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Victorian Climate Projections 2024

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Disclaimer

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Executive summary

This report presents the Victorian Climate Projections 2024, featuring the latest global and regional climate modelling simulations which describe how the climate of Victoria may respond to global warming. Future climate change is explored under different scenarios of human greenhouse gas emissions. This work was commissioned by the Victorian Department of Energy, Environment and Climate Action (DEECA) to supplement previous projections of climate change for Victoria. The chapters of this report provide context for interpreting the latest climate projections, details on the data and methods used to create the new projections, and results of future projected change for a number of climate variables and hazards. Victoria's Climate Science Report 2024 (DEECA, 2024) draws on the information presented here and provides a concise summary of the past and future state of the climate for Victoria, as well as further detail on selected climate hazards.

Climate change projections, including those presented in this report, are underpinned by data from climate models that simulate climate processes on powerful supercomputers. An important consideration when developing regional projections is to avoid basing the projections on a single modelling system or an individual line of evidence. The projections presented in this report use a best practice approach which draws on multiple lines of evidence, including the latest Global Climate Model (GCM) simulations contributed to the international Coupled Model Intercomparison Project Phase 6 (CMIP6) project, as well as more detailed modelling from four different regional downscaling programs. This more detailed modelling consists of new nation-wide climate modelling undertaken as part of the Australian Climate Service (ACS) and the Coordinated Regional Climate Downscaling Experiment (CORDEX) Australasia project, simulating weather and climate on scales of 10–20km. It also consists of even more detailed, ~4km resolution simulations for southeast Australia run by the Government of New South Wales as part of the New South Wales and Australian Regional Climate Modelling 2.0 (NARCliM2.0) project which simulate weather and climate on a ~4km scale.

The new climate modelling shows incremental improvements over previous generations, and adds new detail and nuance to projections messages, and does not contradict or overrule most of the key messages from previous climate projections for Victoria. This report highlights emerging results from the downscaling simulations. Research assessing the dominant physical drivers behind the projected changes, and the plausibility of future climate conditions simulated by the downscaling models (as opposed to evaluation of the simulation of the current climate) is an ongoing process and not presented in full in this report. Further work would facilitate the translation of the results presented in this report into representative climate futures that are useful for climate change risk assessments. This includes work by the climate science community to better understand and assign levels of confidence to results from the new modelling and the generation of 'bias corrected' or 'application-ready' climate data for downstream impacts analysis. This work would enable better integration of the projections with information from beyond the climate science community on the exposure and vulnerability of the systems being assessed.

The main findings of the projections are summarised below:

- It is a *fact* that Victoria's climate has warmed, and *virtually certain* that it will continue to warm, with the amount of warming strongly dependant on future greenhouse gas emissions. Under a scenario where the world meets the Paris Agreement, Victoria is projected to warm by around 1 °C relative to 1986-2005 and stabilise this century. However, under a scenario of ongoing high greenhouse gas emissions, warming is projected to continue steadily throughout the century by around 3 °C or more.

- Warming temperatures will bring more hot days and hot nights, increases in heatwave duration, frequency and intensity and temperature extremes beyond those experienced in the past.
- It is certain that rainfall will change in Victoria as the climate system warms. These changes include changes to average rainfall, changes to seasonal rainfall patterns and increases in heavy rainfall. It is highly likely that we will see increases in rainfall variability across extreme dry periods and extreme wet periods at various timescales, including day-to-day variability and possibly including interannual variability. The precise nature of these changes in rainfall is difficult to model, with a range of future rainfall states plausible.
- Cool season rainfall in Victoria has declined in recent decades, but with large annual to decadal variability. Cool season rainfall is projected to continue declining with ongoing large variability (*medium to high confidence*). However, the possibility of little change or an increase in rainfall driven by increased annual variability can't be ruled out.
- Summer rainfall change is less certain and new climate modelling doesn't narrow our outlook, with both decreases or increase in total summer rainfall possible. It is *likely* that summer rainfall will increase in both variability and extremes, regardless of the change in the average.
- Changes to the variability and extremes of rainfall can be at least as impactful as changes in average rainfall. More extreme rainfall, especially short duration extreme rainfall events, and longer dry periods between rain events are projected (*high confidence*).
- Managing water risk for Victoria should consider climate scenario storylines appropriate for managing risks, in terms of rainfall (as presented here) and also broader water availability (not part of this study). For rainfall, such storylines could include a severely drier climate to a wetter and much more variable climate.
- Along with the projected changes described here, there are numerous other relevant factors to consider when planning for the future, including:
    - The downstream effects of the changes on the biophysical environment, including to soil moisture and runoff, agricultural growing conditions, and so on.
    - Changes to the coastal and marine environment, including ongoing committed sea level rise, and an increase in marine heatwaves.
    - Changes to compound and coincidence climate events (e.g., storms associated with both damaging winds and heavy rainfall), as well as consecutive events (e.g., droughts followed by extreme fire danger weather).
    - The exposure and vulnerability of natural and socioeconomic systems to climate changes, including the potential for cascading impacts within and between systems.

The updated climate projections for Victoria described in this report can be used with other information to support planning and policy decisions made by the Victorian Government and broader community. In particular, results from the projections can inform risk assessments if they are combined with appropriate knowledge of climate exposure, vulnerability and adaptive capacity. Such assessments should also be informed by knowledge of Victoria's vulnerabilities to the impacts of climate change elsewhere through, for example, impacts on national transport and energy infrastructure, supply chains, trade and migration.

While the VCP24 projections describe a range of possible future changes in Victoria's climate, the projections do not represent all possibilities. Global tipping points are abrupt and irreversible changes to the global climate triggered by global warming. They are not included in the VCP24 modelling but may have important impacts on Victoria. Limitations of climate models mean than not all climate hazards are confidently modelled in VCP24. These include storms, megadroughts and compound events, where multiple hazards occur together. Decision-makers should use a risk management approach that considers high-impact, low likelihood risks to account for tipping points and unmodelled hazards.

Summary of future projections

This report considers future projections under two scenarios (Shared Socioeconomic Pathways, SSPs) for future global greenhouse gas emissions that 'bracket' or 'bookend' a plausible range of change (but exclude extreme outlier emissions scenarios):

- 'SSP1-2.6', a low emissions scenario, under which global emissions are cut and reach net zero around 2075, with global average temperature stabilising at about 1.8 °C above pre-industrial levels by 2100 (roughly compliant with the goals of the 2015 Paris Agreement).
- 'SSP3-7.0', a high emissions scenario, under which annual global emissions continue to rise to roughly double present levels by 2100, and global average temperature reaches about 3.6 °C above pre-industrial levels by 2100.

Temperature: Victoria has warmed by approximately 1.4 °C between the pre-industrial (1850-1900) period and the recent decade 2011-2020. The last three years (2021-2023) were cooler relative to the preceding decade but were still well above the long-term average. Temperatures are expected to increase until at least the middle of the century, although natural variability means that warming will vary year-to-year. The rate and magnitude of warming beyond the near-term will depend on the future trajectory of global greenhouse gas emissions. Under a low emissions scenario, the CMIP6 global modelling suggests that the average temperature of Victoria will likely continue to rise until around 2050 and will then likely remain between 1.4 °C and 2.6 °C warmer than the pre-industrial period to the end of the century. Under a high emissions scenario, warming will continue throughout the century, reaching between 3.0 °C and 4.6 °C above pre-industrial temperatures by 2090. Some climate model simulations produce more extreme warming values of over 5.7 °C by 2090. These simulations are considered to be *low-likelihood* but cannot be ruled out and provide a useful 'high impact' scenario for managing risks related to temperature. Warming over Victoria is expected to be roughly in-line with the whole global average warming or slightly higher (but lower than the global land average).

Heat extremes: Consistent with previous studies of projected regional climate change, heat extremes are projected to become more frequent and severe as the century progresses, especially under the high emissions scenario. This means more frequent hot days and heat extremes which are hotter than Victoria has experienced before. Heatwaves are projected to become longer and more frequent, and a larger proportion of the year could be subjected to summer-like heatwaves.

Rainfall: Victoria's average rainfall has been decreasing over the past half century, with this decline most apparent in autumn, winter and spring and not in summer. There is notable evidence that this decline was at least partly driven by human caused climate change. All past and future trends in rainfall are overlaid by a great deal of natural rainfall variability. The future projections indicate that Victoria will *likely* continue to become drier overall and in spring and winter, with all model ensembles in relative agreement on this. Most climate model ensembles also project decreasing rainfall in autumn, although the range of uncertainty is larger. Even if there is an overall long-term drying, periods of higher average rainfall lasting years to decades are plausible due to interannual to multi-decadal variability obscuring the climate change trend. There is large uncertainty around the future direction of summer rainfall changes with the evidence less clear than for the cool season. The modelling shows significant differences between different climate models, with little change, significant reduction and significant increase in summer rainfall all being plausible.

Rainfall extremes: On top of changes to average rainfall, rainfall extremes are also changing. Dry periods are projected to be drier and hotter, while short-duration extreme rainfall events are projected to become more intense. Multiple lines of evidence suggest that short heavy rainfall events (scale of hours to days) will become more intense in the future. Most of the new downscaled simulations indicate that very heavy rainfall days are likely to get heavier, especially for the most extreme measure of daily rainfall examined (the 99.9th percentile daily rainfall, which occurs on average 3 to 4 times per decade). However, there is a great deal of variation between different model simulations, highlighting the importance of multiple lines of evidence. For example, some of the high resolution NARCliM2.0 simulations show significant decreases in extreme rainfall intensity in the future, a result which is not well understood and at odds with other lines of evidence showing increasing extreme rainfall. Further research would be needed to understand and assign confidence to this result. Decision-makers should consider multiple lines of evidence when planning for changes in extreme rainfall and consult the updated Australian Rainfall and Runoff (AR&R) guidelines. Further research on extreme rainfall, including extreme multi-day rainfall accumulations relevant to flood impacts, is recommended.

1 Introduction

This chapter provides a background to the project, including the motivation behind creating this new set of Victorian Climate Projections (VCP24), a general update on the state of the climate globally and in Australia and some context for understanding climate modelling and the new climate projections information.

The Victorian Department of Energy, Environment and Climate Action (DEECA) commissioned the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to undertake a climate projections analysis for the state in 2024, based on climate modelling available as of February 2024. The primary purpose of this Technical Report is to inform the development of Victoria's Climate Science Report (VCSR) 2024[1]. The VCSR is a statutory requirement under the Victorian *Climate Change Act 2017* that aims to provide a summary of the best available climate change science and its implications for the state. The VCSR is required to be updated every 5 years, with the previous iteration being released in 2019 (DELWP, 2019), informed by VCP19.

This work provides a valuable opportunity to update the previous Victorian Climate Projections, released in 2019 (VCP19) (Clarke, et al., 2019)[2]. Since then, a new set of global climate modelling has been released – Coupled Model Intercomparison Project Phase 6 (CMIP6) (O'Neill, et al., 2016), the models used to inform the most recent Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021). There is strong demand from users of climate projections information for updated projections based on CMIP6, although it is also worth noting that the release of new climate modelling and projections does not invalidate or replace previous projections.

As the climate science community's understanding of past and future climate is continually improving, the analyses reported here draws on the latest CMIP6 global and regional climate modelling as well as previous projections, including those from the VCP19. Since no single climate model can be perfect, the analyses use a best-practice multi-ensemble climate projections approach, in line with the IPCC and the National Partnership for Climate Projections (NPCP) (DCCEEW, 2023). This is supported by a wealth of new climate model data covering Victoria that has been generated since the analysis undertaken for VCP19. More detail about the climate modelling approach used is provided in Section 1.2 and methods in Section 2.2.

There are some key differences between the VCP24 projections presented in this report and the projections analysis completed for Victoria in 2019 (VCP19). The VCP19 projections analysis drew on the previous set of global climate modelling undertaken for the Coupled Model Comparison Phase 5 (CMIP5) and included 5km resolution modelling using CSIRO's Cubic Conformal Atmospheric Model (CCAM) (McGregor & Dix, 2008) for Victoria. There was more in-depth analysis in VCP19 and in some sections of this report, we draw on information from VCP19 supplemented with the latest scientific literature. A more detailed comparison of VCP19 and VCP24 is provided in Section 5.1.

[1] https://www.climatechange.vic.gov.au/victorias-changing-climate/Victorias-Climate-Science-Report-2024.pdf

[2] https://www.climatechange.vic.gov.au/victorias-changing-climate/Vic-Climate-Projections-2019-Technical-Report_1.pdf

1.1 The changing climate

1.1.1 Why climate change is important to Victoria

Like the rest of Australia, Victoria has already experienced increasing temperatures, shifting rainfall patterns and rising oceans. These changes, and the potential effects of future climate change, are presenting significant challenges to individuals, communities, governments, businesses, and the environment.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that the socioeconomic costs of climate variability and climate change have already increased in Australia due to climate trends and extreme events combining with exposure and vulnerabilities in human and natural systems. Climate risks are projected to continue to increase in the future for a wide range of systems, sectors and communities. In its Sixth Assessment Report (Lawrence, et al., 2022), the IPCC identified the following climate risks that are relevant to Victoria:

- Loss of alpine biodiversity due to less snow
- Transition or collapse of some forest ecosystems due to hotter and drier conditions with more fires
- Loss of kelp forests due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins
- Loss of natural and human systems in low-lying coastal areas due to sea level rise
- Disruption and decline in agricultural production and increased stress in rural communities due to hotter and drier conditions
- Increase in heat-related mortality and morbidity for people and wildlife due to heatwaves
- Compound events involving cascading, and aggregate impacts on cities, settlements, infrastructure, supply chains and services due to wildfires, floods, droughts, heatwaves, storms and sea level rise
- Inability of institutions and governance systems to manage climate risks

More recently, Australia’s National Climate Risk Assessment has identified 11 priority climate risks, all of which are relevant to Victoria (DCCEEW, 2024):

- Risks to domestic disaster response and recovery assistance from the competing need to respond to multiple natural hazard events as well as national security contingencies, resulting in concurrency pressures and overwhelming the Government’s capacity to respond effectively
- Risks to health and wellbeing from both slow onset and extreme climate impacts
- Risks to critical infrastructure that impact access to essential services
- Risks to aquatic and terrestrial ecosystem condition and function or landscape function and collapse, including through species loss and extinction
- Risks to primary industries that decrease productivity, quality and profitability and increase biosecurity pressures
- Risks to regional, remote and First Nations communities that are supported by natural environments and ecosystem services
- Risks to communities from legacy-and-future planning and decision-making that increases the vulnerability of settlements

- Risks to the real economy from acute and chronic climate change impacts, including from climate-related financial system shocks or volatility
- Risk to adaptation from maladaptation and inaction from governance structures not fit to address changing climate risks
- Risks to supply and service chains from climate change impacts that disrupt goods, services, labour, capital and trade
- Risks to water security that underpin community resilience, natural environments, water-dependant industries and cultural heritage

1.1.2 How has the climate changed

The IPCC assesses the current and future state of the climate system and reported its most recent findings in the Sixth Assessment Report (IPCC, 2021). The report concluded that 'it is unequivocal that human influence has warmed the atmosphere, ocean and land' causing 'widespread and rapid changes occurring in the atmosphere, ocean, cryosphere and biosphere'.

Global surface temperatures have increased particularly strongly over the course of the 20th century, especially since the 1980s. The previous 10-year average (2014-2023) was the warmest on record globally, 1.2°C above the pre-industrial baseline (1850-1900) temperature, and the year 2023 was clearly the warmest year on record globally, at 1.45°C above the pre-industrial baseline (WMO, 2024) (Figure 1).

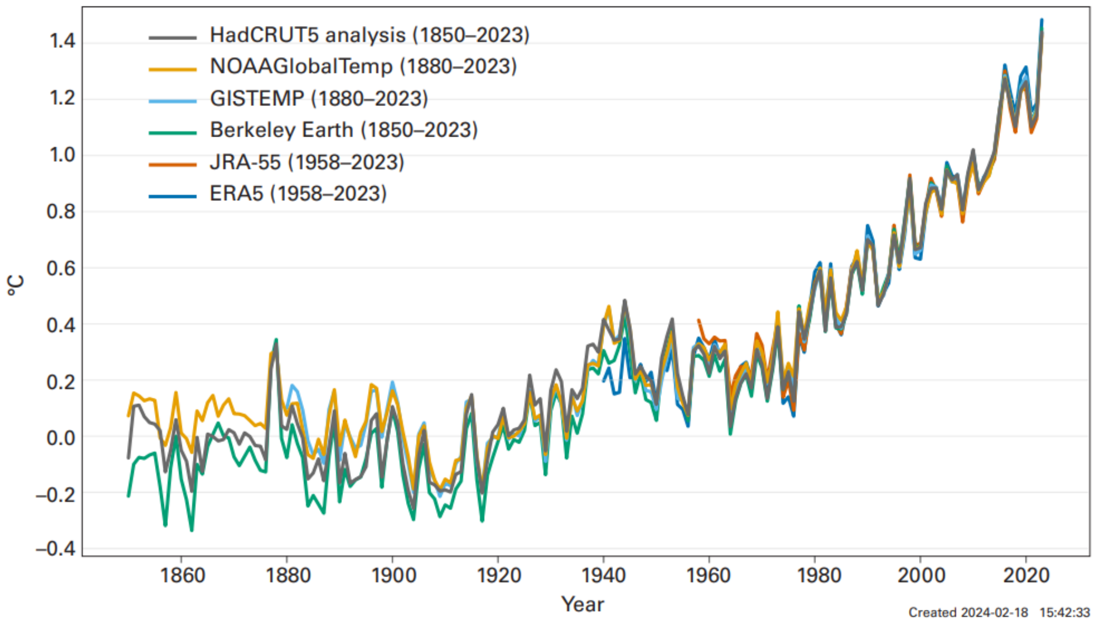

Figure 1 Annual observed global mean temperature anomalies from 1850 to 2023. Temperature anomalies are the temperature difference from the 1850–1900 pre-industrial baseline. Data are from six observational data sets as indicated in the legend (WMO, 2024)

Australia's average near-surface land temperature warmed by approximately 1.6 °C (± 0.3 °C) between the pre-industrial period and 2020 (Grose, et al., 2023). This is about 1.4 times the observed global average increase, but close to the increase in the global land surface alone – the ocean surface generally warms at a slower rate than land, meaning the global average is lower when the ocean surface is included. Between 1910 (when standardised national records began) and 2021, Australia's land surface warmed by about 1.47 °C (±0.24 °C) (CSIRO and Bureau of Meteorology, 2022).

As the globe and Australia have warmed, different aspects of Victoria's climate have been changing. For example:

Temperature: Victoria has been warming at a slightly lower rate than Australia as a whole, an estimated 1.4 °C (± 0.4 °C) from the pre-industrial 1850-1900 baseline to the recent decade 2011-2020 (Grose, et al., 2023). Temperature extremes and heatwaves have become more frequent and intense (Perkins-Kirkpatrick, 2020). Figure 2 shows observed warming over Victoria.

Rainfall: Victoria's average rainfall has been declining since 1961-1990 (CSIRO and Bureau of Meteorology, 2022), especially in the cool season (April to October). It has been particularly low in recent decades. Decreases in rainfall have been impacting streamflow in rivers. For example, major catchments in the southern Murray-Darling Basin have experienced declining average streamflow since the 1970s (CSIRO and Bureau of Meteorology, 2022). At the same time as average rainfall has been decreasing, heavy rainfall events have been becoming more intense (CSIRO and Bureau of Meteorology, 2022), especially during the warm season (October to March) (Osburn, et al., 2021).

Fire Weather: Fire seasons are becoming longer and more severe (Dowdy, 2018). There has been an increase in the frequency of extreme fire weather across most of Victoria since the 1950s (CSIRO and Bureau of Meteorology, 2022).

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

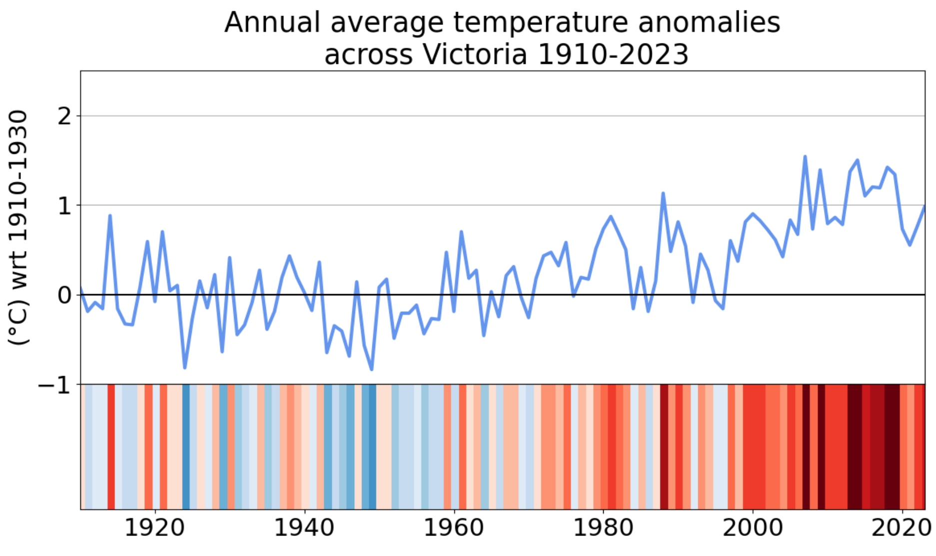

Figure 2 Annual observed Victorian mean temperature anomalies from 1910-2023, relative to the 1910-1930 average. The bottom panel shows 'climate stripes' for each year, with the colour of each stripe representing the temperature anomaly. Blue stripes represent cooler and red represents warmer than the 1961-1990 average, with the colour scale ranging from -1 °C to +1° C. Data source: ACORN-SAT v2, BOM

1.1.3 How will the climate change in the future

It is *virtually certain* that further global warming will continue for at least several decades into the future. If significant cuts in global greenhouse emissions are not made immediately, global average temperatures will exceed 1.5 °C above the pre-industrial baseline in the early 2030s could be breached by the end of this decade (Lamboll, et al., 2023). Current emissions reduction policies put the world on track for global warming by the end of the century of 2.5–3 °C (Rogelj, et al., 2023).

Victoria is expected to experience an overall warming trend associated with this continued global warming, although this could be interrupted by relatively cooler periods of several years due to natural climate variations. Further changes in rainfall and other aspects of the climate, such as climate extremes, are expected. For example, there will be more frequent heatwaves (CSIRO and Bureau of Meteorology, 2022).

Information about the potential scale of future warming in Victoria and other future changes in the climate can be obtained by developing 'climate projections'. A climate projection is the simulated response of the climate system to a scenario of future emissions or atmospheric concentrations of greenhouse gases and aerosols, generally derived using climate models, augmented by observations and established scientific understanding. In combination with information about what systems and assets are exposed to climate hazards, and how vulnerable they are, climate projections can be used to inform climate change impact and risk assessments. Climate projections for Victoria are the focus of this report.

1.2 Climate modelling

Projections of future climate conditions are generally underpinned by data from climate models. Global climate models (GCMs, also referred to as general circulation models) are our best source of information regarding how increasing greenhouse gas concentrations can affect the global climate of the Earth. These models are mathematical representations of the entire global climate system, including the atmosphere, oceans, sea ice and vegetation, run on powerful computers. By using prescribed scenarios of greenhouse gas emissions, it is possible to use GCMs to simulate the response of the climate system to changing greenhouse gas concentrations, for example to estimate how much the Earth could warm and how different Earth system components respond to this warming. More detail on emissions scenarios is provided in section 2.1.

Various research organisations around the world build, maintain and run GCMs. To coordinate this research and modelling activity, these organisations collaborate through the Coupled Model Intercomparison Project (CMIP) under the World Climate Research Program. This collaborative effort is currently in its sixth phase (referred to as CMIP6) (Eyring, et al., 2016).

The GCMs represent the global atmosphere, ocean and land surface on three-dimensional grids, with a typical grid cell resolution between 80km and 250km across. They can explicitly represent large-scale synoptic features of the atmosphere, such as the progression of high- and low-pressure systems. However, because of their coarse resolution, GCMs are not able to simulate changes in some types of extreme climate events, such as extreme rainfall or storms. They also do not contain highly detailed spatial information, for example detailed topography and coastlines, so may miss important regional processes relating to those features. Their low resolution can be a limitation when it comes to assessing extremes, for example short duration rainfall extremes, or informing assessments of climate change impacts and risks which require highly localised climate information.

A technique known as 'dynamical downscaling' is often employed to add detail to the output of a GCM, through the use of a regional climate model (RCM). Instead of using the available computer power to simulate the entire global climate at low-resolution, an RCM simulation focusses on just the region of interest at much higher resolution. Simulations at resolutions of 10 to 17 km covering Australia have recently been run. However, dynamical downscaling can achieve higher horizontal resolutions of less than ~5km for targeted areas, and simulations at this kind of resolution have also been run for parts of Australia. At the time of writing, the highest resolution climate simulations that cover the whole of Victoria are New South Wales and Australian Regional Climate Modelling 2.0 (NARCliM2.0) simulations covering southeast Australia at a resolution of ~4km. The increased spatial resolution of RCMs means they can represent local scale geographic features and physical processes at higher resolution, potentially adding value to the coarser GCM. This makes RCM simulations the preferred choice for producing information on climate extremes and hazards at local scales.

1.2.1 A best-practice, multi-model approach to climate projections

An important consideration when developing climate projections is to avoid basing the projections on one single model or modelling system. There is significant uncertainty in projecting future climate. Part of this uncertainty comes from the fact that the future evolution of global emissions is unknown and unknowable, as emissions depend on a myriad of decisions made around the globe now and in the future. However, even if the future evolution of greenhouse gas emissions was known, uncertainty about how the climate responds to emissions would remain. This uncertainty is addressed in part by using a range of different climate models.

Climate models are our best tools for exploring the future evolution of Earth's climate under varying greenhouse gas concentrations, but they will always be an approximation of the real world. Even though climate models are all based on the same fundamental physical principles, they differ in some of their approximations, assumptions and setup, and will simulate different outcomes for the same emissions scenario. No one model can be considered superior to all others or used in isolation. The climate is also inherently chaotic in nature, so that even though climate models are broadly very good at simulating earth's climate, they will never (and are not required to) simulate the exact future climate evolution at a particular future time point. Rather, they provide plausible responses of climate to changing greenhouse gas emissions over time.

Using different models helps address the uncertainty in simulating the climate response to scenarios of changing greenhouse gasses, and the level of agreement between different models and types of models (for example global models, regional models, models developed by different research institutes, models with different configurations) can be used to assess confidence in the results. For some climate variables, like average temperature, there is less uncertainty in the climate response and models are in strong agreement. For other climate variables, like rainfall, there is greater uncertainty, and this is reflected in less agreement between climate models. Using multiple models provides a better representation of uncertainties and variability, providing a more comprehensive understanding of potential future climate outcomes.

In this latest set of climate projections for Victoria, VCP24, a best-practice multi-ensemble climate projections approach is used, in line with the IPCC and National Partnership for Climate

Projections[3] and the vision outlined in the Climate Projections Roadmap for Australia (DCCEEW, 2023)[4]. VCP24 draws on all available CMIP6 global climate modelling as well as regional downscaling over Australia and Victoria from four different regional climate modelling centres. Different regional models have different characteristics and potential strengths, weaknesses and biases. Drawing on downscaling from multiple different modelling centres reduces the risk of not accounting for potential future outcomes.

The results presented in this report draw on CMIP6 data from:

- 34 CMIP6 Global Climate Models
- Highly detailed, 4 km resolution modelling from the NARCliM2.0 project. Five GCMs are downscaled by two different RCM configurations, providing 10 model configurations.
- Nation-wide, intermediate-resolution (10–17 km) modelling undertaken by CSIRO, the Government of Queensland and the Bureau of Meteorology in preparation for the Coordinated Regional Climate Downscaling Experiment (CORDEX) Australasia project and the Australian Climate Service. In total, 22 different model configurations (different combinations of GCMs and RCMs) are provided.

More details about the climate modelling datasets are provided in Section 2.2.

When developing regional climate projections, it is also important that multiple reputable lines of information and evidence are examined in addition to climate model output, for example, observations, trends and the latest scientific understanding of climate processes. This approach ensures that the different possible future climates simulated by climate models are considered and an appropriate level of confidence is assigned to different outcomes of global warming. Confidence assessment is further discussed in Section 3.1.

1.2.2 Existing projections products for Victoria

The most recent national climate projections for Australia were released in 2015 (CSIRO and Bureau of Meteorology, 2015) and can be accessed via Climate Change in Australia (CCiA)[5], a platform that provides access to climate summary information and projection data for all of Australia. The CCiA resources were developed by CSIRO and the Bureau of Meteorology and are broadly applicable across a wide range of sectors and applications. Most of the data is based on CMIP5 GCMs, although some CMIP6 high-resolution data is also being made newly available.

In parallel to CCiA, most states and territories have provided their own climate projections resources, designed with stakeholders within their own jurisdiction in mind. These typically use dynamical downscaling to provide more detailed climate modelling, but for a more limited area appropriate for their jurisdiction and with a subset of downscaled global climate models.

In Victoria, Victoria's previous climate science report (DELWP, 2019) has built on resources such as the VCP19 (Clarke, et al., 2019), as well as research from the Victorian Water and Climate Initiative[6] (DELWP, et al., 2020) and research from academic institutions. VCP19 developed a

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[3] https://www.dcceew.gov.au/climate-change/policy/climate-science/climate-science/climate-change-future

[4] https://www.dcceew.gov.au/climate-change/publications/climate-projections-roadmap-for-australia

[5] https://www.climatechangeinaustralia.gov.au/

[6] https://www.water.vic.gov.au/our-programs/climate-change-and-victorias-water-sector/hydrology-and-climate-science-research/victorian-water-and-climate-initiative

comprehensive set of 5km datasets for use in climate change impact and risk assessments. It featured a dynamically downscaled set of simulations based on the Conformal Cubic Atmospheric Model (CCAM) and drew on the full range of outputs from CCiA using CMIP5 GCMs and other climate modelling data sets. For the CCAM simulations, six CMIP5 GCMs were downscaled to 5km resolution over Victoria. These six GCMs were selected from the full set of CMIP5 GCMs on their ability to simulate the large-scale drivers of the Australian climate (e.g., the El Niño Southern Oscillation, monsoons, etc.) and the representation of the range of projected changes in climate simulated by the CMIP5 GCMs.

1.2.3 New projections for Victoria

This report forms the basis of updated climate projections to inform Victoria's Climate Science report 2024. There have been two major developments in Australian climate model projections since the previous report was published in 2019.

Firstly, the Australian climate projections community has started to use data from the CMIP6 GCMs that underpin the climate projections presented in the latest Sixth Assessment Report (AR6) from the IPCC (IPCC, 2021). CMIP6 provides more global simulations at a finer resolution than CMIP5 and includes models that incorporate the latest understanding of ocean and atmospheric processes (such as improved descriptions of cloud processes and biogeochemical cycles). The CMIP6 projections also have a longer simulation of the historical period, to 2014 rather than 2005, allowing projections into the future to be made from a more recent baseline (1995-2014) in addition to the 1986-2005 baseline used in CMIP5. CMIP6 also contains more models which provide multiple simulations (known as large ensemble simulations) which can be useful in separating the future climate change signal from natural variability (e.g. see 4.5.5 for analysis of large ensemble simulations representing the very dry end for projections).

Although the advent of CMIP6 does not make CMIP5 redundant, we have slightly more confidence in conclusions supported by CMIP6, especially where they reinforce conclusions drawn from CMIP5. Relative to the CMIP5 GCMs, the CMIP6 GCMs show incremental improvements in the simulation of the climate in the Australian region (Grose, et al., 2020). For example, they generally have a better simulation of some aspects of sea surface temperatures in the oceans around Australia and links between these and rainfall over Australia (Chung, et al., 2023). The representation of extreme heat events is also generally superior in the CMIP6 GCMs. Projections of Australian temperature and rainfall from the CMIP6 GCMs broadly agree with those from CMIP5, except for a group of CMIP6 GCMs with greater warming and increases in some extremes after 2050.

The other major development in Australian climate model projections since 2019 is the running of more comprehensive and nationally consistent and detailed dynamic downscaling simulations. Several Australian Commonwealth, State and Territory projections initiatives are dynamically downscaling the CMIP6 GCMs to produce fine resolution regional climate projections for Australia. This new modelling falls into two main categories:

- **Nation-wide intermediate-resolution modelling**

  Simulations with national coverage are being run at resolutions of 10–20km, coordinated through the National Partnership for Climate Projections and guided by the Climate Projections Roadmap for Australia (DCCEEW, 2023). These simulations contribute to the

CORDEX Australasia[7] project and are being utilised by the Australian Climate Service (ACS) to underpin a suite of national climate hazard products, covering tropical cyclones, heatwaves, fire weather, and heavy rainfall that leads to flooding. A subset of the CMIP6 GCMs to be used for downscaling was selected on the basis of model performance and diversity of simulations of the recent and future climate (Grose, et al., 2023) (Di Virgilio, et al., 2022). These GCMs are being downscaled by various organisations using a variety of downscaling models (RCMs). CSIRO and the Queensland Department of Environment and Science use various configurations of the CCAM model[8] (McGregor & Dix, 2008), the Bureau of Meteorology uses the Unified Model and the New South Wales Government's NARCliM2.0 project uses the Weather Research and Forecasting (WRF) model (Skamarock, et al., 2008). For more details about model data used in VCP24, see Section 2.2.2.

- **Regional fine-resolution modelling**

  Various initiatives are downscaling CMIP6 simulations to resolutions finer than 10km to provide additional detail in specific regions. These use a variety of geographic domains and spatial resolutions. Of particular relevance to this report is the NARCliM2.0 project. As well as running national ~18km CORDEX simulations, NARCliM2.0 has downscaled five CMIP6 GCMs with two slightly different versions of the WRF model. The two versions are identical except for a key part of the model that is important for simulating how the atmosphere interacts with the land surface (more detail in Section 2.2).

Research by the climate science community analysing both the NARCliM2.0 and nation-wide downscaled simulations is still underway. This report highlights emerging results from the downscaling simulations and notes where further research is needed to assign greater confidence to the conclusions drawn. More in-depth analysis of how well the different model simulations represent climate processes within the model would be beneficial. This further work would require analysis of additional climate variables and climate model simulations and is necessary to understand why a particular model gives a particular result, enabling strengthened assessments of how much confidence can be placed on a particular projection result.

[7] https://cordex.org/domains/region-9-australasia/

[8] https://research.csiro.au/ccam/

2 Methods

This chapter covers the frameworks for representing future climate change, including details of the future emissions scenarios used. It describes the methods behind the climate projections and the climate datasets used for the information presented in this report and associated datasets.

This report considers two scenarios (Shared Socioeconomic Pathways, SSPs) for future emissions that ‘bracket’ or ‘bookend’ a plausible range of change but exclude extreme outlier emissions scenarios. It also looks at projected changes in terms of ‘Global Warming Levels’. Both frameworks are useful and may meet different stakeholder needs, as outlined in Section 2.1.

2.1 Projections frameworks

Climate projections are views of future climate states relative to a historical climate, given scenarios or ‘pathways’ of driving factors, primarily different pathways of human emissions of greenhouse gases and aerosols as well as land use changes. Projections aren’t predictions of the sequence of future events but rather descriptions of how the climate could plausibly respond to future scenarios of these driving factors. As such, future projections can be presented using three different frameworks or ‘dimensions of integration’ (IPCC, 2021), each with advantages and drawbacks for particular purposes. They are outlined below and detailed further in Table 1:

1. **Emissions pathway and time horizon:** Projections of climate change from some historical baseline to a certain future time horizon (usually defined over 20-year period), under a particular emissions pathway, for example a low emissions (rapid reduction) or high emissions (fossil fuel intensive) pathway.
2. **Global Warming Levels:** Projections of local/regional climate change when the world reaches a particular level of globally averaged warming (not just local warming) from the pre-industrial temperatures (usually taken as 1850-1900). Commonly used global warming level (GWLs) are 1.5 °C, 2 °C, 3 °C above the pre-industrial temperatures.
3. **Cumulative CO2 emissions:** Projections of climate change when total cumulative emissions of CO_2 since the start of the industrial era (usually taken to be 1850-1900) reach a certain level. The total cumulative CO_2 emissions can be directly related to the level of global warming, therefore of regional climate change.

The most appropriate framework can be chosen for a given application or question, but general use projections can present projections with the option to select either emissions pathways or GWLs, as is done for the IPCC Interactive Atlas[9], and the Copernicus Projections portal[10]. Note also that the National Climate Risk Assessment (NCRA, currently underway in 2024) is prioritising GWLs, with the rule of thumb for timing presented here (Figure 3).

In this report the emissions pathways approach is primarily used (with a high and a low emissions pathway and a useful subset of time horizons), with the Global Warming Levels approach (for 1.5 °C, 2 °C and 3 °C GWLs) used for some results. The details on how the projections are constructed under each framework are in Section 2.1.3 and the emissions

[9] https://interactive-atlas.ipcc.ch/

[10] https://climate.copernicus.eu/climate-projections

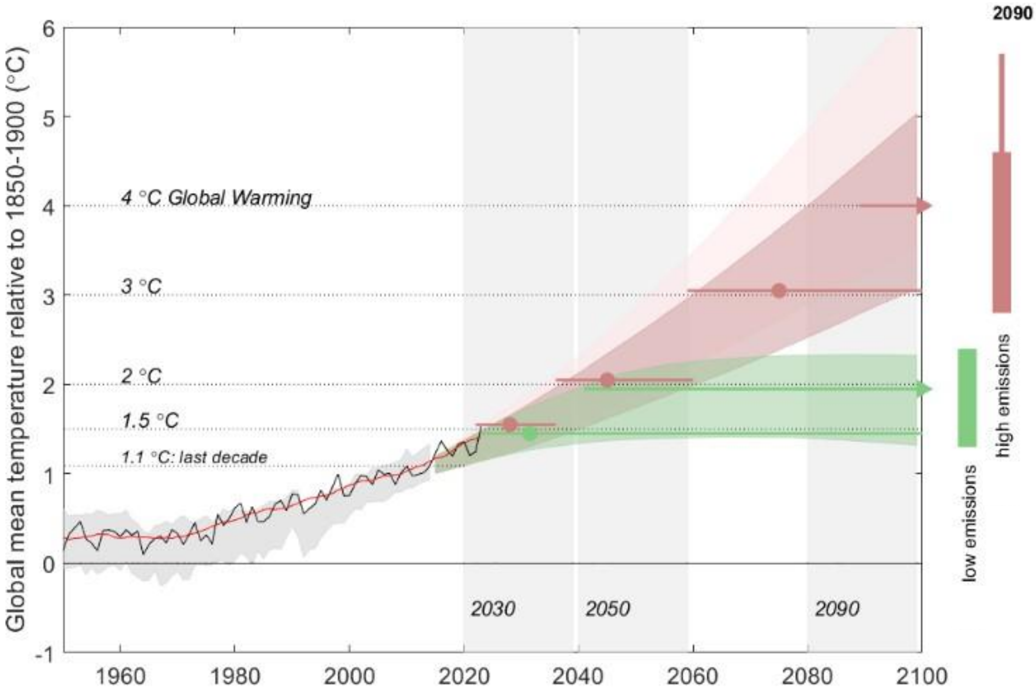
pathways are described by the Shared Socioeconomic Pathways (SSPs), outlined in more detail in Section 2.1.3.

Table 1 Details on the two frameworks (or 'dimensions of integration') for describing future climate change in this report, and the advantages, disadvantages and uses of each

1. Emissions pathway and time horizon	2. Global warming levels (GWLs)
Projections of climate change from some historical baseline to a certain future time horizon (e.g. 2050, 2090), under a particular emissions pathway (e.g. a low, medium or high emissions pathways). The current generation of scenarios is the Shared Socio-economic Pathways (SSPs).	Estimates of the climate state if/when the world reaches a certain level of warming relative to the pre-industrial climate (commonly 1850-1900). Typically reported values include 1.5 °C, 2 °C, 3 °C and sometimes 4 °C.
Advantages	Advantages
Gives narratives about the future world Visualises evolution through time, including diverging pathways in time – often using simple and intuitive 'low, medium and high' scenario. Can be related to future planning horizons Most commonly used and longstanding framework, presented since the earliest climate projections in the 1970s and 1980s. Used already for decision making and risk assessments in Victoria (e.g. Vic Future Climate tool).	Policy relevant (e.g., the Paris Agreement) Can relate to the level of increased impacts from climate change ('reasons for concern') Simple and intuitive, produces just a few future cases/contexts (e.g., no need to report different scenarios and timeframes). Can compare and integrate across different model ensembles and scenario sets on a common basis, and solves problems such as the CMIP6 'hot model' problem*
Disadvantages	Disadvantages
Scenario sets change with each generation of Climate Model Intercomparison Projects (CMIPs) therefore not easily comparable (e.g. CMIP5 used RCPs, CMIP6 uses SSPs). Creates a lot of future cases (e.g., 3 pathways x 4 time horizons = 12 combinations Issues when using model ensembles – independence, the 'hot model' problem* etc. May suggest we know the precise trajectory	Time dimension and emissions dimension not intrinsic and explicit – so less intuitively relatable to planning horizons and timing of emissions reduction (but these can be added on) No time evolution Not suitable for changes with a strong time dependence, including sea level rise
Best applications	Best applications
Understand the impact of emissions reductions on climate outcomes, by comparing different emissions scenarios Informing time bound pathways for adaptation options	Stress testing and planning to a particular magnitude of change, independent of when that change occurs (although timing of warming levels being reached can be estimated). Assessing specific impacts of achieving certain warming levels e.g. those outlined in the Paris Agreement.

** The CMIP6 'hot model' problem is where the CMIP6 global model ensemble has an over-representation of models with high climate sensitivity and high warming* (Hausfather, et al., 2022). *Details of how we deal with this problem are provided in Sections 2.1.3, 2.2.1 and 2.3.*

Although the GWL framework has been less widely used in past climate projections, it is rapidly gaining popularity for its policy-relevance and simplicity. It has long been recognised as a broad measure of the extra impacts from climate change we face (the 'reasons for concern' used in IPCC Assessment Reports of impacts and adaptation), including the rule of thumb that 2 °C of global warming roughly relates to a 'dangerous' level of climate change used in the 2015 Paris Agreement (UNFCCC, 2016). However, questions arise about how and when we reach these warming levels. Therefore, we present a 'rule of thumb' guide to the timing of reaching GWLs for the two SSPs used here (Figure 3), where under all scenarios we will be at around 1.5 °C in 2030 (the 2021-2040 era as a whole), then at 2 °C in 2050 and around 3 °C in 2090 under the very high SSP, but between 1.5 and 2 °C in 2050 and around 2 °C in 2090 under the very low emissions scenario.



When Global Warming Levels may be reached

GWL	SSP1-2.6 (low emissions)	SSP2-4.5	SSP3-7.0 (high emissions)
1.5 °C	2025-2040		
2 °C	Possible from mid -century	2043 - 2062	2037-2056
3 °C	Not possible	Possible late century	2055-2074

Figure 3 The estimated timing of Global Warming Levels (GWLs) being reached under different emissions scenarios. The graph at the top shows the time series of observed global temperature (grey) and future modelled global temperature under two emissions scenarios–a low emissions scenario (SSP1-2.6, green) and a high emissions scenario (SSP2-3.7, red). Temperatures are shown relative to 1850-1900. Red and green horizontal lines show the time window (and central estimate) of when each GWL is reached under each scenario. The green and red vertical bars at the right-hand side of the plot show the projected global warming range by the end of the century under each scenario. The table below shows the time window (or qualitative statement) of this timing

The three dimensions of integration can be related to each other using a simple relationship, since there is a linear connection between cumulative CO_2 emissions and global temperature, and therefore to scenarios of emissions (IPCC 2021). As noted above, scenarios change with each generation of projections, from the earliest days of projections (e.g., Hansen A, B and C in 1988; the IS92 scenarios used in IPCC 1992), through to the Representative Concentration Pathways (RCPs, explained below) and SSPs of recent years. The next section gives some details about the SSPs.

2.1.1 Future emissions scenarios

The future of anthropogenic greenhouse gas emissions is highly uncertain and unknowable, tied to significant unknowns in future population and economic growth, social and political changes, technological developments and more. Using scenarios of different future greenhouse gas emissions trajectories allows us to explore potential future climate evolution pathways, through climate modelling. CMIP6 introduced some important changes in how emissions scenarios are described in the models in comparison to CMIP5. The following sections outline the previous and current future scenarios.

Representative Concentration Pathways (RCPs) used in previous projections

The CMIP5 GCMs considered several different trajectories for future changes in the concentration of atmospheric GHGs described using Representative Concentration Pathways (RCPs) (Vuuren, et al., 2011). An RCP describes a trajectory for future GHG concentrations based on assumptions about how different natural processes and human activities may change the rate of emissions (and sequestration) of GHGs. These assumptions do not just relate to emissions policy and activities, but also other factors including social, economic and natural forces. There were four standard RCPs applied in CMIP5 climate modelling, summarised in Table 2.

Table 2. An overview of the four Representative Concentration Pathways (RCPs) applied in CMIP5 climate modelling.

Representative Concentration Pathways (RCPs) from CMIP5
RCP2.6 – describes a pathway of ambitious mitigation, with emissions peaking around 2020 and rapidly declining to net-zero around 2075. It is aligned with mitigation efforts aiming to limit the increase of global mean temperature to 2 °C. Equivalent to SSP1-2.6.
RCP4.5 – describes a medium emissions pathway with global emissions of carbon dioxide peaking around 2040 before declining to 1960s levels by 2100. Net zero emissions are not achieved under this scenario. This is one of the two scenarios used in the 2019 Victorian Climate Projections. Equivalent to SSP2-4.5.
RCP6.0 – describes an emissions pathway where GHG emissions continue to rise until around 2060 and then stabilise shortly after 2100.
RCP8.5 – describes a very high emissions pathway with carbon dioxide emissions continuing to increase to almost triple present levels by 2100. This is one of the two scenarios used in the 2019 Victorian Climate Projections. Equivalent to SSP5-8.5.

Shared Socioeconomic Pathways used in new CMIP6 projections

CMIP6 describes future GHG trajectories using Shared Socioeconomic Pathways (SSPs). The SSPs are based on five different narratives that describe the broad trends that could shape society in the future. These include population growth, economic growth, technological development, education and urbanisation. SSPs are intended to span the range of plausible futures, but it is important to note other combinations of factors are possible. While there are similarities with the RCPs, the SSPs are more highly developed, more coherent and able to be used in a broader range of applications in addition to climate modelling.

Within the SSPs are a range of mitigation targets and resultant greenhouse gas concentration pathways, encompassing the previous four RCP's and also adding additional RCPs: RCP1.9, RCP3.4 and RCP7.0. Not all combinations of the SSPs and RCPs are compatible because of conflicting policy assumptions. As a result, CMIP6 climate modelling initiatives focus on a set of five combined scenarios, as described in Table 3 and Figure 4.

SSP1-2.6 and SSP3-7.0 are the scenarios used in this report, representing low emissions (rapid reduction in emissions) and high emissions (fossil fuel intensive) respectively. They are the two scenarios prioritised by the Coordinated Regional Climate Downscaling Experiment (CORDEX) and hence by the nationally coordinated downscaling conducted for Australia, and also the high resolution NARCliM2.0 downscaling over Victoria. Downscaled model simulations from these two scenarios were available at the time of writing, while simulations for a medium emissions scenario (moderate reduction, SSP2-4.5) were in the pipeline for later release. These two scenarios span the plausible range of future emissions pathways, noting that there are lower (SSP1-1.9) and higher (SSP5-8.5) emissions scenarios which, given existing international emissions reductions commitments, seem less likely to eventuate.

In their design, no scenario is inherently more or less likely than the others and they are not forecasts. However, a scenario may appear to be more or less likely depending on how policy and other parameters evolve in comparison to their assumptions or how actual GHG concentrations track against the modelled trajectories over time.

Table 3 An overview of the five Shared Socioeconomic Pathway (SSP) narratives and associated emissions scenarios. Indications of global temperature increase for each scenario is relative to pre-industrial (1850-1900).

Shared Socioeconomic Pathways (SSPs) narratives and associated scenarios from CMIP6
SSP1: A more sustainable, equitable and inclusive world with more focus on human wellbeing and environmental boundaries. • *SSP1-1.9 – This is the most optimistic of the emissions scenarios, where global GHG emissions are cut aggressively to net zero by about 2050. This scenario aligns most closely with the goal of keeping warming below 1.5 °C at 2100 (although temperatures may temporarily rise beyond the 1.5 °C goal before dropping below the goal by the end of the century). No equivalent RCP.* • *SSP1-2.6 – Under this scenario, global emissions are cut but don't reach net zero until around 2075 and warming stabilises at about 1.8 °C by 2100, roughly compliant with the Paris Agreement. This is the 'low emissions' scenario used in this report and represents rapid emissions reduction. Equivalent to RCP2.6.*

SSP2: A 'middle of the road' world where social, economic and technological trends do not shift markedly from historical patterns.

- *SSP2-4.5 – This is a medium emissions scenario with global emissions of carbon dioxide peaking around 2040 before declining to 1960s levels by 2100. Net zero emissions are not achieved under this scenario. Temperatures rising by about 2.7 °C by the end of the century. Equivalent to RCP4.5.*

SSP3: A fragmented world of nationalism and regional rivalry where priority is increasingly placed on national and regional interests, including energy and food security over sustainability goals.

- *SSP3-7.0 – Under this scenario, emissions continue to rise and roughly double by 2100. Temperatures continue to rise to about 3.6 °C by 2100. This is the 'high emissions' scenario used in this report and represents ongoing fossil fuel intensive development. No equivalent RCP.*

SSP4: A world of ever-increasing inequality leading to disparities in economic opportunity and political power. *No equivalent RCP.*

SSP5: A world of rapid and unconstrained economic growth and energy use with increasing faith in competitive markets and innovation to deliver sustainable development goals.

- *SSP5-8.5 – This high-growth, energy-intensive scenario has emissions roughly doubling by 2050 and global average temperatures rising by about 4.4 °C by the end of the century. Equivalent to RCP8.5.*

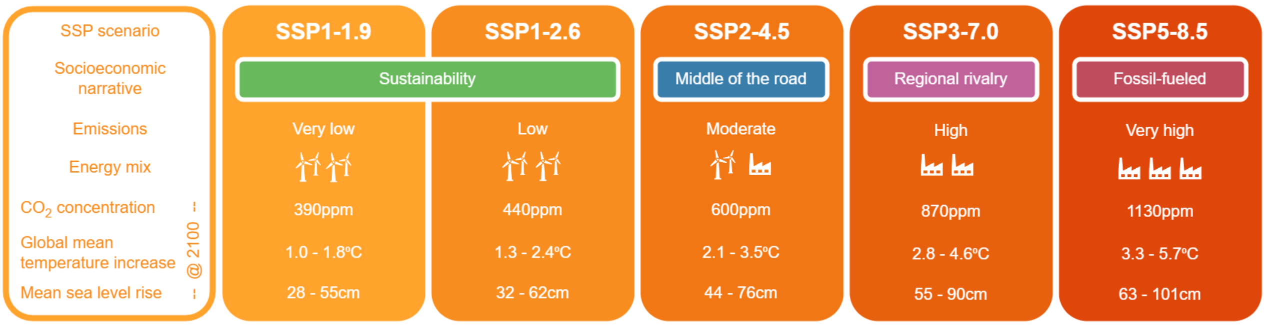


Figure 4 An overview of the five Shared Socioeconomic Pathways (SSPs) used in modelling the global climate. Socioeconomic narrative describes the broad socioeconomic trends that could shape future society that will influence future emissions and adaptive capacity (population growth, economic growth, technological advances, patterns of consumption, inequality etc.). Emissions provides a high-level description of the resulting emissions trajectory to 2100. Energy mix describes the assumed composition of energy generation technologies including renewables and fossil-fuels. CO_2 concentration is the resulting atmospheric concentration of greenhouse gases in 2100. Global mean temperature increase provides the modelled likely range of the increase in global mean temperature by 2100. Mean sea level rise provides the modelled likely range of sea level rise globally under each scenario by 2100, noting that increases above this range are possible. Sources: IPCC AR6 WG1 and CarbonBrief

2.1.2 Uncharted projections and alternative narratives

The projected changes to the climate state presented in VCP24 show plausible changes under internationally standard scenarios this century, bracketing a range of plausible developments from roughly meeting the Paris Agreement (SSP1-2.6) to a high pathway with significantly more climate change (SSP3-7.0). While we won't follow either one of these pathways precisely, and other events will unfold over time, these projections are a useful tool in understanding a range of possibilities to inform decisions.

However, we must acknowledge the range of alternative possibilities and specific ways in which events may play out this century to supplement the standard projections for the two pathways. These futures come from two sources:

- Climate ‘forcing’ outside the two scenarios presented in this report – through anthropogenic emissions more or less than the high and low emissions scenarios, or an emissions scenario such as ‘overshoot’ where technology is used to rapidly drawdown greenhouse gases; or through major natural events such as large volcanic eruptions producing temporary climate effects.
- Large-scale climate responses that are outside the range of the incremental and linear changes we model – through abrupt changes such as ‘regime shifts’ in the climate system, and the reaching of ‘tipping points’; or global changes that are not yet well understood and represented in global climate models. These are covered in more detail below.

Climate responses not fully included or accounted for in model simulations

Climate tipping points and regime shifts are abrupt and irreversible changes to the global climate triggered by global warming. They are not included in the VCP24 modelling but may have important impacts on Victoria. It is being increasingly acknowledged that major components and drivers of the Earths and regional climates are at risk of abrupt ‘tipping’ into new states that are irreversible on a long timescale. Examples include the rapid transition of Greenland and Antarctic ice sheets to a low ice state, the thawing of permafrost, and the shutdown of major ocean circulations that transfer heat and nutrients across the globe. There are also local-scale climate and ecological tipping points and regime changes that can occur, such as a change from woodland to grassland through frequent fires. Further global warming increases the risk of triggering tipping points, with different thresholds for different tipping elements.

Global and regional climate modelling also does not account for tipping points. This is because while we know that abrupt change can occur, there remain considerable unknowns about how and when they might take place and the full dynamic effect they have. The effects of triggering tipping points would be significant, but specific to how and when they are triggered. Therefore, rather than give explicit predictions that are likely to be incorrect, we note abrupt changes as a possibility that cannot be ignored, especially for the higher warming scenario. This additional risk should be accounted for in addition to the risks implied by the projections

Different global climate tipping points would have different direct and indirect effects on Victoria. For example:

- A collapse of the Greenland or Antarctic ice sheets would lead to greater and more rapid sea level rise than in the reported range of likely change.
- Rapid permafrost thaw and, Amazon dieback would produce enhanced global and regional warming, with some effect on Victoria.
- A shutdown or reversal of the Atlantic Meridional Overturning Circulation (AMOC), the system of ocean currents within the Atlantic Ocean, would result in dramatic changes in the northern hemisphere but also possible changes to the average temperature and rainfall of Victoria.

- Indirect effects of major climate disruption in other places around the world would potentially flow on to Victoria in the form of disruptions to trade, supply chains, migration, conflict and other factors.

2.1.3 Projections methods

The basic premise behind constructing future climate change projections is comparing the modelled climate at a future time with the modelled climate of a past time (referred to as the baseline). The future time period may be a set range of years (i.e., the projections by emissions scenario and time slice approach) or years which are determined by when the model reaches certain levels of global warming (i.e., the global warming levels approach).

Raw model data is used for all analysis in this report, which means any bias in the model has not been corrected. Correcting model bias is important when using absolute values from the model in isolation, for example when looking at the future temperature in a model. However, when comparing modelled historical values with modelled futures values and calculating the change between them, as is done here, any bias in a model is negated under the assumption that the model biases are consistent across the historical and future periods.

Projections from an 'ensemble' of models ('ensemble' refers to a group of models – see Section 2.2 for details of models used) are generally presented as a central estimate (median) and range (most often the 10^{th} to 90^{th} percentile range of all model simulations).

Projections by emissions scenario and time slice

In line with international practice (IPCC, 2021), a time-slice approach was used to compute future change in climate compared to a historic baseline, under different emissions pathways. This involved calculating the difference between the model simulated past and future climate (each averaged over 20-year periods) for each future pathway (SSP) and future time period.

Two baseline periods were used, 1986-2005 and 1995-2014, consistent with the IPCC's Fifth and Sixth assessment reports, respectively. The 1986-2005 baseline has been commonly used in projections using CMIP5 GCMs and was used for the VCP19 projections. The more recent 1995-2014 baseline is commonly used for CMIP6 projections and was used in the IPCCs most recent assessment reports. The IPCC shifts to a more recent baseline for each round of reporting to provide a 'recent past' reference period (IPCC, 2021), and the 1995-2014 baseline is also selected to align with CMIP6 modelling of the past climate, which ran until 2014.

The four future time periods (or time slices) for which projected changes were calculated were 20-years centred on 2030, 2050, 2070 and 2090 (corresponding to the 20-year periods 2020-2039, 2040-2059, 2060-2079 and 2080-2099, respectively). The use of 20-year periods is consistent with IPCC projections methods, being shorter than the 30-years traditionally used for climatological averages, to allow for the transient nature of a changing climate to be captured. Results for 2050 and 2090 are highlighted in key statements throughout this report, but results for all periods are also available through accompanying datasets. Time slice projections were carried out under low emissions, SSP1-2.6, and high emissions, SSP3-7.0, scenarios.

Projections by global warming levels

Global warming level (GWL) projections refer to the projections from a historical baseline to a twenty-year window where the global mean temperatures first reach thresholds of 1.5, 2 and 3 °C above a pre-industrial 1850-1900 baseline. These temporal windows vary for each climate model and projected emissions pathway. The future years for these windows have been calculated by the IPCC Working Group 1 for a range of CMIP6 models and SSPs using a standardised process and are available on the public repository for the IPCC Interactive Atlas (Iturbide, et al., 2021). These windows have been used for the GWL projections in this report. Projected changes by warming levels can then be calculated by comparing a baseline climate (e.g. 1986-2005) with the climate during the future time window in which the GWL is met. This is a standard method used in the IPCC Sixth Assessment Report, and portals such as the IPCC Interactive Atlas and the Copernicus Interactive Climate Atlas, so is used here as a standard good practice. However, examining change between a recent period fixed in time to a future period defined by the level of global warming has an important limitation: it doesn't account for the difference between modelled and observed global warming to the set historical baseline. Models with less warming to that baseline will in effect show greater change to a GWL than it should, and vice versa. Methods are currently being developed to address this, for example through examining the difference between a recent warming level (e.g., 1.1 °C global warming seen in 2011-2020) to a future warming, hence a like-with-like comparison. But these methods are not fully developed and published, so are not used here.

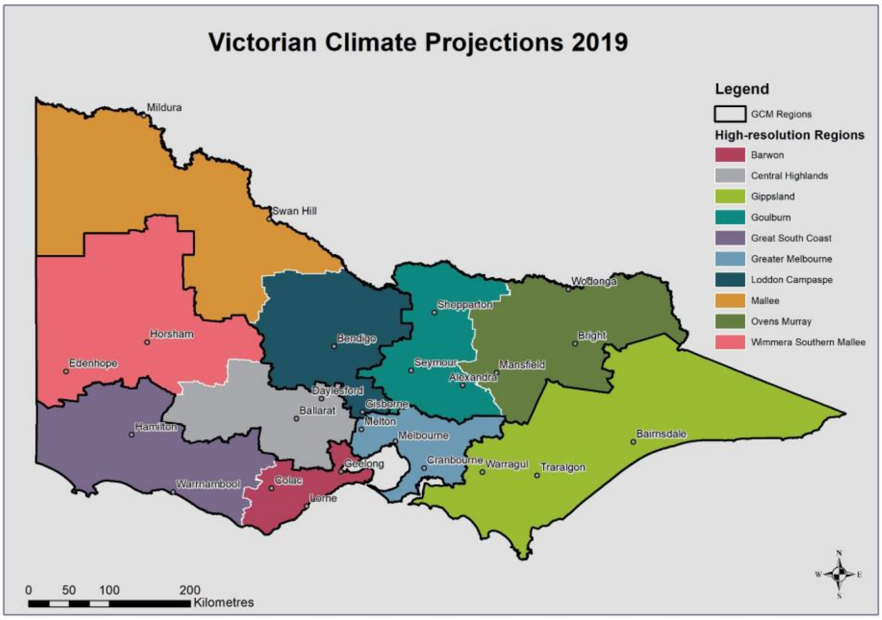
Dealing with high climate sensitivity models

For presenting results by 'emissions scenario and time slice', a further consideration is dealing with an over-representation of 'hot models' in the CMIP6 ensemble of global models (Hausfather, et al., 2022). 'Hot models' are those with a high equilibrium climate sensitivity (ECS, the amount of warming occurring for a certain increase in greenhouse gas concentrations). We consider 'hot' models to be those with and ECS of greater than 4.5, in line with published assessments of Earth's likely climate sensitivity (Sherwood, et al., 2020).

We present projections of the CMIP6 global model ensemble of 34 models as well as a 'constrained' set 22 of models which excludes models with ECS greater than 4.5 (or less than 2.3). ECS values for each model are provided in Table 18. We apply the same constraints to the combined ensemble of all downscaled simulations (model details on downscaled in 2.2).

2.1.4 Regionalisation

Throughout this report and the accompanying regional reports, projected changes are presented as state-wide or regional-wide averages. Regional analysis was undertaken by averaging gridded climate projections output spatially over the regions. This regional analysis was undertaken at two different scales depending on the spatial resolution of the gridded data, consistent with VCP19 projections (Clarke, et al., 2019). The lower-resolution global model output was aggregated over Victoria and 6 sub-regions, while the high-resolution regional model outputs were aggregated over Victoria and 10 sub-regions, as outlined in Figure 5. The smaller high-resolution regions are too small to sensibly sample from the coarsely gridded GCM data, as not enough grid cells can be sampled.



High-resolution regions	GCM regions
Barwon	Barwon South West
Great South Coast	
Gippsland	Gippsland
Wimmera Southern Mallee	Grampians
Central Highlands	
Ovens Murray	Hume
Goulburn	
Loddon Campaspe	Loddon Mallee
Mallee	
Greater Melbourne	Metropolitan

Figure 5 The 10 sub-regions over which projected change was aggregated. The 10 regions used for regionalisation of downscaled data are shown by colours and the thick black outlines show the larger regions used for the regional aggregations of coarse resolution climate models

2.2 Climate datasets

A best practice, multi-model, multi-ensemble approach was used to ensure that the span of plausible climate futures for the respective SSPs is represented. This approach draws on a wide range of global and regional model output. For more detail on the multi-model approach, see section 1.2.1.

Details of the various climate modelling datasets are outlined below, with details about the downscaled modelling summarised in Table 4, and a full list of CMIP6 GCMs is presented in Appendix Table 18.

2.2.1 CMIP6 Global Climate Model ensemble

Data from 34 CMIP6 GCMs were analysed to provide the most comprehensive set of projections for Victoria and to provide an overall projections context for the downscaled modelling. A complete list of GCMs is provided in the Appendix Table 18. These models comprise a comprehensive subset of CMIP6 GCMs that have projections for both of the SSPs (SSP1-2.6, SSP3-7.0, consistent with the methods of the IPCC Interactive Atlas (Gutiérrez, et al., 2021)[11].

A feature of the CMIP6 model ensemble which was not present in CMIP5 is the presence of a subset of models which have higher equilibrium climate sensitivity (ECS) than the expected range. ECS is defined as the estimated equilibrium global temperature change for a doubling of

[11] https://interactive-atlas.ipcc.ch/

carbon dioxide concentration (Gregory, et al., 2004). Models with high ECS produce more warming and larger increase in temperature extremes for a given emissions scenario. The likely range of ECS was estimated as 2.3 to 4.5 according to multiple lines of evidence assessed (IPCC, 2021) (Sherwood, et al., 2020). Models with ECS above the likely range represent a low-likelihood but high-impact future. They are not necessarily considered inconceivable, but more so that they are over-represented in the CMIP6 ensemble compared to mid-range or cooler projections (Hausfather, et al., 2022). We deal with this issue by presenting results for a subset of GCMs which fall within the very likely ECS range of 2.3 to 4.5 as constrained projections, in addition to the projections from all 34 GCMs, including the high ECS models.

2.2.2 National downscaled data

The following sets of nationally consistent downscaling simulations provide data for at SSP3-7.0 and SSP1-2.6 from the mid-20th century to the end of the 21st century. Table 4 provides a summary of the downscaled datasets used in this report, including which GCMs were downscaled by each RCM and available at the time of reporting. The process behind the GCM selection was based on model evaluation and selection of a representative subset of models (Grose, et al., 2023).

Table 4 Summary of global climate models downscaled by each regional climate model to create the regional model ensembles. Details about the downscaled members for each model is included in Appendix, Table 18. The * and ** denote GCMs which have climate sensitivity above 4.5 (outside the very likely range) and 5 (low-likelihood, high-warming) respectively.

	NARCLIM2.0	CCAM-ACS	QLDFCP-2	BARPA-ACS
Horizontal resolution	~4km	~12.5km	~10km	~17km
GCMs downscaled	ACCESS-ESM1.5 EC-Earth3-Veg MPI-ESM1-2-HR NorESM2-MM UKESM1-0-LL**	ACCESS-CM2* ACCESS-ESM1.5 CESM2** CMCC-ESM2 CNRM-ESM2-1* EC-Earth3* NorESM2-MM	ACCESS-CM2* ACCESS-ESM1.5 CMCC-ESM2 CNRM-CM6-1-HR EC-Earth3* GFDL-ESM4 MPI-ESM1-2-LR NorESM2-MM	ACCESS-CM2* ACCESS-ESM1.5 CESM2** CMCC-ESM2 EC-Earth3 MPI-ESM1-2-HR NorESM2-MM

CCAM-ACS

As part of its contribution to the Australian Climate Service, CSIRO has downscaled CMIP6 GCMs to a resolution of 12.5km over Australia using the Conformal Cubic Atmospheric Model (CCAM) (McGregor & Dix, 2008). CCAM is a global atmospheric model with a variable-resolution grid. It can be used for regional downscaling by focussing the high-resolution part of the grid on the region of interest.

In the CCAM-ACS simulations, the model is constrained by spectral nudging rather than by lateral boundaries. This results in CCAM constrained to resemble the host GCM at length scales above 3,000km for air temperature and winds (above 850hPa) and for surface pressure. This method encourages CCAM to more closely resemble the host GCM, but also inherits some of the errors found in the GCM. Note that humidity is not nudged in CCAM. CCAM employs the same CABLE land-surface model as used for the ACCESS GCMs, but an independent set of physical parameterisations. CCAM also supports feedback due to prognostic aerosols on rainfall and solar radiation as well as an optional stretched grid coupled ocean for improving coastlines, bays and lakes.

CCAM-Qld

The Queensland Department of Environment and Science has downscaled 15 CMIP6 GCMs to a resolution of 10km using the CCAM model as the basis of the Queensland Future Climate Projections 2 (referred to as QldFCP-2) (Chapman, et al., 2023). Eight downscaled GCMs for SSP1-2.6 and SSP3-3.70 were accessible at the time of this study. Two different configurations of the CCAM model were used: most runs were done with atmosphere only configuration (CCAM-v2105) but one run was done with coupled ocean-atmosphere (CCAMoc-v2112, used to downscale ACCESS-CM2). Model configuration details can be found in the Appendix, Table 18.

For the CCAM-Qld CCAM simulations, the same spectral nudging constraint method is used as described above for CCAM-ACS simulations. However, the CCAM-QLD simulations use bias adjusted sea surface temperatures (SSTs) (i.e. corrected to realistic values of SSTs) prior to downscaling (Hoffmann, et al., 2016). This reduces the bias in the downscaling simulations. This approach is similar to what was used for VCP19, where GCM biases are reduced but reliance on the CCAM physics and dynamics for predicting changes in regional climate is increased. The CCAM model was run in both atmospheric and coupled atmosphere-ocean versions, as indicated in Appendix, Table 18Table 4.

BARPA-ACS

BARPA (Bureau of Meteorology Atmospheric Regional Projections for Australia) is part of the Australian Bureau of Meteorology's contribution to the Australian Climate Service (Su, et al., 2022). The BARPA project has downscaled seven CMIP6 GCMs to a resolution of 17km using the Unified Model (UM) that is also used for ACCESS weather and seasonal prediction. The Unified Model can be run as a GCM, but for downscaling has been run in a high-resolution limited-area configuration. BARPA has similar physical parameterisations to the ACCESS GCMs, except for the land-surface that uses a model called JULES (Best, et al., 2011).

2.2.3 NARCliM2.0 ~4km downscaled data

NARCliM2.0 (NSW and Australian Regional Climate Modelling project) is based on the internationally developed Weather Research and Forecasting (WRF) model, a dynamical regional climate model (RCM). The NARCliM2.0 models are used to dynamically downscale from coarse resolution GCMs to the Australasia domain at ~18-20km (AUS-18), followed by a second downscaling to a domain over the SE corner of Australia at a resolution of 0.0352 degrees or approximately 4km. For this project, a subset of the 4km data clipped to cover a suitable area just beyond the extent of Victoria (140.5°, -33°) (151°, -39°) was provided by the NSW DCCEEW through DEECA. Data from the 18km resolution data was not available at the time of the analysis for inclusion in this report.

NARCliM2.0 downscaled five GCMs from the CMIP6 suite (see Table 4) using two different configurations of the Weather Research and Forecasting Model (WRF) v4.12, referred to as 'N20-WRF412R3' and 'N20-WRF412R5' (Di Virgilio, et al., 2024). These two configurations of the WRF regional climate model differ in their configuration of planetary boundary layer (surface layer) physics. Version N20-WRF412R3 and N20-WRF412R5 use the MYNN2 and ACM2 planetary boundary layer parameterization schemes, respectively. Both configurations use the same configurations for microphysics, cumulus physics, shortwave and longwave radiation physics, land surface and dynamic vegetation. These two versions were selected as superior performing by the NARCliM2.0 modelling team, following evaluation of numerous other configurations of the WRF model (Ji, et al., 2024). The two different configurations of the WRF model are not independent, differing only in one aspect, they allow the effect of different boundary layer physics configuration on simulated climate change to be explored.

The NARCliM2.0 data was provided on a 0.0352 degree rotated pole grid. We interpolated the native output to a regular latitude/longitude 0.0352 degree grid using bilinear interpolation.

2.3 Combining projections from multiple ensembles

Projections of future climate change were created for the following ensembles:

- two NARCliM2.0 4 km ensembles – each ensemble downscales 5 GCMs with a different configuration of the WRF RCM (5 simulations per SSP per ensemble).
- the three national scale ensembles – consisting of the BARPA-ACS, CCAM-ACS and CCAM-Qld regional downscaling of 7 or 8 GCMs each (7 or 8 simulations per SSP per ensemble)
- a combined '*All RCMs*' ensemble – the ensemble includes the two NARCliM2.0 4km ensembles and the three national scale ensembles**.** Projections are provided both including ('unconstrained', 32 simulations per SSP) and excluding ('constrained', 24 simulations per SSP) simulations from GCMs with ECS outside the very-likely range[12].
- the CMIP6 GCM ensemble, consisting of the raw GCM simulations. Ensemble projections are provided both including ('unconstrained', 34 simulations per SSP) and excluding ('constrained', 22 simulations per SSP) simulations from GCMs with ECS outside the very-likely range.

The 'constrained' projections are created to deal with the overrepresentation of *low-likelihood, high-warming* models which have high ECS, in the CMIP6 model ensemble. This mainly impacts temperature projections, with high ECS models showing greater increase in temperature.

For temperature over Victoria, the constrained GCM ensemble projected change is presented as the primary projection, with the full RCM projections noted separately to provide the full range of projections, including **the** upper end of projections from low-likelihood, high-warming' models.

For example, from section **4.3**: '*The likely further warming from a 1986-2005 baseline to end of century (2080-2099) is 2.2–3.6 °C (3.1 median) under high emissions.'* → this is the GCM constrained range from **Table 6**.

'However, there is a low-likelihood, high-warming future which projects warming up to 5.0 °C by 2090 under high emissions' → this is from the NARCliM2.0 downscaling of a low-likelihood, high-warming GCM (UKESM1-0--LL).

Not all projections draw on all model ensembles. The full GCM and RCM ensembles were analysed for changes to average temperatu**re** and rainfall but for extreme temperature and rainfall, only the RCMs were analysed. For hazards metrics (heatwaves and drought) only the NARCliM2.0 modelling was analysed (see **Table 5**), due to prioritisation of the high-resolution NARCliM20 data. The ensembles contributing to each projection are noted, in text and figures.

For Victoria's regional reports, the projections from the combined *All RCMs* ensemble are used rather than the GCMs, allowing for changes at the finer spatial scales to be captured. The comparison of the GCM and RCM results provided in this report give us confidence that the combined RCM range represents the full GCM range well, with the main difference being that the combined RCM range provides a broader projected range for rainfall in some seasons

2.4 Climate variables

Projected changes were made for a number of measures of mean and extreme temperature and rainfall. Details on the metrics used and which analysis was completed for which model ensembles is outlined in Table 5. The metrics were chosen in part to be consistent with metrics planned for delivery by the Australian Climate Service.

Priority was given to doing a full analysis of all available modelling for average temperatures and rainfall. This provides the broader context and comparison of all the global and regional modelling. The more detailed analysis, for example on extremes and hazards, focussed on the 4km resolution NARCliM2.0 downscaling, and the national-scale downscaling where possible. The finer resolution of the regional climate models, compared to the global climate models, makes them a more appropriate choice for assessing extreme climate metrics.

Table 5 Description of climate variables for which projected changes were calculated, including specific metrics for each variable. The model ensembles for which each variable was analysed is also listed – 'all' denotes all of the CMIP6 GCMs, national downscaling and NARCliM2.0 downscaling

CLIMATE VARIABLE	METRICS	APPLIED TO ENSEMBLES
Average mean temperature	Monthly, seasonal*, annual	all
Average minimum temperature	Monthly, seasonal, annual	all
Average maximum temperature	Monthly, seasonal, annual	all
Extreme daily maximum temperature (hot days)	99^{th}, 99.9^{th} percentile daily maximum temperature. Number of days above the historical 99^{th} and 99.9^{th} thresholds.	national downscaling, NARCliM2.0
Extreme daily minimium temperature (hot nights)	99^{th}, 99.9^{th} percentile daily minimum temperature. Number of days above the historical 99^{th} and 99.9^{th} thresholds.	national downscaling, NARCliM2.0
Average rainfall^{+}	Monthly, seasonal, annual	all
Extreme rainfall	99^{th} , 99.9^{th} percentile total daily rainfall Number of days above the historical 99^{th} and 99.9^{th} thresholds	national downscaling, NARCliM2.0
Heatwaves	Excess Heat Factor (EHF): heatwave duration, frequency and heatwave season length	NARCliM2.0
Drought	Number of months below the historical 10^{th} percentile	NARCliM2.0

Note: Reference to seasonal includes the seasons summer (DJF), autumn (MAM), winter (JJA) and spring (SON), as well as cool seasons [MJJASO and AMJJASO] and warm season (NDJFMA).

[12] Ensembles constrained to exclude models with Equilibrium Climate Sensitivity (ECS) greater than 4.5 ('hot' models) or below 2.3 (Sherwood, et al., 2020).

Extreme temperatures and precipitation

We assessed change in the 99^{th} and 99.9^{th} percentile daily extremes for hot days (hottest daily maximum temperature), hot nights (hottest daily minimum temperature) and maximum daily rainfall. We also assessed the number of days above the historical 99^{th} and 99.9^{th} percentile daily extremes. A 99^{th} percentile daily value is one which occurs on average approximately 3-4 days per year, and a 99.9^{th} percentile daily value occurs on average approximately 3–4 days per decade.

Assessing extreme temperature and rainfall through percentile based metrics such as the 99^{th} and 99.9^{th} percentile, has a number of advantages over looking at absolute thresholds, for example 40 °C. Because percentile-based metrics are determined for the temperature or rainfall distribution at each location, they can account for place-to-place variation i.e. what may be considered extremely hot or wet at one location may not be considered extreme at another location. Percentile based metrics are also not affected by model bias in the way that absolute values are, because the percentiles are defined separately for each model's historical temperature distribution, taking bias into account.

The projected change calculations for percentile extremes comprise of three steps:

1. Determine the modelled historical baseline values of the 99^{th} and 99.9^{th} percentiles for both the baseline period. To do so, all daily values in the 20-year baseline period are combined to determine the values of the 99^{th} and 99.9^{th} percentiles over the whole period.
2. For the projected change in the 99^{th} and 99.9^{th} percentile daily extremes: repeating step 1 but for the future periods, and then computing the difference between the historical and future values. This gives the amount of change in these extremes from the historical to future periods.
3. For the projected number of days above the historical 99^{th} and 99.9^{th} percentiles values, the historical values of these extremes are taken as a threshold over which to count the number of occurrences above this threshold in the future period.

Heatwaves

Future changes to heatwaves were assessed using various heatwave metrics based on the Excess Heat Factor (Nairn & Fawcett, 2013). The threshold used to determine a heatwave day is the 95^{th} percentile of daily average temperature over a baseline period of 20 years (baselines 1986-2005 and 1995-2014 used). For a heatwave to be defined, there must be 3 consecutive heatwave days. The methods used for defining heatwaves and heatwave metrics are consistent with those being used by the Australian Climate Service.

The heatwave metrics used are mean number of heatwave days per year, mean heatwave duration, and length of heatwave season. The mean number of heatwave days per year is calculated by first calculating the number of heatwave days for each calendar year, and then averaging this number of the 20 years of each projection period. Mean heatwave duration is the average duration from the beginning of a heatwave to its end and is calculated by dividing total number of heatwave days over the 20-year period by the total number of heatwaves over the same period. Heatwave season length is calculated first for each year (beginning in July) as the length in days from the first heatwave day after July 1^{st} until the last heatwave day before June

31st the following year. These individual heatwave season lengths are averaged over the 20-year projection periods to determine the mean heatwave season length.

Due to the 360-day calendar used in the UKESM1-0-LL model being incompatible with the current heatwave code, UKESM1-0-LL NARCliM model data are not used in the analysis of heatwave metrics shown here. This model is the hottest model in the NARCliM2.0 ensemble, and as such the heatwave projections outlined in this report are may not capture the highest end of the range of potential future changes in heatwaves.

Drought

Two different indicators of drought were used in analysis of future projected drought changes in the NARCliM2.0 simulations: 1) changes to the number of low rainfall months (below the 10th percentile) and 2) changes in the Keetch-Byram Drought Index (KDBI).

The threshold for low rainfall months were defined by the 10th percentile monthly rainfall (i.e. monthly rainfall below which 10 percent of months fall) in a historical baseline period. Projected change in the number of low-rainfall months was calculated by first defining the value of 10th percentile monthly rainfall in the model simulated 20-year historic period (1986-2005 and 1995-2014 baseline periods used) and then comparing the number of months below this threshold in the historical and future periods. It is worth mentioning that while a significant drought was observed in Victoria during both these baseline periods, this drought is not necessarily incorporated into the baselines used in the projected changes in dry months due to the model-specific nature of the baselines.

The Keetch-Byram Drought Index (KBDI) is a drought index which is particularly relevant to fire risk, as it aims to represent cumulative soil moisture deficiency and therefore indicate vegetation dryness. The KDBI is formulated by calculating for each day the mean annual rainfall, maximum daily temperature, previous 20 hours rainfall and previous day's KDBI index (Finkele, et al., 2006; Dowdy, et al., 2009).

3 Model evaluation and confidence

3.1 Confidence and likelihood assessment

How to best use projections depends on the degree of confidence we have that they are reliable and complete, and how likely we assess the outcomes to be. Projections with higher confidence and changes with higher likelihood can inform choices more definitely. In contrast, lower confidence projections shouldn't be used in rigid decision making but can be used to inform scenario-based adaptive planning or risk-management approaches that can account for uncertainty. Confidence ratings are therefore a key tool when using projections. For example, the finding that the world, Australia and Victoria will continue warming in coming decades is *virtually certain*, so responses can be definite – we should adapt to a warmer climate not a cooler one. In contrast, whether large hailstorms will become more or less frequent or intense due to climate change (or stay similar to today) is currently unclear, so decisions around resilience to hail (e.g., building codes) should consider a range of possibilities, not 'lock in' a narrow policy decision, and instead consider different 'pathways' of change and response. Confidence is highest for projections such as temperature and sea level rise, lower for things like regional rainfall patterns, and lowest for phenomena such as storms. Confidence is generally higher at larger spatial and temporal scales (e.g., global temperature over decades), than for smaller scale (e.g., local temperature at one location for a single decade).

We follow the conventions of the most recent national climate projections (CSIRO and Bureau of Meteorology 2015) and the Intergovernmental Panel on Climate Change (IPCC) assessment reports (Mastrandrea et al. 2010) in assigning confidence ratings to projections. This is also the same approach used in the VCP19 projections.

Confidence statements applied to a climate projection are determined through an expert elicitation process, drawing on multiple lines of evidence to produce a semi-quantitative rating. Given the nature of future climate assessment, using expert judgment supported by evidence is the most useful approach, rather than using simple model statistics. Model evaluation is one key line of evidence used to assess confidence in projections. The other lines include process understanding, theory, agreement with past trends that can be attributed to human influence, consistency between models and expert judgment. Confidence in a projected change is based on the type, amount, quality and consistency of evidence and the extent of agreement among the different lines of evidence (see Figure 6).

Different lines of evidence are easy to combine and assess for some changes. For example, for warming of the average annual temperature, the trend is clear in observations, the theory is well developed (the basics of the enhanced greenhouse effect) and there is high agreement between observations and models, and models agree on the sign of future change. For other changes, observed records are shorter, there is a lot of climate variability, the theory is less straightforward, and models don't agree as much, for example in the changes to hail, tropical cyclone attributes or 'dry lightning' driving fires. The confidence assessment draws on multiple scientific experts' judgment of the reliability of a result or statement as a guide to the range of real-world change for a given input scenario. For VCP19, confidence was assessed from previous studies including IPCC assessments, the national climate projections (CSIRO and Bureau of Meteorology, 2015) and the Victorian Climate Initiative (VicCI). The project also drew on new evidence at the time, such as VCP19 CCAM downscaled model simulations, and also the expert judgement of the project team and technical reference group to refine and add to confidence statements.

For this project, with a slightly more limited scope than VCP19, we used previously determined confidence levels from the VCP19 projections as a starting point. We then assessed if, and if so how, any new evidence may strengthen or weaken confidence in a particular projection, and updated confidence statements where necessary. New evidence considered includes the new CMIP6 and downscaled projections and some limited assessment of new insights published in the scientific literature. Confidence is assessed and reported for two specific aspects, 1) in the direction of change (increase, decrease or no change), and 2) whether the magnitude of future change sits within the reported range of change. Understandably the second aspect represents a balance in terms of the precision in the reported range, from very high confidence in a very wide range to lower confidence in a very narrow range.

Here, we report the range produced by the models surveyed, only modifying this if there is good reason, and then reporting confidence in this range, which is typically broad but not unhelpfully broad. Confidence and likelihood in future change are assessed for a standard context of roughly 2 °C global warming since the pre-industrial era (expected roughly mid-century under high emissions, stabilising near that level by 2100 under low emissions). Changes may be less confident, or less distinguishable from natural variability, for lower levels of warming, or higher for more extreme levels of climate change.

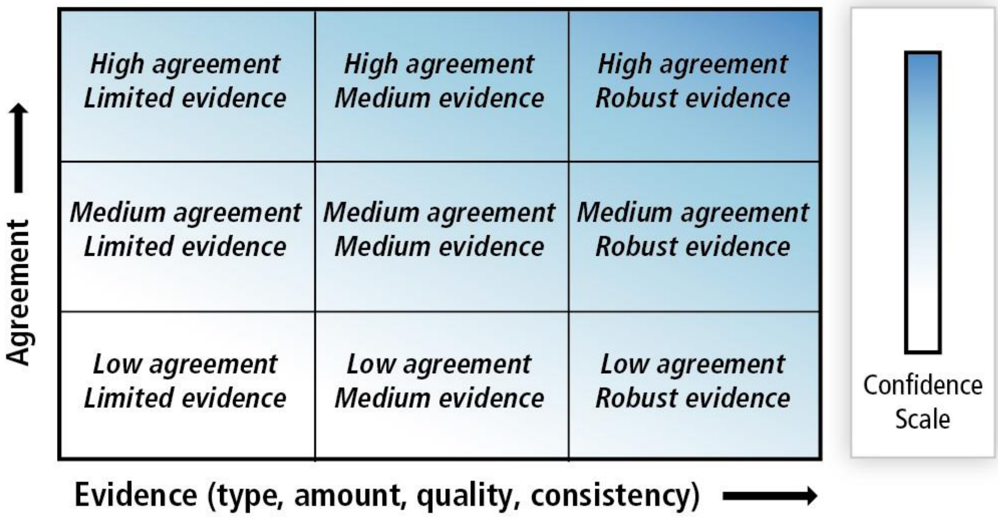


Figure 6 A depiction of how the degree of evidence (type, amount, quality and consistency) and agreement contribute to various levels of confidence. Confidence increases towards the top-right corner as suggested by the increasing strength of shading

3.2 NARCliM2.0 evaluation

Evaluation has two purposes. The first is to find where a climate model has egregious errors or differences from the observed world to the point where there is little confidence in the projections produced by the model. This is the basis for rejecting or down weighting the model simulation in the projection. The other purpose is to inform the confidence assessment for a given purpose and determine how the outputs can be used into further applications. If an aspect of the climate is different from the observed world (e.g., the rainfall inter-annual variability is too low), then this should be accounted for when discussing future variability and how the results are used for assessments such as changes to seasonal drought. If evaluation doesn’t suggest outright model rejection, then importantly, model biases can be removed statistically in the output so that the data are usable in applications.

An evaluation of biases or error between the observed climate and the model simulated climate for the historical period, was conducted for the NARCliM2.0 downscaled model output. Model performance was assessed for mean annual and seasonal temperatures (minimum, mean and maximum) and rainfall as well as extreme daily temperatures and rainfall. The evaluation results are detailed in the following sections.

The key messages from the NARCliM2.0 evaluation:

- The high resolution NARCliM2.0 downscaling significantly improves the representation of mean and extreme temperature and rainfall, compared to the host GCMs. E.g. observed spatial patterns are better resolved.
- There are relatively large biases in temperatures, particularly a cold bias over the Alps, which could be a reason for lower confidence. There are notable differences in bias between the two different WRF versions, especially for rainfall.
- The biases are not of a magnitude to reject the simulations outright, following typical assessments of models in Australia and elsewhere.
- Bias correction will be necessary for any applications needing absolute values from the NARCliM2.0 model output (as opposed to the relative projected change presented in this report). This is especially important for temperatures where absolute values matters a lot, such as temperature thresholds, snow and frost formation.

Further evaluation of the NARCliM2.0 simulations could aid in assessing confidence in the future projections but was not conducted for this report due to time constraints and limitations in data availability. This evaluation could include evaluation of representation of large-scale circulation patterns, evaluation of representation of recent observed trends and comparison of NARCliM2.0 18km and 4km simulations.

3.2.1 Evaluation methods

Evaluation of mean (annual and seasonal) and extreme daily (99th and 99.9th percentile) temperature and rainfall climatology was conducted. For temperature, the daily mean, minimum and maximum temperatures were evaluated. The difference between the modelled climatology and the Australian Gridded Climate Data (AGCD v1) 5km gridded observational reference data (Evans, et al., 2020) (Jones, et al., 2009) were calculated over a 1981–2010 historical period. A 30-year reference period was preferred for the historical evaluation over a 20-year period, with the choice of which 30-year period being fairly arbitrary for the purpose of model evaluation.

NARCliM2.0 4 km model data was regridded using bilinear interpolation to match the AGCD grid ~5 km resolution for the NARCliM2.0 evaluation, so that the observations could be subtracted from the model data to calculate the difference, or bias, between the two. A comparison of GCM and RCM biases was also conducted for all downscaled GCMs. For GCM biases, the AGCD data was regridded to match the coarser native resolution of each of the CMIP6 GCMs.

3.2.2 Evaluation of mean temperatures

The temperature biases are shown for the two ensemble sets of 5 downscaled GCMs, from the two NARCliM2.0 RCM versions (N20-WRF412R3 and N20-WRF412R5) in Figure 7. In general, the models overestimate minimum temperatures (a warm bias) and underestimate maximum temperatures (a cold bias). This overestimation of the minimum daily temperature and underestimation of the maximum daily temperature means the diurnal range is underestimated in the model. These larger differences are consistent with the sorts of differences seen in the GCMs, where the diurnal range can be an issue for the models. However, the strong cold bias in maximum temperatures is accentuated in the NARCliM2.0 model compared to the host GCMs (see Appendix, Figure 55). Over most of the Victorian region, both ensembles have differences of within ± 1 °C although there are some general differences between the versions.

For mean annual temperature, the N20-WRF412R3 ensemble shows a stronger cold bias compared to the observations over parts the Great Dividing Range and extending to the coast, up to more than 2 degrees cooler on areas of highest topography. This cooler bias over the ranges is also evident in the R5 ensemble albeit not as strongly (Figure 7), and instead there is a tendency towards a warm bias across parts of the state, particularly in the inland north. This bias is important to consider, and a reason for lower confidence, particularly for processes where the absolute temperature matters a lot (for example, such as where the snow line sits on average). However, it is not of a magnitude to reject the simulations outright, following typical assessments of models in Australia and elsewhere.

Both ensembles display the strongest warm biases over the Hume Dam region and the Melbourne metropolitan region, indicating the model is resolving land surface-atmosphere interactions at the finer resolution (i.e., over urban areas and over water). The ‘urban heat island effect’ is where land covered in mostly concrete results in higher minimum air temperatures compared to the surrounding vegetated area and the ability of urban surfaces to absorb and store heat during the day and release heat over night. Other factors include the effect of nonporous obstacles (such as tall buildings) affecting turbulent fluxes, a 'trapping' of solar radiation in the canyon due to reflections, as well as a reduction in latent heat flux due to reduced vegetation (i.e., reduced ability to cool through evaporative processes). See VCP19 for more detail and note that results are similar here (Clarke, et al., 2019).

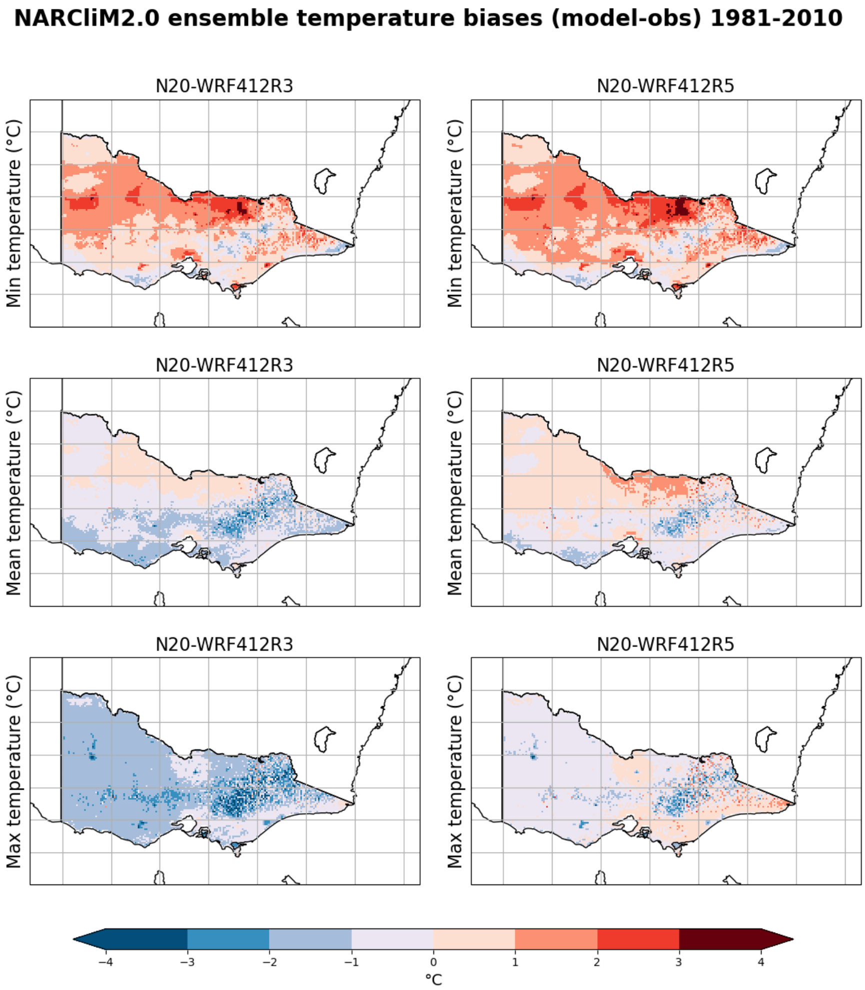


Figure 7 Temperature bias evaluation maps for minimum temperatures (top row) mean temperature (middle row) and maximum temperature (bottom row), showing NARCliM2.0 ensemble temperatures minus observed AGCD observed temperatures from 1981-2010. The two NARCliM2.0 RCM versions (N20-WRF412R3 and N20-WRF412R3) are shown separately, each consisting of 5 downscaled GCMs averaged. Blue values mean the model ensemble is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias)

Figure 8 shows the evaluation of mean temperature bias for the individual 5 models downscaled by each version of NARCliM2.0, as well as the bias in the host GCMs. The same plots but for minimum and maximum temperatures are in the Appendix (Figure 54, Figure 55). Evaluating the bias in the downscaled and host models side-by-side allows us to assess how much the bias in the downscaled model is 'inherited' from the host GCM and how much comes from the downscaling. The individual model bias plots show a diversity of bias across the models, with individual RCM/GCM combinations exhibiting biases in opposite directions. This is expected as models were selected on the basis of covering aspects of different model behaviours. The biases in the downscaled models are sometimes the reverse of the bias signal in the host GCM. Especially for the N20-WRF412R3 version, the cooling bias overrides areas where the host model has a warm bias. This indicates the bias stems from processes simulated by the RCM. The RCM ensemble simulates a consistent cool bias even when given high quality inputs from reanalysis (Di Virgilio, et al., 2024) (in press), indicating a persistent behaviour that affects confidence in the projection but again doesn't suggest outright model rejection given commonly used evaluation thresholds.

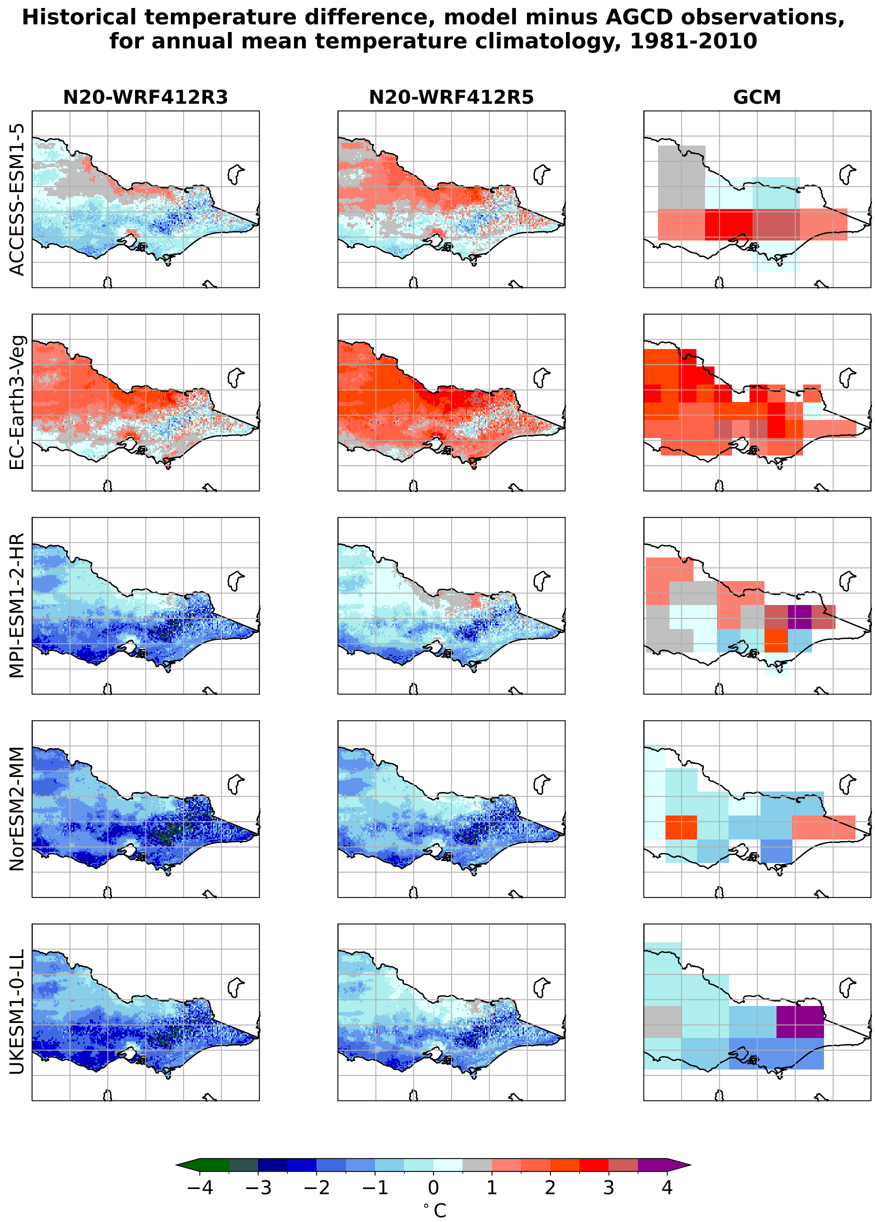


Figure 8 Temperature evaluation maps for mean average annual temperature (mean 2m air-surface temperature) showing the difference between observed (AGCD) and modelled temperatures from 1981-2010. Blue values mean the model is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias). The first two columns show results from the two different versions of the downscaling model (N20-WRF412R3 and N20-WRF412R5) and the third column shows the results for the host GCM. The five rows show the five different GCMs

In addition to looking at the annual mean temperature biases, we can also examine seasonal differences. Additional figures in the Appendices show the full seasonal bias evaluation for all NARCliM2.0 runs (Figure 56, Figure 57). The warm to cold biases are present as in the annual mean cases, with not a lot of difference in bias between the seasons, except for the cold bias being stronger in winter and hot inland biases being stronger in summer.

3.2.3 Evaluation of temperature extremes

Comparing observed extreme temperature values over Victoria with the GCM and NARCliM2.0 RCM modelled values over a historic period (1986-2005) shows that the RCM resolves the spatial patterns of extreme temperatures much better than the host GCM. Examples of this are shown in Figure 9 for the ACCESS-ESM1.5 model. The RCM picks up the spatial patterns of cooler temperature extremes associated with high elevation regions and some coastal areas, remarkably similarly to the AGCD observed data.

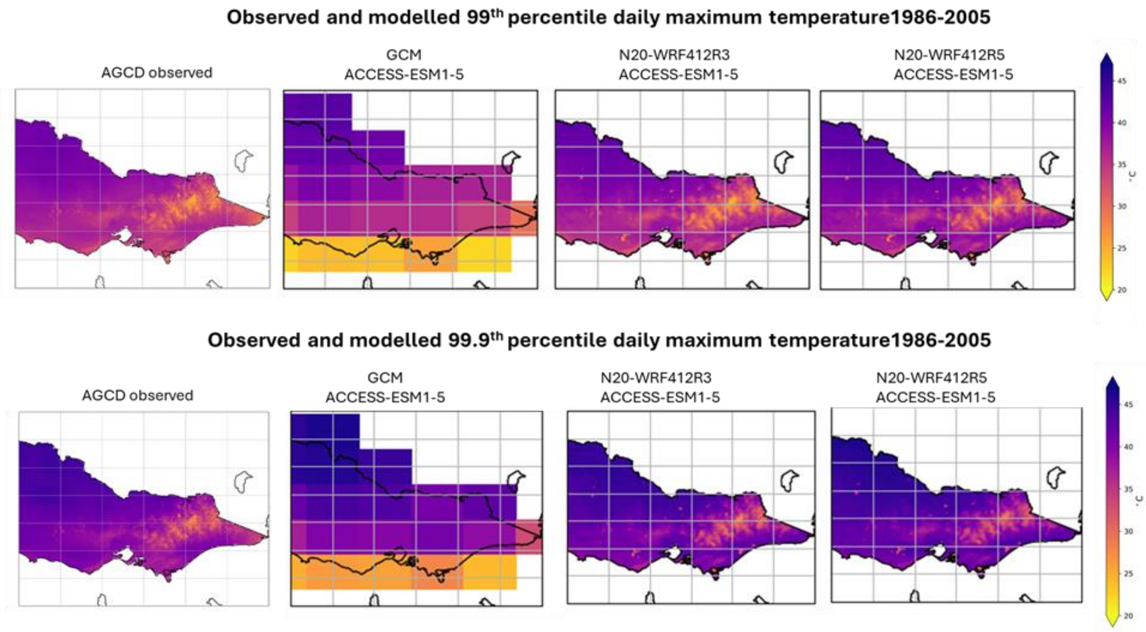


Figure 9 99.9th Observed (AGCD) and modelled values for the 99.9th percentile daily maximum temperature (top) and the 99.9th percentile daily maximum temperature (bottom) from 1986-2005. Modelled values are shown for one GCM, ACCESS-ESM1.5, and the two NARCliM2.0 RCM downscaled versions, N20-WRF412R3 and N20-WRF412R4.

Figure 10 shows the spatial patterns of bias between the observed 99th percentile daily temperatures from 1986-2010 and the modelled temperatures over the same period, from the 5 GCMs downscaled by the two NARCliM2.0 RCMs. The GCMs tend to have a warm bias (overestimating extreme temperatures), and the magnitude of this warm bias is in many places more than 3.5 °C, larger than that for mean temperatures. The biases in the RCM representation of extreme temperatures roughly mirror those of the host GCMs, although tend to be smaller. This is likely because of the cold bias present in the RCMs for mean temperature (Figure 8), especially in the WRF412R3 version and along the coastal and mountainous areas. The same figure but for the 99.9th percentiles daily temperatures shows quite similar results and is included in Appendix Figure 58. These biases in extreme temperatures highlight the importance of bias correction if using raw model output. These biases are much less critical when assessing future projected changes from a modelled historical to modelled future period, under the assumption that the model bias is also present in the future.

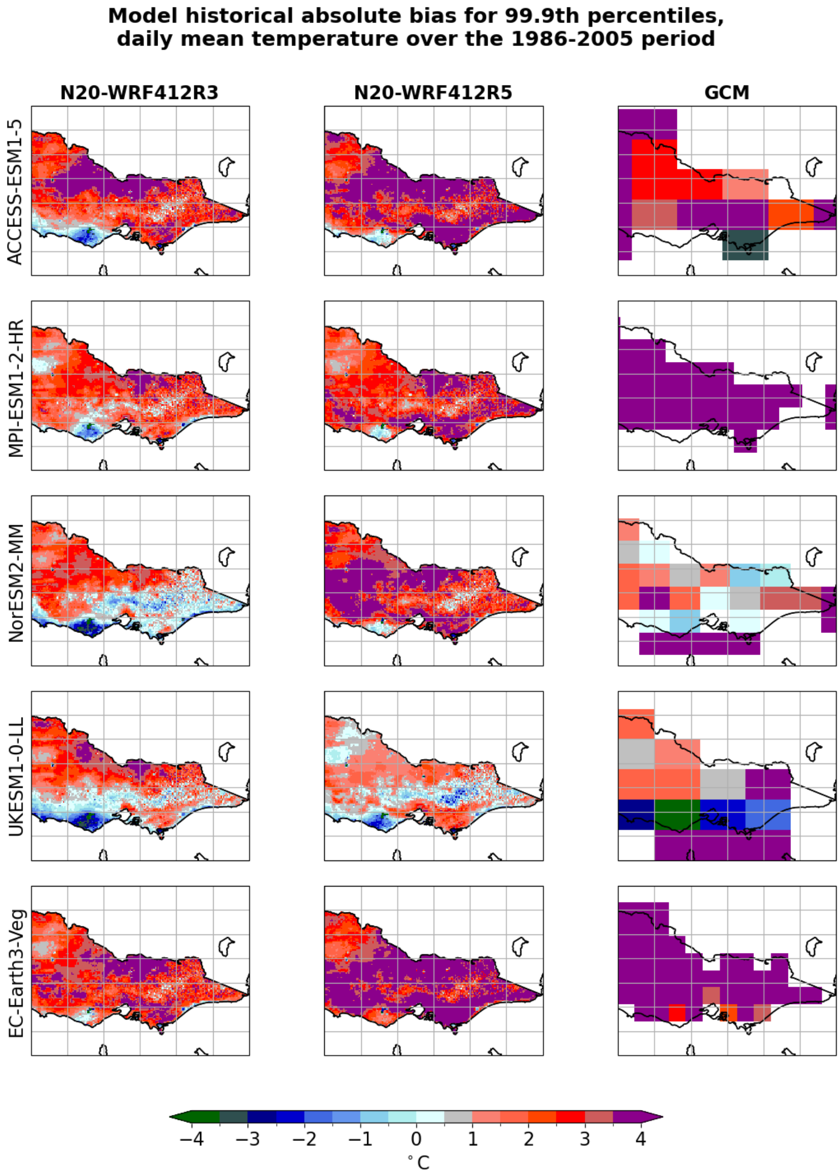


Figure 10 Temperature evaluation maps for 99th percentile of annual temperature (mean 2m air-surface temperature) showing the difference between modelled temperatures from 1986-2005 and observed (AGCD) data. Blue values mean the model is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias). The first two columns show results from the two different versions of the downscaling model (N20-WRF412R3 and N20-WRF412R5) and the third column shows the results for the host GCM. The five rows show the five different GCMs

3.2.4 Evaluation of mean rainfall

Figure 11 shows the mean annual rainfall bias for the N20-WRF412R3 and N20-WRF412R5 NARCliM2.0 versions respectively, alongside the bias plots for the corresponding host GCMs. The five host GCMs show a range of biases from wet to dry.

There is a marked difference in the pattern of biases between the two NARCliM2.0 versions. Version R3 tends to have a wet bias, especially if the host model also has a wet bias, but sometimes even in areas where the GCM had a dry bias. For two models there is also a relatively clear dry bias on the inland side of the Victorian Alps. Version R5 tends to show a dry bias, often larger than the dry bias in the host GCM and sometimes reversing the GCM bias from wet to dry. Similar to the temperature results, this wet bias is present in the RCM even when given high quality inputs from reanalysis (Di Virgilio, et al., 2022), which signals a feature of the RCM, not just an issue in the GCM-RCM interaction. The magnitude of the bias is notable and is considered when assessing confidence, however we do not use this as a basis to reject models. Despite having a bias, the model can still provide a valuable simulation of future change under enhanced greenhouse gasses. Model bias is of less concern when calculating the projected change between modelled historic and modelled future simulations, assuming the model bias remains constant and is negated by assessing the difference rather than absolute values.

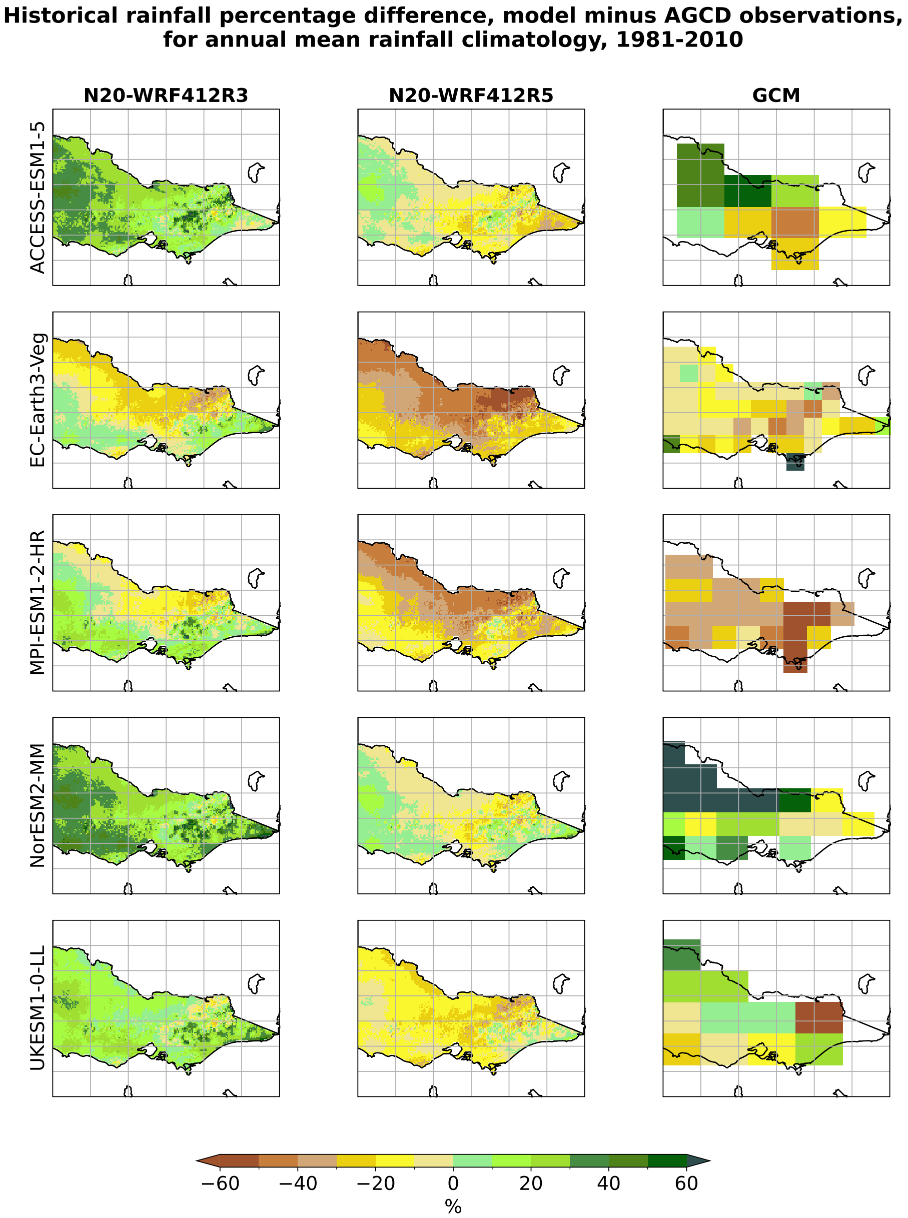


Figure 11 Bias evaluation for the NARCliM2.0 RCMs and CMIP6 GCMs, with bias presented as a % difference between the observed AGCD annual rainfall and the modelled annual rainfall, from 1981–2010. Green values mean the model is wetter than the observations and yellow/brown shows the model is drier than the observations. The first two columns show results from the two different versions of the downscaling model (N20-WRF412R3 and N20-WRF412R5) and the third column shows the results for the host GCM. The five rows show the five different GCMs

Seasonal changes in rainfall are of high relevance both in terms of impacts and also in terms of different potential mechanisms at play. As well as the annual biases already looked at, we reviewed seasonal rainfall biases in both RCM ensembles (Appendices Figure 59, Figure 60). Both RCM versions show a strong wet bias in the winter and dry bias in autumn, although with N20-WRF412R5 showing the drier and less wet biases. Biases are more mixed for summer and spring, with N20-WRF412R5 tending to have a dry bias, especially in spring inland of the Victorian Alps. N20-WRF412R3 shows more wet bias for summer and a mixture for spring, depending on the GCM.

3.2.5 Rainfall extremes

The high resolution NARCliM2.0 modelling improves the representation of rainfall extremes (99^{th} and 99.9^{th} percentile daily rainfall) compared to the host GCM, in particular capturing the observed heavier rainfall extremes over the Alps, east Gippsland and some coastal areas (example for ACCESS-ESM1.5 shown in Figure 12).

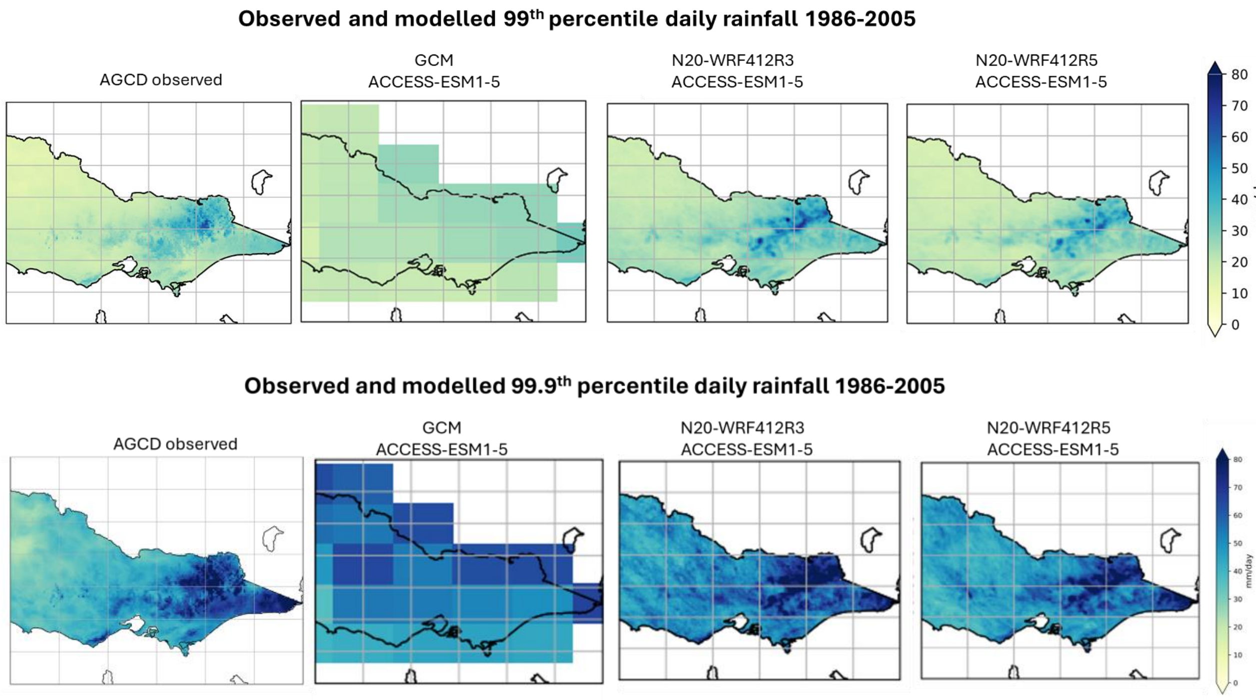


Figure 12 The 99^{th} percentile (top) and 99.9^{th} percentile (bottom) extreme daily rainfall value in observed data (AGCD, left) and examples from one GCM (ACCESS-ESM1.5) and that GCM downscaled by the two NARCliM2.0 RCMs (N20-WRF412R3 and N20-WRF412R5). Values are averages from the 1986-2005 historical period in mm/day.

Bias in the model representation of 99^{th} percentile daily rainfall is shown in Figure 13. The same figure but for 99.9^{th} percentile rainfall is shown in Appendix Figure 61. The GCMs range from underestimating rainfall extremes (brown) to overestimating them (green), especially in north-western Victoria. The NARCliM2.0 downscaling tends to reduce the magnitude of the rainfall biases, however with a tendency to have additional wet bias in the R3 RCM version, especially over Gippsland and the alps. This wet bias in the R3 RCM version is also present when downscaling high quality inputs from reanalysis (Ji, et al., 2024).

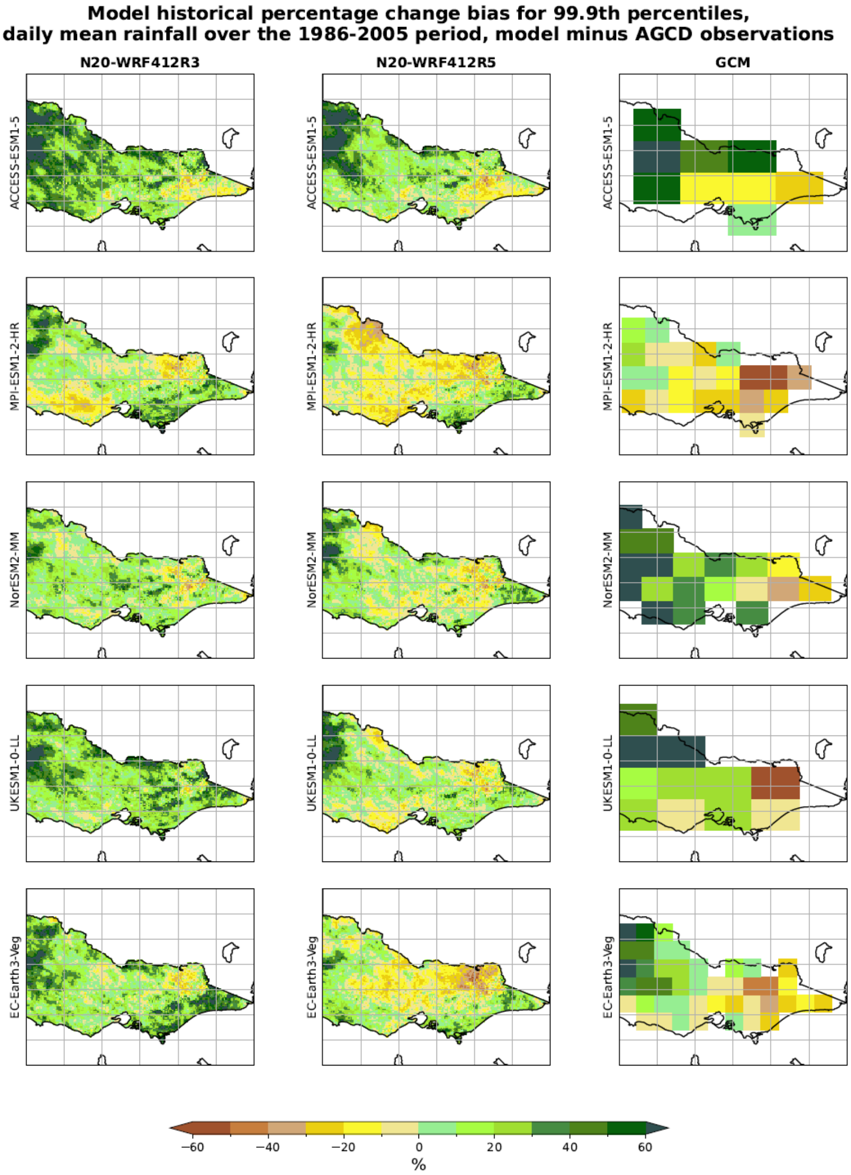


Figure 13 Rainfall evaluation maps for 99th percentile of daily rainfall, showing the percentage difference between modelled rainfall from 1986-2005 and observed (AGCD) data. Brown/yellow values mean the model is showing less extreme amounts of rainfall at the 99th percentile, and green shades shows the model has more extreme rainfall at the 99th percentile than the observations. The first two columns show results from the two different versions of the downscaling model (N20-WRF412R3 and N20-WRF412R5) and the third column shows the results for the host GCM. The five rows show the five different GCMs.

3.3 CMIP6 and CORDEX model evaluation

The high resolution NARCLIM2.0 ensemble simulations depend on the input from the host CMIP6 models, so will inherit limitations and biases from these stages. As a whole, CMIP6 shows incremental improvements over CMIP5, but retains some of the long-standing issues models have (IPCC 2021). For features relevant to Australia and for the climate over Australia, CMIP6 also shows incremental improvement over CMIP5 (Grose et al. 2020). Some evaluation of CMIP6 GCMs has been conducted by various downscaling groups as part of model selection for downscaling experiments (DiVirgilio et al. 2022 for NARCliM2.0, Grose et al. 2023 for CORDEX).

However, there are many open questions about the appropriate evaluation metrics for GCM selection.

We assessed the option of rejecting models which had been evaluated as less suitable for downscaling in Australia by Grose et al. (2023), however the Grose et al. evaluation was not deemed comprehensive enough to warrant rejecting any of the GCMs. We compared CMIP6 ensemble projections from 34 available GCMs and with projections from a subset of 23 better performing GCMs and found very little difference in the results. Figure 14 shows the individual rainfall/temperature projections for all individual GCMs and there is no clear pattern of poorly evaluated models skewing in any particular direction. It was decided to use all 34 GCMs. Our approach of presenting the projections as the 10th to 90th percentile range from all models means that the main results are not excessively affected by outlier models.

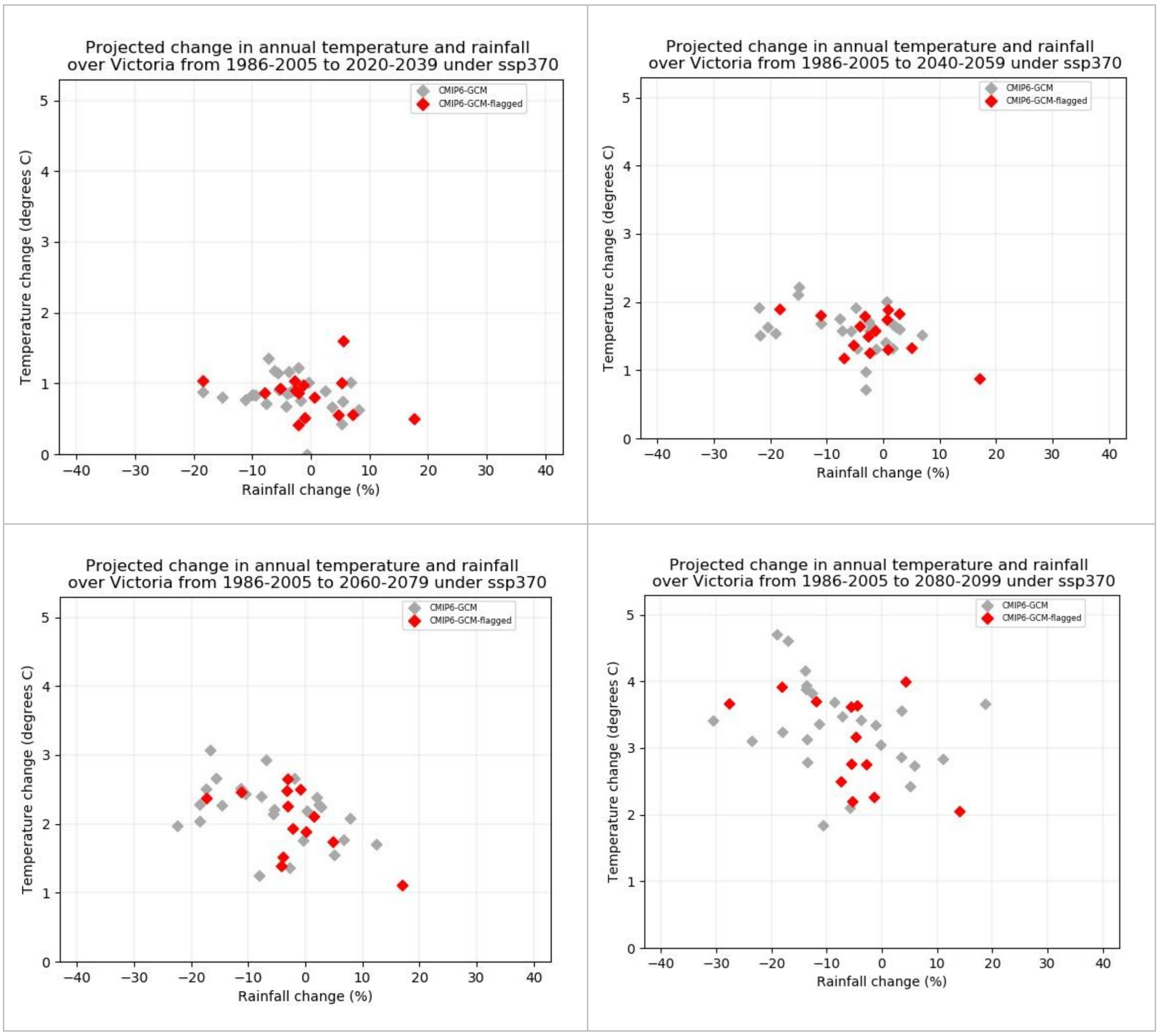


Figure 14 Projected changes in annual temperature (vertical axis) and rainfall (horizontal axis) for all CMIP6 GCMs used in this study, with red points highlighting GCMs which were evaluated as less suitable for Australia by Grose et al. (2023). The four plots show projections for four different future time periods under a high emissions scenario, clockwise from top left: 2030, 2050, 2090 and 2070.

Evaluation of the emerging national downscaled ensemble is ongoing by the responsible modelling groups, but initial results of the other (non NARCLIM2.0) regional model simulations suggests they are generally close to observations and an improvement over the CMIP6 hosts.

An evaluation of BARPA found good overall performance (Howard, et al., 2024), with a tendency for a cool bias over Victoria and reduced diurnal range (warm bias for minimum temperatures, cool bias for maximum temperatures) and wet bias over most of Victoria except along the coastal areas which showed a dry bias. Temperature trends between 1985-1994 and 2005-2014 were mostly well represented over the Southern Slopes and Murray Basin regions (which encompass Victoria) although observed increases in hot days, hot nights and summer days seem to be under represented in the model simulations. Observed cool season rainfall decline in the Murray Basin was well captured in the model simulations.

Evaluation of the Qld-CCAM found that the downscaled simulations over Australia showed an improvement over the host GCMs, especially for mean and seasonal rainfall and temperature and rainfall extremes (Chapman, et al., 2023).

4 Victoria’s changing climate

This chapter describes observed past changes and projected future changes in various climate variables, including average temperature and rainfall, extreme temperature and rainfall, heatwaves and drought. Some information about recent changes in climate is presented to provide context, but the focus is on the new analysis of projected future changes, drawing on the multiple ensemble approach which incorporates simulations from CMIP6 GCMs, nation-wide downscaling and fine resolution NARCliM2.0 downscaling.

4.1 Climate features and drivers

Anthropogenic warming, through the enhanced greenhouse effect, is driving changes to the energy balance and related physical processes of the climate system. These changes have flow-on effects to the atmospheric circulation of the southern hemisphere, including over Victoria. Persistent shifts in the amplitude, frequency and duration of the major modes of climate variability may also occur. Such changes would affect the averages, variability and extremes of the climate of Victoria. Some examples of projected or observed changes to the modes of climate variability influencing Victoria’s climate include:

- The dominant westerly winds and associated weather systems, which bring cool season rainfall to Victoria, are projected to weaken and/or move further south resulting in less rainfall over Victoria. This is related to the poleward shift of the Hadley Cell, and trend to more positive phase Southern Annular Mode, increasing the chance of reduced winter rainfall (McKay, et al., 2023).
- The subtropical ridge, the belt of high pressure located over Australia, has increased in strength resulting in a trend towards higher pressure and less rainfall over Victoria. The frequency of high-pressure systems over southern Australia, including Victoria, has increased, accounting for around 30% of the observed cool-season rainfall decline (Pepler, et al., 2019).
- Declines in cool season rainfall are also associated with increases in the frequency of positive Indian Ocean Dipole (McKay et al., 2023).
- Recent research also indicates that the likelihood of drought-breaking extreme rainfall events over southeast Australia is projected to decline under anthropogenic warming (Holgate, et al., 2023).

There is a range of projected change in climate features from models which would result in a range of rainfall change from little change to significant reductions. However, there is some evidence that the projected changes leading to significant reductions are more plausible than those resulting in little change (Grose et al. 2017a; Grose et al. 2019a). Notwithstanding, further evidence is needed before the range of plausible change can be confidently reduced. Therefore, at the time of writing the entire range should be considered plausible. Also, the latest climate modelling reviewed here suggests that wet periods in the future may occur due to an increase in annual rainfall variability (see Section 4.5.3).

Changes in such features at the broad scale can interact with Victoria’s physical environment – such as coastlines and mountain ranges – causing regional change. For example, a warmer atmosphere and changes to the atmospheric flow over the Australian Alps may drive an enhanced rainfall reduction on the inland slopes of the Alps (Grose, et al., 2019). However, the new range of climate modelling suggests a different spatial signature over mountains is also possible (see Section 5.3). Further analysis of drivers important to rainfall in Victoria are covered in outputs from the Victorian Climate Initiative (VicCI) (DELWP, et al., 2020).

4.2 Downscaled projections in the broader ensemble context

To fully explore the range of possible future climate conditions for Victoria, we look to the projected changes in annual average temperature and rainfall from all the available NARCliM2.0 and nation-wide downscaling simulations and compare them with changes directly from the CMIP6 GCMs (with no downscaling).

Figure 15 gives an overview of the projected changes for annual average temperature and rainfall for all global (GCMs) and regional (RCMs) climate models for 2080-2099 under SSP3-7.0. This end-of-century time period and high emissions scenario affords the best opportunity to identify similarities and differences between the simulations related to climate change (as opposed to phasing of natural variability). The downscaled GCMs are labelled to allow for a comparison of the projected change between the host GCMs and downscaled RCMs. Equivalent plots for seasonal rainfall and temperatures are shown in the Appendix, Figure 62, to allow the changes in different seasons to be compared.

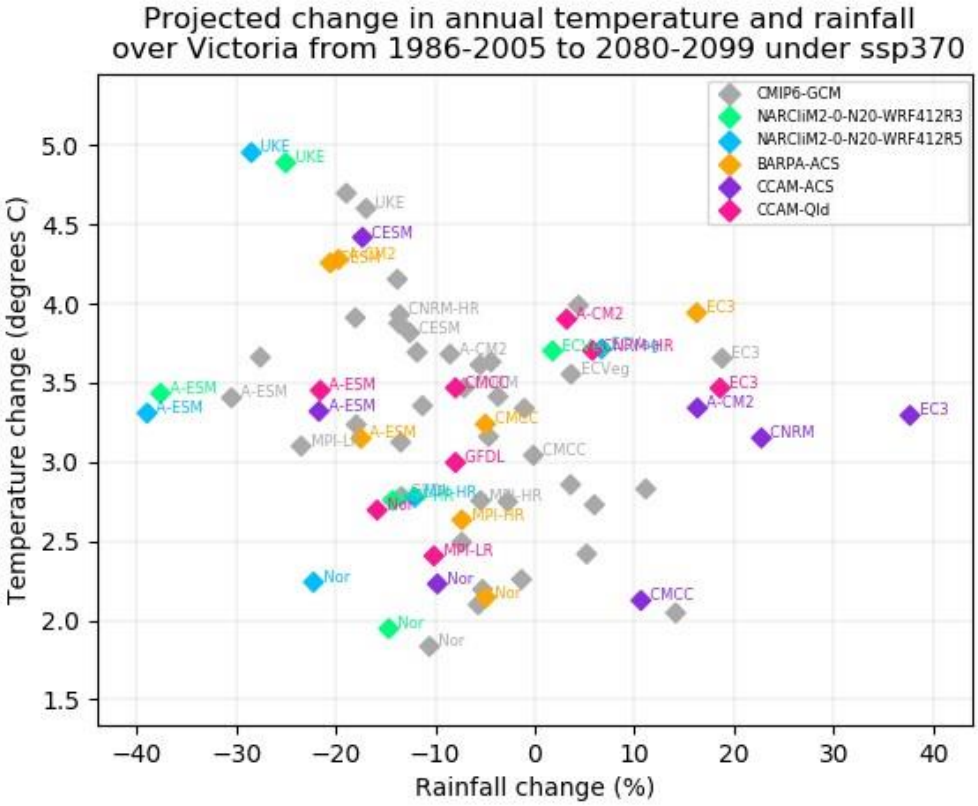


Figure 15 Projected change in mean annual rainfall (horizontal axis) and temperature (vertical axis) over Victoria under a high emissions scenario (SSP3.70), from a 1986-2005 baseline to a 2080-2099 future period. Each point represents a single model, with colours indicating the downscaling ensemble to which it belongs. GCMs are shown in grey and the different RCMs indicated by the coloured legend. Model names are shown for RCMs and host GCMs which were downscaled by RCMs.

Notably, the largest changes (i.e., greatest warming, wetting and drying) are all projected by RCMs rather than GCMs. This means that the RCMs have in some cases significantly changed the signal from the host GCM and represent possible climate futures which would be missed using the GCMs alone. No ensemble of RCMs or GCMs represents the whole range in entirety on its own. This highlights the importance of considering multiple sets of models to building an overall picture of the future projected climate and inform the range of projections to be communicated and used by decision makers. It highlights the risks of under-sampling uncertainty by limiting projections to a subset of models without first considering where they sit in the whole range of projections. In the projections presented in this report, wherever possible, we show the projections data from individual sets of models, the GCM ensemble and all the downscaling simulations combined.

NARCliM2.0 downscaled models represent the greatest warming and greatest drying bounds of the projections but do not represent the wetter futures projected by some of the other GCMs and RCM members. A much wetter future is shown by the EC-Earth3 GCM and the downscaled versions of this GCM from CCAM-ACS, CCAM-Qld and BARPA, with the CCAM-ACS downscaling showing significantly enhanced wetting relative to the GCM.

4.3 Average temperature

The enhanced greenhouse effect, caused primarily by ongoing anthropogenic greenhouse gasses emissions, is driving changes to the global energy balance and causing warming of the atmosphere, land and oceans. Average temperatures across Victoria have risen clearly in response and are projected to continue increasing. This section outlines observed and future changes in Victoria's average temperature.

Key messages:

- Victoria's average temperature has warmed approximately 1.2 °C since observational records began, or 1.4 °C since the pre-industrial period (from 1850-1900 to 2001-2020). This is slightly more than the global average observed warming.
- Victoria's climate will continue to warm over the coming decades. Warming will only plateau or stabilise if global emissions reach net zero (*very high confidence*).
- The likely warming from a 1986-2005 baseline[13] to mid-century (2040-2059) is 0.5– 1.5 °C (1.1 °C median) under the low emissions scenario or 1.1–1.9 °C (1.5°C median) under high emissions. However, there is a low-likelihood, high-warming future represented by some simulations, showing warming up to 2.5 °C by 2050 under high emissions.
- The likely warming from a 1986-2005 baseline to end of century (2080-2099) is 0.6–1.8 °C (1.0 °C median) under low emissions or 2.2–3.6 °C (3.1 °C median) under high emissions. However, there is a low-likelihood, high-warming future represented by some simulations, showing up to 5.0 °C by 2090 under high emissions.
- Victorian warming is expected to continue at a similar rate to the global warming rate, projected to reach 1.8–2.3 °C (median 2.0 °C) warmer than the 1850-1900 pre-industrial

[13] For reference, there has been 0.7 °C of warming already from the 1986-2005 baseline to the most recent decade 2011–2020, in addition to 0.7 °C warming from pre-industrial to the 1986–2005.

period, when global warming reaches 2 °C. The 2 °C warming level may be reached in the second half of the century under low emissions or from 2037-2056 under high emissions.

- Warming over Victoria is projected to be 2.5–3.4 °C (median 2.9 °C) warmer than the 1850-1900 pre-industrial period, when global warming reaches 3 °C. The 3 °C warming level may be reached from 2055-2075 under high emissions scenario, but not reached at all under the low emissions scenario.
- Warming is projected to be most pronounced in maximum daily temperatures in summer. Most of the high-resolution modelling shows patterns of enhanced warming over the higher elevation areas of the Great Dividing Ranges, i.e. affecting the Victorian Alps.

4.3.1 Observed mean temperature changes

The average temperature across Victoria has warmed by approximately 1.2 °C since the first two decades of official Bureau of Meteorology records[14], and approximately 1.4 °C (range 1.2–1.6 °C) since pre-industrial times[15]. The additional 0.2 °C warming between 1850-1900 and the start of official records is estimated from paleo reconstructions and models (Grose et al. 2023). Figure 16 shows the annual temperature over Victoria and highlights the various baselines referred to in this report. The observed warmings from the pre-industrial period to the more recent 1986-2005 and 1995-2014 baselines are approximately 0.7 °C and 1.0 °C respectively.

The observed 1.4 °C warming over Victoria since the pre-industrial baseline is more than the global average of 1.2 °C(Figure 1), but slightly less than the global land-only average (which is the same as the Australian average warming) of 1.6 °C since 1850-1900 (Grose, et al., 2023).

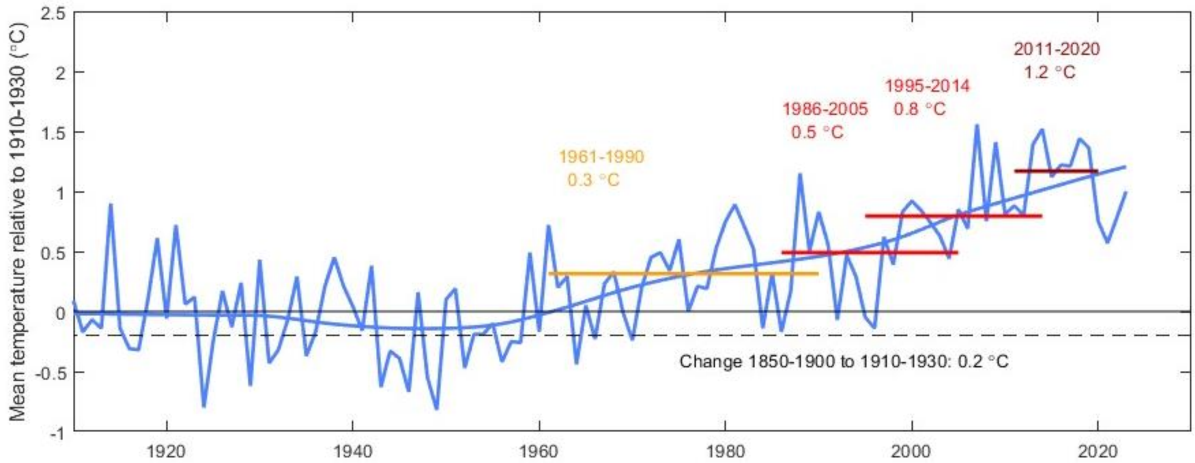


Figure 16 Observed annual mean temperature over Victoria from 1910-2023, relative to 1910-1930 (the beginning of official observational records). The 0.2 °C change between 1850-1900 and the start of official records is estimated from paleo reconstructions and models (Grose et al. 2023) and shown by the dashed horizontal line. The coloured horizontal bars show the average change for various baseline periods.

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[14] ACORN-SAT (Trewin, 2013) available online. Comparison of climatology from 1910-1930 to 2011-2020, but linear trend from 1910-2020 or 1910-2023 gives the same result

[15] Approximated from a 1850-1900 baseline (Grose, et al., 2023)

In line with the global and Australian trends, Victoria warmed relatively gradually for most of the 20th century, with 0.5 °C warming observed from the start of records to 1986-2005 (Figure 16). Recent decades have seen much more rapid warming, with a further 0.7 °C warming from 1986-2005 to 2011-2020. The last three years (2021-2023) have been cooler relative to the preceding decade but were still well above the long-term average.

4.3.2 Summary of projected temperature changes over the 21st century from CMIP6 GCMs

Victoria's climate will continue to warm over the coming decades and will only plateau or stabilise if global emissions reach net zero (*very high confidence*). Over the long term, warming is highly dependent on the emissions scenario while in the near term, the difference in the average amount of warming between emissions scenarios is less significant.

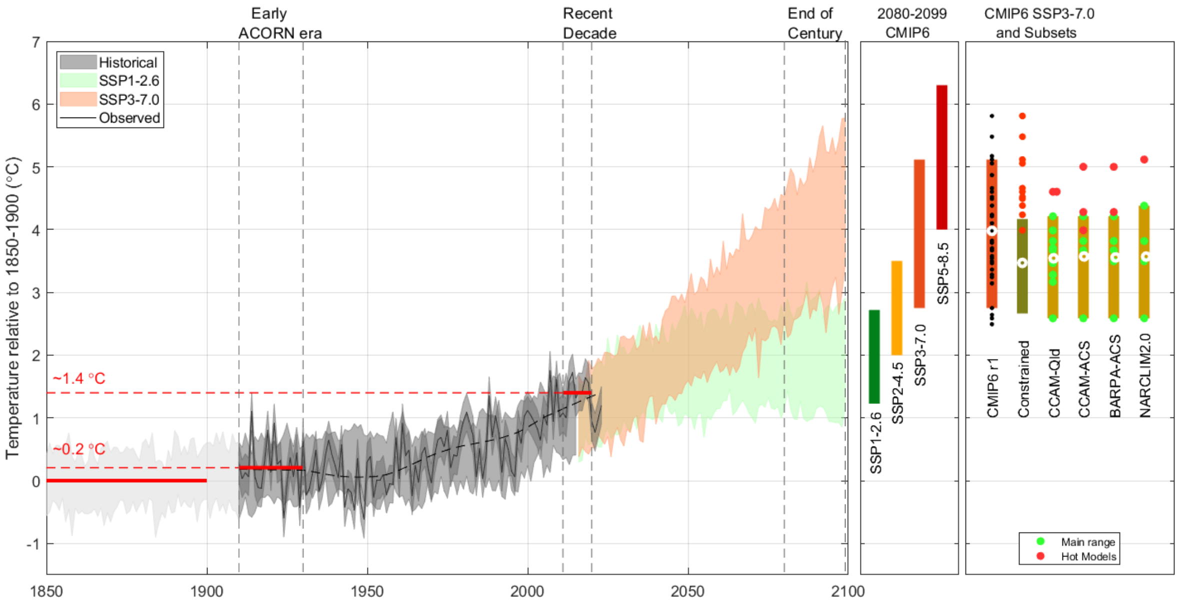


Figure 17 Observed historical, modelled historical and modelled future change in average annual temperature over Victoria. The temperature change is shown as degrees Celsius change relative to a pre-industrial baseline (1850–1900). Historical observed temperature is shown by the thin black line (dark grey band indicates the observed uncertainty), modelled historical temperature from CMIP6 GCMs is shown by the light grey shading. The warming from the pre-industrial baseline to the beginning of instrumental records in Australia (1910-1930) is estimated at 0.2 °C (Grose, et al., 2023) and 1.4 °C to the most recent decade (2011-2020). Future warming under SSP1-2.6 and SSP3-7.0 are shown out to 2100 in orange and green shading (intermediate green/orange shading is where the ranges for the two SSPs overlap). Shaded regions show 10th to 90th percentile ranges across data from all CMIP6 GCMs. In the panels to the right, the range of warming by the end of the century (2080-2099) is indicated for four SSPs and also for the various model subsets selected for downscaling by various regional climate models. The constrained CMIP6 bar and all RCM bars show change only from the models with effective climate sensitivity (ECS) within the likely range, dots above are from the high-warming models.

Figure 17 shows observed and modelled historical warming as well as future modelled warming out to 2100 from the CMIP6 GCM ensemble under low emissions (SSP1-2.6) and high emissions (SSP3-7.0). It highlights that under SSP1-2.6, with emissions reducing to net zero after 2050, temperature continues to rise before levelling off by around 2050 and remaining between 1°C and just under 3°C degrees warmer than pre-industrial out to 2100. Under high emissions, warming continues to increase throughout the century, reaching around 3–5 °C above pre-industrial by 2090 (2080-2099). Individual models with high climate sensitivity (beyond the likely range) are indicated separately and some of these indicate warming greater than 5 °C under high emissions.

Figure 17 also shows the projected range of change by 2080-2099 under other emissions scenarios[16]. The moderate emissions scenario, SSP2-4.5, sits between SSP1-2.6 and SSP3-7.0. The very high emissions scenario, SSP5-8.5, which is a high-growth, fossil-fuel intensive scenario considered less likely to eventuate, results in warming of more than 6 °C in some models.

4.3.3 Projected temperature changes over the 21st century from multiple ensembles

The range of projected temperature change under low and high emissions scenarios and two time-horizons (2050 and 2090) is shown in Table 6. The projected changes in temperature for the combined RCMs is very similar to that projected by the CMIP6 GCMs, generally within 0.1 °C. This indicates that the combined RCM ensemble represents the range from all the GCMs well. Note that 0.7 °C of warming has been experienced already from the 1986-2005 baseline to 2011-2020.

Table 6 Projected changes in average annual mean temperature from 1986-2005 to 2050 (2040-2059) and 2090 (2080-2099) under both the low emissions (SSP1-2.6) and high emissions (SSP3-7.0). Projected changes are shown for the constrained and unconstrained CMIP6 GCM ensemble, the constrained and unconstrained combined RCM ensemble (comprising of all downscaling: CCAM-ACS, CCAM-Qld, BARPA-ACS and NARCliM2.0), and the two NARCliM2.0 ensembles. 'Constrained' indicates that models with equilibrium climate sensitivity greater than 4.5 or less than 2.3 are excluded. Ensemble projected change is in degrees, shown as median (10th to 90th range in brackets for CMIP6 GCMs and All RCMs) (min to max range in brackets for NARCliM2.0). The asterisk (*) denotes results at the upper end of the range are from 'low-likelihood high-warming' GCMs.

MULTI-ENSEMBLE PROJECTED CHANGE (°C) IN MEAN ANNUAL TEMPERATURE, FROM 1986-2005 BASELINE				
ENSEMBLE	2050		2090	
	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)
Projected temperature change (°C) from CMIP6 GCM and combined RCM ensembles. The values shown are median with the ensemble 10th to 90th percentiles range in brackets.				
CMIP6 GCMs (unconstrained)	1.2 (0.6 to 1.5)	1.6 (1.2 to 2.0)	1.2 (0.8 to 1.9)	3.4 (2.3 to 4.2)
CMIP6 GCMs (constrained)	1.1 (0.5 to 1.5)	1.5 (1.1 to 1.9)	1.0 (0.6 to 1.8)	3.1 (2.2 to 3.6)
All RCMs (unconstrained)	1.1 (0.5 to 1.5)	1.6 (0.9 to 2.1)	1.3 (0.6 to 1.8)	3.3 (2.2 to 4.3)
All RCMs (constrained)	1.0 (0.5 to 1.4)	1.5 (0.9 to 1.8)	1.1 (0.5 to 1.5)	3.2 (2.2 to 3.7)
Projected temperature change (°C) from selected RCM ensembles. The values shown are median with ensemble minimum to maximum range in brackets.				
NARCliM2.0 (WRF412R3)	1.0 (0.4 to 1.5)	1.6 (0.6 to 2.4*)	1.3 (0.4 to 1.7)	3.4 (1.9 to 4.9*)
NARCliM2.0 (WRF412R5)	0.9 (0.5 to 1.5)	1.6 (0.8 to 2.5*)	1.1 (0.6 to 1.7)	3.3 (2.2 to 5.0*)

[16] The very low emissions scenario, SSP1-1.9, is not shown

The projected warming from the ECS-constrained ensembles, with low-likelihood high-warming models excluded, is sightly less than the full ensemble, especially by 2090 under the high emissions scenario and especially the upper end of the range.

The warming to mid-century (2040-2059) projected by the ECS-constrained CMIP6 GCM ensemble is 0.5–1.5 °C (1.1 °C median) under low emissions and 1.1–1.9 °C (1.5 median) under high emissions, from a 1986-2005 baseline. At the extreme upper end, the NARCliM2.0 simulations from the low-likelihood high-warming UKESM1-0-LL model future show up to 2.5 °C warming by 2050 under high emissions.

For the end of the century (2080-2099), projected warming is 0.6–1.8 °C (1.0 °C median) under low emissions and 2.2–3.6 °C (3.1 median) under high emissions. At the extreme upper end, the NARCliM2.0 simulations from the low-likelihood high-warming UKESM1-0-LL model shows up to 5 °C warming by the end of the century under high emissions.

Figure 18 shows this information graphically for all time horizons and all model ensembles. The projected changes from the various regional climate model ensembles are similar to each other and to the CMIP6 GCMs as a whole. This is expected, as the sub-set of host models were selected to be representative of CMIP6 as a whole, and the regional modelling doesn't alter the mean warming signal significantly at this spatial scale (meaning warming is broadly inherited from the large-scale processes in the host model, regional modelling aims to distinguish finer scale details and better resolve extremes, etc.).

However, there are some differences between the RCM ensembles. The NARCliM2.0 ensembles span the highest warming for SSP3-7.0 because of the inclusion of the low-likelihood high-warming UKESM1-0-LL GCM, which was not included in the other RCM ensembles. The NARCliM2.0 RCMs also further enhance the warming. Further investigation would be needed to understand the plausibility and reasons behind this enhanced warming, but previous VCP19 projections similarly showed enhanced warming in regional models.

Projected changes in average minimum and maximum daily temperatures are similar to projections for average temperature, although minimum temperatures warm slightly less and maximum temperatures slightly more (~0.5 °C difference by 2090 under high emissions).

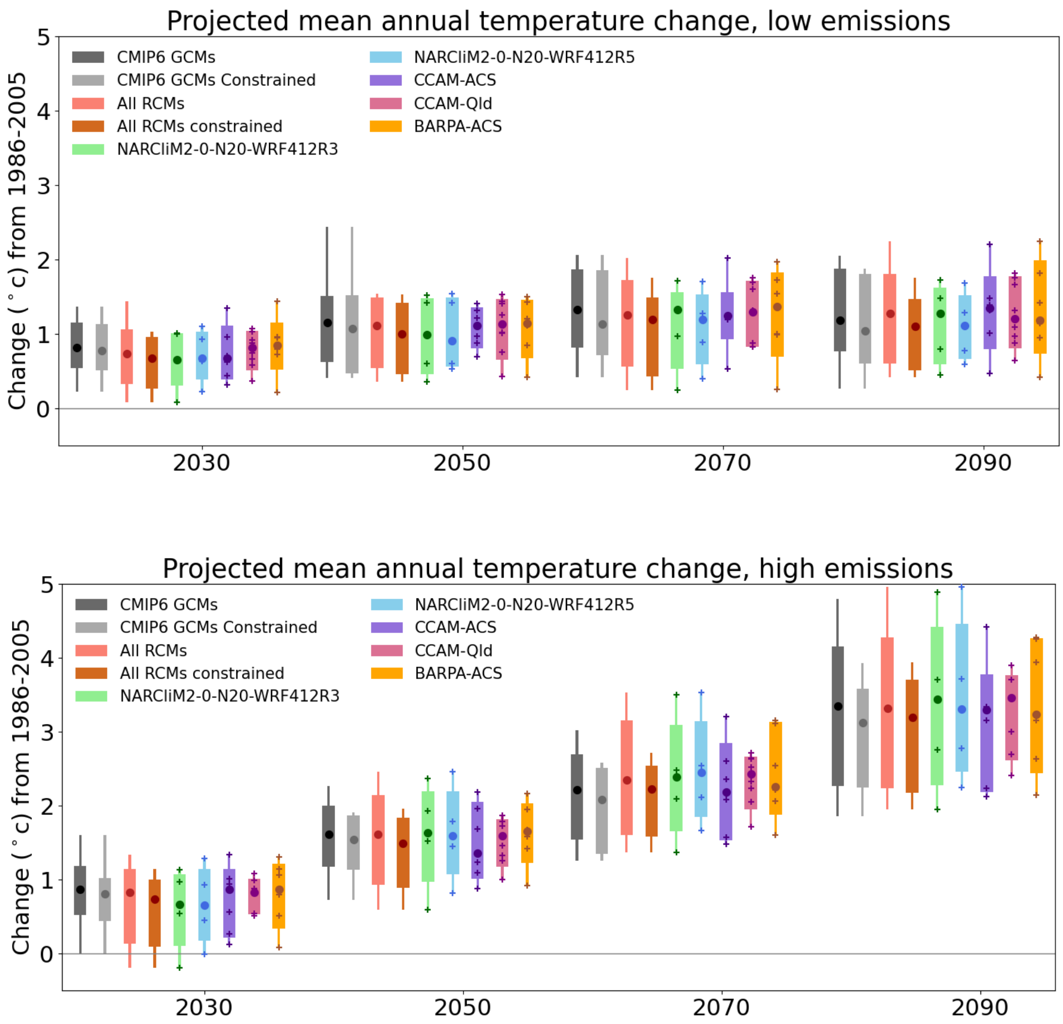


Figure 18 Change in annual mean temperature over Victoria as projected by various model ensembles under a low emissions scenario (SSP1-2.6, top) and high emissions scenario (SSP3-7.0, bottom), for 4 future time-periods. The thick bars show the 10th to 90th percentile range, the thin lines show the full minimum to maximum range and the dark circle shows the ensemble median. Individual models are shown as small spots for the individual RCM ensembles.

4.3.4 Temperature projections by Global Warming Levels

Future projected change in Victoria's climate can also be presented in terms of Global Warming Levels. An advantage of using projections by Global Warming Levels is that is allows a comparison of projections regardless of the emissions scenario. In the VCP19 projections (Clarke, et al., 2019), when using the GWL framework was less common practice, Victorian warming at a 2 °C global warming level was estimated using three different methods:

1. 2.4 to 2.6 °C using an extrapolation of observed historical warming
2. 2.2 to 2.5 °C using BRACE project modelling
3. 1.2 to 2.0 °C using a method of sampling from a set of 18 CMIP5 GCMs

The new projections show that Victorian warming is projected to be 1.8 °C to 2.3 °C warmer when the globe is at 2 °C global above pre-industrial levels, according to CMIP6 GCMs (Table 7).

When a 3 °C global warming level is reached, Victoria will be 2.5 to 3.4 °C warmer. These projections indicate that Victoria will increase closely in line with the global average temperature increase.

However, the observed warming rate over Victoria has been slightly higher than the global rate, and extrapolation of observed warming gives higher potential warming future warming (point 1 above). This indicates the possibility that future Victorian warming may be slightly above the global rate.

Table 7 shows warming level projections from the CMIP6 GCMs and NARCliM2.0 downscaling. Note that warming levels projections are not affected by the low-likelihood high-warming models, because the projections are not bound to timeframes so it does not matter if a model warms more rapidly. Projections by warming level are not presented here for the whole RCM ensemble.

Table 7 Projected changes in average annual temperatures over Victoria when global warming reaches 1.5 °C, 2.0 °C and 3.0 °C above pre-industrial climate (1850-1900). Projected change is given relative to a 1986-2005 baseline and the 1850-1900 pre-industrial baseline (calculated by adding the observed 0.7 °C warming from 1850-1900 to 1986-2005, to the future change from 1986-2005). Projected changes are shown for the CMIP6 models (median plus 10th to 90th percentile range of the ensemble projections) and the two different versions of the NARCliM2.0 downscaling (median with minimum and maximum range of the 5 models), simulated under the high emissions scenario.

	1.5 °C GLOBAL WARMING	2.0 °C GLOBAL WARMING	3.0 °C GLOBAL WARMING
Victorian warming from 1986-2005 baseline			
CMIP6 all models	**0.8 (0.6 to 1.1)**	**1.3 (1.1 to 1.6)**	**2.2 (1.8 to 2.7)**
NARCliM2.0 N20-WRF412R3	0.7 (0 to 1.2)	1.3 (0.8 to 1.9)	2.5 (2.0 to 2.6)
NARCliM2.0 N20-WRF412R5	0.8 (0.1 to 1.2)	1.4 (0.9 to 1.8)	2.4 (2.1 to 2.6)
Victorian warming from 1850-1900 baseline (pre-industrial)			
CMIP6 all models	**1.5 (1.3 to 1.8)**	**2.0 (1.8 to 2.3)**	**2.9 (2.5 to 3.4)**
NARCliM2.0 N20-WRF412R3	1.4 (0.7 to 1.9)	2.0 (1.5 to 2.6)	3.2 (2.8 to 3.3)
NARCliM2.0 N20-WRF412R5	1.5 (0.8 to 1.9)	2.1 (1.6 to 2.5)	3.1 (2.8 to 3.3)

Near-term warming and tracking recent warming against projections

Despite the overall warming trend, there may still be periods of little warming or even relative cooling in the future due to natural variability. Conversely, there may also be periods when warming occurs more rapidly than the long-term trend. Temperatures will still vary year-to-year and decade-to-decade, influenced by processes such as the El Niño Southern Oscillation and related processes in the Pacific Ocean. However, the effect of a warming climate is persistently increasing the odds of hotter years, and the ongoing warming trend will dominate in the long-term.

Figure 19 shows the observed mean annual temperature anomaly over Victoria from 1950-2023, overlaid by the projected range of change from the whole CMIP6 GCM ensemble from 1995 (1986-2005) to 2030 (2020-2039), as well as the individual NARCliM2.0 downscaled ensemble members. The downscaling of the low-likelihood, high-warmingUK-ESM-1-0-LL GCM sits at the top of the GCM range for 2030. NARCliM2.0 downscaling of the three GCMs in the likely range of climate sensitivity compare closely to the CMIP6 range. Downscaling of the NorESM2-MM lower-warming GCM is not only at the low end of the CMIP6 range but in fact shows slight cooling. Observed temperatures have been tracking at the upper end of the CMIP6 and NARCliM2.0 projections from 1995 out to 2030, suggesting that the model range is a reliable indication of temperature trends so far, and are not overrepresenting potential warming. More years have been warmer than the average projected range than have been cooler, with the exception of the last 3 years which were slightly cooler over Victoria, but still significantly warmer than what previously would have been considered a cool year.

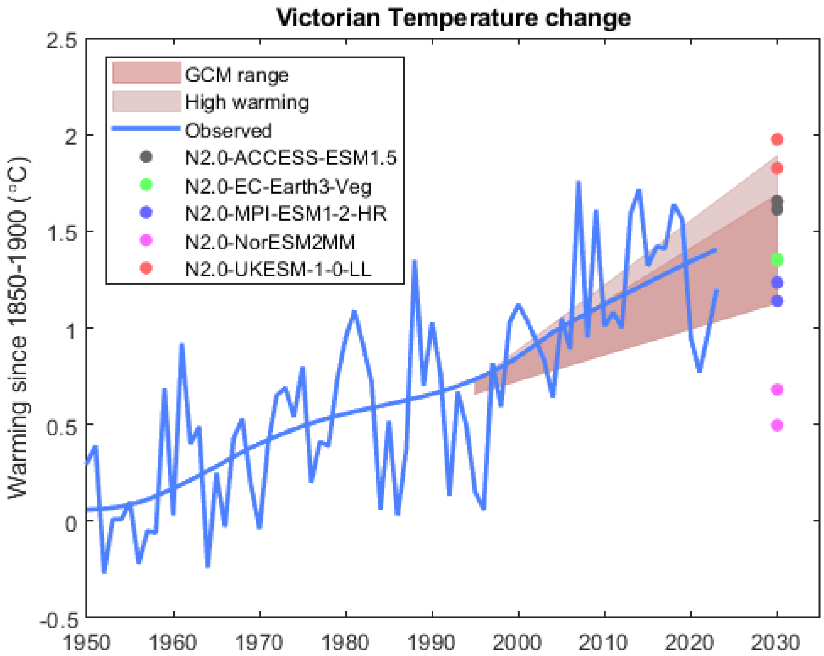


Figure 19 A comparison of observed annual temperature anomaly over Victoria from 1950 to 2023 in observations and projected range of temperature change under the high emissions scenario, out to 2030 from models. Warming is shown relative to the 1850-1900 pre-industrial baseline. Shown is the observed annual temperature (zigzag blue line), the smoothed observed trend (41-year lowess filter) and the projected range (10th to 90th percentile) of change from 1986-2005 to 2020-2039 from the GCM ensemble (pink shading, high warming GCMs light pink) and the projections for the same time period from the individual NARCliM2.0 downscaled ensemble members (coloured dots) are also shown.

As noted, the near term (2020-2039) projection from the two NARCLIM2.0 downscaling runs of the NorESM2-MM GCM not only show the lowest warming but show a slight cooling (of ~0.2 °C) from 1986-2005 to 2020-2039, as inherited from the host model (Figure 20). This projection falls below the 10th percentile projections from all the GCMs (i.e. outside the shaded pink range shown in Figure 19). Closer investigation shows that the NorESM2-MM GCM shows a short-term, transient, localised spot of cooling over southern Australia for this period. Such features are sometimes termed a 'warming hole' (Figure 20) and are temporary. A 'warming hole' occurred in observations in the northwest of Australia in approximately 1990-2015, and in other places such as the southeast USA, and while they are not as likely in southeast Australia as some other places, they are possible (Grose et al. 2017). Periods of cooling are more likely in this lower-warming model under lower emissions scenarios and occur once warming stabilises (see the series for SSP1-2.6 in Figure 30).

In interpreting this, it is important to keep in mind that simulations from climate models are not intended to predict individual events or sequences of events. The cooling period from 2010-2030 shown by NorESM2-MM represents plausible natural variability. However, it is not an extension of the observed sequence and in particular does not reflect the observed warming since 2010. This type of natural variability means that we should not expect future warming to happen at an even, steady rate. Average warming trends may be overlaid by periods where warming appears to slow or stall or conversely periods where warming may accelerate for a period of time.

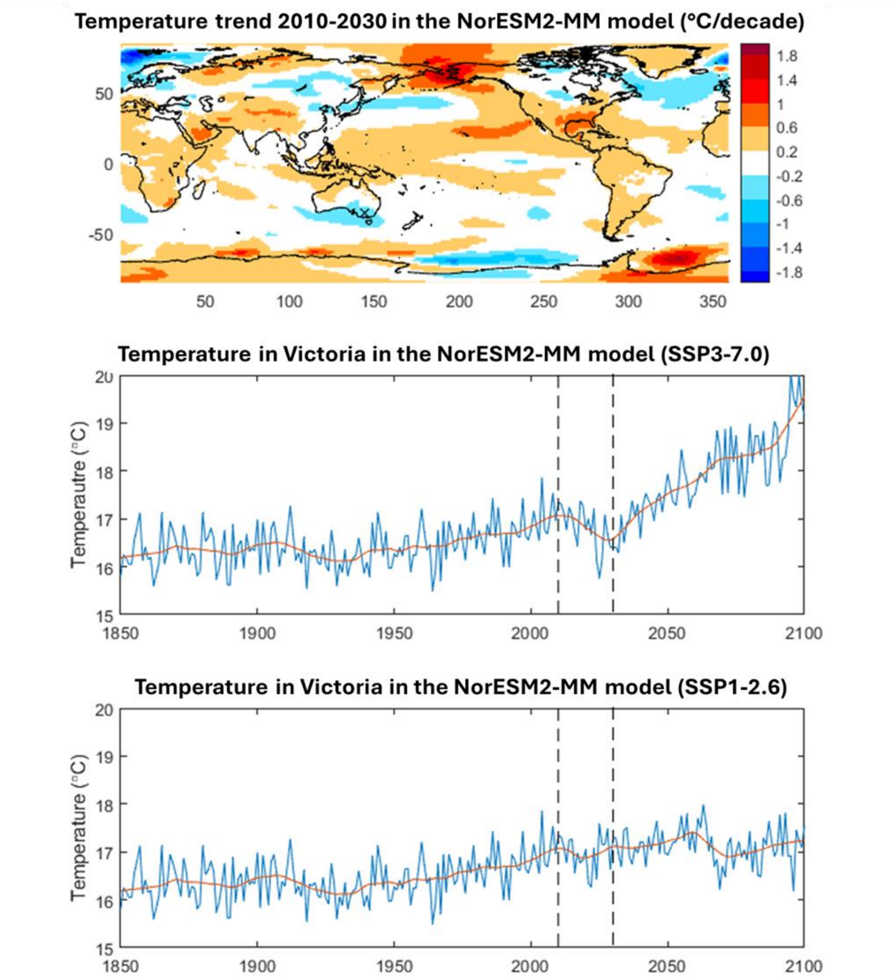


Figure 20 Illustrations showing a temporary cooling including over southern Australia simulated by the NorESM2-MM GCM. Top: Simulated linear trend in annual average temperature from in 2010-2030, showing area of temporary cooling including over southern Australia. Middle: Annual temperature timeseries over Victoria, as simulated by the NorESM2-MM GCM, under SSP3-7.0, and Bottom: the same under SSP1-2.6. This plot shows the annual and multi-year natural variability in temperature, and particularly a transient period of cooling around 2010-2030 in SSP3-7.0, and cooling periods in SSP1-2.6.

4.3.5 Seasonal and spatial patterns in warming

Seasonal projections for warming show a tendency for summer to show the greatest projected warming and also the largest range of uncertainty between models, and for winter to show the smallest change and a smaller uncertainty range. This is clearest in the case where the climate change signal is greatest (i.e. high emissions and end-of century) (shown in Figure 21).

Some of the regional downscaling shows enhanced warming in spring of approximately 0.5 °C, compared to the GCMs. Enhanced spring and summer warming relative to GCMs was also presented in the VCP19 downscaled projections, and this was attributed in part to the higher resolution simulation of the response of the land surface to lower rainfall in the regional model potentially contributing to warmer temperatures (Clarke, et al., 2019). There was *medium to high confidence* in the projection of enhanced spring warming in VCP19, and seeing this enhanced warming also in the VCP24 simulations may add to this confidence.

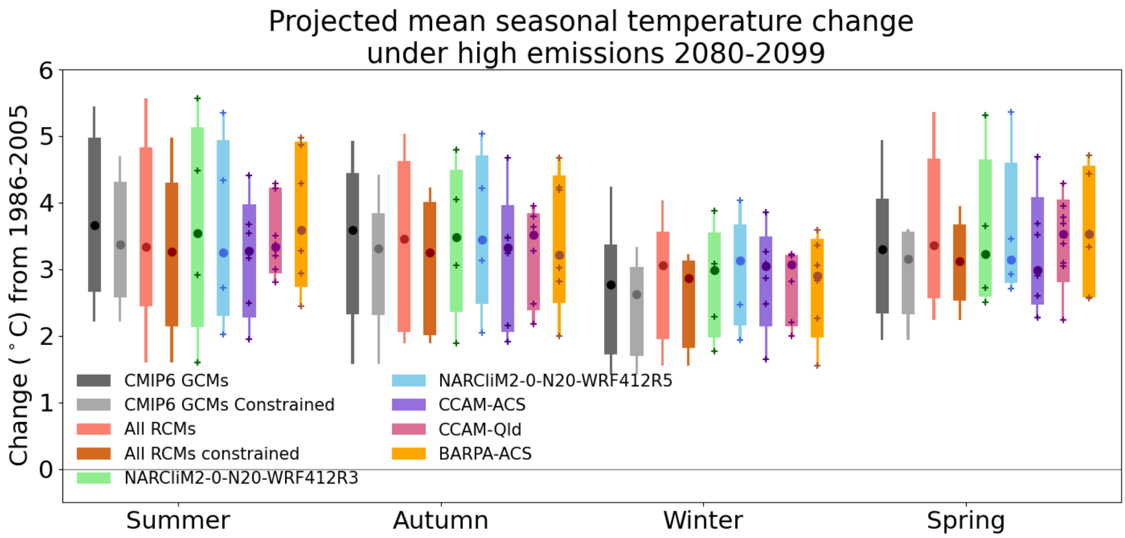


Figure 21 Change in mean seasonal temperature over Victoria as projected by various model ensembles for the high emissions scenario SSP3-7.0 for 2090 under high emissions scenario. The thick bars show the 10th to 90th percentile ranges, the lines show the full minimum-maximum range and the dark point the ensemble median.

Spatial patterns of future projected change in high resolution modelling can potentially reveal locally important signals of change. Figure 22 shows maps of projected change in mean maximum daily temperature for summer, from a selection of the models. Similar maps of change are provided for all models in the Appendix Figure 70 to Figure 73. A notable feature shown on the maps of projected change is that many of the high resolution simulations, from all downscaling models, show enhanced warming over the higher elevation areas of the Great Dividing Ranges, i.e. the Victorian (and NSW) Alps.

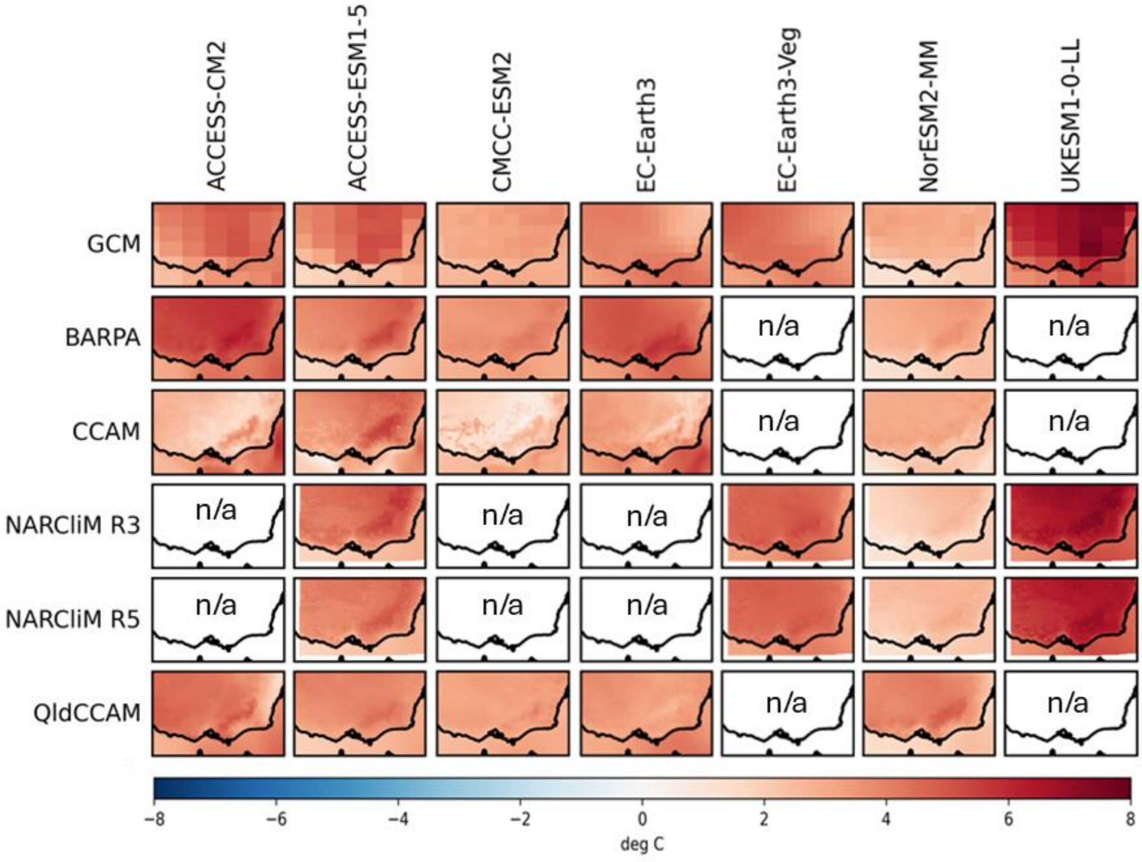


Figure 22 Spatial patterns of projected change in summer (DJF) mean maximum daily temperature from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0). The columns show 7 selected host GCMs (top row shows GCM projected changes) and the 5 rows below the top row show the downscaled versions from the 5 different downscaling models (rows).

4.4 Temperature extremes and heatwaves

Rising temperatures are felt not only through increasing average temperatures but also more acutely through increased incidence and intensity of hot days and heatwaves. We look at the change in the temperature of the 99th and 99.9th percentile hot days and nights according to all of the downscaling simulations. In addition, the NARCliM2.0 modelling is used to assess potential future changes in the number of days warmer than the historical 99th and 99.9th percentile hot days and future change in heatwave duration, frequency and season, based on the excess heat factor. Analysis of extreme temperatures is not included for the GCM simulations – priority was given to analysis of the regional modelling for variables beyond average temperature and rainfall.

Assessing extreme temperatures through percentile-based metrics such as the 99th and 99.9th percentile maximum temperatures has several advantages over looking at absolute temperature thresholds, for example 40 °C, as outlined in section 2.4.

Key messages for temperature extremes:

- The number of hot days (99th percentile hot days, occurring on average 3–4 time per year) and very hot days (99.9th percentile hot days, occurring on average 3–4 times per decade) have increased all over Victoria, but especially over inland Victoria. Very hot days has seen the largest increases, especially over the past decade.

- Hot days and hot nights will become hotter, and the frequency of historically rare hot days and nights will increase.
- Hot days and hot nights will warm more than average temperature. Previous modelling for Victoria (VCP19) projected similar outcomes for extreme temperatures.
- The number of hot days is expected to increase under all scenarios. By the end of the century under high emissions, hot days could occur 7–30 times per year instead of 3–4 times per year. The even more extreme 99.9th percentile hot days could occur 10–100 times per decade, instead of 3–4 times per decade. These projections include simulations from a *low-likelihood high-warming* model.
- Heatwaves are projected to become longer, more frequent and the season in which summer-like heatwaves occur will start earlier and end later than in the past. Under a high emissions scenario, it is plausible that by the end of the century, the season over which summer-like heatwaves could occur could span more than 6 months, meaning heatwaves occurring much earlier in spring and later in the autumn.

4.4.1 Observed temperature extremes

As average temperatures increase, so too does the occurrence of hot days and temperature extremes. Table 8 shows the observed incidence and recent change in 'hot' (99th percentile) and 'very hot' (99.9th percentile) days (i.e. hot days which occur on average 3–4 time per year and per decade, respectively) for the 7 stations in Victoria that have high-quality daily temperature records available (ACORNSAT, 2023). All locations have seen increases in the frequency of hot and very hot days, with the locations closer to the coast showing less dramatic increases than the inland locations. Across the sites there were increases in the number of 99th percentile hot days from approximately 3.5 days per year for 1986-2005 to 4.6–7.6 days per year for 2003-2022, depending on the location. The increase in the more extreme 99.9th percentile hot days has been more dramatic, with the number of days per decade increasing from ~3–4 to 621 times per decade.

Figure 23 shows the number of hot and very hot days for Melbourne, one of the locations that has seen a more moderate increase than some of the inland locations. The number of hot days (above the 99th percentile, or 37 °C for Melbourne) increased from an average 3.8 per year for most of the 20th century to an average of just over 5 per year for the past 20 years. The more extreme very hot days (99.9th percentile, or 41.2 °C for Melbourne) increased to an average of 10 times per decade over the past two decades, up from an average of 4 per decade for most of the 20th century and the 1986-2005 baseline.

Figure 24 shows the same for Kerang, in Victoria's north near Swan Hill. Here the number of hot days (days above 40.3 °C) has close to doubled and the more very hot days (above 43 °C) have been around 6x more frequent over the past 20 years compared to the 1986-2005 baseline and even more so when compared to earlier in the 20th century.

Historical number of hot and very hot days for the other 5 ACORNSAT sites in Victoria are shown in Appendix, Figure 63. Note that while the average incidence may be 3–4 times per year for days above the 99th percentile, the number of hot days can vary greatly year-to-year such that in any single year this can vary from none to 10 or more.

Table 8 Details of recent change in the number of days above the 99th and 99.9th percentile maximum daily temperature threshold, for the seven observational stations in Victoria with high-quality daily temperature datasets (ACORNSAT, 2023). The historical values of these thresholds, for the 1986-2005 baseline, is listed along with the average number of days (per year for the 99th percentile hot days, per decade for the 99.9th percentile hot days).

	99th percentile			99.9th percentile		
	1986-2005 value	1986-2005 days/year	2003-2022 days/year	1986-2005 value	1986-2005 days/decade	2003-2022 day/decade
Sale	36.4 °C	3.5	4.5	39.9 °C	3	11.5
Cape Otway	33.3 °C	3.5	4.7	38.8 °C	4	9
Kerang	40.3 °C	3.6	6.4	43 °C	3.5	21
Melbourne	37.0 °C	3.6	5.1	41.2 °C	4	10
Mildura	41.8 °C	3.6	5.6	45.5 °C	4	6
Nhill	39.7 °C	3.6	5.7	43.2 °C	3.5	11.5
Rutherglen	38.4 °C	3.4	7.5	41.8 °C	2.5	19.5

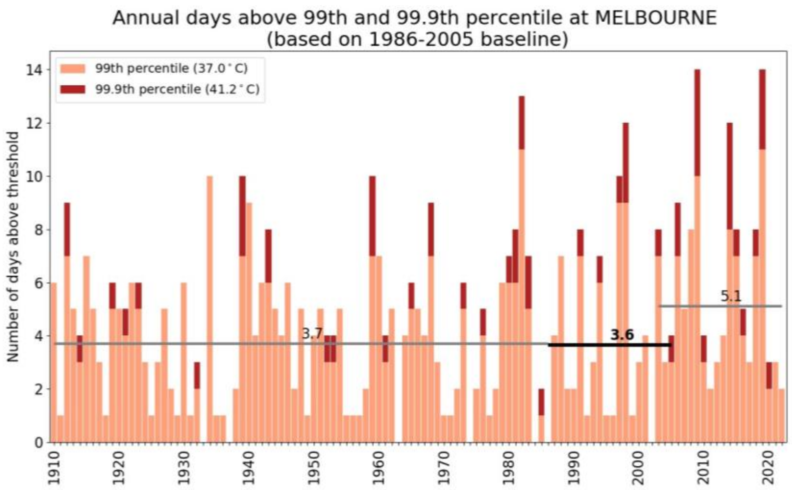


Figure 23 The annual number of days above the 99th percentile (orange bars) and 99.9th percentile (red bars) maximum daily temperature for Melbourne, from 1910 to 2022. The 99th and 99.9th percentile temperature thresholds are defined over a 1986-2005 baseline period. For Melbourne, the 99th percentile threshold is 37.0 °C and the 99.9th percentile threshold is 41.2 °C. The horizontal bars indicate the average number of days above the 99th percentile threshold for 1910-1985, 1986-2005 and 2003-2022.

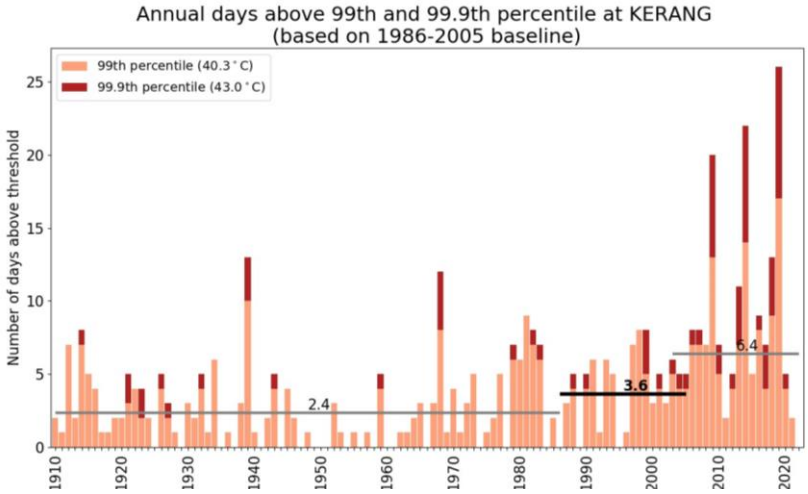


Figure 24 The annual number of days above the 99th percentile (orange bars) and 99.9th percentile (red bars) maximum daily temperature for Kerang, from 1910 to 2022. The 99th and 99.9th percentile temperature thresholds are defined over a 1986-2005 baseline period. For Kerang, the 99th percentile threshold is 40.3 °C and the 99.9th percentile threshold 43.0 °C. The horizontal bars indicate the average number of days above the 99th percentile threshold for 1910-1985, 1986-2005 and 2003-2022.

4.4.2 Future incidence of hot and very hot days

The number of hot and very hot days and nights are projected to continue increasing. We assessed the number of hot and very hot days and nights per year in the NARCliM2.0 ensembles. Note that the NARCliM2.0 ensembles generally captured the warmest end of the projections for average temperature, so can reasonably be expected to capture the warmest end for temperature extremes too.

Table 9 and Table 10 show the modelled number of days above the historical 99th and 99.9th percentile thresholds for daily maximum temperature (from the 1986-2005 baseline), averaged over the whole of Victoria. The historical baseline values of these temperature thresholds are shown in Figure 25. Historical baseline values are also shown for several stations in Table 8, for example a 99th percentile day over the 1986-2005 baseline was 37 °C and a 99.9th percentile day was 41.2 °C for Melbourne.

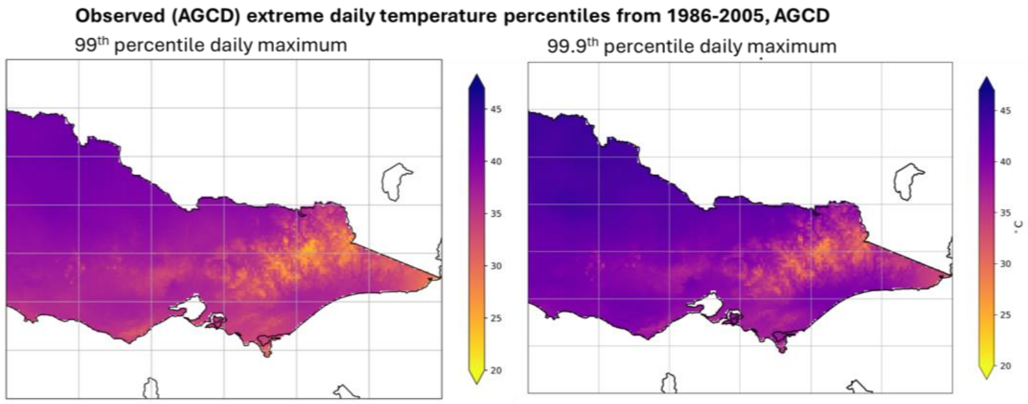


Figure 25 Observed historical values of the 99th and 99.9th percentile extreme daily temperatures, from the AGCD gridded observed dataset.

The number of days above the 99th percentile could increase from an average 3–4 per year to an average 4–11 per year according to the NARCliM2.0 simulations, under low emissions (similar for both 2050 and 2090). Under high emissions, these hot days could occur on average 4–17 times per year by 2050 or 7–30 times per year by 2090, according to the NARCliM2.0 ensemble. Individual years could have fewer or many more than the average number of hot days.

Note that the recent decade has already seen an average 4–8 days per year across the seven sites shown in Table 8. The lower end of the projections shows less increase in hot days than what has already been observed, but this is due to an anomalously cool period around 2050 in some of the NorESM2-MM simulations. Although there is a warming trend, cooler periods with relatively few hot days may still occur due to natural variability in the climate.

Table 9 Projected number of days above the historical 99th percentile threshold for daily maximum temperature, from all individual NARCliM2.0 model runs. *The UKESM1-0-LL model is highlighted as the low-likelihood, high warming model.

Projected number of days per year above the historical (1986-2005) 99th percentile maximum daily temperature. (Historical occurance ~3–4 days/year.)					
		2050		2090	
RCM version	Host GCM	ssp126	ssp370	ssp126	ssp370
NARCliM2.0 N20-WRF412R3	NorESM2-MM	4.1	3.1	4.2	6.8
	MPI-ESM1-2-HR	5.4	9.0	6.1	12.7
	ACCESS-ESM1.5	7.0	10.3	6.7	16.4
	EC-Earth3-Veg	6.9	10.2	6.6	20.2
	UKESM1-0-LL*	9.2	15.0	9.6	25.7
NARCliM2.0 N20-WRF412R5	NorESM2-MM	5.2	4.2	4.7	9.1
	MPI-ESM1-2-HR	4.6	6.9	5.1	10.8
	ACCESS-ESM1.5	8.0	9.2	6.0	16.2
	EC-Earth3-Veg	6.3	9.4	7.2	19.6
	UKESM1-0-LL*	10.6	17.5	11.5	29.6

A day above the 99.9th percentile would occur on average 3–4 times per decade in the baseline period. The projections show that under a low emissions scenario, very hot 99.9th percentile day occurrence could increase from historically 3–4 times per decade to an average of 3–36 times per decade by the end of the century. Noting again that as the past decade already saw an increase to 6–21 of these very hot days at selected locations, the higher part of the projections may seem more plausible than the lower end, which has already been exceeded. Under high emissions, NARCliM2.0 projections show very hot days could occur 3–75 times per decade by 2050 or 10–132 times per decade by 2090.

Table 10 Projected number of days above the historical 99.9th percentile threshold for daily maximum temperature, from all individual NARCliM2.0 model runs. *The UKESM1-0-LL model is highlighted as the low-likelihood, high warming model.

Projected number of days per decade above the historical (1986-2005) 99.9th percentile maximum daily temperature. (Historical occurance (on average 3–4 times per decade).					
		2050		2090	
RCM version	Host GCM	ssp126	ssp370	ssp126	ssp370
	NorESM2-MM	6	3	3	10
	MPI-ESM1-2-HR	6	12	10	24
	ACCESS-ESM1.5	9	13	10	38
NARCliM2.0	EC-Earth3-Veg	8	15	13	59
N20-WRF412R3	UKESM1-0-LL*	16	34	14	69
	NorESM2-MM	7	5	4	15
	MPI-ESM1-2-HR	8	17	11	32
	ACCESS-ESM1.5	13	14	10	45
NARCliM2.0	EC-Earth3-Veg	7	15	15	54
N20-WRF412R5	UKESM1-0-LL*	28	75	36	132

Projected changes in the number of hot and very hot nights (days with minimum temperatures above 99th and 99.9th percentiles) are similar to those for maximum temperature extremes ().

For all measures of extreme temperatures, the future projected change is greatest for the downscaling of the low-likelihood, high-warming UKESM1-0-LL GCM, especially for the N20-WRF412R5 version of the RCM.

Table 11 Projected number of nights above the historical 99th percentile threshold for daily minimum temperature, from all individual NARCliM2.0 model runs. *The UKESM1-0-LL model is highlighted as the low-likelihood, high-warming model.

Projected number of nights per year above the historical (1986-2005) 99th percentile minimum daily temperature. (Historical occurance 3-4 days/year).					
		2050		2090	
RCM version	Host GCM	1SSP1-2.6	SSP3-7.0	SSP1-2.6	SSP3-7.0
	ACCESS-ESM1.5	7.7	9.3	7.1	16.8
	EC-Earth3-Veg	7.4	12.1	9.5	30.1
	MPI-ESM1-2-HR	4.6	8.0	5.5	13.4
NARCliM2.0	NorESM2-MM	4.3	3.9	4.6	9.0
N20-WRF412R3	UKESM1-0-LL*	9.5	14.3	9.2	28.1
	ACCESS-ESM1.5	7.4	8.0	5.9	14.8
	EC-Earth3-Veg	5.1	10.3	7.3	25.2
	MPI-ESM1-2-HR	5.3	7.7	5.7	12.9
NARCliM2.0	NorESM2-MM	4.4	4.3	4.3	9.4
N20-WRF412R5	UKESM1-0-LL*	9.5	14.2	9.6	30.3

4.4.3 Future increases in temperature extremes

The maximum temperatures reached on the hottest days or nights will continue to increase. We assessed the projected future change in the annual 99th and 99.9th percentile maximum and minimum daily temperatures in the combined downscaling (NARCliM2.0 and CORDEX ensembles). The combined downscaling ensemble projects that hot and very hot days will become hotter, especially under a high emissions scenario. By 2050, the 99th percentile hottest day will be approximately 1.8 °C hotter (0.8 to 2.4°C range, excluding low-likelihood, high-warming models, averaged over Victoria) under the high emissions scenario. By 2090, the differences between the emissions scenarios are stark, with 1.2 °C (range 0.6 to 1.8 °C) warming under low emissions and 2.5 °C (range 2.5 to 4.2 °C) under high emissions.

Additionally, the *low-likelihood, high-warming* model simulations under high emissions show hot days being up to 4.9 °C hotter by 2050 and 6.4 °C hotter by 2090, and very hot days up to 5.1 °C hotter by 2050 and 7.1 °C hotter by 2090. This is significantly higher than the increase in average temperature projected by those same *low-likelihood, high-warming* model simulations, which showed 2.5 °C and 5.0 °C hotter for 2050 and 2090 respectively. For very hot (99.9th percentile) days the increase is even greater. This result of enhanced warming of extreme temperatures compared to average temperatures is in alignment with existing evidence and projections, including the VCP19 projections.

The previous VCP19 projections found more warming for more extreme temperature events (1-in-20-year hottest day) than for the increase in average temperatures, with a warming of up 10 °C for 1-in-20 year heat extremes for 2090 under a very high emissions scenario, RCP8.5 as much for extreme as for average temperatures. One reason for the amplification of heat extremes can be related to reduced rainfall, with less rainfall and less evaporative cooling allowing hotter temperatures through soil moisture‑temperature feedback (Seneviratne, et al., 2010).

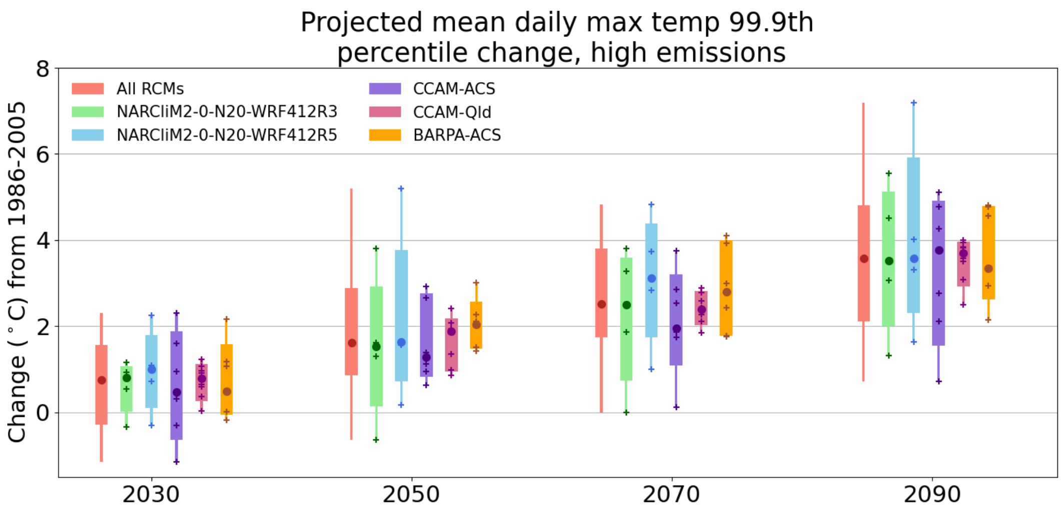
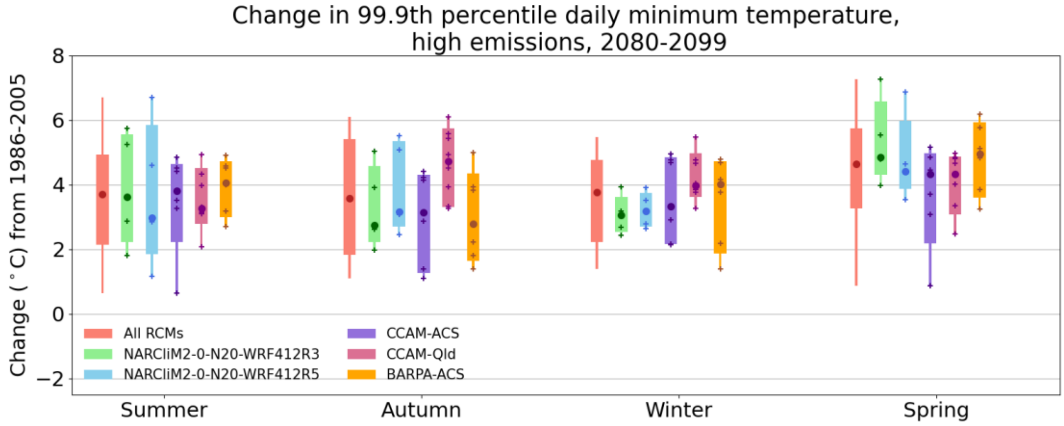


Figure 26 Future change in the 99.9th percentile maximum daily temperature over Victoria, as projected by various model ensembles under a high emissions scenario (SSP3-7.0), for 4 future time-periods. The thick bars show the 10th to 90th percentile range, the thin lines show the full minimum to maximum range and the dark circle shows the median. Individual models are shown as small spots for each of the RCM ensembles.

For both minimum and maximum temperatures under a high emissions scenario, the 99.9th percentiles show substantial warming relative to the 1986–2005 baseline across all seasons (Figure 27). Increases in very hot days (99.9th percentile maximum daily temperature) show slightly larger increases than very hot nights (99.9th percentile minimum daily temperature).

There is generally more warming of the temperature of hot days in spring than the other seasons, up to 1 °C more than the other seasons according to the combined All RCMs ensemble. The NARCliM2.0 simulations show the greatest season-to-season differences, with greatest warming of spring hot days showing almost 2 degrees more warming than winter hot days by 2090 under high emissions.



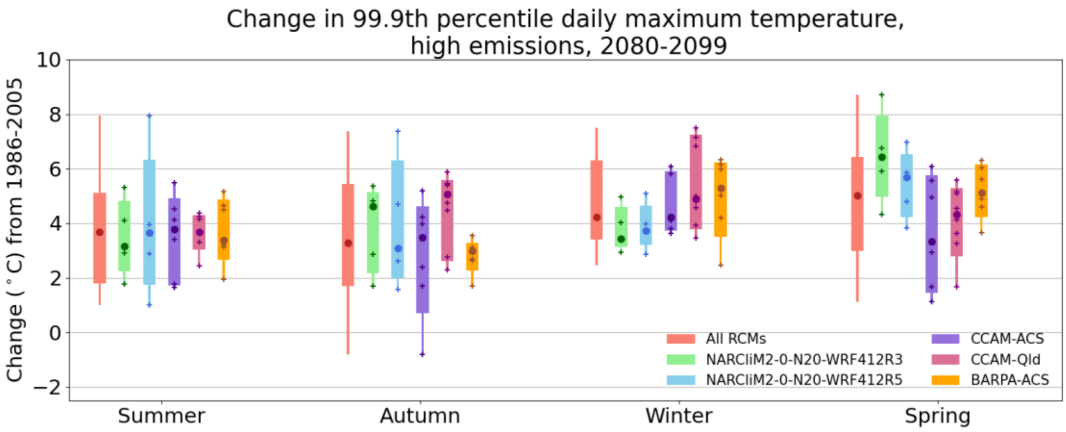


Figure 27 Projected change in the 99.9th percentile extreme daily minimum (top) and maximum (bottom) temperature over Victoria under the high emissions scenario, SSP3-7.0. Projected change is change from a 1986-2005 baseline to 20-year future periods. The thick coloured bars represent the 10th to 90th percentile range from each of the model ensembles, while the thin lines represent the full range and small points the individual models.

4.4.4 Future changes to heatwaves

The heatwaves metrics presented here are defined according to the Excess Heat Factor (Nairn & Fawcett, 2013). The threshold for a heatwave day is the 95th percentile of daily average temperature, and a heatwave event is defined when three consecutive heatwave days occur. We assess future changes in the frequency of heatwave days (average number of heatwave days per year), duration (average length of heatwaves) and also the length of the season in which heatwaves occur, defined as the time from the first to the last heatwave of the warm season. Increases are projected in all heatwave metrics.

The following figures refer to analysis done on the NARCliM2.0 modelling, although not including the low-likelihood high-warming future projected by UKESM1-0-LL (due to data availabilities issues), which could be associated with especially large increases in heatwave intensity, frequency, duration. Therefore, the possibility of even greater increases should not be disregarded.

By the 2050s, model-mean heatwave day frequency is projected to increase on average by 45% and 84% under the low and high emissions scenario, respectively, relative to the 1986-2005 period. By the 2090 period, model-mean heatwave day frequency is projected to increase by 53% under the low emissions scenario and more than triple under the high emissions scenarios to around 60 days per year (Figure 28).

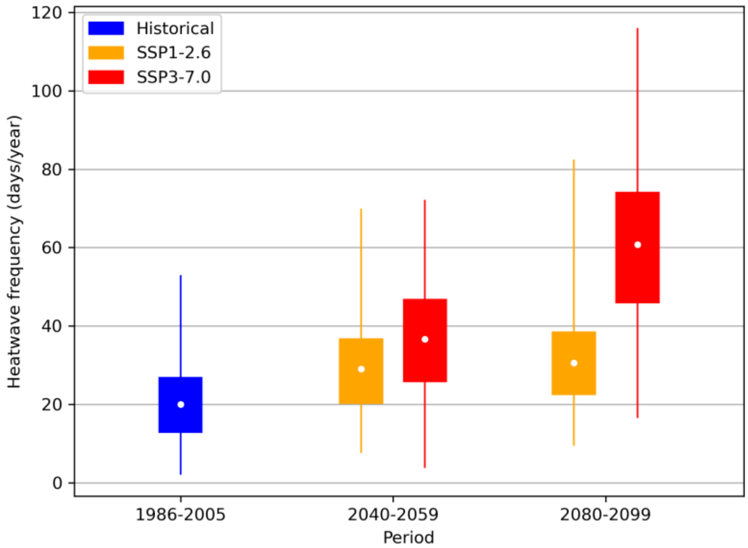


Figure 28 Box plots for annual average number of heatwave days per year (heatwave frequency) for the NARCliM2.0 data using a 1986-2005 baseline. White dots indicate the mean value across the eight NARCliM2.0 simulations analysed (simulations downscaling the UK-ESM1-0-LL GCM were not analysed). Boxes span the interquartile range (25^{th} to 75^{th} percentile range), and whiskers span the full range of the ensemble data.

The model-mean annual mean heatwave duration averaged over Victoria in the 2050s is projected to increase by around 0.7 days under low emissions and by around 2.2 days under high emissions, relative to the 1986-2005 period (Figure 29). Figure 29 also shows that by the 2090s, the model-mean annual average heatwave duration under high emissions increases by 6.5 to 15 days. Under high emissions scenario, the potential range of the mean heatwave duration expands dramatically by the 2090s, with some model years having a mean heatwave duration of over 50 days, more than double the greatest annual mean heatwave duration of around 22 days in the 1986-2005 period.

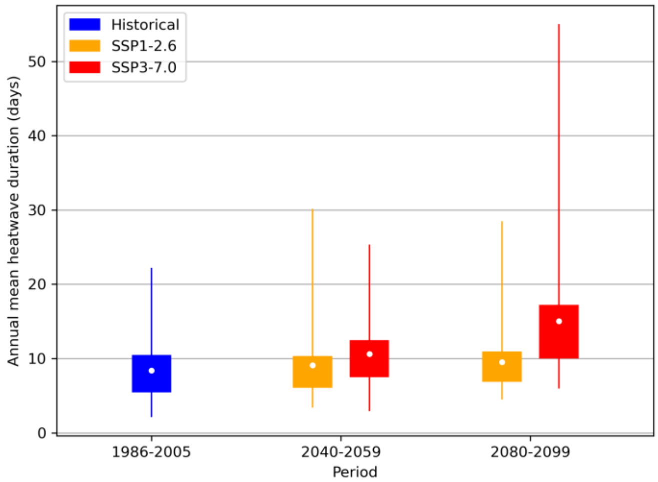


Figure 29 Box plots for annual mean heatwave duration (days) for the NARCliM2.0 data using a 1986-2005 baseline. White dots indicate the mean value across the NARCliM2.0 ensembles for each time period and emissions scenario. Boxes span the interquartile range (25th to 75th percentile range), and whiskers span the full range of the ensemble data.

The length of the heatwave season (that is, the time from the first to last heatwave day each year) is also projected to increase, with the model-mean heatwave season in the 2050s increasing by about 50% (27 days in the low emissions scenario and by 37 days in the high emissions scenario) from the mean season length of 61 days in the 1986-2005 period (Table 12). The length of the heatwave season is not projected to change significantly between 2050 and 2090 under the low emissions scenario. However, under high emissions model-mean results suggest a tripling of the length of the season relative to 1986-2005 and some model runs suggest that by the 2090s it will be possible for the heatwave season to extend over more than half the year. This means that what we currently consider heatwaves will occur earlier in the spring and later into the autumn.

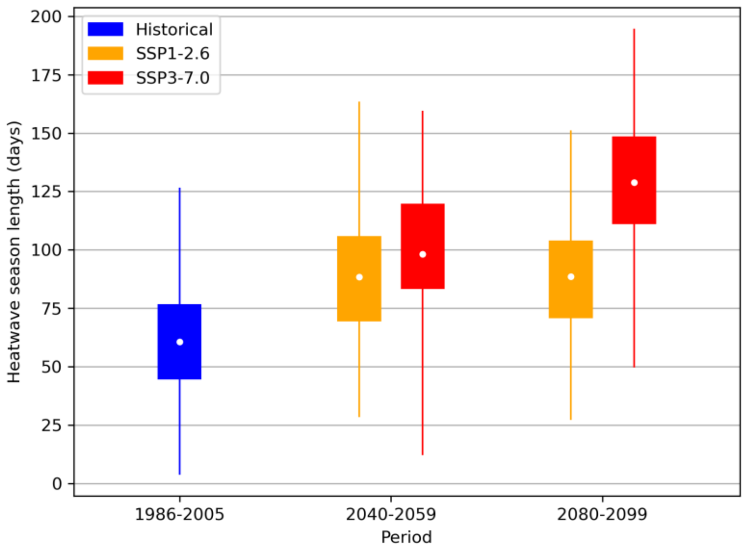


Figure 30 Victorian mean heatwave season length for the NARCliM2.0 data using a 1986-2005 baseline. White dots indicate the mean value across the NARCliM2.0 ensembles for each time period and emissions scenario. Boxes span the interquartile range, and whiskers span the full range of the ensemble data.

Table 12 Summary table of the NARCliM2.0 multimodel-mean annual mean heatwave season length for both baseline periods, and for future projections using heatwave thresholds defined by the baseline period. Multimodel-means here exclude UKESM1-0-LL, due to the model's use of a 360-day calendar, and thus are likely to understate future changes in heatwaves across the full NARCliM2.0 ensemble.

Baseline for heatwave definition	Baseline period	2040-2059		2080-2099	
		SSP1-2.6	SSP3-7.0	SSP1-2.6	SSP3-7.0
1986-2005	60.6	88.3	98.2	88.6	128.8
1995-2014	60.2	84.9	94.5	85.4	126.3

Figure 31 shows the different spatial change patterns in 2050 heatwave frequency under the high emissions scenario. The downscaling of the ACCESS-ESM1.5 GCM shows the greatest increase in the number of heatwave days, with largest increases being seen inland of the Great Dividing Range, as well central western Victoria. The downscaling of EC-Earth3-Veg shows slightly lower increases in heatwave frequency, but the increase in heatwave days is more even across Victoria, with greater increases in heatwave days in North-Eastern Victoria. The downscaling of MPI-ESM1-2-HR shows a moderate increase in heatwave frequency compared to the downscaling of ACCESS-ESM1.5 and EC-Earth3-Veg, with different spatial patterns in the change occurring for the two emissions scenarios. Finally, the downscaling of NorESM2-MM suggests that, even in the higher emissions scenario, the frequency of heatwave days may decrease in south-western Victoria, with modest increases in the north-east. This is consistent with the temporary cooling seen in the NorEMS2-MM simulations. However, it is not consistent with observations and therefore is a projection with low confidence.

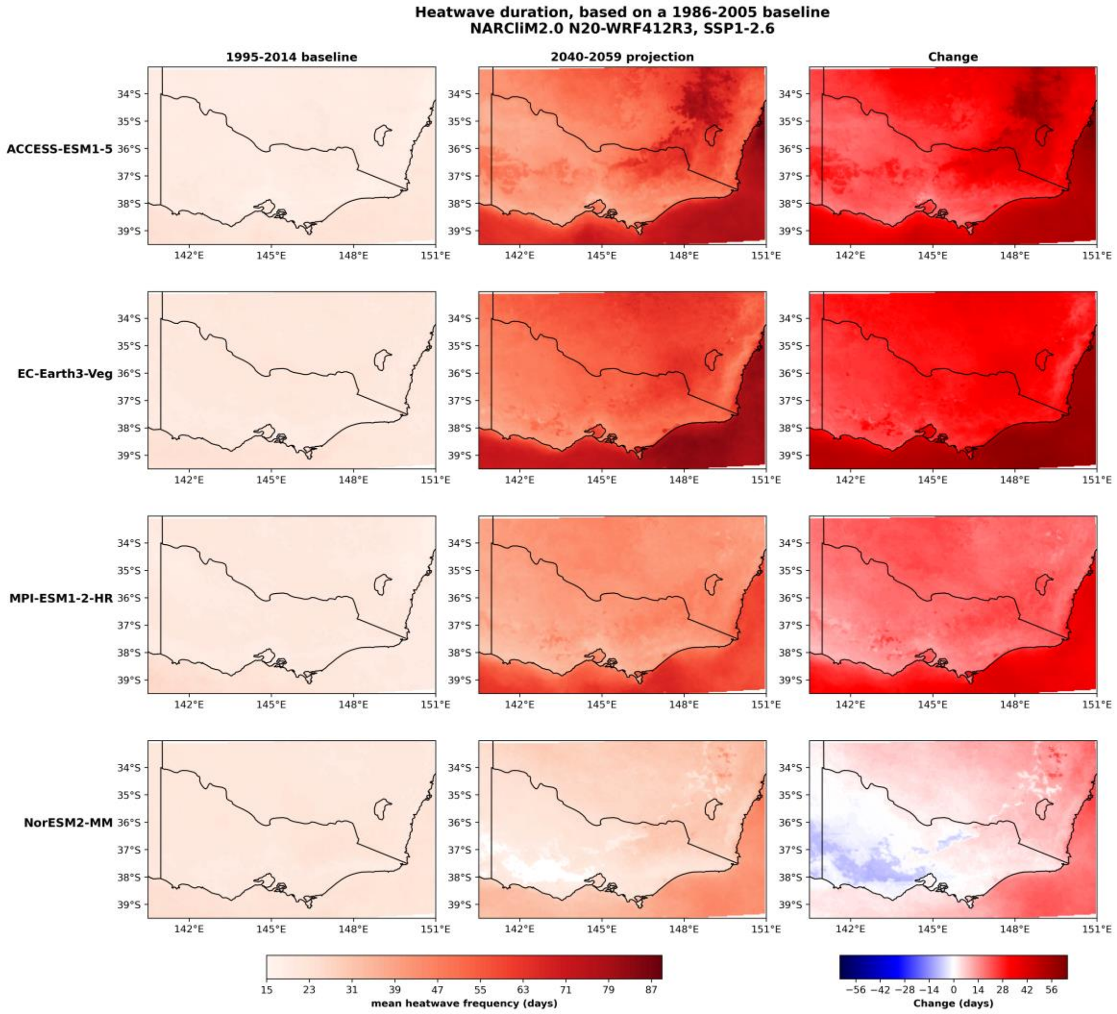


Figure 31 Spatial patterns of mean heatwave frequency for the 1986-2005 baseline (first column), 2040-2059 NARCliM2.0 model projections (second column) and the changes between these projections and the baseline (third column) for the SSP1-2.6 (top half) and SSP3-7.0 (bottom half) N20-WRF412R3 members of the NARCliM2.0 ensemble, as labelled for each row.

4.4.5 Frost

Frost-risk days are where daily minimum temperature is below 2 °C, or below 0 °C for higher frost risk. The frequency of frost-risk days has generally decreased in recent decades as the climate has warmed. However, there are some regional and seasonal exceptions to this, where frost-risk has increased due to an increase in clear nights, particularly in Spring where frosts can have the greatest impact to agriculture (Crimp, et al., 2016).

Looking to the future, in a warming climate, frosts are expected to generally become less frequent over time. In the next few decades, it is possible for there to be an increased risk and impact of frost in some regions and seasons when cold clear nights persist longer than is suggested by the projected change in mean minimum temperature, as reported in the 2019 Victorian Climate Projections Technical Report (Clarke, et al., 2019). Also, as the climate warms and some plants start to flower earlier, the sensitive period for crops, pasture and horticulture may fall more often in the frost window, meaning the impact of frosts may stay similar or even increase (Crimp, et al., 2019). No new analysis on frost occurrence has been done as part of this report, however over time (e.g., beyond 2050) the effect of increasing minimum temperatures is expected to overpower the other effects and lead to a decrease in frost risk. A review of the literature on this topic indicates that there is little in the way of any more recent research that would cause us to revise this assessment.

4.5 Average Rainfall

Ongoing changes in rainfall are likely to lead to significant impacts on Victoria. These changes could impact water resources, agriculture, flooding and bushfires in ways that could disrupt Victorian ecosystems, businesses and communities.

Warming of the climate will bring changes to rainfall through two main sets of processes – 1) a warmer atmosphere can hold more moisture and cause overall global rainfall to increase; and 2) changes in atmospheric circulation and weather systems can cause changes to rainfall distribution around the globe. Victoria sits in the ‘mid latitudes’, a region that is generally projected to become drier as a result of changing circulation patterns, however regional rainfall is influenced by many factors and projections are subject to greater uncertainty than temperature. In addition, Victoria’s rainfall in naturally highly variable, so any long-term trends will be overlayed by year-to-year and decade-to-decade.

Analysis of multiple lines of evidence, including model ensembles, past trends, process understanding and attribution and emergence (Rauniyar & Power, 2020) suggests *high confidence* that cool-season rainfall is projected to decline through the century in Victoria, especially under high emissions (or high levels of global warming). Average warm season rainfall may remain unchanged (reported with only *medium confidence*), or may show an increase or decrease, and will *very likely* show changes to variability and extremes. There is also *high confidence* that natural variability will remain large relative to any anthropogenic changes, at least for the near future (2030), and that this variability will remain an important determinant of the mean climate in all periods through the century.

This section covers projected changes to average seasonal rainfall from the new CMIP6 global and regional modelling. We start with observed changes and then explore ‘central estimates’ and uncertainty ranges for change future changes in rainfall until the end of the 21st century. We then take a deeper dive into some plausible scenarios for future rainfall change. These are intended to support ‘storylines’ approaches to managing climate risk (Fiedler, et al., 2024).

Extreme heavy rainfall is covered in Section 4.6 and additional detail on drought is covered in Section 4.7.

Key messages:

- It is certain that rainfall will change in Victoria as the climate system warms. These changes include changes to average rainfall, changes to seasonal rainfall patterns and increases in heavy rainfall. It is highly likely that we will see increases in rainfall variability across extreme dry periods and extreme wet periods at various timescales, including day-to-day variability and possibly including interannual variability. The precise nature of these changes in rainfall is difficult to model, with a range of future rainfall states plausible.
- Victoria's average rainfall has been decreasing over the past 50 years, with this decline most apparent in autumn, winter and spring. Summer rainfall has shown little change. Annual to decadal variability in rainfall is naturally large.
- Cool season (April-October) rainfall is projected to continue declining, especially under the high emissions scenario, with ongoing large variability (medium to high confidence). However, the possibility of little change or an increase in rainfall can't be ruled out, with scenarios showing increases in average rainfall potentially driven by increased variability and increases in wet periods.
- Future changes in summer rainfall are less certain and the new climate modelling doesn't narrow our outlook – the new regional downscaling shows that both significant decreases and significant increases in summer rainfall are possible. It is *likely* that summer rainfall will increase in both variability and rainfall extremes, regardless of the change in the average.
- On top of changes to average rainfall, rainfall extremes are also changing. Dry periods are projected to be drier and hotter with more time spent in extreme drought, while extreme rainfall events are projected to become more intense (for more see Sections 4.6 and 4.7)
- Water resource management should consider a range of future rainfall scenarios, from a much drier climate to a wetter and much more variable climate, with the middle range 'central estimate' of decreased average cool season rainfall. The influence of change in other variables, such as temperature and evaporation increase, should also be accounted for.

4.5.1 Rainfall past changes

Over the past 30 years, Victoria's rainfall has declined, more so in the cool season (April-October) than the warm season (November-March) (Figure 32). The last few decades have seen a more than 10% reduction of cool-season rainfall from the 1961-1990 climate period. The decreasing average rainfall trend since 1970 has been clear in all seasons except summer (Figure 33). The rainfall change is not spatially uniform in any season (Figure 33), with larger declines over and inland of the Victorian Alps than elsewhere, in all seasons except summer.

Along with the change in the average rainfall, the nature of rainfall has also changed. Most of the decreases in the total rainfall are due to reductions in light and moderate rainfall, despite increasing heavy rainfall (Tolhurst, et al., 2023). Extreme rainfall events have increased in severity (see Sections 4.6).

The cool-season rainfall decline in Victoria is part of a decline across southeast Australia as a whole, as reported in the State of the Climate reports (CSIRO and Bureau of Meteorology, 2022). This is associated with decreased rainfall from rain-producing weather systems, as well as persistent shifts in climate drivers including strengthening of the subtropical ridge and changes to related features, and resulting trend towards higher air pressure over the region (McKay, et al., 2023; McKay, et al., 2021). There is notable evidence that observed cool-season rainfall decline has been at least partly driven by human influence (Rauniyar & Power, 2023; Rauniyar & Power, 2020). Climate change is likely leading to changes in natural modes of variability which influence rainfall over Victoria such as the Indian Ocean Dipole, Southern Annular Model and El Niño Southern Oscillation. For more on changes to climate drivers, refer to Section 4.1.

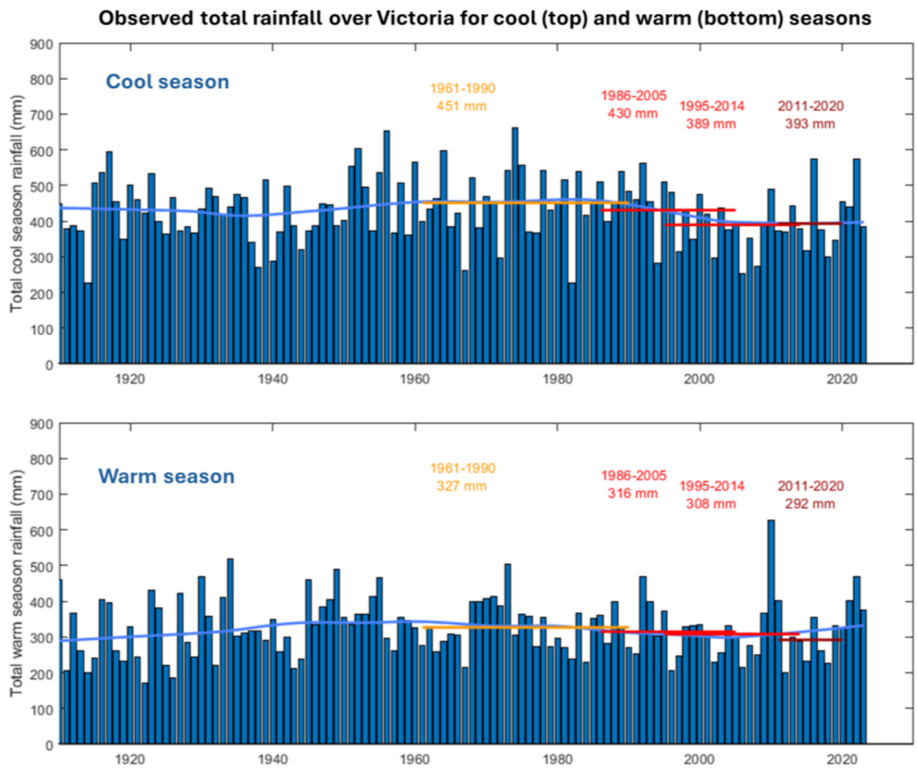


Figure 32 Observed total seasonal rainfall (cool season and warm season) over Victoria from 1910-2023, for the cool and warm seasons. Observed data is from the Australian Gridded Climate Dataset (AGCD). Various historical baselines are shown for comparison.

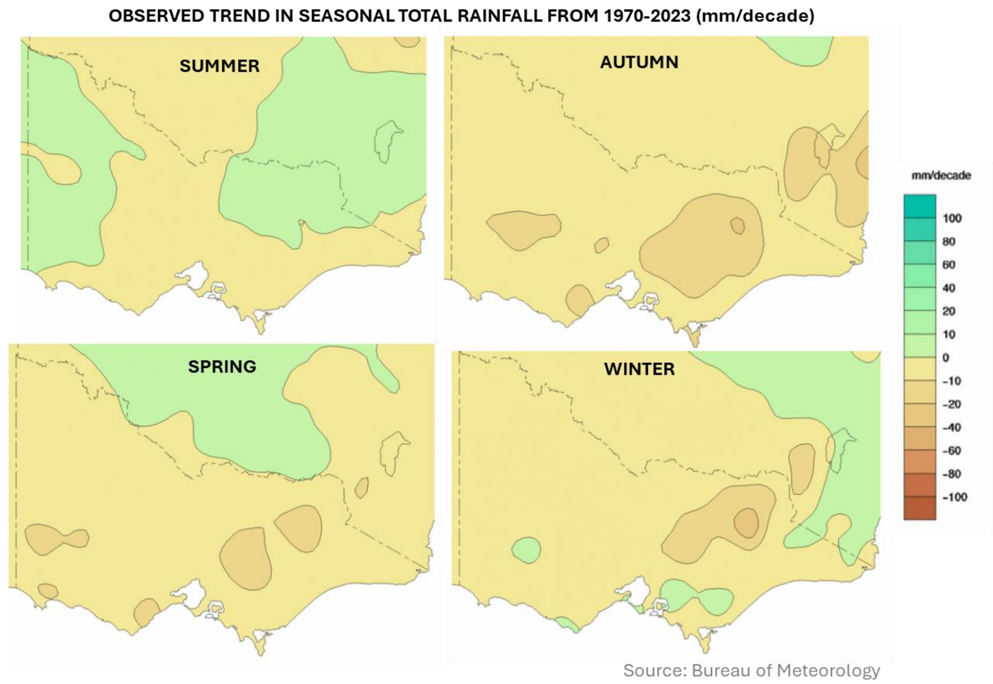


Figure 33 Observed rainfall trend (in mm/month) from 1970-2023 over Victoria for summer, autumn, winter and spring. Brown indicates reduced rainfall and green, increased. Source: Bureau of Meteorology.

Projecting future rainfall change

There is less certainty in projections of rainfall than projections of temperature. All models agree that temperatures will continue to rise under increasing atmospheric greenhouse gas concentrations. However, regionally, some models may project decreasing rainfall while others may project no change or increasing rainfall. Rising temperatures are a direct result of the enhanced greenhouse effect warming the earth's surface and atmosphere, and the connection between rising greenhouse gases and widespread increasing temperatures is relatively predictable to simulate and model. Rainfall is a much more complex variable, and warming can cause rainfall to increase or decrease in different locations, due to both thermodynamic processes (related to a warmer atmosphere), as well as dynamic processes, including a variety of different weather processes from local to synoptic scales. Long-term trends in rainfall can also be obscured by natural climate variability and rainfall is an inherently complex climate variable that is hard to simulate reliably in climate models.

While Victoria sits in the 'mid latitudes', a region that is generally projected to become drier as a result of changing circulation patterns, changes in circulation can be difficult to predict. In addition, 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 means there is considerable uncertainty in projecting how rainfall may change in the future.

For rainfall projections, drawing on multiple lines of evidence and different type of modelling is particularly important. The comparison of different regional modelling ensembles and global modelling, in Section 4.2, highlighted this importance, as no single downscaling ensemble captured the range of projections represented by all the modelling combined. Using a limited set of modelling could mean plausible futures are missed and confidence may be overestimated by using a set of modelling with more limited range.

Changes in rainfall also propagate through hydrological systems, for example through changes in runoff, streamflow, soil moisture or groundwater recharge. In addition, it is important to consider other influences on the hydrological cycle and how they may change in conjunction with rainfall changes. One such example is evapotranspiration, which is closely linked to temperature and is projected to increase and may further exacerbate any projected reduction in rainfall.

Near term rainfall projections and recent rainfall trends

The hypothesis that the recent decrease in cool season rainfall is likely driven in part by human influence is supported by the consistency between recent rainfall observations and near-term projections to 2030, relative to the baseline 1986-2005 (centred on 1995). Until 2020, observed cool-season rainfall was tracking at or below the dry end of the cool season projections for many regions of southern Australia, but within the range of decadal variability (Figure 34). This includes the influence of the Millenium Drought in the early 2000s. However, with a few relatively wet years recently (e.g., 2022), observed rainfall is now more consistent with the main projected range.

The changes we observe are combinations of any long-term trend caused by anthropogenic climate change, and short-term variability which can act on timescales of years to decades to enhance or mask long-trends. The observed decline could be due to a long-term drying trend, or a temporary natural swing toward drier conditions or most likely a combination of both. The coming years to decades will likely also see further swings in rainfall variability, and periods above or below any long-term trend. However, the main message from this analysis so far is that the projection of drier future cool seasons broadly agrees with the recent observed rainfall trends, and this contributes towards increased confidence in the projected further decline reported previously (e.g. VCP19) and in the new projections presented here.

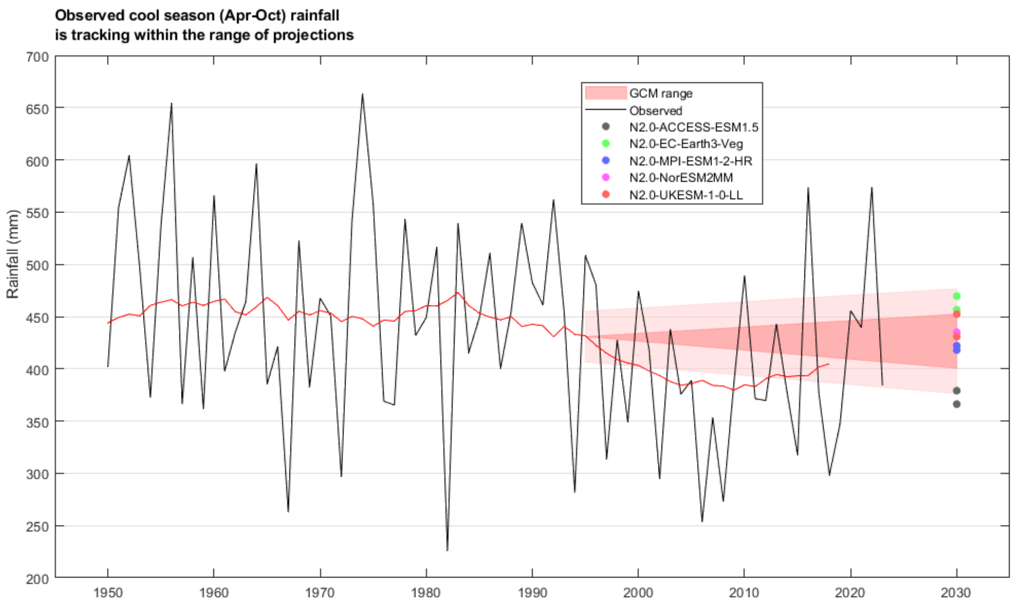


Figure 34 Observed cool-season (April-October) rainfall averaged over Victoria, showing the 20-year running mean and the projected rainfall change from 1986-2005 to 2020-2039 under the high emissions scenario from CMIP6 GCM and NARCliM2.0 ensemble projections (darker red shading) plus an indication of decadal variation (light shading).

4.5.2 Future projected annual and seasonal rainfall change

This section covers projected changes to annual and seasonal average rainfall over Victoria. Projections of future rainfall change are presented by annual and seasonal breakdown. Rainfall projections are presented for all the different regional climate model ensembles as well as the CMIP6 GCMs and all the regional climate models combined. There are quite significant differences in projected rainfall from the different sets of regional climate models. This highlights the importance of not relying solely on one set of regional climate modelling, as was also shown in Section 4.2.

A comparison is also shown for projections from the full set of GCMs as well as the ECS-constrained set of GCMs. Unlike temperature, there is little difference between the rainfall projections from models with ECS within the likely range or outside the likely range. Summary rainfall projections, including those shown in the VCP24 Regional Reports, include all models including those with ECS outside the likely range.

Mean annual rainfall change

Figure 35 shows the projected change in annual rainfall from all regional climate models combined, for four future time periods under the low and high emissions scenarios. Projections for the different regional models and comparison to global models is shown in Figure 36 (by time period) and Figure 37 (by season).

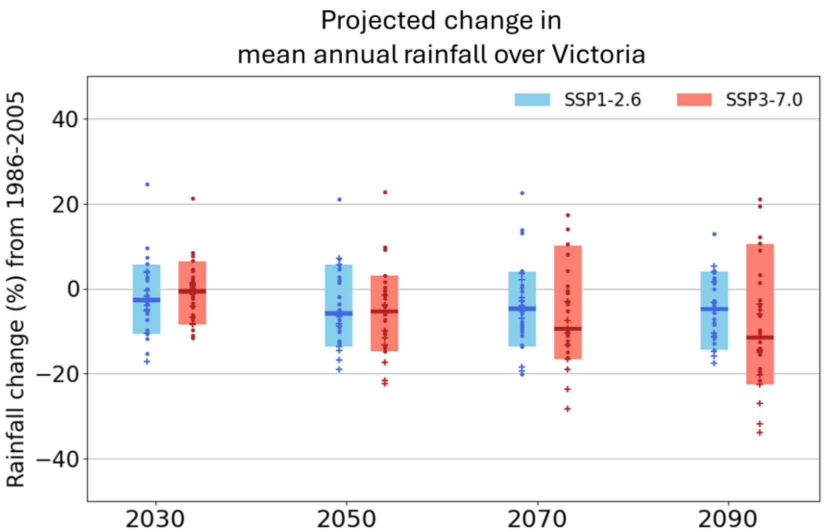
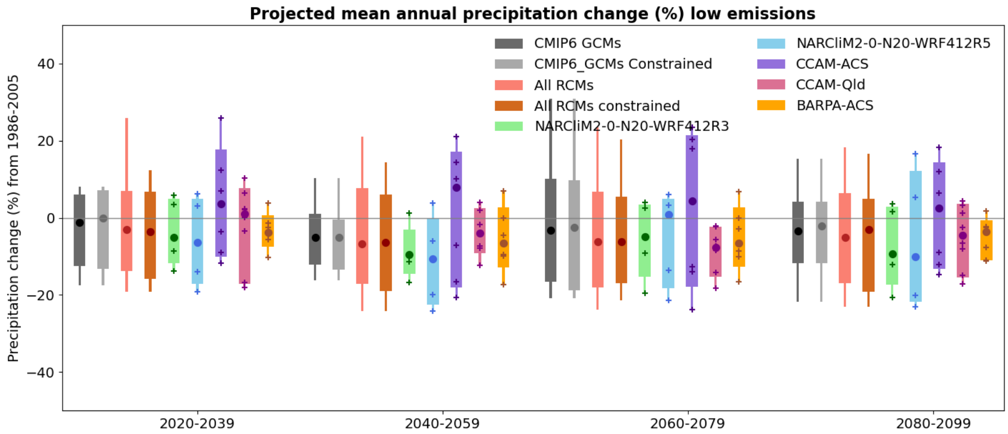


Figure 35 Change in annual mean rainfall over Victoria, as projected by all regional climate model simulations combined, under a low emissions scenario (SSP1-2.6, blue) and high emissions scenario (SSP3-7.0, red), for 4 future time-periods. The thick bars show the 10th to 90th percentile range, the horizontal line shows the multi-model median and the dots show each individual model.

The multi-model median shows decreases in mean annual rainfall for almost all time periods and both emissions scenarios. However, there is a range of projections, ranging from increase to decrease although most models show decreases. The range of change is largest for the high emissions scenario and for the end of the century, reflecting that the more the climate shifts away from a known state, the less certain we are about changes to Victoria's rainfall.

It is important to consider the range of projections, and not just the median value, as there can be plausible differences between projections from individual models. For instance, a median projection of 'no change' in rainfall from an ensemble of models could be a result of some models showing a plausible decrease and others showing a plausible increase – indicating that change is projected but the direction of change is not certain.



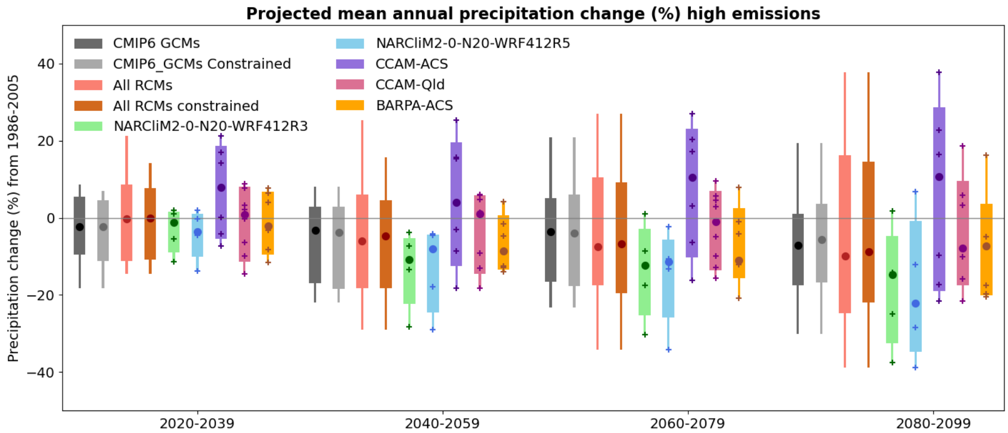


Figure 36 Change in annual mean rainfall over Victoria, as projected by various model ensembles under a low emissions scenario (SSP1-2.6, top) and high emissions scenario (SSP3-7.0, bottom), for 4 future time-periods. The thick bars show the 10th to 90th percentile range, the thin lines show the full minimum to maximum range and the dark circle shows the ensemble median. Individual model points are included

Seasonal rainfall changes: autumn, winter and spring

Like many regions in the mid-latitudes, cool season rainfall is projected to continue decreasing in Victoria in a warming climate. This is supported by the majority of climate models and other lines of evidence. There is *medium* to *high confidence* in this projection, meaning further drying is considered at least *likely* (>67% chance), but a wetter and much more variable future can't be ruled out, so should be considered in planning as well.

Figure 37 shows the seasonal projected changes from all ensembles for 2090 under low emissions and high emissions. The 'CMIP6 GCMs' and 'All RCMs' bars give the most robust summary of change, but it is interesting also to assess differences between the individual downscaling ensembles. Table 13 summarises the values for the GCM and combined RCM ensembles for both 2050 and 2090 and low and high emissions.

The combined RCM projections show decrease in all seasons except summer for both high and low emissions. The range of projected change is significantly larger in the combined RCM ensemble than the CMIP6 GCM ensembles for summer and spring. There is generally strong agreement between the various model ensembles in projecting a decrease in winter rainfall under high emissions, and to a lesser degree under high emissions. Most model ensembles tend toward drying in spring and autumn, although there is a larger range of change than for winter.

There are some large differences between the individual RCM ensembles. In general, the NARCliM2.0 ensembles are more weighted towards decreases in cool-season rainfall than the other ensembles, while the CCAM-ACS ensemble is more weighted towards increases. For example, the NARCliM2.0 ensembles show multi-model median springtime drying of around 40%. The CCAM-ACS ensemble shows little multi-model mean change but includes simulations showing large projected increases in spring rainfall. The remaining ensembles show multi-model mean changes of 10 to 20% decrease. Further investigation would be needed to assess the plausibility of the individual simulations within the ensembles and assign greater confidence to any of the different downscaling model projections.

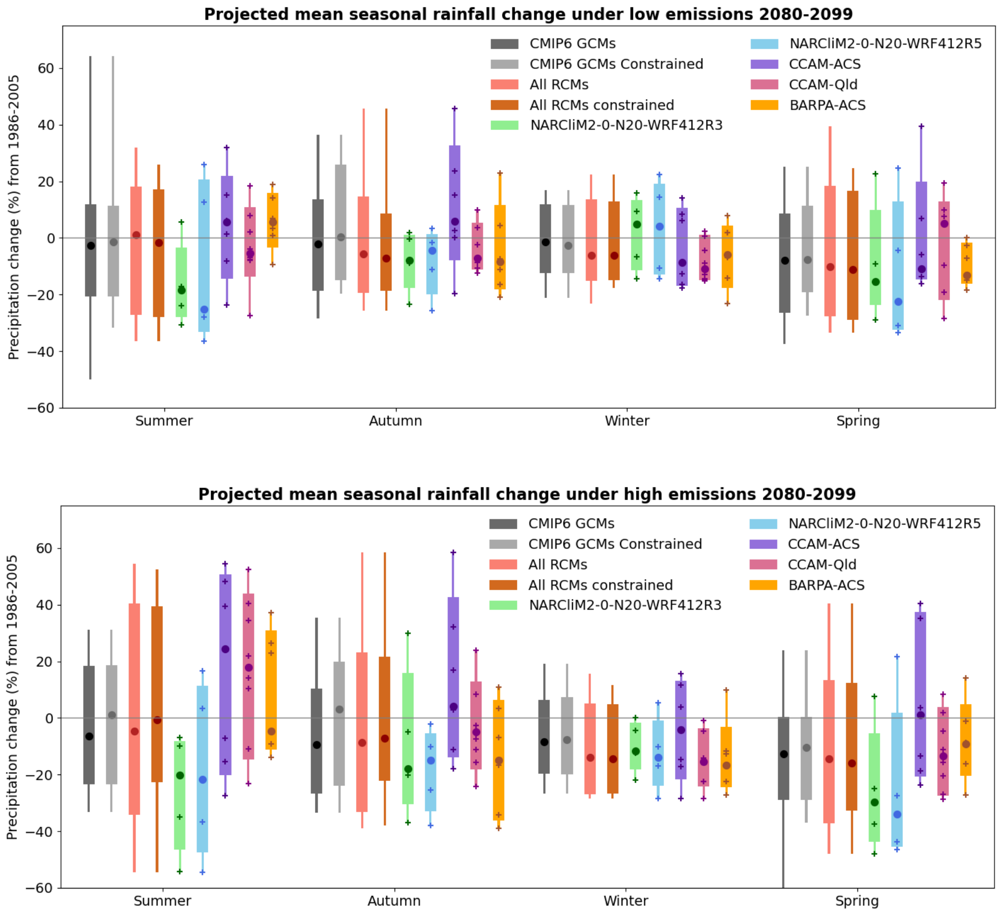


Figure 37 Change in mean seasonal rainfall over Victoria for 2080–2099, as projected by various model ensembles under high emissions (SSP3-7.0). The thick bars show the 10th to 90th percentile ranges, the lines show the full minimum-maximum range, and the dark point the ensemble median. Individual model points are included

Seasonal rainfall changes: summer rainfall

For summer rainfall, the impact of climate change is less certain than for the cool season, and new climate modelling doesn't narrow our outlook. Past trends and their attribution are less clear than for the cool season and average summer rainfall over Victoria has shown little indication of long-term change. Previous projections indicated that the direction of change in summer rainfall is uncertain. Summer rainfall is influenced by a larger diversity of climate drivers and synoptic patterns than the cooler seasons, which may contribute to the lack of a consistent signal in the model projections. The VCP19 CCAM simulations showing a spread from 20% more to 20% less rainfall, centred around zero for change to the end of the century under very high emissions (RCP8.5).

The newest modelling suggests no narrowing of this spread, or even a wider spread of projections than VCP19. The CMIP6 GCMs show a range from 20% less to 20% more summer rainfall by the end of the century under high emissions scenario. The new downscaling shows larger changes in summer rainfall but do not agree in the direction of change. The new NARCliM2.0 modelling indicates enhanced drying compared to the host models in most cases (in seven out of ten simulations for the high SSP3-7.0 over the whole century), but especially in summer. The driest NARCliM2.0 simulations project 40% dryer conditions in summer by 2090 under high emissions. However, the two ensembles of downscaling with the CCAM model (CCAM-Qld and CCAM-ACS) show significant increases in summer rainfall, with some simulations projecting a 40% increase. The range of uncertainty is largest under high emissions and towards the end for the century, as the climate changes further away from the present state.

The results of enhanced summer drying or wetting seem to be related to large decreases and increases in extreme summer rainfall in these models (see Section 4.6.2). Further research is needed before a determination can be made on whether more confidence should be assigned to certain results. Therefore, planning for climate change should consider scenarios (or ‘representative climate futures’ or ‘storylines’) where summer rainfall increases and scenarios where summer rainfall decreases.

Table 13 Projected changes in average seasonal rainfall from a 1986-2005 baseline to future 20–year periods centred on 2050 (2040-2059) and 2090 (2080-2099) under low (SSP1-2.6) and high (SSP3-7.0) emissions scenarios. Projected changes are shown for all CMIP6 GCMs and the combined RCM ensemble, including NARCliM2.0, CCAM-ACS, CCAM-Qld and BARPA-ACS. Projected change in percent change, shown as ensemble median with the 10th to 90th percentile range in brackets.

MULTI-ENSEMBLE PROJECTED CHANGE (°C) IN SEASONAL RAINFALL (% CHANGE FROM 1986–2005 BASELINE)				
ENSEMBLE	2050		2090	
	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)
Annual				
CMIP6 all GCMs	-5 (-12 to 1)	-3 (-17 to 3)	-3 (-12 to 4)	-7 (-18 to 1)
All RCMs	-7 (-17 to 8)	-6 (-18 to 6)	-5 (-17 to 6)	-10 (-25 to 16)
Summer (DJF)				
CMIP6 all GCMs	-5 (-26 to 10)	-5 (-23 to 9)	-3 (-21 to 12)	-6 (-23 to 18)
All RCMs	1 (-29 to 17)	-2 (-29 to 19)	1 (-27 to 18)	-5 (-34 to 40)
Autumn (MAM)				
CMIP6 all models	-1 (-17 to 11)	-2 (-22 to 16)	-2 (-19 to 14)	-9 (-27 to 10)
All RCMs	-7 (-20 to 16)	-2 (-19 to 17)	-6 (-19 to 15)	-9 (-33 to 23)
Winter (JJA)				
CMIP6 all models	-4 (-12 to 5)	-4 (-14 to 9)	-1 (-12 to 12)	-8 (-20 to 6)
All RCMs	-4 (-16 to 13)	-6 (-17 to 9)	-6 (-15 to 14)	-14 (-27 to 5)
Spring (SON)				
CMIP6 all models	-5 (-20 to 3)	-5 (-22 to 3)	-8 (-26 to 9)	-13 (-29 to 0)
All RCMs	-8 (-19 to 5)	-8 (-21 to 3)	-10 (-28 to 18)	-14 (-37 to 13)

4.5.3 Projected changes to rainfall by Global Warming Levels

Projected changes in rainfall can also be presented in terms of global warming levels, rather than by SSPs and time periods. Table 14 shows the projected change in seasonal rainfall for the CMIP6 GCMs and the combined NARCliM2.0 ensemble The CMIP6 GCMs show a median estimate of no change to 11% decrease across all seasons and warming levels, with the largest decreases for spring and the 3.0 °C warming level. The NARCliM2.0 ensemble shows significantly larger drying for all warming levels, but as was shown in previous sections, the NARCliM2.0 modelling represents the dry end of projections and other downscaling (not shown for warming levels) shows less extreme drying.

Estimates of rainfall change by warming levels were also estimated for VCP19, allowing comparison despite different emissions scenarios being available. Victorian rainfall change under a 2.0 °C global warming was estimated, using CMIP5 GCMs, to change -11 to +2% for annual rainfall and -16 to +8% for winter. These results are remarkably similar to the CMIP6 projections shown in Table 14.

Table 14 Projected changes in average seasonal rainfall from 1986–2005 baseline to future periods where global warming reaches 1.5 °C, 2.0 °C and 3.0 °C above pre-industrial climate (1850–1900). Projected changes are given as % change. Projected changes are given for all CMIP6 GCM and the two NARCliM2.0 versions. Ensemble projected change in percent change, shown as median with the 10th to 90th percentile range in brackets for the GCMs and minimum to maximum range for NARCliM2.0.

	% CHANGE FROM 1986–2005 BASELINE		
	1.5 °C GLOBAL WARMING	2.0 °C GLOBAL WARMING	3.0 °C GLOBAL WARMING
		ANNUAL	
CMIP6 all	**-4 (-12 to +5)**	**-2 (-14 to +2)**	**-6 (-18 to +3)**
NARCliM2.0 combined	-4 (-19 to -1)	-6 (-27 to 0)	-17 (-35 to -12)
VC19 CMIP5 projections		*-11 to +2*	
		Summer (DJF)	
CMIP6 all	**-8 (-21 to +10)**	**-5 (-23 to +16)**	**-4 (-23 to +13)**
NARCliM2.0 combined	-11 (-20 to +26)	-18 (-42 to -20)	--30 (-36 to +2)
		Autumn (MAM)	
CMIP6 all	**-1 (-14 to +14)**	**0 (-18 to +19)**	**-4 (-18 to +15)**
NARCliM2.0 combined	-8 (-26 to +13)	-7 (-30 to +17)	-22 (-44 to +6)
		Winter (JJA)	
CMIP6 all	**-2 (-15 to +7)**	**-2 (-14 to +10)**	**-6 (-18 to +6)**
NARCliM2.0 combined	-1 (-19 to +10)	0 (-18 to +10)	-5 (-28 to +2)
VC19 CMIP5 projections		*-16 to +8*	
		Spring (SON)	
CMIP6 all	**-7 (-19 to +6)**	**-7 (-17 to +4)**	**-11 (-27 to +1)**
NARCliM2.0 combined	-9 (-23 to +20)	-17 (-31 to +21)	-29 (-36 to -7)

4.5.4 Spatial patterns of projected rainfall change

High-resolution regional climate modelling can potentially reveal spatial patterns in future rainfall change at levels of detail that global models cannot. The VCP19 rainfall projections suggested a few plausible regional patterns of change related to topography revealed by high resolution modelling, outlined in the VCP19 report (Clarke, et al., 2019) and a supporting paper (Grose et al. 2019). The VCP19 findings showed enhanced drying on the windward (inland) slopes of the Alps in the cool season, especially in winter. While this remains a possibility, the new modelling does not necessarily support this finding. Figure 38 shows the comparison of the VCP19 winter rainfall change projection next to the VCP24 NARCliM2.0 winter rainfall change projection, highlighting very different patterns between these two sets of high-resolution modelling.

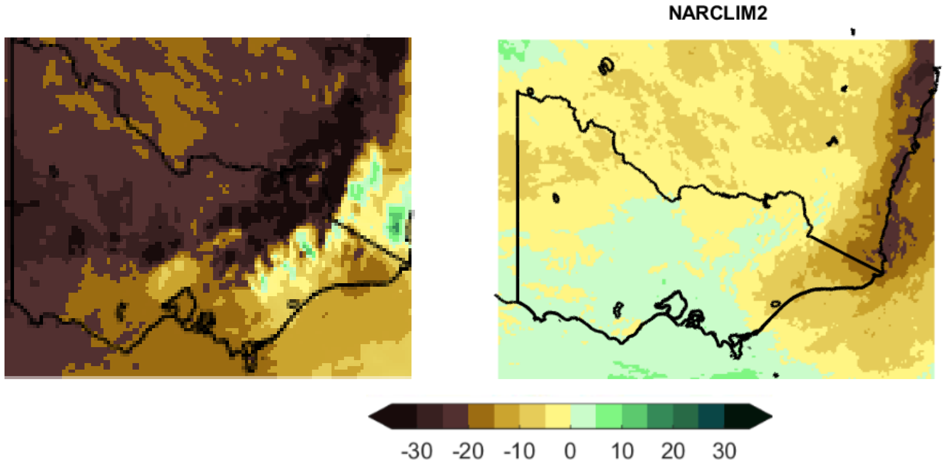


Figure 38 Projected change in 2090 winter rainfall (%) for VCP19 5km CCAM downscaling (left) (under the very high emissions scenario RCP8.5) and for the new CMIP6 4km NARCliM2.0 downscaling (right, under the high emissions scenario SSP3-7.0).

For VCP24 we have a larger suite of downscaling to draw on to investigate spatial details in projected rainfall change, with 32 downscaling simulations using 11 different GCMs and 5 different downscaling models. A selection of maps of projected rainfall change for the various model combinations are shown in Figure 39 (winter) Figure 40 (spring) and Figure 41 (summer), allowing for comparison of spatial patterns of rainfall change between the host global models and different versions of downscaling. Maps of projected rainfall change in all seasons and from all downscaled modelling are shown in the Appendix, Figures 65 to 69.

There are a few spatial patterns of seasonal rainfall change that stand out in the new downscaled projections (all referring to 2090, high emissions projections):

- More than half of the 32 simulations show enhanced winter drying over the southeast coast of NSW and easternmost part of Victoria (East Gippsland) on the seaward side of the ranges (Figure 39). Some of this regional drying signal appears also in the host GCMs. The opposite signal was seen in VCP19 modelling for winter (Figure 38), and is also seen in some of the new CCAM modelling.
- Roughly half of the 32 simulations display enhanced drying on the windward (inland) side of the Great Dividing Range in spring (Figure 40). This is most consistently seen in the BARPA downscaling, which also shows this pattern for some simulations in autumn and summer. Windward drying in spring was also seen in VCP19 modelling.
- There is a very large spread in summer rainfall, with some downscaling greatly increasing and others greatly increasing the amount of rainfall compared to the host GCM. They range from large decreases (NARCliM2.0 ensembles) to large increases (CCAM-ACS, CCAM-Qld), is also reflected in the spatial patterns of summer rainfall.

There are some notable differences between the rainfall change signals and spatial patterns between the different RCMs, compared to the host GCMs:

- The CCAM-ACS ensemble shows some greatly enhanced wetting projections compared to the host GCMs and other ensembles, especially for summer and spring rainfall. This can occur even where the host GCM has shown drying, and doesn't seem to have a particular spatial signal expect for possibly being stronger inland than for coastal areas.
- The NARCliM2.0 ensemble clearly enhances the drying signal where the GCM already shows drying (i.e. ACCESS-ESM1.5, NorESM2-MM and UKESM1-0-LL), especially in inland and northwestern Victoria and in spring and summer. Winter drying along the eastern seaboard (more affecting NSW) is particularly strong in NARCliM2.0 simulations.
- The BARPA ensemble tends to add spatial detail without significantly changing the overall signal or magnitude of change from the host GCM. In particular, it tends to show mostly enhanced drying on eastern seaboard in winter, but also shows the opposite signal of enhanced drying in the inland sides of the Australian Alps.

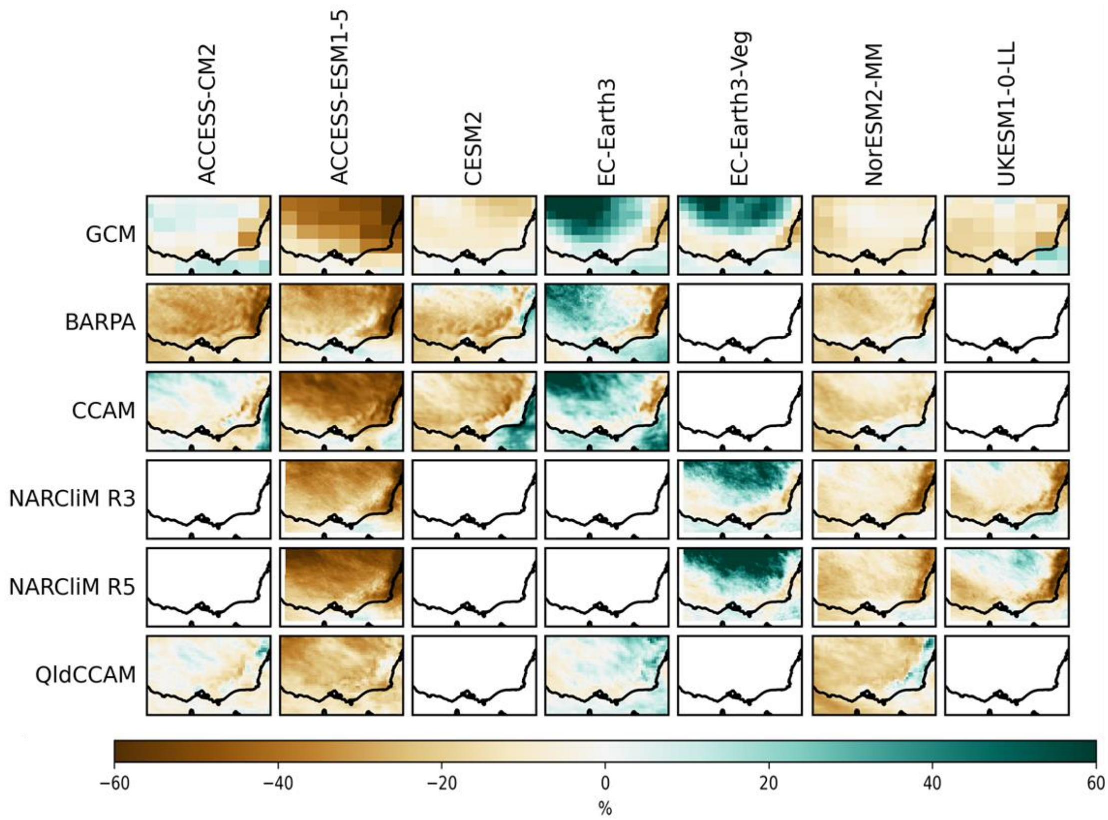


Figure 39 Projected change in mean winter rainfall from 1986–2005 to 2080–2099 under high emissions (SSP3-7.0) for selected combinations of downscaled RCMs (rows) and GCMs (columns).

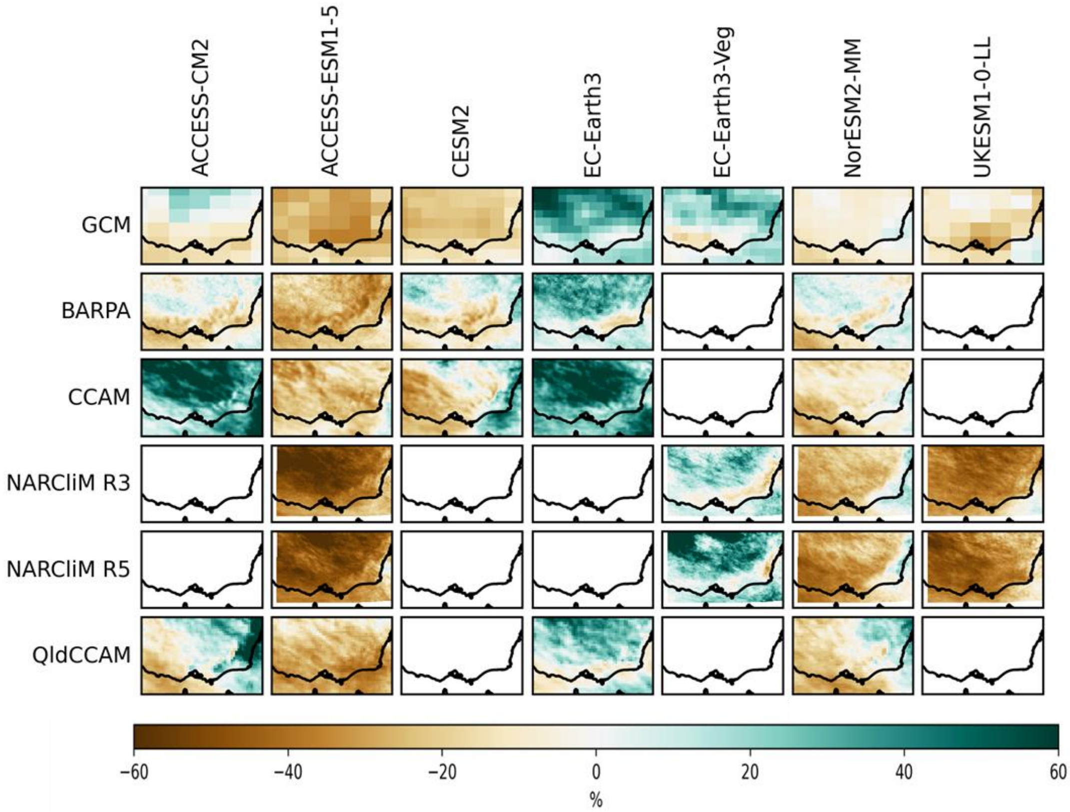


Figure 40 Projected change in mean spring rainfall from 1986–2005 to 2080–2099 under high emissions (SSP3-7.0) for selected combinations of downscaled RCMs (rows) and GCMs (columns).

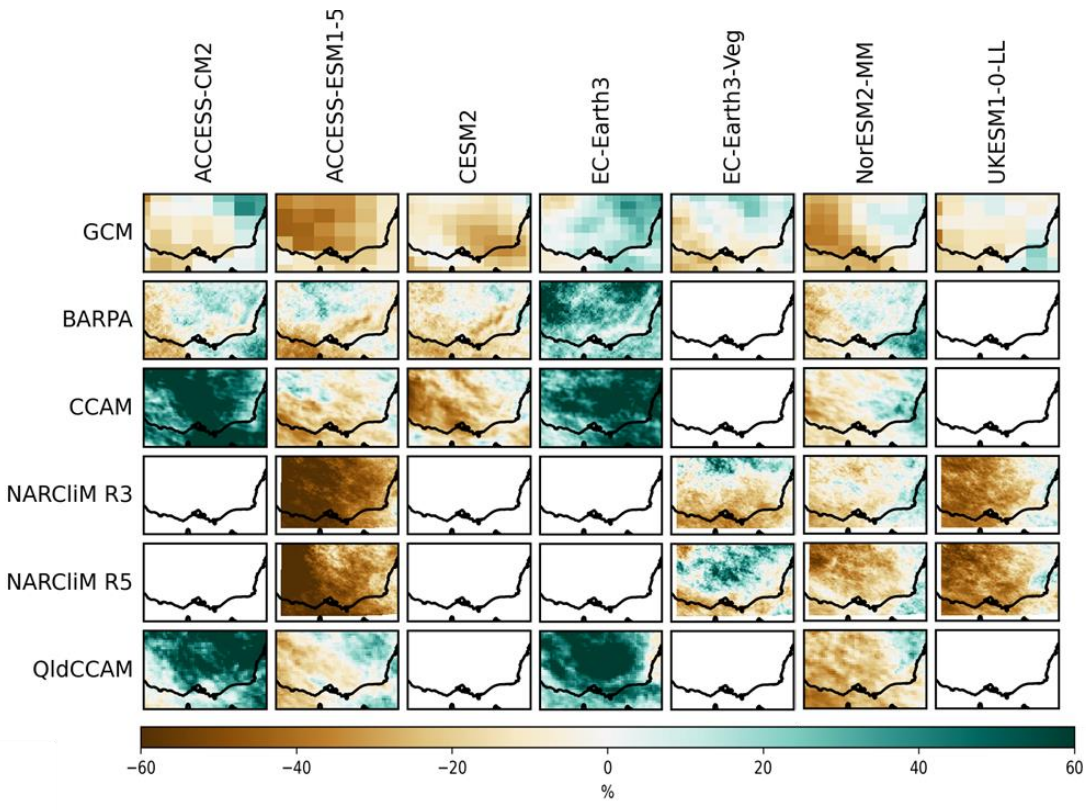


Figure 41 Projected change in mean summer rainfall from 1986–2005 to 2080–2099 under high emissions (SSP3-7.0) for selected combinations of downscaled RCMs (rows) and GCMs (columns).

Figure 42 provides a closer look at the rainfall projections from the highest resolution new modelling, from the NARCliM2.0 ensemble. Where the VCP19 CCAM projections showed the least projected decrease (or even an increase) in rainfall in summer, NARCliM2.0 simulations show the opposite, with the largest drying signal in summer. The projected drying in the summer and spring seasons in this model ensemble is evident, particularly in western and central Victoria. In winter there appears to be a projected increase in rainfall in the central and southwestern areas and the western parts of the ranges, while there is very pronounced drying along the eastern seaward side of the Great Diving Range in the eastern part of the Gippsland region (the projection also affects the entire eastern seaboard region of NSW).

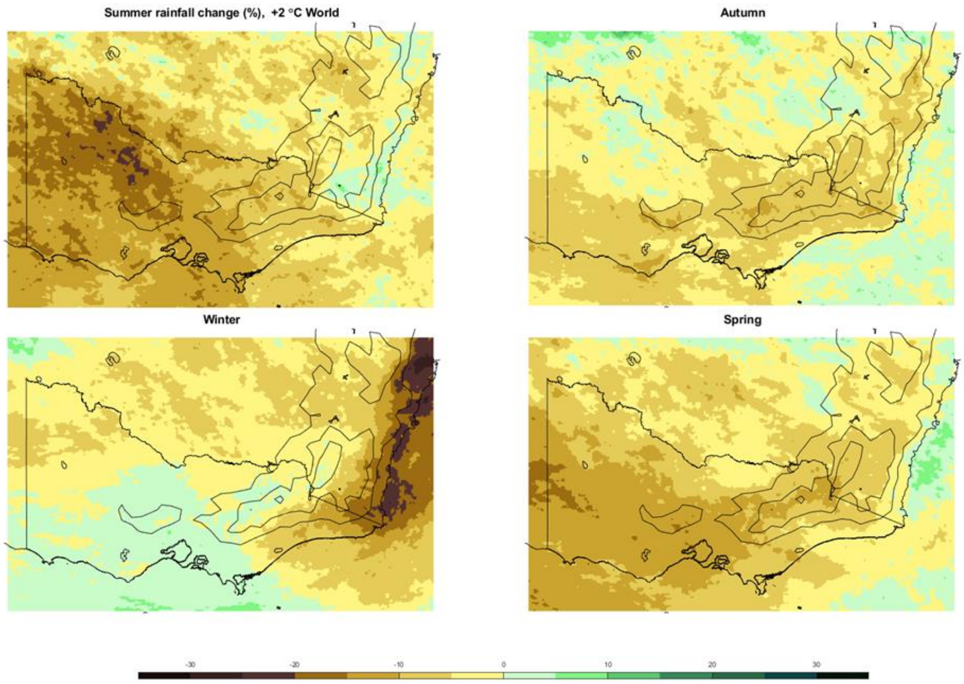


Figure 42 Multi-model mean projected change in seasonal rainfall (% change) over southeastern Australia at 2 degrees of global warming from the NARCliM2.0 ensembles (2 °C global warming sampled from the SSP3-7.0 simulations). Green indicated wetter, brown indicates drier.

Further investigation as to the causes (in particular, plausible physically processes) of these differing signals and spatial patterns between different downscaling models is needed to assign confidence to the various projections. If multiple lines of evidence support a projection of a particular change, in particular the possibility of enhanced drying over a particular region, this could be highly relevant. Detailed assessment of the new rainfall projections, including plausible physical drivers behind simulated change and more detailed evaluation of model performance, is something the Australin climate science community and modelling centres are actively working on. This is particularly the case where the downscaling provides a signal which differs greatly from the host GCM.

It is clear that different downscaling models can modify rainfall changes from a host GCM in different ways. This highlights the value of considering different downscaling models, and hence the importance of inter-comparable downscaling such as that encouraged through the CORDEX framework, the National Partnership for Climate Projections and the National Climate Projections Roadmap (DCCEEW, 2023). Agreement in the projected change signals from multiple different RCMs can give us higher confidence in a projection, while choosing to rely on downscaling from just one regional model may provide a narrowed and falsely confident view of potential future change.

4.5.5 A deeper dive on the wet and dry projection

While we are quite confident that Victoria will dry due to human influence, there is a range in the magnitude of change. At one end of the range, little change or an increase in rainfall cannot be ruled out for a given future era. Conversely, the dry end of change is much more severe than the mid-range. Here we look at these ends of the range.

We examine cool-season rainfall change from 1986-2005 to mid-century (2040-2059) and end of century (2080-2099) under the high emissions scenario for CMIP6 models and downscaling simulations. Traditional projection methods use a 'one model one vote' approach, where results from each model are regarded as equally plausible. Using this method, with 34 CMIP6 models and displaying the multi-model median and the 10^{th} to 90^{th} percentile range gives a projection of -4% (-12 to +4%) and -10% (-22 to +1%) by 2090. From this range of models, we look more closely at some examples which show more extreme wetting or drying.

To summarise the scenarios representing the wet and dry ends of rainfall projections:

- Scenarios representative of a wetter climate future show an increase in average cool-season rainfall by the end of the century, but this is driven predominantly by a large increase in variability with longer and wetter wet periods, rather than a steady increase. Within the same scenario, much drier periods are also possible depending on the sequence of climate variability we actually see.
- Scenarios representing the dry end of the rainfall projections show a strong and steady drying signal and a reduction in the frequency of very wet years.

Wetter end

The GCM chosen as a representative hotter and wetter climate future (EC-Earth3) shows an increase in average cool-season rainfall by the end of the century (Figure 43a). However this is driven predominantly by a large increase in variability with longer and wetter wet periods, rather than a steady increase. Without the very wet years in future, the average rainfall would be lower than that for the baseline.

GCMs are sometimes run multiple times with slight differences in their initial conditions, to get more than simulation (or 'run') of the future. For the VCP24 projections, only the first simulation from each model is used ('run 1'). The EC-Earth3 model was run for 57 simulations, shown in Figure 43b. We see an increase in variability and wet years in many runs but not in all, and many show a decreased average rainfall. The ensemble mean rainfall change by the end of the century across the 57 simulations is -6% (-15% to 8% range). Run 1, used in the VCP24 GCM ensemble, projects the most wetting. The increase in variability and frequency of wet years is reproduced in two regional models using this simulation as input (CCAM-ACS and BARPA) but is reduced somewhat in CCAM-Qld. A similar projection is also seen in the downscaling of the related model EC-Earth3-Veg, by NARCliM2.0 (Figure 44), further supporting this projection.

These results suggest that a wetter cool season in Victoria cannot be ruled out. However, a representative model future indicates this could be more accurately described as an increase in variability and the frequency of very wet years, creating the possibility of eras with a wetter average, rather than a steady wetting of the climate.

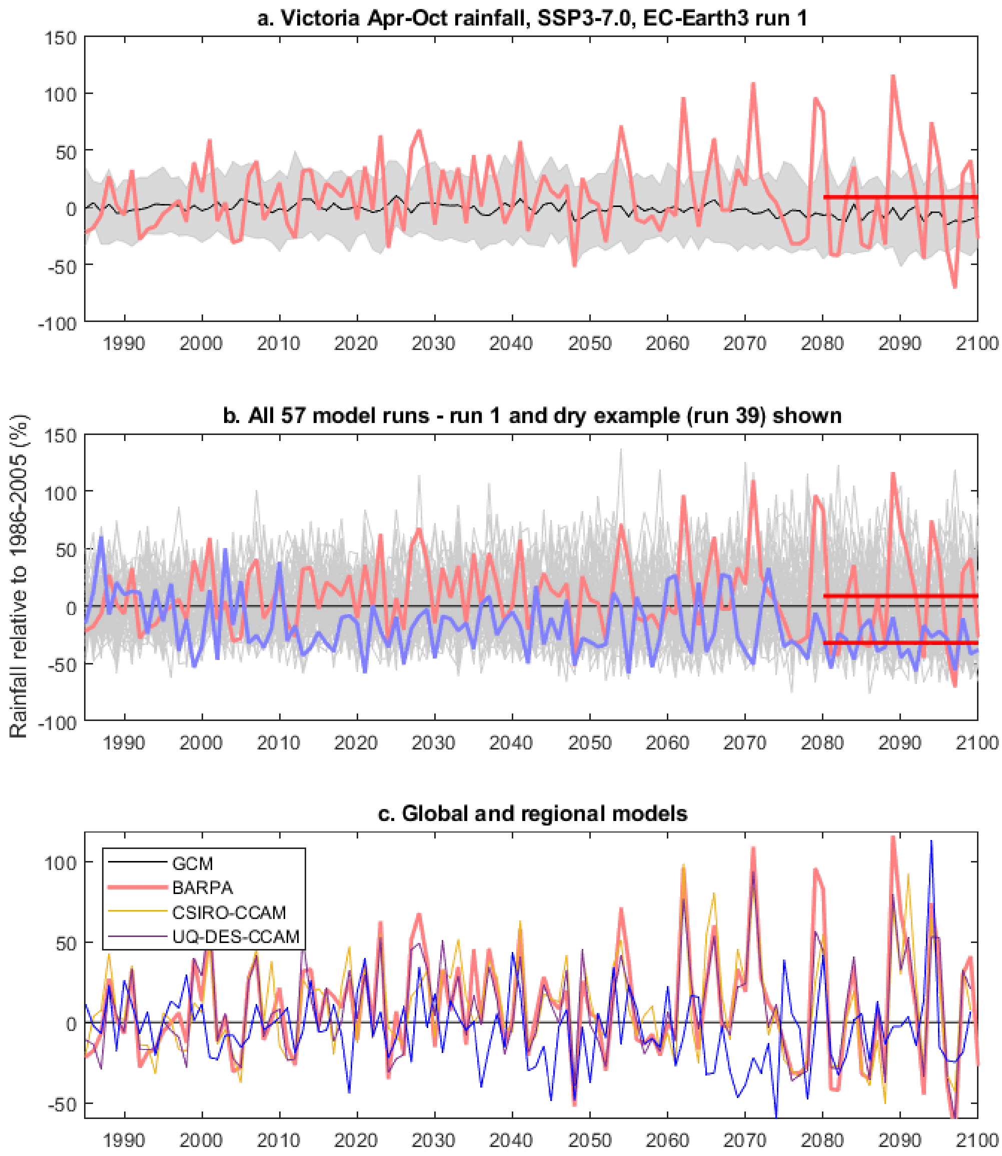


Figure 43 The Victorian cool season (Apr-Oct) rainfall simulated by CMIP6 models relative to the 1986–2005 baseline: a) shows the range of all CMIP6 models, overlaid by one simulation (EC-Earth3) and the average of that model for the period 2080–2099; b) shows 57 runs of the same model (grey), run 1 (red) and run 39 (blue); c) shows rainfall from run 1 of the Global model and three regional models using this model as input.

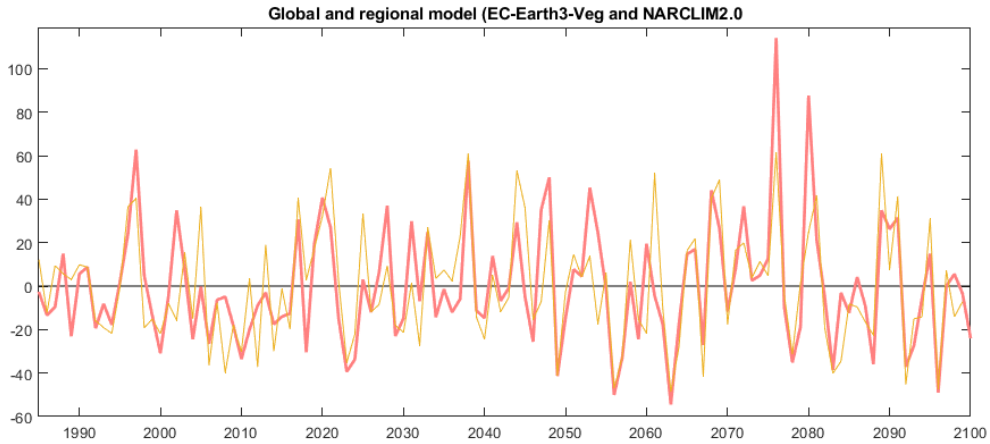


Figure 44 As for Figure 43 but showing EC-Earth3-Veg global model and NARCLIM2.0 downscaling of this model (WRF-R3 RCM version shown).

Very Dry End

In marked contrast to the wet end, the dry end of the projected range shows a strong and steady drying signal and a reduction in the frequency of very wet years, as explored through the representative climate model ACCESS-ESM1.5 and downscaling from this GCM (Figure 45).

In 2080–2099, run 6 of the ACCESS-ESM1.5 GCM, the simulation that was downscaled and included in VCP24, shows a 29% decrease in average cool-season rainfall under the high emissions scenario. This constitutes a large climatological change. However, the ACCESS-ESM1.5 GCM was run for 40 simulations and shows a mean change across all simulations of -31% (-40 to -23% range), with dry years very much below the 20-year average cool-season rainfall. Run 6 is in the mid-range of projected changes from all the ACCESS-ESM1.5 simulations. Downscaling of run 6 by both configurations of CCAM, BARPA and NARCliM2.0, all reproduce this strong drying for Victoria (Figure 41, Appendix Figure 65). There is an increase in variability at yearly to multi-decadal timescales (the inter-annual standard deviation increases notably), but there is a significant lack of wet years in the future.

Similarly to the wetter and much more variable projection presented above, this dry future is at the extreme end of the range but also cannot be ruled out. It represents a severe stress test for water management and agriculture in Victoria. Further work, such as an analysis of the physical processes in the model, and comparison to past trends, may add insights to the plausibility of this future. In southwest Western Australia, members of this model ensemble were the only ones to reproduce the observed rainfall decline (Rauniyar, et al., 2023), adding credibility to the projection there, and given that observations have tracked at the lower end of projections in Victoria at times (Figure 36), this suggests that the projection certainly cannot be ruled out as implausible.

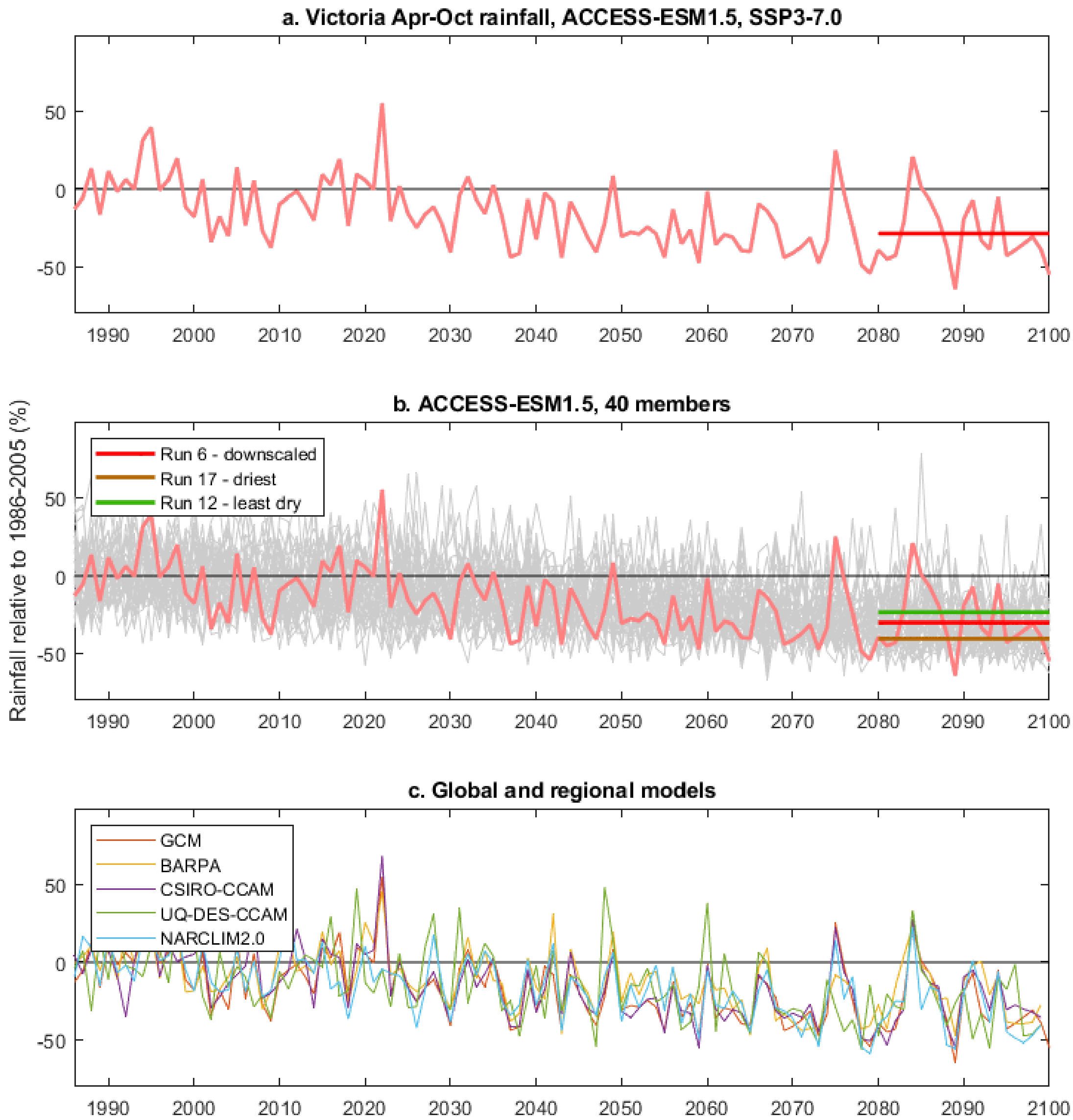


Figure 45 As for Figure 43 but showing the model ACCESS-ESM1.5, the horizontal bars in panel b shows the average in 2080–2099 of the downscaled simulation (run 6), the driest and least dry members. Panel c shows all four RCMs, as they all used this model as input.

4.5.6 Snow

No new analysis of past or projected future changes to snow cover or snow depth is presented here. However, with snowfall and snowmelt closely linked to temperature, snow depths and snow cover have decreased as temperatures have increased, a trend which is likely to continue into the future. Snow depth has been declining in the Australian alpine region, including in Victoria, since the 1950s, especially at lower elevations and during spring, with the decline linked to warming (Davis, 2013). The incidence of persistent heavy snow cover has become rarer (CSIRO and Bureau of Meteorology, 2022). The length of the ski season has contracted by 17-28% across most Australian alpine resorts between 1954 and 2012 (Harris, et al., 2016).

Existing climate projections information for snow indicates *very high confidence* of decreasing snowfall, and increase in snowmelt and thus reduced snow cover (CSIRO and Bureau of Meteorology, 2015). This will particularly affect snow at lower elevations. The magnitude of reduction in snow depends, like temperature, heavily on the future emissions pathway followed. Projected reduction in winter rainfall would also impact future snowfall. Even in a climate trending towards warmer and drier conditions less conducive to snowfall, heavy snowfall events will still occur.

Ski resorts can supplement a lack of natural snow with snow making up to a point, but eventually this can become unviable as temperatures increase and the number of suitable snowmaking hours decreases. Various natural ecosystems and alpine species of animals and plants are vulnerable to a warmer climate and cannot retreat to higher ground since they are already in alpine regions.

4.6 Extreme rainfall

Extreme rainfall events occur when a large amount of rain falls in a short time. They are important both from an impacts perspective (inundation, flooding, storm damage etc), and also contribute to the annual rainfall total for Victoria (Warren, et al., 2021).

Based on our understanding of the climate system, in a warming world the atmosphere can hold more moisture and hence, when an extreme rain event does occur, it can result in heavier rainfall. This effect is particularly relevant for heavy downbursts of rainfall on the sub-daily (minutes to hours) timescale. However, the characteristics of the weather systems that bring heavy rainfall also play a role in the occurrence of extreme rainfall events.

Overall, more extreme rainfall (especially at sub-daily timescales), and longer dry periods between rain events, are projected (*high confidence*). In general, short-duration rainfall extremes (hourly or sub-daily rainfall) are expected to increase in intensity more than longer-duration rainfall extremes (daily total rainfall). A recent meta-analysis of extreme rainfall observations and projections undertaken as part of an update to the Australian Rainfall and Runoff (AR&R) guidelines suggests that daily rainfall extremes may increase approximately 8% per degree of warming while sub-daily rainfall extremes may increase approximately 15% per degree of warming (Wasko, et al., 2024).

4.6.1 Observed extreme rainfall changes

There has been a slight increase in the wettest day of the year over much of Victoria since 1958, with a trend of 1–3mm/decade more rainfall per day between 1958 and 2014 (DELWP, et al., 2020). The maximum daily rainfall of the year is a measure of the amount of rainfall on the wettest day of the year.

Extreme, short-duration rainfall events are generally becoming more intense in Victoria. A recent study of hourly rainfall extremes (Osburn, et al., 2021) found an almost 90% increase in the incidence of extreme rainfall events with more than 18mm/hour from 1958–1985 to 1987–2014. Estimated changes in more extreme measures of maximum hourly rainfall, such as 1-in-10 or 1-in-100 year return period hourly rainfall also indicate an increase between 1958–1985 and 1987–2014 (Osburn, et al., 2021).

Short duration extreme rainfall events can have impacts such as urban runoff and flash flooding or land management and erosion. A few examples of such incidents include (DELWP, et al., 2020):

- Late December 2016 Viewbank received 40mm in 15 minutes and Bundoora had over 100mm, its highest December daily rainfall on record. Flash flooding occurred, with creeks breaking their banks. There was extensive storm and water damage and disruptions to road and rail travel.

- In December 2018, Wangaratta experienced a typical months' worth of rain in less than 24 hours, resulting in at least 100 cars trapped by flash floods on the Hume Freeway.

The most extreme rainfall events have been increasing in intensity more than more moderate extremes, with larger increases during the warm season (Osburn, et al., 2021). The proportion of rainfall that could be attributed to extreme rainfall events during the warm season has increased in recent decades, even while annual rainfall totals have been declining.

High extreme daily rainfall totals have notably occurred in dry years. For example, while the 2023 annual rainfall for Victoria as a whole was 5.3% below the 1961–1990 average, some parts of the State experienced their highest daily rainfall on record[17].

4.6.2 Future extreme rainfall changes

Previous climate projections for Victoria indicated that even when average total annual rainfall decreases, the amount of rainfall from wet days and the intensity of heavy rainfall and extreme daily rainfall is projected to increase under a high emissions scenario (CSIRO and Bureau of Meteorology, 2015; Clarke, et al., 2019). Multiple lines of evidence point towards ongoing increases in extreme rainfall events in a warming climate, including scientific understanding of physical processes (warmer air can hold greater amounts of moisture), observations of past increases in rainfall extremes, and model simulations showing increasing extreme rainfall in the future. The increase of heavy rainfall events is something that has been recognised in climate projections over the past few decades. The largest increases are projected for shorter duration events, for example a 1 hour extreme rainfall downburst compared to extreme 1-day total rainfall (Wasko, et al., 2024). More extreme (rare) metrics are projected to increase more than less extreme metrics, for example 1-in-20 year extreme daily rainfall extreme is projected to increase more than the 99th percentile (on average 3-4 times per year) daily rainfall event.

To assess projected changes in extreme daily rainfall in the new climate model simulations, we assess the projected change in the 99th and 99.9th percentile daily rainfall. The 99th percentile daily rainfall is exceeded on average approximately 3–4 days per year, and a 99.9th percentile daily rainfall is exceeded on average approximately 3–4 times per decade (noting that these are average occurrences, so some years can have many more or less such events). Defining rainfall extremes in this way simplifies analysis across regions with different rainfall climatologies and model data that may contain biases in extreme rainfall amounts. However, there are other measures of extreme rainfall that can be more relevant to some users but are not assessed here. For example, multi-day accumulated rainfall is a crucial factor in causing flooding. Further research on extreme rainfall, including extreme multi-day rainfall accumulations relevant to flood impacts, is recommended. Sub-daily extreme rainfall i.e. extreme rainfall bursts lasting less than one day (e.g. scale of minutes to hours) can also be highly impactful.

The new regional modelling from NARCliM2.0 and the CORDEX ensembles indicate some mixed signals for future changes to 99th and 99.9th percentile daily rainfall (Figure 46, Table 15).

[17] http://www.bom.gov.au/climate/current/annual/vic/summary.shtml#recordsRainDailyHigh

Generally, a larger increase is projected for the more extreme 99.9th percentile 'very heavy' rainfall days than the more common 99th percentile 'heavy' rainfall days. This is in line with findings from VCP19 and other research (Wasko, et al., 2024) that projects larger increases for rarer extremes. The three national scale CORDEX model ensembles tend to show an increase, on average, although this is most pronounced in the two ensembles using CCAM modelling (CCAM-ACS and CCAM-Qld). The NARCliM2.0 downscaling tends to show a decrease in extreme rainfall, at odds with other modelling and against expectations, based on scientific understanding, observations and previous projections.

The combined set of NARCliM2.0 and CORDEX simulations shows a wide range of change. For heavy rainfall days, there is little change in the multimodel median, but the upper end of the range (90th percentile from all simulations) shows 15% increase by 2050 and 29% increase by 2090 under high emissions, compared to 1986–2005. Under the low emissions scenario the upper end stays around 11% higher. For very heavy rainfall days, the multimodel median shows a moderate increase of 5% by 2050 and 12% by 2090, under high emissions. The upper end of the projections shows 20% increase by 2050 and 39% increase by 2090 under high emissions. For low emissions, the upper end of projections stays around 15% increase over the century.

Table 15 Projected changes in average annual 99th and 99.9th percentile extreme daily rainfall from a 1986–2005 baseline to future 20-year periods centred on 2050 (2040–2059), and 2090 (2080–2099) under two different emissions pathways SSP1-2.6 and SSP3-7.0. Projected changes are shown for the combined 'all RCMs' ensemble, the national downscaling (all RCMs excluding NARCliM2.0) and the combined NARCliM2.0 ensemble. Ensemble projected change is in percent change, shown as median with the 10th to 90th percentile range in brackets for All RCMs and min to max range for NARCliM2.0.

	2050 (SSP1-2.6)	2050 **(SSP3-7.0)**	**2090 (SSP1-2.6)**	2090 **(SSP3-7.0)**
% change in annual 99th percentile extreme daily rainfall, from 1986–2005 baseline				
All RCMs	0 (-10 to 12)	0 (-10 to 15)	2 (-9 to 11)	1 (-7 to 29)
all RCMs excluding NARCliM2.0	2 (-8 to 13)	4 (-7 to 15)	3 (-6 to 11)	5 (-5 to 29)
NARCliM2.0 combined	-6 (-8 to -2)	-5 (-13 to 0)	-3 (-8 to 4)	0 (-15 to 9)
% change in annual 99.9th percentile extreme daily rainfall, from 1986–2005 baseline				
All RCMs	4 (-10 to 14)	5 (-5 to 20)	5 (-5 to 14)	12 (0 to 39)
all RCMs excluding NARCliM2.0	6 (-2 to 16)	8 (-3 to 22)	9 (-2 to 14)	14 (1 to 39)
NARCliM2.0 combined	-3 (-11 to 4)	-3 (-10 to 10)	1 (-7 to 11)	6 (-16 to 15)

Figure 46 shows the range of projections from each of the downscaling ensembles, as well as the combined results. The multi-model mean projections for each of the CORDEX ensembles show an increase in both measures of extremes, but most notably for the 99.9th percentile extremes, for 2090 under high emissions. The most extreme multi-model mean changes come from the CCAM-ACS ensemble. In contrast to the CORDEX ensembles, most, but not all, of the NARCliM2.0 simulations project a decrease in the 99th percentile daily rainfall. For the more extreme 99.9th percentile measure, the NARCliM2.0 ensembles show a larger spread but tend to show an increase, especially under the high emissions scenario and towards the end of the century.

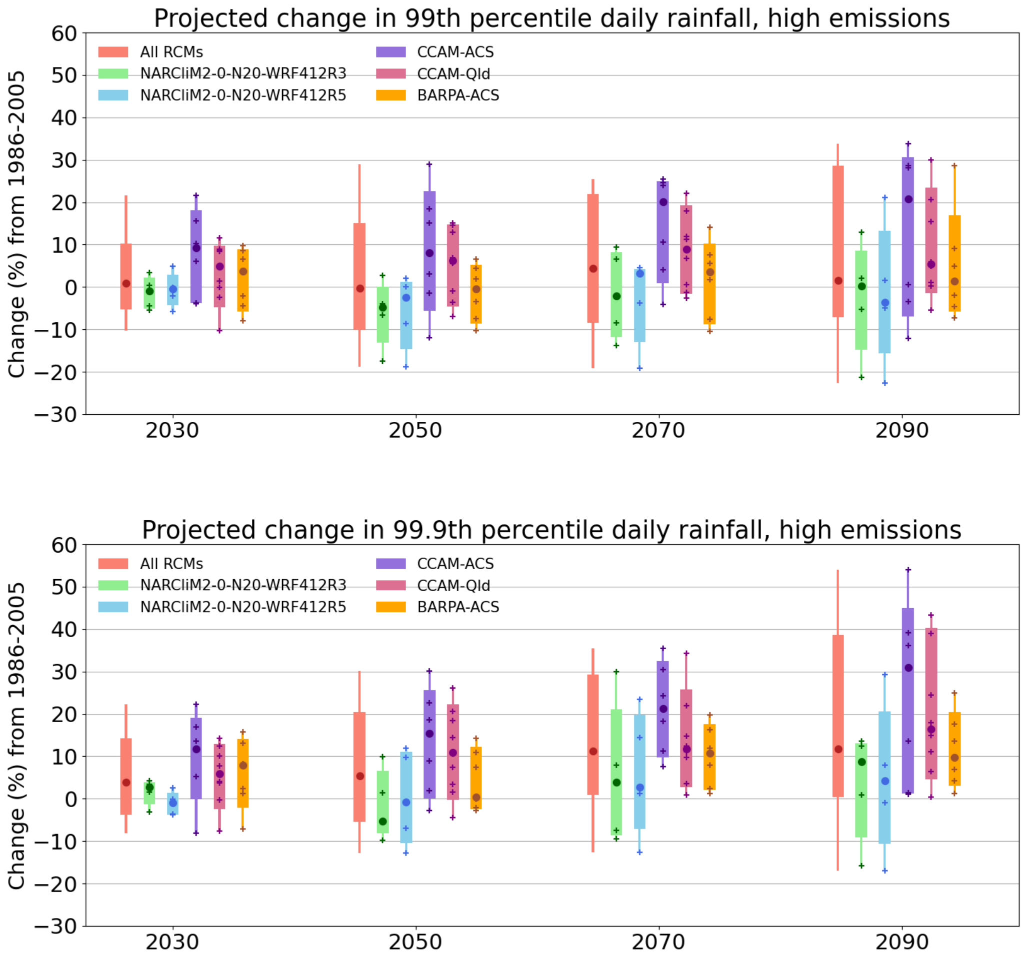
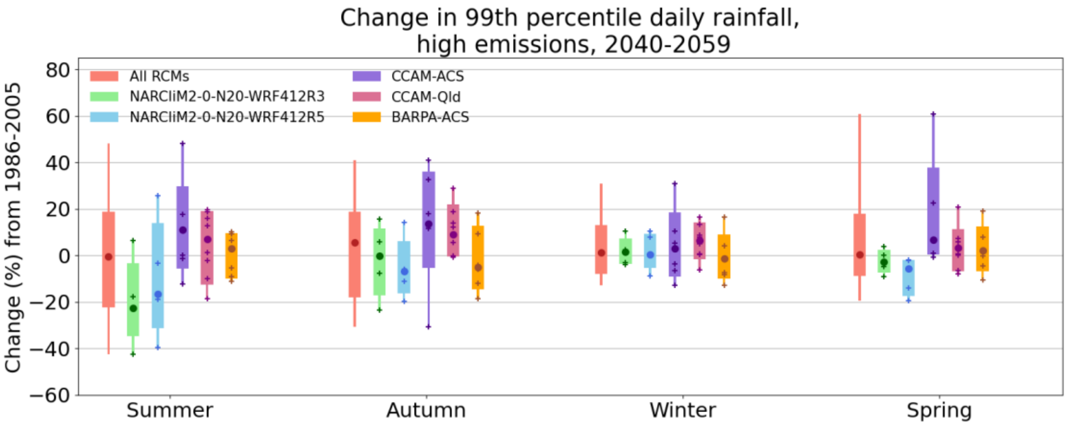


Figure 46 Projected change in the 99th percentile (top) and 99.9th percentile (bottom) extreme daily rainfall over Victoria under the high emissions scenario, SSP3-7.0. Projected change is % change from a 1986–2005 baseline to 20-year future periods. The thick coloured bars represent the 10th to 90th percentile range from each of the model ensembles, while the thin lines represent the full range, the solid dot represents the ensemble median and the small crosses show the individual models in the RCM ensembles.

Looking at the seasonal projected changes to extreme rainfall, there are some clear differences between the different downscaled model ensembles and different seasons. The change in extreme rainfall is least in winter, for all modelling. NARCliM2.0 shows large decreases in extreme summer rainfall, while the CCAM models tend to show an increase. CCAM-ACS, which showed the largest increases in annual extreme rainfall days, projects very large increases in extreme spring rainfall events, as well as in summer (Figure 47). The projection of larger increases in extreme rainfall in the warmer seasons is consistent with the timing of observed increases in extreme rainfall events.

Spatial patterns of projected change in very heavy rainfall days (99.9th percentile) from the NARCliM2.0 downscaling, compared to the host GCM (Figure 48) does not show any significant spatial patterns and also shows that the NARCliM2.0 downscaling can show increased or decreased extreme rainfall compared to the host GCMs.



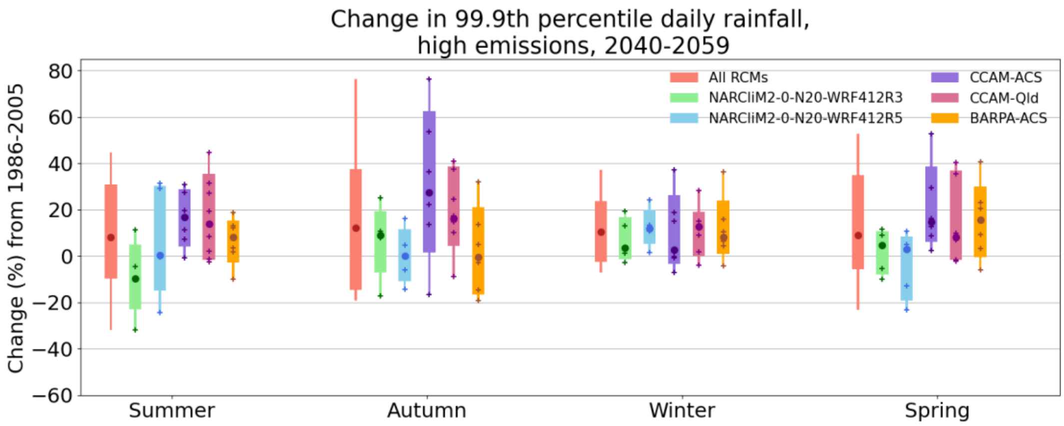


Figure 47 Projected change in seasonal 99th percentile (top) and 99.9th percentile (bottom) extreme daily rainfall over Victoria under the high emissions scenario, SSP3-7.0 for 2050. Projected change is % change from a 1986-2005 baseline to 20-year future periods. The thick coloured bars represent the 10th to 90th percentile range from each of the model ensembles, while the thin lines represent the full range, the solid dot represents the ensemble median and small crosses show the individual models in each ensemble.

Scientific process understanding and past observations and projections point to more significant future increases in extreme rainfall than shown in the projections from NARCliM2.0, highlighting the importance of drawing on multiple lines of evidence. Extreme sub-daily rainfall and more extreme measures of rainfall extremes (e.g. 1-in-20 extreme daily rainfall used in VCP19) tend to show larger changes than for the metrics shown here. Despite this broad range of projected change, including some projections of decrease in 99th and 99.9th percentile daily rainfall in NARCLIM2.0, this is only one line of evidence to consider. Overall, the evidence does not provide a compelling reason not to follow the forthcoming update to the Australian Rainfall and Runoff (AR&R) guidelines of scaling by warming per degree global warming, with a higher value for sub-daily rainfall than daily.

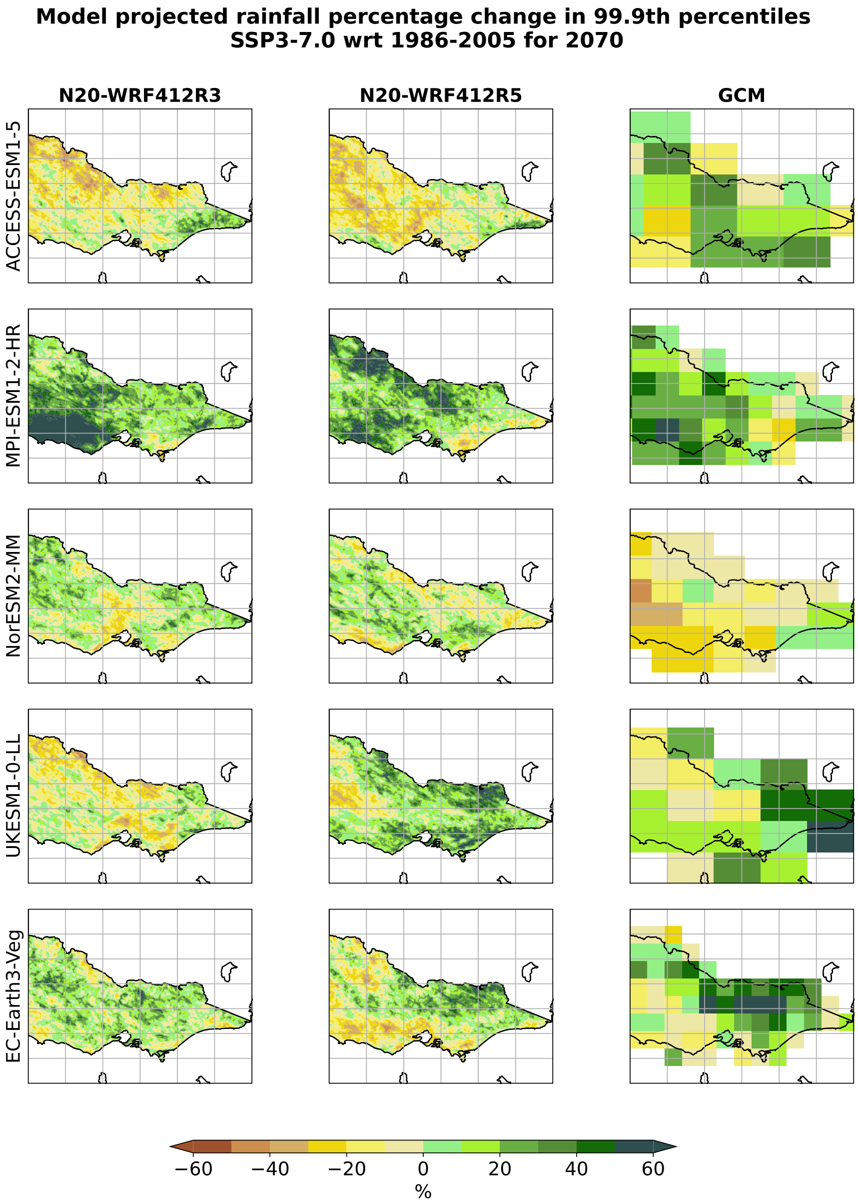


Figure 48 Spatial patterns of annual 99.9th percentile extreme rainfall change (%) for 5 GCMs downscaled by two versions of the NARCliM2.0 RCM (N20-WRF421R3, left, and N20-WRF421R5, middle) and the GCM itself (right). Change is calculated from a 1986–2005 baseline to the end of the century (2080–2099) under high emissions scenario SSP3-7.0.

4.7 Drought

There are many different definitions of 'drought', but generally it refers to a prolonged period of water deficit relative to normal conditions. Depending on the definition of drought, deficits in water could be deficits in rainfall, runoff or soil moisture. In this section, we provide information on projected changes in different measures of drought from existing publications, and also look at projected changes in a selection of measures of rainfall deficit from the NARCliM2.0 downscaling.

With rainfall in Victoria being naturally variable, periods of rainfall deficit or drought are an expected part of the climate, as are periods of increased rainfall. All measures of drought looked at show a tendency for increasing drought. This is not an unexpected outcome under a projected overall drying trend. The detailed look at potential extreme wet futures and increases to rainfall variability in Section 4.5.5 indicate that extended wet periods could also be a feature in the future climate.

Although we look at drought predominantly from a rainfall perspective (meteorological drought), it is important to keep in mind that rainfall deficit cascades through and is often amplified in soil moisture deficit (agricultural drought), runoff deficit (hydrological drought) and impacts (socioeconomic drought). Catchment characteristics can also change as a result of drought, which means the full implications of potential future increases in drought are not reflected by projections of rainfall deficit alone. For example, during the Millennium Drought more than half of Victorian catchments experienced 20–40% more decline in runoff than in rainfall, due to changes in rainfall-runoff relationships (DELWP, et al., 2020).

4.7.1 Future SPI12 Drought from CMIP5

The most recent drought projections for Australia were produced in 2020 using the previous (CMIP5) generation of GCMs (Kirono, 2020). These drought projections use the Standardised Precipitation Index (SPI12) which is a measure of rainfall anomaly (difference from the average) over 12 months. When the 12-month accumulated rainfall falls below certain levels for 3 months or more, a drought event is identified. This metric represents long-term rainfall deficit, making it relevant to hydrological and agricultural systems.

To help contextualise the SPI12 drought metrics in terms of droughts experienced over Victoria in the past, Figure 49 shows the SPI12 record since 1910 with 'drought' and 'wet' events identified. Events of different severity are associated with different SPI12 thresholds. The Millenium Drought was an extended period of 'severe' and 'extreme' drought. The middle decades of the 20th century were characterised by a relative lack of extended droughts while in the early 20th century Victoria experienced more droughts, including periods of extreme drought.

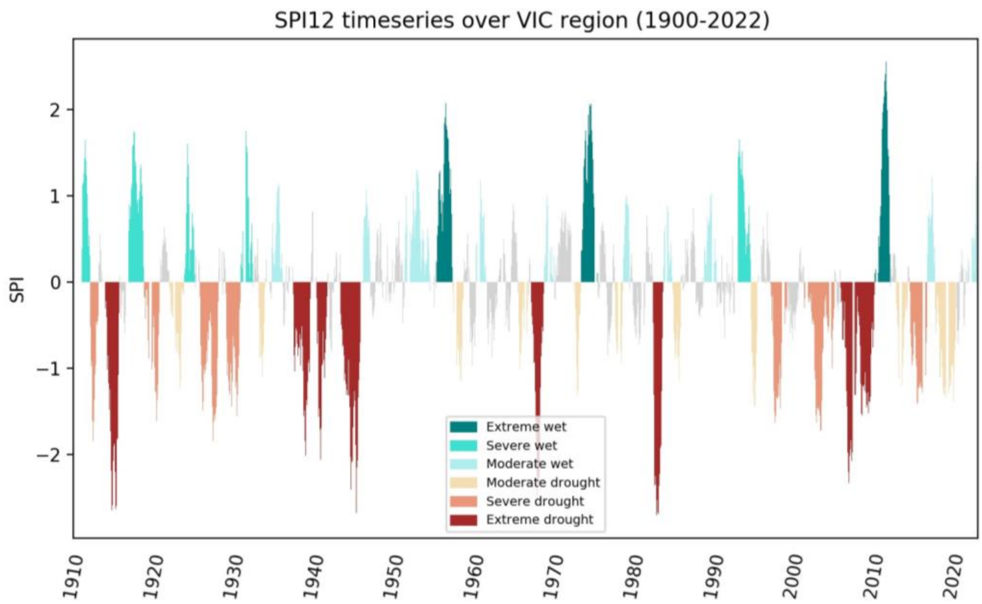


Figure 49 Timeseries of 12-month Standardised Precipitation Index (SPI12) over the whole of Victoria, from 1910–2023. SPI12 is a measure of rainfall anomaly (difference from the average) over 12 months, with negative values representing dry conditions. Periods of 'wet' and 'drought' of various severity are indicated with the red and blue colours. See (Kirono, et al., 2020) for more detail on SPI12 drought definitions.

Although there can be considerable disagreement between models on drought projections, Victoria is one of the regions of Australia where models have greatest agreement about increasing drought. A summary of the Kirono (2020) CMIP5 projections of changes in SPI12 drought between the 20th and 21st centuries under a very high emissions scenario (RCP8.5) is presented in Table 16. Using such a long time period allows for more robust signals of change to be detected, important for a variable like drought which can vary naturally on decadal timescales. These projections for a very high emissions scenario give us a plausible upper end of projected change.

The key messages are:

- Although there is a range of projections between the models, with some models showing decreases to drought metrics, most models show increases.
- Droughts are projected to become longer and more intense and with more time being spent under drought conditions.
- Drought intensity is projected to more often be extreme (i.e. a larger water deficit).
- Over Victoria, 80% of CMIP5 GCMs project that there will be an increase in the amount of time spent in extreme drought conditions. The multi-model median projects more than a doubling in the amount of time spent in extreme drought conditions.
- Increases in drought are projected to be more severe over western Victoria than eastern Victoria

The IPCC's Sixth Assessment Report also stated that drought increases are projected for Southern Australia for global warming levels of 2 °C or higher, with medium confidence (IPCC, 2023).

Table 16 Projected change in drought and extreme drought metrics (with drought being defined by the standardised precipitation index, SPI, over 12 month periods) over Victoria from Kirono et al (2020), based on CMIP5 GCMs under a very high emissions scenario (RCP8.5). The values are the projected change between the whole of the 20th century (1900–2005) to the whole 21st century (2006–2100) as the multi-model median and 10th to 90th percentile range in brackets.

Drought metrics	Drought	Extreme drought
Duration (% change)	+20 (-15 to +84)	+18 (-23 to +86)
Percent time in drought (% change)	+34 (-19 to +85)	+123 (-11 to +291)
Frequency (% change)	-3 (-28 to +15)	+50 (-17 to +143)
Intensity per event (% change)	+43 (-14 to +168)	+31 (-19 to +132)

4.7.2 Future dry months from NARCliM2.0

A simple way of assessing the prevalence of dry conditions is to look at the number of 'dry months'. Dry months are defined here as months with total rainfall below the 10th percentile from the 1986–2005 baseline period. Here we look at dry months in the NARCliM2.0 downscaling. While the NARCliM2.0 projections do not capture the full range of future rainfall changes spanned by the whole CMIP6 GCM or CORDEX ensembles, they do tend to represent the dry end of the projections. This means that the drought projections from NARCliM2.0 are assumed to be capturing the 'worst-case' in terms of drought for the emissions scenarios investigated, in the context of the wider range of projections.

Dry months are projected to increase by mid-century according to the NARCliM2.0 projections and increase further through the latter half of the century under the high emissions scenario.

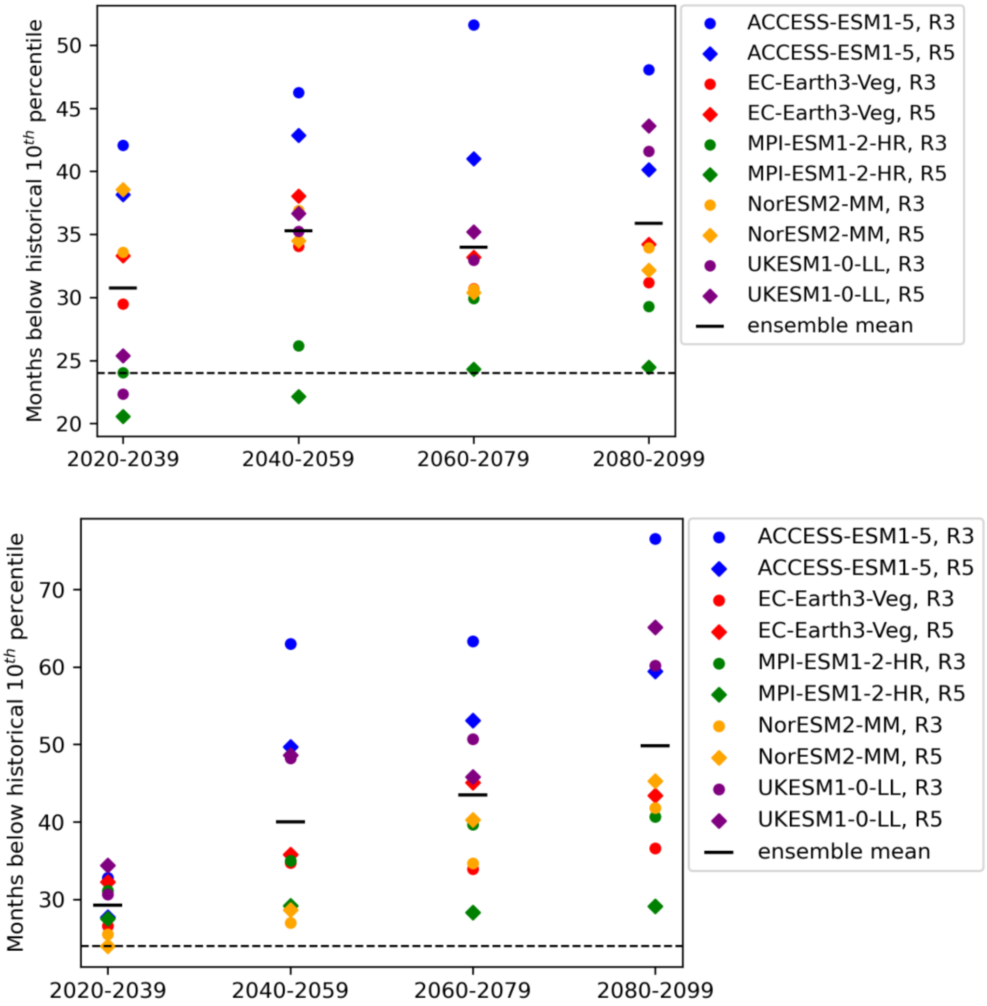


Figure 50 Mean occurrence of dry months in NARCliM2.0 projections for SSP1-2.6 (top) and SSP3-7.0 (bottom), defined by the 10th percentile in monthly precipitation in the 1986-2005 baseline. The dashed line at 24 months represents 10% of a 20-year period (i.e. the occurrence of dry months in the baseline).

For 2050 and beyond, all of the NARCliM2.0 simulations project increases in time spent in drought, except for 2050 under low emissions, for which one model projects small decreases. However, the scale of increases varies considerably across the NARCliM2.0 ensemble, with ACCESS-ESM1.5 generally projecting the greatest increases, and the simulations downscaling MPI-ESM-1-2-HR and EC-Earth3-Veg consistently projecting smaller than average increases. Indicative multi-model mean projections show 12 additional dry months in the 20 years centred on 2090 under low emissions and 26 additional dry months under high emissions (relative to the baseline of 24 dry months in the 1986–2005 period) – this is a doubling of dry months by the end of the century under high emissions (Figure 50**Error! Reference source not found.**). Maps of modelled changes in dry months from NARCliM2.0 are included in the Appendix, Figure 64.

4.7.3 Keetch-Byram Drought Index (KBDI) from NARCliM2.0

An alternative measure of drought is a drought factor based on the Keetch-Byram Drought Index (KBDI), as recommended by Dowdy et al. (2009) as input to calculations of the conduciveness of weather conditions to bushfire. The KBDI calculation tracks rainfall deficit over time and, though it does not account for water losses through evapotranspiration, is logically more closely related to soil moisture deficit than the number of dry months, which do not necessarily show consecutive dry months. The KBDI drought factor is capped at a maximum value of 10, which imposes a limit on projected changes due to climate change.

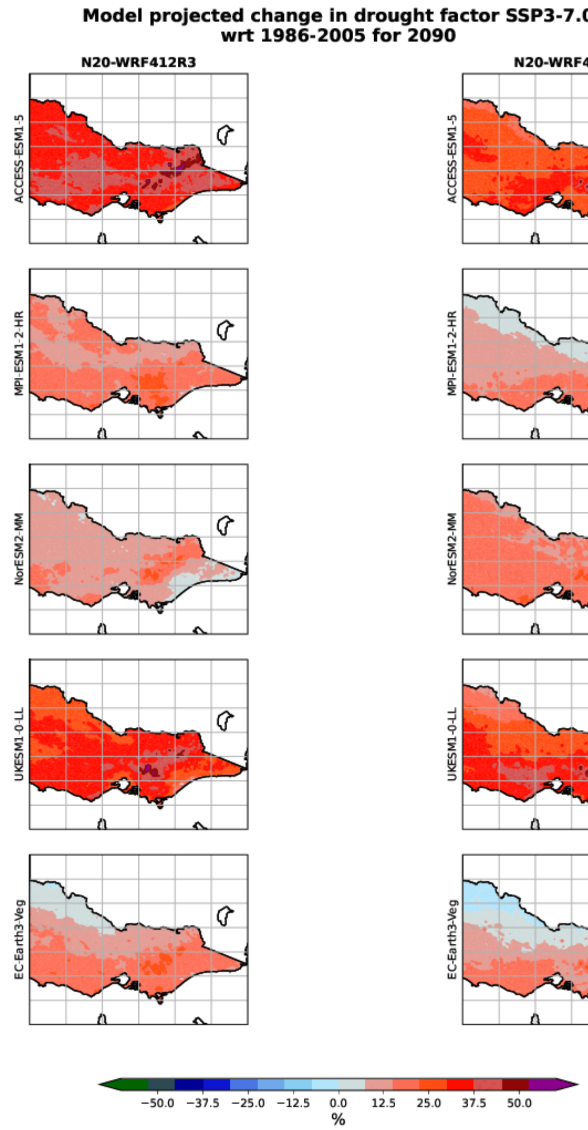


Figure 51 Change in drought factor predicted by the NARCLiM2.0 downscaling for 2080-2099 relative to 1986-2005 for SSP3-7.0 concentration pathway.

Projected changes in KBDI drought factor from NARCliM2.0 between 1986-2005 and the end of the century under the high emissions scenario are shown in Figure 51. Changes in drought factor depend most on host GCM, location and emissions scenario. They depend on downscaling model to a lesser extent. The changes vary between –15% and +30% under low emissions and between -10% and +60% under high emissions. Under high emissions, there is a tendency for increases in drought factor to be especially high along the Victorian Alps.

5 Summary and guidance

This chapter provides guidance on how the new projections for Victoria can be interpreted and used. It does so in the context of pre-existing information from the VCP19 projections. Recognising the limitations of the new projections, it also highlights further work related to the projections that may benefit decision makers in Victoria.

5.1 Comparison with VCP19 projections

VCP24 provides an update to VCP19 based on updated climate modelling. However, that does not mean that the new projections contradict or replace previous climate projections for Victoria – rather, they represent an evolution of VCP19. VCP24 has taken an approach to producing climate change projections consistent with that used for VCP19. In both sets of projections, multiple ensembles of climate model simulations are analysed and confidence statements are assigned to results based on multiple lines of scientific evidence, including from observations and our scientific understanding of climate processes. Both VCP24 and VCP19 contain projections information based on both global climate modelling and detailed regional climate modelling and information about the future climate using both emissions-scenario and GWL framings.

Although there are many broad similarities between the VCP24 and VCP19 projections, there are some important differences in inputs, outputs, scope and analysis. These are summarised below and in Table 17**Error! Reference source not found.**.

Updated modelling

VCP24 draws on the most recent, CMIP6, generation of Global Climate Models (GCMs), whereas VCP19 drew on the previous generation, CMIP5. As well as reporting results from a wide range of GCMs, VCP19 included results from regional downscaling of 6 GCMs to a resolution of ~5 km over Victoria. VCP24 incorporates information from a more comprehensive set of RCMs, totalling 32 regionally downscaled simulations for each emissions scenario. This includes ~4 km resolution regional downscaling over southeast Australia from the NSW Government's NARCliM2.0 project. It also includes national-scale ~10-20 km downscaling from the Queensland Government and the Australian Climate Service, a partnership between the Bureau of Meteorology, CSIRO, the Australian Bureau of Statistics and Geoscience Australia[18]. This multi-model approach is in alignment with the goals of the *Climate Projections Roadmap for Australia* published by the Australian Government[19]. It allows greater comparability with emerging national and state projections which draw on some of the same modelling.

Emissions scenarios

The move from CMIP5 to CMIP6 has necessitated the use of the emissions scenarios used by CMIP6, described by SSPs, rather than the emissions scenarios used by CMIP5, described by RCPs. The use of SSPs by VCP24 has the advantage that the projections use emissions scenarios that are consistent with contemporary scenarios used by the IPCC, and more generally by the climate projections community in Australia and internationally. The two SSPs chosen for analysis

[18] Australian Climate Service (acs.gov.au)

[19] DCCEEW - Climate Projections Roadmap for Australia

in VCP24 are consistent with current international standards on priorities for regional downscaling.

VCP19 used a medium (RCP4.5) and very high (RCP8.5 – referred to as high emissions at the time) emissions scenarios. VCP24 uses a low (SSP1-2.6 and high (SSP3-7.0) emissions scenarios. Global CO_2 emissions under these four scenarios are shown for comparison in Figure 52.

The SSP3-7.0 high emissions scenario used by VCP24 has emissions significantly lower than those of RCP8.5 by 2100, but still appropriately high to support challenging yet plausible climate scenarios for risk analysis and adaptation planning. The RCP8.5 projections from VCP19 provides what are now considered low likelihood, worst case projections.

The SSP1-2.6 low emissions scenario used by VCP24 assumes more immediate reductions in global emissions than the RCP4.5 medium emissions scenario used by VCP19 and represents the future climate if global emissions are reduced in alignment with the Paris Agreement, reaching global net zero emissions by around 2075.

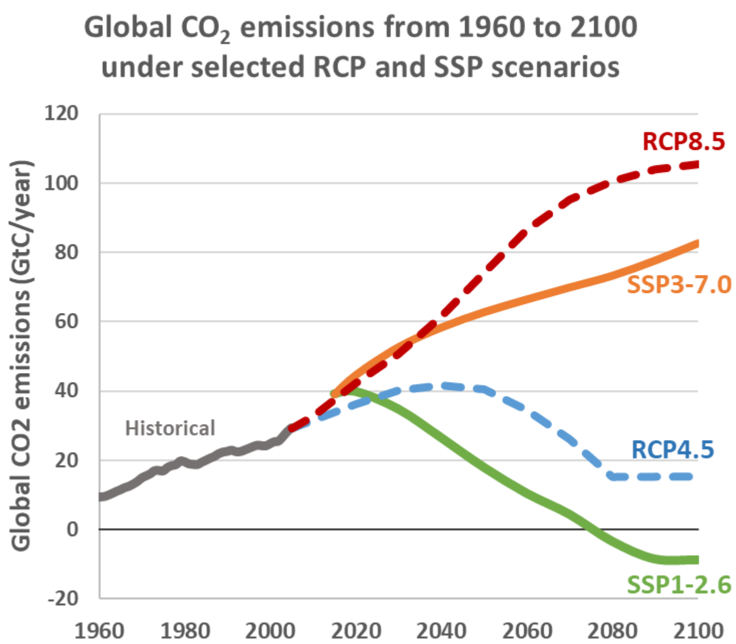


Figure 52 Global CO2 emissions out to 2100 under the emissions scenarios used in VCP19 (RCP4.5 and RCP8.5) and VCP24 (SSP1-2.6 and SSP3-7.0). Historical emissions are shown in grey from 1960 to 2005

Depth of analysis

At the time of the VCP24 analysis, the NARCliM2.0 4km simulations and the CORDEX simulations had only just been made available. As a result, the depth of analysis in VCP24 is less than in VCP19. VCP24 highlights emerging results from the latest downscaling simulations covering Victoria. These are mainly based on analysis of temperature and rainfall. Other variables related to relevant climate processes (e.g., atmospheric circulation, moisture transport, surface fluxes) that might help to explain these results have not been performed. Due to a lack of available data, it has also not been possible to analyse NARCliM2.0 simulations that are complementary to the 4km projections simulations, including intermediate-resolution (~18km) simulations and simulations forced with reanalysis data. It is anticipated that further research by the climate science community over the coming years will lead to greater understanding of the new downscaling simulations. This could lead to confidence in individual VCP24 results being either enhanced or lessened. Users should treat those results in VCP24 that rely on the new downscaling simulations accordingly.

Climate variables analysed

To expedite analysis of a large number of new downscaling simulations, the number of climate variables analysed by VCP24 is less than in VCP19 and the climate extremes analysed by VCP24 are less extreme (occurring more frequently) than those analysed by VCP19 (i.e. 99th and 99.9th percentile vs 1-iin-20-year temperature and rainfall). VCP24 prioritised analysis of changes in average and extreme temperature and rainfall. Other variables that are included in VCP19, such as pressure, winds, humidity and evaporation, are not included in VCP24. However, although the number of climate variables analysed by VCP24 is less than in VCP19, VCP24 includes some key impact-relevant variables that VCP19 does not. These relate to heatwaves and drought.

Application-ready data

VCP19 developed a comprehensive set of 5km ‘application-ready’ datasets from the VCP19 CCAM simulations. In these datasets, aspects of the biases in the climate model simulations were removed, making them suitable for use in some climate change impact and risk assessments. Generating such datasets for the updated modelling used in VCP24 was beyond the scope of VCP24 and, at the time of writing, such datasets are not yet available for the NARCliM2.0 and CORDEX Australasia simulations. This means that VCP24 cannot, on its own, be used in applications for which the absolute value of climate variables is important. This includes impact assessments where, for example, days with temperatures or rainfall above certain thresholds are important. Global climate models can have significant biases in temperature and rainfall, and these biases can flow through to the regionally downscaled simulations. Some significant temperature and rainfall biases were identified in the NARCliM2.0 4km data (see section 3.2) and also exist in other downscaling. If absolute values are to be used, some form of bias correction is necessary before using raw-model output.

Comparison of projections results in VCP19 vs VCP24

Differences between the SSPs used in VCP24 and the RCPs used in VCP19 mean that the quantitative projections are not directly comparable for any given time period in the future. However, qualitative results can be compared between VCP24 and VCP19 and it is also possible to quantitatively compare GWL projections (the influence of differences between SSPs and RCPs is largely removed in the GWL framing).

VCP24 broadly supports the main findings of VCP19 – that Victoria will get hotter and drier. Many of the results of VCP19 are further strengthened by the VCP24 projections:

- Both VCP24 and VCP19 suggest that warming of the average temperature of Victoria will continue at a rate close to warming of the global average temperature. VCP19 projected a warming in the average temperature of Victoria between 1.5 and 2.3 °C relative to pre-industrial times for a global warming of 2 °C, while VCP24 projects 1.8 to 2.3 °C warming.
- Both VCP24 and VCP19 suggest that heat extremes (i.e. the temperature reached on hot days) will warm more than the rate of warming for average temperatures.
- Overall, both the modelling considered in VCP24 and in VCP19 suggests that the average annual rainfall for Victoria will decrease in future. Both VCP24 and VCP19 show the size of potential decreases in rainfall varies between individual model simulations and some simulations show increases in rainfall. For global warming of 2 °C, VCP19-projected

changes in annual rainfall in Victoria are -11 to +2% relative to the 1986-2005 baseline, while VCP24 projects -14 to +2% change.

- Both VCP24 and VCP19 suggest a future decline in the average rainfall over Victoria in the cool season. Within the cool season, there is greatest agreement on a rainfall decline among model simulations for winter. For global warming of 2 °C, VCP19-projected changes in winter rainfall in Victoria are -16 to +8% relative to the 1986-2005 baseline, while VCP24 projects -14% to +10% change.
- Both VCP19 and VCP24 project that extreme rainfall events will become more intense, with the more extreme rainfall events intensifying the most.

There are also some differences in the results of VCP24 and VCP19:

- VCP19 found a larger difference in warming between extreme and average temperatures than VCP24. This may be because VCP19 analysed more extreme temperature events than VCP24 (1-in-20 year rather than 99th and 99.9th percentile daily maximum temperature). However, a contribution to the differences in relative warming due to differences in the VCP24 NARCliM2.0 and VCP19 CCAM regional modelling cannot be ruled out.
- While there is agreement between the VCP24 and VCP19 on a continued decrease in cool season rainfall, there is less certainty around future changes in summer rainfall. VCP19 noted that increases and decreases in summer rainfall are possible. The new VCP24 rainfall projections do not narrow the outlook, with simulations showing a mix of increasing and decreasing summer rainfall. Notably, the new ~4 km NARCliM2.0 simulations project more pronounced decreases in average summer rainfall than were projected by any of the modelling contributing to VCP19, whereas some other new regional climate model simulations (such as those prepared as part of the Australian Climate Service) show large increases in summer rainfall.
- High-resolution regional modelling can potentially represent spatial patterns in future rainfall change at levels of detail that global models cannot. However, the highest-resolution modelling contributing to VCP19 and VCP24, the ~5 km resolution modelling from CSIRO and the ~4 km resolution NARCliM2.0 modelling respectively, project quite different spatial patterns of future rainfall changes for Victoria. More in depth analysis is being done by the Australian climate science community to understand these differences. A new feature of VCP24 that arises from the use of CMIP6 global modelling is the inclusion of several climate models simulations that project especially rapid warming in response to future increases in the amount of greenhouse gas in the atmosphere. Such ‘high climate sensitivity’ simulations were not as numerous in CMIP5 and did not influence VCP19 to the same degree as VCP24. Research on ‘high climate sensitivity’ models is ongoing. Currently, the high-warming futures arising from these models are not considered to be likely. However, they cannot be ruled out and so are presented separately in VCP24 as ‘low-likelihood, high-warming’ temperature projections.

Table 17 Summary of differences in inputs and scope between VCP24 and VCP19

	What was in VCP19?	What's in VCP24?
Global modelling	**CMIP5**	**CMIP6**
Regional downscaling used	• **Downscaling to ~ 5 km** using one regional climate model to downscale 6 global models • **Contextualisation using CMIP5 GCMs and other existing modelling**	• **Downscaling to ~ 4 km** for southeast Australia using two regional climate model variants to downscale 5 global models • **National-scale downscaling to ~10-20 km** from three regional climate modelling centres (each downscaling 6 or 7 global models)
Emissions scenarios	• **RCP4.5 -** a **medium emissions scenario** with global emissions of carbon dioxide **peaking around 2040** before declining to **1960s levels by 2100**. Net zero emissions are not achieved under this scenario. • **RCP8.5** - a **very high emission scenario** with carbon dioxide emissions continuing to increase to almost **triple present levels by 2100**. In VCP19 this is termed the 'high' emission scenario.	• **SSP1-2.6** - a **low emissions scenario** following a 'sustainability' narrative with immediate significant cuts in emissions to reach **net zero around 2075**, roughly compliant with the Paris Agreement. Equivalent to RCP2.6. • **SSP3-7.0** - **a high emissions scenario** following a 'fossil-fuelled development; narrative with carbon dioxide emissions continuing to increase to roughly double present levels by 2100. There is no equivalent RCP.
Climate variables	• average temperature and rainfall • extreme temperature (1-in-20-year hottest day and night and coldest night) • days above heat thresholds (days above 35 and 45 °C) • extreme rainfall (1-in-20 year wettest day) • other variables, such as pressure, winds, humidity and evaporation • 13 variables total	• average temperature and rainfall • extreme temperature (99th and 99.9th percentile hottest days and nights) • days above heat thresholds (days above 99th and 99.9th percentile) • extreme rainfall (99th and 99.9th percentile daily rainfall) • drought (months below 10th percentile) • excess heat factor heatwave metrics • 9 variables total

5.2 Guidance

The VCP19 technical report (Clarke, et al., 2019) provides detailed guidance on how climate projections can be used in impact assessments. This guidance applies equally to VCP24. This section is not intended to duplicate the VCP19 content. Instead, it briefly addresses some of the challenges in using the information from the new projections in impact assessments.

Uncertainty in projections and addressing uncertainty with climate scenarios

A key challenge in using climate projections in impact assessments, which applies to both VCP19 and VCP24 as well as any other climate projections, is how to address the navigate the large amount of climate information provided and address the uncertainty associated with future projections. Uncertainty in projections arises mainly due to uncertainty in future global greenhouse gas emissions and uncertainty in how the climate will respond to emissions of greenhouse gasses in the future. The future evolution of global emissions is unknown and unknowable, as it depends on a myriad of decisions made around the globe now and in the future. In VCP24, emissions uncertainty is addressed by considering future climate change under a low emissions and a high emissions scenario, spanning two extremes of possible future emissions. Even if we knew how greenhouse gas emissions would evolve, there is still uncertainty in how the climate will respond to emissions. This uncertainty is addressed in part by using a range of different climate models. In VCP24 we draw on a range of global and regional downscaling models to represent this range of uncertainty. Natural climate variability also contributes to uncertainty around future climate response, something also accounted for in part by using a range of climate models.

Representative climate future scenarios, which encompass different emissions scenarios and models, can be used to deal with these uncertainties. These climate scenarios may also be referred to as storylines (Fiedler, et al., 2024). One technique of addressing uncertainty is to identify representative examples of 'best', 'worst' and, sometimes 'maximum consensus' climate scenarios. Precisely how these are identified will depend critically on the climate sensitivities of the systems being assessed. However, plots showing projections of changes in a small number of relevant, but uncorrelated, climate variables can be helpful. Figure 53 shows an example that may be applicable to a high-level impact assessment for Victoria. It shows the full range of projected changes in average annual temperature and rainfall for Victoria projected over the 21st century under a high emissions scenario by the CMIP6 and downscaling simulations considered in this report. Risk-averse decision-makers may want to consider some of the most extreme scenarios shown in the figure:

- the significant warming and extreme drying scenarios simulated by the downscaling of the ACCESS-ESM1.5 GCM by NARCliM2.0 (see blue and green points labelled 'A-ESM' to the left of the diagram)
- the extreme warming and significant drying scenarios simulated by the downscaling of the UKESM1-0-LL GCM by NARCliM2.0 (blue and green points labelled 'UKE' in the top-left of the diagram')
- the significant warming, extreme wetting scenario simulated by the downscaling of the EC-Earth3 GCM by one of the CCAM ACS simulations (purple point labelled 'EC3' to the right of the diagram)

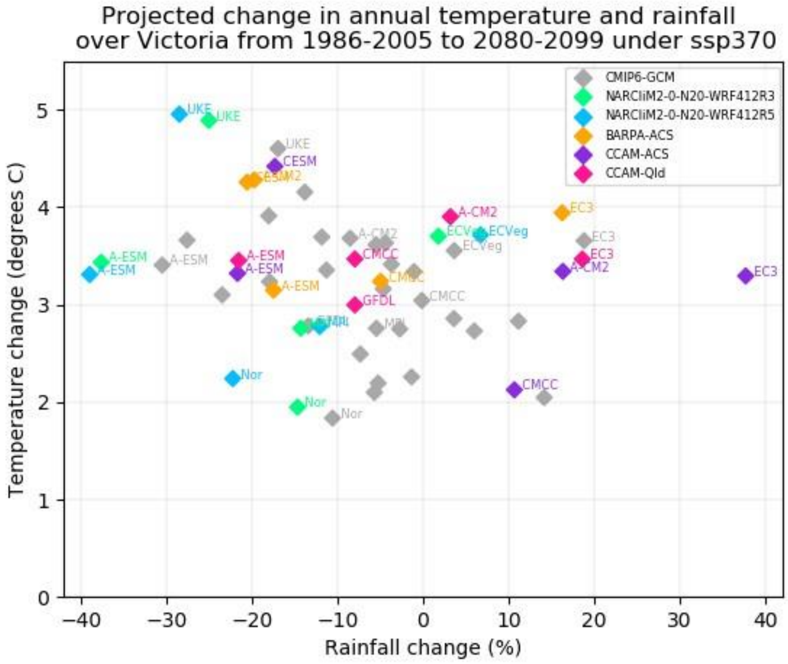


Figure 53 Example: plots like this (albeit with many less points or highlighting just the relevant models) can be used to highlight individual models which can be used to represent a particular future e.g. NARCliM2.0 UKE (green, top left) represent the extreme hot and dry case while CCAM-ACS EC3 (purple, far right) represent a future with high increase in rainfall.

In some cases, 'application-ready' or 'bias corrected' climate data will be required for in-depth analysis of the above scenarios, and others. Application-ready bias corrected data is generated from climate model output and observations in such a way as to reduce the influence of climate model biases. It is designed to be more compatible with downstream climate impact assessments than unprocessed climate model outputs. At the time of writing, application-ready or bias-corrected data are not yet available for the climate model simulations considered by this report.

Information beyond climate projections is needed to assess climate risks

VCP24 provides information about future changes to climate and climate hazards for assessing the risks posed by climate change and climate-related stressors. However, to effectively assess and manage climate change risks, decision-makers must combine information from VCP24 with other sources of information. Information on climate and other related physical hazards is only one part of a climate change risk assessment and needs to be combined with appropriate knowledge of the assets or values being considered, including their climate exposure and vulnerability:

- **Exposure:** the extent to which people, assets and ecosystems are in areas that could be adversely affected by climate hazards. For example, the high density of housing and critical infrastructure in a climate hazard prone area. Exposure information includes data about the components of a system and where they are located, such as maps of infrastructure and housing.
- **Vulnerability:** likelihood or predisposition of systems, communities or individuals to be negatively impacted by climate hazards. Vulnerability information can include knowledge on

a system, community or individuals susceptibility to harm if exposed to a climate related-stressor, such as economic, educational and social resources.

Information on vulnerability and exposure can include expert knowledge on how the system operates and historical information on its performance when presented with climate-related stressors. Importantly, exposure and vulnerability are dynamic and will also change in the future. This means that climate change risk assessments may need to include projections of future changes in relevant exposure and vulnerability variables (e.g., population and demographic projections), in addition to projections of future climate changes.

Victoria is of course interconnected with the rest of Australia and the wider world. This means that climate changes outside Victoria, and beyond the scope of VCP24, will impact the state. Decision-makers assessing climate risks to Victoria should account for dependencies on other systems that may be impacted by climate change. This could be dependencies on national systems (e.g., nationwide energy and transport systems) and international systems (e.g., the global finance system, international trade). This may require generating scenarios that are consistent between the climate projections for Victoria and climate change and its impacts elsewhere in Australia or overseas. This will be facilitated by the use in this report of standard global climate modelling (i.e., from CMIP6) and emissions scenarios (i.e., SSPs).

Appendices

Appendix: List of CMIP6 Global Climate Models

Table 18 List of CMIP6 GCMs which were used in the projections. The horizontal resolution and the equilibrium climate sensitivity (ECS) values are listed. The equilibrium climate sensitivity (ECS) is listed and models with ECS outside the likely range of 2.3-4.5 are indicated with *. Where a GCM has been used for downscaling by a regional climate model this is indicated in the right-hand column. The model ensemble member is provided in (round brackets) if it is anything other than r1i1p1f1. For the CCAM Qld downscaling, the version of the CCAM is specified in [square brackets].

CMIP6 GCM name	Horizontal resolution	Equilibrium Climate Sensitivity (ECS)	Used for downscaling by these RCMs (ensemble member in brackets where it is not r1i1p1f1) [downscaling model version for CCAM Qld in square brackets]
ACCESS-CM2	1.2x1.8°	4.66*	CCAM CSIRO (r4i1p1f1), CCAM QLD (r2i1p1f1) [CCAMoc-v2112] BARPA (r4i1p1f1)
ACCESS-ESM1.5	1.2x1.8°	3.88	NARCliM2.0 (r6i1p1f1), CCAM CSIRO (r6i1p1f1), CCAM QLD (r6i1p1f1) [CCAM-v2105], BARPA (r6i1p1f1)
AWI-CM-1-1-MR	0.9x0.9°	3.16	
BCC-CSM2-MR	1.1x1.1°	3.02	
CanESM5	2.8x2.8°	5.64*	
CanESM5-CanOE	2.8x2.8°	hot	
CAS-ESM2-0	1.4x1.4°		
CESM2	~1.0°	5.15*	CCAM CSIRO, BARPA
CESM2-WACCM	1.0x1.3°	4.68*	
CMCC-CM2-SR5	~0.9°	3.55	
CMCC-ESM2	0.9x1.3°	3.58	CCAM CSIRO, CCAM QLD [CCAM-v2105], BARPA
CNRM-CM6-1	1.4x1.4°	4.9*	
CNRM-CM6-1-HR	~0.5°	4.33	CCAM QLD(r1i1p1f2) [CCAM-v2112]
CNRM-ESM2-1	1.4x1.4°	4.79*	CCAM-ACS(r1i1p1f2)
EC-Earth3	0.7x0.7°	4.26	CCAM CSIRO, CCAM QLD [CCAM-v2105], BARPA
EC-Earth3-Veg	0.7x0.7°	4.33	NARCliM2.0
EC-Earth3-Veg-LR	0.7x0.7°		
FGOALS-f3-L	2.3x2.0°	2.98	
FGOALS-g3	2.3x2.0°	2.87	
GFDL-ESM4	1.0x1.3°	2.65	CCAM-QLD [CCAM-v2105]
GISS-E2-1-G	2.0x2.5°	2.71	
IITM-ESM	~1.89°		
INM-CM4-8	1.5x2.0°	1.83	
INM-CM5-0	1.5x2.0°	1.92	
IPSL-CM6A-LR	1.3x2.5°	4.7*	
KACE-1-0-G	2.2x2.2°	4.93*	
MIROC6	1.4x1.4°	2.6	
MIROC-ES2L	4.5x4.5°	2.66	

MPI-ESM1-2-HR	~0.9°	2.98	NARCliM2.0(r1i1p1f1), BARPA (r1i1p1f1)
MPI-ESM1-2-LR	~2.0°	3.03	CCAM-QLD(r9i1p1f1) [CCAM-v2105]
MRI-ESM2-0	1.1x1.1°	3.13	CCAM QLD(r1i1p1f1)
NorESM2-LM	1.9x2.5°	2.56	
NorESM2-MM	0.9x0.9°	2.5	NARCliM2.0(r1i1p1f1), BARPA(r1i1p1f1), CCAM-ACS (r1i1p1f1), CCAM-QLD(r1i1p1f1) [CCAM-v2112]
TaiESM1	0.9x0.9°	4.36	
UKESM1-0-LL	1.3x1.9	5.36*	NARCliM2.0 (r1i1p1f2)

Appendix: Additional projected change summary tables

Table 19 Projected changes in average annual mean daily minimum and maximum temperatures from 1986-2005 2050 (2040-2059) and 2090 (2080-2099) under low emissions (SSP1-2.6) and high emissions (SSP3-7.0). Projected changes are shown for the full and constrained CMIP6 GCM and RCM (comprising of all downscaling: CCAM-ACS, CCAM-Qld, BARPA-ACS and NARCliM2.0) ensembles. 'Constrained' indicates that models with equilibrium climate sensitivity greater than 4.5 or less than 2.3 are excluded. Ensemble projected change is in degrees, shown as median (10th to 90th range in brackets).

ENSEMBLE	2050		2090	
	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)
MEAN ANNUAL MAXIMUM DAILY TEMPERATURE				
CMIP6 GCMs	1.2 (0.7 to 1.8)	1.7 (1.3 to 2.4)	1.3 (0.7 to 2.1)	3.5 (2.5 to 4.5)
CMIP6 GCMs (constrained)	1.2 (0.6 to 1.7)	1.7 (1.2 to 2.1)	1.1 (0.7 to 2.1)	3.4 (2.4 to 4.0)
All RCMs	1.2 (0.6 to 1.7)	1.7 (1.0 to 2.4)	1.3 (0.7 to 1.9)	3.6 (2.5 to 5.0)
All RCMs (constrained)	1.1 (0.6 to 1.6)	1.6 (1.0 to 2.2)	1.3 (0.7 to 1.7)	3.4 (2.5 to 3.9)
MEAN ANNUAL MINIMUM DAILY TEMPERATURE				
CMIP6 GCMs	1.0 (0.4 to 1.3)	1.4 (1.0 to 1.8)	1.0 (0.6 to 1.7)	3.0 (2.0 to 4.0)
CMIP6 GCMs (constrained)	1.0 (0.4 to 1.3)	1.4 (0.9 to 1.7)	0.9 (0.5 to 1.6)	2.9 (2.0 to 3.7)
All RCMs	1.1 (0.4 to 1.4)	1.5 (0.9 to 2.0)	1.1 (0.4 to 1.7)	3.1 (2.1 to 4.0)
All RCMs (constrained)	0.9 (0.4 to 1.3)	1.4 (0.8 to 1.7)	1.0 (0.4 to 1.3)	2.9 (2.1 to 3.7)

Table 20 Projected changes in average annual and seasonal temperatures over Victoria when global warming reaches 1.5°C, 2.0°C and 3.0°C above pre-industrial climate (1850-1900). Projected change is given relative to the 1986-2005 baseline. Projected changes are shown for the whole CMIP6 model ensemble (range shown is the 10th to 90th percentile of the ensemble projections). Note that there has already been an observed 0.7°C warming from 1850-1900 to 1986-2005.

MULTIMODEL PROJECTED CHANGE (°C) IN MEAN SEASONAL TEMPERATURE BY GLOBAL WARMING LEVELS, FROM THE CMIP6 GCM ENSEMBLE			
	1.5°C GLOBAL WARMING	2.0°C GLOBAL WARMING	3.0°C GLOBAL WARMING
Victorian warming from 1986-2005 baseline, projected by CMIP6 GCM ensemble			
Annual	**0.8 (0.6 to 1.1)**	**1.3 (1.1 to 1.6)**	**2.2 (1.8 to 2.7)**
Summer (DJF)	0.9 (0.7 to 1.4)	1.6 (1.2 to 2.0)	2.5 (2.1 to 3.1)
Autumn (MAM)	0.8 (0.4 to 1.3)	1.4 (1.0 to 1.7)	2.4 (1.7 to 2.9)
Winter (JJA)	0.7 (0.4 to 0.9)	1.1 (0.7 to 1.4)	1.9 (1.5 to 2.3)
Spring (SON)	0.8 (0.6 to 1.1)	1.3 (1.0 to 1.7)	2.2 (1.9 to 2.9)

Table 21 Projected changes in the average 99th and 99.9th percentile maximum daily temperature from 1986-2005 to 2050 (2040-2059) and 2090 (2080-2099) under low emissions (SSP1-2.6) and high emissions (SSP3-7.0). Projected changes are shown for the full and constrained RCM ensemble (comprising of all downscaling: CCAM-ACS, CCAM-Qld, BARPA-ACS and NARCliM2.0) ensembles. 'Constrained' indicates that models with equilibrium climate sensitivity greater than 4.5 or less than 2.3 are excluded. Ensemble projected change is in degrees, shown as median (10th to 90th range in brackets). Additionally, the maximum projected value from the NARCliM2.0 low-likelihood, high-warming model is indicated by *.

ENSEMBLE	2050		2090	
	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)
99TH PERCENTILE MAXIMUM DAILY TEMPERATURE				
All RCMs	1.4 (0.6 to 2.4)	2.0 (0.8 to 2.7) *4.9	1.5 (0.7 to 3.0)	3.7 (2.5 to 4.9) *6.4
All RCMs (constrained)	1.1 (0.5 to 1.9)	1.8 (0.8 to 2.4)	1.2 (0.6 to 1.8)	3.5 (2.5 to 4.2)
99.9TH PERCENTILE MAXIMUM DAILY TEMPERATURE				
All RCMs	1.2 (0.5 to 2.5)	1.6 (0.9 to 2.9)	1.3 (0.6 to 2.9)	3.6 (2.1 to 4.8)
All RCMs (constrained)	0.9 (0.4 to 1.8)	1.6 (0.7 to 2.2)	1.3 (0.5 to 2.1)	3.5 (1.8 to 4.4)

Table 22 Projected changes in the average 99th and 99.9th percentile minimum daily temperature (i.e. hot and very hot nights) from 1986-2005 to 2050 (2040-2059) and 2090 (2080-2099) under low emissions (SSP1-2.6) and high emissions (SSP3-7.0). Projected changes are shown for the full and constrained RCM ensemble (comprising of all downscaling: CCAM-ACS, CCAM-Qld, BARPA-ACS and NARCliM2.0) ensembles. 'Constrained' indicates that models with equilibrium climate sensitivity greater than 4.5 or less than 2.3 are excluded. Ensemble projected change is in degrees, shown as median (10th to 90th range in brackets). Additionally, the maximum projected value from the NARCliM2.0 low-likelihood, high-warming model is shown preceded by *.

ENSEMBLE	2050		2090	
	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)	LOW EMISSIONS (SSP1-2.6)	HIGH EMISSIONS (SSP3-7.0)
99TH PERCENTILE MINIMUM DAILY TEMPERATURE				
All RCMs	1.1 (0.5 to 1.9)	1.8 (1.2 to 2.5) *3.4	1.4 (0.5 to 2.1)	3.4 (2.5 to 4.8) *5.7
All RCMs (constrained)	1.0 (0.5 to 1.4)	1.7 (0.8 to 2.3)	1.1 (0.5 to 1.6)	3.1 (2.2 to 4.4)
99.9TH PERCENTILE MINIMUM DAILY TEMPERATURE				
All RCMs	1.1 (0.1 to 2.3)	1.7 (0.7 to 2.9)	1.5 (0.4 to 2.6)	3.5 (2.1 to 4.8)
All RCMs (constrained)	0.9 (-0.0 to 1.8)	1.7 (0.2 to 2.3)	1.2 (0.3 to 2.1)	3.2 (1.5 to 4.6)

Appendix: Additional NARCliM2.0 evaluation plots

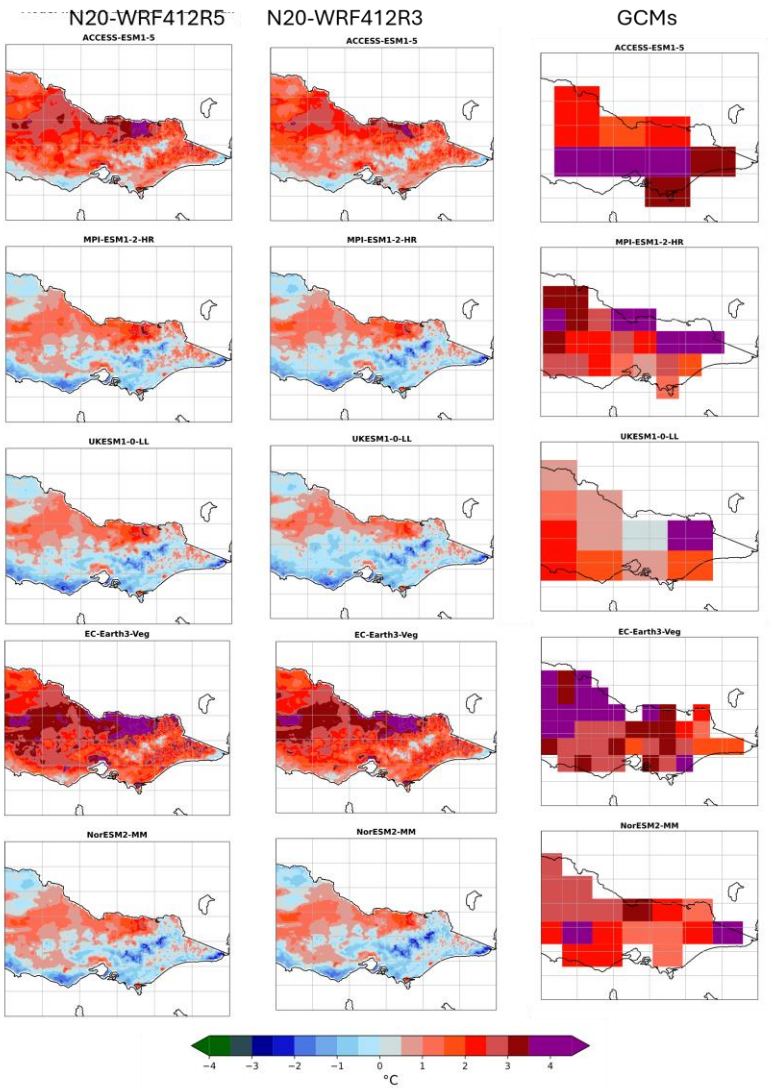


Figure 54 Temperature evaluation maps for mean minimum daily temperature (minimum 2m air-surface temperature) showing the difference between observed (AGCD) and modelled temperatures from 1981-2010. Blue values mean the model is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias). The first two columns show results from the two different versions of the downscaling model (N20-WRF412R5 and N20-WRF412R3) and the third column shows the results for the host GCM. The five rows show the five different GCMs.

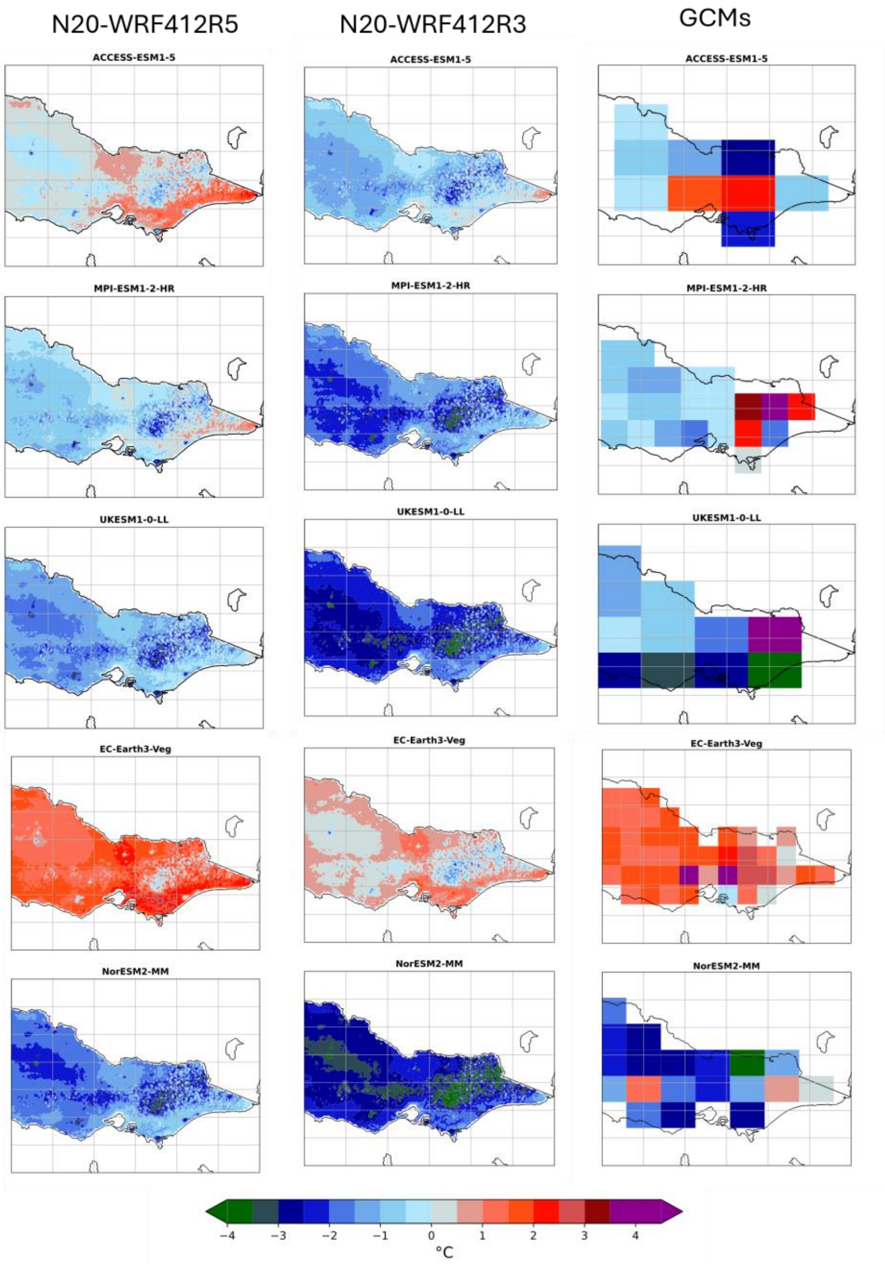


Figure 55 Temperature evaluation maps for mean maximum daily temperature (maximum 2m air-surface temperature) showing the difference between observed (AGCD) and modelled temperatures from 1981-2010. Blue values mean the model is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias). The first two columns show results from the two different versions of the downscaling model (N20-WRF412R5 and N20-WRF412R3) and the third column shows the results for the host GCM. The five rows show the five different GCMs.

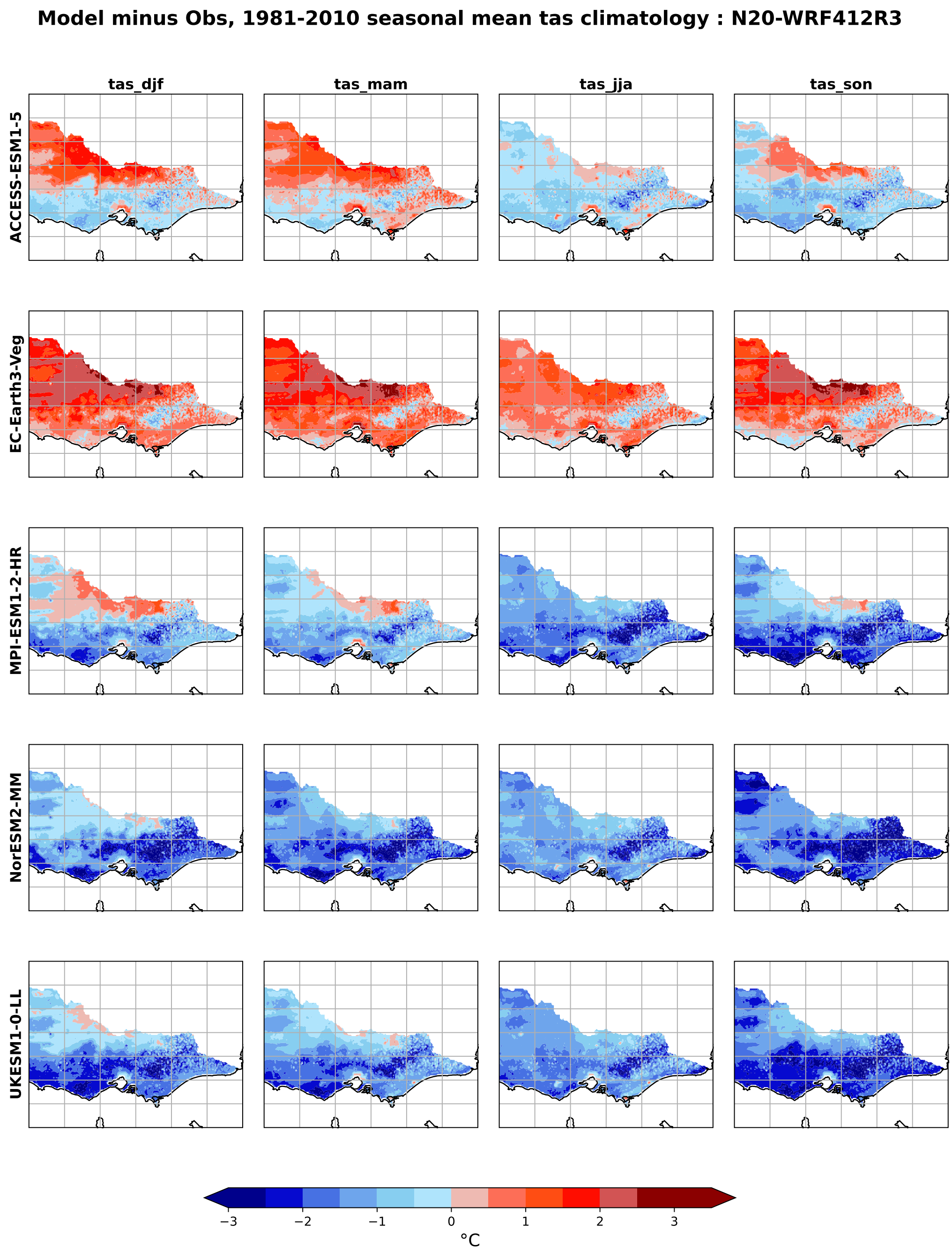


Figure 56: Seasonal temperature evaluation maps for NARCliM2.0 RCM version N20-WRF412R3, for mean daily temperature (mean 2m air-surface temperature) showing the difference between observed (AGCD) and modelled temperatures from 1981-2010. Blue values mean the model is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias). The four columns show the four seasons, and the rows show the different downscaled models.

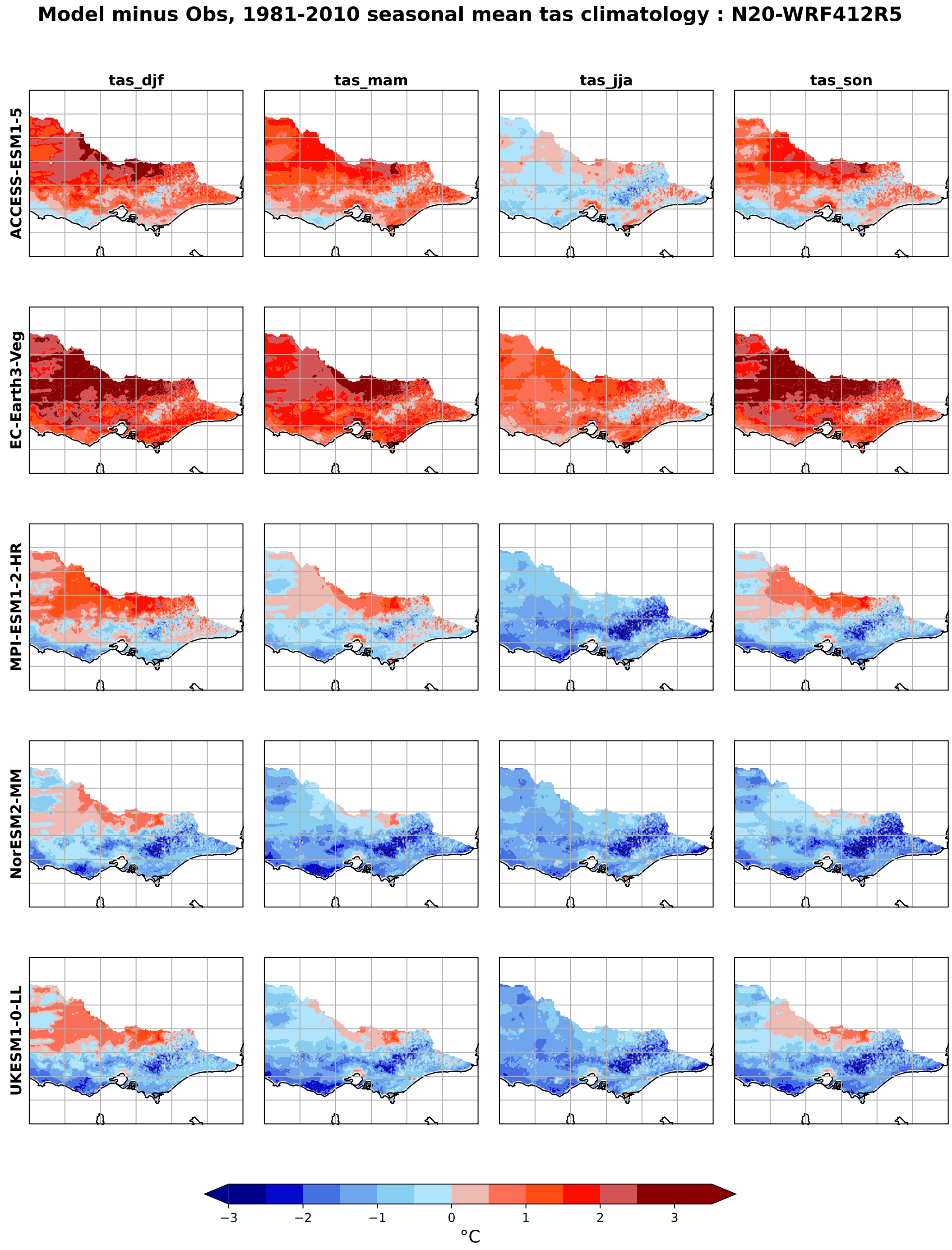


Figure 57: Seasonal temperature evaluation maps for NARCliM2.0 RCM version N20-WRF412R5, for mean daily temperature (mean 2m air-surface temperature) showing the difference between observed (AGCD) and modelled temperatures from 1981-2010. Blue values mean the model is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias). The four columns show the four seasons, and the rows show the different downscaled models.

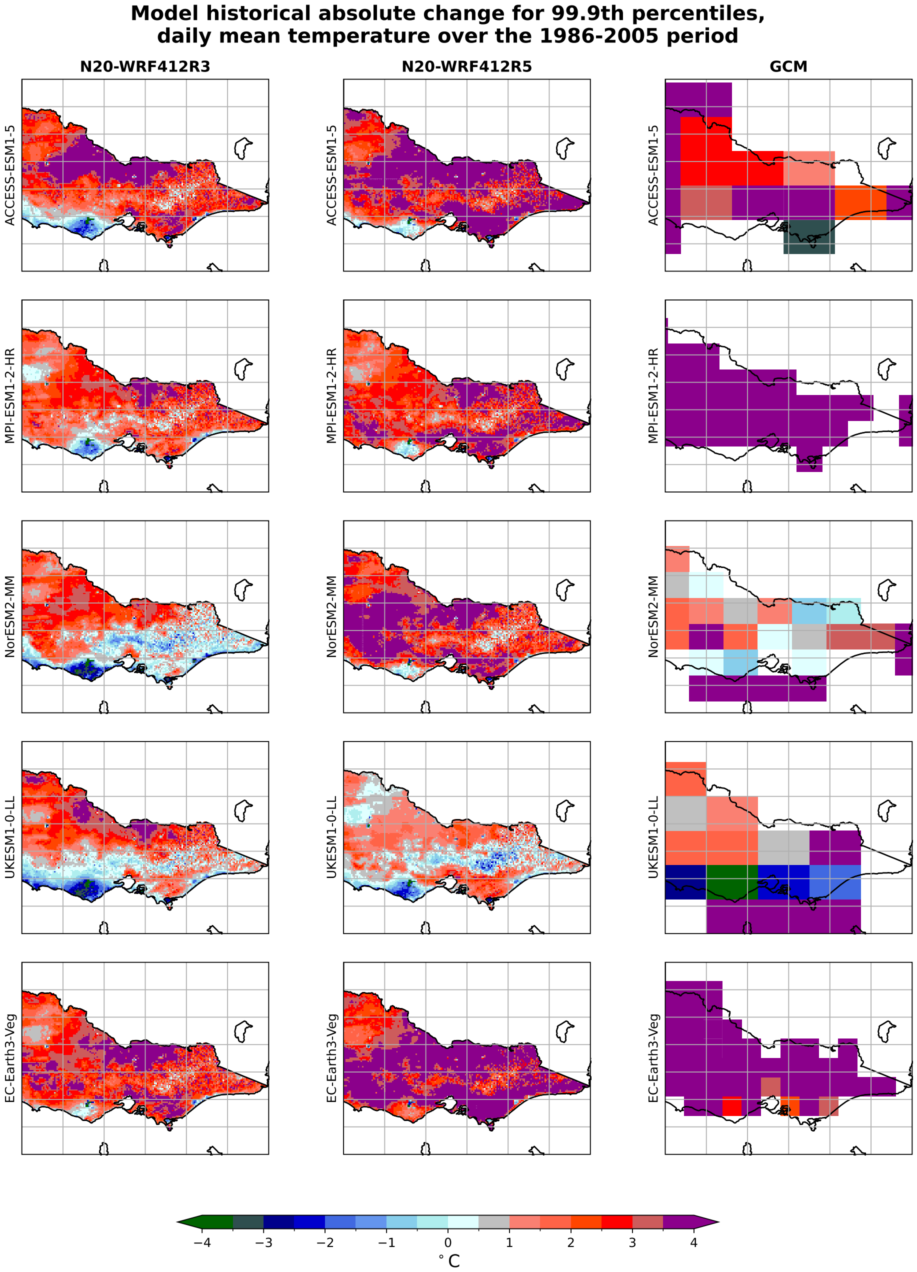


Figure 58 Temperature evaluation maps for 99.9th percentile of annual temperature (mean 2m air-surface temperature) showing the difference between modelled temperatures from 1986-2005 and observed (AGCD) data. Blue values mean the model is colder than the observations (a cold bias) and red shows the model is hotter than the observations (a hot bias). The first two columns show results from the two different versions of the downscaling model (N20-WRF412R5 and N20-WRF412R3) and the third column shows the results for the host GCM. The five rows show the five different GCMs.

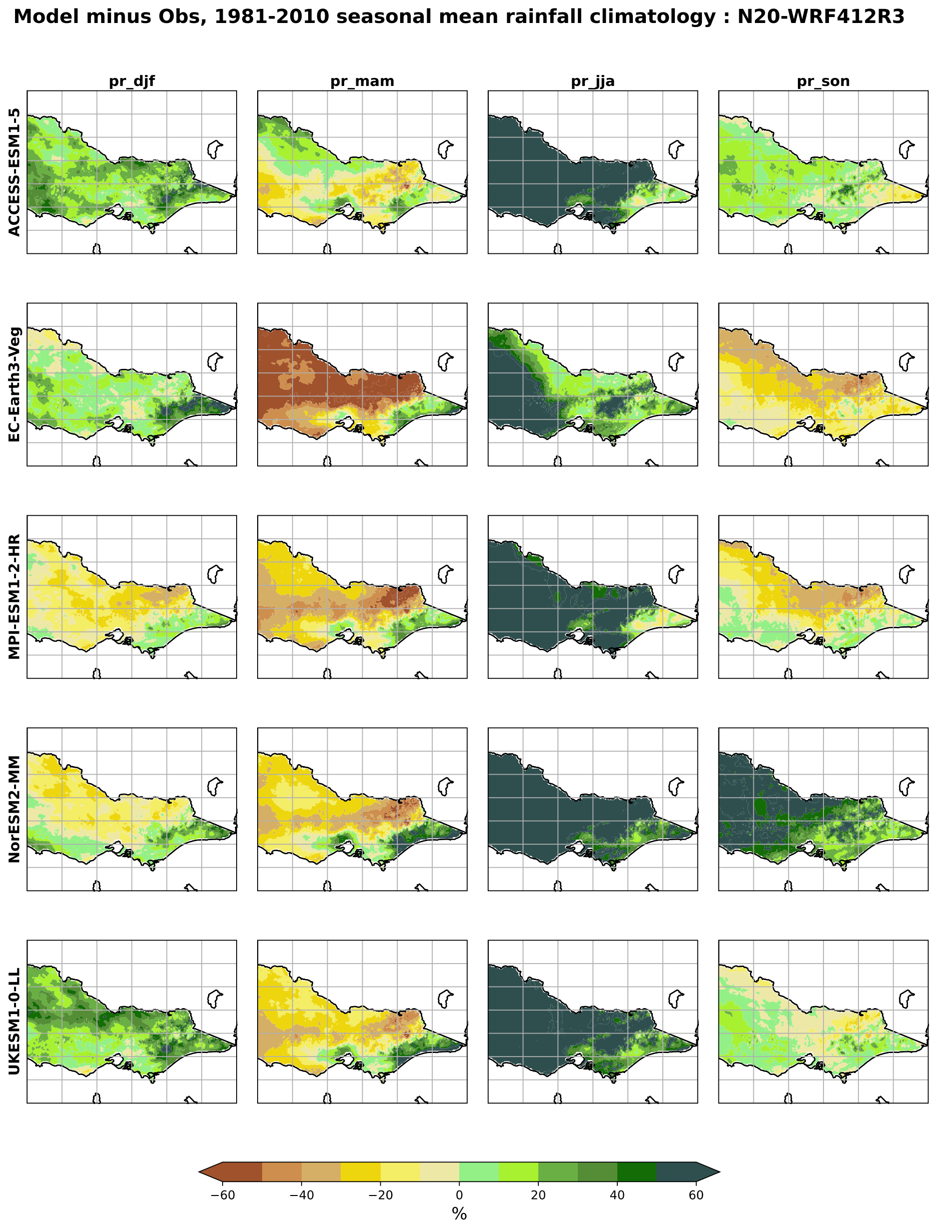


Figure 59 Seasonal mean rainfall evaluation maps for NARCliM2.0 RCM version N20-WRF412R3, showing the difference between observed (AGCD) and modelled rainfall from 1981-2010. Green values mean the model is wetter than the observations (a wet bias) and yellow/brown shows the model is drier than the observations (a dry bias). The four columns show the four seasons, and the rows show the different downscaled models.

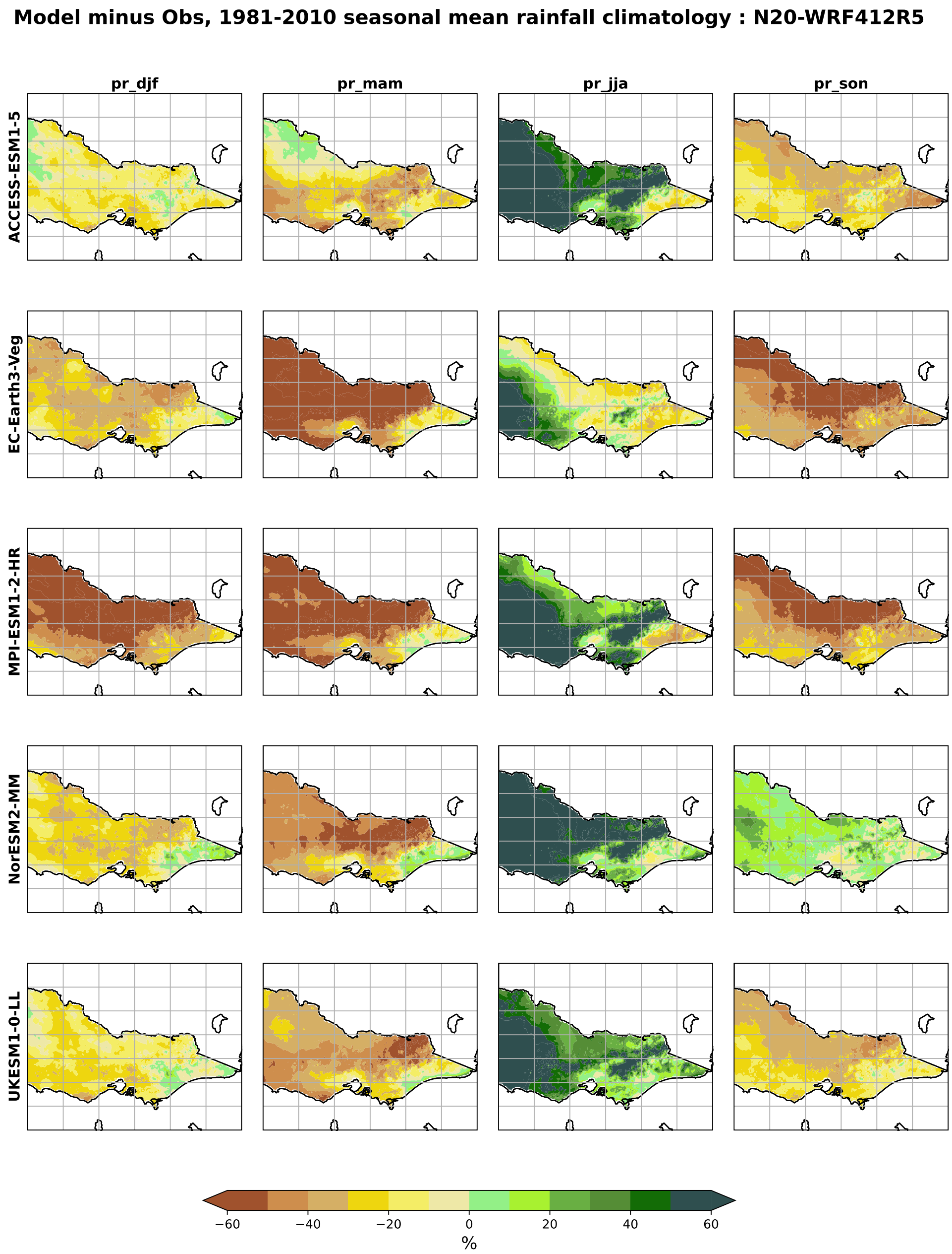


Figure 60 Seasonal mean rainfall evaluation maps for NARCliM2.0 RCM version N20-WRF412R5, showing the difference between observed (AGCD) and modelled rainfall from 1981-2010. Green values mean the model is wetter than the observations (a wet bias) and yellow/brown shows the model is drier than the observations (a dry bias). The four columns show the four seasons, and the rows show the different downscaled models.

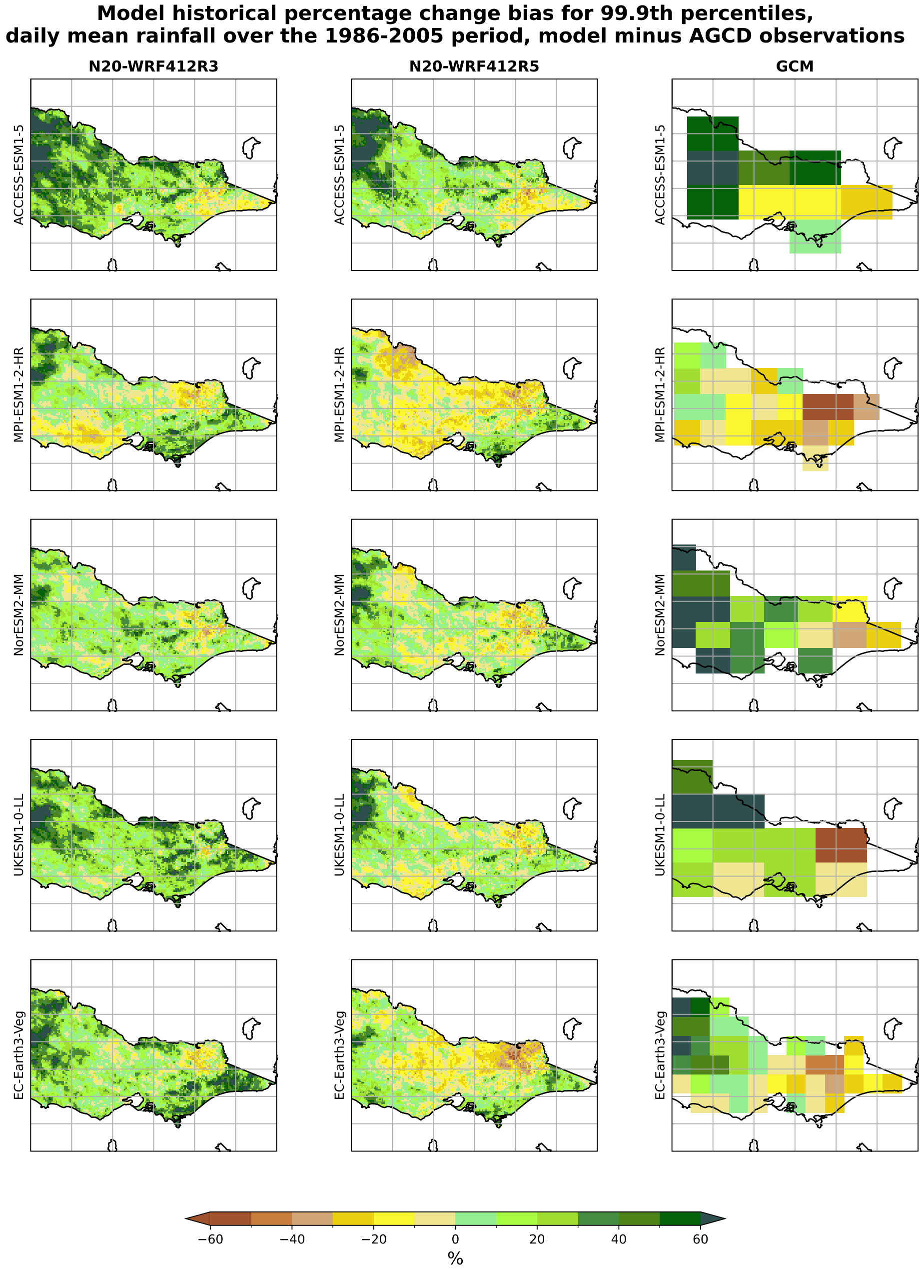


Figure 61 Rainfall evaluation maps for 99.9th percentile of annual rainfall showing the percentage difference between modelled rainfall from 1986-2005 and observed (AGCD) data. Brown/yellow values mean the model is drier than the observations (a dry bias) and green shades shows the model is wetter than the observations (a wet bias). The first two columns show results from the two different versions of the downscaling model (N20-WRF412R5 and N20-WRF412R3) and the third column shows the results for the host GCM. The five rows show the five different GCMs.

Appendix: Additional future projections plots

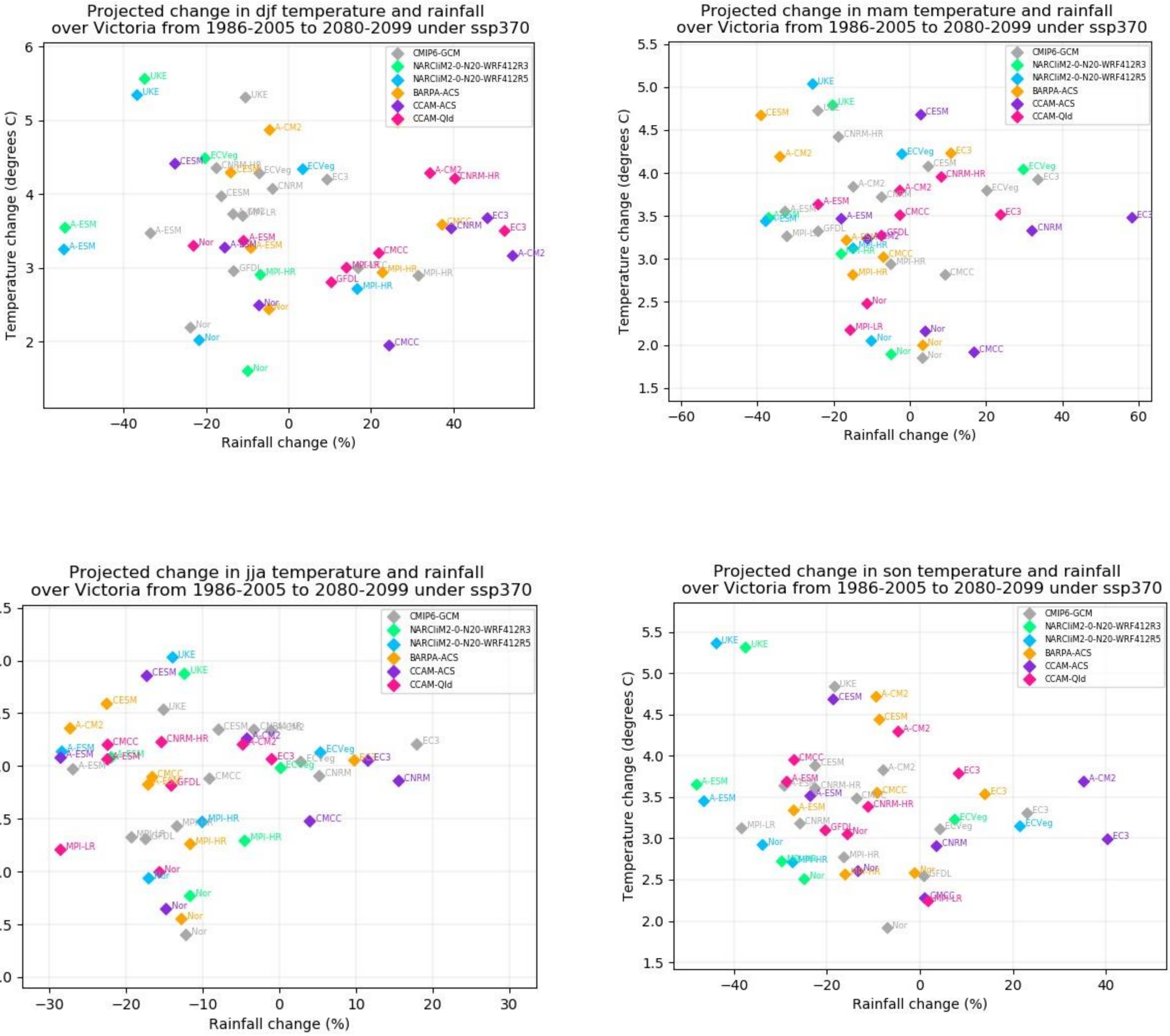
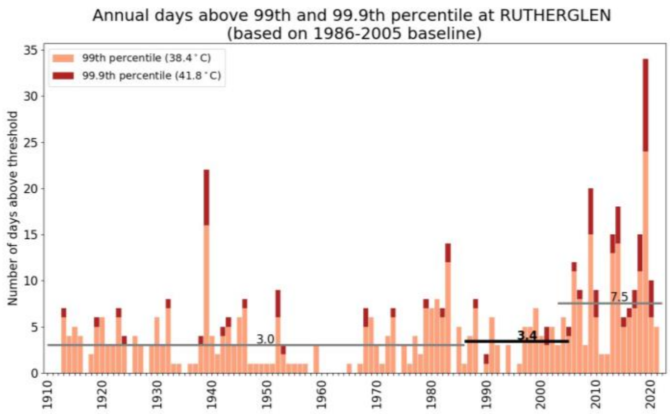
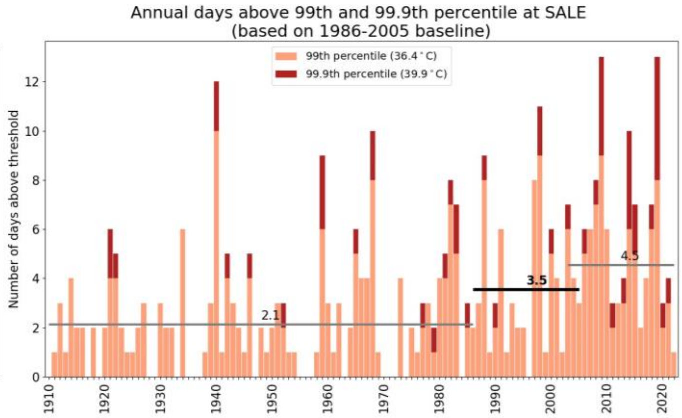
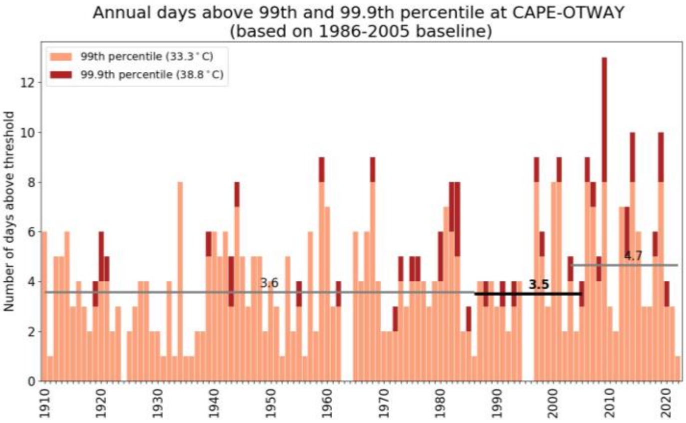
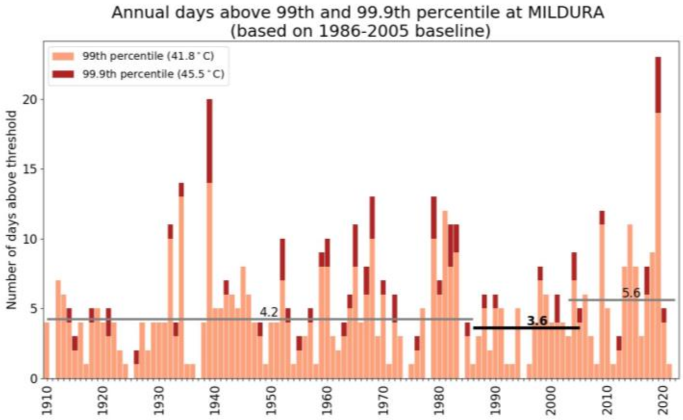


Figure 62 Projected change in mean seasonal rainfall (horizontal axis) and temperature (vertical axis) over Victoria under a high emissions scenario (SSP3.70), from a 1986-2005 baseline to a 2090 (2080-2099) future period. Seasons shown are summer (djf, top left), autumn (mam, top right), winter (jja, bottom left) and spring (son, bottom right). Each point represents the projected change from an individual model - host GCMs are shown in grey and the different RCMs indicated by the coloured legend. Note the scales are not the same on each plot, to allow easier readability.









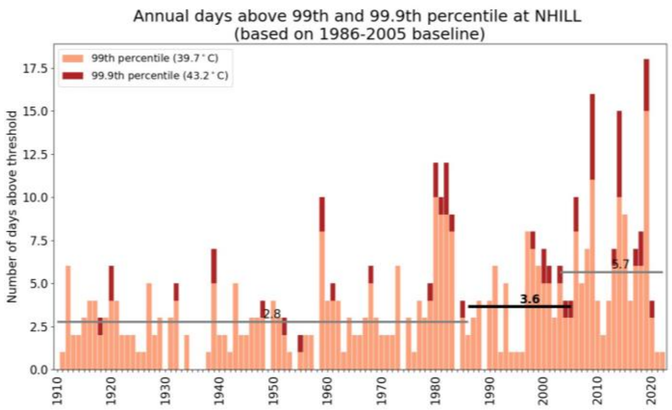


Figure 63 The annual number of days above the 99th percentile (orange bars) and 99.9th percentile (red bars) maximum daily temperature for 5 ACORNSAT stations (labelled), from 1910 to 2022. The 99th and 99.9th percentile temperature thresholds (values provided in top-left corner of each plot) are defined over a 1986-2005 baseline period. The horizontal bars indicate the average number of days above the 99th percentile threshold for 1910-1985, 1986-2005 and 2003-2022.

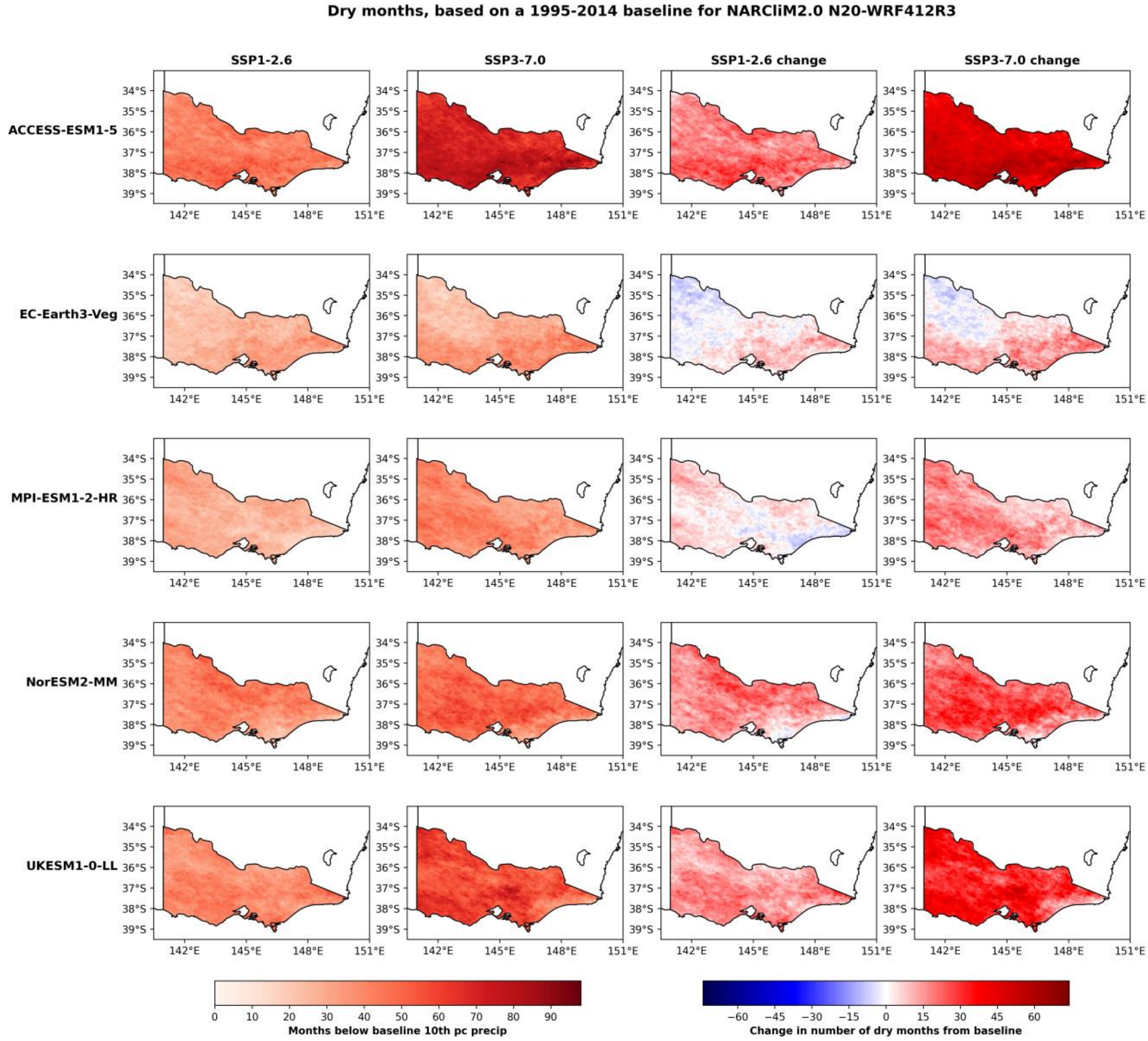


Figure 64 The number of 'dry months' with rainfall below the historical 10th percentile monthly rainfall (left two columns for low and high emissions), and the projected change in the number of dry months (two righthand columns, for low and high emissions) according to the NARCliM2.0 downscaling of 5 GCMs. Projected change is from the 1986-2005 to 2090 (2080-2099).

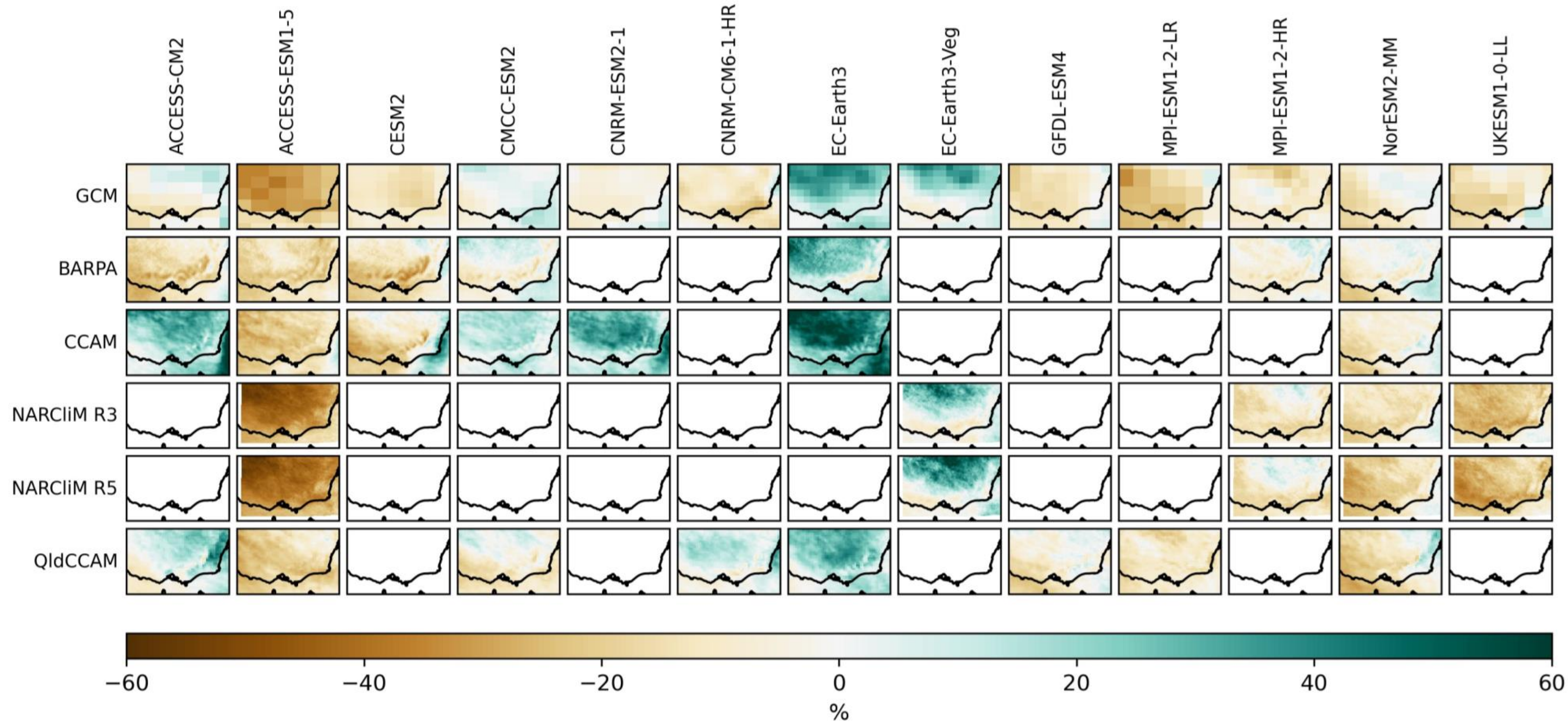


Figure 65 Projected change in mean annual rainfall from 1986-2005 to 2040-2059 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

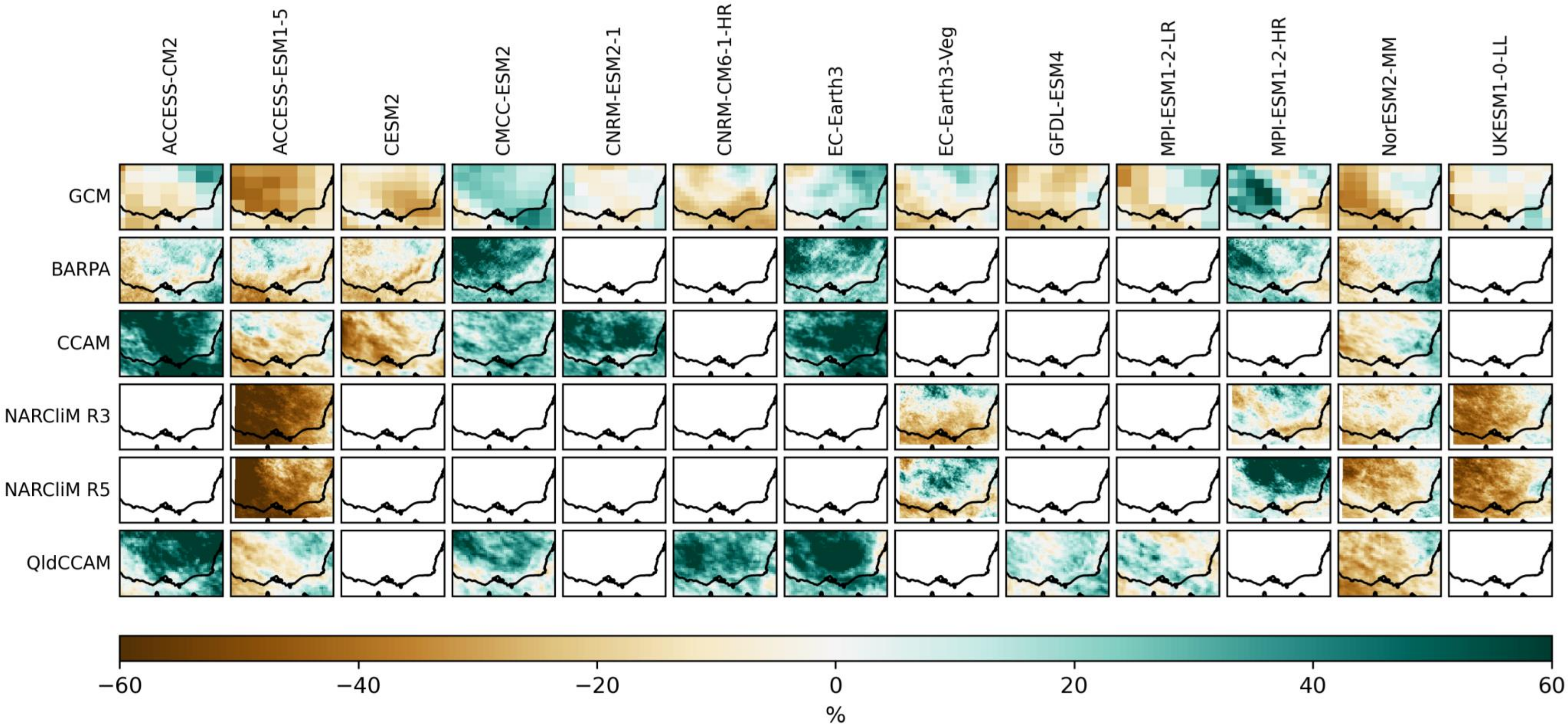


Figure 66 Projected change in mean summer rainfall from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

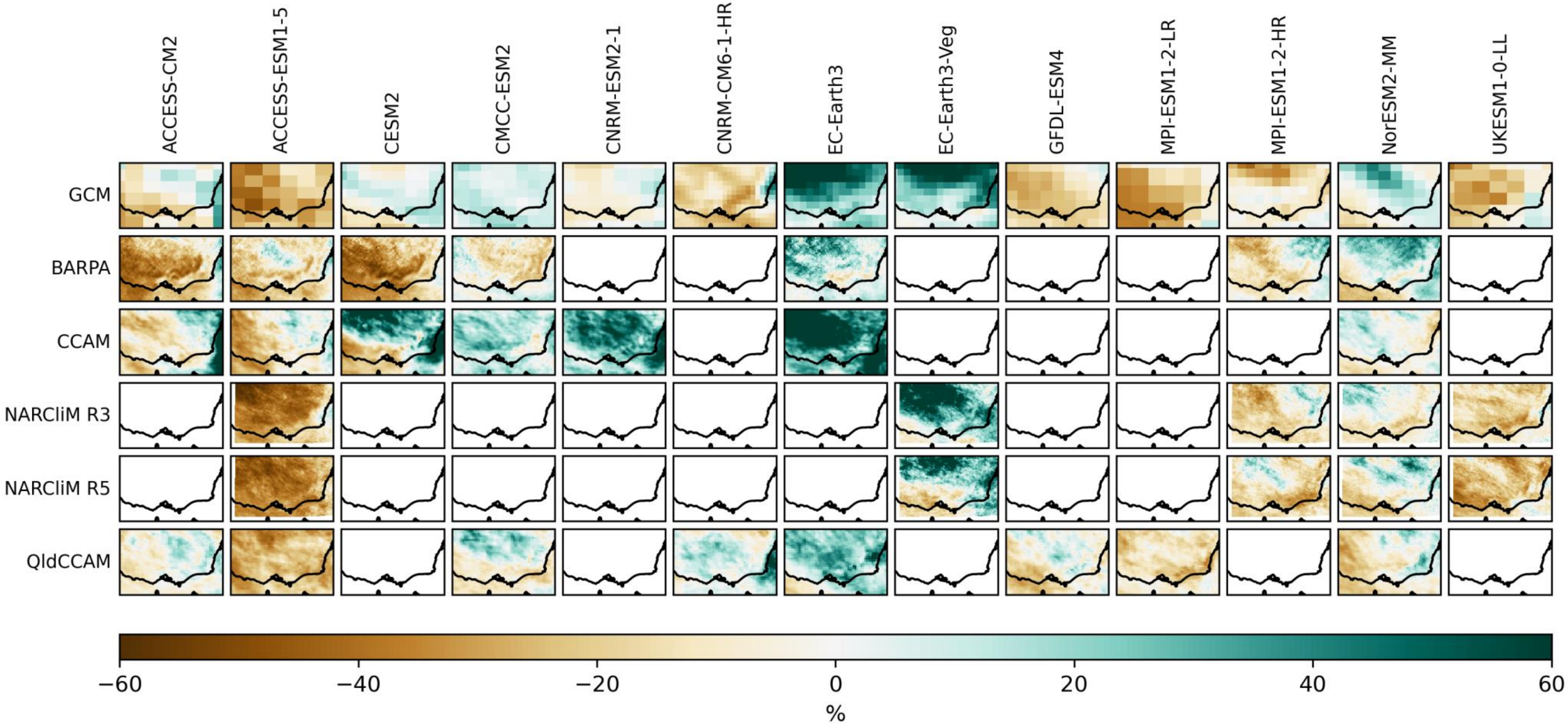


Figure 67 Projected change in mean autumn rainfall from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

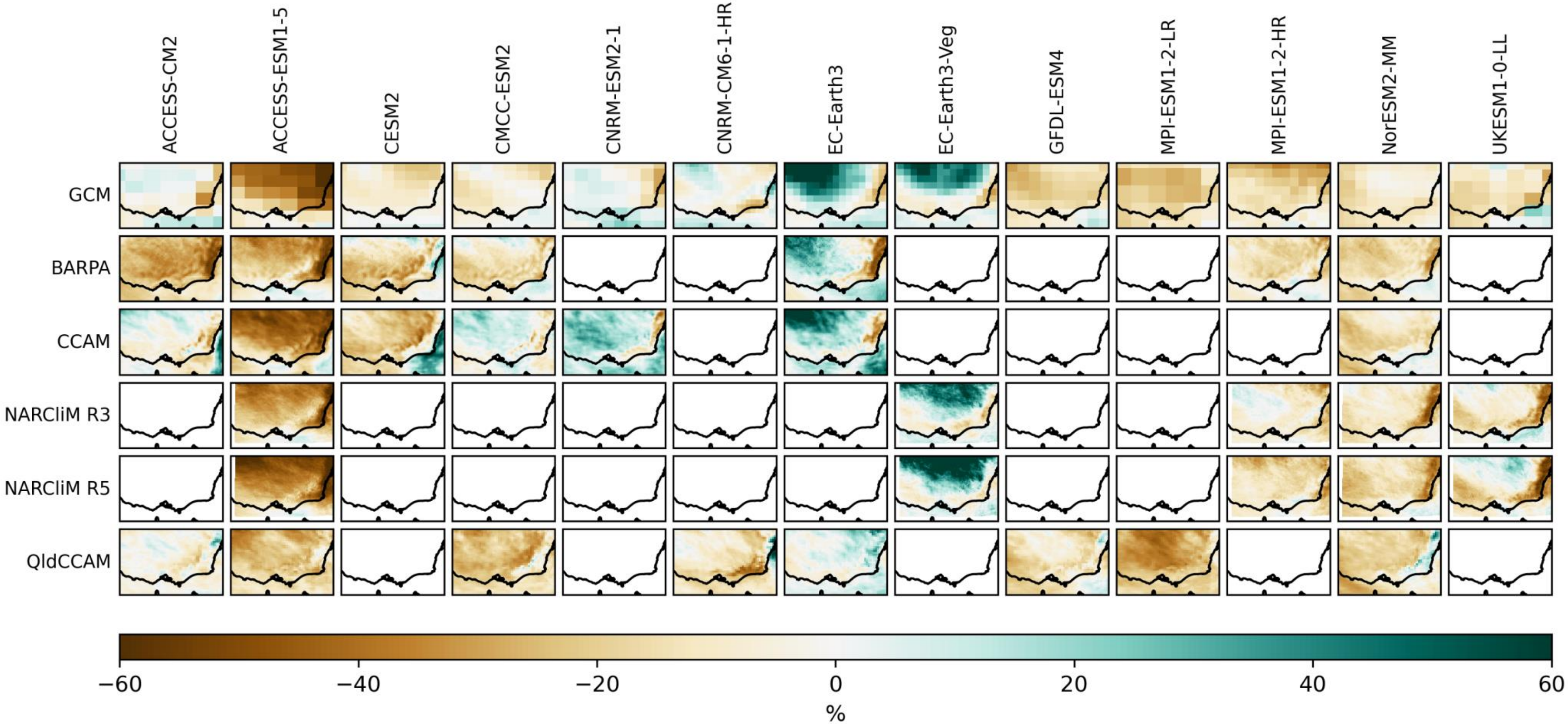


Figure 68 Projected change in <u>mean winter rainfall</u> from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

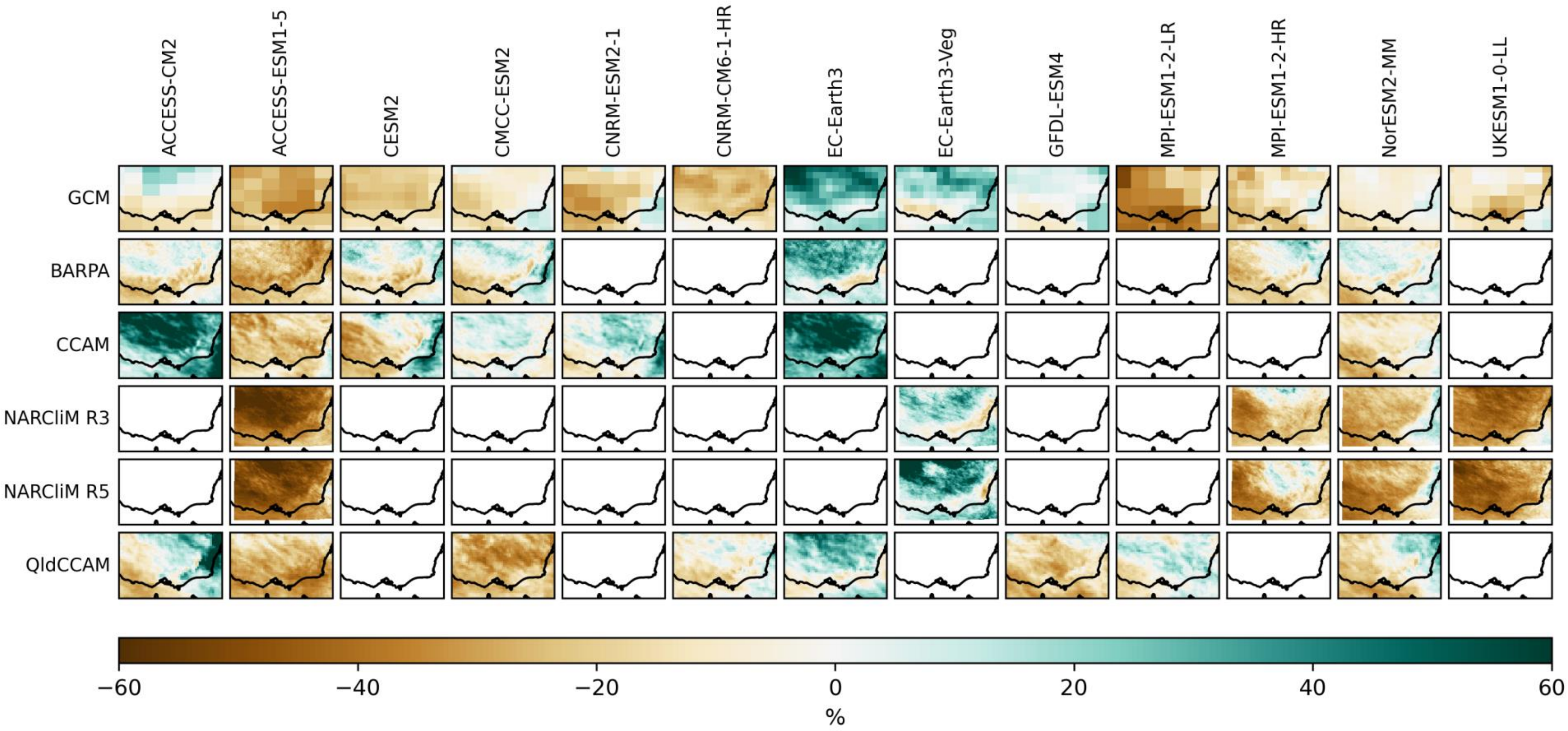


Figure 69 Projected change in mean spring rainfall from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

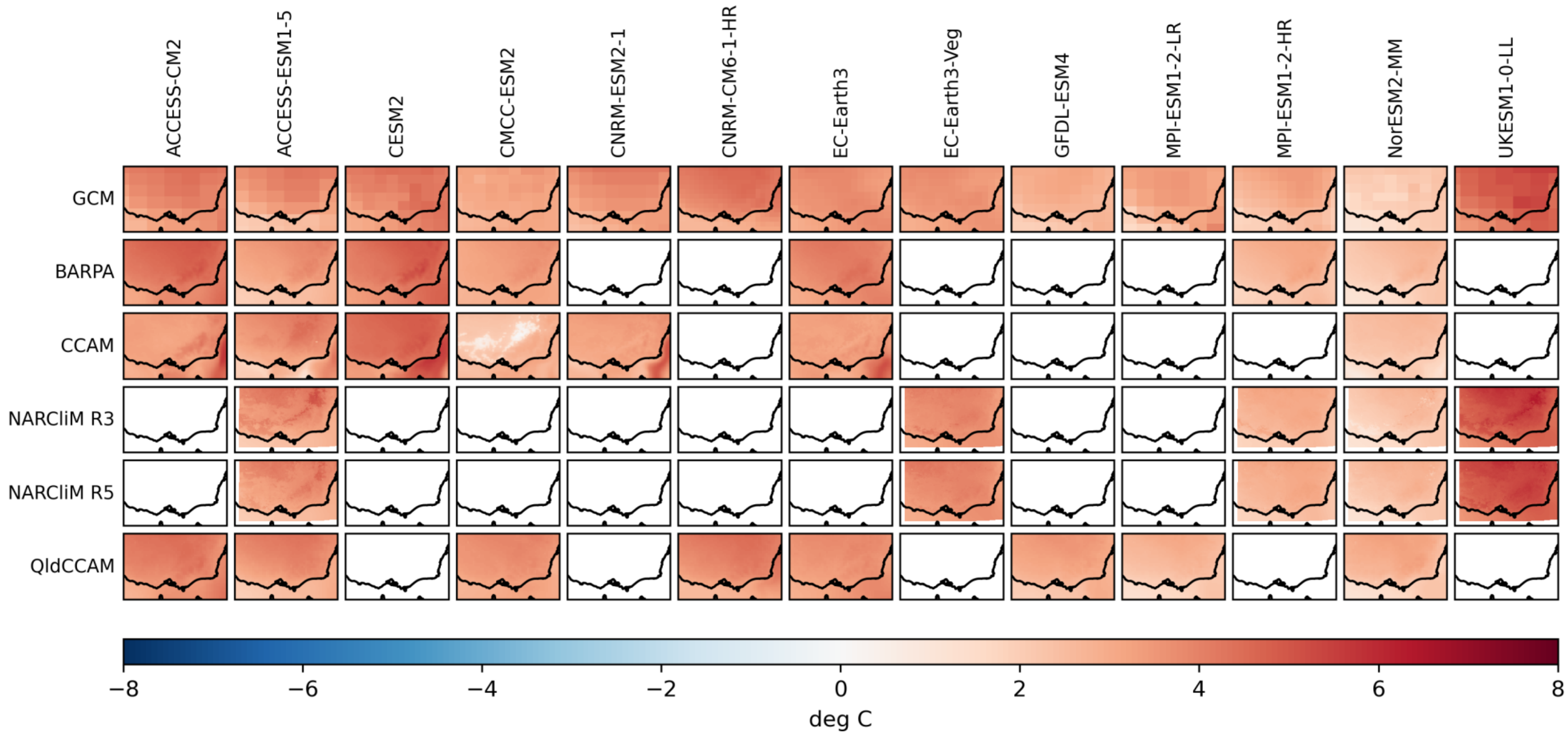


Figure 70 Projected change in annual mean temperature from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

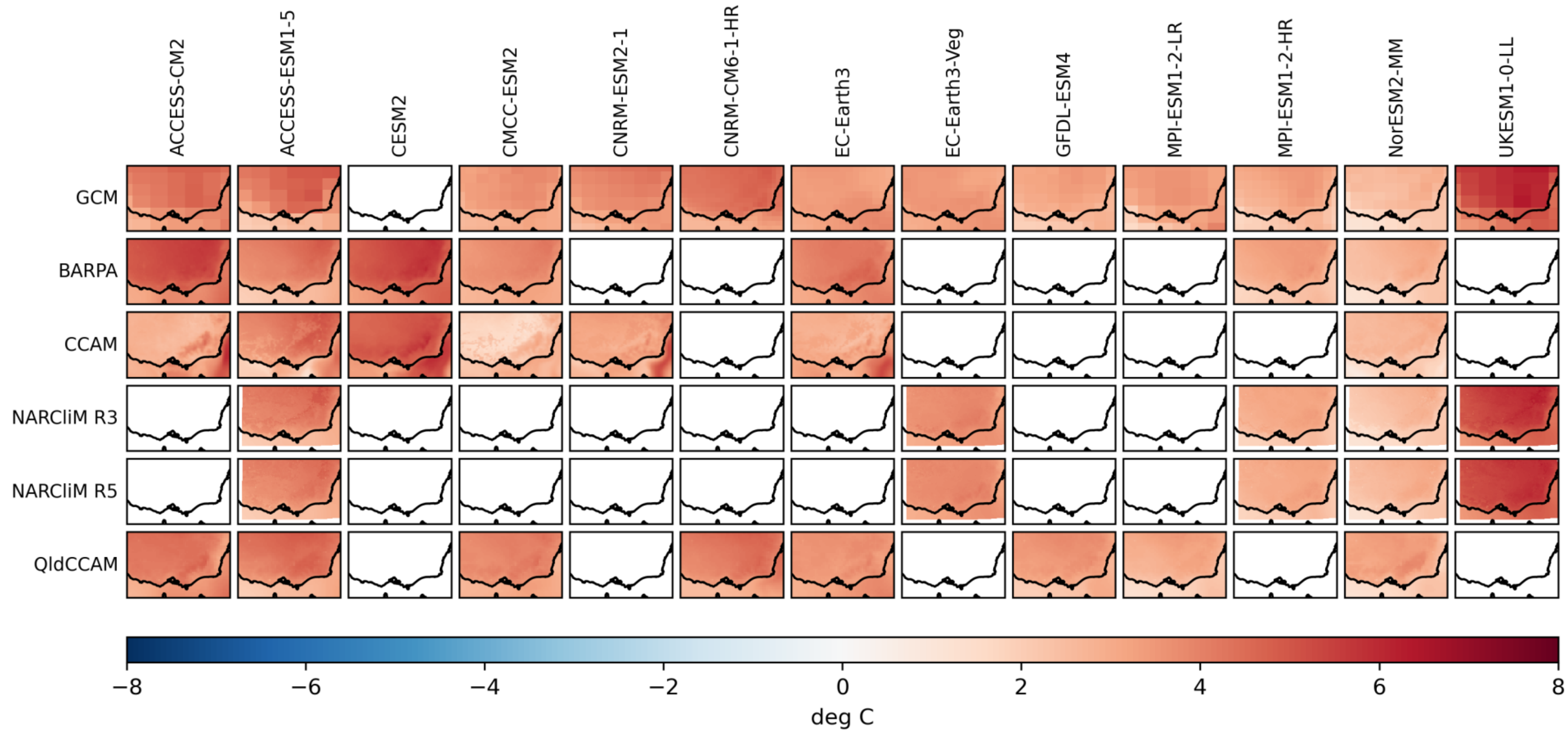


Figure 71 Projected change in annual mean daily maximum temperature from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

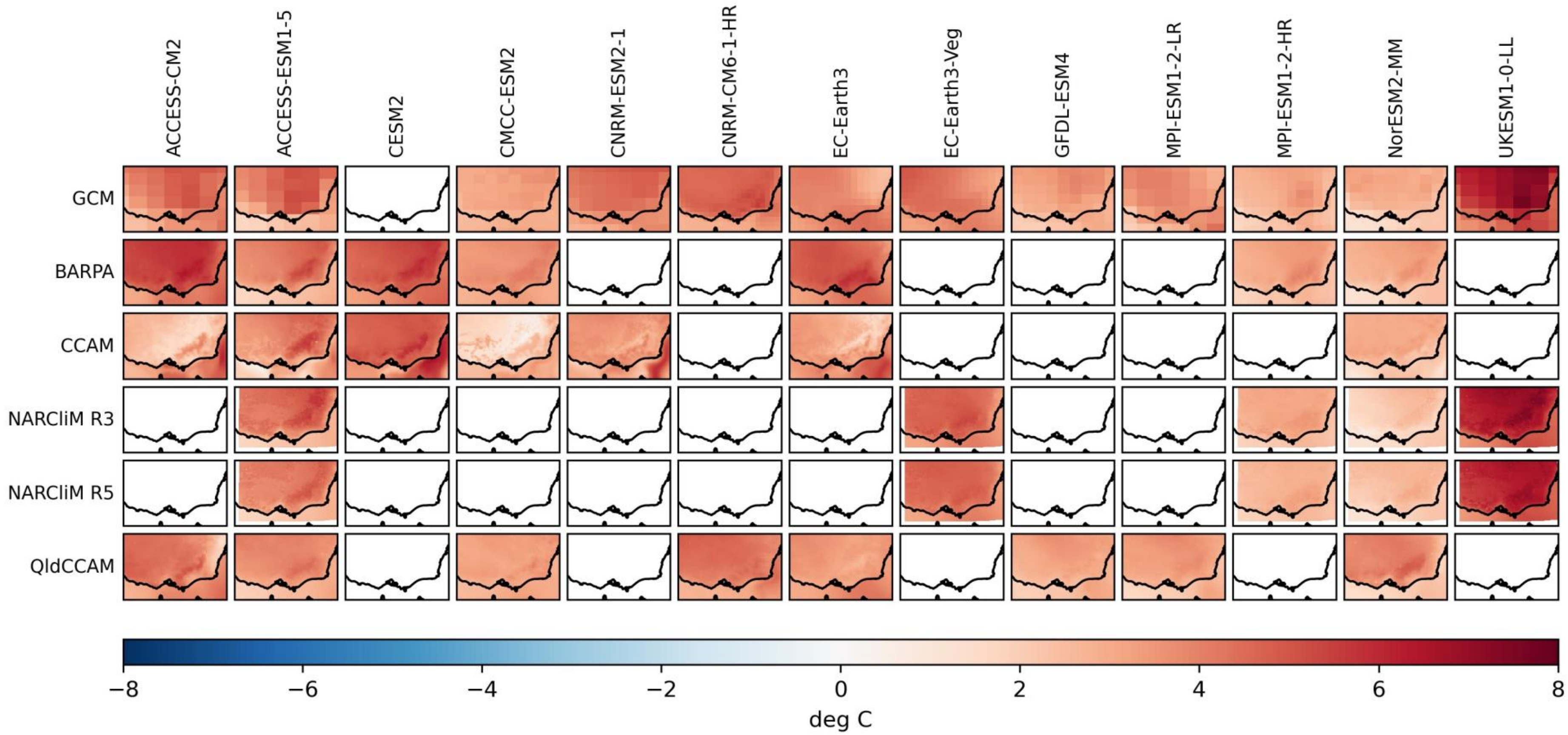


Figure 72 Projected change in summer mean maximum daily temperature from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

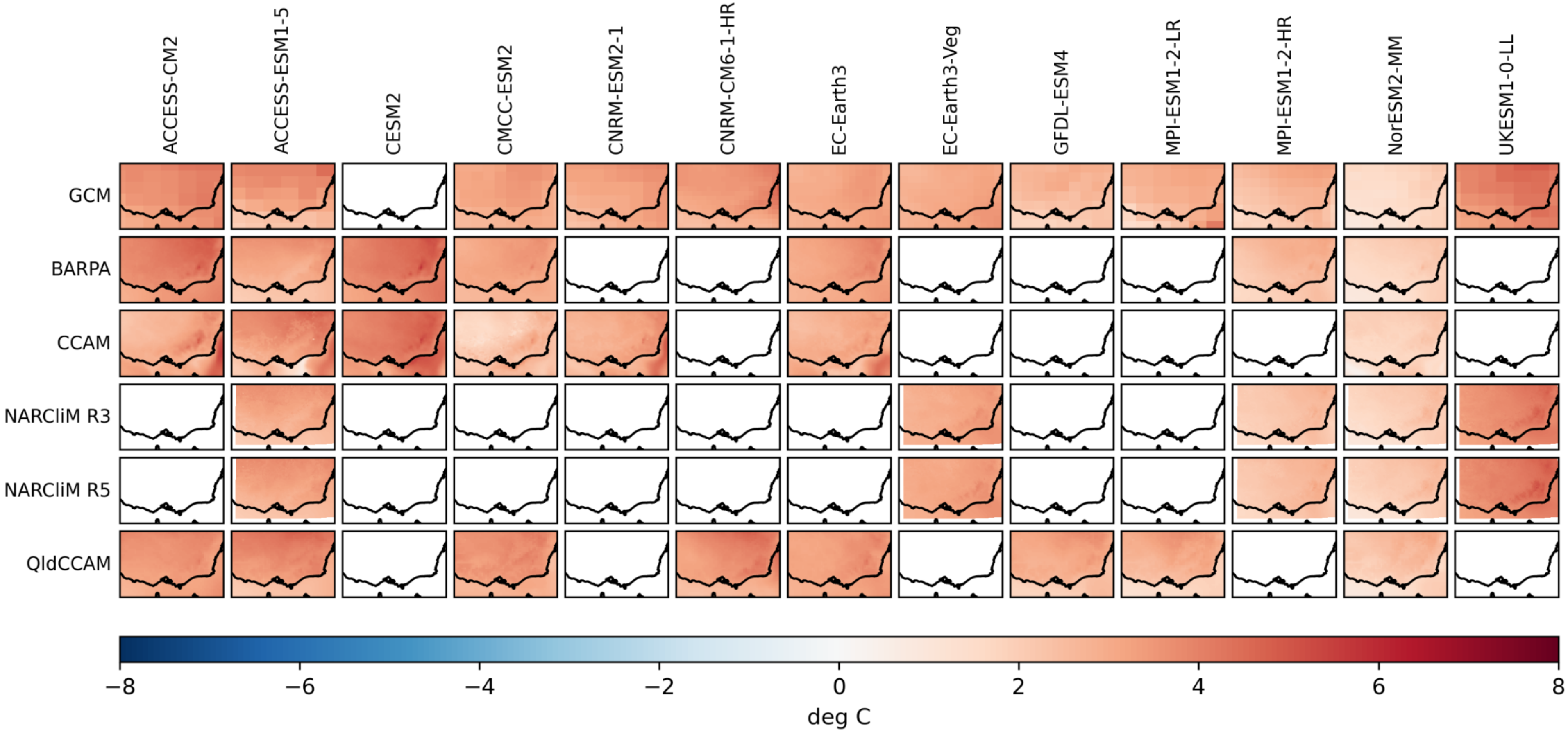


Figure 73 Projected change in winter mean maximum daily temperature from 1986-2005 to 2080-2099 under high emissions (SSP3-7.0) for all combinations of downscaling RCMs (rows) and host GCMs (columns)

Shortened forms and Glossary of terms

Shortened forms

Acronym	Definition
ACS	Australian Climate Service
BARPA	Bureau of Meteorology Atmospheric Regional Projections for Australia
BOM	Australian Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CCAM	Conformal Cubic Atmospheric Model
CORDEX	Coordinated Regional Climate Downscaling Experiment
CMIP5, CMIP6	Coupled Model Intercomparison Project Phase 5, Phase 6
DEECA	Department of Energy, Environment and Climate Action
DJF	Summer months – December January February
ECS	Equilibrium Climate Sensitivity
GCM	Global Climate Model
GWL	Global Warming Levels
IPCC	Intergovernmental Panel on Climate Change
JJA	Winter months – JJA is June July August
MAM	Autumn months – MAM is March April May
NARCliM	NSW and Australian Regional Climate Modelling
NPCP	National Partnership for Climate Projections
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SON	Spring months – September October November
SSP	Shared Socioeconomic Pathway
VCP19, VCP24	Victorian Climate Projections 2019, 2024
WRF	Weather Research and Forecasting model

Glossary of terms

For more definitions, see http://www.ipcc-data.org/guidelines/pages/glossary/glossary_a.html

Term	Description
Anomaly	The departure of an element from its long-period average value for the location concerned. For example, a positive temperature anomaly means that the temperature was warmer than normal.
Bias	The tendency of a climate model to over- or under-estimate the value of a population parameter. For example, a positive temperature bias indicates that the simulated temperature is too warm compared to observed temperatures.
Carbon dioxide (CO_2)	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal, of burning biomass, of land use changes and of industrial processes (e.g. cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance

CCAM	Conformal Cubic Atmospheric Model, a dynamical model used to simulate the atmosphere, ocean surface and land. For this project it is used as a regional climate model to dynamical downscale global climate model outputs to add finer detail.
Climate	The average weather experienced at a site or region over a period of many years, ranging from months to many thousands of years. The relevant measured quantities are most often surface variables such as temperature, rainfall and wind
Climate change	A change in the state of the climate that can be identified (e.g. by statistical analysis) by changes in the mean and/or variability of its properties, and that persists for an extended period of time, typically decades or longer
Climate feedback	An interaction in which a perturbation in one climate quantity causes a change in a second, and that change ultimately leads to an additional (positive or negative) change in the first.
Climate projection	A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which in turn is based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised. Throughout this report, we differentiate between 'climate projection data sets' and 'climate projections': Climate projection data set – data relating to future climate, usually obtained from a climate model. Climate projection – statements and/or data that describe future climate states that have been assessed as plausible, given the current state of knowledge of the climate system and informed by climate projection data sets.
Climate scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models
Climate sensitivity	An estimate of the global mean surface temperature response to doubled carbon dioxide concentration that is evaluated from model output or observations for evolving non-equilibrium conditions (units °C).
Climate variability	Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).
CMIP5 and CMIP6	Phases 5 and 6 of the Coupled Model Intercomparison Project, which coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. In CMIP5, future climate is modelled under emissions scenarios by representative concentration pathways (RCPs), whereas CMIP6 uses shared socioeconomic pathways (SSPs).
Confidence	The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement
Downscaling	A method that derives local to regional-scale information from larger-scale models or data analyses. Dynamical downscaling is used in the VCP24 projections, using regional climate models.
Emissions scenario	A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g. greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships

Ensemble	A collection of comparable datasets that reflect variations within the bounds of one or more sources of uncertainty and that, when averaged, can provide a more robust estimate of underlying behaviour. In the VCP24 projections, ensembles are created by combining various groupings of simulations, for example simulations from each regional downscaling model individually (e.g. NARCliM2.0, CCAM-ACS) or combined ("All_RCMs").
Global climate model or general circulation model (GCM)	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. The climate system can be represented by models of varying complexity and differ in such aspects as the spatial resolution (size of grid cells), the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterisations are involved
Greenhouse gas	Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. 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.
Host model	The model used as input when downscaling. In the case of climate simulations, the global climate model (such as ACCESS 1.0) is the host, and the regional climate model (in this case CCAM) takes input from this host and produces a finer-scale simulation.
Hot day, very hot day	A hot day in this report refers to a day which is above the historical 99th percentile maximum daily temperature, occurring on average 3-4 times per year. A very hot day in this report refers to a day which is above the historical 99.9th percentile maximum daily temperature, occurring on average 3-4 times per decade.
Intergovernmental Panel on Climate Change (IPCC)	An organisation established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The IPCC provides governments at all levels with scientific information that they can use to develop climate policies (https://www.ipcc.ch/about/)
Net zero	Net zero refers to achieving a net balance between greenhouse gas emissions produced and greenhouse gas emissions taken out of the atmosphere.
Percentile	A value on a scale of one hundred that indicates the percentage of the data set values that is equal to, or below it. The percentile is often used to estimate the extremes of a distribution. For example, the 99th percentile may be used to refer to the threshold for the upper extremes, exceeded by just 1% of values. A 99th percentile daily value would be exceeded on average 3-4 times per year while the 99.9th percentile would be exceeded 3-4 times per decade.
Regional climate model (RCM)	A climate model for downscaling GCM results. Like a GCM, an RCM runs 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.
Representative concentration pathway (RCP)	A scenario that includes time-series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/cover. The word 'representative' signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics (van Vuuren et al. 2011).
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
Risk assessment	The qualitative and/or quantitative scientific estimation of risks.
Risk management	The plans, actions, or policies implemented to reduce the likelihood and/or consequences of risks or to respond to consequences.

Storyline	A climate storyline or scenario storyline is a narrative that illustrates potential future climate change, based on specific scenarios (e.g. emissions scenarios) and model projections. A storylines approach to assessing climate impacts is a way of making complex climate data simpler to use. For more on using storylines for climate risk assessment, see Fiedler, et al., 2024.
SSP scenarios	Similar to RCP's, these are scenario's that include a time-series of emissions and concentrations of the full suite of greenhouse gases, aerosols and chemically active gases, as well as land use/cover. The Shared Socioeconomic Pathways provide a number of possible scenarios that would lead to the specific radiative forcing characteristics up to the year 2100, as defined in the IPCC Sixth Assessment Report on climate change (IPCC, 2021).
Temperature (near-surface air temperature	Unless specified otherwise, when the term temperature is used it refers to the temperature in observations, gridded data sets and models as that measured at weather stations at 1.2 to 2 m above the land surface in a clearing and behind a shading Stevenson's screen. Other terms for this include near-surface temperature, 2 m temperature and screen temperature.
Wet day, very wet day	Awet day in this report refers to a day which is above the historical 99^{th} percentile daily rainfall, occurring on average 3-4 times per year. A very wet day in this report refers to a day which is above the historical 99.9^{th} percentile daily rainfall, occurring on average 3-4 times per decade

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