

Executive summary

Victoria's changing climate

Victoria's climate has warmed since the 19th century, becoming drier in recent decades and experiencing more frequent and intense climate hazards. As global greenhouse gas emissions increase, these changes are projected to continue.

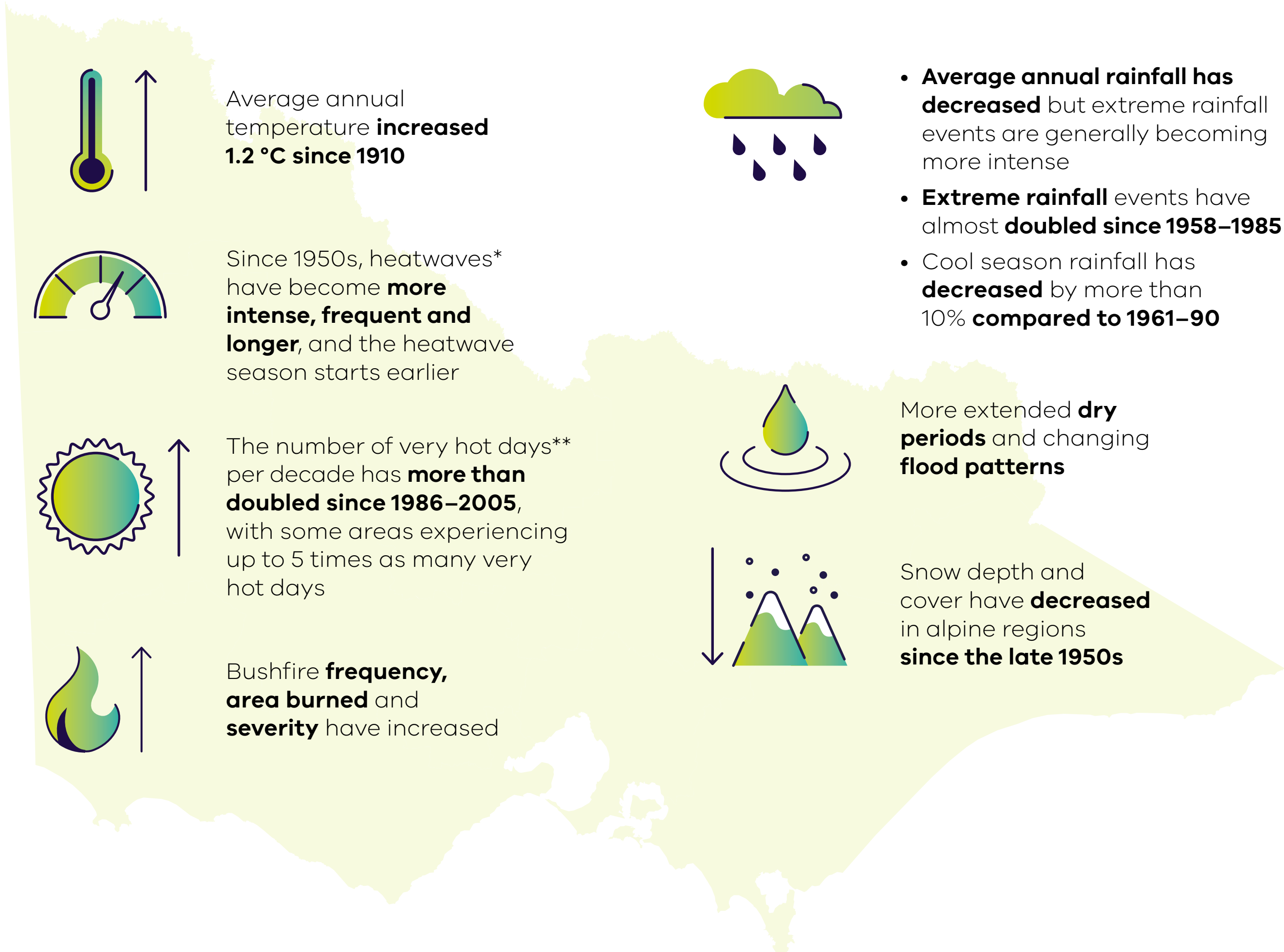
The global climate system is changing, with rising temperatures and more frequent and intense extreme weather events. These changes are predominantly caused by increasing concentrations of greenhouse gases (such as carbon dioxide) in the atmosphere, primarily due to human activities such as fossil fuel combustion and land-use change. Human-caused greenhouse gas emissions have contributed to an increase of over 1.1 °C in global average surface temperature from the pre-industrial baseline period (1850–1900) to the last decade (2011–2020) (IPCC, 2023).

Victoria's climate is shaped by large-scale climate drivers (such as the El Niño–Southern Oscillation), seasonal influences and weather systems. It varies across regions and from year to year and decade to decade. Despite these natural variations, the long-term warming trend is evident in Victoria's climate.

Victoria's climate has warmed by about 1.2 °C since national records began in 1910, and by around 1.4 °C since the pre-industrial era. This is slightly higher than the global average of 1.1 °C since the pre-industrial era. Hot days and heatwaves have become hotter and more frequent.

Victoria's average rainfall has decreased in all seasons except summer, with more than a 10% decline in cool season rainfall over the past 30 years. The most extreme rainfall events have increased, especially short-duration extreme rainfall.

Victoria's climate has already changed. Observed as of 2024:



* A heatwave is defined as at least 3 consecutive days above the 95th percentile of daily average temperatures

** Very hot days are defined as days with daily maximum temperature exceeding the 99.9th percentile

Updated projections for Victoria

Climate projections provide information on plausible climate conditions decades to centuries into the future to support decision-making, planning and adaptation. Ongoing advances in climate science and modelling are improving climate projections. Projections need to be regularly updated to take advantage of this.

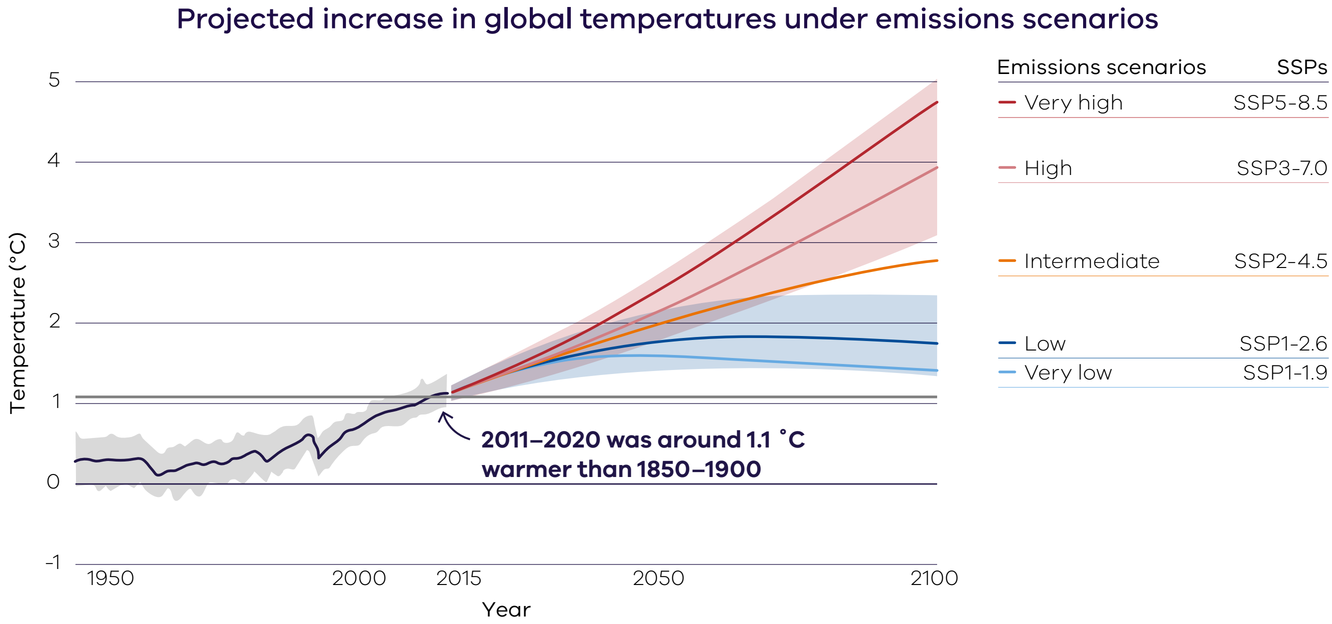
VCSR24 adds to the suite of climate projections for Victoria presented in VCSR19, based on the latest (sixth) generation of global climate modelling (CMIP6). In alignment with Australia's National Partnership on Climate Projections (NPCP) and internationally recognised guidance, the 'low emissions scenario' (SSP1-2.6) and 'high emissions scenario' (SSP3-7.0) have been prioritised by regional climate modellers across Australia and for analysis in VCSR24.

Additional emissions scenarios are explored in this report where relevant studies have been produced.

Under this new modelling, Victoria is expected to continue to become hotter and have a drier cool season.

Victoria's average temperature is projected to continue to warm over the century, with more warming projected for higher future global emissions of greenhouse gases. Warming will only stabilise if global emissions reach net zero. Victoria is also virtually certain to experience hotter and more frequent hot days.

While future changes in rainfall are less certain, Victoria is expected to continue to become drier during the cool season and may experience more extreme rainfall events. Despite these long-term trends, cooler and wetter periods will still occur in the future due to natural variations in the climate.



Projected average global temperatures under 5 possible emissions scenarios (very low, low, intermediate, high and very high) up to 2100 relative to the 1850–1900 average, as shown in the IPCC Sixth Assessment Report. The black line shows observational data of global average temperature from 1950 to 2015. The shading represents the range of uncertainty for the low (blue shading) and high (pink shading) emissions scenarios. Source: Adapted from IPCC, 2023.

Victoria's future climate will depend on the global emissions scenario

Low emissions scenario	High emissions scenario
Projections compared to 1986–2005 baseline*	
Average temperature will increase by: • 1.1 °C (0.5–1.5 °C) by 2050 • 1.0 °C (0.6–1.8 °C) by 2090	Average temperature will increase by: • 1.5 °C (1.1–1.9 °C) by 2050 • 3.1 °C (2.2–3.6 °C) by 2090
Hot days of the year hotter by: • around 1 °C by 2050 • around 1 °C by 2090	Hot days of the year hotter by: • around 2 °C by 2050 • around 4 °C by 2090
Average number of heatwave days per year: • around 30 days by 2050 • around 30 days by 2090	Average number of heatwave days per year: • around 40 days by 2050 • around 60 days by 2090
Decline in cool season rainfall More intense extreme rainfall	Larger decline in cool season rainfall Increasingly intense extreme rainfall
Increase in average number of dry months: • around 40% by 2050 • around 40% by 2090	Increase in average number of dry months: • around 60% by 2050 • around 100% by 2090
Projections compared to 1995–2014 baseline**	
Sea-level rise of: • 0.12 to 0.27 m by 2050 • 0.31 to 0.83 m by 2120	Sea-level rise of: • 0.13 to 0.32 by 2050 • 0.52 to 1.29 m by 2120

Very high emissions scenario

Sea-level rise of:

- 0.14 to 0.34 m by 2050
- 0.61 to 1.50 m by 2120

* Downscaled CMIP6 projections, based on plausible low (SSP1-2.6) and high (SSP3-7.0) emissions scenarios. Average temperatures are given as the median followed by the range. Hot days are defined as days with daily maximum temperature exceeding the 99th percentile. Heatwave days are defined as 3 consecutive days with daily average temperature exceeding the 95th percentile. A dry month is defined as a month below the 10th percentile in average monthly precipitation.

** CMIP6 projections, based on low (SSP1-2.6), high (SSP3-7.0) and very high (SSP5-8.5) emissions scenarios. Sea level is lowest and highest as taken from the Melbourne, Warrnambool or Gabo Island locations from projected changes (17–83% uncertainty range). Very high emissions scenario provided as additional CMIP6 sea-level rise projections study available for Victoria.

Hazards affecting Victoria

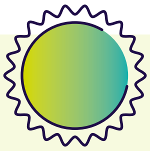
The climate hazards that affect Victoria, including floods, heatwaves, drought, bushfires and sea-level rise, are also changing under a warming climate.

The historical trend of small floods in Victoria becoming smaller and large floods becoming larger is likely to continue at a greater rate.

Heatwaves are expected to increase in intensity, frequency and duration in Victoria as the climate continues to warm. Drought duration and intensity may increase, and fire weather and fire activity are projected to increase, with changes dependent on the location. Sea-level rise around Victoria's coastline is expected to accelerate and continue to the end of the century and well beyond.

Climate hazards in Victoria are changing under a warming climate

Heatwaves



The **more the planet warms**, the **longer, more intense**, and **more frequent** heatwaves will be

Projections indicate **significant increases** in the intensity, frequency and duration of **concurrent droughts and heatwaves**

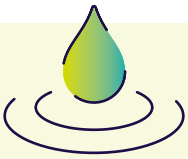
Bushfires

Observations and climate change studies suggests **fire activity is increasing** in many fire-prone ecosystems and will continue to do so

Observed changes in fire regimes, activity and fire drivers are **likely to escalate** with an increase in global warming

Projected changes are likely to lead to **significant shifts** in fire activity across Victoria

Floods

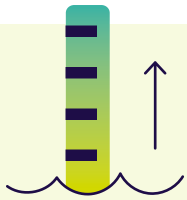


Extreme floods (1-in-100 events) are projected to **increase in magnitude** in many parts of Victoria by 2100

The historical trend of **small floods becoming smaller** and **large floods becoming larger** will continue at a greater rate

If greenhouse gas emissions continue to rise at a moderate to high rate, **flood risks will double by the end of this century**

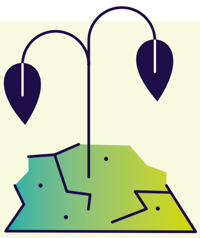
Sea-level rise



The rates of sea-level rise to the north and **south-east of Australia** have been significantly higher than the global average, which is accelerating

Sea levels will continue to rise in the next 100 years under all emissions scenarios. Following a lower emissions pathway will help to **slow the rate** of sea-level rise in the longer term

Drought



Droughts have become **significantly warmer** in the 21st century. Future droughts will be hotter than past droughts, which can affect compounding heat and drought events

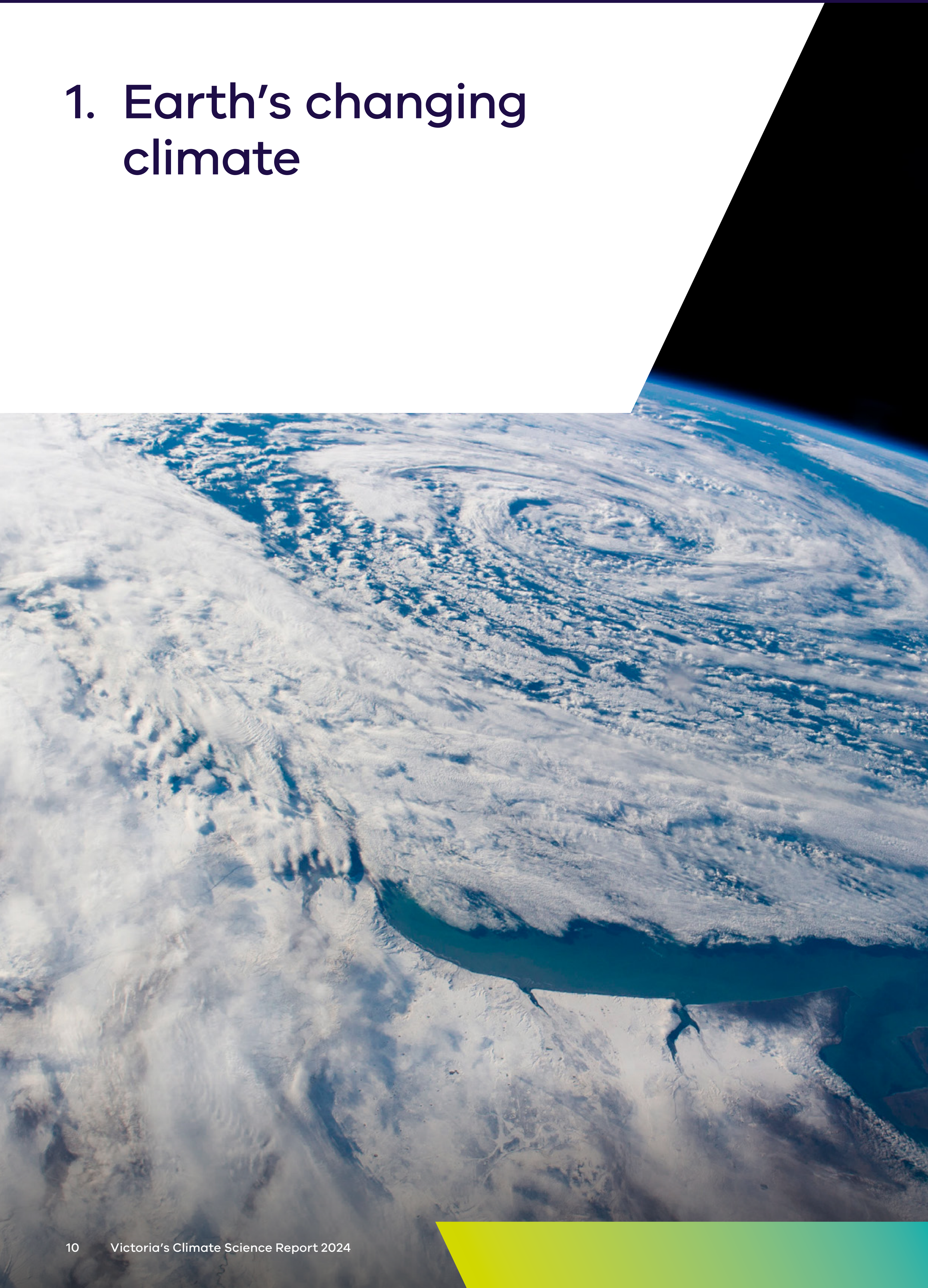
Some global studies show that **future droughts** may develop **more quickly** with a thirstier atmosphere, leading to a **faster onset of drought**

Findings based on peer-reviewed literature

Climate science supporting decision-making

Climate science helps Victorian businesses, the community, and the government understand and adapt to the current and future climate. The climate experienced in the past is no longer a good indicator of the climate we can expect. As a result, consideration of the latest climate science information about likely future changes is critical to good governance and decision-making. This will assist Victorians to plan and respond to the effects of climate change.

1. Earth's changing climate



Global atmospheric and ocean temperatures are increasing, sea levels are rising, extreme weather events are becoming more frequent and intense, and the global water cycle is changing. These changes have occurred predominantly in response to increasing atmospheric concentrations of greenhouse gases, primarily caused by human activities.

1.1 Global temperatures have increased

Human-caused greenhouse gas emissions have increased global average surface temperatures by over 1.1 °C since the pre-industrial era (1850–1900).

Changes in the climate can be caused by natural drivers, including fluctuations in the sun's activity and volcanic eruptions. However, since industrialisation, human-caused drivers, including burning fossil fuels and land-use change (IPCC, 2023) have resulted in a warming trend in global temperatures.

Global temperatures have risen since the 1850s (Figure 1). Human-caused drivers of climate change have dominated natural drivers from 1850 to 2020. During this period, the contribution of natural climate drivers to global surface warming was small, estimated at about plus or minus 0.2 °C compared to the overall warming of about 1.1 °C observed during the same period (IPCC, 2023).

Global temperatures have risen since the 1850s

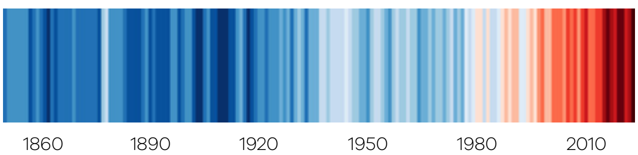


Figure 1. Increases in global average temperature relative to the 1961–2010 baseline period for the period 1850–2023. Blue shades indicate cooler temperatures, and red shades represent warmer temperatures. Source: Hawkins, 2023, University of Reading, under CC BY 4.0.

The World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC) to provide regular comprehensive assessments of the scientific basis of climate change. The latest IPCC report, the Sixth Assessment Report, states:

> *'Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1 °C above 1850–1900 in 2011–2020'* (IPCC, 2023).

The greenhouse effect

When the sun's energy passes through the atmosphere, some energy is reflected back to space by bright surfaces such as clouds and ice, and some is absorbed by the Earth's land and ocean surfaces. Heat re-emitted from the Earth's surface either escapes into space or is absorbed by gases in the atmosphere.

Although greenhouse gases make up less than 0.1% of the Earth's atmosphere, they are very good at trapping heat that would have otherwise escaped into space. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the dominant greenhouse gases that contribute to human-caused climate change.

During 2022, concentrations of atmospheric CO_2 reached over 417 parts per million, more than 50% above pre-industrial levels (around 278 parts per million) (Friedlingstein et al., 2022). As greenhouse gases increase in the atmosphere, a corresponding temperature rise has occurred.

1.2 The carbon cycle is changing

Earth's natural carbon cycle is being disturbed by human-caused CO_2 emissions.

The carbon cycle describes how carbon flows between the Earth's atmosphere, oceans and land, including the locations where it is stored and released. Carbon can be stored in plants, animals, rocks and soil or dissolved in water.

The amount of carbon on Earth is fixed. Carbon can be cycled:

- quickly; for example, through biological processes such as photosynthesis or respiration of CO_2
- slowly; for example through biological and geological processes such as the decomposition of organic matter under heat and pressure into fossil fuels such as oil, natural gas or coal. The formation of fossil fuels can store carbon underground for hundreds of millions of years.

Humans are impacting the carbon cycle by accelerating the release of carbon into the atmosphere through activities such as land-use change and burning fossil fuels (Figure 2). Excess CO_2 remains in the atmosphere for hundreds of years. The release of carbon from the slow carbon cycle has long-lasting consequences on our climate system.

The simplified global carbon cycle

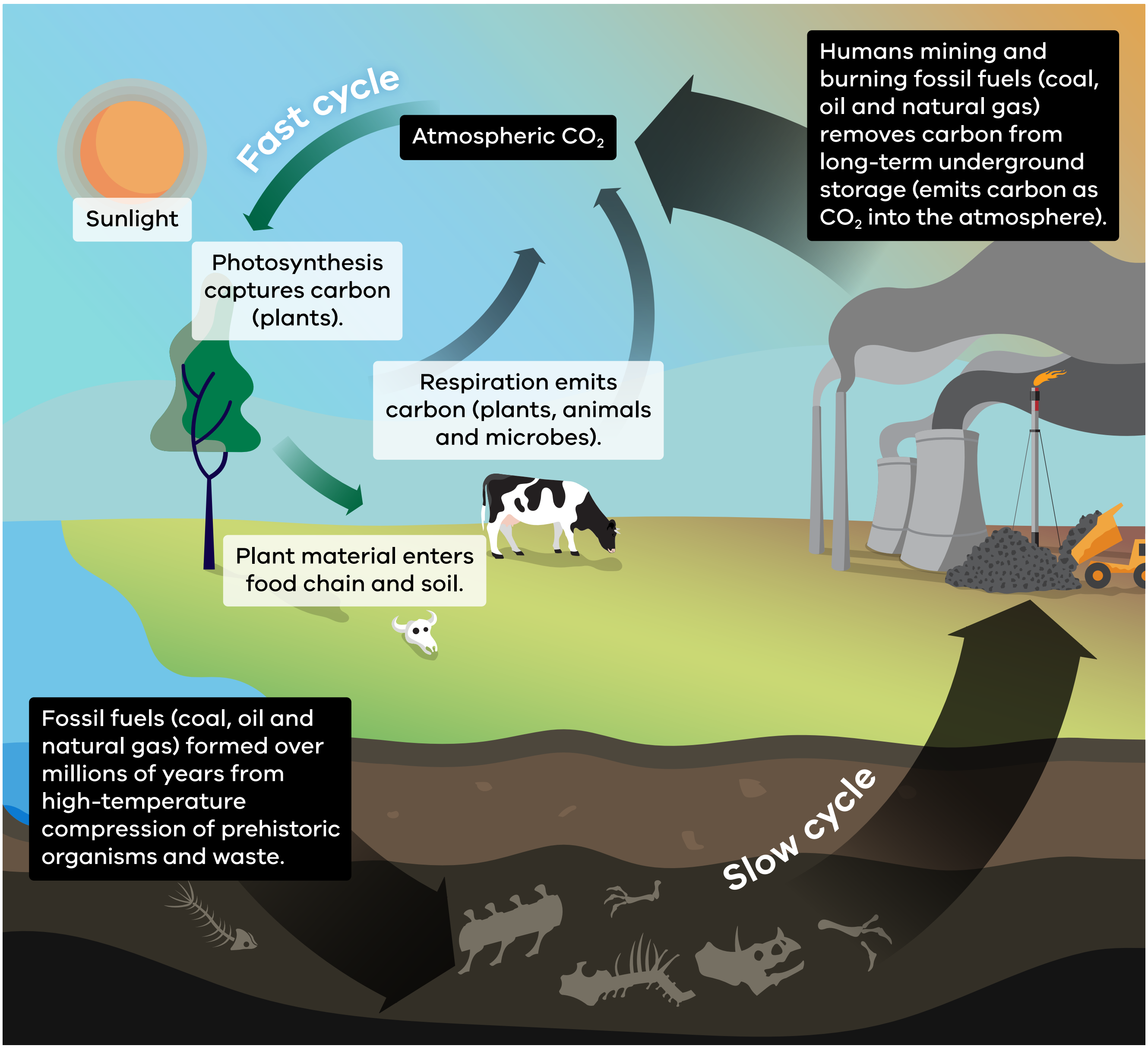


Figure 2. Simplified representation of the carbon cycle and human activities that are disturbing it. The inner circle represents the fast carbon cycle, while the outer circle represents the slow carbon cycle. Fossil fuels are formed over millions of years when the remains of plants and plankton are buried under high pressure and heat conditions. Source: Adapted from National Oceanic and Atmospheric Administration (NOAA), 2019, under CC BY 4.0, with redesigning.

The Global Carbon Project is an international project that aims to develop a complete picture of the global carbon cycle. It produces an annual update, the Global Carbon Budget, which tracks trends in carbon movement between the atmosphere, ocean and land. Carbon sinks absorb more carbon than they release (e.g. forests and oceans), while carbon sources release more carbon than they absorb (e.g. fossil fuel burning and livestock) (National Geographic, 2024).

The 2023 Global Carbon Budget, summarised in Figure 3, found the following.

- The burning of fossil fuels by humans in 2023 released 36.3 billion tonnes of CO_2 into the atmosphere.
- An additional 4.4 billion tonnes of CO_2 was transferred into the atmosphere via the burning and removal of forests, which would otherwise have acted as a carbon sink. Emissions from permanent deforestation are too high to be offset by current CO_2 removal from reforestation and afforestation efforts (which comprise a small segment of the existing land sink).
- The land and ocean CO_2 sinks combined continued to take up around half (53% over the past decade) of the human-caused CO_2 emitted into the atmosphere despite the impact caused by ocean acidification.
- If 2023 CO_2 emission levels persist, there is a 50% chance that warming will permanently exceed 1.5 °C in about 7 years (from the beginning of 2024). Returning global temperatures below this threshold after it has been crossed would require a massive scale-up of the removal of CO_2 from the atmosphere, even after global net zero emissions have been reached.

Global carbon dioxide sinks and sources

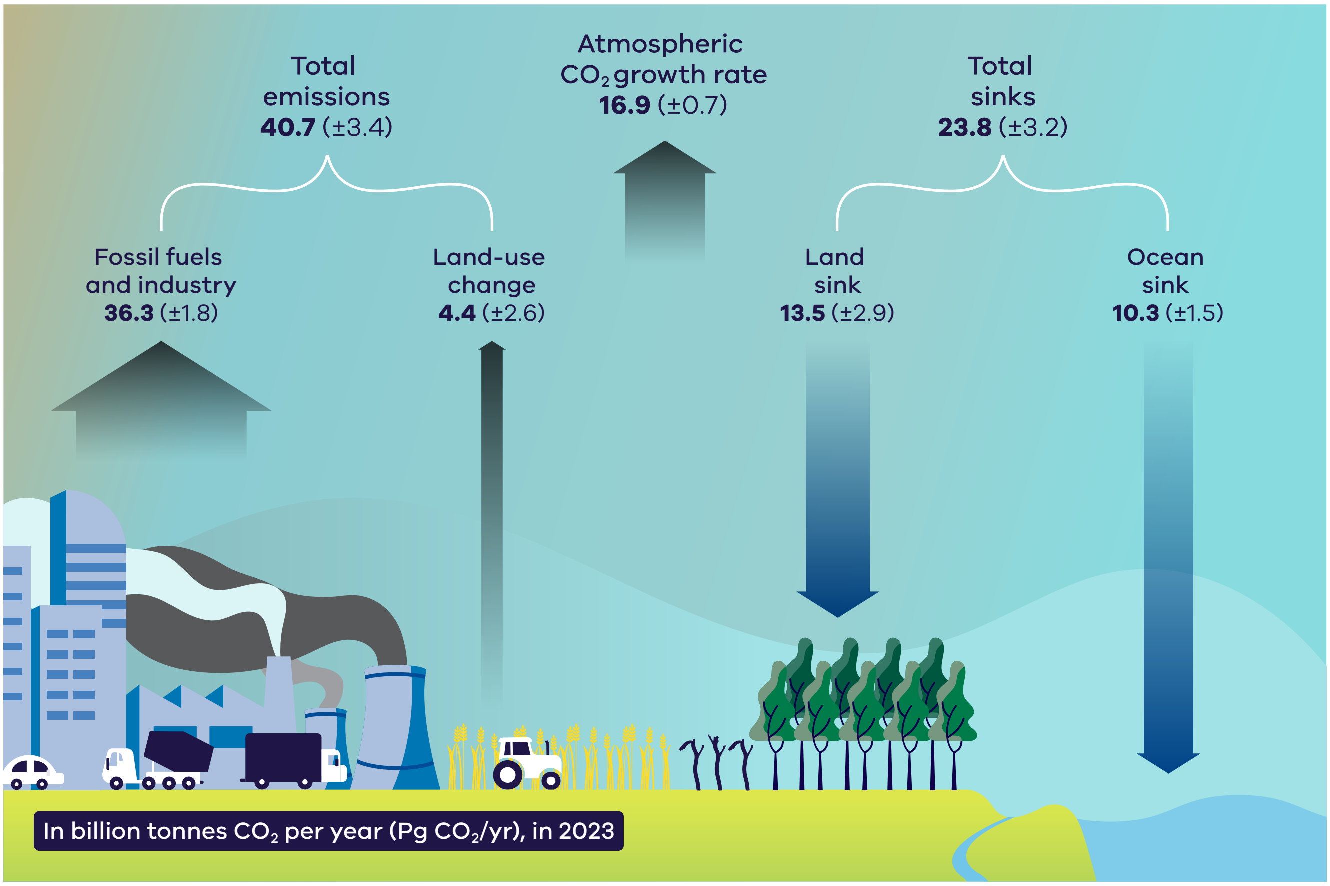


Figure 3. The global sources (fossil fuels, industry, and land-use change) and sinks (land and oceans) of CO_2 emissions in 2023. The sources of emissions are larger than the sinks, resulting in increased concentrations of CO_2 in the atmosphere. Source: Adapted from the Global Carbon Project, 2023, under CC BY 4.0, with redesigning.

Our oceans are an important carbon sink

The oceans store a huge amount of carbon and hold far more carbon than the atmosphere. Since 1850, the world's oceans have absorbed more than a quarter (26%) of human-caused CO_2 (Friedlingstein et al., 2022).

As atmospheric CO_2 levels increase, much will be absorbed by the oceans. However, while the ability of the ocean to capture and store carbon has helped reduce atmospheric levels, increased CO_2 in the ocean has altered the chemistry of sea water. This has caused an increase in the acidity of ocean waters through a process known as ocean acidification. Ocean acidification can make it harder for organisms such as corals, molluscs and shelled plankton to build their shells and skeletons and can affect the behaviour of some marine species, such as reef fish (CSIRO, 2015).

1.3. Future global climate change impacts

Climate change is affecting the atmosphere, land, oceans and ice, and these changes are projected to continue.

The IPCC Sixth Assessment Report confirms that human activity has already resulted in widespread and rapid changes in Earth's atmosphere, ocean, cryosphere (ice and snow) and biosphere. These changes are expected to continue. The report states: *'Evidence of observed changes such as heatwaves, heavy precipitation, drought, and tropical cyclones, in particular their attribution to human influence, has strengthened.'*

As the Earth and oceans warm, glaciers and ice sheets are melting and becoming smaller (Bureau of Meteorology & CSIRO, 2022) (Figure 4). Further warming will amplify the loss of seasonal snow cover, the thawing of permafrost and the loss of Arctic and Antarctic sea ice. Increasing global temperatures are causing sea levels to rise as water expands and ice sheets and glaciers melt. Climate change is causing an increase in the frequency and intensity of ocean heatwaves. These events are prolonged periods of excessively warm sea surface temperatures that can devastate marine ecosystems.

Climate change impacts on the Earth system

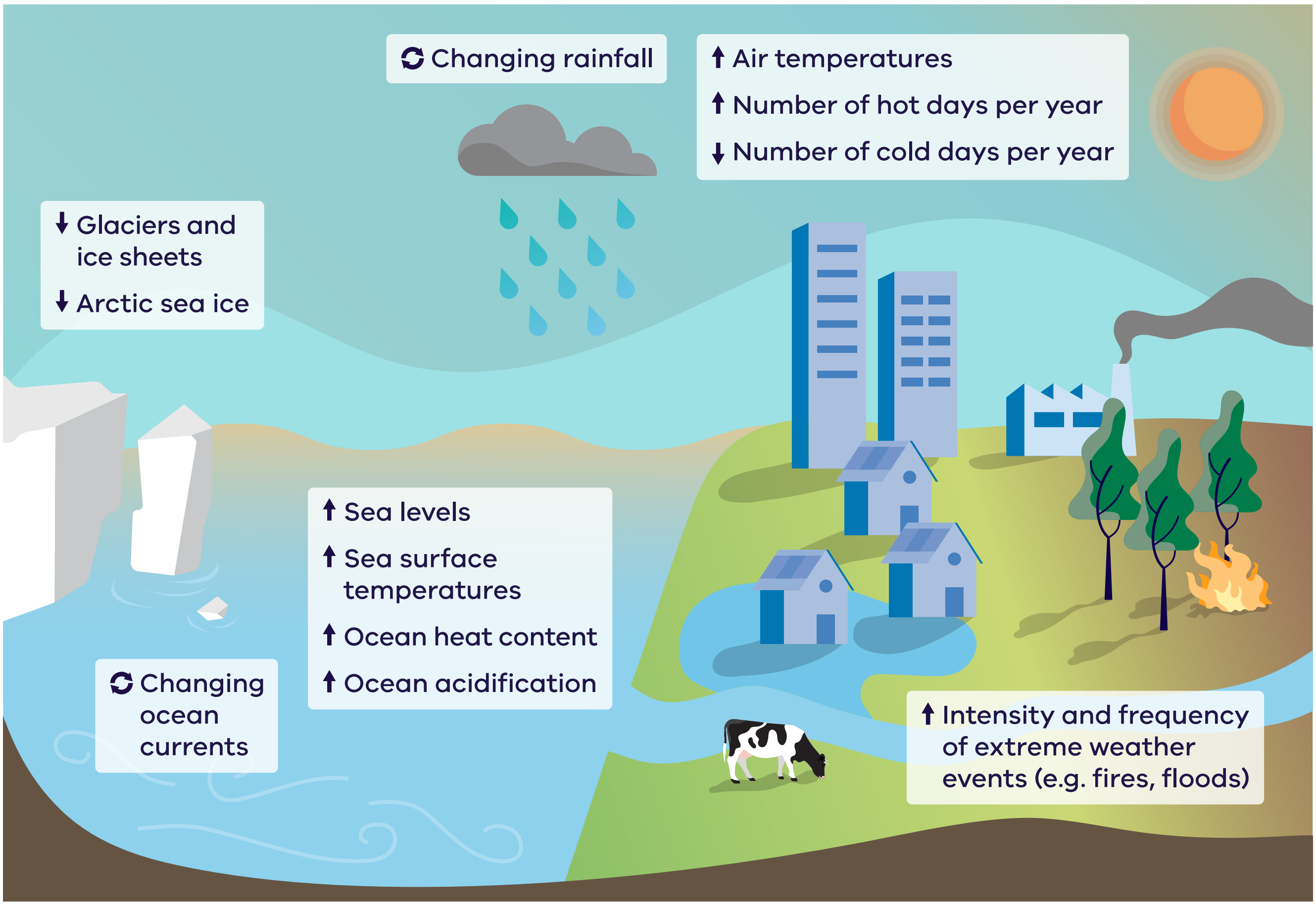


Figure 4. Many aspects of the Earth system are changing and will continue to change due to increased greenhouse gases in the atmosphere. Source: Adapted from Department of Climate Change, Energy, the Environment and Water (DCCEEW), 2024, under CC BY 4.0, with redesigning.

The atmosphere can hold about 7% more water vapour for each degree of warming. An atmosphere with more moisture can produce more intense precipitation events (Bureau of Meteorology & CSIRO, 2022). This has increased extreme rainfall in some regions of the world, including Australia. The increased moisture in the atmosphere has also led to an intensification of the water cycle, with an increase in both wet and dry extremes and the general variability of the water cycle. Changes to atmospheric circulation and weather systems due to human influences also affect extreme rainfall events.

Globally, heavy precipitation is likely to increase more under a 2 °C warmer world than under a 1.5 °C warmer world. Similarly, there are likely to be more droughts and dryness if temperatures rise by 2 °C rather than 1.5 °C (IPCC, 2018).

Global surface temperatures are projected to continue to rise under all emissions scenarios.

Global warming of 1.5 °C and 2 °C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades (IPCC, 2021).

Atmospheric CO_2 concentrations are higher than at any time in the past 2 million years (IPCC, 2021). Despite a temporary global decline in fossil fuel emissions during the COVID-19 pandemic, CO_2 emissions returned to pre-pandemic levels in 2021 and have continued to rise. The temporary observed decline will not significantly affect the long-term warming trend (Bureau of Meteorology & CSIRO, 2022).

Climate feedbacks and ocean circulation

Climate feedbacks are processes that respond to climate change by amplifying (positive feedback) or reducing (negative feedback) changes in the climate system. For example, as the ice sheets melt, the bright surface area of ice that reflects sunlight reduces, and more sunlight is absorbed by the darker land and ocean surfaces. This increases warming, leading to further melting of ice sheets in a positive climate feedback loop.

Ocean circulation helps to distribute heat around the Earth and regulate climate. For example, the Gulf Stream and the Atlantic Meridional Overturning Circulation of the western North Atlantic Ocean helps regulate climate by redistributing heat from the equator towards the poles. Increases in land and ocean temperatures have resulted in the melting of ice in the Arctic and Greenland. This has led to an influx of cold freshwater into the North Atlantic that has slowed down the northwards flow of the Gulf Stream and disrupted the northbound heat transfer. As a result, regions typically influenced by the Gulf Stream may now experience altered temperature and precipitation patterns.

2. Victoria's changing climate

Victoria's climate is shaped by large-scale climate drivers, seasonal influences and weather systems. Observations of Victoria's climate show it continues to change, with increasing temperatures, hotter extremes and changing rainfall patterns.

Victoria's climate varies from place to place and season to season. It can be below 0 °C in winter in the mountains to the east and extremely hot in summer in the dry north-west of the state. In summer months, conditions across Victoria are generally warm, with spells of hot weather (greater than 35 °C) occurring when northerly winds bring hot air from Australia's interior. Cool changes can occur as a front crosses Victoria, sometimes lowering temperatures by 15 to 20 °C in an hour. In winter, temperatures are less variable than in summer and vary less from north to south. Frost can occur when temperatures are less than 2.2 °C, with severe frosts occurring below 0 °C (Agriculture Victoria, 2023a).

Most of Victoria's annual rainfall occurs during the cooler months between April and October. Rainfall is variable across Victoria and ranges from an average of around 300 mm per year in the north-west of the state near Mildura to more than 2,000 mm per year in the alpine region. The mountains in the east of Victoria – the Great Dividing Range – influence the distribution of rainfall across the state. The elevated landscape acts as a barrier to prevailing airflow, forcing it to rise. As the moisture-laden air rises, it cools and condenses, forming clouds and rainfall. More rainfall occurs on the eastern side of the range, while drier conditions are often experienced on the western side. Higher annual rainfall is typically recorded south and east of the range and along the coastal regions. To the north and west of the Great Dividing Range, the landscape flattens into dry inland plains, receiving lower annual rainfall (Agriculture Victoria, 2023b).

Weather versus climate

Both climate and weather refer to atmospheric conditions such as temperature, precipitation and wind. Weather refers to the short-term variations in the atmospheric conditions at a location, usually over days to weeks. Climate refers to the average of weather conditions at a location that persist over multiple decades, usually over a 30-year period or more (IPCC, 2022). Climate refers to the processes and interactions of the climate system, comprising the atmosphere, oceans, land and ice.

Consideration of changes at different climate and weather scales are relevant to decision-making (Figure 5).

Linking climate change to weather

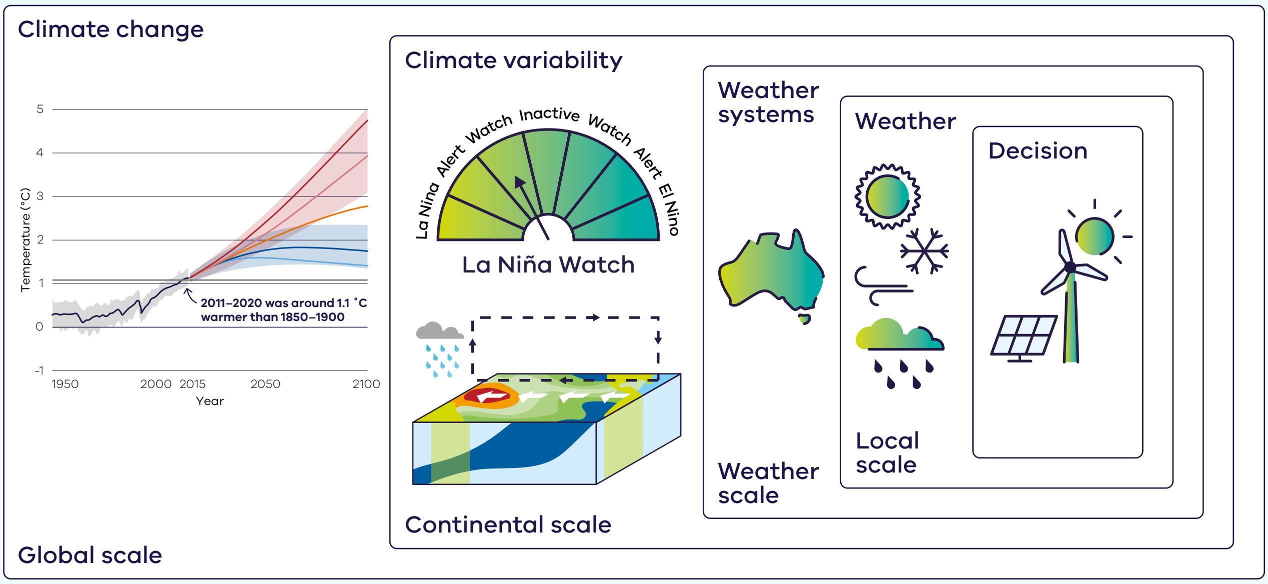


Figure 5. A visual representation of climate and weather scales, showing how global climate change has cascading impacts on climate variability and weather, and their relationship to decision-making. Source: Adapted from C. Jakob, Director, ARC Centre of Excellence for the Weather of the 21st Century, 2024.

2.1 Naturally occurring patterns of variability

Victoria's climate varies due to large-scale climate drivers and is affected by seasonal and local weather systems.

El Niño–Southern Oscillation (ENSO) is a climate pattern in the Pacific Ocean that influences rainfall, temperature and wind patterns worldwide (Figure 6). ENSO has 3 phases: El Niño, La Niña, and neutral. El Niño typically brings drier conditions and warmer daytime temperatures to Victoria, leading to an increased likelihood of drought and greater bushfire risk (Bureau of Meteorology, 2021). La Niña is usually associated with higher rainfall and cooler daytime temperatures in Victoria and is associated with an increased likelihood of flooding (Bureau of Meteorology, 2016a).

The Indian Ocean Dipole (IOD) can influence rainfall and temperature patterns over Australia. It alternates between 3 phases: positive, neutral, and negative. It can interact with ENSO events, magnifying the effects on regional climate. A positive IOD generally leads to warmer and drier conditions over much of the country, including Victoria. A negative IOD typically leads to higher rainfall and cooler temperatures in Victoria. The IOD can cause extreme conditions in Victoria, including an increased chance of flooding and a higher risk of bushfires (Bureau of Meteorology, 2023a).

The Southern Annular Mode (SAM) influences rainfall across southern Australia. It varies between positive, neutral, and negative phases. The effect of SAM on rainfall in Victoria greatly depends on the time of year. A positive SAM phase during winter typically results in drier conditions, as does a negative SAM phase during summer. There is an increased chance of rainfall in Victoria when SAM is negative during winter and positive during summer (Hope et al., 2017).

The Madden–Julian Oscillation (MJO) is an eastward-moving 'pulse' of cloud and rainfall near the equator that typically recurs every 30 to 60 days. Although it primarily affects the tropical areas of Australia, it can influence rainfall in Victoria, especially when combined with other weather events.

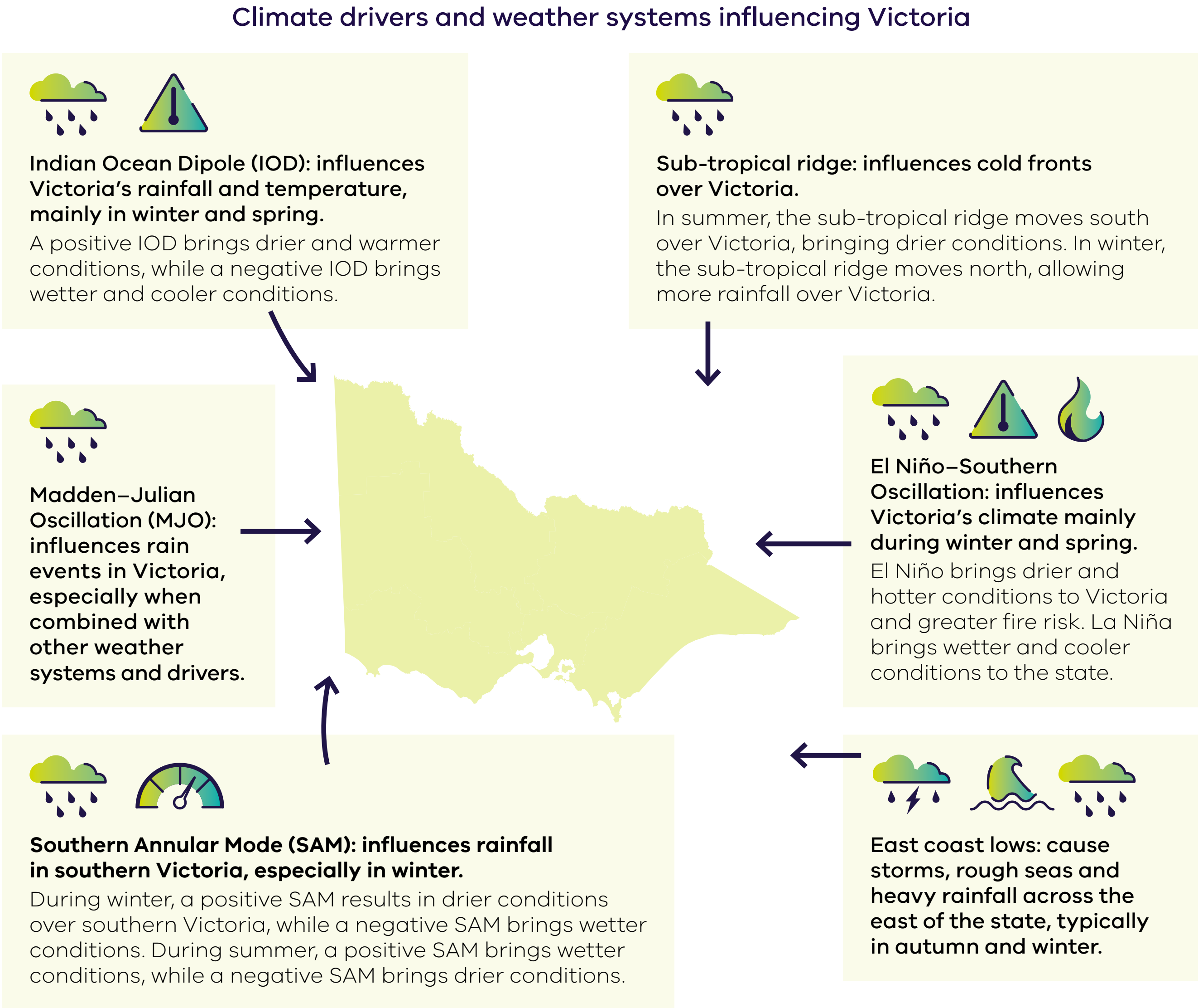


Figure 6. Key large-scale climate drivers and weather systems that influence Victoria's climate. These drivers can act alone, can be combined, or can counteract each other. The arrows represent the direction of movement of each driver (i.e. from east to west or from the north-west, etc.). Source: Clarke, 2019.

The sub-tropical ridge is a zone of high air pressure over southern Australia surrounding the Earth. During the warmer months, when the ridge is south of Australia, it brings more stable and settled conditions to Victoria during summer. As it shifts further north over central Australia during the cooler months, it allows more cold fronts to reach Victoria, resulting in showery conditions and colder south-westerly winds (Bureau of Meteorology, 2023b).

An east coast low is an intense low-pressure system that brings sustained heavy rainfall with strong gusty conditions to the east coast of Australia, including Victoria. It can occur at any time of year but is more common in autumn and winter. East coast lows can cause widespread damage through strong winds, prolonged heavy rainfall and very rough seas.

Cold fronts are a major contributor of rainfall in Victoria throughout the cooler months. Cold fronts are typically associated with a rapid drop in temperature, a change in wind direction and gusty conditions (Bureau of Meteorology, 2023c). In winter, cold fronts can bring heavy rainfall, damaging winds and snow. In summer, hot and dry air ahead of the front, combined with strong and gusty wind changes and possible thunderstorms, can lead to high fire danger (Bureau of Meteorology, 2016b).

2.2 Climate drivers and weather systems under a changing climate

As concentrations of greenhouse gases continue to increase in the atmosphere, further shifts in the scale and timing of climate drivers and weather systems are likely to occur, with flow-on effects for Victoria's climate.

Climate change will also likely result in changes in natural variability. As heat is added to the oceans and lower atmosphere, an altered distribution of energy will influence the natural climate oscillations and patterns. Climate change will also impact on the type, pattern and frequency of daily weather. For example, a decline in co-occurring low pressure over south-east Australia and high pressure over the Tasman Sea under a changing climate may reduce the frequency of drought-breaking extreme rainfall events (Holgate et al., 2023).

Australia and Victoria experience significant extremes of high and low rainfall and high temperatures. These extremes are due to the natural variability of our climate, associated with climate drivers. Climate change can push in the same direction as these drivers in any given year or season, and this leads to record-breaking extremes – as experienced in the past 20 years. For example, the 3 consecutive La Niña events between 2020 and 2023 brought high rainfall to south-eastern Australia. This was combined with a negative IOD in 2021 and 2022 and led to high water storage levels and wet catchments, contributing to significant and widespread flooding in eastern Australia (Gillett & Taschetto, 2022).

Climate drivers can also influence prolonged hot and dry conditions. For example, extended periods of El Niño and a positive IOD, which can cause lower rainfall and soil-moisture deficits, can lead to drought conditions (King, 2023). SAM can exacerbate underlying dry conditions. For example, throughout the summer of 2019–20, IOD and SAM influenced the extremely hot and dry conditions despite ENSO remaining neutral. As a result, Australia experienced its hottest and driest year on record in 2019, which primed the landscape and fuel loads for the 2019–20 bushfires (Abram et al., 2021).

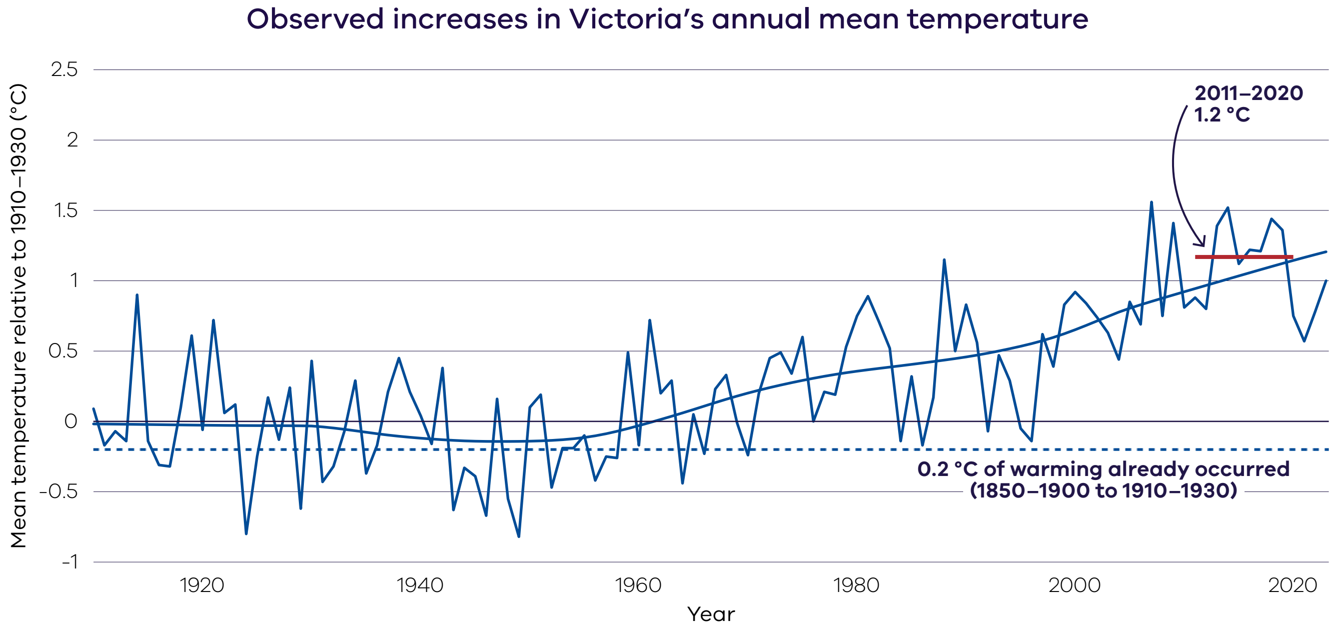
2.3 Victoria's climate has changed

Victoria's climate has continued to warm since the 19th century, becoming drier in recent decades and experiencing more frequent and intense extreme events.

Temperature

Victoria's climate has warmed by about 1.2 °C since national records began in 1910 (CSIRO, 2024) (Figure 7). However, Victoria likely experienced another 0.2 °C of warming between the pre-industrial baseline period (1850–1900) and 1910 (Grose et al., 2023). Victoria's overall warming of 1.4 °C since the pre-industrial era is slightly less than the Australian-wide average warming of 1.6 °C between 1850–1900 and 2011–20.

Despite the years 2021, 2022 and 2023 being cooler compared to the previous decade, these were still well above the 20th century average, and the long-term warming trend continues (Bureau of Meteorology, 2024a). Such variations from the long-term warming trend are expected due to natural variability in the climate, like that associated with ENSO.



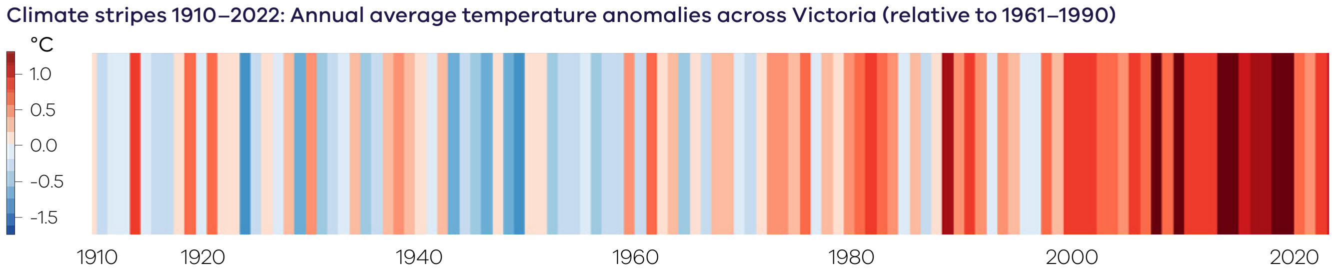


Figure 7. a) Observed annual mean temperature over Victoria from 1910 to 2023 relative to the 1910–1930 baseline period. The dashed line indicates the 1850–1900 average temperature and shows the additional 0.2 °C of warming between 1850–1900 and 1910. The smooth blue line shows the long-term trend, and the brown-coloured horizontal line shows the amount of warming for the most recent decade (2011–2020). **b) Increases in global average temperature shown using 'stripes' of colour.** The colour of the stripe represents the temperature anomaly for that specific year, where blue shades indicate cooler temperatures and red shades represent warmer temperatures. Red colours (warmer temperatures) have been dominant more recently, illustrating the rise in average Victorian temperatures. Source: Adapted from CSIRO, 2024.

Hot days

The number of hot days (99th percentile maximum daily temperature) and very hot days (99.9th percentile maximum daily temperature) continues to increase across Victoria, especially inland. The more extreme hot days have experienced the largest increases, especially over the past decade. What is considered a hot or very hot day is location specific when using percentile definitions.

The number of hot days in Melbourne (above 37 °C) increased from a late 20th century average of around 4 days per year to around 5 days per year on average for the past 20 years. The number of very hot days (above 41.2 °C for Melbourne) has seen a larger increase – from an average of 4 per decade to an average of 10 per decade (Figure 8).

Inland locations have experienced larger changes. For example, the number of very hot days in Rutherglen (above 38.4 °C) increased from an annual average of less than 4 days in the 1986–2005 period to almost 8 days in the 2003–22 period, while very hot days (above 41.8 °C) increased from 2.5 days per decade to an average of nearly 20 days.

However, the number of hot and very hot days can vary greatly from year to year. While the average number of hot days may be 3–4 per year, this can vary from none to 10 or more in any single year.

Definition of 'hot' and 'very hot' days

Defining hot and very hot days using percentiles allows temperature extremes to be analysed easily across Victoria, even though a hot day in one location may be significantly hotter than a hot day in another. For example, a hot day on the coast at Cape Otway would not be considered to be very hot at inland Mildura. The temperature values of these days is defined using an historical baseline of 1986–2005.

Hot day

- 99th percentile
- Historically occurs on average 3–4 times **per year**

Very hot day

- 99.9th percentile
- Historically occurs on average 3–4 times **per decade**

Observed increase in hot and very hot days

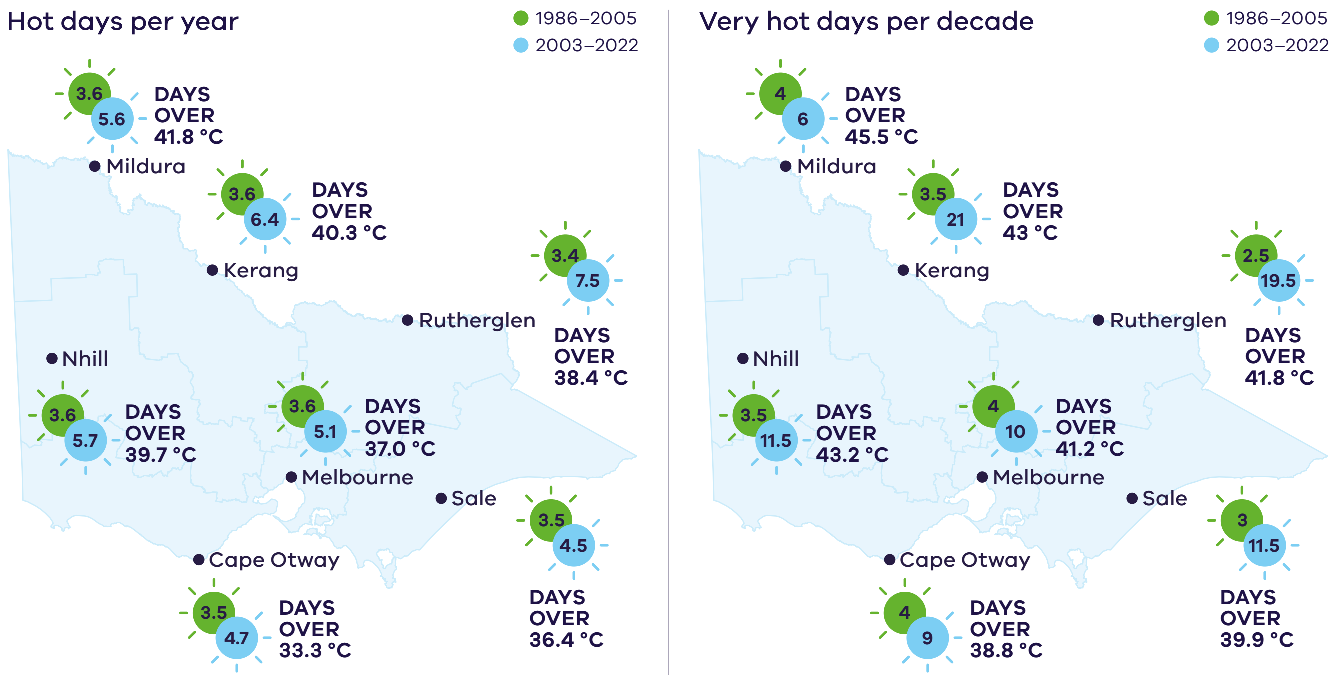


Figure 8. Recent changes in the average number of days above the 99th percentile (hot days) and 99.9th percentile (very hot days) maximum daily temperature threshold. Data are shown for the 7 observational stations in Victoria with high-quality daily temperature datasets (ACORN-SAT, 2023). The historical values of these thresholds (1986–2005) are listed along with the average number of days (per year for hot days and per decade for very hot days) over the 1986–2005 historical baseline and the most recent 20 years (2003–22). Source: Adapted from CSIRO, 2024.

Rainfall

Victoria's average rainfall has decreased over the past half-century in all seasons except summer (CSIRO, 2024). Over the last 30 years, Victoria's cool season (April–October) rainfall has declined by more than 10% compared to the 1961–90 period (Figure 9). The decline in cool season rainfall in Victoria is part of a broader decline across south-east Australia. This decline is associated with decreased rainfall from weather systems and shifts in climate drivers, such as increases in the frequency of positive IODs (McKay et al., 2023).

These observed rainfall trends have been at least partly driven by human-caused climate change (Rauniyar & Power, 2020; 2023).

Rainfall changes have not been constant across the state, with larger declines experienced in the alpine region than elsewhere.

Long-term rainfall trends are overlaid by a great deal of natural variability. This can make the trends hard to discern from our lived experience, which will likely be dominated by alternating dry and wet periods. For example, despite the drying trend, 2022 was the wettest year since 1974 and the fifth wettest year on record for Victoria. While annual rainfall for Victoria in 2023 was 5.3% below the 1961–90 average, some parts of the state received their highest daily rainfall on record (Bureau of Meteorology, 2024a).

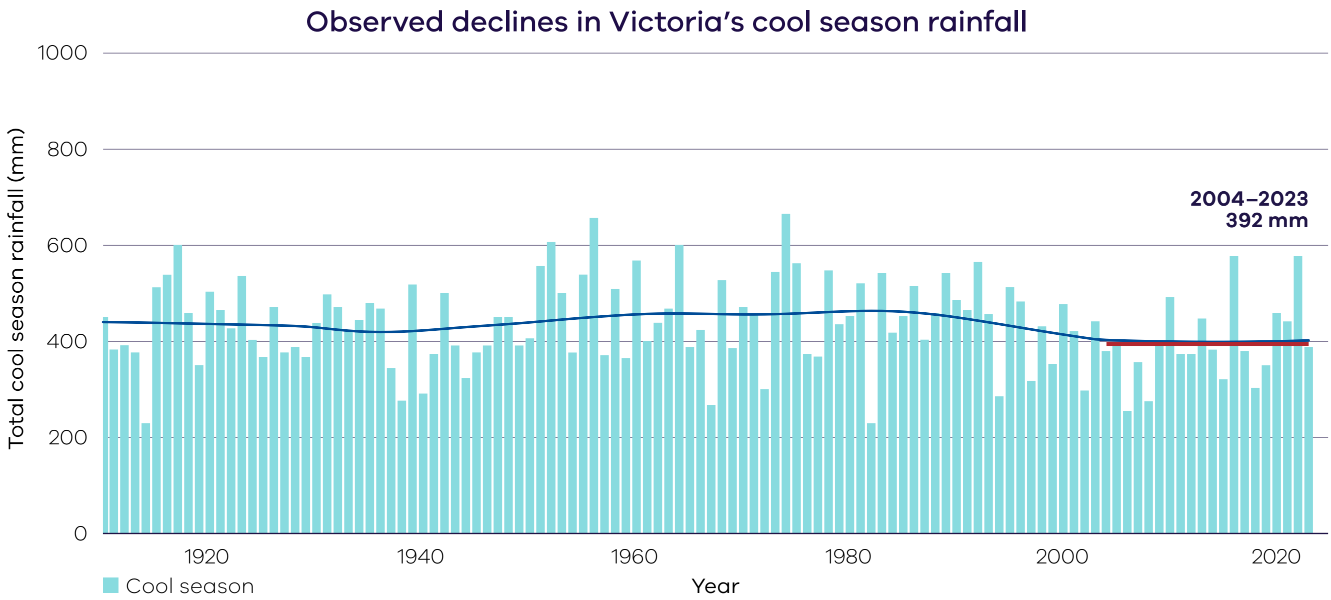


Figure 9. Observed total cool season (April to October) rainfall over Victoria from 1910 to 2023. Data are from the Australian Gridded Climate Dataset (AGCD). Rainfall is shown in millimetres (mm), with each bar representing the total rainfall per year and the smooth blue line representing the long-term trend. The maroon horizontal line represents a recent 20-year average (2004–2023). Source: Adapted from CSIRO, 2024.

Extreme rainfall

Extreme rainfall events occur when a large amount of rain falls over a short period. Extreme rainfall events are generally becoming more intense in Victoria. For example, there has been an almost 90% increase in the incidence of extreme hourly rainfall events with more than 18 mm per hour from 1958–1985 to 1987–2014 (Osburn et al., 2021). The most extreme rainfall events have increased in intensity more than less extreme events, especially during the warm season.

Observed changes in frost and snow

Snow depth and cover have decreased in Victorian alpine regions since the late 1950s (Bureau of Meteorology & CSIRO, 2022).

The frequency of frost-risk days has generally decreased in recent decades. However, there are some regions and seasons where the risk of frost has increased due to more clear nights particularly in spring (CSIRO, 2024).

Information on changing trends in key Victorian hazards, including heatwaves, drought, fire, floods and sea-level rise, is provided in Section 4 of this report.

2.4 Partnerships and initiatives

Mediterranean Climate Action Partnership

At the 2023 United Nations Climate Change Conference (COP28), Victoria became one of 15 inaugural members of the Mediterranean Climate Action Partnership (MCAP). MCAP is the first international partnership Victoria has joined that is focused on furthering adaptation to climate change. It gives Victoria with the opportunity to share climate leadership and to tackle shared climate challenges with other regions that have Mediterranean climate characteristics (between 30° and 44° north and south latitudes) including California, United States, and Catalonia, Spain.

MCAP will support its members as they deploy effective climate action to adapt to bushfire, extreme heat and drought impacts exacerbated by climate change. In announcing the formation of MCAP, leaders from the inaugural members spoke of the importance of sharing climate knowledge to strengthen climate resilience.

The Partnership has 5 goals.

1. Expand public awareness of climate impacts and solutions in member regions and around the world.
2. Learn from each other and build capacity to confront shared climate threats.
3. Share approaches on policies, programs and governance, investment and economic development strategies, and foster research collaboration.
4. Accelerate concrete actions in Mediterranean regions to protect communities from climate change impacts.
5. Track and report progress to the global community.

Victorian Water and Climate Initiative

The Victorian Water and Climate Initiative is a collaborative research program between the Victorian Department of Energy, Environment and Climate Action and multiple research partners, such as the Bureau of Meteorology, CSIRO and universities. This significant investment in climate, hydrology and water resources research aims to better understand Victoria's climate and how it impacts our water resources. Through this long-term program, researchers are investigating topics such as:

- where runoff rates across Victoria have declined over time and the reasons for the decline
- different climate drivers and weather types and their influence on Victoria's rainfall
- climate projections tailored for the Victorian water sector.

Understanding our climate and water resource situation better is important for long-term planning and climate change adaptation.

The initiative also focuses on working with the water sector to apply this knowledge to water resource management. Technical findings from earlier phases of the research program have been translated into a set of climate change guidelines for the water sector. The guidelines provide a consistent foundation for practical applications to support decisions on future urban water security and water resource planning, including the application of climate projections.

The water sector is not the only audience with an interest in the Victorian Government's investment in the Victorian Water and Climate Initiative, with some of the science presented in this report linked to the scientific outputs from the initiative.

21st Century Weather: a partnership to minimise risk and maximise opportunities from climate change

Victoria is a partner to the Australian Research Council Centre of Excellence for the Weather of the 21st Century (21st Century Weather), a 7-year partnership between Australian and international research, government and industry. 21st Century Weather aims to equip partners with the knowledge to minimise risk and maximise opportunities from climate change by understanding the mechanisms that affect weather and incorporating that understanding into next-generation climate models. A research program co-designed by 21st Century Weather partners will contribute to robust and evidence-based climate change decision-making.

The weather-climate connection

The traditional approach to climate science separates weather-climate interactions into components, including weather, climate variability and global climate change. Improving understanding of these interdependent parts will address uncertainty in how global climate change affects weather systems. Investigating the multi-scale interactions provides great potential for scientific advances.

Weather and climate occur in a flow of energy that ranges from local weather events to a planet-wide scale and back down again. These energy flows are shaped by the strongly connected atmosphere and ocean and by interactions with the land surface.

21st Century Weather is a fully integrated research centre that connects global climate change to ocean-atmosphere circulation and weather changes. This will increase understanding of the mechanisms underlying these interactions and increase confidence in predictions of future weather.

Modelling weather-climate interactions

Current understanding and prediction of weather change are limited by climate models' inability to resolve processes critical to representing key weather phenomena. The coarse grid spacing of 100 kilometres or more typically used by global climate models prevents the representation of the critical scale interactions.

In response, 21st Century Weather will build and apply Australia's first ultra-high-resolution climate models with grid spacings of a few kilometres or less to resolve the scale interactions in the coupled climate system. This will enhance our understanding of weather-climate interactions and build tools to predict the weather of the 21st century with the detail and confidence required to support robust decision-making in weather – and climate-sensitive sectors.

3. Updated climate projections for Victoria

Climate projections provide information on plausible climate conditions decades to centuries into the future to support decision-making, planning and adaptation. The climate projections summarised in this report represent some of the most up-to-date information about Victoria's climate. They indicate that the state will likely continue to get hotter, and the cool season climate is expected to get drier. Despite these long-term trends, cooler and wetter periods may still occur due to natural variations in the climate.

3.1 Understanding climate science

Advances have been made in climate science, modelling and projections since the 2019 Victorian Climate Science Report.

Our understanding of past and future climate continually improves, and climate models increase in sophistication over time. This has resulted in a larger evidence base, improved information and potentially more confidence in climate projections.

Modelling the future

Climate models are important tools for assessing how our climate has changed, what has caused these changes, and how the climate may continue to change. However, the climate system is extremely complex, and it is now changing in ways that have never before been experienced.

Climate models are complex mathematical representations of the climate system. The models draw on knowledge of climate processes and are underpinned by the laws of nature (primarily the laws of physics). Climate models are used to develop representations or 'simulations' of past, current and future climates. These models are critical for understanding how the different components of the climate system (such as oceans, atmosphere, snow and ice, and land) interact and change due to natural and human influences.

Different types of climate models are used to explore various aspects of how our climate is changing. Global models that simulate the entire planet are our best source of information on how increasing greenhouse gas concentrations can affect the Earth's global climate. Global models divide the global atmosphere, ocean and land surface into grid cells (generally about 80 to 250 km across for an atmospheric grid cell) and calculate the key properties of the cells, such as temperature, humidity, air pressure, and movement of the air between cells in the atmosphere (Figure 10).

Climate models represent the climate system on 3D grids

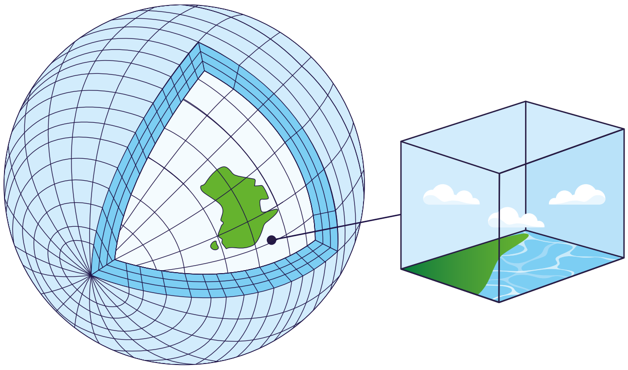


Figure 10. Global models represent the climate system, including the atmosphere, land, oceans and sea ice, on 3D grids. Each Earth system component has equations calculated on the global grid for a set of climate variables, such as temperature. Global climate models are an important tool for projecting possible future climate.

However, global climate models cannot provide information on variations in the climate that occur on scales smaller than a grid cell, such as small-scale and local climate conditions – a limitation for informing some climate change impact and risk assessments. This is where regional climate models can help. Although regional models still cannot provide information on scales smaller than their grid cells, they have smaller grid cells than global models. Regional models can be used to add detail to the output of global models and provide more information about how local and extreme climate conditions may change.

What is dynamical downscaling and why is it important for understanding Victoria's climate?

Global climate models generally have a relatively low spatial resolution of 80 to 250 km. As a result, climate processes (such as thunderstorms) and topography (such as mountains and coastlines) that vary on smaller scales are not well-represented.

Dynamical downscaling is the process of using regional domain climate models to provide regional-level climate projections at much higher resolutions for a particular area. Output from coarse resolution global climate models is run through a higher resolution regional model. Dynamical downscaling can achieve resolutions finer than 20 km across continents and finer than 5 km for more limited areas.

Understanding climate projections and emissions scenarios

Climate models are continuously developed by modelling centres around the world. Output from many different climate models is coordinated through international collaborations, such as the World Climate Research Programme's Coupled Modelling Intercomparison Project (CMIP) (for global climate modelling) and the Coordinated Regional Climate Downscaling Experiment (CORDEX) (for regional climate modelling).

CMIP and CORDEX produce hundreds of new climate model simulations worldwide every 6–7 years. Each new phase includes model improvements based on advances in supercomputing and science, builds on past modelling efforts, and adds to our understanding of future changes. Relative to the climate models used for previous projections, the latest phases of CMIP (CMIP6) and CORDEX provide more simulations at a higher resolution based on a more up-to-date understanding of ocean and atmospheric processes. As part of the National Partnership for Climate Projections, various modelling groups around Australia have coordinated downscaling on a national scale for Australia.

Beyond CMIP and CORDEX, even higher resolution regional modelling covering limited areas is becoming increasingly available. VCSR19 drew on modelling at a resolution of 5 km over Victoria provided by CSIRO. VCSR24 projections include finer resolution modelling covering Victoria at a scale of 4 km from the New South Wales and Australian Climate Modelling 2.0 (NARCliM2.0) project.

While most climate models that contribute to projects such as CMIP and CORDEX perform well enough to help answer some of our questions about the climate, there is no single 'best' model, as no model can perfectly represent all aspects of Earth's climate. As a result, using and analysing an 'ensemble' of models (more than one model) is best practice and helps researchers and decision-makers to understand the range of possible future climate conditions.

Climate models are critical tools for understanding past and present climate and projecting future climate change.

Climate models are run on some of the world's largest supercomputers. They are underpinned by the laws of nature (physics, chemistry, biology). These data and understandings are used to develop representations or 'simulations' of past, current and future climates. Climate models simulate the Earth's climate using input such as observational data (e.g. atmospheric temperature, pressure, density, water vapour and wind speed) and well-documented processes that occur across Earth's systems. The models are initialised to known conditions in the past (such as pre-industrial conditions present in 1850). Greenhouse gas emissions are then added to the atmosphere to simulate resulting changes in the climate.

The IPCC Sixth Assessment Report has used climate models to develop emissions scenarios and provide insights into the Earth's future climate (Figure 11). Under all emissions scenarios assessed, global surface temperatures are projected to rise until at least mid-century. Even under low emissions scenarios, it is very likely that global average temperatures for 2081–2100 will increase by 1 °C to 1.8 °C, relative to the 1850–1900 average. The IPCC highlights that under very high emissions scenarios, there is very likely to be an increase in temperatures between 3.3 °C and 5.7 °C.

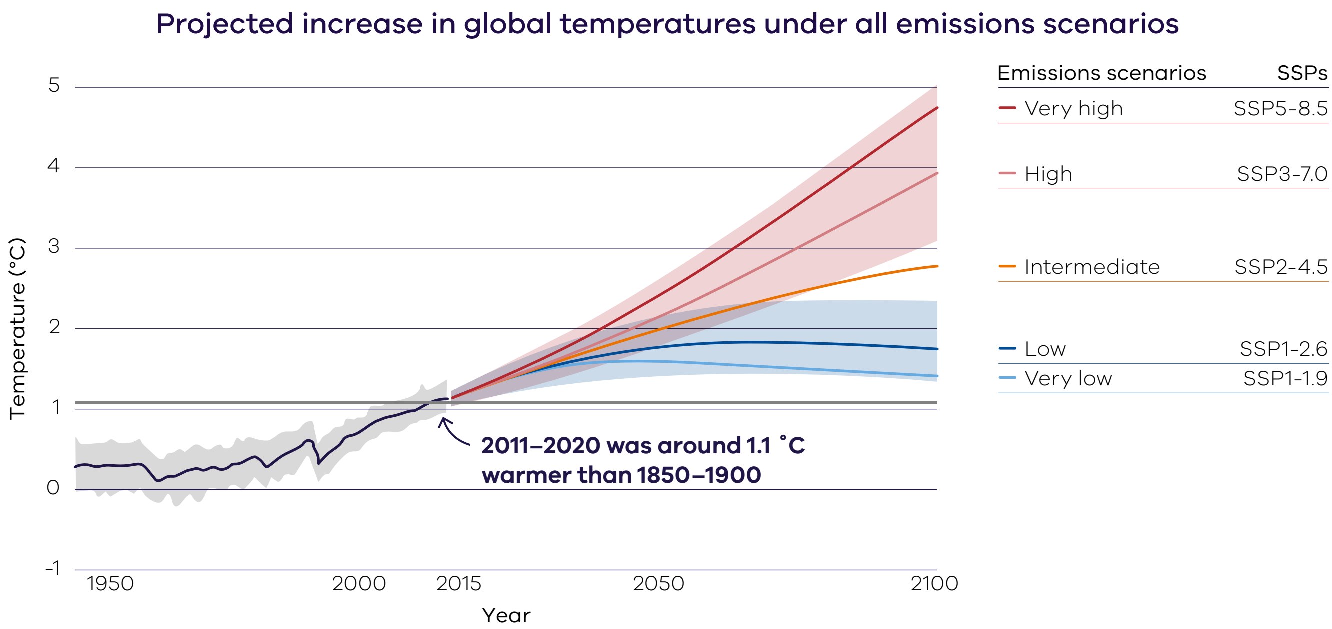


Figure 11. Projected average global temperatures under 5 possible emissions scenarios (very low, low, intermediate, high and very high emissions scenarios) up to 2100 relative to the 1850–1900 average, as shown in the IPCC Sixth Assessment Report. The black line shows observational data of global average temperature from 1950 to 2015. The shading represents the range of uncertainty for the low (blue shading) and high (pink shading) emissions scenarios. Source: Adapted from IPCC, 2023.

Understanding climate projections and emissions scenarios

Climate projections present plausible representations of the future climate if the world follows a given scenario for future emissions of greenhouse gases. However, projections are not predictions or forecasts and do not aim to precisely pinpoint the timing or size of a particular change in the climate. Instead, projections can provide a likely range of change to a given climate variable over a given time horizon in response to a specific greenhouse gas emissions scenario. For example, a projection for Victoria might be presented as ‘Under a high emissions scenario, Victoria will likely warm by approximately 1.5 °C (range 1.1 to 1.9 °C) by the 2050s, compared to the 1986–2005 period’.

Projections can also provide information about the range of change for a given climate variable for a region under a specific amount of global warming (see the *Victoria’s climate projections under global warming levels* box provided later in this section).

As the amount of greenhouse gases that will be emitted in the future is unknown, climate projections are based on emissions scenarios that provide a set of plausible futures.

Before the release of the physical science component of the IPCC's Sixth Assessment Report in 2021, the climate modelling community primarily used Representative Concentration Pathways (RCPs) to represent future scenarios. In the IPCC’s Sixth Assessment Report, Shared Socio-Economic Pathways (SSPs) were used for the first time. These scenarios explore how societal choices, such as population growth, economic growth, urbanisation, and technological developments, will likely affect global emissions. While there are similarities with the RCPs, the SSPs are more highly developed and coherent and can be used in a broader range of applications in addition to climate modelling.

There are 5 SSPs that describe different possible broad socio-economic trends (Figure 12). These include the sustainability-focused pathways SSP1-1.9 and SSP1-2.6, which are in broad alignment with the 2015 Paris Agreement and feature the use of new technology that removes CO_2 from the atmosphere to achieve net zero emissions. The SSPs also include the contrasting SSP5-8.5 pathway, which features fossil-fuelled development and unconstrained growth with no CO_2 removal and accelerating emissions.

Overview of Shared Socio-economic Pathways

	SSP1-1.9 'Sustainability'	SSP1-2.6 'Sustainability'	SSP2-4.5 'Middle of the road'	SSP3-7.0 'Regional rivalry'	SSP5-8.5 'Fossil-fuelled development'
RCP equivalent	No equivalent RCP	RCP2.6	RCP4.5	No equivalent RCP	RCP8.5
The way the world might change in the future					
Emissions reduction	Very high and immediate	High and immediate	Moderate from 2040s	None	None
Energy sources	Renewables	Renewables and biofuels	Renewables and fossil fuels	Fossil fuels	Increased fossil fuels
Carbon dioxide removal	New technology	New technology	None	None	None
Global socio-economic trends	Gradual move towards sustainability and environmental respect; increasing action towards Sustainable Development Goals (SDGs)	Gradual move towards sustainability and environmental respect; increasing action towards SDGs	Similar to the past; unevenly distributed; slow progress towards SDGs	Slow growth at the expense of the environment and increasingly unequal	Rapid growth at the expense of the environment; resource-intensive lifestyles and industries; dependence on technological solutions
What the future climate may look like under each SSP					
Global warming by 2100	1.0–1.8 °C	1.3–2.4 °C	2.1–3.5 °C	2.8–4.6 °C	3.3–5.7 °C
Resulting global warming levels*	Overshoots 1.5 °C slightly around 2050 then returns and stabilises near 1.5°C by 2100	Reaches 2 °C around 2050s and stabilises	Reach 2 °C around 2050s 2.7 °C by 2100	Reach 2 °C around 2050s 3 °C around 2070s 4 °C possible by 2100	Reach 2 °C around 2050s 3 °C around 2060s 4 °C by around 2080s

*As a general guide or 'rule of thumb'

Figure 12. An overview of the 5 SSPs used in modelling the global climate. The socio-economic narrative describes the broad socio-economic trends (such as population and economic growth, technological advances, patterns of consumption, inequality, etc.) that could shape future society and influence future emissions and adaptive capacity. Source: Adapted from National Environmental Science Program's Climate Systems Hub, 2024, under CC BY 4.0.

3.2 Methodology and approach for updating Victoria's projections

Climate projections for Victoria are based on multiple lines of evidence, including best-practice modelling.

Victoria's new climate projections have been developed using a range of regional and global climate model ensembles. A model ensemble is a set of modelling results that are designed to avoid reliance on a single modelling system or one individual line of evidence. This best-practice multi-model approach ensures Victoria's projections comprehensively consider as broad a range of plausible future change as possible.

The projections draw on the following climate model ensembles, including global climate modelling and regional downscaled modelling (see the previous box *What is dynamical downscaling and why is it important for understanding Victoria's climate?*):

- CMIP6 global climate modelling: 34 global climate models; 80 to 250 km resolution
- the NARCliM2.0 project: 5 downscaled global climate models with 2 downscaling model variants; approximately 4 km resolution
- nationwide regional climate model simulations prepared as part of the Australian Climate Service and CORDEX: 22 different combinations of global and downscaling regional climate models.

CMIP6 simulations were used to develop the new Victorian climate projections. The CMIP6 models show incremental improvements in representing the Australian climate relative to previous generations of global models, including improvements in representing sea surface temperatures and extreme heat events. CMIP6 models were used in the IPCC's Sixth Assessment Report (IPCC, 2021).

Some CMIP6 models simulate especially rapid warming in response to future greenhouse gas increases. Research is ongoing to understand the reasons for this projected warmer future. While these simulations are not considered impossible, they are potentially overrepresented in the CMIP6 ensemble (Hausfather et al., 2022). Therefore, the temperature projections presented in this report are primarily based on a subset of the models that do not include these low-likelihood, high-warming models, but this more rapidly warming future cannot be ruled out and is also presented separately.

Results from the multiple climate model ensembles were drawn on to create the best understanding of how the various aspects of Victoria's climate are expected to change in the future. The 34 CMIP6 global climate models provide the starting point for the broader context for temperature and rainfall projections based on the largest number of different models. These were supplemented with results from the nationwide downscaling model simulations and the higher-resolution 4 km downscaling model simulations from NARCliM2.0 (Victoria's highest-resolution climate modelling simulations). The downscaling models provide more detail on local changes than the coarser global climate models, improve the representation of extremes, and provide new insights into the future climate.

For some variables, such as rainfall and temperature extremes, only analysis from the regional downscaling was used, and more in-depth analysis of hot-day frequency and heatwaves draws only on the NARCliM2.0 4 km downscaling. Where ranges are provided, they represent the 10th to 90th percentile range of the model ensembles (i.e. representing 80% of the models unless otherwise specified). The source of modelling for specific projections and figures is provided.

In addition to climate model output, other sources of evidence and information were considered when developing Victoria's climate projections, including observations, understanding of recent climate trends and the latest scientific understanding of climate processes (Figure 13).

Multiple lines of evidence informing Victoria's updated projections

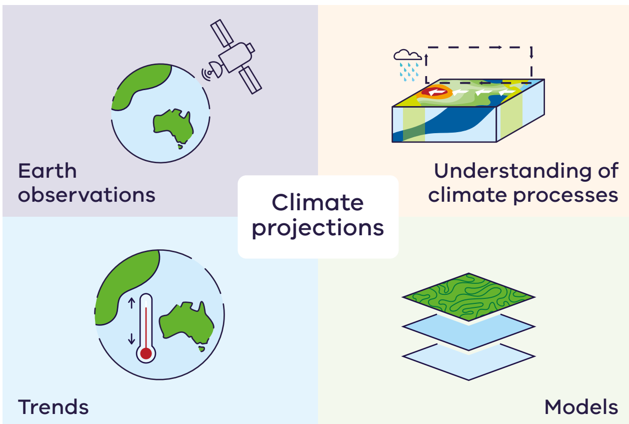


Figure 13. Climate projections for Victoria are informed by climate modelling results and draw on observations, trends, and an understanding of climate processes. Source: Adapted from CSIRO, 2024.

By considering multiple lines of evidence, such as, agreement between different climate model ensembles, levels of confidence can be assigned to statements about Victoria's future climate (see the *Understanding uncertainties and confidence* box below). The projections presented in this report follow the conventions of the IPCC assessment reports (Mastrandrea et al., 2011) in assigning confidence ratings to projection outputs.

While these new climate projections will be relevant to a diverse range of Victorian stakeholders, bespoke analysis of climate projections and climate model outputs and tailored climate projections are likely to continue to be developed by specific sectors to address their needs and applications. The projections presented in this report were developed with consideration of projections datasets used for the Victorian Climate Projections 2019 (VCP19).

Understanding uncertainties and confidence

While many advances continue to be made in understanding the climate system, climate models and observation methodologies, uncertainties remain. These include future levels of greenhouse gas emissions, feedback loops, unpredictable natural variability and uncertainty in climate models.

The IPCC has adopted 2 terms to describe uncertainty that are used to judge the level of confidence in the evidence and the likelihood of the projected events occurring.

'Likelihood' is used to describe quantified uncertainty. It gives the probability of a particular result or outcome, such as a climate projection, occurring. Likelihood is measured on a scale from 'exceptionally unlikely' to 'virtually certain'.

'Confidence' refers to how certain researchers are in a particular result or finding. In contrast to likelihood, confidence is a qualitative or subjective measure. It is assigned based on the type, amount, quality and consistency of the evidence. Confidence is described using 5 levels: 'very low', 'low', 'medium', 'high' and 'very high'. The level of confidence increases as the evidence becomes more robust and the scientific agreement increases.

Selected emissions scenarios, time horizons and baseline period

This section presents climate projection results using 2 SSPs: SSP1-2.6 and SSP3-7.0. Under the CMIP6 framework, SSP1-2.6 and SSP3-7.0 are considered plausible low and high emissions scenarios, respectively. These selected SSPs are also used in the IPCC Sixth Assessment Report. While other scenarios may be useful for risk assessment and may be explored/added in the future, these SSPs were used to develop Victoria's updated projections and they represent broad coverage of plausible future climates. These SSPs have been prioritised by regional climate modellers across Australia in downscaling CMIP6 global climate models, which aligns with Australia's National Partnership on Climate Projections and global CORDEX guidance.

The low emissions scenario (SSP1-2.6) is consistent with enhanced emission reduction policies that limit warming to 1.3–2.4 °C above the pre-industrial global average temperature. Under this scenario, global net zero emissions are expected to be reached around 2075. The high emissions scenario (SSP3-7.0), under which policy ambitions are not met, is consistent with warming of 2.8–4.6 °C. Under this scenario, emissions will continue to rising, doubling present levels by 2100. Depending on the effectiveness of current emission reduction policies, global warming relative to the pre-industrial period could reach as much as 3 °C by the end of the century (Rogelj et al., 2023).

Having a near-future time horizon and a far-future horizon provides decision-makers with information relevant to the time period most important to their work. This section presents projections for 2 time horizons: 2050 and 2090. These represent climate over a 20-year period: 2040–2059 for 2050 and 2080–2099 for 2090. For example, statements that a climate variable (such as temperature) has changed 'by 2050' relate to changes between a recent 'baseline' period and the 20-year period (centred on 2050).

The use of 20-year periods allows robust information to be provided about the effect of climate change on average climate conditions (such as average temperature). However, results related to extreme events (such as floods and extreme drought) are difficult to represent through comparisons of 20-year periods as these events are, by nature, out of the ordinary and are more affected by chance events than average conditions. This contributes to a greater chance that future extreme events will differ from projections.

Selecting an appropriate baseline from which to express changes in the climate is also important. Common baseline periods used by climate researchers include 1986–2005 (used in VCSR19 and previous CMIP global climate models) and 1995–2014 (used in the IPCC's Sixth Assessment Report and CMIP6). For consistency with VCSR19, the 1986–2005 baseline is used in projections for this section.

Where to find more information on projections methodology and results

Further information on climate projections, including a visualisation tool, is available at www.climatechange.vic.gov.au. The Victorian Climate Projections 2024 (VCP24) Technical Report presents further information about the methodology and climate models used to prepare Victoria's updated climate projections (CSIRO, 2024).

3.3 Victoria's climate will continue to warm

Victoria is projected to experience a warmer future climate with increasing average temperatures, more frequent and intense hot days, and longer and more frequent heatwaves.

Victoria's climate is projected to continue to warm over the century (very high confidence). Warming will only stabilise if global emissions reach net zero (very high confidence) (Figure 14).

Average temperatures

Average temperatures in Victoria will likely increase by approximately 1.1 °C (0.5 to 1.5 °C range) by 2050 compared to 1986–2005 under a low emissions scenario, with little subsequent warming. Under a high emissions scenario, average temperatures are likely to rise by approximately 1.5 °C (1.1 to 1.9 °C range) by 2050 and by approximately 3.1 °C (2.2 to 3.6 °C range) by 2090.

However, there is a low-likelihood, high-warming future projection of up to 2.5 °C warming by 2050 and up to 5.0 °C by 2090 under the high emissions scenario, represented by high-warming global climate models and enhanced in the high-resolution downscaled projections for Victoria using NARCliM2.0 modelling.

A warmer Victoria by 2100

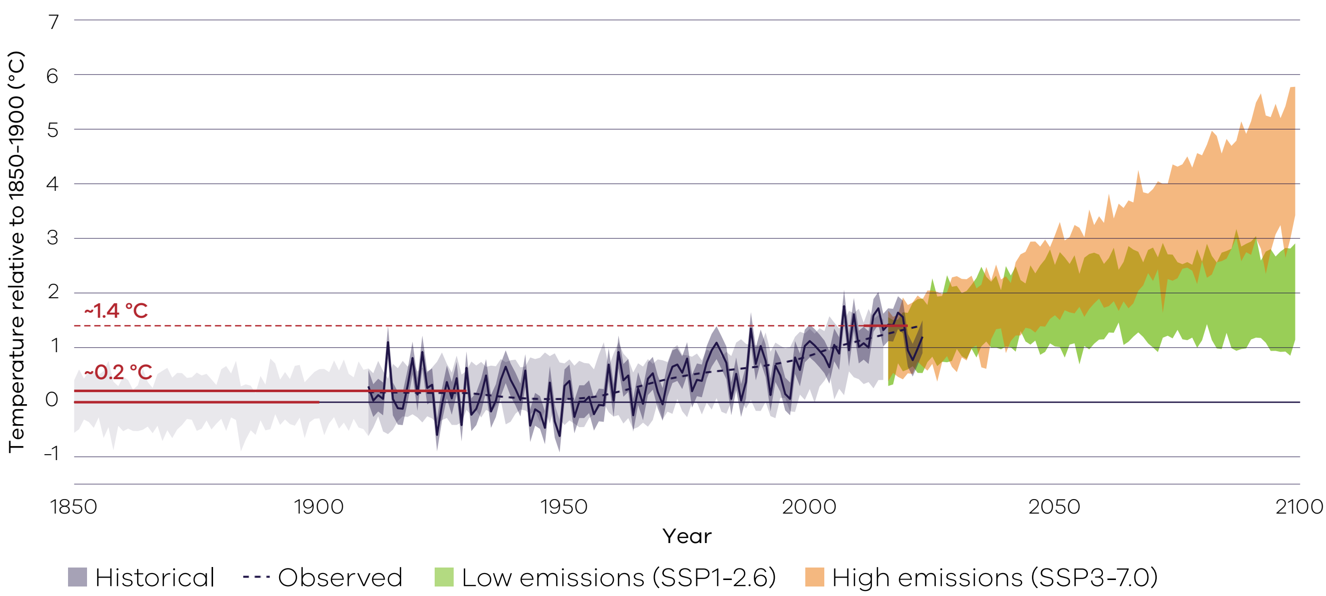


Figure 14. Observed and modelled historic and modelled future changes in average annual temperature over Victoria relative to the pre-industrial baseline (1850–1900). The light grey shading shows the modelled historical temperature range from CMIP6 global climate models, and the historical observed temperature is shown by the thin black line (dark grey band indicates the observed uncertainty). Future warming under SSP1-2.6 (green shading) and SSP3-7.0 (orange shading) from all global models, including low-likelihood, high-warming models, are shown to 2100. The red horizontal lines show the 0.2 °C of warming experienced between the pre-industrial baseline (1850–1900) and 1910, and the 1.4 °C of warming experienced between the pre-industrial baseline and the 2011–2020 period. Source: CSIRO, 2024.

Temperatures are projected to increase slightly more during summer and autumn and less during winter, with the differences largest under the high emissions scenario by the end of the century. Daily minimum temperatures are projected to warm slightly less than the average temperature, while the daily maximum is projected to increase slightly more.

Regional modelling indicates that slightly greater warming will likely occur inland and over high-altitude areas of Victoria. This spatial pattern of warming reflects observed warming (which has generally been greater inland) and physical processes that can amplify warming at high altitudes.

A comparison of observed temperatures and projections suggests Victoria's temperature is tracking towards the warmer end of the projections, although so far, it is tracking below the high-warming future projected by some climate models (Figure 15). This increases confidence that climate models provide a reliable indication of temperature trends so far, and are not overrepresenting potential warming (CSIRO, 2024).

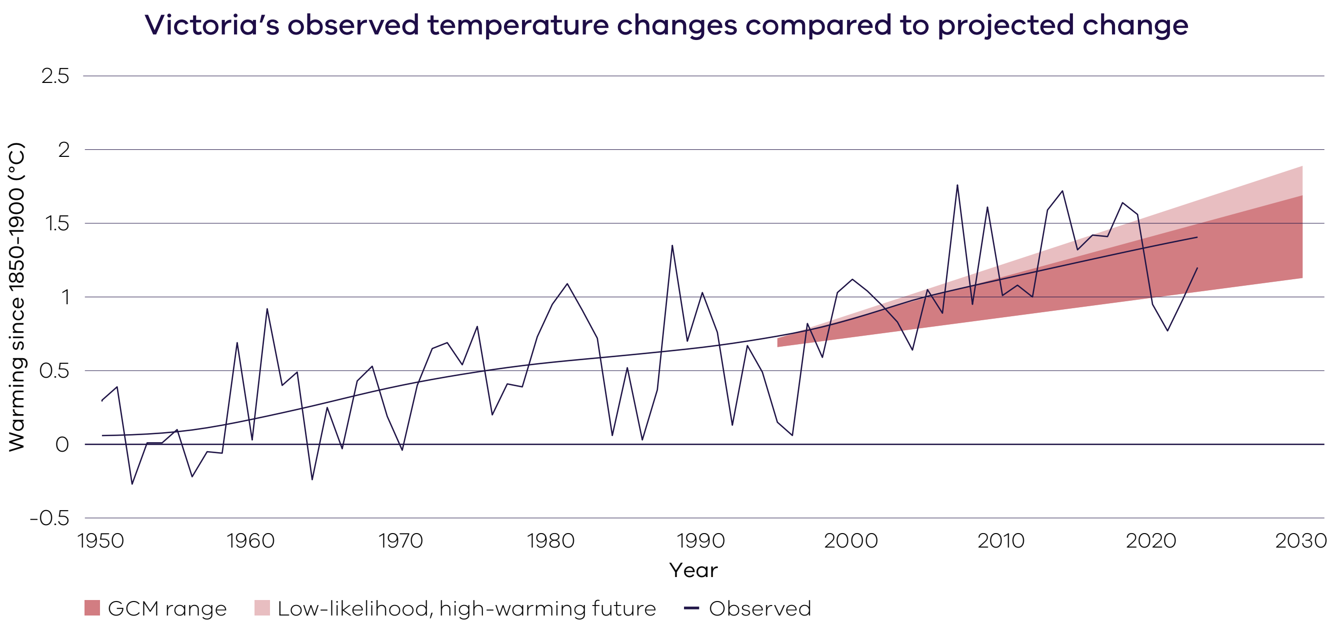


Figure 15. A comparison of observed annual temperature anomaly over Victoria from 1950 to 2023, to the projected range of temperature change out to 2030 from models under a high emissions scenario (SSP3-7.0), relative to the 1850–1900 pre-industrial baseline. The black zigzag line shows the observed annual temperature (ACORN-SAT v2, 2023), and the smooth black line shows the observed trend. The dark pink shading shows the projected range from the global climate model (GCM) ensemble of temperature change (10th to 90th percentile range) from 1986–2005 to 2020–2039. The light pink shading shows the results of high-warming global climate models. Source: CSIRO, 2024.

Despite the overall warming trend, Victoria may still experience short periods of little warming or even relative cooling due to natural variability. Temperatures will vary from year to year and decade to decade, as they have done in the past, due to processes such as ENSO. However, the ongoing warming trend will continue, increasing the odds of hotter years and more extreme temperatures. The rate and magnitude of warming beyond the near future will largely depend on the amount of greenhouse gases emitted globally.

Hot days

A warming climate also means that hot days will become hotter and more frequent.

The number of hot days is expected to increase under all emissions scenarios and time horizons. For example, under the high emissions scenario:

- Hot days (99th percentile from the historical baseline) could occur on average 4–17 times per year by 2050 or 7–30 times per year by 2090 compared to the 3–4 times per year experienced historically.
- Very hot days (99.9th percentile from the historical baseline) could occur on average 3–70 times per decade by 2050 or 10–100 times per decade by 2090 compared to the 3–4 per decade experienced historically. Recent decades have already experienced the average number of hot days at the low end of the 2050 projections.

Future changes in the number of hot days will depend on location (Figure 16).

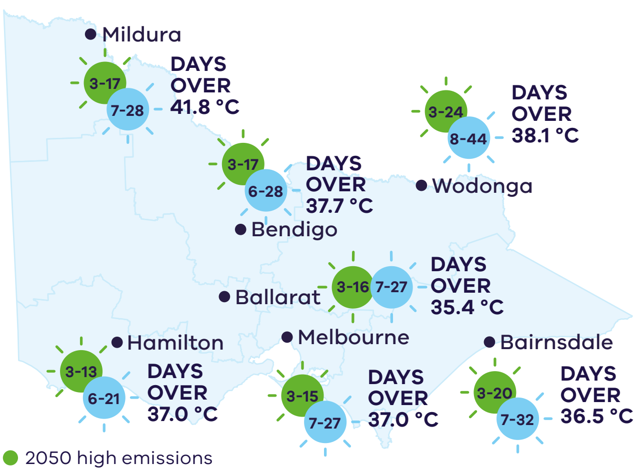


Figure 16. A comparison at key locations of the range of projected hot days per year under a high emissions scenario in the 2050s and 2090s compared to 3-4 days a year (relative to the 1986–2005 baseline). Source: Adapted from CSIRO, 2024.

The examples shown in Figure 16 are drawn from the high-resolution NARCliM2.0 modelling and include the full range of projections (incorporating the 10th and 90th percentile), because of the smaller sample size when just using NARCliM2.0. This includes simulations from a low-likelihood, high-warming model, which represents the upper end of the range.

Heat extremes are expected to become hotter in a warming climate, resulting in more hot days and hotter maximum temperatures than previously experienced.

According to projections from the nationwide and NARCliM2.0 modelling:

- By 2050, hot days in Victoria could get hotter by approximately 1.8 °C (range of 0.8 to 2.4 °C) under the high emissions scenario, although the low-likelihood, high-warming future model simulations show an increase of up to 4.9 °C.
- By 2090, the differences between the emissions scenarios are significant, with hot days in Victoria getting hotter by approximately 1.2 °C (range of 0.6 to 1.8 °C) under the low emissions scenario, and approximately 3.5 °C (range of 2.5 to 4.2 °C) under the high emissions scenario. The low-likelihood, high-warming model simulations show an increase of up to 6.4 °C.

An approximate way of interpreting these projections is to add the value of change onto the baseline. For example, what historically would have been a 40 °C day could be a 43.5 °C day under a future projected increase of 3.5 °C.

Regional modelling suggests hot days will warm the most during spring and the least in winter. The increase in the temperature of heat extremes is projected to be more than the increase in average temperatures, a finding that was also reported in VCP19 and other research..

Similarly to hot days, hot nights are projected to get hotter and more frequent, with potential consequences for human health and agricultural production.

Future changes in frost and snow

While future changes to frost occurrence and snow were not analysed as part of the updated Victorian projections, previous work has shown that changes are likely to occur under a warming climate.

Frosts are expected to become less frequent. However, it is still possible for frost occurrence to increase in some regions and seasons when cold, clear nights persist longer than suggested by projected minimum temperatures (Clarke et al., 2019). Over time, the effect of increasing minimum temperatures is expected to overpower the other factors that affect frost, leading to a decrease in frost occurrence.

Snow depth and extent are projected to continue decreasing due to reductions in snowfall and increases in snow melt (Bureau of Meteorology & CSIRO, 2022). The magnitude of the decrease depends on the emissions scenario, with significant reductions under a high emissions scenario.

3.4 Victoria is likely to get drier with more extreme heavy rainfall events

Victoria is likely to continue to become drier on average, especially in winter and throughout the cool season. This long-term drying trend will be overlaid by large natural year-to-year and decade-to-decade variability. Dry periods are projected to be drier and hotter, while extreme rainfall events are projected to become more intense.

Warming of the climate will bring changes to rainfall through 2 main processes:

- a warmer atmosphere can hold more moisture and cause overall global rainfall to increase
- changes in atmospheric circulation and weather systems can cause changes to rainfall distribution across the globe, and can lead to drying in some regions.

Victoria sits in the 'mid-latitudes', a region generally projected to become drier under a warming climate and changing circulation patterns. However, changes in circulation are difficult to predict, and it is often not possible to say whether the rainfall of a particular location or region will increase or decrease due to climate change. Rainfall changes can also be sensitive to changes in the atmosphere other than those caused by the enhanced greenhouse effect. For example, aerosols from volcanic eruptions and human activity can affect regional rainfall. This adds further uncertainty to how rainfall may change in the future.

As a result, climate model projections of future regional rainfall are less certain than temperature projections. Some of the climate and weather processes that strongly influence rainfall (such as atmospheric circulation and weather systems) are complex and harder to simulate reliably in climate models. This can lead to large differences between projections from individual models. Therefore, it is important to consider the full range of rainfall projection results to plan for all plausible futures.

Cool season rainfall

Victoria's cool season (April to October) rainfall is projected to continue decreasing, especially under the high emissions scenario (medium to high confidence). This projection broadly agrees with the recent observed rainfall trends (Figure 17).

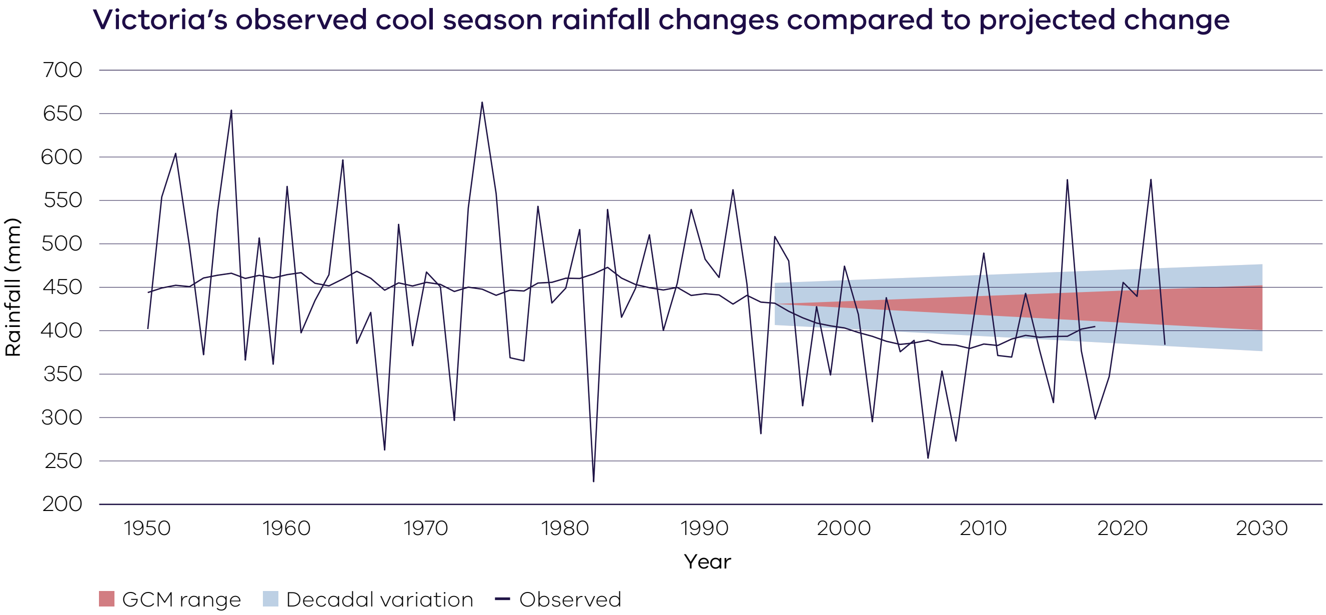


Figure 17. A comparison of the observed average cool season (April–October) rainfall over Victoria from 1950 to 2022, to the projected range of rainfall change from models out to 2030 under the high emissions scenario (SSP3-7.0), relative to the 1986–2005 baseline. The zigzag black line shows the observed average rainfall, and the smoothed black line shows the observed trend. The dark pink shading shows the projected range of rainfall change from 1986–2005 to 2020–2039 from the global climate model ensemble (GCM range). The light blue shading shows the decadal variation. Source: CSIRO, 2024.

The projected rainfall declines are clearest in spring (Figure 18). Almost 90% of the high-resolution downscaled simulations project that long-term decreasing spring rainfall will occur under the high emissions scenario. Projected changes in winter rainfall are smaller than in other seasons, but there is still strong model agreement that a declining trend will occur.

Projections for autumn rainfall vary between models, with some models simulating increasing rainfall and others decreasing rainfall (although more models simulate a decrease).

Victoria's rainfall will remain highly variable. This means that periods of high rainfall, wet years, sequences of wet years, and a wetter cool season are still possible even if there is a long-term drying trend. Although the cool season is likely to continue drying, periods where rainfall is similar to or greater than recent times could still occur. Rather than a steady increase in average rainfall, this would likely be caused by an increase in variability and wet years.

Summer rainfall

Large uncertainty remains in the future direction of change in summer rainfall (December to February), with different global and regional climate models indicating that both significant reductions and increases are possible (Figure 18). Summer rainfall will likely increase in variability and extremes, regardless of the change in the average. Therefore, planning for climate change should account for increased variability in summer rainfall and consider both wetter and drier scenarios during summer.

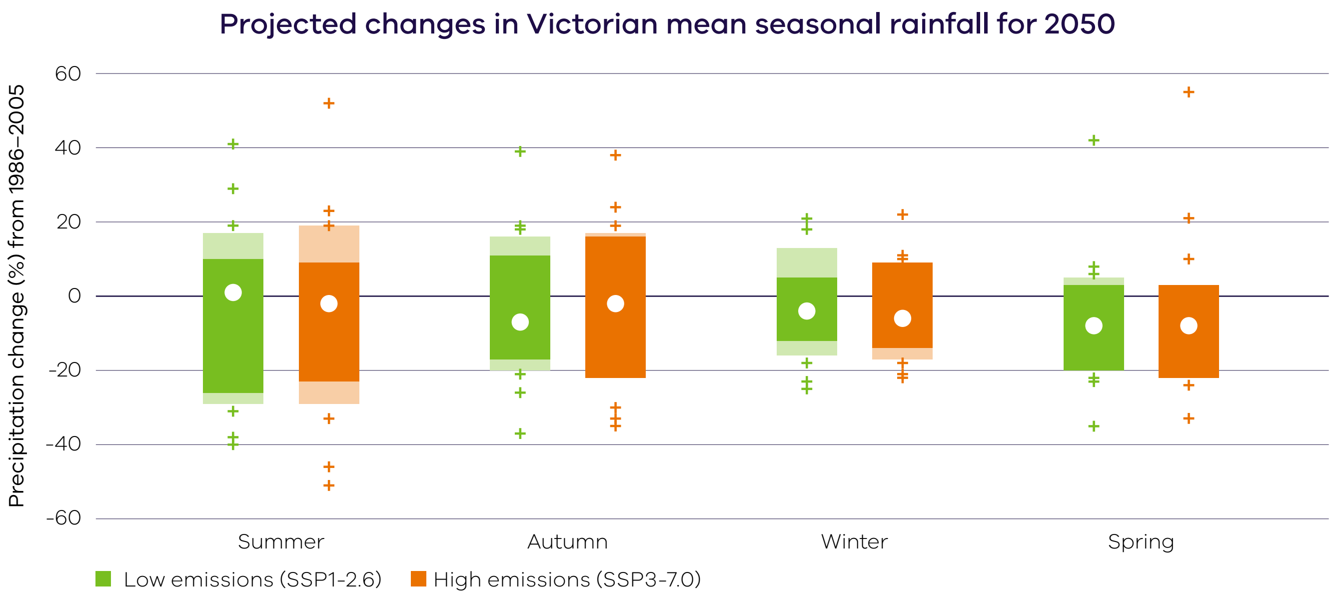


Figure 18. Projected mean seasonal rainfall change (%) over Victoria for 2050 (2040–2059) for the low emissions scenario (SSP1-2.6) and the high emissions scenario (SSP3-7.0) compared to the 1986–2005 period. The green boxes represent the low emissions scenario, and the orange boxes represent the high emissions scenario. The darker-coloured segments of each bar represent the 10th to 90th percentile range of projections from all global climate models, while the lighter 'extension' segments of each bar represent the 10th to 90th percentile range projected by the regional climate models. The crosses on each box show individual models outside the 10th to 90th percentile range, and the white circle in each bar represents the median of all the regional climate models. Source: Adapted from CSIRO, 2024.

Regional rainfall trends

Compared to global modelling, regional modelling is better able to represent the details of how projected changes in rainfall could differ across Victoria. However, different regional models project different spatial patterns of rainfall change for Victoria.

Regional modelling undertaken for VCP19 identified a projected decrease in rainfall on the western slopes of the Australian Alps (primarily in the Ovens Murray region) in autumn, winter and spring compared to the surrounding regions (*medium to high confidence*). Similar changes are evident in some of the new nationwide regional downscaling but are not present in the new NARCliM2.0 high-resolution regional modelling.

Differences in regional rainfall signals between different sets of modelling may reduce confidence in projected regional rainfall changes. The previous projections for Victoria and the new set of regional modelling are both plausible and should be considered in decision-making processes.

Understanding and projecting regional rainfall changes over Victoria (and Australia) remains an ongoing scientific challenge.

Extreme rainfall

Extreme rainfall events occur when a large amount of rain falls over a short period. In a warming world, the atmosphere can hold more moisture, so when an extreme rain event does occur, it can result in heavier rainfall. This effect is particularly relevant for heavy downbursts of rainfall on a sub-daily (minutes to hours) timescale. However, the characteristics of the weather systems that bring heavy rainfall also play a role in extreme rainfall events.

Generally, short-duration rainfall extremes (hourly or sub-daily rainfall) are expected to increase more than longer-duration rainfall extremes (daily rainfall). A recent overview study of extreme rainfall observations and projections (Wasko et al., 2024) conducted as part of the update to the Australian Rainfall and Runoff Guidelines, suggests that:

- even if the average total annual rainfall decreases, the amount of rainfall from wet days, heavy rainfall and extreme daily rainfall could increase
- daily rainfall extremes may increase by approximately 8% more rainfall per degree of warming
- shorter sub-daily rainfall extremes may increase in Australia by approximately 15% more rainfall per degree of warming.

For information about how changes in extreme rainfall relate to floods, please refer to Section 4.1 of this report.

The projections for Victoria include analysis of the amount of rainfall on heavy (99th percentile, occurs 3–4 times per year) and very heavy (99.9th percentile, occurs 3–4 times per decade) rainfall days. Generally, a larger increase is projected for the more extreme very heavy rainfall days. This aligns with findings for VCP19 identified and other research, which shows the largest increases for the rarer extremes.

The combined nationwide and NARCliM2.0 downscaling simulation show a wide range of change, but the upper end of the range (90th percentile from all simulations) shows up to around 15% and 20% increases in the amount of rainfall on heavy and very heavy rainfall days, respectively, by 2050 under the high emissions scenario. By the end of the century, the increase under the high emissions scenario could be around 30% and 40% for heavy and very heavy rainfall days, respectively. Under the low emissions scenario, the increase is likely to be smaller (around 10% for heavy rainfall and around 15% for very heavy rainfall).

The NARCliM2.0 ensemble tends to show a minimal increase or a decrease in daily heavy rainfall in the future, particularly in summer. This is at odds with other lines of evidence. Understanding the plausibility of various extreme rainfall projections is an ongoing area of research.

Victoria's climate projections under global warming levels

Projections under global warming levels present changes to regional climate when global mean temperatures reach certain thresholds, such as at 1.5 °C, 2 °C and 3 °C above the pre-industrial climate. Global or regional impacts can be tracked at these temperature thresholds, providing another useful approach to understanding and communicating climate projections.

Various frameworks can be used to understand climate projections. Emissions scenarios, such as SSPs, provide narratives about multiple plausible future worlds over time. Emissions scenarios are the most commonly used and well-known framework for describing climate projections.

However, global warming levels is an emerging framework (described in the latest IPCC Sixth Assessment Report) that provides estimates of changes to the regional climate if the world reaches a specific level of warming relative to the pre-industrial climate. Warming levels most often used include 1.5 °C, 2 °C, 3 °C and sometimes 4 °C of warming above pre-industrial levels globally. Global warming levels provide a simple and intuitive method of communicating climate projections that can be compared and integrated across different model ensembles and scenarios, but are not linked to specific time horizons. The removal of time horizons attempts to provide a framing that accounts for uncertainty around the pace of climate change this century.

Global warming levels and emissions scenarios can also be related to each other to determine when we can expect to reach the various global warming levels under different emissions scenarios (Figure 19).

Connection between global warming levels and SSPs

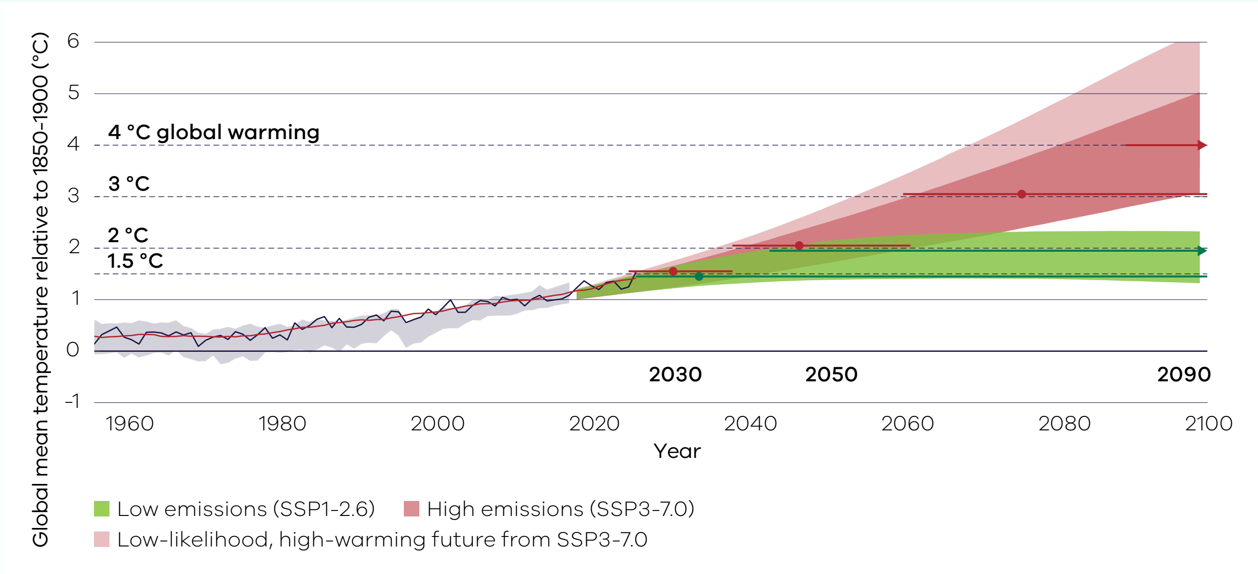


Figure 19. Global temperature observations and projections relative to the 1850–1900 period mapped against common global warming levels. The black line indicates historical observations, and the grey shade shows the historical modelled range. The green shading shows the range in projections under the low emissions scenario (SSP1-2.6) and the dark pink shading shows the range of projections for the high emissions scenario (SSP3-7.0). Light pink shading shows the range of low-likelihood, high-warming models under the high emissions scenario. The horizontal green and red lines show the time windows at which the common global warming levels (1.5, 2, 3 and 4 °C) are projected to occur under the emissions scenarios. Source: CSIRO, 2024.

Victoria is expected to warm at a similar rate to the global warming rate. As a result, warming in Victoria is projected to reach 2 °C above the pre-industrial era around the time the world reaches the 2 °C global warming level. Under the high emissions scenario, temperatures are likely to exceed the UN Framework on Climate Change Paris Agreement's primary goal of 2 °C by 2050, and exceed 3 °C by 2090. Under the low emissions scenario, temperatures are likely to stabilise at around 2 °C in the second half of this century.

To enable easy comparison with the findings of Victoria's Climate Science Report 2019, and for consistency with other recent climate science reports and initiatives, this report primarily uses the emissions scenario approach. However, some key global warming level findings are provided in the next column.

Key global warming level projections for Victoria

Under a 2 °C warmer world, Victoria's climate is projected to experience:

- warming of about 2.0 °C (range of 1.8 to 2.3 °C) compared to the pre-industrial period (1850–1900), or warming of about 1.3 °C (range of 1.1 to 1.6 °C) compared to the more recent 1986–2005 period (an amount similar to the global average but less than northern hemisphere land regions or the Arctic)
- a 2% decrease (range of -14 to +2%) in average annual rainfall compared to the 1986–2005 period
- a 7% decline (range of -17 to +4%) in average spring rainfall compared to the 1986–2005 period.

Under a 3 °C warmer world, Victoria's climate is projected to experience:

- warming of about 2.9 °C (range of 2.5 to 3.4 °C) compared to the pre-industrial period, or warming of about 2.2 °C (range of 1.8 to 2.7 °C) compared to the more recent 1986–2005 period
- a 6% decrease (range of -18 to +3%) in average annual rainfall compared to the 1986–2005 period
- a 11% decline (range of -27 to +1%) in average spring rainfall compared to the 1986–2005 period.

4. Understanding climate hazards in Victoria

Victoria's changing climate affects naturally occurring hazards in various ways. Common and damaging climate hazards include floods, heatwaves and extreme heat, droughts, bushfires, and sea-level rise.

Australia's climate is highly variable, with fluctuating temperatures, rainfall and wind creating conditions for climate hazards. Human-induced climate change affects natural climate variability, as well as average, slow-onset and extreme weather conditions.

Using the latest climate science to understand how climate hazards are changing and are likely to change in future is crucial to support local decision-making processes and responses. When hazards overlap with communities, places of natural and cultural value and the economy, and when the impacts of hazards exceed our ability to avoid, cope or recover, disasters can occur (Commonwealth of Australia, 2023).

Based on the availability of current datasets, this section includes scenarios in addition to the SSP1-2.6 and SSP3-7.0 referenced previously in this report.

What is extreme climate event attribution?

The emerging field of extreme climate event attribution allows scientists to establish the causes of extreme weather and climate events. Many causes can be considered, including prior conditions, climate drivers, like La Niña and El Niño, and climate change.

Findings from attribution analyses that examine the role of climate change in altering the frequency, magnitude or intensity of specific extreme events can be transformed into statements and communicated to contribute to our understanding of changing climate risks.

Generally, attribution statements answer questions about the changing nature of events and can be applied to a range of variables. For example, questions include 'How many more times would this heat event occur, and how much warmer was it in today's climate, relative to a world without climate change?' or 'How much more intense was this rainfall event in today's climate, relative to an equally rare event occurring in a pre-industrial climate?'

Detection of the extreme and its attribution are conducted by first defining the event. For example, the area affected, time period, or temperature threshold could be considered. The frequency of the event in a hypothetical climate without human influence is then estimated. Comparing that result to the frequency of the event in the actual climate, with natural drivers and human influence, shows the increase or decrease in the probability of an extreme event due to climate change (Lewis et al., 2014).

Different methods can also be used to attribute the change in the extremity of an event (Hope et al., 2022), for example, whether it was hotter or wetter in the current climate. An attribution statement can then be made. Figure 20 shows how frequently temperature records are broken in climate simulations affected by human influences, such as greenhouse gas emissions, compared to climates without these influences.

Attributing human influence on temperature records

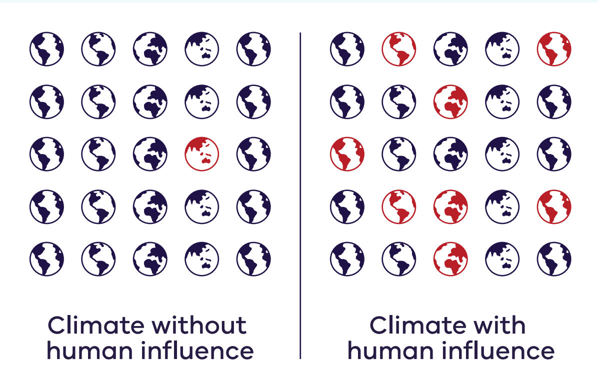


Figure 20. Graphic showing how frequently temperature records may be broken in climates with (right) and without (left) human influence. Red icons indicate record-breaking heat. Source: National Environmental Science Program's (NESP's) Climate Systems Hub and the Bureau of Meteorology.

Can we say the climate change influence is clear in Victoria's extremes?

A number of extreme event attribution research studies have been conducted for south-eastern Australia, including on extremes of heat, temperature and different types of rainfall events.

The scientific literature increasingly points to a clear link between human-caused climate change and **extreme heat** events' frequency, intensity and duration (Steffen et al., 2014) in Victoria. For example, the 2-week heatwave in Victoria prior to the Black Saturday bushfires in February 2009 was 3 °C warmer than it would have been without climate change (Abhik et al., 2023).

For **temperature extremes**, the climate change influence is clear when looking on a global scale. However, when looking at a city scale for a shorter time period, such as a few days, local factors and variability can make attribution less clear. For example, in 2014, Melbourne had 4 consecutive days above 41 °C, from 14 to 17 January. In this case, the influence of climate change was not clearly found in the analysis of the event (Black et al., 2015).

Rainfall attribution studies have analysed different types of events and timeframes.

For multi-week extreme rainfall events in south-east Australia, natural variability means the influence of human-caused climate change has been less evident (King et al., 2013; Lewis & Karoly, 2015; Hope et al., 2018; King, 2018).

However, a clearer climate change signal is emerging for longer term rainfall declines in Victoria, especially during the cool season months of April to October since 1997. These recent dry decades are unusual compared to the historical record, and some of the decline across 3 different climate regions of Victoria is attributed to climate change (Rauniyar & Power, 2023), as summarised in Table 1. By 2037, approximately 90% of climate models project further drying in the south-west of the state. By the end of the century, while year-to-year natural rainfall variability may offset some of the drying trends, reduced rainfall is projected to dominate in all 3 regions.

Table 1. Average rainfall decline (%) in 1997–2018 compared to 1900–1959 in 3 different climate regions of Victoria and the estimated proportion of this decline that can be attributed to climate change.

Climate region	Rainfall decline in 1997–2018 compared to 1900–1959 average (%)	Proportion of the decline estimated to be due to climate change (%)
North (Murray Basin)	15%	18%
South-west	8%	30%
East	11%	17%

Find out more

Researchers from the National Environmental Science Program Climate Systems Hub are conducting attribution studies on other Australian extreme events, as well as supporting the development of a real-time attribution service. For more information see: https://nesp2climate.com.au/research/people-and-country/extreme-events-explained/

This content is based on information provided by the National Environmental Science Program Climate Systems Hub.

Climate Systems
National Environmental Science Program

4.1 Floods

Key messages

- Over the past 50-70 years, Victoria has experienced:
  - extreme flood events at different locations at least 10 times
  - an increase of approximately 3% per decade in the magnitude of large floods, due to increasing rainfall intensities
  - a decrease of between 5% and 13% per decade in the magnitude of smaller floods.
- Smaller and more frequent floods that contribute to the health of our floodplain and riverine environment have been decreasing in magnitude, despite increases in extreme rainfall.
- The historical trend of small floods becoming smaller and large floods becoming larger is projected to continue at a greater rate in future, depending on the emissions pathway followed.
- If greenhouse gas emissions continue to rise at a medium to high rate, flood risk in Victoria is likely to double by the end of the century. That is, a flood with a historical 1-in-100 chance of being exceeded now may occur twice as often by 2100.
- The precise rate at which floods will increase is subject to uncertainty.

Describing floods

Floods are a natural part of Victoria's environment. While they are generally a result of intense rainfall, their behaviour and magnitude are influenced by a range of factors.

Most floods are the result of natural phenomena. They provide an essential contribution to the health of floodplain environments. Flooding acts as a trigger for the germination of new plants, dispersal of important nutrients for invertebrates and fish, and stimulation of breeding conditions for many species. However, floods can have devastating effects, and the social, economic and environmental impacts can last for many years, permanently altering lives and livelihoods.

Flooding occurs when water inundates land that is normally dry. This usually occurs when water escapes the confines of a natural or constructed watercourse (such as rivers, creeks, retarding basins and dams). It may also occur when water from heavy rainfall has nowhere else to go. The former type of flooding is sometimes referred to as a fluvial or riverine flood and the latter a pluvial or stormwater flood. The information presented here on floods primarily considers the effects of climate change on fluvial floods, which present large risks for Victoria.

In Australia, most floods arise from intense rainfall. In coastal areas, inundation due to rainfall may be amplified by high sea levels or by storm surges resulting from strong onshore winds and intense low-pressure systems. The frequency and occurrence of floods in Victoria are primarily caused by large-scale climate drivers that vary greatly from year to year, with periods of extended wet or dry conditions often occurring every 3 to 8 years.

While heavy intense rainfall tends to produce large floods, flood behaviour and magnitude are strongly influenced by a range of variable and fixed factors (Figure 21).

Variable factors include the following.

- Rainfall: rainfall concentrated in space or time tends to produce larger floods than rainfall distributed more uniformly.
- How wet or dry a catchment is before the rainfall: dry soils can absorb a large portion of the storm rainfall, so high rainfall may yield a smaller flood. Conversely, wet soils may be unable to absorb further water, leading to a larger flood from low or moderate rainfall.
- The combination of a flood peak and high tide: this combination can increase the height (and extent) of flood waters and is an important factor in some coastal areas.

Fixed factors include the following.

- The difference in flood runoff between urban and rural catchments: urban catchments include more hard surfaces that do not absorb rainfall, and water moves along drains and roadways much faster than in natural catchments. As a result, floods in urban areas tend to be larger and rise more quickly than those in a rural catchment that experience the same amount of rainfall.
- The nature and extent of the drainage network or other related infrastructure.
- The size and location of any water bodies in the catchment.
- Other factors: such as how steep or flat the catchment is and the presence of vegetation cover.

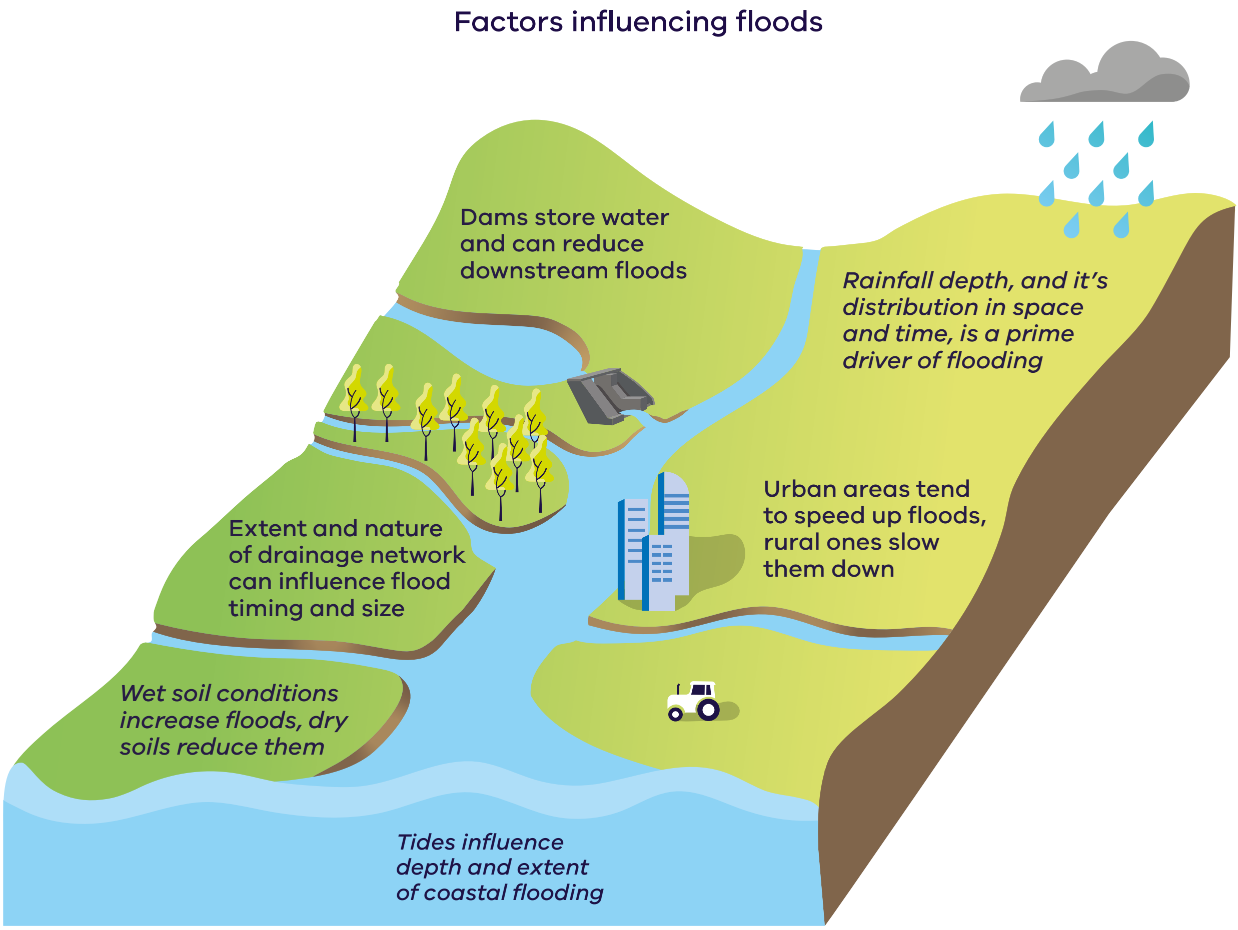


Figure 21. Flood response to rainfall is influenced by variable factors (shown in italic text) and fixed factors (shown in plain text). Source: Rory Nathan and Conrad Wasko for VCSR24.

Flood severity and risk

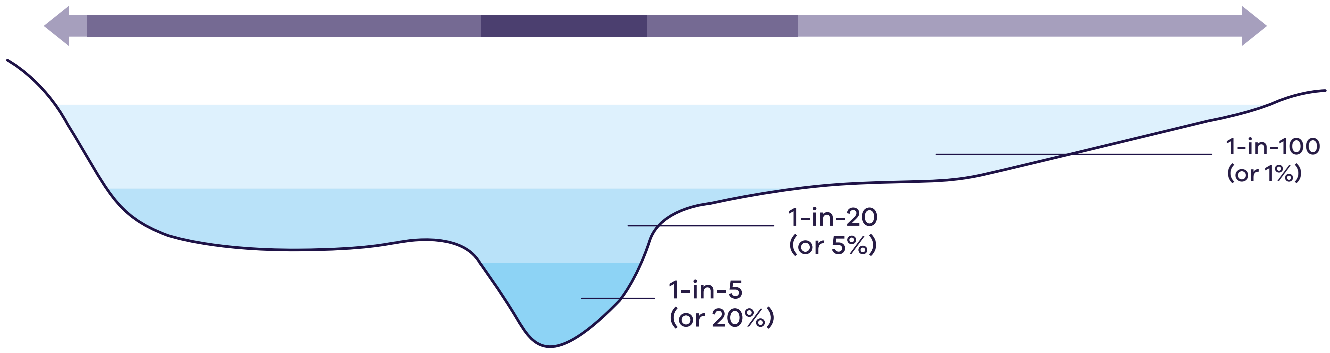
There are many ways to describe flood severity. Engineers and planners usually describe the severity of a flood event in terms of the likelihood of its occurrence (Figure 22b). The likelihood of a flood may refer to specific attributes of the flood, such as its peak flow rate, volume, inundation extent or level. However, as the consequences of a given flood are generally the result of many factors, it is preferable to describe severity solely in terms of likelihood, such as the annual probability of its exceedance (Figure 22a).

For example, an event at a particular location could be referred to as having a 1-in-100 (1%) chance of being equalled or exceeded in any one year. There is no certainty that a 1-in-100 flood will actually occur, or that it will occur only once in a 100-year period.

The expectation that we might wait another 99 years before the next 1-in-100 event is a misconception. It is also location specific, with a 1-in-100 event in one location having no particular inference for a neighbouring location. As a result, a broader region may see multiple 1-in-100 events at different locations in the same year. It is common for climate scientists to use the term 'extreme' to refer to events that might occur on average 2 to 3 times per year, whereas flood hydrologists and planners usually apply such terminology to events that occur once every 20 years, or more rarely. In this report, the term 'extreme flood' refers to events that are likely to cause major rivers to overtop their banks, such as those with an annual likelihood of 1-in-20 to 1-in-100 flood events, and rarer.

Flood magnitude and probability

The extent of flooding depends on both the severity of the event and topography



Average recurrence interval	Period	Probability (chance) of occurrence in the given period	
		Fractional odds	Percentage
'5 year' flood	occurring in any one year	1 in 5	20%
'20 year' flood	occurring in any one year	1 in 20	5%
	occurs at least once over the period of a typical house mortgage (25 years)	~ 7 in 10	72%
'100 year' flood	occurring in any one year	1 in 100	1%
	occurs at least once over the period of a typical house mortgage (25 years)	~ 1 in 5	22%
	occurs at least once over the period of multi-generational property ownership (100 years)	~ 3 in 5	63%

Figure 22. a) Illustration of flood heights for differing exceedance probabilities. A flood with a 1-in-100 chance of being exceeded is always greater in magnitude than a flood with a 1-in-5 chance of being exceeded. Differences in the extent of flooding depend heavily on whether the land being inundated is flat or steep. **b) Various ways of describing flood likelihood using language based on average or recurrence intervals and probability concepts.** Examples are given of the chance (in fractional odds and percentages) that a flood is likely to occur over a particular period of time, such as over the period of a typical house mortgage and annually. Source: Rory Nathan and Conrad Wasko for VCSR24.

Observed changes in Victoria's floods

Victoria has experienced 1-in-100 flood events somewhere in the state at least 10 times in the past 50 years.

Since the 1900s, floods in Victoria (Figure 23) have generally resulted from widespread rainfall soaking into the ground, with any additional large or heavy rainfall increasing the risk of flooding. For example, the floods in 1909 affected many towns in western Victoria after they experienced their highest monthly rainfalls, with 4 deaths recorded at Winchelsea. The flood events of 1934, which affected Melbourne and South Gippsland, resulted in 36 fatalities. The flood events of 2010–12, which mainly occurred in north-east and south-west Victoria, led to a state of emergency being declared across many parts of the state. In October 2022, a low-pressure system moved east across Australia bringing heavy rainfall and storms over catchments that were already sodden from wet conditions over the preceding month. This led to one of the most devastating flooding events in Victoria's history (Victorian State Emergency Services, 2022).

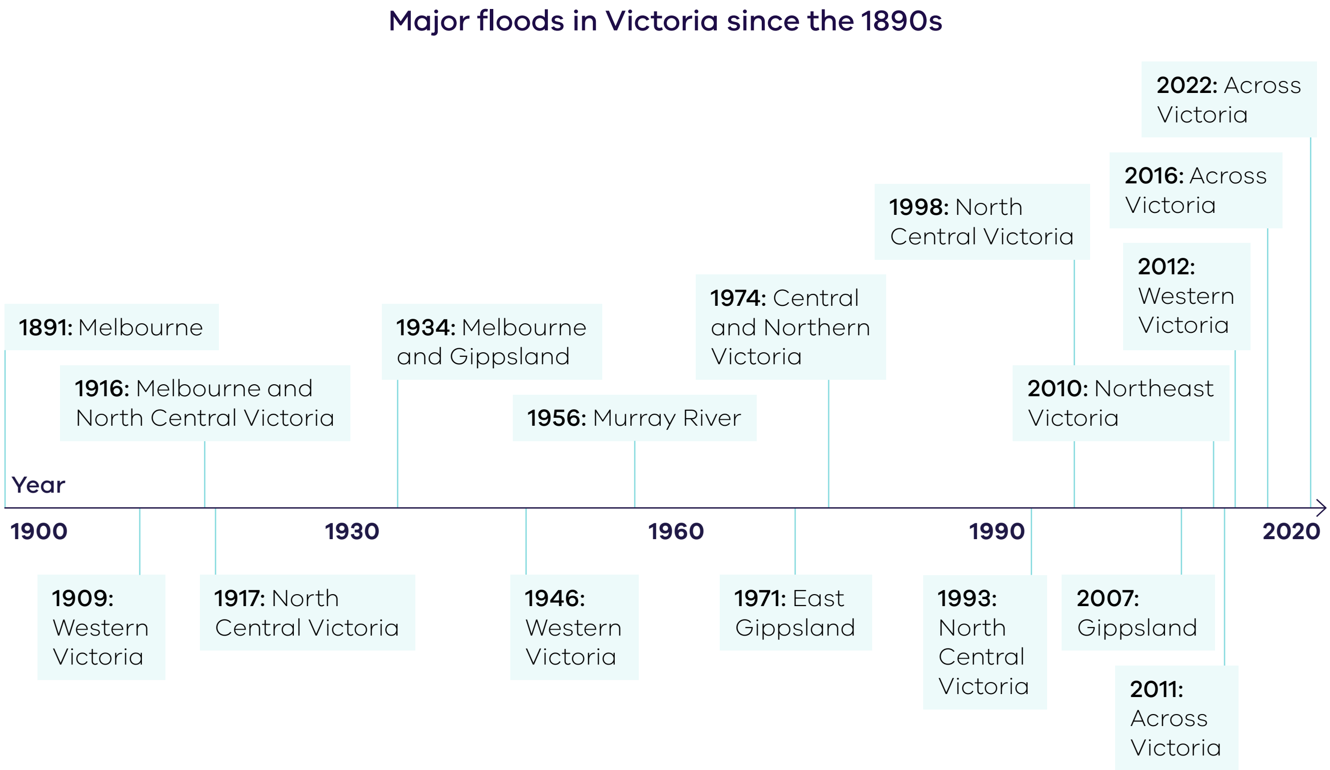


Figure 23. Timeline of major regional flooding in Victoria since 1891. The number of flood events and their severity has increased, but with improvements in technology, the reporting of flood events has also increased over time. Source: Rory Nathan and Conrad Wasko for VCSR24, based on DELWP, 2016.

Heavy rainfall events and floods can occur anywhere in Victoria. In rural catchments, topography and proximity to a floodplain determine whether an area is vulnerable to flooding. The closer to a floodplain, the more likely an area will experience flooding.

Similarly, in an urban catchment, areas near waterways are generally more prone to fluvial flooding from water that has escaped a natural or constructed watercourse. Flooding of rivers in the flat areas of the north and north-west regions of Victoria may last for several weeks, or even months, and can lead to major losses of livestock, damage to crops and extensive damage to rural towns and road and rail links. Conversely, floods can occur more quickly in large rivers that rise in the mountainous central and eastern areas of the state. These rivers are steeper and flow faster, with flooding sometimes lasting only a few days. These regional differences in flood behaviour have implications for how communities should respond before, during and after a flood – advice on this is provided by the National Emergency Management Agency and Victoria State Emergency Service.

Streamflow in Victoria exhibits a wide range of variability that is largely representative of conditions found across Australia (Dykman et al., 2023). Compared to average conditions, some years are warmer with less rainfall, while others are cooler with more rainfall. This variability affects the occurrence and severity of flood events. The frequency of extreme wet and dry rainfall periods is largely controlled by large-scale climate drivers related to sea surface temperatures. This results in flood events that often occur in relatively quick succession, which is at odds with the common expectation that once a large flood event has occurred, it is unlikely one will occur again for some time.

Streamflow gauges record water level observations, which are used to estimate the volume of flow over a given time. There are over 1,200 flow gauging sites in Victoria, with around 130 considered 'high quality'. A gauge is considered high quality if it has been well maintained by the relevant state water agencies, and if the catchments are largely unaffected by water resource development and changes in land-use that may impact streamflow (Bureau of Meteorology, 2020). The percentage of high-quality streamflow gauges in Victoria that recorded a flood event with a 1-in-100 chance of being exceeded in any one year is shown in Figure 24.

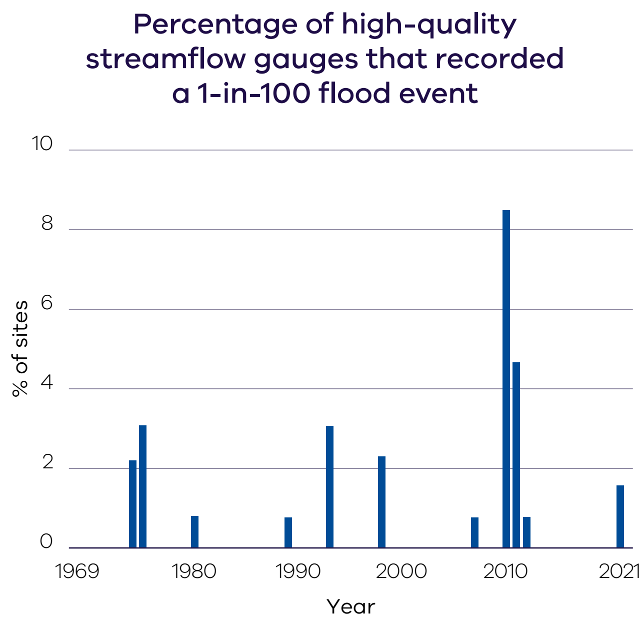


Figure 24. Proportion (%) of high-quality streamflow gauging stations in Victoria in the past 50 years (1969 to 2021) that have experienced floods with a 1-in-100 chance of being exceeded. Source: Rory Nathan and Conrad Wasko for VCSR24.

From 2010 to 2012, different parts of the state experienced a 1-in-100 flood event. Victoria has experienced floods in excess of a 1-in-100 event somewhere in the state at least 10 times in the past 50 years, with the most recent events having the most widespread impacts. The risks of such extreme events occurring *somewhere* in Victoria in any one year is much greater than 1-in-100. There will be some locations that have not experienced a 1-in-100 event in the past 100 years, and others where 2 or more such events may have occurred.

Changes in land-use associated with urbanisation and deforestation generally increase the proportion of rainfall that appears as runoff, causing floods to be larger and rise more quickly. Climate change is also affecting flood behaviour. Rainfall and floods of varying severity have been changing in Victoria since records began.

Extreme rainfall – one of the main drivers of flood events – has been increasing regardless of how frequent or rare the rainfall occurrence. Extreme rainfall events with an annual likelihood of 1-in-20 have increased by about 3% every decade over the past 50 or so years, and these rainfall increases have led to flood magnitudes increasing at a similar rate. When considered with historical increases in global temperatures, these changes are in excess of 7% per degree of global warming (Wasko & Nathan, 2019).

Floods that are more frequent than a 1-in-20 event are a fundamental part of the health of our floodplain and riverine environment. These floods have been decreasing despite increases in extreme rainfall. This is due to a drying trend in Victoria's soils due to decreasing annual rainfall alongside increasing temperatures and evaporation (Wasko & Nathan, 2019).

The complexity of these changes means that small floods are becoming smaller and large floods are becoming larger (Figure 25). Smaller floods carry less volume and hence are proportionally more affected by drier soils soaking up water. Conversely, large floods are driven by large rainfalls and the changes in soil moisture represent only a small proportion of the volume of the flood, meaning that the drier soils tend to have a smaller effect on flood response (Wasko & Nathan, 2019). The reduction in small floods increases the risk of water shortages (as small floods are needed to top up the water supplies), while increases in larger floods raise the risk of flood damage.

Small floods are becoming smaller and large floods are becoming larger

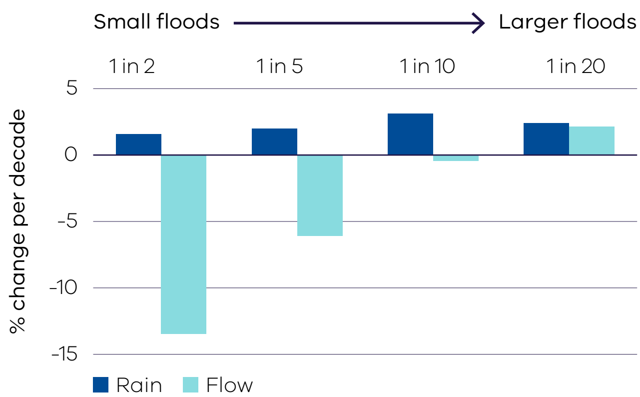


Figure 25. Historical changes in extreme rainfall and flood magnitude in Victoria between 1969 and 2019. Climate change is increasing rainfall intensities historically, but changes in flooding vary. Source: Rory Nathan and Conrad Wasko for VCSR24, based on Wasko & Nathan, 2019.

Climate change impacts on factors influencing floods

Increasing global temperatures are changing the conditions that lead to floods.

Higher global temperatures are increasing the frequency and severity of extreme weather, with consequences for flooding. Most large floods are caused by large rainfalls, and higher temperatures increase the amount of atmospheric moisture available to generate storms. This means that storms may be more intense in future, leading to greater subsequent flood runoff (IPCC, 2023).

It may never be possible to predict floods with 100% accuracy due to the variability of weather systems and the randomness of the factors that jointly combine to produce large floods. However, this uncertainty can be reduced through better information and models of weather and flood processes. As a result, a range of plausible flood futures should be considered when planning for the future.

Rainfall intensity

Importantly, across Australia, rainfall intensities of long-duration events (24 hours and over) are expected to increase by 8% per degree of global warming (Wasko et al., 2024). Shorter duration events, such as thunderstorms, are expected to increase at an even higher rate of around 15% per degree of global warming.

Further information on extreme rainfall and downscaled CMIP6 rainfall projections for Victoria are provided in Section 3.4 of this report.

Soil moisture

Greater evaporation and longer periods without rain contribute to drying soil. In Victoria, drier soils are expected to absorb around 5% more rainfall for every degree rise in global warming (Ho et al., 2022). Therefore, by 2050 under a medium emissions scenario (RCP 4.5), rainfall losses by soil absorption during storm events will increase by around 10% compared to conditions over the past few decades, and by 20% by 2100 (Ho et al., 2023).

Sea-level rise and storm surges

In coastal areas, increases in sea levels and storm surges will mean that lower sections of rivers and estuaries that are sensitive to tide levels will experience higher and more extensive flooding (Steffen & Alexander, 2016). Impacts of sea-level rise are likely to include more frequent and extensive inundation of low-lying areas, and erosion of cliffs, beaches and foreshores (State of Victoria (Victorian Coastal Council), 2018).

Vegetation

Flood risk is heightened by the bare soils and lack of vegetation caused by drought and bushfires.

Dam storage

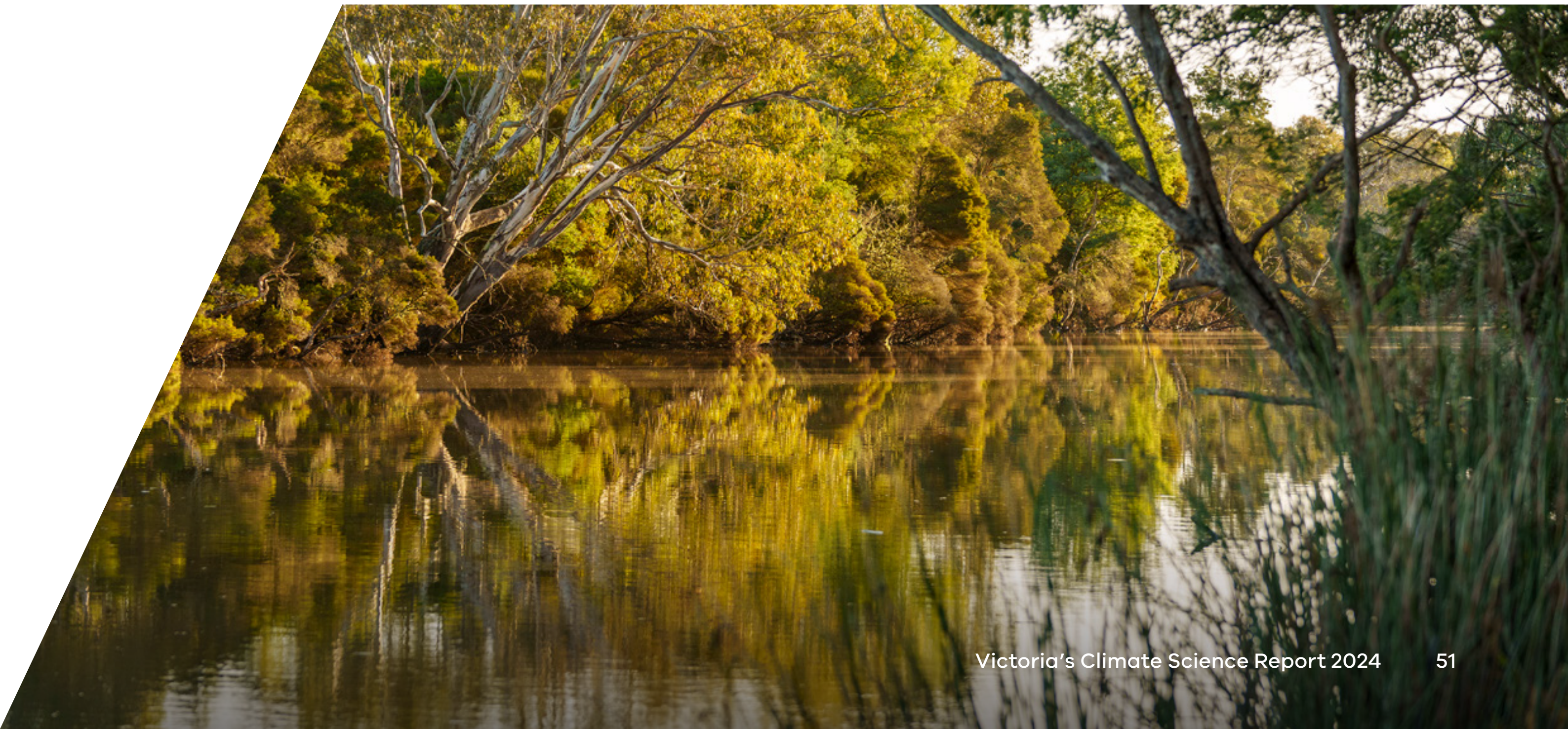
Downstream of dams, floods may get smaller as rising temperatures increase water demand and evaporation rates. This may reduce the volume of water in storage (Henley et al., 2019), leaving capacity to absorb any incoming floods. While dams can reduce the impacts of flooding, dams in Victoria are generally built to provide water supplies. Any flood mitigation benefits from dams are mostly incidental and not easily achieved without reducing water security in the long term. The understanding of flood risks has improved over time due to improvements in methods and the quality of information on which estimates are based.

Future changes to floods

It is likely that small floods will get smaller and large floods will get larger.

The precise changes in flood magnitude in southern Australia are uncertain due to the compensating effect of more intense extreme rainfall versus projected drier conditions (IPCC, 2023). The process of converting global climate model output into changes in hazard or risk involves several steps and assumptions that introduce uncertainty, such as the choice of future emissions scenario, the global or regional climate models used, and the hydrologic model used to model the flood risk. Despite these uncertainties, climate models remain one of our best sources of information on climate.

Climate projections provided by the Bureau of Meteorology (Wilson et al., 2022) indicate that the historical trends that we have seen in Victoria of small floods getting smaller and large floods getting larger are likely to continue to occur in the future, where the rates of future change depend on the emissions scenario (Wasko & Nathan, 2019).



Projected changes in small floods (with an annual probability of 1-in-5) in rural areas are likely to be modest. Drying soils as a result of higher temperatures and longer periods without rain means that small floods will continue to get smaller across much of the state (Wasko et al., 2023). For more extreme events (such as 1-in-100 flood events), widespread increases in flood magnitude are projected, exceeding 30% in many parts of the state. In contrast to floods in rural areas, floods in urban areas are likely to increase in line with extreme rainfall increases, as they are relatively unaffected by drier soils due to the lack of porous surfaces.

If greenhouse gas emissions continue to rise at a moderate to high rate, flood risk in Victoria is likely to double by the end of the century (Wasko et al., 2023) (Figure 26). That is, a flood with a 1-in-100 chance of being exceeded now might be twice as likely to occur by 2100.

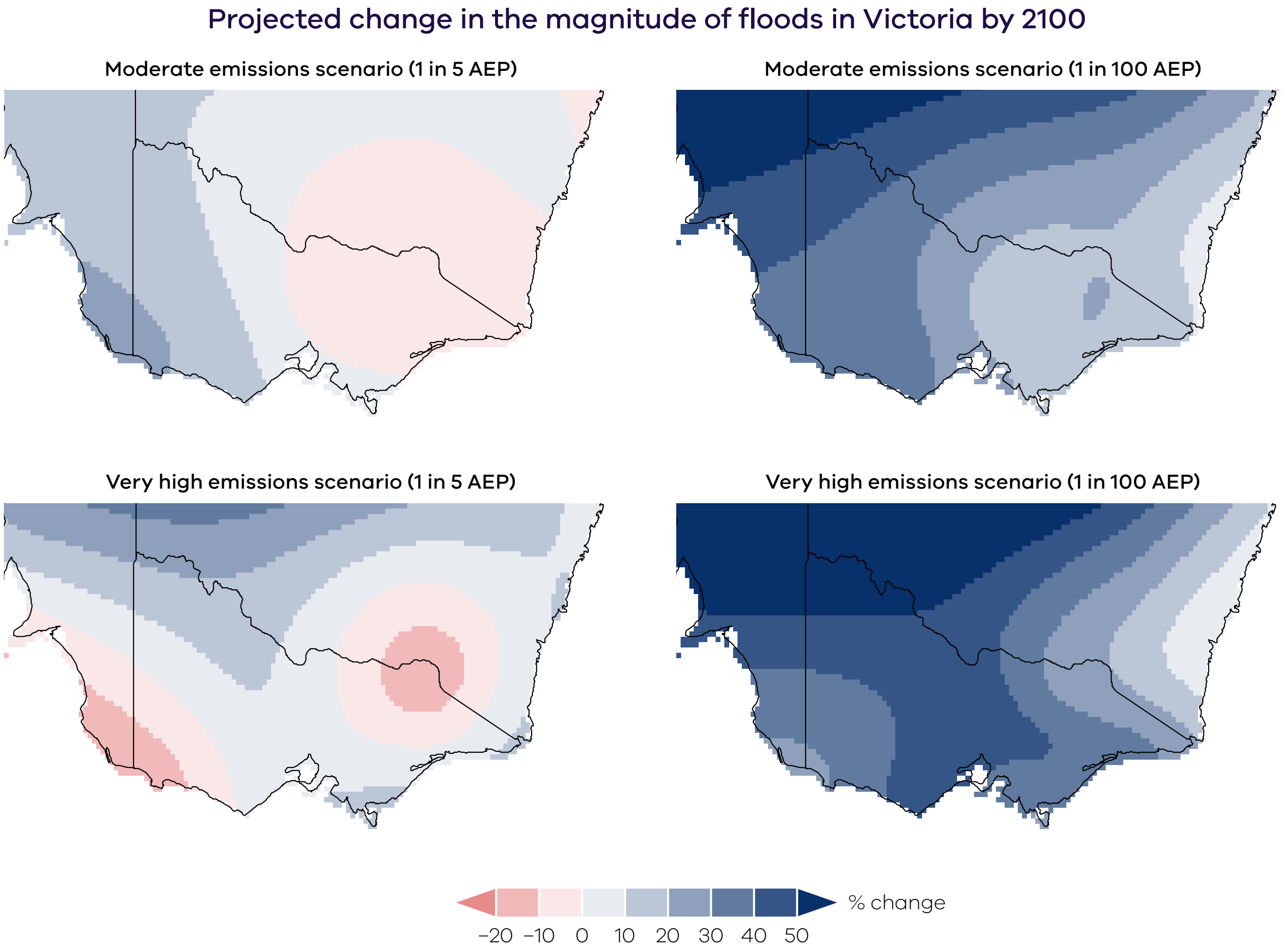


Figure 26. Projected change in the magnitude of floods in Victoria by 2100 for both medium (RCP4.5 – top maps) and very high (RCP8.5 – bottom maps) emissions scenarios compared with historic conditions. Blue colours represent increasing magnitude, and red colours represent decreasing magnitude. AEP = annual exceedance probability. Source: Rory Nathan and Conrad Wasko for VCSR24.

How does the Victorian Floodplain Management Strategy consider climate change?

The Victorian Floodplain Management Strategy is helping prepare Victoria for a range of climate conditions by modelling different climate change scenarios as part of flood studies. Flood studies for urban and regional areas are informed by the most recent edition of the Australian Rainfall and Runoff Guideline. This national guideline is published by Engineers Australia to guide the development of flood studies. The Climate Change Considerations chapter of the guideline continues endeavours to keep pace with current climate science. The Climate Change Considerations chapter has undergone a review in 2024, with the updated chapter due for release soon.

A key aspect of the Victorian Floodplain Management Strategy is the requirement for the 9 Catchment Management Authorities to be accountable for developing and periodically reviewing Regional Floodplain Management Strategies in partnership with Local Government Areas, the Victoria State Emergency Service, water corporations, other partner agencies, and local communities. The purpose of the regional strategies is to apply the policies and accountabilities set out in the Victorian Floodplain Management Strategy at local levels. They are the vehicle for aligning the efforts of all agencies with floodplain management responsibilities to deliver flood risk mitigation outcomes according to community priorities. The regional strategies include local investment priorities for flood studies, warning systems and mitigation infrastructure, such as levees.

Each Regional Floodplain Management Strategy is based on an assessment of a region's flood risks. These risks include considering future risk in a changing climate. The community considers their tolerance for these risks, and a range of mitigation measures for intolerable risks are explored. In practice, this involves comparing measured flood risks against the level of risk assumed in the Total Flood Warning System for the locality. If the level of risk assumed in the warning system is lower than the actual risk, then the Total Flood Warning System must be upgraded to reflect this.

Regional strategies prioritise the actions necessary to put preferred mitigation measures in place and assign a lead agency responsible for delivering each action. Measures that do the most to narrow the difference between existing flood risks and the community's willingness to accept those risks are at the top of the list. Mitigation measures might include strategic plans for land-use and flood warning and response arrangements.

4.2. Heatwaves and extreme heat

Key messages

- Since the 1950s:
  - the intensity, frequency and duration of heatwaves in Victoria have increased, and the typical Victorian heatwave season is now longer and starts earlier
  - observed heatwave trends have increased at a faster rate over the past few decades
- Future changes in Victorian heatwaves will be driven by increasing global temperatures. More warming will result in longer, more intense and more frequent heatwaves.
- There is some evidence that expansion of Melbourne's urban areas could result in higher night-time temperatures during heatwave events due to excess heat accumulated during the day.
- CMIP6 projections indicate that the frequency of heatwave days in Victoria is likely to increase from the historical average of 20 days a year (1986–2005). By 2090, under a high emissions scenario, the frequency of heatwave days could more than triple. Victoria could experience around 60 heatwave days rather than the 20 experienced historically.

Describing heatwaves

Heatwaves are prolonged periods of excessive heat that generally last for at least 3 or more successive days.

For the Victorian CMIP6 heatwave projections, a heatwave is defined as at least 3 consecutive days above the 95th percentile of daily average temperatures over a baseline period of 20 years (1986–2005). There is no universal agreement on the minimum number of days a heatwave must last or the threshold used to determine excessive heat (Perkins & Alexander, 2013). A heatwave longer than a week is exceptionally rare in Australia.

In Australia, heatwaves are often forecast and projected using the Excess Heat Factor (EHF) (Nairn & Fawcett, 2014). While other heatwave metrics and frameworks exist, the EHF has been shown to be useful in forecasting heatwaves, providing heatwave warnings, constructing future heatwave projections, and understanding the impacts of heatwaves on human health. The EHF accounts for extreme day and night conditions by averaging daily minimum and maximum temperatures. It compares conditions over a 3-day period with the previous 30 days as well as a climatological threshold that represents extreme temperatures. It can therefore detect the intensity, severity, duration, and spatial extent of an individual heatwave. The EHF also provides information on the number of heatwave days and seasonal length across the entire heatwave season. What determines 'extreme' is highly dependent on the local climate.

Historically, the heatwave season in Victoria is November to March.

Heatwave mechanisms

Heatwave conditions are affected by a number of physical mechanisms that cause prolonged periods of excessive heat.

Atmospheric dynamics

A persistent high-pressure system, also known as an anti-cyclonic system, is one of the most important mechanisms responsible for the development of heatwaves. In the absence of an anti-cyclonic system, it is extremely unlikely for heatwave conditions to develop (Hirschi et al., 2011). Large-scale dynamics are particularly important for the development of the persistent highs that cause heatwaves over south-east Australia and Victoria. Tropical cyclones off the coast of north-west Australia can also lead to heatwaves in Victoria (Parker et al., 2013). For example, the interaction between north-western tropical cyclones and south-eastern heatwave conditions was a key driver of the heatwave that immediately preceded the Black Saturday bushfires in 2009.

Pre-existing soil moisture

Land surfaces that are drier than normal can also influence heatwave development (Alexander, 2011). The factors that drive heatwave development, such as a lack of soil moisture and persistent high-pressure systems, can interact and amplify each other (Miralles et al., 2019), as shown in Figure 27.

Short durations of low soil moisture immediately before a heatwave have contributed to previous south-east Australian heatwaves, intensifying the impacts of high-pressure systems (Kala et al., 2015).

Mechanisms that drive heatwave development

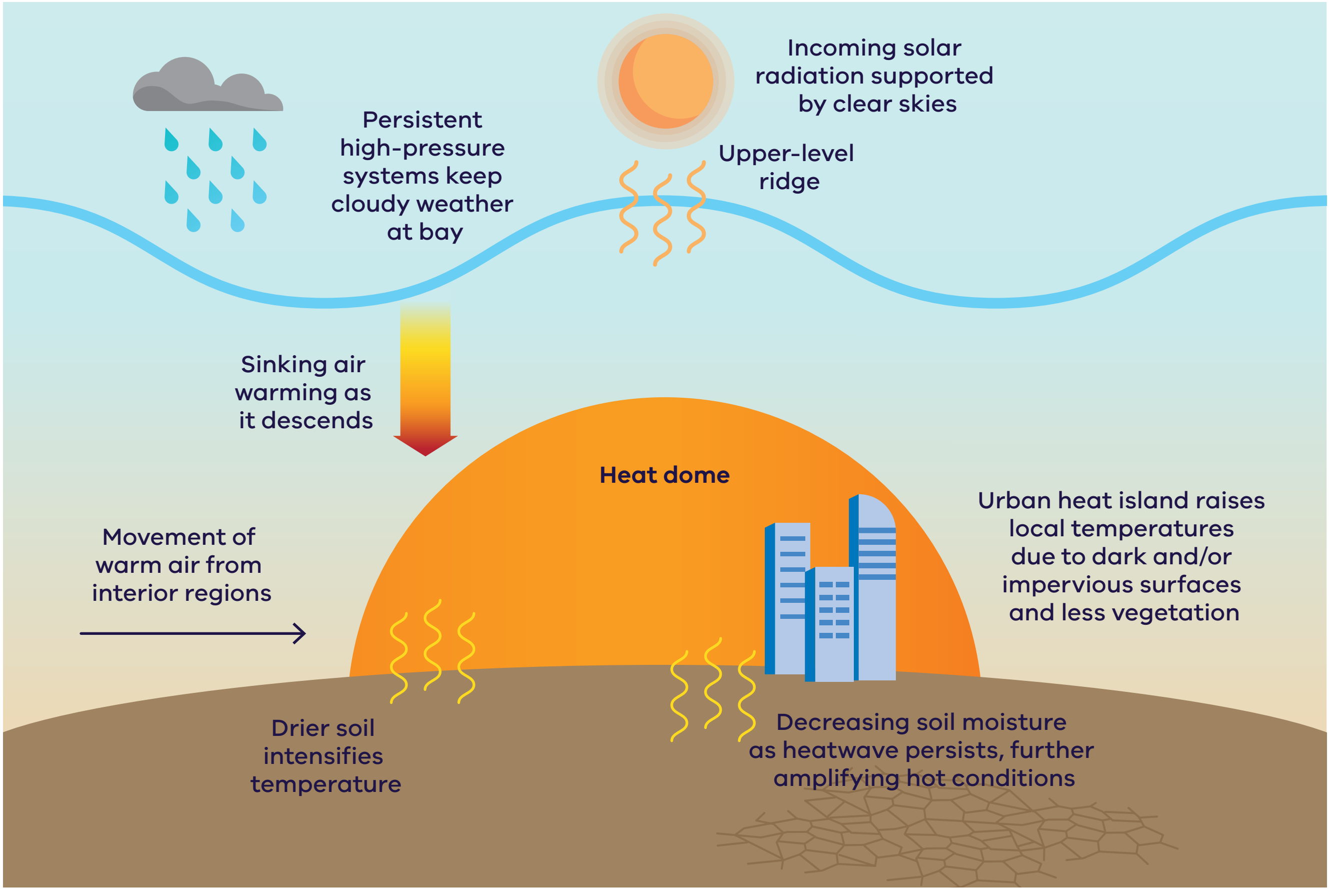


Figure 27. Physical mechanisms, and their interactions, that contribute to the development of heatwave conditions in Victoria. The heat dome represents the hot conditions within the bounds of the high-pressure systems. Source: Sarah Perkins-Kirkpatrick for VCSR24.

Local land-use

Heatwave conditions can be further exacerbated by local land-use, especially in urban areas where dark impermeable surfaces, human-made structures and a lack of vegetation are more common. The presence of an urban heat island, where heat from the sun is absorbed by hard surfaces, can further increase temperatures during a heatwave in Australian urban environments (Hirsch et al., 2021). The presence of an urban area is unlikely to be the initial cause of a heatwave, but can help amplify the intensity and duration of heatwaves.

During a heatwave, increases in temperature are highly localised and can vary across an urban area. For example, a leafy suburb with well-spaced houses will likely experience a smaller temperature rise than a suburb with little or no vegetation and houses built close together from dark or heat-retaining materials (Kong et al., 2021). Changes in the land surface can also influence heatwave conditions, such as a reduction in vegetation due to deforestation or changes from a forested area to farmland or city.

These land-use changes can increase the intensity and duration of heatwaves locally. Conversely, land management practices, such as increased irrigation (Broadbent et al., 2018) and localised re-vegetation (Maggiotto et al., 2021), may reduce the severity of local heatwaves.

Climate change impacts on drivers that influence Victorian heatwaves

As the planet warms, natural variability itself, including climate drivers and other physical processes, are likely to change. As a result, the climate experienced in the past is no longer a good indicator of the climate we can expect in the future.

There are multiple large-scale climate drivers that influence Victorian heatwaves over different timescales, and their influence on Australian and Victorian heatwaves is complex. While El Niño strongly affects heatwave frequency and intensity over northern and eastern Australia (Reddy et al., 2022a), this is not necessarily the case over Victoria (Figure 28). Victorian heatwaves are commonly associated with convection (the vertical transport of heat and moisture in the atmosphere) over tropical Australia, caused by climate drivers such as La Niña and the MJO (Parker et al., 2014a). Heatwaves in Victoria are also affected by the concurrent occurrence of a positive IOD, El Niño and drought (Reddy et al., 2022b). The combined interaction of a positive IOD and an El Niño results in more intense (and possibly a higher frequency of) heatwaves that are associated with drought conditions (Reddy et al., 2022b). For example, a strong positive IOD increased heatwave conditions during the lead-up to the 2019–20 Black Summer bushfires (Abram et al., 2021).

Relationship between heatwave days and El Niño conditions

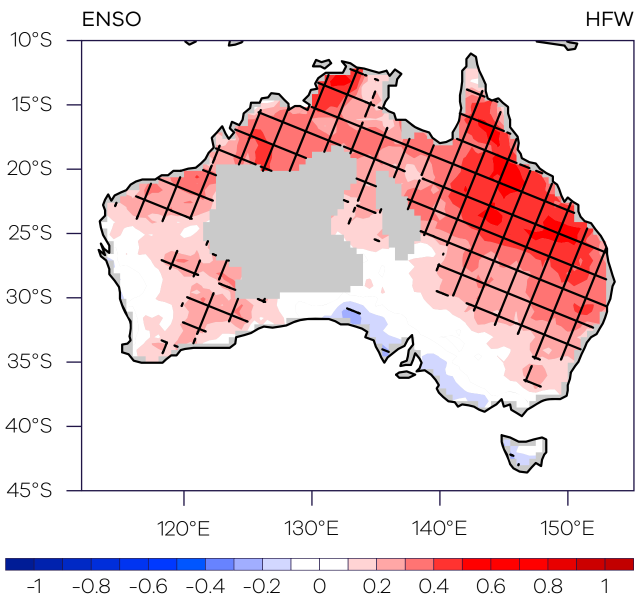


Figure 28. Correlation between the number of heatwave days (HWF) during the heatwave season (November–March) and the Niño3.4 index (a measure of the strength and phase of ENSO via sea surface temperature anomalies in the Central Equatorial Pacific Ocean). A positive correlation (red colours) means that more heatwave days are experienced when El Niño conditions occur. Hatching indicates a significant relationship. No data exist for the grey area. Source: Perkins et al., 2015.

The relationship of SAM to Australian heatwaves is weaker compared to that of ENSO and IOD (Parker et al., 2014b). While the likelihood of extreme temperatures occurring increases during negative SAM phases over most of Australia (Marshall et al., 2014), SAM does not significantly influence the frequency of heatwaves in Victoria.

The majority of Victorian heatwaves have occurred when the MJO is building towards the peak of Australian tropical summertime convection (Parker et al., 2014b). During these MJO phases, interactions between tropical cyclones and Victorian heatwaves occur (Parker et al., 2013). Victorian heatwaves that occur during other MJO phases are less common.

Observed changes in Victorian heatwaves

The intensity, frequency and duration of Victorian heatwaves have increased, and the heatwave season is now longer and starts earlier compared to the middle of the 20th century.

Heatwave trends

Heatwave trends in Australia are largely consistent with other regions globally. However, the magnitude of these trends (the rate at which heatwave characteristics are changing) varies regionally. In general, the rate of change is largest in tropical and sub-tropical regions. Increasing annual numbers of heatwave days and heatwave intensity are occurring almost everywhere in the world (Perkins-Kirkpatrick & Lewis, 2020). For many parts of the world, the most severe local heatwave season has occurred in the past 1–2 decades, consistent with increasing greenhouse gas emissions. This includes southern Australia, where the worst heatwave season happened in the summer of 2008–09, during which the Black Saturday bushfires occurred. Long-term heatwave trends across the planet would not have been possible in the absence of historical greenhouse gas emissions (see the *Attribution of observed heat extremes* box below).

Since at least the 1950s, the intensity, frequency, and duration of heatwaves have increased, and the overall heatwave season has lengthened. The first heatwave of the season now occurs earlier over many parts of Australia (Reddy et al., 2021a). However, rates of change vary for different heatwave characteristics and locations (Trancoso et al., 2020). There has been a significant increasing trend in the annual number of heatwave days across Australia (Figure 29).

Other trends include the following (Reddy et al., 2021a).

- Over two-thirds of Australia has experienced an additional 1–3 extra annual heatwave days per decade.
- The annual number of heatwave events and the longest heatwave per year also show a similar increasing trend, with respective changes of an additional 0.6–1.2 events per decade and 0.3–0.6 days per decade.
- Measures of heatwave intensity, including peak heatwave temperature and cumulative heat, display the largest trends over south-east Australia (including Victoria). Peak heatwave temperature is likely to increase by up to 2.7 °C per decade, while cumulative heat may increase by 15 °C per decade.
- The heatwave season has also increased in length by an extra 2–8 days per decade over south-east Australia, and the first heatwave of the season occurs significantly earlier, between 6–9 days earlier each decade.

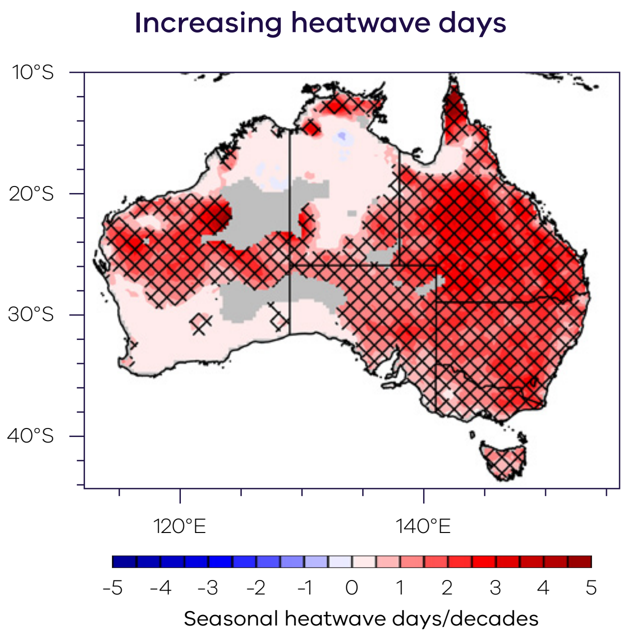


Figure 29. Decadal trends in Australian heatwaves days (days/decade) using the EHF index. Red colours represent an increase in heatwave days and blue colours represent a decrease. Hatching indicates where trends are significant. Grey areas are where observations are of insufficient quality for trends to be computed. Source: Reddy et al., 2021a, under CC BY 4.0. Font and map scale changed.

City-scale changes in heatwaves

Different heatwave characteristics are changing at various rates across Australian capital cities (Reddy et al., 2021a). For example, from 1950 to 2011, Melbourne experienced no change in the length of the longest annual heatwave, the intensity of heatwaves increased by 1.5–2 °C and the heatwave season started 2.5 weeks earlier on average. However, in Canberra, the number of heatwave days per year doubled over the same period, but changes in heatwave intensity and the start of the season were less pronounced (Steffen et al., 2014).

A more recent and detailed analysis that expanded on these results found that the 4 cities that have data for 1911–65 did not display trends in any heatwave characteristic (Reddy et al., 2021a). The analysis suggests that long-term heatwave trends are largely driven by changes in the past 6–7 decades, and it is unlikely that significant heatwave trends existed for any part of Australia prior to the 1960s. In the more recent period (1965–2019), all cities showed a significant increase in the annual number of heatwave days (although magnitudes and the period over which the trends occurred varied), with increases in heatwave intensity being largest for Melbourne and Adelaide.

Attribution of observed heat extremes

As every heatwave is distinct, with differing characteristics, locations and underpinning mechanisms, the attribution signals for each event are unique and cannot be assumed for other heatwaves, no matter how similar they might appear.

Extreme heat attribution studies for Australia (especially at regional scales or above) are based on high-quality observations, are generally simulated well by climate models, and are supported by a well-developed understanding of what drives them (Lane et al., 2023), ensuring robust results.

Multiple extreme event attribution studies have been undertaken for Australian extreme temperature events, focusing on seasonal temperature extremes and specific heatwaves over various spatial scales. For example, the likelihood of a summer as hot as 2012–13 has increased by at least 2.5 times due to the human influence on the climate, with a further increase in the likelihood of at least 5-fold projected for 2005–20 (Lewis and Karoly, 2013). The likelihood of Australia experiencing a summer at least as extreme as 2012–13 in any given year is 44% in the current climate (at the time of the study, 2017), and 57% and 77% respectively at global warming thresholds of 1.5 °C and 2 °C (King et al., 2017).

Heatwaves occurring at least as often and being at least as intense as those in 2012–13 have increased in likelihood by 2- and 3-fold (Perkins et al., 2014). These results show how different event definitions (e.g. seasonal temperature, heatwave frequency or heatwave intensity) at various times (current versus future) can result in a range of detected human signals. These findings support the evidence that climate change had a significant influence on the extreme temperatures of the 2012–13 Australian summer.

Further information about the attribution of climate extremes can be found in the *What is extreme climate event attribution?* box at the start of this Section.

Future changes to heatwaves

Projections indicate significant increases in the intensity, frequency and duration of heatwaves, and the concurrent occurrence of droughts and heatwaves.

Projections of Australian-wide heatwaves

Increases in heatwave frequency, duration, and intensity are projected over much of the globe and over Australia throughout the 21st century (Cowan et al., 2014). These increases are driven by the warming effect of additional greenhouse gases in the atmosphere. Projections of heatwave intensity, frequency and duration are tracking with global temperature increases (Perkins-Kirkpatrick and Gibson, 2017). As heatwaves are expected to occur more often under a warming climate, there is a higher chance that more regions will experience heatwaves concurrently.

Projections of Victorian heatwaves and extreme heat

CMIP3 projections

Downscaling from a previous generation of NARCliM (based on CMIP3) (Evans et al., 2014) has shown that under a high emissions scenario (RCP8.5):

- the return period of a historical 1-in-20 year heat extreme over Victoria would reduce to between a 1-in-2 to a 1-in-5 year event by 2060–79 (Herold et al., 2021).
- over Melbourne, the historical 1-in-20 year event is almost 7 times more likely to occur by 2060–79 than in the climate around 2020, with an average occurrence of around once every 3 years (Herold et al., 2021).

CMIP5 projections

Projections using the CMIP5 global climate model ensemble indicate that, in Australia, peak heatwave intensity is projected to increase by around 1.2 °C per degree of global warming (Perkins-Kirkpatrick & Gibson, 2017). Around 16 extra heatwave days, 1–2 extra heatwave events, and an increase in the longest seasonal heatwave of 4–5 days are also likely per degree of global warming. However, regional differences do exist, and these global warming projections may not fully represent heatwave projections at more regional scales.

Increases in heatwave intensity, frequency and duration are projected to occur over Australia under both a medium (RCP4.5) and high emissions scenario (RCP8.5) (Taylor et al., 2012), with larger changes projected under the high scenario by the end of the century. Under both scenarios, increases in the number of heatwave days and heatwave length are projected to be greater in tropical and sub-tropical regions, whereas increases in heatwave intensity are projected to be greater over southern regions (Cowan et al., 2014).

Increases in the intensity, frequency and duration of concurrent droughts and heatwaves are also likely in future, with greater changes under a high emissions scenario, particularly over Northern Australia (Tripathy et al., 2023).

CMIP6 projections

The new projections from NARCliM2.0 show increases in the frequency of heatwave days in Victoria under both low and high emissions scenarios. There is considerable uncertainty on how large the increases could be, especially for the 2090s under the high emissions scenario.

However, indicative results from the high-resolution regional modelling (CSIRO, 2024) suggest the following.

- By 2050, the frequency of heatwave days could increase by around 45% under the low emissions scenario and by around 84% under the high scenario, compared to 1986–2005. An average year in 2050 is projected to experience around 30 heatwave days rather than the 20 experienced historically (Figure 30).
- By 2090, the frequency of heatwave days could increase by around 53% under the low emissions scenario and more than triple under the high emissions scenario, compared to 1986–2005. An average year in 2090 is projected to experience around 60 heatwave days rather than the 20 experienced historically (Figure 30).

The outputs from the low-likelihood, high-warming future NARCliM2.0 modelling are not included in these heatwave projections. Therefore, it is plausible that heatwave increases could be even larger than those shown here.

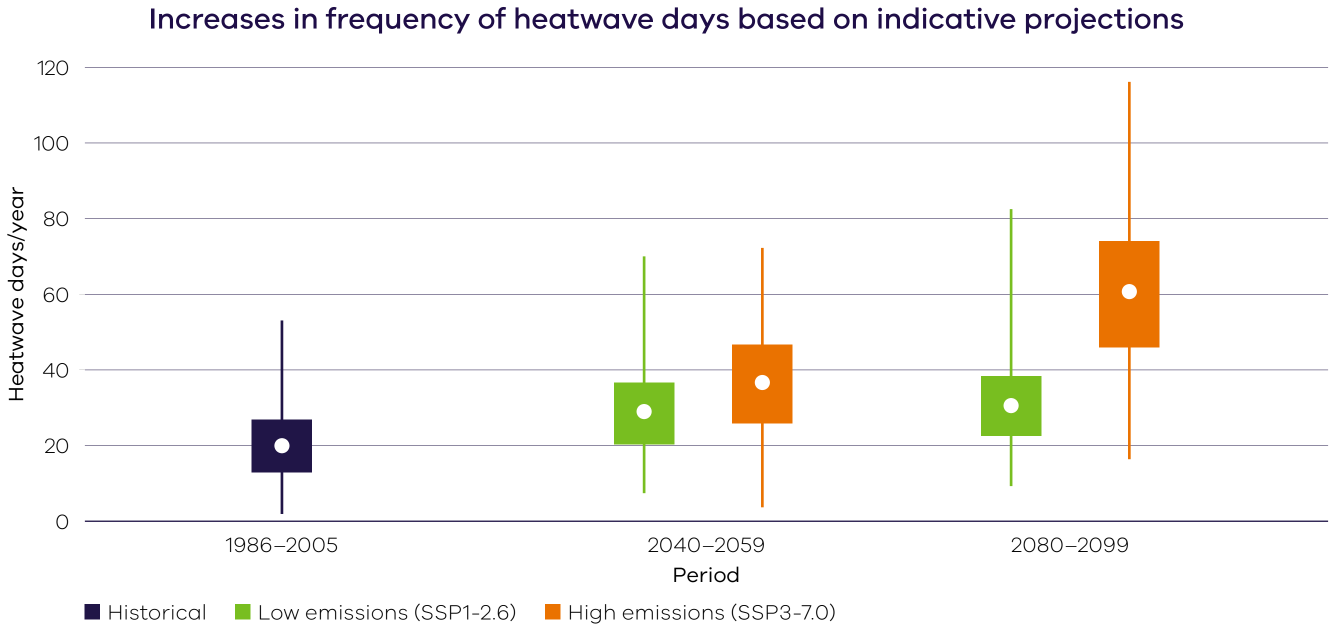


Figure 30. Indicative projected mean annual heatwave day frequency (heatwave days/year) for 2040–2059 (2050) and 2080–2099 (2090) compared to 1986–2005 using NARCliM2.0 data for Victoria. The dark blue box represents the historical period (1986–2005), the green boxes represent the low emissions scenario (SSP1-2.6), and the orange boxes represent the high emissions scenario (SSP3-7.0). The height of each box denotes the 25th to 75th range, while the whiskers indicate the full range of data. Source: CSIRO, 2024.

Heatwave duration is also projected to increase. By 2050, indicative projections indicate that the average heatwave duration over Victoria could increase by 0.7 days under the low emissions scenario and 2.2 days under the high scenario compared to 1986–2005. By 2090, the average heatwave duration under the high emissions scenario will likely increase by between 6.5 and 15 days.

The length of Victoria's heatwave season (the time from the first to last heatwave day each year) is also projected to increase under the high emissions scenario. The average heatwave season in 2050 could become about 50% longer. This means that in future, heatwaves are likely to occur earlier in the spring and later into the autumn.

Under the high emissions scenario by the end of the century, it is plausible that some years in Victoria will experience heatwave seasons that extend over more than half the year.

Further details on the approach and methodology to developing CMIP6 projections are provided in Section 3 of this report.

4.3 Drought

Key messages

- Droughts have become significantly warmer in the 21st century due to human-caused climate change.
- A few studies report increases in drought duration and intensity in south-east Australia.
- Droughts in Victoria are likely to continue to increase under a warming climate, although the precise nature and extent of the impacts are unclear.
- Future droughts will be hotter than past droughts, which can affect compounding heat and drought events.
- Future droughts may develop more quickly under a thirstier atmosphere.
- Some evidence suggests changes to drought characteristics may follow shifts in rainfall distributions.
- Projections developed using NARCliM2.0 high-resolution downscaling (CMIP6 projections) indicate that there may be an increase in the occurrence of dry months in Victoria in future, with almost a doubling of dry months projected by 2090 under the high emissions scenario relative to 24 dry months experienced during the 1986–2005 period.

Describing drought

Major historical droughts have affected large areas of Victoria and have occurred at least once per decade.

Drought is a pervasive part of the Victorian landscape and has widespread impacts (Kiem et al., 2016). Generally, drought is defined as the condition of extreme scarcity of surface water over a prolonged period, typically for months or longer (Hoffmann et al., 2020). Droughts are commonly characterised by their frequency of occurrence, intensity, severity, duration, rate of onset, seasonality, and extent (Sheffield & Wood, 2012). Every drought is different, with different impacts (Grainger et al., 2021).

There are different types of drought, including meteorological, agricultural, hydrological, ecological, socio-economic, anthropogenic (human-caused) and flash drought (Figure 31).

A single drought may encompass more than one type of drought, and different types of droughts can coexist. An anthropogenic drought can span nearly all time scales because human-related activities, such as climate change, water management and environmental degradation, occur across all time scales (AghaKouchak et al., 2021).

Droughts tend to have a large geographical footprint compared to other natural hazards. Many significant historical meteorological droughts have spanned large parts of Victoria (Figure 32).

Droughts affecting smaller regions within the state are usually confined to regions with a similar climate. Most meteorological droughts in Victoria begin during autumn and winter (Gibson et al., 2022).

Without a period of significant rainfall, drought conditions will persist (Gibson et al., 2022) and can become multi-year droughts (King et al., 2020; Parker & Gallant, 2022), which can have prolonged effects on the state's hydrology and landscape.

Episodic drought should also be regarded distinctly from reductions in seasonal rainfall. These changes can contribute to an increase in aridity. Increasing aridity can influence the likelihood of drought.

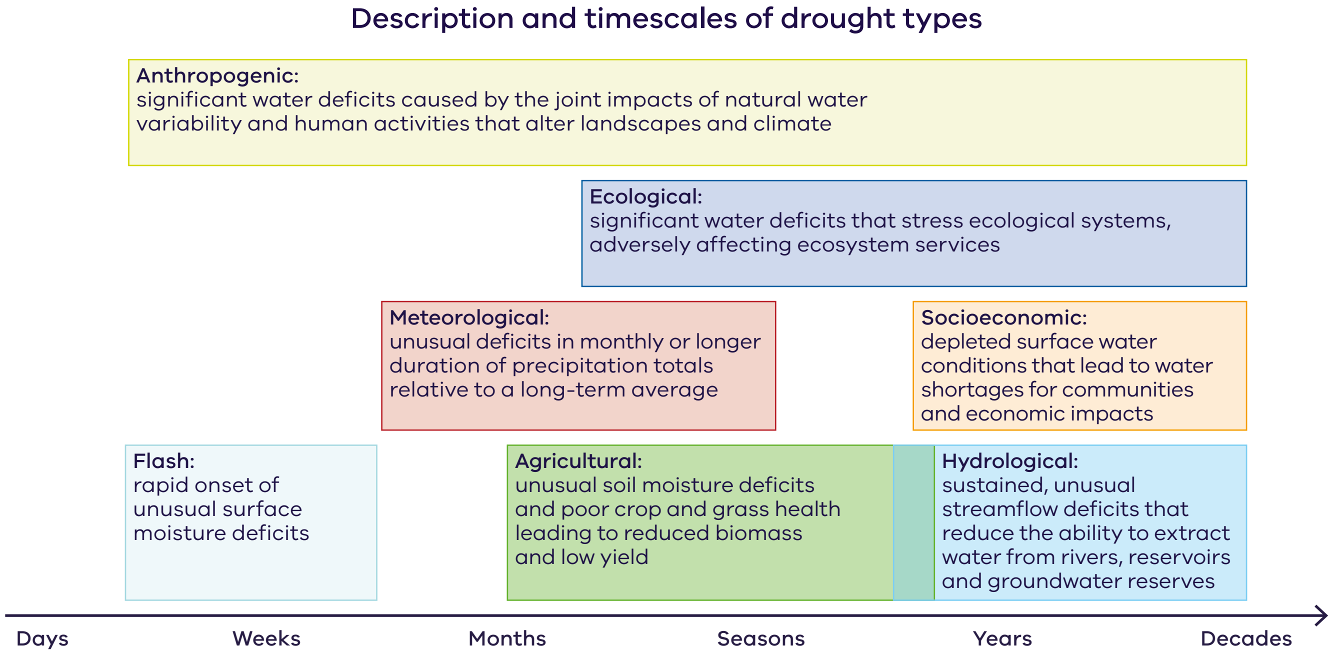


Figure 31. Description and typical timescales of different types of drought. The horizontal axis shows increasing timescales, from days to decades. Text sources: Wilhite & Glantz, 1985; Crausbay et al., 2017; AghaKouchak et al., 2021; Otkin et al., 2018; and Pendergrass et al., 2020. Source: Gallant & Goswami for VCSR24

Severe and long-lasting droughts in Victoria

Key drought periods in Victoria	Top 5 longest multi-year droughts		Top 5 most severe multi-year droughts		
Description	Duration/ intensity rank	Mean rainfall deficit	Severity/ extent rank	Mean annual rainfall deficit for most severe year	Percent of Victoria affected
Federation Drought (1895–1902) Widespread Red Tuesday bushfires in 1898	3rd	47 mm			
The 1912–1915 Drought Failure of national wheat crop; warmest spring on record until the 21st century	5th	114 mm	4th	266 mm **(1914)**	93%
The 1926–1928 Drought One of the worst summer rainfall deficits, more than 50% of the state in the lowest decile					
World War II Drought (1938–1944) The Black Friday bushfires in 1939; wheat crop failure in 1944, and severe hydrological drought and dust-storms in 1944–45	2nd	117 mm	5th	244 mm **(1938)**	84%
The 1967–1968 Drought One of the driest years on record, close to 100% of the state under meteorological drought			1st	295 mm **(1967)**	97%
The 1982–1983 Drought The most severe 9-months rainfall deficit on record (July-February) for most of Victoria; Ash Wednesday bushfires and dust-storms, water restrictions in Melbourne			3rd	286 mm **(1982)**	94%
Millennium Drought (1997–2009) 13 years of below-average rainfall; associated with high temperatures and heatwaves, Black Saturday bushfires in 2009	1st	104 mm	2nd	293 mm **(2006)**	96%
The 2012–2015 Drought Dry springs in both years, with current hottest spring temperatures on record; flash drought in September 2015	4th	193 mm			
Tinderbox Drought (2017–2019) Severe winter-time deficits; the Black Summer 2019–2020 bushfires; driest 3 years on record					

1895 1907 1919 1931 1943 1955 1967 1979 1991 2003 2015 **Year**

Figure 32. The 9 drought periods since 1895 where large areas of Victoria experienced significant impacts that were particularly severe and/or long-lasting. Key information on each drought is provided in the description (left). The figure shows severe years (defined by Victorian-averaged rainfall deficits) and prolonged droughts (defined as consecutive or near-consecutive years with rainfall deficits below 1 standard deviation). The figure includes drought duration/intensity ranking, mean annual rainfall deficit (mm) during the drought period, the drought severity/extent ranking, mean annual rainfall deficit (mm) for the most severe years (stated in the brackets), and the percentage of Victoria affected. Rows with no data are not in the top 5 drought categories. Source: All data and indices were sourced from the Bureau of Meteorology (2024b).

The most severe droughts on record, in terms of the intensity of the rainfall deficit and geographical extent, occurred in 1967, closely followed by 2006 and 1982 (Figure 33). All 3 years experienced extensive meteorological and agricultural droughts, with significant fire seasons.

Several of the droughts experienced in Victoria can be described as multi-year droughts. During these periods, meteorological drought was not present throughout the entire period or over all areas of Victoria. Some months, seasons and years had near-normal rainfall (Fowler et al., 2022). However, dry conditions persisted with land surface and hydrological indicators showing little recovery, so the impacts of drought continued.

The long-duration droughts include some years of severe rainfall deficit and years with near-normal rainfall. A prolonged absence of large rainfall totals can result in a lack of recharge to streamflow and reservoirs, leading to hydrological drought. For example, there were persistent reductions in streamflow, very low reservoir levels, impacts on groundwater, and reductions in water quality during the Millennium Drought (Leblanc et al., 2012).

Periods of low mean rainfall in Victoria similar in magnitude to the Millennium Drought have been identified in paleoclimate records (Gallant & Gergis, 2011; Gergis et al., 2012). Paleoclimate records use environmental responses to the climate in tree rings, ice cores, corals, cave deposits and lake sediments to glean information about past climate changes.

Recent studies indicate that the spatial extent and duration of the Millennium Drought appear either very much below average or unprecedented in southern Australia over at least the last 400 years (Freund et al., 2017).

Drought mechanisms

The development of drought is influenced by precipitation variability, climate drivers, weather systems, land surface feedbacks and hydrologic processes.

Victoria is a water-limited environment (Gardiya Weligamage et al., 2023), with evaporation and the subsequent balance between precipitation and evaporation primarily controlled by rainfall variability.

North-west and north Victoria straddle the southern edge of the sub-tropics and have a semi-arid climate. The southern and eastern regions are closer to the mid-latitudes and experience a more temperate climate. Topographical influences from the Great Dividing Range cause distinctly different climate zones in rainfall. Rainfall across the state is typically either winter-dominated or lacks a clear seasonal signal (Zhao et al., 2013).

Precipitation variability

Precipitation variability can lead to drought onset (Vincente-Serrano et al., 2020; Parker & Gallant, 2022). However, once a drought has begun, a combination of precipitation variability and land surface feedbacks become important in maintaining a drought. Droughts end with high precipitation totals that restore surface moisture (King et al., 2020).

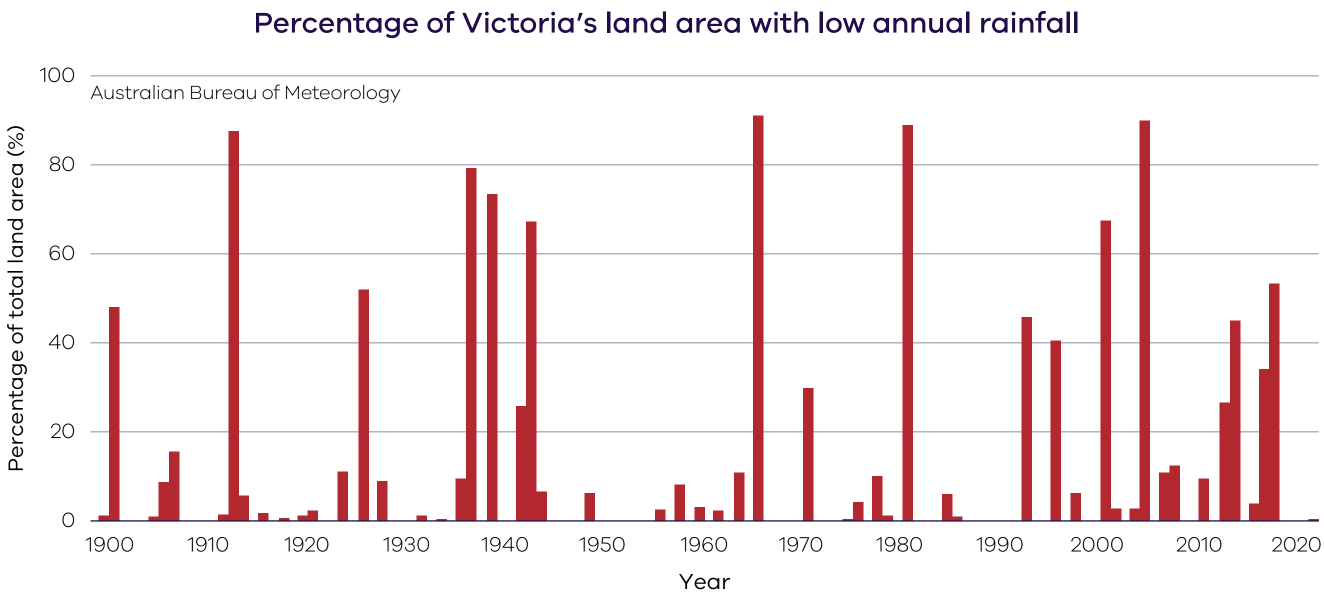


Figure 33. The percentage of Victorian land area with annual rainfall in the lowest 10% of all recorded years (1900–2020). The large geographical footprint of the significant droughts described in Figure 32 is evident. Source: Bureau of Meteorology, 2024c, under CC BY 4.0. Font changed.

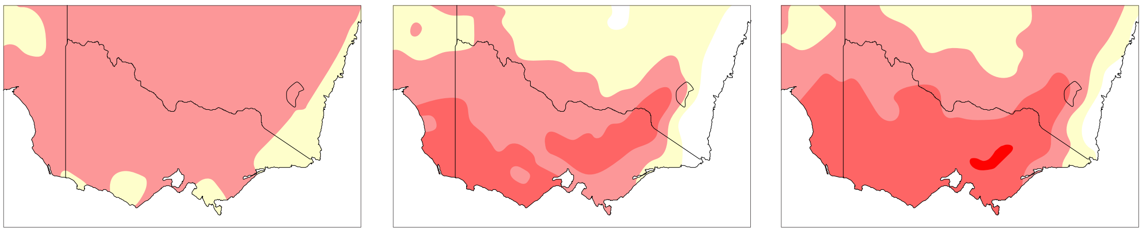
Climate drivers

El Niño and positive IOD events have contributed to Victorian rainfall variability and meteorological droughts, particularly during winter and spring (Freund et al., 2017; Risbey et al., 2009). These 2 drivers influence soil moisture and streamflow, leading to agricultural and hydrological drought. El Niño and positive IOD often occur at the same time and are unlikely to be independent of each other (Meyers et al., 2007). For example, El Niño may play a role in energising the Indian Ocean, leading to positive IOD-like events (Liguori et al., 2021). The coincidence of El Niño and positive IOD events results in a stronger rainfall response over Victoria than from the influence of a single driver alone (Figure 34 (right); Meyers et al., 2007; Gallant et al., 2012).

El Niño has long been recognised as the primary, predictable influence on precipitation variability across Australia (McBride & Nicholls, 1983). However, there is evidence that the most prolonged and severe meteorological droughts in south-east Australia, including in Victoria, have a slightly stronger association with positive IOD events than El Niño (Ummenhofer et al., 2011). This is also the case for agricultural drought. The severe drought in 2019 that preceded the Black Summer bushfires occurred during a positive IOD but no El Niño (Devanand et al., 2023). However, a drought in 1940, in which approximately 78% of Victoria experienced annual rainfall in the lowest 10% on record (Bureau of Meteorology, 2024c), occurred with an El Niño but no positive IOD (Meyers et al., 2007).

Although El Niño events and positive IODs are connected to Australian droughts, droughts can still occur without them (Risbey et al., 2009). For example, the severe drought in Victoria in 1938 that was the precursor to the devastating 1939 Black Friday fires occurred during a La Niña year with neutral IOD conditions (Crompton et al., 2010).

Combined effects of El Niño and positive IOD result in larger rainfall reductions



Winter–spring mean rainfall deciles for periods during 14 El Niño years	Winter–spring mean rainfall deciles for periods during 8 positive IOD years	Winter–spring mean rainfall deciles for periods during 7 positive IOD & El Niño years
(1905, 1914, 1940, 1941, 1946, 1965, 1972, 1977, 1982, 1991, 1994, 1997, 2002, 2015)	(1961, 1963, 1967, 1972, 1994, 1997, 2015, 2019)	(1963, 1972, 1982, 1994, 1997, 2006, 2015)

Figure 34. Typical winter and spring rainfall responses associated with El Niño years (left), positive IOD years (centre), and combined El Niño and positive IOD years (right). Red colours represent drier areas and blue colours represent wetter areas. The decile level indicates how unusual the rainfall is in the record, with decile 5 being near-normal. Source: Adapted from Bureau of Meteorology, 2024c (left, centre, right), under CC BY 4.0. Individual figures cropped and recreated.

Weather systems processes

Rain-bearing weather systems can interact with climate drivers, affecting the weather system and moisture transport. For example, during El Niño, there can be a reduction in rain-bearing weather systems across eastern Australia, including Victoria (Hauser et al., 2020).

Changes in the number of rain days and rainfall intensity are associated with many multi-year droughts (Verdon-Kidd & Kiem, 2009). Most rainfall reductions during short and longer multi-year droughts are caused by a reduction in heavy rainfall days (Parker & Gallant, 2022). When the frequency and intensity of these events decline, a drought can begin and persist in Victoria. Droughts break when these heavy rainfall events increase in frequency and intensity (Jin et al., 2024).

The frequency and intensity of mid-latitude low-pressure weather systems affect cool season Victorian rainfall variability (Risbey et al., 2013). There has been a reduced frequency and intensity of such systems during very dry years and prolonged periods of drought north of the Great Dividing Range in Victoria (Jin et al., 2024). For example, the Tinderbox Drought (2017–19) featured a significant reduction in heavy rainfall events related to low-pressure weather systems (Devanand et al., 2024), with 2019 experiencing a record-low number of these events during winter (Pepler, 2020). Reduced movement of moisture through the atmosphere from the Tasman Sea to these weather systems is another driver of reduced rainfall over eastern Australia during drought (Holgate et al., 2020). Together with a reduction in the frequency and intensity of rain-bearing weather systems during drought, there has been an increase in rain-suppressing systems during dry years in south-east Australia (Jin et al., 2024).

Land surface feedbacks

Land surface feedbacks play a role in sustaining, intensifying and prolonging drought (Evans et al., 2017). These feedbacks affect evaporation from soil and evapotranspiration from vegetation. Changes to evapotranspiration, controlled by solar radiation, humidity, temperature and windspeed, can affect agricultural and hydrological droughts. Evaporation changes can intensify and prolong droughts in the absence of rainfall sufficient to replenish surface moisture. These changes can also lead to flash drought under aridity-favouring conditions, where soil moisture dries rapidly to drought conditions in a matter of weeks (Otkin et al., 2018; Pendergrass et al., 2020).

Flash drought occurred in the Wimmera region of Victoria in the spring of 2015 and in eastern Victoria in the spring of 2019. The 2015 flash drought was caused by high surface radiation combined with a dry surface air mass and unseasonably warm conditions, exacerbating surface evaporation and evaporative demand (Parker et al., 2021).

Hydrologic processes

Multi-year meteorological droughts have been connected to hydrological droughts through changes in rainfall-runoff relationships. Specifically, multi-year drought periods have been linked to reductions in runoff for a given amount of rainfall compared to normal conditions (Potter & Chiew, 2011). For example, the rainfall-runoff relationship changed in Victoria during the Millennium Drought (Figure 35), where the runoff for a given amount of rainfall was significantly reduced (Peterson et al., 2021).

Changes to the rainfall-runoff relationships during Victorian droughts are primarily related to catchment characteristics. Every catchment responds differently to multi-year drought and drying. The groundwater table, and its interactions with surface water, may also play a role (Deb et al., 2019).

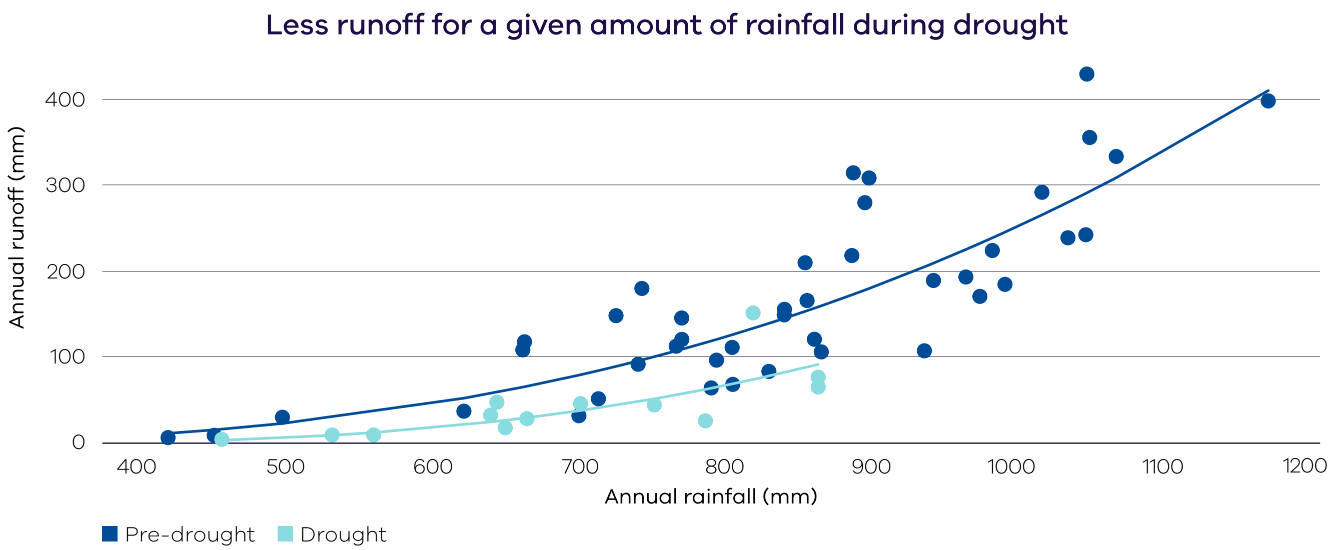


Figure 35. An example of a reduction in runoff for a given amount of rainfall prior to (dark blue) and during (light blue) a multi-year drought. During drought, less runoff occurs for a given amount of rainfall. Source: DELWP, 2020, under CC BY 4.0, colours and font changed.

Climate change impacts on drought trends and processes

Drought conditions are influenced by trends in precipitation, temperature and evapotranspiration.

Climate change has caused droughts to become significantly warmer in Australia during the 21st century (Alexander & Arblaster, 2017). Future droughts will be warmer droughts and have the potential to be thirstier in terms of evaporation from rising temperatures. However, the exact nature of the change in evaporation is unclear as it is also strongly influenced by aspects like solar radiation and wind, so changes in those things would likely offset any changes that temperature would have on evaporation during drought. The actual changes occurring are not clear because of a lack of long-term and reliable observations of those aspects influencing evaporation and its relationship to soil moisture.

Climate change can affect drought in Victoria in several ways, including through changes to precipitation and evapotranspiration. Changes in precipitation distribution and timing (i.e. seasonality) can act individually and together to change the characteristics of drought. As Victoria is a water-limited environment, changes to precipitation will affect future changes in drought (Dai et al., 2018). The frequency and intensity of meteorological drought increases with declining average precipitation. There could also be an increase in drought duration with decreasing average precipitation. An increase in evapotranspiration due to climate change can exacerbate agricultural and hydrological drought intensity through land surface feedbacks. Climate change can also affect the rate of drought onset, transitioning the drought into a faster, more flash drought-like state (Yuan et al., 2023).

Observed changes in Victoria's drought conditions

Increases in the frequency, intensity and duration of Victorian meteorological and agricultural drought may be associated with the reduction in cool season rainfall from 1911 to 2009 (Gallant et al., 2013). Increases in hydrological drought have occurred at the same time as reductions in cool season rainfall in south-east Australia (Wasko et al., 2021; Yildirim et al., 2022).

Significant decreases in periods of extreme high streamflow across Victoria in the cooler months have also occurred. Streamflow reductions have occurred as a step-change, consistent with step-changes identified in rainfall at around the same time.

Changes in the mid-1990s have affected surface water availability, with groundwater reductions occurring (Fowler et al., 2022). Groundwater has yet to recover in some central Victorian catchments despite significant wet years and recharge events (Peterson et al., 2021).

There has been a small increase (6.5%) in the proportion of the state in drought since 1900. However, more research is required to understand the cause of this trend and determine whether it might continue.

Temperature

Periods of drought are typically warmer than normal due to land surface feedbacks (Lockart et al., 2009; Yin et al., 2014). Australian droughts have also become significantly warmer in the 21st century due to human-caused climate change (Nicholls, 2006; Alexander & Arblaster, 2017).

Evapotranspiration

An increase in solar radiation often occurs at the onset of flash drought and is likely to be an important regulator of elevated evaporation (Nguyen et al., 2023). Though trends in solar radiation have been linked to changes in evaporation worldwide (Peterson et al., 1995), its role in evaporation in Australia is unclear.

Elevated CO_2 levels in the atmosphere increase plant growth, which may act to increase evapotranspiration. However, under elevated levels of CO_2, plants need to exchange less air to receive the same amount of CO_2, which may act to reduce evapotranspiration (Zhang et al., 2022). South-east Australia has experienced increasing vegetation coverage (Rifai et al., 2022), consistent with global trends. The result of the competing effects of CO_2 fertilisation on evapotranspiration as the climate warms is still being determined.

Future changes to drought

Droughts in Victoria are likely to increase in duration and intensity with climate change, although the precise nature and extent of the impacts are unclear.

Determining how climate change may affect droughts is challenging due to Victoria's variable hydroclimate and the incomplete understanding of the impacts of the drivers of droughts and how these may change under a warming climate. Most studies infer changes in drought from changes in mean rainfall or other hydroclimatic variables (Cook et al., 2020). Future drought trends also depend on how key drought processes (e.g. El Niño) will change, and these can have significant uncertainty.

CMIP5 projections

Projected changes to drought characteristics will likely follow shifts in rainfall distributions (Kirono et al., 2020). For example, in south-west Victoria, cool season drying will likely occur by 2037, even under a low emissions scenario (Rauniyar & Power, 2023). By the end of the 21st century, there is a strong chance (88%) that the climate change signal will be the dominant feature of decadal-scale Victorian rainfall variability (Rauniyar & Power, 2023).

Meteorological drought duration, intensity and the percentage of time spent in drought in south-east Australia are projected to increase (Ukkola et al., 2020; Kirono et al., 2020). The changes are largest for the more severe measures of drought, where the percentage of time spent in extreme drought conditions is projected to roughly double over the 21st century compared to the 20th century (Kirono et al., 2020). Assessing changes to drought frequency can be less meaningful as a decrease in frequency could be caused by droughts becoming less frequent but longer. For example, rather than 2 short droughts, one long drought could occur. Droughts of moderate severity are projected to become less frequent, but extreme droughts are likely to become more frequent (Kirono et al., 2020).

For agricultural drought, changes in soil moisture are used to infer likely future changes in drought. There are amplified trends in indices based on soil moistures that have occurred compared to rainfall-based indices in climate model projections, which are attributed to concurrent increases in potential evaporation (Kirono et al., 2020). Stronger changes in mean soil moisture and runoff compared to precipitation change over south-east Australia have also occurred, associated with increased drought (Cook et al., 2020).

CMIP6 projections

The CMIP6 modelling for Victoria (CSIRO, 2024) assessed changes to dry months and the Keetch-Byram Drought Index in the high-resolution (NARCliM2.0) data.

These simulations show increasing numbers of dry months in Victoria in the 20 years centred on 2090 (compared to the 1986–2005 period), including:

- an average of 10 additional dry months experienced under the low emissions scenario (SSP1-2.6)
- an average of 24 additional dry months experienced under the high emissions scenario (SSP3-7.0) by the end of the century.

The high-resolution regional modelling (NARCliM2.0) tends to represent the dry end of model projections. These projections are therefore likely to capture the upper end of drought results from currently available modelling.

The Keetch-Byram Drought Index is a measure of drought that accounts for rainfall deficit but also uses maximum temperatures to get an indication of soil-moisture deficiency. It is commonly used in calculations of the Forest Fire Danger Index (FFDI) as this drought factor can provide an indication of vegetation dryness. By 2090, this drought factor is projected to change by between -15% and +30% under the low emissions scenario and by between -10% and 60% under the high emissions scenario compared to the 1986–2005 period.

Other studies of CMIP6 projections show increases in the incidence of extreme low (lowest 10%) single-year precipitation, soil moisture and streamflow are projected during the cool season, primarily due to increases in evaporation under a warmer climate. There is no trend or a slight decrease in drought risk during the warmer months (Cook et al., 2020).

The Australian Agriculture Drought Indicators

The Australian Agriculture Drought Indicators project was established by the Australian Government Department of Agriculture, Fisheries and Forestry and undertaken by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) in partnership with CSIRO.

The project will develop a set of national indicators for measuring and forecasting the extent and severity of drought impacts in the Australian agricultural sector. The project will combine climate data with agricultural models to generate 'outcome-based' drought indicators, translating climate data into specific agricultural impacts (such as crop yields, pasture growth and farm business outcomes). These indicators will be forward-looking, accounting for both historical weather data and Bureau of Meteorology seasonal forecasts, and will be produced nationally at high resolution (approximately 5 km). At the completion of the first phase of this project, these indicators will be published online via the prototype Climate Services for Agriculture platform currently under development by the Bureau of Meteorology and CSIRO.

Agriculture Victoria – Climate updates, newsletters and webinars

The Agriculture Victoria Climate Updates webpage provides access to a range of agricultural-relevant climate information, including seasonal forecasts, soil moisture information from across Victoria, and a range of climate and weather podcasts.

- Seasonal Forecasts: The Fast Break Newsletter details oceanic and atmospheric climate driver activity over the last month and summarises 3 month model predictions for the Pacific and Indian Oceans, rainfall and temperature for Victoria. Similarly, the Very Fast Break is delivered as a YouTube video, providing information on oceanic and atmospheric climate drivers and the summarised model predictions for rainfall and temperature for Victoria.
- Soil Moisture Monitoring: Agriculture Victoria has installed or commissioned soil probes across a range of soil and pasture and crop types across Victoria. The soil moisture monitoring probes provide real time soil water content data. They record soil water content at one source point from 30 cm down to 1 m as a reference point for a paddock.

Agriculture Victoria - Soil moisture monitoring in cropping regions

Agriculture Victoria - Soil moisture monitoring of pastures

4.4 Bushfire

Key messages

- There is strong and robust evidence that climate change affects fire weather.
- Observations suggest fire activity is increasing in many fire-prone ecosystems and will continue to do so.
- A range of changes in fire regimes, activity and drivers in Victoria have already been observed, including a longer fire season, with more frequent days of significant fire danger. These changes are likely to escalate with increasing global temperatures.
- Low fuel moisture plays an important role in fire ignitions in Victoria, with potential increased ignition risk projected under warmer and drier future climates.
- Changes in fire risk will not be the same everywhere and will depend strongly on local fire conditions.
- Fire weather and fire activity are projected to increase in many regions of south-east Australia.
- Most of the evidence on changes to Victoria's fire activity focuses on forest and woodland environments, but important changes could also take place in grassland and semi-arid areas.

Describing bushfires

Bushfires have long been an intrinsic part of Australia's landscape and culture.

Fire is ancient, complex and inextricably linked to human activities across Australia. Fire naturally occurs in the Australian landscape, and has done so for millions of years, as evidenced by our evolved ecosystems. Humans have lived in Victoria for the past 40,000 years or more, and have had a significant impact on fire regimes. The climate of Australia and Victoria provides sufficient moisture for vegetation growth and extended periods of dryness that result in vegetation that can easily combust.

Australia's First Peoples have employed fire to celebrate, hunt, cook and Care for Country. First Peoples land management practices include 'cultural burning', which is fundamentally different from the western approach of prescribed burning. While reduction in fuel load and bushfire risk reduction may be outcomes of cultural burning, they are not the primary aim (Tynan et al., 2021). Cultural burning focuses on Caring for Country and is sensitive to environmental and cultural needs. Country instructs when to burn rather than the needs of humans. These carefully managed fire practices used by First Peoples were altered drastically by the arrival of Europeans in the 18th century. The widespread suppression of cultural burning has affected vegetation and fire regimes in ways that we are only beginning to understand. There is renewed support across government, industry and community for First Peoples-led cultural land management.

While the continent has evolved alongside fire, it can cause significant damage to the environment, people, property and other things that people value. During 1901 to 2011, 260 bushfires in Australia were associated with 825 known human deaths, including firefighters and civilians (Blanchi et al., 2014). In recent years, there have been several catastrophic fire events across Australia comprising the following.

- The 2019–20 Black Summer fires featured the largest forest fires recorded in recent history in Australia (Nolan et al., 2020). Between September 2019 and March 2020, fires affected more than 7 million hectares across south-eastern Australia, an area greater than the size of Tasmania. The fires were widely viewed as an example of the catastrophic nature of climate change on environmental and social values (Nolan et al., 2021), killing 33 people and an estimated 3 billion animals (Van Eeden et al., 2020).
- The 2009 Black Saturday fires in Victoria were the deadliest on record, with 173 people killed and over 2,000 houses destroyed.
- The 1983 Ash Wednesday fire in Victoria and South Australia resulted in 75 deaths and nearly 1,900 houses destroyed (Oliver et al., 1983).

Bushfire mechanisms

Major landscape fires will not occur without sufficient fuel that is dry enough to burn, weather conditions favourable to fire spread, and an ignition source.

Although all bushfires share some features, there is a large variation in fire across Australia and around the world. The term 'fire regime' describes the key properties of fire in a landscape, including its frequency, seasonality, intensity and severity. Fire severity most commonly refers to the consumption of vegetation. Fire intensity, in contrast, represents the energy released during the fire.

Fire regimes can be separated by the 2 major fuel types: woody/litter (featuring prominent tree cover) and grass/herbaceous fuels (Bradstock, 2010). A recent study found Victoria is home to 4 major fire regions: wet temperate forest, dry temperate forest, temperate cropping zone, and dry cropping zone (Cunningham et al., 2024)

Drivers of fire

Major landscape bushfires are limited by 4 biophysical drivers: fuel amount (i.e. vegetation growth of a large enough area to permit fire spread); fuel dryness; an ignition source; and weather conditions favourable to fire spread (Bradstock, 2010) (Figure 36). These drivers can be regarded as hypothetical 'switches', which must all be activated for a fire to occur. Therefore, fire can be constrained when different switches are turned off.

A fire regime can be characterised partly by the variability of these 4 drivers across space and time. In some landscapes fuel is plentiful, but it does not dry out frequently, limiting overall risk. In other landscapes, such as deserts, conditions are frequently hot and dry, but these same conditions limit fuel growth and the risk of major fires.

Human activities such as clearing, planting, and fuel treatment (including controlled burns) can directly affect ignition, fuel amount and vegetation type. Human-caused increases in CO_2 are also changing the climate and influencing vegetation type.

Conditions that favour the development of extreme fires

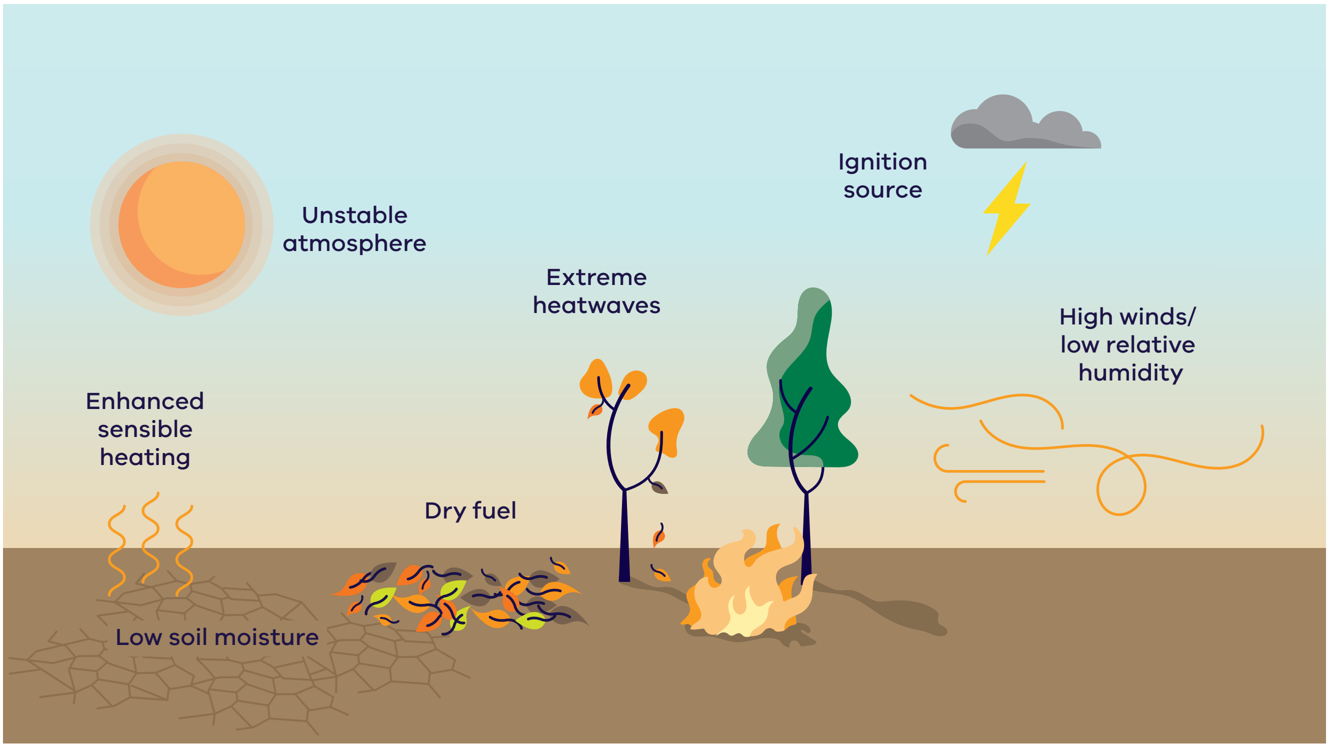


Figure 36. Conditions conducive to large and extreme forest fires. Sensible heat is heat that can be felt and measured by a thermometer. Source: Adapted from Abram et al., 2021, under CC BY 4.0, with redesigning.

Fire activity pre-colonisation

Paleoclimate evidence indicates that climate variability has affected historical fire activity in Australia, with temperature as the most important factor (Daniau et al., 2012). Colder periods led to decreased vegetation productivity, reduced fuel availability and less burning (Mooney et al., 2011). South-eastern Australia's fire history has varied on millennial time scales, with Tasmania and southern Victoria experiencing decreased fire activity, and eastern New South Wales experiencing increased activity (Mooney et al., 2011). The significance of First Peoples cultural burning during this time should also be noted, with the extent, regional variation and interrelationship of fire with climatic change an active area of research.

Since the industrial revolution, fire dynamics at the global scale have shifted from primarily climate-driven to a human-affected regime, influenced by land clearing, landscape management and direct human intervention in ignition and suppression (Marlon et al., 2008; Pechony & Shindell, 2010).

Observed changes in Victoria's bushfires

Bushfires have become more frequent and severe, burning larger areas.

Globally, fire regimes are undergoing rapid transformations due to changes in the drivers of fire, including evolving climate patterns, extreme weather events, shifts in land-use, population changes and changes in vegetation (Andela et al., 2017). These changes are expected to persist and be exacerbated in the coming decades, potentially affecting ecosystems, biodiversity, biogeochemical cycles, climate and society (Rogers et al., 2020).

In south-east Australia, observations show that increases in fire activity and fire severity have occurred, and there is growing evidence that fire weather conditions are worsening (Abram et al., 2021; Nolan et al., 2021). However, there is considerable variability in observed fire activity, fire severity and fire weather trends across different regions and seasons. Evidence regarding changes in fuel load and ignition is currently limited.

Fire frequency

Fires in Victoria have occurred more frequently in recent decades, with 3 of the 4 '1 million hectare' fire seasons since 1930 occurring since 2000.

Since 1950, worsening fire weather conditions and seasonal drought severity have increased the risk of larger fires and fires burning at high severity in south-eastern Australia (Collins et al., 2022). Between 1990 and 2020, there was an increase in the average annual area burnt by fire in Australia (Canadell et al., 2021) (Figure 37). In recent decades, fires have occurred more frequently.

Increasing burnt area in Victoria

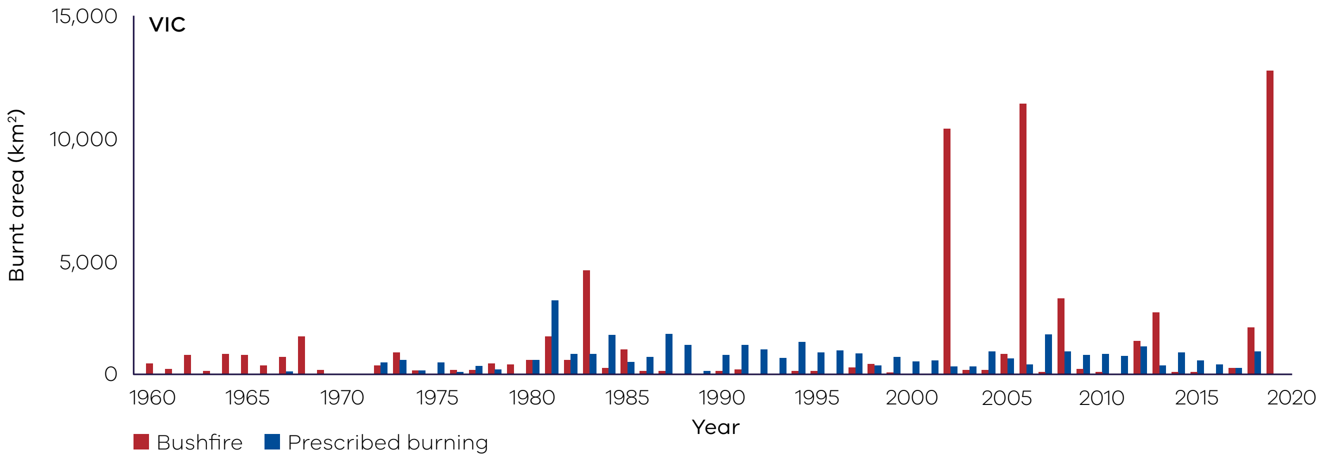


Figure 37. Area burnt (km²) from bushfires and prescribed burns in Victoria between 1960–61 to 2019–20. Red bars represent bushfires and blue bars represent prescribed burning. Source: Canadell et al., 2021, (Supp. Fig 4), under CC BY 4.0. Font changed.

Due to variations in fire activity, different parts of the landscape have gone different lengths of time without fire. However, with an increase in the frequency of large fires, there is less variation in time since fire, and more areas that have been recently burnt (Figure 38). These changes have important consequences for biodiversity as well as risk more broadly. There has been an increase in forest fires despite a decline in total forest area due to land clearing and an increase in fire suppression.

Increasing bushfire frequency

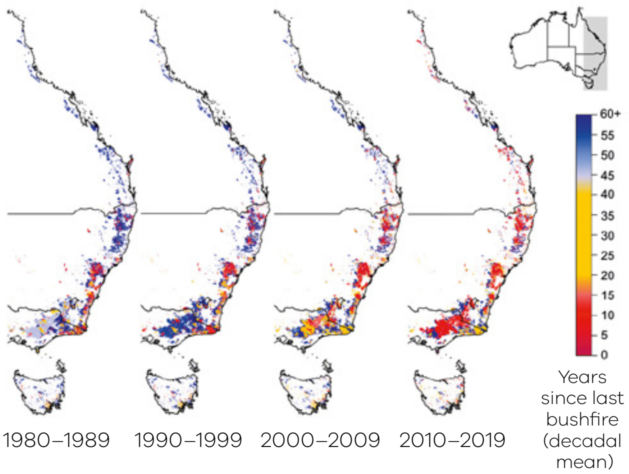


Figure 38. Number of years since the last bushfire (decadal mean) for forested areas, based on forested areas that have burnt at least once since fire records began in the 1930s for most states. Blue colours represent more years since the last bushfire while red colours represent less years since the last bushfire. Source: Canadell et al., 2021, under CC BY 4.0. Font and legend changed.

Fire severity

Any given fire will burn at a range of different fire severities within the overall fire footprint. In some vegetation types, there is a trend towards higher severity fires, with a greater impact on vegetation.

The increase in the frequency of severe fires has consequences for the environment, with some areas of forests being burnt up to 4 times in quick succession. This can significantly affect Victoria's high-elevation 'ash type' forests, leading to the collapse of local populations and the transition to different forest types (e.g. from tall open forest to low open shrubland or woodland) (Bowman et al., 2014).

The proportion of high-severity bushfires in temperate south-eastern Australia (especially in wet forests, rainforests and woodland communities) has increased since 1988 (Collins et al., 2022).

However, the proportion of high-severity fires in dry forests has remained constant. Since 1950, fire weather conditions have increased the risk of both large fires and fires burning at high-severity in South East Australia. In Victoria, the proportion of high-severity fire reached a record high during the 2019–2020 season in the Australian Alps, South East Corner and Central Highlands regions due to the massive area affected (Collins et al., 2021).

Worsening surface fire weather conditions and seasonal drought severity drive changes in fire frequency, area burnt and fire severity (Abram et al., 2021; Harris & Lucas, 2019).

The frequency of long fire seasons and extreme fire weather days in wet eucalyptus forests that supply water to Melbourne has recently increased (Benyon et al., 2023). During the 20th century, long fire seasons occurred once every 30 years, but this increased to once every 4 years between 2005 and 2020.

Fuel, fire weather and ignition

Trend analyses of fuel load are generally lacking, partly due to difficulties in reconstructing historical fuel values. There was no trend in fuel accumulation identified in the 30 years prior to the 2019–20 fires. The fuel amount (Nolan et al., 2021) and fuel hazard (Collins et al., 2022) during these fires were not unusually high. Over the longer term, changes in vegetation have occurred due to colonisation and the cessation of First Peoples burning practices, including a shift towards more shrubs and fewer grasses in forest and woodland areas in south-eastern Australia (Mariani et al., 2022).

In southern Australia, there has been an increase in upper atmospheric conditions that contribute to the development of fire storms (pyrocumulonimbus) (Dowdy & Pepler, 2018). Cold fronts bring dangerous wind gusts and wind changes that can turn the flank (side) of a fire into the head front (Mills, 2005). This can greatly increase the area of actively burning fire. In recent decades, the frequency and intensity of cold fronts have increased in south-eastern Australia (Cai et al., 2022).

Until recently, Australian fire weather has largely been monitored using the Forest Fire Danger Index (FFDI) – see *Heatwaves, drought and bushfires* box below, which shows that the frequency of dangerous fire weather days has increased significantly in recent decades across many regions, especially in the south and east (Bureau of Meteorology & CSIRO, 2022) (Figure 39).

Dry lighting, which is a source of fire ignition, has increased in parts of south-eastern Australia, including Victoria, due to an increase in the frequency of low-rainfall thunderstorm environments (Dowdy, 2020).

Increasing frequency of dangerous fire weather across Australia

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

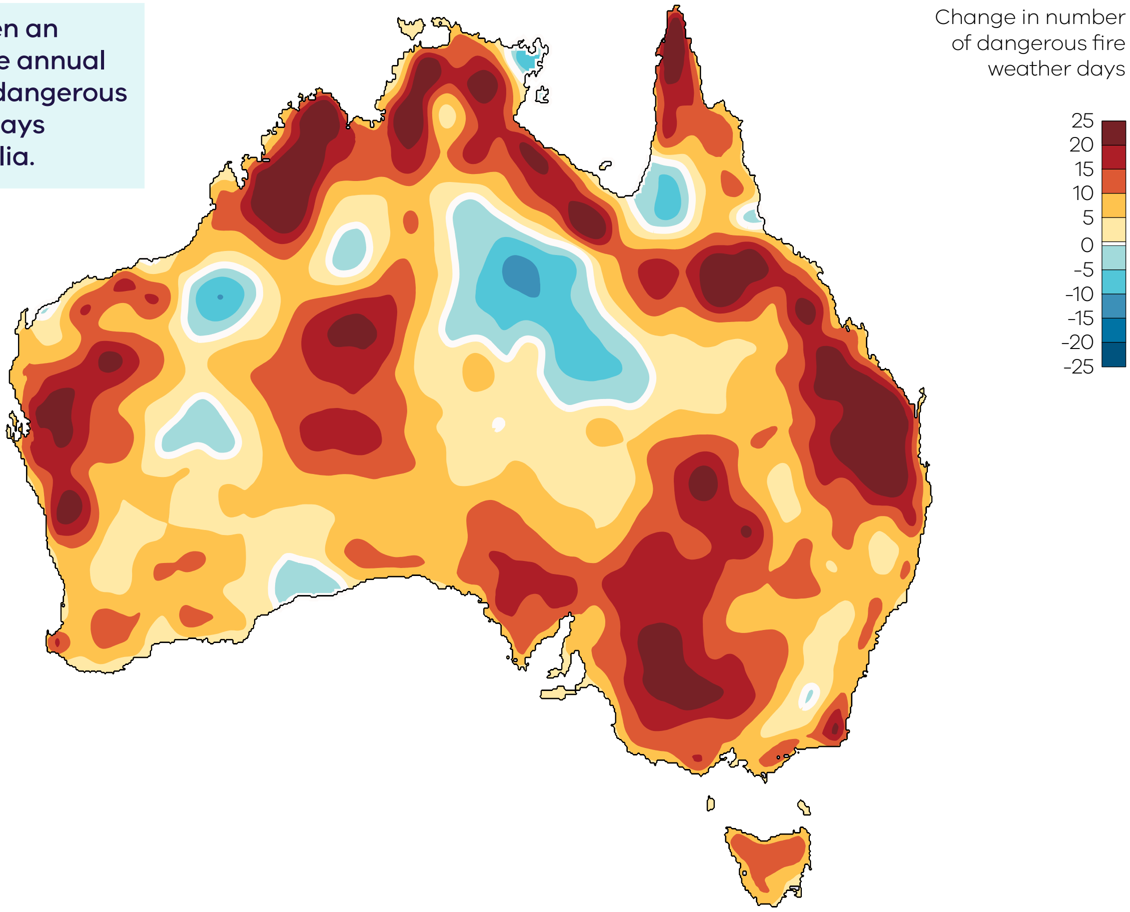


Figure 39. Change in the number of dangerous fire weather days across Australia. Red colours represent an increase in dangerous fire weather days and blue colours represent a decrease. The map shows the change in the annual (July to June) number of days that the FFDI exceeds its 90th percentile between the 2 periods: July 1950 to June 1986 and July 1986 to June 2022. The FFDI is an indicator of dangerous fire weather conditions for a given location. Source: Adapted from Bureau of Meteorology & CSIRO, 2022, CSIRO and Bureau of Meteorology.

Attribution of fire weather

Climate change has caused some of the observed increases in fire weather in south-eastern Australia, including during the 2019–2020 Black Summer bushfires, primarily through increased temperatures (van Oldenborgh et al., 2021). Increasing temperatures also affected extreme fire weather in Queensland in 2018, but an analysis of eastern Australian extreme fire weather in 2017 (Hope et al., 2019) did not identify a clear influence of increasing temperatures. The complex nature of fire weather conditions and bushfire risk make attribution studies of bushfire weather difficult. A recent study found that climate change made the conditions associated with high-impact fires in Greece, Amazonia and Canada much more likely (Jones et al., 2024).

Climate change impacts on factors influencing bushfires

Climate drivers, such as SAM and ENSO, also affect fire weather. Understanding the influence of climate drivers on fire danger remains a challenge. Changes to SAM under a warmer climate will likely drive increased fire activity in southern Australia (Mariani et al., 2018). The links between climate drivers, such as ENSO and IOD, and water availability across temperate Australia (including Victoria) contribute to extreme low rainfall and streamflow events, and therefore bushfire risk (Khaledi et al., 2022).

Significant trends in fire weather across Victoria have occurred since 1979, with an increase of at least 30% due to climate change (van Oldenborgh, 2021). This heightened risk is mainly driven by rising temperatures, leading to more extreme heat. Climate models may underestimate the actual increase in likely future extreme heat, implying that the fire risk is higher than estimated. There is no clear trend in extreme annual drought or dry months during the fire season.

Fuel management is a complex challenge in Victoria. As global temperatures increase and precipitation patterns become more erratic, the quantity, composition and moisture content of flammable vegetation will change. Understanding the intricate relationship between changing climatic conditions and fuel dynamics is vital for predicting fire behaviour and developing effective fire management strategies. Projections of fire risk need to consider both climate and vegetation changes.

Fuel load across forested and grassy landscapes in Australia may increase by the end of the century due to vegetation responses to increasing atmospheric emissions (Clarke, 2015). However, these effects may be counteracted by nutrient limitations and drought; for example, in temperate eucalypts (Bendall et al., 2022). Despite fuel load being a critical contributor to bushfire risk, the lack of high-quality, long-term data makes it challenging to establish baselines and track changes.

Extended periods of drought, low humidity and increased temperatures contribute to increased fuel aridity. This makes landscapes, such as the dry eucalypt forests in south-east Australia, more susceptible to ignition and rapid fire spread (Matthews et al., 2012). Fuel moisture is likely to decrease over much of south-eastern Australia in May and June, increasing the period available for prescribed burning in much of Victoria and south-eastern Australia, but decreasing the period in more arid areas to the north (Di Virgilio et al., 2020).

Changes in rainfall generally lead to changes in vegetation growth, moisture, ignition, fire weather and activity, impacts and post-fire recovery. Decreasing rainfall generally leads to an increase in bushfire risk in forested and woody ecosystems.

The United Nations Environment Programme (2022) undertook an assessment of the impact of climate change on bushfire risk globally. The assessment found that increases in burnt areas are likely for south-eastern Australia but that the change is far lower than in other fire-prone parts of the world. Increased fire activity may also lead to more greenhouse gas emissions, driving further climate change.

There is confidence that climate change is causing increasing fire weather and fuel dryness, with some uncertainty about the effects on fuel load and ignition (Abram et al., 2021) (Figure 40).

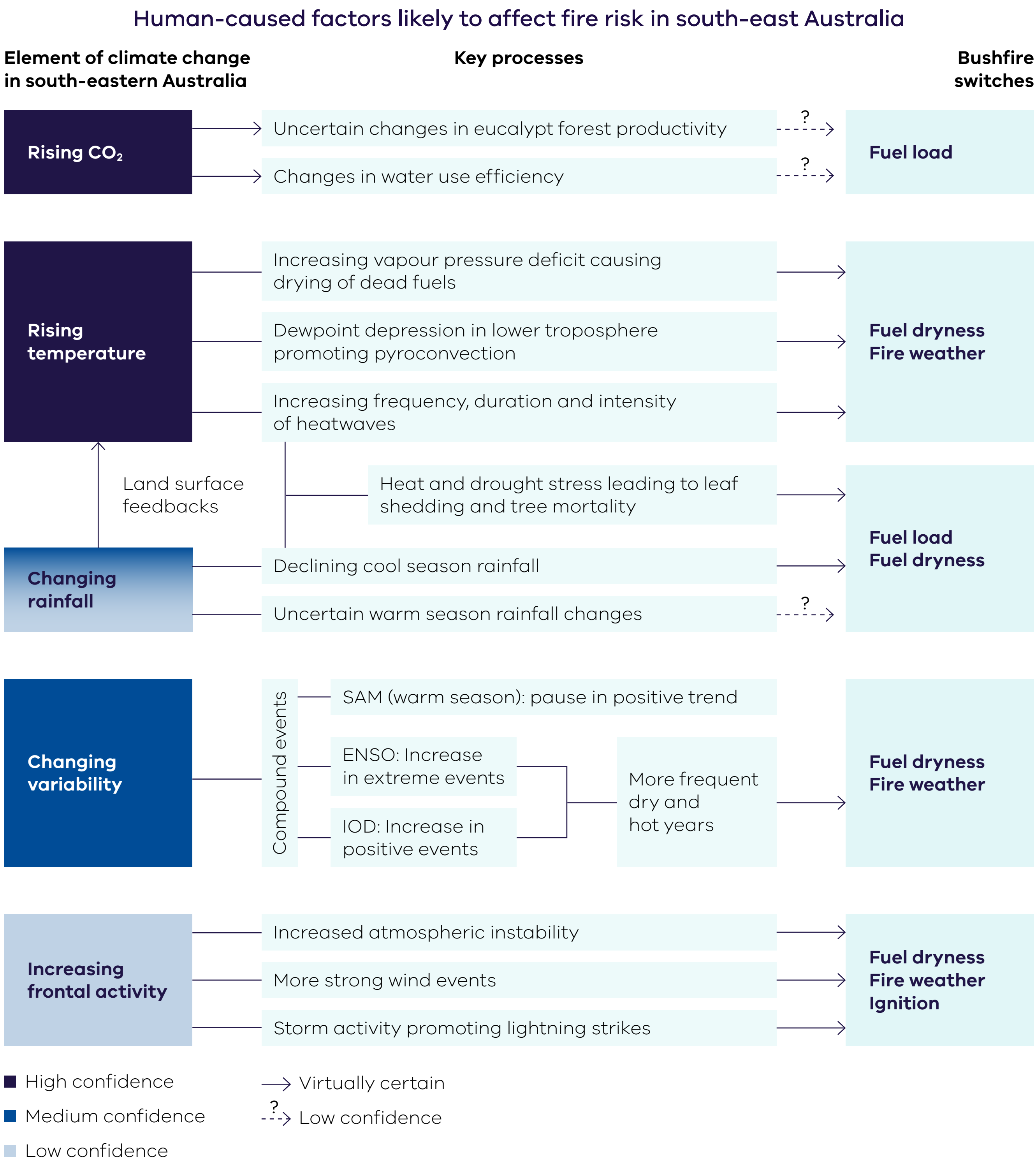


Figure 40. Summary of human-caused changes likely to alter forest fire risk in south-east Australia. The dotted arrows indicate low confidence. Source: Abram et al., 2021, under CC BY 4.0, with redesigning.

Future changes to bushfire

Fire weather severity, area burnt and fire intensity are projected to continue increasing in many regions of south-east Australia, with consequences for Victoria's forests, vegetation types, fuel moisture and overall fire risk.

Understanding how climate change is likely to affect bushfires is challenging (Figure 41). Some aspects of climate are likely to influence the drivers of bushfire risk, fire behaviour, and downstream effects of fire on plants and ecosystems.

Understanding fire in the local context is important when looking to the future. Projections should be tailored to local regions and their fuel types. A change in fire weather (or any other driver) will likely lead to different bushfire risks in different locations and landscapes with varying fuel types.

Under climate change, different landscapes and ecosystems will likely change how they interact with fire (Cunningham et al., 2024), with many regions projected to experience fire regimes never before experienced. In Victoria, these changes will likely be greatest for non-forested areas, particularly in temperate cropping zone croplands, pastures and grasslands. Other areas, such as alpine ash forests, may experience fires of greater intensity and frequency, putting two-thirds of the alpine ash distribution at risk of not reaching maturity (McColl-Gausden et al., 2022a).

There is intense interest and research in understanding the interactions between climate, fire and management interventions such as timber harvesting, prescribed burning and fire suppression. Overall, hotter and drier climates are expected to pose significant fire management challenges for ash forests.

Projections of fire behaviour show a likely increase in area burnt and fire intensity, with a decreased fire interval. Projected fuel load changes may either enhance or dampen these effects. This highlights the crucial interplay between fuel and climate in the distinct fire regimes of south-eastern Australia (McColl-Gausden et al., 2022b).

Forests in south-eastern Australia are projected to increase in flammability, although at a lower rate than globally (Clarke et al., 2022).

Increasing fire weather severity is projected for south-east Australia (Clarke & Evans, 2019; Touma et al., 2021). Frequent severe fire weather conditions could increase fire risk in forests but decrease fire risk in grasslands (Clarke et al., 2020). Projected changes in vegetation type could significantly affect bushfire risk. Changes in forest structure may be more important than climate in driving overall fuel moisture levels (Brown et al., 2024).

Confidence in observed and projected changes related to fire activity and drivers

		Observed changes	Projected changes
Fire activity	Fire frequency, area burnt and fire severity – forests	Medium confidence of increase	High confidence of increase
	Fire frequency, area burnt and fire severity – grasslands	Low confidence in direction	Low confidence in direction
Drivers of fire	Fuel	Low confidence in direction	Low confidence in direction
	Fuel dryness	Medium confidence of increase	Medium confidence of increase
	Fire weather	High confidence of increase	High confidence of increase
	Ignition	Low confidence in direction	Medium confidence of increase

Figure 41. An assessment of the evidence related to fuel, fuel moisture, fire weather, ignition, fire frequency, area burnt and fire severity in Victoria. High confidence equates to high agreement and robust evidence. Low confidence equates to low agreement and limited evidence. Source: Hamish Clarke, Victoria Reynolds and Tom Fairman for VCSR24.

Fire activity, especially high-severity fire, is likely to significantly impact south-eastern Australia's temperate eucalypt forests, affecting forest structure, resilience, and carbon storage (Fairman et al., 2022).

Evidence of fuel moisture impacts on fire is increasing, while the situation for ignitions and fuel load is considerably more complex and requires further investigation. Low fuel moisture plays an important role in fire ignitions in Victoria, with a warmer, drier future likely to lead to higher ignition risk (Dorph et al., 2022).

Rainfall changes are likely to strongly influence the response of different vegetation types to climate change in south-eastern Australia due to the complex links between climate (temperature and rainfall) and fuel properties (load, litterfall and decomposition) (Thomas et al., 2014).

Heatwaves, drought and bushfires interactions

Heatwaves, drought and bushfires can interact and co-occur, resulting in devastating impacts.

Drought increases the likelihood of heatwaves (Alexander, 2011), while heatwaves exacerbate drought conditions by increasing the rate of land surface drying. This results in a positive feedback loop whereby heatwaves amplify drought conditions which then increase the severity and duration of heatwaves, leading to further surface drying (Miralles et al., 2014). In addition, the persistent high-pressure systems that are essential for heatwave development are more likely to occur during drier periods.

Since 1971, there has been an increase in co-occurring droughts and heatwaves in south-eastern Australia. This trend has intensified over the last 2 decades (Laz et al., 2023). Hotspots of co-occurring events have become more apparent in northern Victoria since 2001.

Severe co-occurring droughts and heatwaves over Victoria are more likely when droughts are more intense and longer (Laz et al., 2023). These co-occurring events can result in catastrophic impacts. Detrimental impacts on Australian flora and fauna have already occurred (e.g. Hoffmann et al., 2019), with prolonged and intense heat combined with water scarcity putting animals and plants at increasing risk.

Heatwaves affect fire weather and fire fuel. Until recently, fire danger in Australia was based on the Forest Fire Danger Index (FFDI) and grass fire danger index (GFDI) (McArthur, 1967). Both indices consider the state and interaction of temperature, humidity, wind and vegetation dryness. Many previous assessments of fire risk are based on the FFDI and/or the GFDI.

The recently developed Fire Danger Rating System is based on the Fire Behaviour Index and captures a broader range of fuel types, fire behaviour and drought (Australian Fire Danger Rating System, 2023), making it a more accurate description of fire risk.

During a heatwave, the risk of fire weather increases with temperature. Heatwaves exacerbate land surface drying, with prolonged drought resulting in increased plant stress and the death of native trees (Ashman et al., 2021). The combination of droughts and heatwaves can prime the Australian landscape for devastating fire conditions. Seasons during which droughts, heatwaves and fires are experienced are increasing globally, with southern Australia a particular hotspot (Richardson et al., 2022).

This was the case with the 2019–20 Black Summer bushfires. A multi-year drought was amplified in spring by one of the strongest positive IOD events ever experienced (Abram et al., 2021), further increasing the occurrence of prolonged and extreme heatwaves. This primed conditions for one of the worst Australian bushfire seasons on record, with 24.3 million hectares of land burned across the nation (Binskin et al., 2020). This amounted to over 4 times the area burned during the previous worst Australian fire season on record (Wang et al., 2022; Bowman & Sharples, 2023), and an 800% increase on the 1988–2001 average (Canadell et al., 2021; Bowman & Sharples, 2023). During the bushfire event, low soil moisture and relative humidity, dry north-westerly winds and intense temperatures created dangerous fire weather conditions in New South Wales (Deb et al., 2020). As the heatwave persisted, fuel loads became drier over the south-east Australian coast (Reddy et al., 2021b), contributing to the devastating bushfires. Climate change is likely to create adverse changes in Australian fire weather, including heatwaves (Di Virgilio et al., 2019).

Bushfire further information

- **Climate Change Engagement and Communications Practice Review:** Through the ongoing Safer Together bushfire risk reduction program, the Department of Energy, Environment and Climate Action (DEECA) and Country Fire Authority are collaborating on projects aimed at assisting emergency management practitioners in engaging with community about climate change issues and encouraging action and behaviour change for risk reduction. The project is being delivered in partnership with researchers at the University of Melbourne and Monash University.
- **Integrated Strategic Bushfire Management in a Changing Climate:** In 2024, DEECA completed Phase 1 and will start Phase 2 of a large research program aimed at enhancing our understanding of the relative cost-effectiveness of bushfire management activities and wildfire suppression to modify future wildfire frequency, extent, intensity and impacts to multiple values. This project is being delivered in partnership with the University of Melbourne. Learnings from this project will support planning decisions on the appropriate combination of mitigation activities across the landscape under current and future climate scenarios.
- **Impact of climate change on fuels:** DEECA is investing in research to better understand how fuel re-accumulates following disturbance and on the effectiveness of fuel reduction activities under different weather and fuel conditions. This will improve our ability to apply our fuel reduction program in the most effective way in a changing climate.
- **Fire management and ecosystem resilience in a changing climate:** DEECA is driving new research aimed at developing tools and approaches for measuring the effectiveness of a range of fire management approaches to mitigate the effects of future bushfires on ecosystem resilience, considering alternative climate scenarios.

4.5 Sea-level rise

Key messages

- Sea-level trends assessed between 1901 and 2018 indicate that globally, the average rate of sea-level rise is accelerating.
- Since 1993, the rates of sea-level rise to the north and south-east of Australia have been significantly higher than the global average, whereas rates of sea-level rise along the other coasts of the continent, including Victoria, have been closer to the global average.
- Sea levels will continue to rise in the next 100 years under all emissions scenarios. Following a lower emissions pathway will help to slow the rate of sea-level rise but will not stop or reverse the rising trend.

Describing sea-level rise

Rising sea levels are primarily caused by the expansion of the ocean as it warms and the added mass from melting of glaciers and the Antarctic and Greenland ice sheets induced by global warming.

Several dynamic mechanisms could cause larger contributions to sea-level rise from Antarctica, increasing the total rates of sea-level rise. However, aspects of these mechanisms and the time frames over which they could occur are still uncertain.

Sea-level mechanisms

Sea-level rise is driven by oceanic and atmospheric influences and more specific mechanisms such as thermal expansion, ocean currents, melting glaciers and ice sheets, and vertical land movement.

The most significant source of water on Earth is found in oceans, seas and bays, with smaller amounts in groundwater systems and frozen on land in ice sheets and glaciers. By comparison, the atmosphere stores a negligible amount of water. This means that despite the increased evaporation and moisture-holding capacity of the atmosphere under climate change (7% increase for every degree of global warming), the resulting extreme overland rainfall that eventually makes its way back to the oceans only has a small and temporary effect on global mean sea levels.

Factors that affect global mean sea level are primarily governed by either ocean mass changes due to additional water from land-based sources, such as glaciers and Greenland and Antarctic ice sheets, or by ocean density changes (without mass changes), which are driven mainly by ocean temperature changes.

Additional factors cause regional variations in sea levels, which include atmospheric pressure, ocean currents and circulation, movements in the Earth's crust due to changes in mass distribution and associated changes in the Earth's gravity field and rotation. Naturally occurring climate variability, such as ENSO, also affects sea levels.

The various processes associated with sea-level rise and extremes are illustrated in Figure 42.

Sea levels are affected by various processes and components

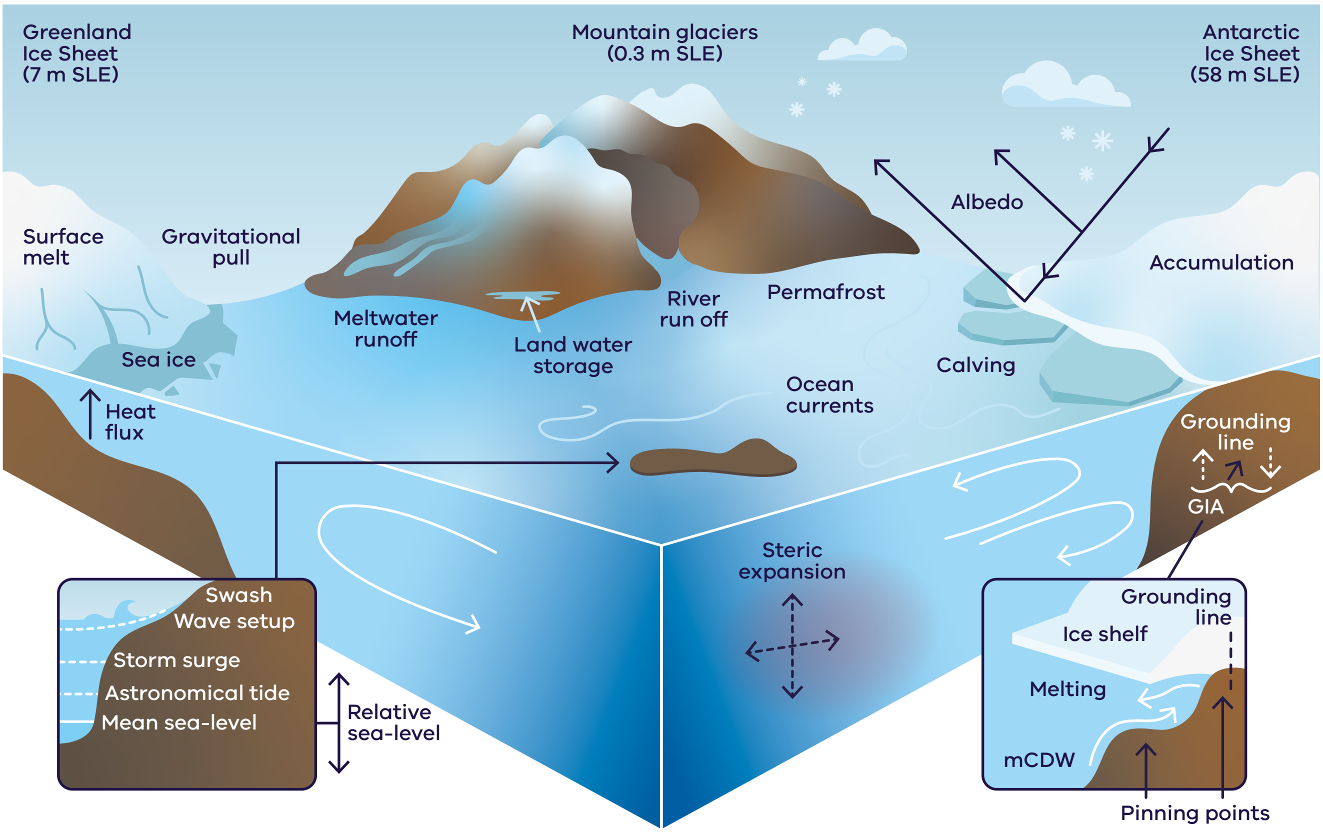


Figure 42. Climate-sensitive processes and components that influence global and regional sea levels. SLE = sea-level equivalent; mCDW = modified Circumpolar Deep Water; GIA = glacial isostatic adjustment. White arrows indicate ocean circulation. Pinning points indicate where the grounding line is most stable and ice-sheet retreat will slow. Source: Adapted from Fox-Kemper et al., 2021.

Thermal expansion

Approximately 93% of the excess energy in the climate system has been absorbed by the oceans, where it has contributed to ocean warming (Rhein et al., 2013; Church et al., 2013; Von Schuckmann et al., 2023). This energy has contributed to ocean warming (Von Schuckmann et al., 2023). Over the 20th century, thermal expansion of ocean water contributed approximately one-third of the measured sea-level rise.

About 60% of the heat absorbed by the ocean is stored in the upper 700 m of the ocean. Although the deep ocean is also warming, the upper 200 m of the ocean has warmed at a greater rate (Fox-Kemper et al., 2021).

Ice sheets and global glaciers

The Antarctic and Greenland ice sheets contain enough water to raise sea levels by 58 m and 7 m respectively if they were to completely melt (Davies, 2023).

Mass gain over ice sheets and glaciers occurs through precipitation. Loss occurs through melting or calving of glacier ice. Recent contributions by the Greenland ice sheet to sea-level rise have primarily been due to surface mass balance and glacial retreat (van den Broeke et al., 2016). Recent contributions to sea-level rise from the west Antarctica ice sheet have primarily been due to ocean-driven melting of the ice sheet at the base, and increased ice-shelf collapse in the Antarctic Peninsula region (Shepherd et al., 2018).

Over the past century, most glaciers across the globe have been retreating. The world's glaciers contain enough mass to raise global sea levels by 0.3 to 0.5 m (Vaughan et al., 2013).

Terrestrial water storage

Terrestrial water storage refers to dams and underground aquifers. Over much of the 20th century, the influence of terrestrial storage on sea-level rise has been small and slightly negative. Global dam building projects impound water that would otherwise flow to the sea, causing sea levels to fall (Frederikse et al., 2020). However, global dam building has slowed in recent decades and groundwater extraction for domestic, agricultural and industrial applications has increased, causing the contribution of terrestrial storage to sea-level rise to increase, although the contribution is relatively small (Church and White, 2011; Wang et al., 2021).

Variations in rainfall patterns, often associated with climate variability (especially ENSO), can also add to terrestrial storage, temporarily altering global mean sea levels for short periods (Fasullo et al., 2013; Ummenhofer et al., 2015).

Sea-level fingerprints

As ice sheets melt, complex processes distribute the meltwater in a distinct pattern that causes sea levels to rise unevenly around the world (Lallensack, 2017). These processes and their resulting sea-level change patterns are known as sea-level fingerprints (Mitrovica et al., 2011). Ice sheets and glaciers exert a slight gravitation pull on the ocean around it. This gravitational pull diminishes as ice sheets melt and lose mass. This causes sea levels close to the ice sheet to fall and sea levels on the opposite side of the Earth to rise. The Earth's rotation also changes with mass changes, which further contributes to regional sea-level patterns. The change in mass from melting ice sheets can cause land to rise or fall vertically. These processes cause the spatial redistribution of sea levels, which can be measured and tracked.

Vertical land movement

The Earth readjusted to the melting of ice sheets that covered land masses during the last ice age. This re-adjustment process leads to vertical land movement, resulting in sea level changes. Similarly, the contemporary melting of land ice also leads to adjustments globally, including vertical land movement and sea-level fingerprints mentioned above. On shorter time scales, urban development, sediment compaction, the removal of groundwater or oil and gas can lead to land subsidence (sinking of the ground) and an increase in relative sea-level rise. Tectonic activity, such as earthquakes and volcanoes, can also lead to ongoing land movement changes or abrupt changes in land level.

In Australia, land subsidence is occurring at most locations. It is likely that the majority of this subsidence has been caused by the mass melting of glaciers and polar ice sheets following the end of the last Ice Age approximately 20,000 years ago (referred to as glacial isostatic adjustment).

Ocean density, atmospheric and ocean circulation

Ocean density is determined by temperature and salinity. Cooler saltier water is denser than warmer fresher water. Factors such as wind stress, freshwater movement and heat exchanges, drive regional differences in ocean density and circulation, which in turn affect sea levels. Atmospheric pressure changes also influence local sea levels, with high- and low-pressure centres causing regional depression or elevation of sea levels.

Sea-level measurements

Sea levels are typically monitored by either coastal tide gauges, which record sea levels along coastlines of continents or islands relative to the local solid earth surface, or by satellite altimeters, which provide near-global sea surface height measurements using an Earth-fixed geocentric reference frame (White et al., 2014). Digital records of many tide gauges in Australia started around 1966, although longer digital records are available for some locations (McInnes et al., 2016) (Figure 43).

Satellite altimeter measurements started in late 1992, providing a shorter record of near-global sea-level change over the past 3 decades. While the 2 datasets are complementary in their coverage, their measuring methods and references are different. As a result, sea level measurements from the 2 data sources differ and must be converted to be directly compared to each other.

Different methods of measuring sea-level rise

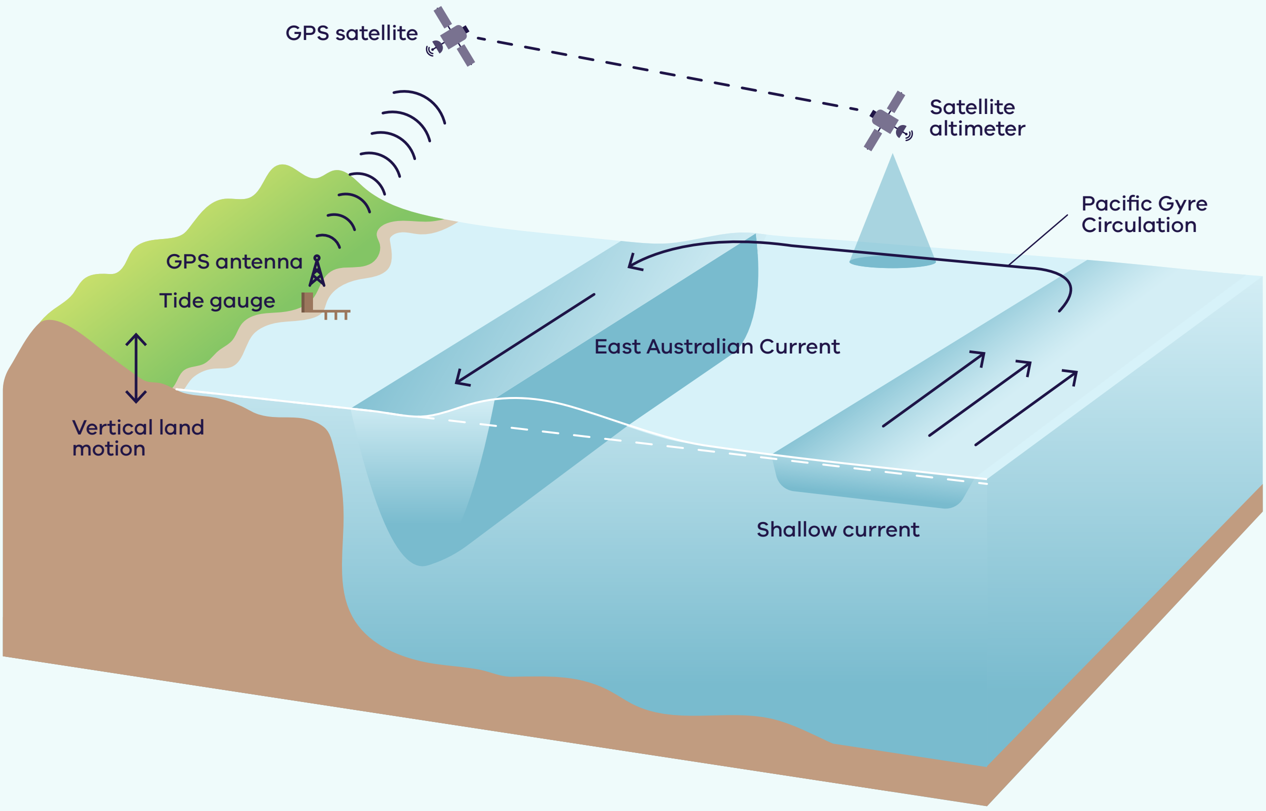


Figure 43. Diagram explaining how differences between rates of sea-level rise measured by satellite altimeters and tide gauges can arise. Tide gauges may move vertically; due to groundwater extraction which leads to land subsidence. As a result, the rates of rise from the tide gauge would appear greater than the rates of rise measured by satellite altimeters. The vertical movement of tide gauges can be measured by GPS (global positioning system). Changes in ocean dynamics, such as the strengthening southward boundary flow of the East Australian Current, cause an increase in the sea-surface height seaward of the current direction so that the rate of sea-level rise measured by the satellite altimeter would be greater than the rate measured at the nearby coastal tide gauge. Source: CSIRO for VCSR24.

Observed changes in sea level

Global mean sea level has risen by over 22 cm since 1900. The rate of sea-level rise since 1993 varies around the Australian region, with the largest values to the south-east of the Australian continent.

According to the IPCC's Sixth Assessment Report, between 1901 and 1971 the average rate of global sea-level rise was 1.3 mm per year (range of 0.6 to 2.1 mm per year). This rate increased to 1.9 mm per year (range of 0.8 to 2.9 mm per year) between 1971 and 2006, and between 2006 and 2018 it further increased to 3.7 mm per year (range of 3.2 to 4.2 mm per year) (Figure 44).

Global mean sea level rise

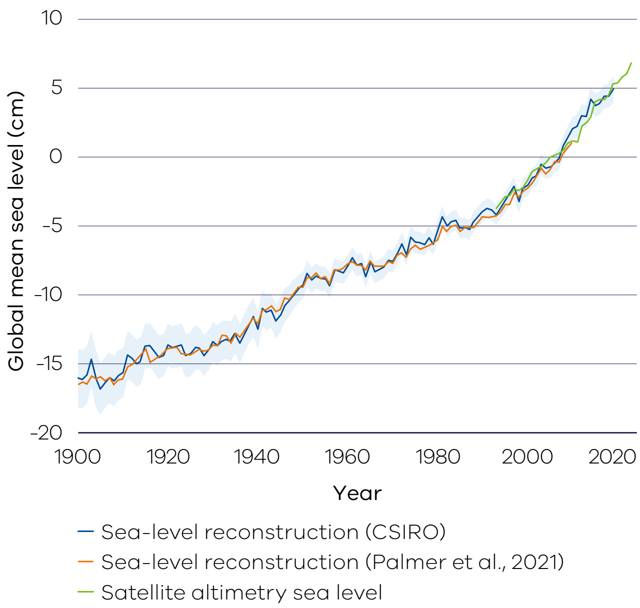


Figure 44. Global mean sea levels with reconstruction based on tide gauges from CSIRO and Palmer et al. (2021) and global mean sea level based on satellite altimetry. Annual global sea-level change from 1900 to 2019 is from sea level reconstruction (blue line from CSIRO, shading indicates confidence range; orange line from Palmer et al., 2021), and annual sea-level change from 1993 to 2023 is based on satellite altimetry observation (green line). Source: Bureau of Meteorology & CSIRO, 2024.

The rate of sea-level rise around Australia's coastline and adjacent oceans since 1993 is based on coastal tide gauges and satellite altimeters (Figure 45). These indicate that sea-level rise around the coastline is not uniform. The rates of sea-level rise to the north and south-east of Australia have been significantly higher than the global average, whereas rates of sea-level rise along other areas of the coast have been closer to or slightly lower than the global average.

Sea levels have risen around Australia

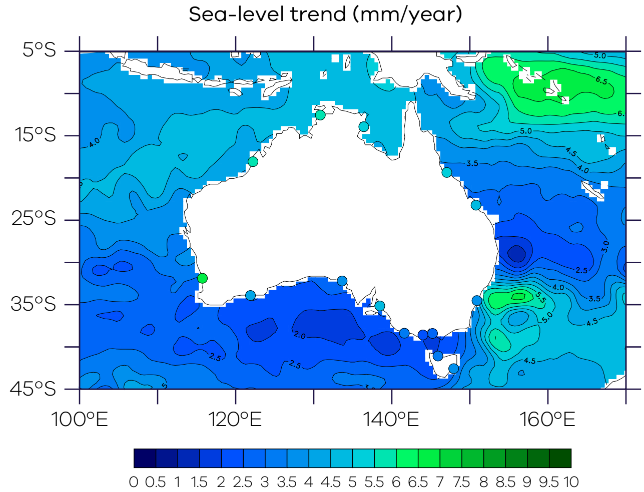


Figure 45. The rate of offshore sea-level rise around Australia from 1993–2023 measured using satellite altimetry and the rate of sea-level rise (coastal points) from tide gauges provided by the Australian Baseline Sea Level Monitoring Project. The colour scale applies to both the shading (satellite altimetry) and dot (tide gauges) observations. Darker green colours represent more sea-level rise and darker blue colours represent less sea-level rise. Source: Bureau of Meteorology & CSIRO, 2024.

Future changes to sea levels

Sea levels are projected to rise regardless of the emissions scenario. Following a low emissions pathway will help to slow the rate of sea-level rise, but it will not reverse the rising trend.

Due to the inertia and internal variability of the climate system, the emergence of a clear signal of human-caused long-term climate change in sea-level rise may take decades to appear (Lyu et al., 2014; Samset et al., 2020).

The regionalised sea-level rise projections for Victoria were developed using the most recent suite of global climate model projections based on CMIP6. Projections are provided out to 2120 at decadal intervals relative to the 1995–2014 baseline period. The projections account for changes in ocean density and circulation as well as the sea-level contributions from melting glaciers, changes in land water storage, and the mass changes of the Antarctic and Greenland ice sheets, and vertical land movement (Fox-Kemper et al., 2021).

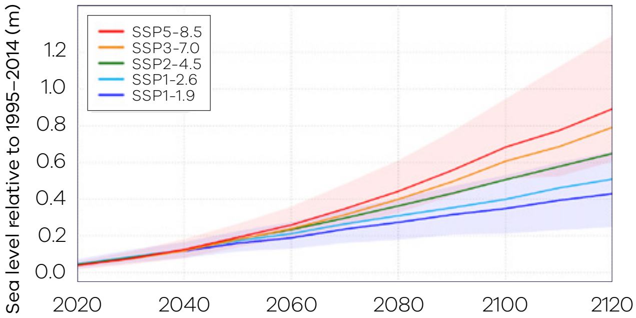
The IPCC Sixth Assessment Report provides medium confidence sea-level rise projections that represent the best assessment of how dynamic ice sheet processes will contribute over the 21st century and beyond. The report also provides low-confidence projections in which the dynamic ice sheet processes contribute more rapidly to sea-level rise (IPCC, 2023). Sea levels will continue to rise up to 2120 under all emissions scenarios due to the longer adjustment time for sea level compared to surface air temperature. The rate at which sea levels will rise, however, depends on the emissions scenario followed.

Sea-level rise projections under 3 emission scenarios are provided: SSP1-2.6 (the low emissions scenario), SSP3-7.0 (the high emissions scenario) and SSP5-8.5 (the very high emissions scenario). The SSP3-7.0 emissions scenario is increasingly considered to be a more realistic high-end scenario than SSP5-8.5 in terms of the underpinning assumptions about future sources of energy and their contributions to emissions (Hausfather & Peters, 2020). Although less likely, very high emissions scenarios cannot be ruled out and can be useful for adaptation planning and risk assessment.

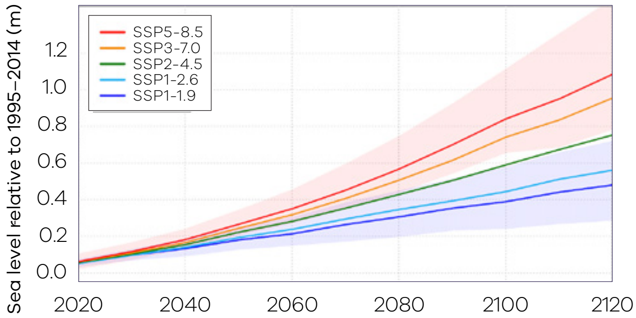
Overall projection results

Three locations in Victoria have been selected for the presentation of sea-level rise results to highlight the regional differences in projections: Warrnambool, Melbourne and Gabo Island. These are summarised in Figure 46 (for information on other emission scenarios and locations refer to McInnes & Zhang, 2024).

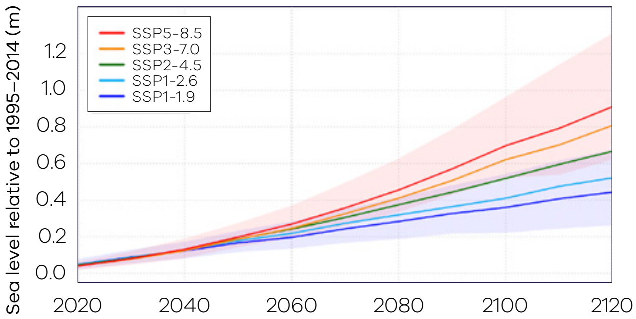
Sea-level rise projections for Victoria



Melbourne				
Emissions pathway		SSP1-2.6	SSP3-7.0	SSP5-8.5
Sea-level rise projections median and range	**2050**	0.17 m (0.12 to 0.24 m)	0.18 m (0.13 to 0.25 m)	0.19 m (0.14 to 0.26 m)
	2120	0.51 m (0.31 to 0.77 m)	0.79 m (0.52 to 1.12 m)	0.89 m (0.61 to 1.29 m)



Gabo Island				
Emissions pathway		SSP1-2.6	SSP3-7.0	SSP5-8.5
Sea-level rise projections median and range	**2050**	0.19 m (0.13 to 0.27 m)	0.24 m (0.18 to 0.32 m)	0.27 m (0.20 to 0.34 m)
	2120	0.56 m (0.35 to 0.83 m)	0.95 m (0.69 to 1.29 m)	1.08 m (0.78 to 1.50 m



Warrnambool				
Emissions pathway		SSP1-2.6	SSP3-7.0	SSP5-8.5
Sea-level rise projections median and range	**2050**	0.18 m (0.12 to 0.25 m)	0.19 m (0.14 to 0.26 m)	0.20 m (0.14 to 0.27 m)
	2120	0.52 m (0.32 to 0.78 m)	0.81 m (0.54 to 1.14 m)	0.91 m (0.62 to 1.31 m)

Figure 46. CMIP6 sea-level rise projections to 2050 and 2120 (*medium confidence*) for 3 locations in Victoria compared to 1995–2014, based on low (SSP1-2.6), high (SSP3-7.0) and very high (SSP5-8.5) emissions scenarios: Melbourne, Warrnambool, and Gabo Island. The projections are expressed as a median and 17-83% confidence range (in brackets), relative to the baseline period of 1995–2014. Source: McInnes & Zhang, 2024.

5. Applying climate science in decision-making

Climate science helps Victorians understand and adapt to our current and future climate. It is essential that the latest climate science is included in Victoria's decision-making processes. Understanding where to access climate information and some of its practical applications is important to equip Victoria's decision-makers with the best planning tools.

To effectively manage impacts and mitigate climate risks, consideration of climate information is integral to good governance and decision-making.

The IPCC recognises that the risks of climate change can be reduced, within limits, when people and systems adapt to the changing conditions (IPCC, 2023). Adapting successfully requires analysis of the risks posed by a changing climate and implementation of measures to reduce these risks. Climate science helps decision-makers understand the scale, pace and nature of climate change, the risks that may emerge, and can inform hazard, vulnerability and exposure assessments.

This report does not provide guidance on how to undertake adaptation planning or complete a climate risk assessment – noting that a nationally consistent approach to undertaking climate risk assessments is being developed (Commonwealth of Australia, 2024). Instead, it provides case studies illustrating how decision-makers have applied climate science.

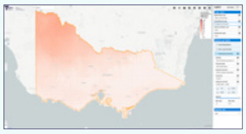
Climate science is generated at global, national and regional scales.

As the leading international body for assessing climate change, the IPCC produces a range of reports that are used by all levels of government in various ways, including to develop localised climate information. The IPCC's assessment reports usually include a summary for policymakers, which provides a high-level synopsis of the report's main findings.

In Australia, the Bureau of Meteorology and CSIRO publish a State of the Climate report every 2 years, informed by the findings of the IPCC and Australian research. The report draws on the latest monitoring, science and projections information to describe variability and changes in Australia's climate. The report supports economic, environmental and social decision-making by governments, industries and communities (Bureau of Meteorology & CSIRO, 2022).

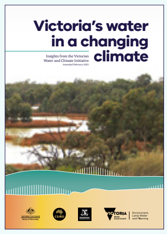
Under Section 51 of the *Climate Change Act 2017*, the Victorian Government is required to produce climate science reports every 5 years, with the first report released in 2019. A range of climate science tools are available to support decision-makers in Victoria (Figure 47).

Climate science resources



Victoria's Future Climate Tool

This spatial mapping tool allows visualisation of the latest projections for Victoria's climate. It allows users to select between different climate models, emissions scenarios, and time horizons.



Victorian Water and Climate Initiative

This initiative conducts climate and hydrology research to better understand Victoria's climate and water resources, including the development of rainfall and streamflow projections.

Climate Change in Australia

Developed by CSIRO and the Bureau of Meteorology, this tool contains summary climate projection statements, climate model data and regional summaries including VCP19

Figure 47. Tools and initiatives that support Victorian decision-making under a changing climate.

Decision-makers can draw on different types of climate information depending on their needs.

Decisions sensitive to short-term climate changes may need to rely on detailed monitoring of weather conditions or specific climate projections (such as rainfall) across several regions. Other sectors may require only high-level insights on historical and likely future trends and information on climate hazards and extremes.

Practical applications of climate science information include:

- using observational data to minimise current exposure to climate change
- applying climate projections to inform – medium- and long-term emissions reduction and adaptation strategies
- understanding climate hazards to prepare and respond to extreme weather.

Quantitative and qualitative analysis methods can be applied to climate information. For example, high-level qualitative analysis can involve summarising key trends to explore the potential range of climate changes from the literature. Data-driven quantitative analysis can involve extracting climate hazard metrics to assess projected changes to scenarios (DCCEEW, 2023).

Wimmera farmers use soil data to improve drought resilience

Background
Wimmera farmers play a critical role in the local and national economy, with significant contributions to the production of dryland broadacre cereals, legume and oilseeds, as well as sheep for meat and wool. So when climate forecasters predict reduced rain, increased temperature and more weather extremes, there's much at stake. Wimmera farmers are no strangers to drought or climate change, and their experiences have led to a range of practice changes and adaptations to minimise climate risk.

Probing soil moisture
Soil moisture is the greatest limiting resource for the production of Wimmera's top commodities, and yet few farms adequately monitor it due to cost and limited confidence in interpreting data from the technology. In response, the Wimmera Catchment Management Authority (CMA) established a free-to-access soil-moisture probe network spanning 3 million hectares at more than 70 locations, funded by the Australian Government's Future Drought Fund.

Soil-moisture probes are installed into the soil profile and connected to a telemetry unit (weather station). Soil-moisture and temperature sensors occur at 10 cm intervals along the length of the probe. Data from each of these sensors are received about every 15 minutes and can be accessed in real-time from the Wimmera CMA soil-moisture platform.

Farming is an expensive and high-risk enterprise. Accurate data from the soil-moisture probe network can be combined with climate forecasts and yield calculators to inform decisions that greatly reduce exposure to risk. One such risk is the application of fertiliser. Farmers can use the soil-moisture data in combination with the Bureau of Meteorology's location-specific decile forecasts to determine the risks and benefits, and the amount of fertiliser required for top dressing nitrogen-deficient paddocks. An increased chance of wetter deciles and a decreased chance of drier deciles provide greater confidence in applying fertiliser at higher rates that allow a crop to reach full yield potential. In seasons when drier deciles are forecast and soil-moisture reserves are low, farmers can reduce risk by lowering nitrogen application rates. Soil-moisture data can also be used to help inform crop selection for sowing, and later in the season if moisture reserves are low, assess if it is more profitable to cut for hay or continue growing the crop through to harvest for grain.

In livestock farming systems, farmers can use soil-moisture data and pasture growth rates to make informed estimates regarding feed on offer to determine how many animals they can run, when they should sell or buy more stock, or even when to sow pastures. Without soil-moisture data, farmers, agronomists, and consultants face limitations. They need to make decisions using a combination of assumptions about soil moisture, past experience, current rainfall, and rainfall forecasts. This method is inherently riskier. Using data from soil-moisture probes significantly reduces this risk.

Science informing agricultural management
The soil-moisture data portal has attracted significant interest from the agricultural sector. User accounts for the portal continue to grow. Extension opportunities are available to increase user confidence in reading and interpreting data from the soil-moisture probes and weather stations. Wimmera CMA and key stakeholders plan to add value to the network through continued climate resilience initiatives. Areas of exploration include the addition of inversion towers to reduce spray drift in the Wimmera region, and, as the network accumulates more data on soil moisture and weather parameters, examining how researchers can use this data for further climate resilience initiatives. As weather stations and soil-moisture monitoring become more commonplace in dryland farming systems, there is greater scope to better understand the interactions between soil moisture, fertility, water-use efficiency and productivity.

Observational data can be used to minimise current exposure to climate change, while climate projections can inform medium- and long-term adaptation strategies.

Information about the changing climate helps decision-makers accurately account for the impacts relevant to their operations and proactively manage these risks. Climate scientists use observations and measurements of our environment to understand how the climate has changed on local, regional and global scales.

However, given the human influence on the global climate system, the past climate is not necessarily the best indicator of the risks that the future climate poses. Climate projections provide information on the range of plausible climate futures, depending on concentrations of greenhouse gas emissions and a variety of socio-economic factors. Section 3.2 of this report outlines the models, scenarios and time horizons used to produce the updated projections for Victoria.

To ensure climate projections are relevant, decision-makers need to consider the climate model, emissions scenarios, and planning horizons used to produce the projections.

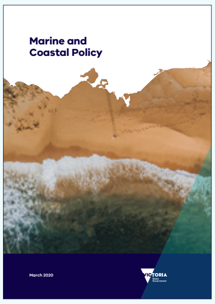
- **Climate model:** While it is desirable to capture projections from a large range of climate models, it is not always possible to use all available climate models. Decision-makers should, therefore, draw on modelling that represents a wide range of plausible future scenarios. The same climate model or models should be used to produce projections for all the required climate variables to enable comparisons of information. For example, it is inappropriate to use a temperature projection and a rainfall projection from 2 different model sources (CCiA, 2020).
- **Emissions scenarios:** It is good practice to consider a range of emissions scenarios (e.g. low and high emissions scenarios). Consideration of only one scenario may inadvertently result in planning and decisions appropriate for a future state that does not eventuate, or a climate threshold that is exceeded. Long-term warming is highly dependent on the emissions scenario, while in the short term, the difference in the average amount of warming between emissions scenarios is less significant (CSIRO, 2024).
- **Planning horizons:** For many planning scenarios, decisions made today will have consequences far into the future (e.g. land-use planning and infrastructure development). As a result, climate change projections that are relevant to your planning horizon should be considered. For example, forest plantings for carbon sequestration may require a time horizon later in the century, while decisions about a new irrigation regime may require a shorter time horizon.

Sea-level rise benchmark supporting Victorian land-use planning and development

Background

Victoria's sea-level rise planning benchmark is the minimum amount of sea-level rise that must be considered and applied by developers, local governments, planners, managers, and the community when making planning decisions and assessing coastal hazard risk.

Marine and Coastal Policy



Victoria's Marine and Coastal Policy 2020 provides instruction to 'plan for sea-level rise of not less than 0.8 m by 2100, and allow for the combined effects of tides, storm surges, flooding, coastal processes and local conditions such as topography and geology, when assessing risks and coastal impacts associated with climate change' (Policy 6.1). The Victorian Government is considering the latest and best available science to review and update the sea level rise planning benchmark in the Marine and Coastal Policy 2020.

Science informing policy

Evidence from climate science reports, such as the IPCC's Sixth Assessment Report, provides global sea-level rise projections based on combined SSPs and RCPs. The combined pathway approach addresses some of the uncertainties associated with past sea-level rise projections, resulting in increased confidence in the projections for 2120 and beyond. The sea-level rise planning benchmark is an example of how planning and policy frameworks can effectively incorporate complex climate projections for non-climate experts to apply in their work.

Targeted management and conservation of threatened species over a 50-year timeframe

Background

Threatened species are often particularly exposed to the impacts of climate change due to factors including low population size, fragmented or isolated habitat, reduced genetic diversity and habitat requirements. To address these factors, threatened species often require targeted management in addition to standard landscape management.

Threatened species decision-making processes

The Victorian Government's Threatened Species Framework team use Specific Needs Assessments (SNAs) to inform and support decision-making processes for threatened species management and conservation. SNA participants – typically species experts – estimate likely future outcomes of various species-specific management actions over a 50-year timeframe. Assessing this over a long period encourages participants to consider how targeted management will support the long-term recovery of a species over many generations, while also capturing the full planning, implementation and maintenance costs. A longer timeframe also permits the potential impacts of climate change to be included in decision-making.

Science informing conservation and management

To determine how they might best support the management of Victoria's threatened species under a changing climate, the Threatened Species Framework team reviewed various climate models and emissions scenarios for Victoria. After a thorough search, Victoria's regional climate projections were preferred over other approaches as they present climate science in a clear and accessible manner for SNA participants that can be adapted to meet species-specific requirements of each SNA.

An ongoing high greenhouse gas emissions scenario (i.e. RCP8.5) is used to represent a 'business as usual' default scenario for SNA, although participants may decide to include other scenarios if they seek to consider the influence of alternative possible future climates on the impact of management actions for their threatened species.

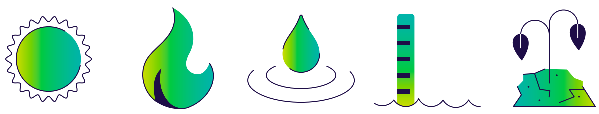
All information from the regional climate projection reports, including the climate analogue tool (where the climate at a certain location is predicted to be similar to the current climate at another location by a particular year) is incorporated into species-specific background reports provided to participants before SNA workshops. Using this information, participants are asked to consider how increases in maximum and minimum daily temperatures, changes in rainfall and possible extreme weather events (such as bushfires and floods) are likely to affect the delivery and effectiveness of potential management over the 50-year timeframe considered in the SNA.

The outcomes of the Threatened Species Framework team's SNAs, informed by climate science information, play an important role in the ongoing management and conservation of some of Victoria's most threatened species.

Information on extreme weather events supports the capacity of organisations and communities to cope with them.

Understanding projected changes in the frequency, duration, location and intensity of extreme weather events can be a key component in supporting the continuation of government function during this period (Figure 48).

Improving resilience to extreme weather events



Information on extreme weather events

Inform preparedness through early detection and disaster management

- develop community resilience strategies
- support communities to lead management approaches

Design engineering solutions and nature-based solutions

- improve resilience of infrastructure
- adapt to and mitigate the severity of hazards

Inform land use planning and development

- identify hazard research needs and management strategies

Support critical service delivery and resource allocation

- help the medical sector prepare for hazards
- inform planning for emergency response procedures

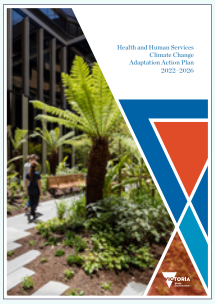
Figure 48. How information on extreme weather events can improve preparedness, response and recovery.
Sourced from the commissioned literature review.

Understanding the vulnerability of health services to severe weather and development of adaptation options

Background

Following the October 2022 floods, the Department of Health commissioned climate risk assessments for 6 regional hospitals to understand the specific vulnerability of health services to severe weather events.

Assessing climate risk



The assessment involved mapping region-specific historic temperature and weather trends to future climate scenarios. Historic data was compared to projections data from low and high emissions scenarios (RCP4.5 and RCP8.5) for 2030 and 2050. Climate projections were consolidated from CSIRO's Climate Change in Australia Murray Basin Cluster and the Loddon Campaspe Regional data in the 2019 Victorian Climate Projections. The Electricity Sector Climate Information tools were also used.

Science informing risk management and adaptation

This assessment found health services are vulnerable to climate change due to the direct impacts to infrastructure and indirect impacts to service delivery. These impacts may be compounded by potential supply chain disruption and the reduced availability of health service staff during severe weather events due to disrupted access routes and the need for staff to manage risks to their own health, family and property.

The assessment proposed a range of potential adaptation options for infrastructure and service delivery. This will inform the department's work to build resilience across the Victorian public health sector.

Understanding the vulnerability of school infrastructure and assets to severe weather to inform management strategies

Background

The Department of Education studied the risks of extreme weather events to the education system. The study specifically looked at the risks of climate hazards to school infrastructure based on geographical region and identified initial mitigation and adaptation considerations to reduce these risks for each established zone.

Climate risk assessment and school assessment management

The department's Climate Risk Assessment and School Asset Management (CRASAM) study applied the 2019 Victorian Climate Projections to inform a risk assessment for 7 shocks or stressors that pose a high or extreme risk to Victorian school infrastructure. These included an increase in temperature, drought, bushfire, storms, intense rainfall, sea-level rise and civil infrastructure failure. The projections were selected based on regional specificity, consideration of seasonal patterns, and their ability to replicate historical climate data. Risk assessments were completed for 2030 (short term), 2050 (medium-term) and 2070 (long-term) time horizons, given the long-term design life of school assets. The assessment adopted the RCP8.5 emissions scenario to account for the potential worst-case consequences of continued high emissions trajectories.

Science informing risk management and resilience

The CRASAM study has allowed the department to develop a better understanding of climate risk across the portfolio, informing the department's work to build climate resilience across the asset base.

Uncertainty should be acknowledged, accepted and used to support action on climate change.

While there is a range of projections indicating that Victoria's climate will change, it is not possible to determine the exact impacts of climate change at any location or time with certainty. Effectively considering climate impacts requires taking into account the precautionary principle and factoring in uncertainty, which can arise from (but is not limited to) the following.

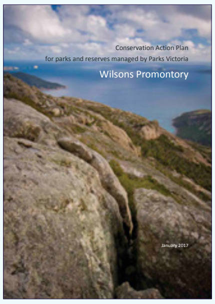
- **Uncertainty associated with the probabilistic nature of climate drivers**
  The climate is influenced by factors that fluctuate and vary without human influences. While climate scientists can observe and forecast general trends in how these climate drivers are changing, there will always be a degree of natural variability. The dominating effect of a single climate driver (e.g. the multi-year La Niña from 2020–2023) and the combined influence of climate drivers, such as El Niño and the positive IOD, can create contrasting seasonal weather conditions. Increasing temperatures will further affect variables such as extreme and cool season rainfall (Australian Research Council [ARC] Centre of Excellence for Climate Extremes, 2023). Given the changing likelihood of conditions associated with climate drivers, planning for a range of scenarios can improve preparedness and response to future climate conditions.
- **Uncertainty associated with climate models**
  No one climate model can perfectly simulate the entire global climate system. While models continue to improve, they remain representations. Each model will generate slightly different projections based on different input assumptions. Before applying model outputs in decision-making, it is important to evaluate a climate model's strengths and weaknesses and understand the confidence ratings associated with climate projections. While climate projections draw on the best available science, uncertainty in projections is inherent due to natural climate variability, the probabilistic nature of emissions scenarios, and confidence in climate models.
- **Uncertainty about global climate action**
  We cannot accurately determine future global emissions, as we do not yet know how the world will implement mitigation policies, strategies and technologies. Different emissions scenarios are representative pathways of how the future may evolve and influence the climate system; the scenarios can only provide a plausible range of future climates.

Some adaptation strategies will be less effective than others, especially as our understanding of system responses to climate risks improves. Some strategies may unintentionally increase vulnerability and exposure to climate risks (known as maladaptation). However, clear thresholds for contingency planning and integration of regular review cycles for decisions or strategies (that consider the latest science) can strengthen climate resilience.

Considering climate change impacts across a range of plausible futures is an effective way to understand exposure and to test potential actions to build resilience. Where possible, decision-makers should allow for flexibility and evolution in their planning as we learn more about the changing climate.

Parks Victoria improves the climate readiness of Conservation Action Plans

Background



At Parks Victoria, Conservation Action Plans (CAPs) provide a basis for strategic landscape-scale conservation planning. Plans have been developed or are in development for 18 planning areas covering Victoria's terrestrial and marine parks and reserves. Parks Victoria has developed an approach to climate change scenario planning to enhance the coverage of climate adaptation actions in CAPs.

Scenario planning is a method that is increasingly employed to incorporate future climate uncertainty into climate adaptation planning. Typically, it involves the identification of multiple plausible climate futures, which are used to generate divergent future narratives. These capture the uncertainty around future climate impacts and can inform strategic planning, decision-making and engagement.

Climate science

Parks Victoria's approach to scenario planning draws strongly on the projections provided by Victoria's Future Climate Tool, an interactive spatial tool which provides detailed climate projections for Victoria from global climate models using both moderate and high emissions scenarios. The approach has been developed to support the CAP program at Parks Victoria, and to address some of the challenges which commonly limit the development and uptake of scenario planning.

One of the cornerstones of Parks Victoria's approach is the use of machine-learning methods to quantify the similarity between the full set of available climate models across both emissions scenarios and more than 20 climate variables. This permits the selection of a manageable subset of highly divergent climate model-emissions scenario combinations. These serve as the basis for climate futures in the scenario planning process in a more objective and reproducible way than other methods.

Other key elements used by Parks Victoria include a:

- structured and systematic approach to elicit expert knowledge (through workshops) to build scenario narratives that assist with engagement and understanding of vulnerability
- process of stress-testing goals and actions to foster the translation of narratives into climate-smart strategies. Planning has been based on projected changes in climate to 2050, which aligns well with the 15-year outlook for Parks Victoria's CAPs.

Science informing climate-ready actions and adaptation improvements

This implementation of scenario planning integrates with well-established CAP processes and has helped Parks Victoria to identify, for several key landscapes, climate-ready goals, low-regret actions, and instances where current adaptation options may not be sufficient or feasible to mitigate climate impacts. More broadly, the work underscores the benefits that can be achieved by using approaches such as scenario planning to facilitate data-driven decision-making in the management of protected areas.

Abbreviations

Abbreviation	Definition
CAP	Conservation Action Plans
CMA	Catchment Management Authority
CMIP5	Coupled Model Intercomparison Project phase 5
CMIP6	Coupled Model Intercomparison Project phase 6
CORDEX	Coordinated Regional Climate Downscaling Experiment
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEEW	Department of Climate Change, Energy, the Environment and Water (Australian Government)
DEECA	Department of Energy, Environment and Climate Action
DELWP	Department of Environment, Land, Water and Planning
EHF	Excess Heat Factor
ENSO	El Niño–Southern Oscillation
FFDI	Forest Fire Danger Index
GCM	Global climate model
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
MCAP	Mediterranean Climate Action Partnership
MJO	Madden-Julian Oscillation
NARCliM2.0	New South Wales and Australian Climate Modelling 2.0 project
RCM	Regional climate model
RCP	Representative Concentration Pathway
SAM	Southern Annular Mode
SNA	Specific needs assessments
SSPs	Shared Socio-economic Pathways
VCSR19	Victorian Climate Science Report 2019
VCSR24	Victorian Climate Science Report 2024
VicWaCI	Victorian Water and Climate Initiative

Glossary

Term	Definition
Adaptation	Changes made to natural or human systems to prepare for actual or expected changes in the climate in order to minimise harm, act on opportunities or cope with the consequences.
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen and oxygen with a number of trace gases (e.g. argon, helium) and greenhouse gases (e.g. carbon dioxide, methane, nitrous oxide). The atmosphere also contains aerosols and clouds.
Bushfire	A bushfire is an unplanned vegetation fire, including grass fires, forest fires and scrub fires. The time of peak bushfire activity varies across the country according to changes in seasonal weather patterns.

Term	Definition
Carbon dioxide	A naturally occurring gas, also a by-product of human actions such as burning fossil fuels or land-use changes. It is the main human-generated greenhouse gas that affects the Earth's atmosphere.
Climate	The average weather experienced at a site or region over a period of at least 30 years.
Climate change	Changes in the state of the climate, including an increase in the occurrence of extreme weather events, long-term changes in weather patterns and sea-level rise, attributed directly or indirectly to human activity. Distinct from climate variability as the changes persist for an extended time, typically decades or longer.
Climate driver	Used in this report to describe the large-scale ocean and atmospheric processes and circulations that influence climate at seasonal to decadal timescales. These drivers can act alone, combine or contradict each other, influencing variability in the climate, particularly rainfall.
Climate hazard	A natural or human-caused event or condition that may cause damage and loss.
Climate projection	The modelled response of the climate system to a scenario of future concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are based on a specific emissions scenario.
Climate signal	Long-term trends or changes in the climate system due to human-caused greenhouse gas emissions.
Coupled Model Intercomparison Project (CMIP)	A multiple-phase project that coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. Models from Phase 6 (CMIP6) fed into the IPCC's Sixth Assessment Report and have been used to produce the climate projections in this report.
Cool season	The Victorian cool season occurs from April to October.
Confidence	The validity of a finding based on how well the physical climate processes are understood and represented in climate models, and the level of agreement between results from different models.
CO_2-eq	CO_2 equivalent, a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential, by converting amounts of other gases to the equivalent amount of warming potential of carbon dioxide.
CO_2 fertilisation	An increase in plant photosynthesis caused by rising levels of carbon dioxide in the atmosphere.
Decile	One of a series of threshold values that divides a set of ordered data into 10 groups with an equal number of data points in each.
Downscaling	A method that produces local to regional-scale climate information from larger-scale models or data analyses. Downscaling methods include dynamical, statistical and empirical.
Drought	A prolonged, abnormally dry period when the amount of available water is insufficient to meet normal use.
East coast low	Intense low-pressure system that occurs off the east coast of Australia, bringing storms, high waves and heavy rain. Generally occurs in autumn and winter off New South Wales, southern Queensland and eastern Victoria.
El Niño–Southern Oscillation (ENSO)	Year-to-year fluctuations in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (the warming of the oceans in the equatorial eastern and central Pacific) and its opposite, La Niña. Over much of Australia, La Niña brings above average rainfall, and El Niño brings below-average rainfall.
Emissions scenario	A plausible representation of the future development of greenhouse gas emissions (such as Shared Socio-economic Pathways [SSPs]) based on a set of assumptions about factors such as demographic and socio-economic development, and technological change.
Evapotranspiration	The processes that move water from the Earth's surface into the atmosphere. It includes both water evaporation and transpiration (water movement through a plant and its evaporation from leaves, stems and flowers).

Term	Definition
Extreme weather	A weather event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally occur less than 10% of the time. Throughout the report, the term 'extreme' is used in multiple differing contexts, including to describe: • temperature; whereby a hot day is defined as within the 99th percentile maximum daily temperature, and a very hot day is defined as within the 99.9th percentile maximum daily temperature • rainfall; with multiple types of intense rainfall considered extreme depending on the timescale (i.e. sub-hourly, sub-daily and multi-day) • flooding; a flood that is likely to cause major rivers to overtop their banks, with an annual likelihood of 1-in-20 to 1-in-100, and rarer.
Fire weather	Weather conditions conducive to wildfires starting and continuing, usually based on a set of factors including temperature, soil moisture, humidity and wind. Fire weather does not measure the presence or absence of fuel load.
Floods	An overflow of water beyond the normal limits of a watercourse. Flooding occurs when water extends over what is usually dry land.
Forcing	Disruption to the Earth's energy balance, which can come from either natural or human activities.
Forest Fire Danger Index (FFDI)	Provides a measure of the potential danger of a bushfire on a given day and location. The index combines a measure of vegetation dryness with air temperature, wind speed and humidity.
Fuel load	The total amount of combustible material in a defined space. Bushfire fuels include living and dead vegetation that influence the speed and intensity of a fire.
Glacial Isostatic Adjustment (GIA)	The ongoing changes in gravity, rotation and viscoelastic solid Earth deformation (GRD) in response to past changes in the distribution of ice and water on the Earth's surface. On a time scale of decades to tens of millennia following mass redistribution, Earth's mantle flows viscously as it evolves towards isostatic equilibrium, causing solid Earth movement and geoid changes, which can result in regional-to-local sea level variations.
Global climate model	A numerical representation of the global climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes. Grid squares in global climate models usually range between 100 km to 200 km.
Global warming	The gradual increase, observed or projected, in global surface temperature.
Global warming levels	An emerging projections framework that describes the expected change that will be experienced at a specific location (such as Australia) when the world reaches particular levels of global warming since the pre-industrial era.
Greenhouse effect	A natural process whereby gases in Earth's atmosphere trap the sun's heat, helping to maintain a warmer temperature on Earth than would otherwise be possible.
Greenhouse gas	Gas that traps heat in the atmosphere and warms the planet. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere.
Heatwave	A period of abnormally hot weather that can last for at least a few days in a row, where the maximum and minimum temperatures are unusually high for a location based on local climate conditions.
High-pressure system	Area of higher pressure, generally associated with lighter winds and fine and settled conditions.
Indian Ocean Dipole (IOD)	A measure of the difference in sea surface temperature in the western and eastern equatorial Indian Ocean. When positive, there is cooler than normal water in the tropical eastern Indian Ocean and warmer than normal water in the tropical western Indian Ocean.
Intergovernmental Panel on Climate Change (IPCC)	An organisation established in 1988 by the World Meteorological Organization and the United Nations Environment Programme.
Likelihood	The chance of a specific outcome occurring, where this might be estimated probabilistically.
Low-pressure system	Area of lower pressure, generally associated with stronger winds, unsettled conditions, cloudiness and rainfall.

Term	Definition
Madden–Julian Oscillation (MJO)	The major fluctuation in tropical weather on weekly to monthly timescales, characterised as an eastward-moving 'pulse' of cloud and rainfall near the equator that typically recurs every 30 to 60 days.
Marine Ice Cliff Instability (MICI)	Hydrofracturing of ice shelves where successive melting and freezing of meltwater in crevasses at the seaward edges of ice cliffs initiates cliff collapse into the ocean.
Marine Ice Sheet Instability (MISI)	The rapid disintegration of the ice sheet when advection of warm water below the ice sheet occurs on bedrock sloping downwards from the coast to the continental interior. This potentially unstable configuration particularly applies to Antarctica.
Model ensemble	In the context of this report, a model ensemble is a collection of climate model outputs grouped in some way. For example, the ensemble of CMIP6 global climate models, or the ensemble from particular downscaling models.
Palaeoclimate	Indirect measurements of climate consisting of geologic (e.g. sediment cores) and biologic (e.g. tree rings) materials that preserve evidence of past changes in climate. Palaeoclimate research provides the opportunity to look at changes in climate beyond the timeline of instrumental records.
Percentile	A value on a scale of 100 that indicates the percentage of the data set values that is equal to, or below it. For example, the 90th (or 10th) percentile may be used to refer to the threshold for the upper (or lower) extremes.
Pre-industrial	Prior to the industrial revolution (i.e. pre-1750), when human activities such as the burning of fossil fuels increased the concentration of greenhouse gases in the atmosphere. Consistent with the IPCC, this report uses 1850–1900 as the pre-industrial baseline, as it is the earliest period with near-global temperature observations.
Regional climate model	A climate model used to generate higher-resolution results from a global climate model. Like a global climate model, a regional climate model is a numerical representation of the climate system that is based on the physical, chemical and biological properties of its components, their interactions and feedback processes, producing results at a regional or local scale.
Representative Concentration Pathway (RCP)	An emissions scenario that includes concentrations of the full suite of greenhouse gases and land-use over time. These are used as inputs to climate models.
Risk	The potential for consequences where something of value is at stake and where the outcome is uncertain. Risk is often represented as a probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur.
Sea-level rise	An increase in the average height of the ocean. Relative sea-level rise occurs where there is a local increase in the level of the ocean relative to land, which could be due to an increase in the volume of the ocean, or land level subsidence.
Socio-economic Pathways (SSPs)	Scenarios used to explore the consequences of greenhouse gases accumulating in the atmosphere. Each SSP outlines ways the world may change in future, including different types of energy generation, rates of population growth, economic development and land-uses. These lead to different levels of greenhouse gas emissions over time.
Southern Annular Mode (SAM)	Describes the north–south movement of the westerly wind belt that circles Antarctica. The changing position of the westerly wind belt influences the strength and position of cold fronts and mid-latitude storm systems, and is an important driver of rainfall variability in southern Australia.
Sub-tropical ridge	A belt of high-pressure that encircles the globe in the middle latitudes. It is part of the global circulation of the atmosphere. The position of the sub-tropical ridge plays an important part in the way the weather in Australia varies from season to season.
Surface Mass Balance (SMB)	The contribution to sea-level rise or fall that arises due to the sum of ice sheet accumulation through precipitation and ablation (loss of ice and snow) through melting and evaporation
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can be represented by qualitative statements (e.g. reflecting the judgment of a team of experts).
Warm season	The Victorian warm season occurs from November to March.

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