



Environment,  
Land, Water  
and Planning



# Victorian Climate Projections 2019

## Technical report

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# Executive summary

This report describes a set of climate projections featuring new high-resolution climate change simulations for Victoria developed by CSIRO's Climate Science Centre (CSC), which describe how the regional climate of Victoria is likely to respond to global warming with different scenarios of human greenhouse gas emissions. This work was commissioned by the Victorian Department of Environment, Land, Water and Planning (DELWP) to supplement previous projections of climate change for Victoria and to develop a tailored climate projections and guidance package for Victoria.

An important consideration when developing regional climate change projections is to avoid basing the projections on a single modelling system or an individual line of evidence. For this reason, it was decided to extend the existing climate change projections information from the *Victorian Climate Initiative* (VicCI) summarised in (Hope et al. 2017), and presented in the guidelines for assessing the impact of climate change (DELWP 2016). Those projections drew strongly on statistically downscaled simulations of climate change for Victoria and were aimed primarily at water managers. The new results presented here feature a dynamically downscaled set of simulations based on the Conformal Cubic Atmospheric Model (CCAM), as well as drawing on the full range of outputs from *Climate Change in Australia* (CCIA) using global climate models and other climate modelling data sets. For the new CCAM simulations, six global climate models were downscaled to 5 km resolution over Victoria. The six high-resolution CCAM simulations are based on a subset of the global climate model simulations recommended by CCIA as representative of the range of projected changes in temperature and rainfall as well as other climate variables. The regional climate change projections described in this report combine the results of the new and previous climate model simulations to provide an assessment of plausible changes to the regional climate that could pose significant risks for the state of Victoria.

The climate of Victoria has been getting warmer, with the mean annual temperature rising by just over 1°C between 1910 and 2018 according to high quality observations from ACORN-SATv2. There have been more warm years than cool years in recent decades, and the last year with below-average

temperature was 1996 relative to the 1961–1990 baseline. Simulations of future warming under plausible greenhouse gas emission scenarios are consistent with a 0.5 to 1.3°C increase in temperature between the 1990s and 2030s. After superimposing natural variability on the global warming signal, it is possible to observe negligible or even negative short-term trends in temperature between 2019 and 2030. Beyond the next couple of decades, the projected change in temperature depends strongly on the greenhouse gas emissions pathway that the world follows. For example, between the 1990s and 2090s, the temperature over Victoria is projected to warm on average by 2.8 to 4.3°C under a high emissions scenario or warm by 1.3 to 2.2°C under a medium emissions scenario. In the case where global warming is limited to 2°C, matching aspirations under the Paris Agreement, then Victoria is expected to warm by a similar amount, in contrast to many other places in the world that will warm by more or less than the global average. The new high-resolution simulations suggest that increases in average temperature can be higher than previously estimated, especially in spring. This means a hotter 'worst-case' scenario should be considered to manage risks appropriately.



Victoria is projected to continue becoming drier in the long term in all seasons except summer, for which models indicate that both increases and decreases in average rainfall are possible. Large rainfall variability at scales from days to decades is expected to continue. The new regional climate model simulations are broadly consistent with previous climate projections across Victoria as a whole, except for the summer and autumn signature where the new simulations show high agreement on a projected decrease whereas previous dynamical downscaling indicated an increase (Grose et al. 2015a; Hope et al. 2015b; Timbal et al. 2015; DELWP 2016; Hope et al. 2017; Potter et al. 2018). The projection of autumn and summer rainfall in the new dynamical downscaling agrees more with the global climate model projections and statistical downscaling, as well as the recent observed decrease in autumn rainfall, leaving the previous downscaling as exceptions. However, there is not sufficient evidence to reject any set of results as implausible and this reinforces the need to consider a range of models and multiple lines of evidence when assessing projected change in the regional climate. The new high-resolution modelling identifies a greater projected decrease in the annual-averaged rainfall than in the surrounding regions – on the windward (western) slopes of the Australian Alps (primarily in the Ovens Murray region) in autumn, winter and spring compared to the surrounding regions.

Consistent with previous studies of projected regional climate change, extreme events such as heatwaves, bushfires and extreme rainfall are expected to continue to become more frequent in the decades to come. The intensity and/or frequency of past 1-in-20-year extreme daily rainfall is expected to increase, even in areas where average rainfall is expected to decline. The number of fire days are expected to increase under most global warming scenarios, with a larger increase in fire days for alpine regions. The results of the new high-resolution modelling are consistent with more favourable conditions for thunderstorms under global warming.

New high-resolution climate modelling has produced several important new insights about the possible future climate of Victoria.

Caution should always be employed when interpreting the results of a single climate modelling system until combined with additional lines of evidence and data from other available models. Nevertheless, the new high-resolution downscaling indicates that it is possible for regional daily average temperatures to increase up to 1°C more than was projected by the global climate models in some seasons and regions. For example, for Gippsland in spring under a high emissions scenario around the end of the century, the upper range of daily average temperature change from global models is 3.9°C. In contrast, the high-resolution simulations suggest the change could be up to 5.1°C. This result is considered plausible as the regional model captures the feedback from the drier landscape under hotter daytime temperatures, and better represents the weather effects from the finer resolution of the boundary between land and oceans. Extreme daily maximum temperatures are projected to increase by as much as twice the increase in the average maximum temperatures. The new high-resolution modelling also indicates that large increases in winter extreme daily maximum temperatures are possible. Another important insight from the new regional projections for Victoria is that the new modelling indicates that rainfall and inflows over the Australian Alps and in the Murray River catchments may be affected to a greater degree than has been previously expected under high greenhouse gas emission scenarios.

The new regional climate projections for Victoria described in this report indicate that climate change poses a serious risk for Victoria. The data in this study are intended to support planning and policy decisions made by the Victorian Government and community as well as being used by scientific researchers to better understand the consequences of global climate change. Regional climate projections will continue to be improved and enhanced as new climate change information becomes available but building on foundations developed in this study as well as previous projects such as VicCI, and findings coming out of the current *Victorian Water and Climate Initiative*. It is important to combine future climate projections with knowledge of climate exposure and vulnerability, as well as adaptive capacity to assess what a changing climate means to any given question or sector.



# 1. Introduction

This chapter gives the background to the project, a quick introduction to how climate change has been assessed at global, Australian and state levels, and the motivation for producing new work at this time.

## 1.1 Background

In 2018 the Victorian Department of Environment, Land, Water and Planning (DELWP) commissioned CSIRO's Climate Science Centre (CSC) to undertake new high-resolution climate modelling and produce a tailored climate projections and guidance package for Victoria. The package was commissioned to supplement the national projections at [www.climatechangeinaustralia.gov.au](http://www.climatechangeinaustralia.gov.au) (CCIA), the *Victorian Climate Initiative* (VicCI) and other projects supported by the Victorian Government. The package is titled *Victorian Climate Projections 2019* (VCP19), and this technical report is part of that package.

VCP19 has developed a new set of high-resolution regional climate simulations for Victoria using alternative methods from that used in VicCI and other previous studies (CSIRO and Bureau of Meteorology 2015; Hope et al. 2015a; Hope et al. 2017; Potter et al. 2018). VCP19 is designed to be complementary to VicCI and CCIA projections by adding new regional insights into future climate change and providing supplementary information and additional guidance to assessing climate change impacts. Projected changes in the climate can be better understood by using multiple lines of evidence and data where possible. For this reason, the new modelling results are put in context of previous work wherever possible, both in terms of identifying messages that are consistent between the different methods and identifying any new projected changes and regional insights from the new modelling. Differences between the different high-resolution climate data sets generally indicate the range of different possible changes to Victoria's future climate that can occur consistent with global warming (e.g. changes in extreme weather). Such differences in climate model results can be used to identify physical processes that underpin the projected changes and generally help to improve our understanding of the future climate. New insights from the climate projections are noted in the executive summary and highlighted throughout the report.

An example of using the new projections as a complement to previous work can be shown for water management. Victoria has a detailed water management plan to manage water resources under a changing climate <https://www.water.vic.gov.au/water-for-victoria>. The risk management plan includes a consideration of a range of projected changes in rainfall and evaporation by the end of the century, as well as the resampling of observations to produce severe hypothetical droughts as a worst-case scenario planning exercise for the coming years. The new VCP19 modelling has produced additional insights into the plausible change in rainfall over mountains, so provides a new dry case for the long-term future on the western slopes of the ranges that is consistent with the previous resampling method used to consider the near-term changes in climate. In this way, the new VCP19 projections add to the existing knowledge base rather than replace it.

DELWP and the Victorian Government supported the production of the *Climate-ready Victoria* set of products in 2016<sup>1</sup>. These products are based on the national climate projections reports and model inputs aggregated for the same regions used in VCP19. The messages and conclusions of *Climate-ready Victoria* are still current and relevant, and as for VicCI, the new VCP19 work presented here complements and adds to this work rather than replaces it.

## 1.2 Climate change in Victoria

Victoria's changing climate presents a significant challenge to individuals, communities, governments, businesses and the environment. Like the remainder of Australia, Victoria has already experienced increasing temperatures (Figure 1), shifting rainfall patterns and rising oceans.

<sup>1</sup> <https://www.climatechange.vic.gov.au/information-and-resources>

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2013) rigorously assessed the current state and future of the climate system, making several important conclusions:

- ▶ Greenhouse gas emissions have markedly increased because of human activities.
- ▶ Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea-level rise, and in changes in some climate extremes.
- ▶ It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century.
- ▶ Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system.

In recognition of the impact of climate change on the management of Australia’s natural resources, the Australian Government funded CSIRO and the Australian Bureau of Meteorology (BOM) to develop tailored climate change projections reports for each of eight natural resource management (NRM) ‘clusters’ (i.e. clusters of existing NRM regions). These projections, *Climate Change in Australia* (CCIA), were released in 2015 and provide guidance on the changes in climate that need to be considered in planning.

Victoria is represented in these national projections as part of the Murray Basin (Timbal et al. 2015) and Southern Slopes (Grose et al. 2015a) clusters.

The 2018 State of the Climate (Bureau of Meteorology and CSIRO 2019) reports that:

- ▶ Australia’s average temperature has increased by more than 1°C since 1910
- ▶ extreme heat events have increased in frequency
- ▶ rainfall in southeast Australia has declined by around 11% in the April to October period since the late 1990s
- ▶ extreme fire weather has increased in frequency and duration
- ▶ sea levels have risen leading to increased inundation risk.

Victoria has its own interests regarding climate change, risk and adaptation. For these reasons, in recent years the Victorian Government has supported climate research, climate projections, risk and adaptation work with a local focus. On the research and projections side, the *South East Australia Climate Initiative* (SEACI) and the *Victorian Climate Initiative* (VicCI) programs have generated science research and communication products targeted at Victoria and the Murray Basin.

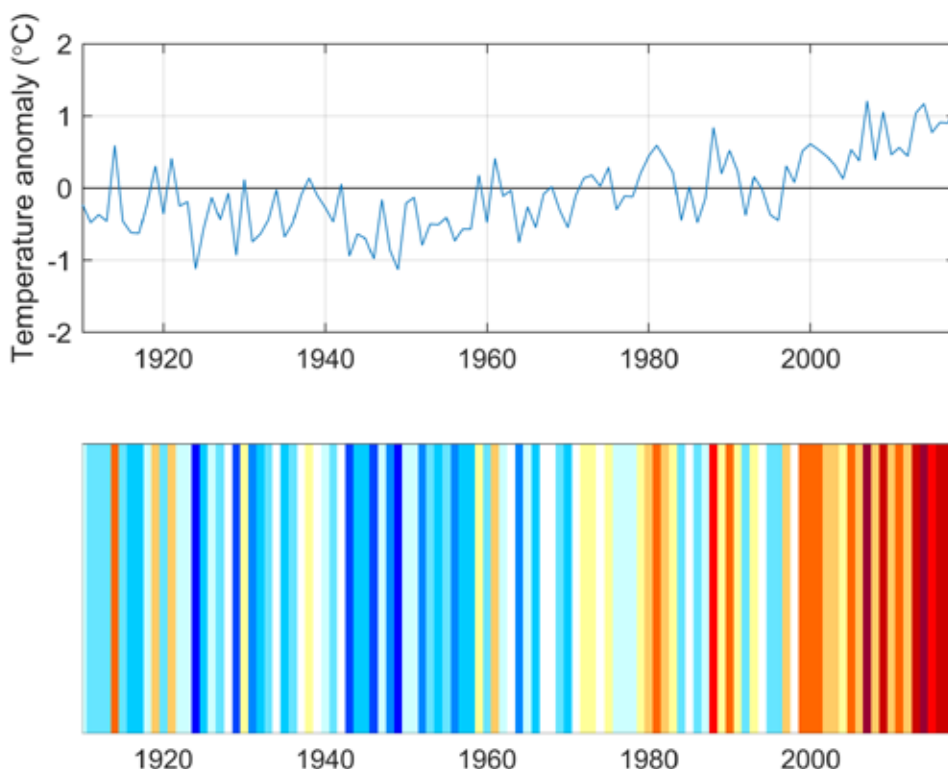


Figure 1. Average annual near-surface (2 m) temperature of Victoria 1910 to 2018 relative to the 1961–1990 baseline average. Panel on the bottom shows ‘climate stripes’ where each stripe represents the temperature anomaly of one year, reds indicate temperatures above the 1961–1990 average and blues, below average (ACORN-SATv2 data set, scale ranges from 1.5 to +1.5°C, methods of Ed Hawkins)



### 1.3 Why produce new projections?

Since climate change operates over longer scales, climate projections do not need to be updated daily or monthly like weather or seasonal forecasts. However, as our observations of the climate continue, our climate knowledge continues to improve, models improve, and needs for climate information and projections continues to evolve. This means the credibility and salience of projections can be higher over time, so it is advisable to update climate assessments and projections when appropriate.

Milestones for developing projections include the release of IPCC assessment reports, and the release of new coordinated climate modelling ensembles under the Coupled Model Intercomparison Project (CMIP) structure. These international milestones then influence the development of projections at the national, state and local level. The most recent IPCC assessment report was released in 2012/13 and this draws on the latest round of coordinated global climate models known as CMIP5 released in 2011/12, among many other lines of evidence. The CCIA climate projections draw on the science and model simulations from this period, as well as drawing on high-resolution climate modelling based on the CMIP5 outputs. VCP19 uses the same CMIP5 outputs, as well as new high-resolution climate modelling, combined with subsequent research and observations. VCP19 is expected to be current until at least the release of the sixth IPCC assessment and CMIP6 in 2022, and for some time beyond as the new research and modelling will take time to be translated to local issues. Future climate research and modelling are likely to incrementally improve our understanding and refine our projections of climate change; however, this work is unlikely to change the fundamental understanding of climate change in Victoria. This means the VCP19 projections are expected to be relevant after 2022, with some contextualising of the results consistent with the future research.

Global climate model data is available for a range of future greenhouse gas emission scenarios agreed to by the international climate research community. However, due to limitations on modern supercomputing resources, the new high-resolution climate modelling focused on a medium emissions scenario (RCP4.5, see the glossary of terms at the end of this report) and a high emissions scenario (RCP8.5).

These emissions scenarios were chosen to explore some of the larger potential changes in the Victorian climate that can arise under different greenhouse gas emission scenarios. The use of the two greenhouse gas emissions scenarios in the high-resolution modelling was made possible by combining the resources of the VCP19 projections project with an existing project undertaken by Wine Australia and lead by researchers at the University of Tasmania. Both sets of high-resolution climate simulations were performed concurrently with common model configuration and methods, allowing for a broader assessment of potential changes to climate than would otherwise be possible. This technical report presents the results of this work at the spatial scale of the state of Victoria and sub-regions within Victoria.

The outputs from the VCP19 project are available to the Victorian Government, broader community and the scientific community to improve understanding and application of climate projections. The outputs of VCP19 are:

- ▶ this technical report – aimed at scientists
- ▶ 10 regional reports – aimed at non-scientists
- ▶ projections and data for medium (RCP4.5) and high (RCP8.5) scenarios of future greenhouse gas emissions
- ▶ projections of Victoria's climate under the Paris Agreement target of 2°C global mean temperature increase compared to the pre-industrial era
- ▶ good practice guidance for how to make best use of the new projections and data sets
- ▶ data sets of projected regional changes for 12 climate variables (including four measures of climate extremes) for 10 regions on annual, seasonal and monthly time scales
- ▶ gridded (5 km) and town-based 'application-ready' data sets for 10 climate variables for annual to daily time scales
- ▶ gridded (5 km) change data sets for 11 climate variables for annual to daily time scales
- ▶ gridded (5 km and 50 km) output for six high-resolution climate model experiments with more than 20 climate variables for up to hourly time scales
- ▶ new functionality on the *Climate Change in Australia* website, providing access to the new data and products.

## 2. Methods

This chapter explains the data sets, models and analysis techniques used to produce the VCP19 climate projections. The chapter outlines the existing set of previous modelling considered in VCP19 and the process to produce the new fine-scale regional climate model (RCM) simulations of the Victorian climate. The chapter also describes the regions considered, and how changes are calculated and presented for the regions.

### 2.1 Climate data sets

When developing regional climate projections for Victoria, it is important that multiple and reputable lines of information and evidence are examined and considered such as observations, trends, global climate models of future climate and higher resolution regional climate models. 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. Without a documented case, no set of outputs should be considered superior to all others and used in isolation, although agreement between different model ensembles can be a source of confidence in the results. It is also important to consider some of the more extreme model simulation results if they are credible, given the significant impacts that could occur if that model projection was realised in our future climate. Developing regional climate projections is a process of collecting all available historical and simulated future climate change information and interpreting that information to understand the probable and possible regional outcomes of global warming.

Global climate models (GCMs) are our best source of information regarding how increasing greenhouse gas concentrations can affect the global climate of the Earth. These GCMs are computer software models that couple various components of the Earth system, including atmospheric processes, land processes, oceans, sea-ice, aerosol feedbacks and carbon cycle feedbacks. By using prescribed scenarios of greenhouse gas emissions, it is possible to estimate how quickly the Earth system can warm and some of the responses to this warming by the different Earth system components (e.g. melting of sea-ice). To aid with the development of climate change projections, the different GCMs all contribute to the Coupled Model Intercomparison Project (CMIP, with the current generation being CMIP5 and the new CMIP6 experiment being underway at the time of writing). For the CMIP5 generation of GCMs, greenhouse gas emission scenarios are described by representative concentration pathways (RCPs). The RCPs comprise RCP2.6, RCP4.5, RCP6 and RCP8.5, where the number after the RCP indicates the increase rate of energy (e.g. stored as heat)

trapped in the Earth system by the increased concentrations of greenhouse gases. A higher number associated with an RCP results in a warmer climate and more severe impacts on the environment. RCP2.6 is the greenhouse gas emission scenario used by the GCM development teams that is the closest to that required to meet the Paris Agreement targets discussed in Chapter 6. RCP4.5 and RCP8.5 are often a focus for climate projections as they have been interpreted as medium and high emissions scenarios, respectively.

The GCMs contributing to the CMIP experiments provide the most diverse set of independent model data sources for developing climate projections. However, a limitation of GCM data sets is that the complexity of the modelling combined with limitations on supercomputing hardware results in GCMs typically having a grid-box resolution of 100 to 200 km. This means that mountains and coastlines are not always well resolved, urban areas can be neglected, and certain atmospheric phenomena can be poorly resolved (e.g. storms). Downscaling techniques are often employed to supplement some of the missing information needed for regional projections of climate change that is not directly available from the GCMs.

Downscaling can use a wide variety of techniques, all with various strengths and weaknesses (Ekström et al. 2015). In general, downscaling attempts to interpret regional changes in climate that are poorly resolved in the GCM simulations. Two popular approaches to downscaling climate models are statistical downscaling and dynamical downscaling. Statistical downscaling, as used for the *Victorian Climate Initiative* (VicCI), relies on relationships between large-scale atmospheric behaviour and the local response in weather. Often statistical downscaling is informed by historical observation records, from which the large-scale and local-scale relationships can be derived. In comparison, dynamical downscaling techniques rely on a computer simulation of different atmospheric and land-surface processes, in a similar way to how the GCMs model the atmosphere. However, dynamical downscaling focuses its computing resources to better spatially and temporally resolve a small region, at the expense of resolving the rest of the globe. Dynamical downscaling models also

usually focus on the atmospheric and land-surface modelling, neglecting ocean and sea-ice components of the GCMs. Combining the results of statistical (e.g. VicCI) and dynamical methods can often be useful for developing regional climate projections, since the statistical approach relies on historical data to interpret regional changes in climate, whereas the dynamical approach relies on computer simulations of atmospheric processes at finer spatial-scales than is practical for the GCMs to simulate. This leads to different assumptions behind the downscaling technique, which can be best understood by combining multiple sources of downscaling when developing regional projections. The learning from comparing these different downscaling techniques is discussed further in Chapter 5.

An example of an important downscaled data set for Victoria is the statistically downscaled 5 km resolution data sets developed for VicCI. This climate data is already being used within the Victorian Government and water corporations and is important for framing new and future climate modelling. Another source of downscaled climate data for Australia is the *Coordinated Regional Climate Downscaling Experiment* (CORDEX) regional climate model inter-comparison experiment (<http://www.cordex.org/>). CORDEX provides 50 km resolution climate data for the Australasia region (including Australia, New Zealand and neighbouring islands), using different climate modelling systems within a common

experiment framework. The New South Wales Government has previously commissioned a dynamical downscaling of the regional climate for their state at 10 km resolution, which is known as the NSW and ACT Regional Climate Modelling (NARCLiM) project, which overlaps with the Victorian region and therefore contributes towards the Victorian regional projections. Another relevant data set for this study is the *Benefits of Reduced Anthropogenic Climate Change* (BRACE), which is a project looking specifically at the reduced impacts of lower emissions scenarios compared to higher ones (Sanderson et al. 2018). This includes climate change under the Paris Agreement global warming targets of 1.5 and 2°C since pre-industrial times, partly produced to inform the IPCC Special Report on 1.5°C (IPCC 2017). The project included the production of a global climate model medium ensemble of the Community Earth System Model (CESM) where global warming plateaus at each target, titled BRACE1.5. The ensemble features 15 climate simulations meaning that variability is well sampled but is dependent on a single global climate model.

The *Victorian Climate Projections 2019* project draws on a range of available data sets in addition to the new high-resolution modelling undertaken specifically for Victoria using the Conformal Cubic Atmospheric Model (CCAM) described in the following section. The climate data sets used to develop regional projections for Victoria are summarised in Table 1.

Table 1. Climate projection data sources drawn on for the Victorian Climate Projections 2019 (VCP19) development

Data set	Provenance	Resolution	Contribution to VCP19
VCP19 CCAM	Focus on Victoria; based on CMIP5, RCP4.5 and RCP8.5	5 km	Primary high-resolution data source (50 km version also used for national context)
GCMs from the Coupled Model Intercomparison Project phase 5 (CMIP5)	International; up to 42 models; source for IPCC Fifth Assessment Report (2013)	60–200 km	Source of host models for CCAM downscaling; key source of CCIA data sets
Climate Change in Australia (CCIA) <sup>1</sup>	Australia-wide (CMIP5 based); published 2015	Application-ready 5 km; change data: 60–200 km	Key data source; critical context for Victorian projections; includes earlier 50 km CCAM data; source of Australian model evaluation information; guidance material
Bureau of Meteorology Statistical Downscaling Model (BOM-SDM) <sup>1,2</sup>	Contributed to CCIA and VicCI data sets	5 km	Context for VCP19
NSW and ACT Regional Climate (NARCLiM) <sup>3</sup>	Focus on NSW, also covers Victoria; based on CMIP3, SRES A2 only	10 km (some data at higher resolution)	Context for VCP19; comparison of higher emissions scenarios (A2)
Benefits of Reduced Anthropogenic Climate Change (BRACE) <sup>4</sup>	International	Global and Victoria	New application to Australian context; future climate under the Paris Agreement targets of 1.5 & 2.0°C warming

1 <https://www.climatechangeinaustralia.gov.au/en/climate-projections/about/modelling-choices-and-methodology/>

2 <http://www.bom.gov.au/research/projects/vicci/>

3 <https://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/About-NARCLiM>

4 <http://www.cgd.ucar.edu/projects/chsp/brace1.5.html>

All currently used, or otherwise current generation climate model outputs have been considered, except for the *Climate Futures for Tasmania* data sets that are not included here as:

- ▶ they were made using the previous generation (CMIP3) of global climate model inputs
- ▶ they were developed using a previous version of the CCAM model
- ▶ the winter rainfall projection for southeast mainland Australia is different from host models (the global climate models used as input) due to a model-specific effect that means the results may not be representative of the broader range of projections.

## 2.2 New modelling

Although there are a number of existing climate data sets described in the previous section, climate change simulations for Victoria at resolutions below 10 km were limited to statistically downscaled data sets that were used for VicCI. Therefore, it was decided that new dynamical downscaling at a resolution of 5 km could be beneficial when developing projections for Victoria, since the dynamical downscaling employs different assumptions and techniques to statistical downscaling, so including them provides a more diverse and independent set of modelling approaches to inform the predicted changes to the regional climate. The new high-resolution dynamical downscaling is not a replacement for the existing VicCI data sets, nor a replacement for the GCM data sets. Rather, the new simulations are intended to provide an additional source of information and data that can help strengthen conclusions drawn from existing data sets, shed new insights into some regional climate phenomena, and help define levels of confidence in the projected regional consequences of global climate change.

There is flexibility in how a dynamical downscaling experiment is undertaken, but in general the regional climate models (RCMs) used for dynamical downscaling adhere to some basic principles:

- ▶ The RCM includes information from the GCMs to determine the large-scale changes to the oceans and Earth system as well as the rate of global warming.
- ▶ The RCM includes mountains, coastlines, urban areas and other details at the surface that are poorly resolved by the GCMs.
- ▶ The RCM improves the representation of atmospheric physical processes that are relevant for the spatial-scales being simulated.

High-resolution dynamical downscaling of global climate simulations can result in improved modelling of regional climate where there is complex orography, such as mountains or coastlines that were poorly resolved by the host global climate model. The higher-resolution dynamical downscaling can also resolve local features such as urban heat islands due to the ability to include urban materials and energy use in the simulation. Regional climate models may also provide better simulation of variability in winds, temperature and rainfall, through better resolution of atmospheric processes (e.g. clouds, boundary layer mixing, etc.). Consequently, certain types of extreme weather such as storms and strong winds are usually better represented by the regional climate models than for the lower resolution global climate models. Dynamical downscaling has been used to produce transient data sets of projected regional climate change (e.g. from 1960–2100) rather than time slices (e.g. 1986–2005, 2041–2060 and 2081–2100) which helps with assessing the progression of change. A possible weakness of standard dynamical downscaling techniques is that errors in the GCM simulation may undermine the performance of the RCM simulation. For this reason, it is common for dynamical downscaling experiments to attempt to address GCM biases and minimise their impact on the RCM simulation (e.g. Katzfey et al. 2016).

For the new VCP19 high-resolution climate simulations, CSIRO's CCAM was used for dynamically downscaling GCM data sets (McGregor 2005; McGregor and Dix 2008). CCAM has been used for numerous regional climate modelling projects in Australia and overseas, including the NRM projections for Australia, *Climate Futures for Tasmania*, *High-resolution Climate Projections for Queensland* and *Climate Projections for the Australian Alps*. CCAM is also contributing to the CORDEX intercomparison experiment and is used in South Africa, New Zealand, South East Asia and the Pacific. The CCAM source code is freely available for scientific researchers (<https://confluence.csiro.au/display/CCAM/CCAM>).

CCAM has a variable resolution global grid that can be focused over a region of interest (see Figure 2). This means the region of interest can be simulated at high resolution, while still maintaining a lower resolution simulation of the entire globe. This is different to the more traditional approach used by RCMs based on a limited area simulation. Limited area climate models only simulate the climate for a region, often defined by a rectangle, and therefore require atmospheric data to be supplied from a GCM at their lateral boundaries that represent the edges of the limited area simulation. Since CCAM does not have lateral boundaries, it can avoid problems arising from the prescription and

interpolation of GCM data at the boundaries of limited area models. Another feature of CCAM is its use of the Community Atmospheric Biosphere Land Exchange (CABLE) land-surface model (Kowalczyk et al. 2013) and the Urban Climate and Energy Model (UCLEM) (Thatcher and Hurley 2012; Lipson et al. 2018). These sub-models were developed to better represent Australian conditions, with the UCLEM model initially developed to represent the climate of Melbourne, including the urban heat island discussed in section 4.2.2. Thirdly, CCAM can operate as a global atmospheric climate model, which allows us to modify the ocean temperatures simulated by GCMs to reduce potential GCM biases that can be introduced into the regional simulation. Although limited area climate simulations also attempt to correct biases in their lateral boundary conditions, these corrections can be complex and non-linear due to the way different atmospheric variables interact with each other such as temperature, moisture, clouds, wind, aerosols, etc. CCAM avoids this problem by using a global simulation where the CCAM physical and dynamical processes can internally resolve the changes arising from correcting GCM biases.

It should be stressed that regional climate simulations do not necessarily improve all aspects of a climate simulation and can feature new biases or errors. Also, different dynamical downscaling models produce different simulations of the future climate, making it more difficult to provide certainty in the production of climate change projections. Regional climate models rely on the same atmospheric physical parameterisations that are used in global climate models and can be prone to the same errors due to the imperfect understanding of the atmosphere. Most regional climate models are atmosphere-only models and do not include feedbacks with the ocean, which can be important for simulating the climate along coastlines. For VCP19, CCAM was configured in an atmosphere-only model, due to the CCAM ocean model being under development. The reduction of GCM ocean temperature biases also weakens the relationship between the downscaled climate and the projections of the host GCM, reducing the diversity in independent sources of climate model data sets.

All climate models and downscaling techniques include different assumptions in their design and hence no single model should be considered a definitive prediction of the future climate. This principle applies to the CCAM dynamically downscaled results provided in VCP19, since CCAM still represents a single modelling system. Therefore, when discussing the projections of future climate, the CCAM results will be presented in the context of existing GCM results, VicCI statistical downscaling and other dynamical

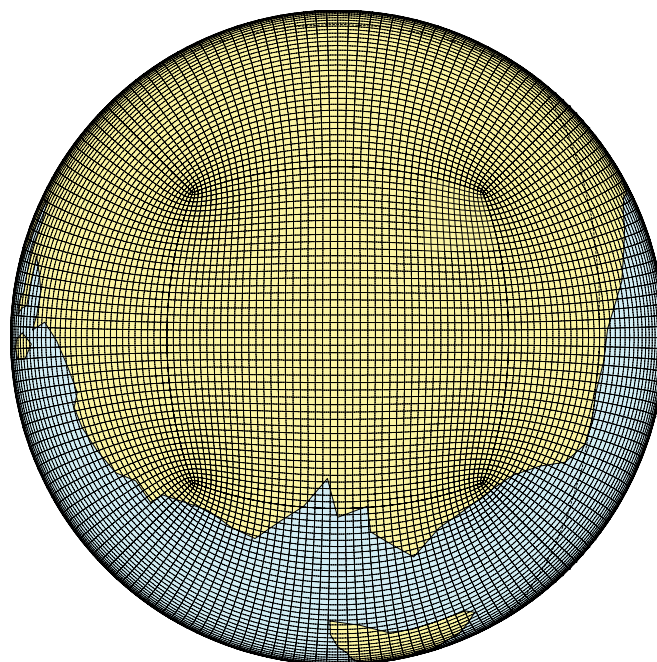


Figure 2. The CCAM variable resolution global grid, focused over Victoria

downscaling experiments such as NARCLiM, where possible. It is then possible to see if the CCAM simulations are an outlier of the existing sources of climate change information and to assign a level of confidence in the CCAM projections. Care is taken to separate the regional changes in climate simulated by CCAM from the larger-scale changes in climate where possible. For example, the simulated change in rainfall by the high-resolution modelling may be modified by the presence of a mountain range that was not resolved in the GCMs, and the simulated change may be supported by a known physical process or mechanism that explains the regional model projection. There may then be more confidence in generalising the simulated regional change in rainfall for regional projections, independently of the larger scale changes found in the individual regional climate simulations.

As well as avoiding using a single source of data for developing regional projections for Victoria, it is also important to downscale multiple GCM simulations of the future global climate to better represent different possible regional changes in climate. This is so that the projected changes in the regional climate as simulated by CCAM are more consistent with the range of different projections of global climate models. This is important when assessing the range of probable and possible future climate scenarios for the regional projections in Chapter 5. Six GCMs were chosen for downscaling by CCAM as listed in Table 2, which were selected from the eight-model subset identified for the CCIA projections. These selected GCMs demonstrated

high simulation skill and are representative of the ranges of projected change for Australia. The six models were chosen to represent a range of climate warming that was consistent with the range of projections made by the CMIP5 ensemble of GCMs, including both drier and wetter future climates, as well as having realistic representations of large-scale drivers of the Australian climate (e.g. ENSO, monsoons, etc.). In this way, the six models downscaled can be considered a combination of higher quality global climate models as well as a sufficient cross-section to represent the broad range of global climate model projections for Australia.

In addition to downscaling the six GCM projections of the future climate, CCAM also downscaled the ERA-Interim reanalysis. A reanalysis is produced using data assimilation techniques to incorporate meteorological and ocean observations of the weather into a global atmospheric simulation. The atmospheric variables are then adjusted to ensure that the global simulation is as consistent with the observations as possible, while still following the governing geophysical equations that describe the functioning of the atmosphere. The assimilation of observations in reanalyses that are not available to the climate GCMs (which are designed to simulate a future climate where the observations do not exist) results in reduced simulation errors for the present climate. Hence downscaling of reanalyses is a useful way to evaluate the downscaling performance of CCAM for the present climate. When downscaling climate GCMs for the future climate, CCAM was run from 1960 to 2100, for two representative concentration pathways (van Vuuren et al. 2011): RCP4.5 and RCP8.5.

There are two stages to CCAM downscaling. The first stage is to simulate the global atmosphere at 50 km resolution, with the sea surface temperatures (SSTs) taken from the host GCM after bias correction of the mean and variance (Hoffmann et al. 2016). These simulations run continuously from 1960 to 2100, although the historic period (up to 2005) is common for both RCP4.5 and RCP8.5. The 50 km simulations represent a reconstruction of the atmosphere after removing biases introduced by the GCM SST bias, but to not include any atmospheric information directly from the host GCM. The second stage is to nest a 5 km resolution simulation, focused over Victoria, using CCAM's stretched grid within the 50 km global simulation. The 5 km simulation is guided at large spatial scales by the 50 km simulation using a scale-selective filter (Thatcher and McGregor 2009) but adds considerable detail in surface features (e.g. mountains, coasts, urban heat islands, vegetation, etc.) as well as providing some better-resolved atmospheric processes compared to the GCM (e.g. extreme rainfall). The use of bias-corrected GCM SSTs has significant implications for the downscaling process. Since the GCM SSTs are modified and the global atmosphere is reconstructed, then the downscaled CCAM data sets can differ in their projections from the host GCM. As a result, care is taken to separate the regional-scale projections from the larger-scale projections of the CCAM 50 km simulations. These differences do not necessarily mean that the CCAM projections are incorrect, rather the projections are influenced using a single CCAM-based downscaling process and should be interpreted in the context of the CMIP5 GCM ensemble and other downscaled data sets. A visualisation of the grid spacing and surface height in each stage shows the increasing detail through downscaling (Figure 3).

*Table 2. The historical reanalysis model and six global climate models used as host models for downscaling over Victoria using CCAM. The relevance of global climate model is based on Climate Change in Australia.*

<b>Model/reanalysis name</b>	<b>Relevance for VCP19 projections</b>
ERA-Interim (reanalysis)	Reanalysis product that is useful when evaluating dynamical downscaling in the present climate.
ACCESS 1-0	A hot, dry model in the south of Victoria. Representative of the consensus of GCM projections in northern Victoria.
CNRM-CM5	Representative of the consensus of GCM projections over Victoria, particularly in the north.
GFDL-ESM2M	Often a hot, dry model for Victoria.
HadGEM2-CC	Often a hot, dry model for Victoria.
MIROC5	Often a low warming, wet model for Australia and Victoria.
NorESM1-M	Often a low warming, wet model for Victoria, especially in the south.

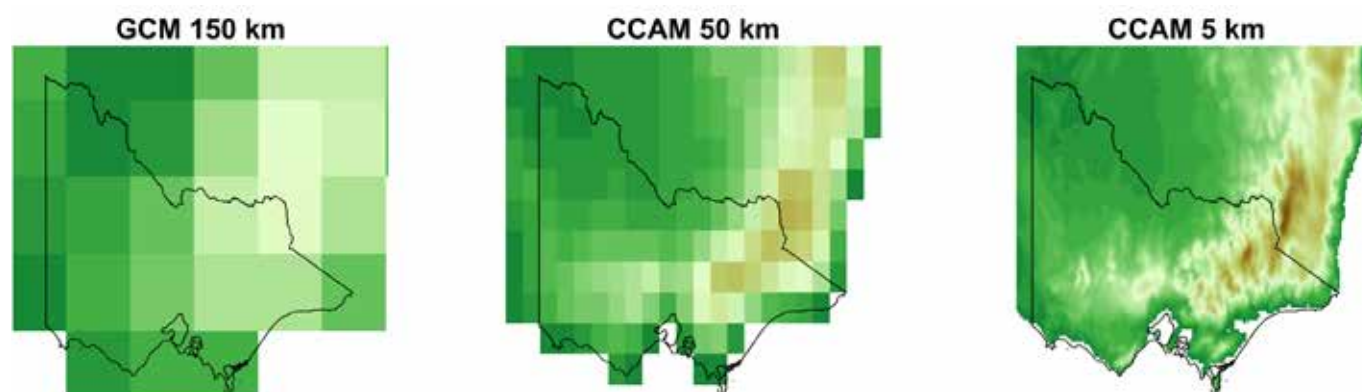


Figure 3. Topography of Southeast Australia in a typical GCM resolution (about 150 km), intermediate downscaling using CCAM (50 km) and high-resolution downscaling using CCAM (5 km), the height scale extends to 2000 m above sea level.

It should be noted that the final report for the VicCI project (Hope et al. 2016) raised some important questions regarding the use of downscaling approaches for developing climate change projections. They observed a marked divergence in the results of the statistically downscaled models compared with the dynamically downscaled models that they examined. This behaviour also occurs for the CCAM dynamical downscaling described in this report. All downscaling models will have broadscale biases and errors in their simulation of the regional climate that are associated with that model. The different biases of downscaling models can be illustrated by comparing the different downscaling data sets, although the model with the smallest biases is usually unknown. Unless there is a physical explanation that can clarify why an individual downscaling approach is incorrect, then no single downscaling modelling system can be preferred over any other downscaling technique. In this way, the CCAM downscaling experiments presented in this report are intended to enhance the amount of climate modelling data that can be used to develop regional projections, rather than be considered a superior data set to other downscaling techniques. There are examples discussed later in this report where CCAM will provide some important insights into future changes in Victoria's climate, but these insights are most effective when their conclusions are reinforced by the other downscaling techniques.

It is important to note that dynamically downscaling to higher resolution does not necessarily eliminate errors from the host GCM's climate simulation. Rather, the dynamically downscaled simulations can supplement and extend projections made by the GCM. For example, the CCAM dynamical downscaling can better represent the mean rainfall near mountains, and better represent extreme rainfall compared to the host GCMs. The CCAM output should not be used independently of the GCM results, which give a much larger ensemble of future climate change for Victoria, but rather be used to better understand the projections of six

representative GCMs, such as how regional influences might modify the rainfall compared to the GCM simulation. For this reason, regionally dependent projections of the model are from the large-scale changes that arise from a combination of changes in ocean temperatures simulated by different GCMs but interpreted by a single CCAM atmospheric model. Chapter 5 contains examples of how the CCAM results can modify some regional aspects of the GCM simulations, so that the results can be interpreted in the broader range of GCM projections.

## 2.3 Area-averaged changes

In line with international practice (IPCC 2013a), a time-slice approach is used to compute future change relative to an historic baseline (see Figure 4). This method involves calculating the difference between a climate model's future and historic values (each averaged over 20 years) for a given emissions scenario and time-period. The historic baseline period used for this calculation was the 20-year period, 1986–2005. This is consistent with the IPCC's Fifth Assessment Report (IPCC 2013a) and the CCIA projections (CSIRO and Bureau of Meteorology 2015).

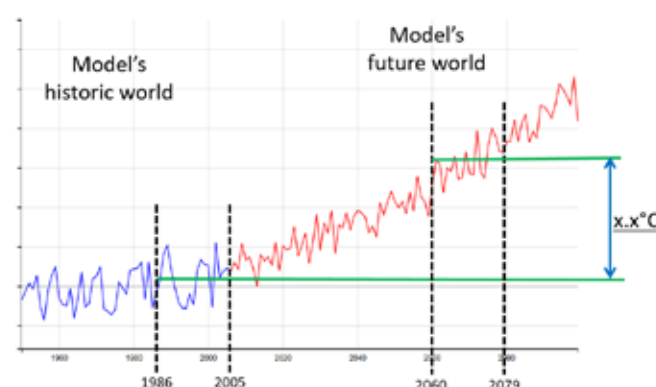


Figure 4. Time-slice method: by computing the difference between the model's future temperature and past values, any inherent bias in the model is removed.

One advantage of this approach is that it corrects for climate model bias (e.g. a model may be consistently slightly too cool or too dry). By comparing the model's simulation of the past with the same model's simulation of the future, the time-slice method removes this bias. Once computed using the time-slice method, the gridded changes were averaged over the regions described in section 2.4. The climate variables that have been computed as regionally-averaged data are described in Table 3.

## 2.4 Regionalisation

Throughout this report, analyses of past and future climate are presented at both state-wide and regional scales. Regional analyses were undertaken at two spatial scales, as appropriate to the projection data sources used. The lower-resolution pre-existing GCM results were analysed for six regions (see Figure 5), consistent with the *Climate-ready Victoria* work previously commissioned by DELWP (hereafter referred to as 'GCM regions'). For the analysis of the higher-resolution RCM results, the six GCM regions were sub-divided into 10 smaller regions (hereafter referred to as VCP19 regions). These 10 VCP19 regions align with the pre-existing Victorian Government Regional Partnership Regions. The nested nature of the two regionalisation schemes permits meaningful comparison between GCM and RCM results.

The two sets of RCM and GCM regions are described in Table 4 and shown in Figure 5.

*Table 4. Description of the regions used for regional analyses of GCM and RCM results, including four larger GCM regions that comprise a pair of smaller RCM regions. Additionally, regional reports were developed for each of the high-resolution regions.*

GCM regions	High-resolution regions
Barwon South West (BARSW)	Barwon (BAR)
	Great South Coast (GSC)
Gippsland (GIPPS)	Gippsland (GIP)
Grampians (GRAMP)	Central Highlands (CEH)
	Wimmera Southern Mallee (WSM)
Hume (HUME)	Ovens Murray (OVM)
	Goulburn (GOU)
Loddon Mallee (LODMA)	Loddon Campaspe (LOC)
	Mallee (MAL)
Metropolitan (METRO)	Greater Melbourne (MET)

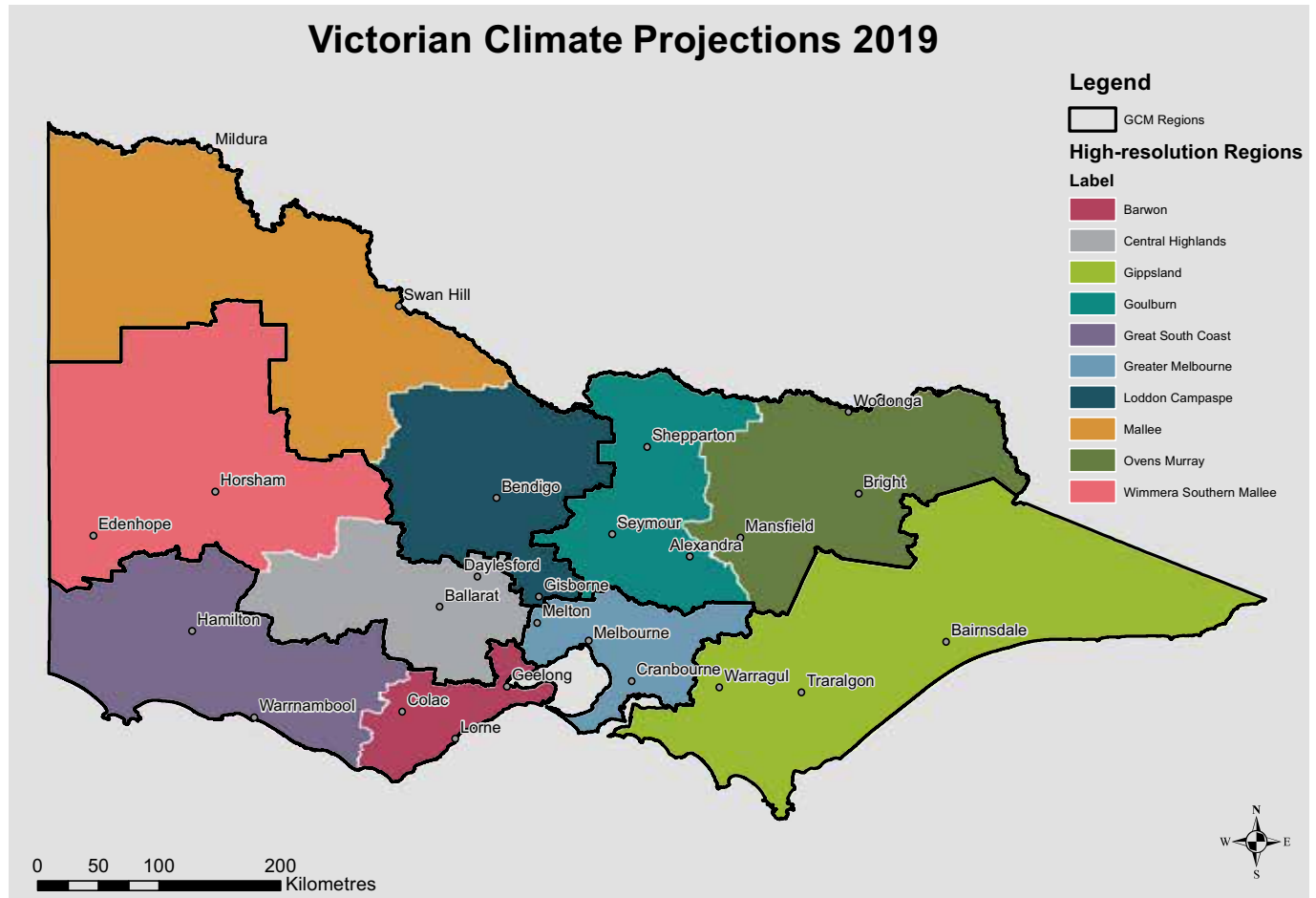
Regionally-averaged changes were computed from GCM and RCM data for the six GCM regions. Averages were computed from just the high-resolution RCM data for the 10 smaller regions shown in Figure 5. Regional reports have been developed for each of the 10 smaller regions. These can be found at <https://www.climatechangeinaustralia.gov.au/vcp19>.

*Table 3. Climate variables for which area-averaged changes have been computed*

Climate variable (change units)	Temporal scale	Availability of gridded data sets
Mean near-surface air temperature (°C)	Annual, seasonal, monthly	Yes
Maximum daily near-surface air temperature (°C)	Annual, seasonal, monthly	Yes
Minimum daily near-surface air temperature (°C)	Annual, seasonal, monthly	Yes
Rainfall (%)	Annual, seasonal, monthly	Yes
Relative humidity (%)	Annual, seasonal, monthly	Yes
Wet areal potential evapotranspiration (%)	Annual, seasonal, monthly	Yes
Mean wind speed (%)	Annual, seasonal, monthly	Yes
Solar radiation (%)	Annual, seasonal, monthly	Yes
Extreme (1-in-20-year) rainfall (%)	Annual, seasonal	No
Extreme (1-in-20-year) daily maximum temperature (°C)	Annual, seasonal	No
Extreme (1-in-20-year) daily minimum temperature (°C)	Annual, seasonal	No
Extreme (1-in-20-year) wind speed (%)	Annual, seasonal	No



Figure 5. Map of the regions used for regionally averaged calculations (GCM and RCM) and for the regional reports (high-resolution regions).



## 2.5 Application-ready data sets

Application-ready data sets are data in a form that is compatible with an applied model or analysis, including a representation of climate variability compatible with the data used to calibrate the applied model (<https://www.climatechangeinaustralia.gov.au/en/support-and-guidance/using-climate-projections/application-ready-data/>). Such application-ready data are often used as inputs to sector-specific impacts models (e.g. crop growth models or ecological models) and can provide useful insights into extremes.

For VCP19, application-ready data is derived by using a percentile-percentile scaling approach on a time-slice of observed data (e.g. AWAP for rainfall between 1980 and 2010) to reproduce the changes in the probability distribution predicted by the CCAM simulations relative to the baseline period of 1986–2005. The climate variables for which application-ready data have been developed from CCAM simulations are shown in Table 5. Application-ready data were developed to produce future 30-year time-series data sets for the periods 2016–2045, 2036–2065, 2056–2085 and 2075–2104. Since the percentile-percentile scaling is applied over a 30-year time period, it is possible for the application-ready data to have a different shorter-term trend than was simulated by CCAM. For this reason, the future time-series application ready data can be regarded as representative of the mean state of the relevant future climate, rather than as a transient climate that is changing over time.

Application-ready data are often easier to use as inputs for applied models (e.g. crop models) than the original CCAM data since simulation biases are removed and the probability distribution of the climate variables are consistent with observed data. There can be limitations to using application-ready data, including that the time-series of the observed data determines the time-series of the future climate data (e.g. the hottest day always occurs on the same day in the 30-year future climate). In some cases, the observed data also has lower resolution than the CCAM 5 km results (e.g. solar radiation). Nevertheless, the application-ready data is generally found to be more compatible with applied models and is often an ideal starting point when using climate model data.

Table 5. Climate variables for which application-ready data is available

Climate variable (units)	Temporal scale
Mean near-surface (2 m) air temperature (°C)	Annual, seasonal, monthly, daily
Maximum daily near-surface (2 m) air temperature (°C)	Annual, seasonal, monthly, daily
Minimum daily near-surface (2 m) air temperature (°C)	Annual, seasonal, monthly, daily
Rainfall (mm)	Annual, seasonal, monthly, daily
Relative humidity (%)	Annual, seasonal, monthly, daily
Wet areal potential evapotranspiration (mm)	Annual, seasonal, monthly, daily
Mean surface (10 m) wind speed (ms <sup>-2</sup> )	Annual, seasonal, monthly
Solar radiation (Wm <sup>-2</sup> )	Annual, seasonal, monthly, daily
Days above/below temperature thresholds (count)	Annual, seasonal

### 3. Important features of Victoria's climate

This chapter gives a brief general introduction to the climate features relevant to Victoria, where features refers to the atmospheric circulation, weather systems and global processes such as the El Niño Southern Oscillation that affect our weather, seasonal climate and drive much of the longer-term changes to the climate. These features have changed in the past and are projected to continue changing in the future, in turn driving the weather and climate that is experienced in Victoria. For a more thorough coverage, please see work such as the *Victorian Climate Initiative* (VicCI), synthesised in Hope et al. (2017). Another useful introduction to some important climate features is the Victorian Government's *Climate Dogs*<sup>2</sup>.

Much of Victoria's climate has a temperate maritime classification, meaning that the moderating effect of the ocean gives generally mild temperatures with more rainfall in winter than in summer. Particularly during the cool season (May to October) Victoria is influenced by the mid-latitude westerlies. The western part of the state receives most of its rainfall from systems such as troughs and fronts embedded in this westerly flow, which are in turn are influenced by features of the general circulation such as the Southern Annular Mode (Figure 6). However, some regions of Victoria, particularly in the east, lack this distinct seasonal cycle of rainfall. The climate in the eastern part of Victoria is more like that of the eastern seaboard of Australia, with a significant proportion of rainfall from weather systems such as cut-off lows, which are low pressure systems that are cut off from the westerly flow. Intense cut-off lows include east coast lows, which can bring some of the most notable extreme rainfalls to the eastern regions of Australia.

In the Victorian region, changes to the atmospheric circulation and incidence of rain-bearing weather systems are likely to be the dominant drivers of changes to rainfall in a warming climate. In general, recent assessments of global climate processes and analysis of climate modelling (IPCC 2013b; Hope et al. 2017), indicate that in the cool season, southeast Australia is expected to see a shift in the dominant circulation and weather systems due to a warming of the climate and changes to the dynamics of the atmosphere. The change can be broken down into changes to the circulation that then manifests in changes in the weather systems and the rainfall they bring. The cool and warm seasons can be influenced in different ways.

The important changes include:

- ▶ a southerly shift in the 'storm track', the band where weather systems tend to travel in the southern hemisphere, to the south of Australia. This shift can reduce the influence of the synoptic-scale weather systems that bring rain to Victoria.
- ▶ an intensification of the subtropical ridge, the high-pressure belt that generally sits on or to the north of Victoria and is a result of the number and intensity of high-pressure systems that occur (highs are generally linked to drier conditions) (see Grose et al. 2015c).
- ▶ an expansion of the Hadley Circulation, the major north-south circulation of the atmosphere over the hemispheres, that determines the edge of the tropics, resulting in a southward extension of the tropics, particularly in summer.
- ▶ a weakening of the subtropical jet stream in winter over the Australian region. This is the westerly middle to upper troposphere air current that flows over southern Australia that sits at about 25–30°S in winter (Grose et al. 2017a).

Factors directly related to a warmer climate (the thermodynamic aspects) are also likely to affect not only temperature and evaporation, but some processes driving rainfall. For example, convective rainfall can increase in a warmer climate, and extreme rainfall events have been associated with the combination of thunderstorms with other weather systems over Victoria (Dowdy and Catto 2017), and greater atmospheric moisture is available to fall in extreme rainfall events.

<sup>2</sup> <http://agriculture.vic.gov.au/agriculture/weather-and-climate/understanding-weather-and-climate/climatedogs>

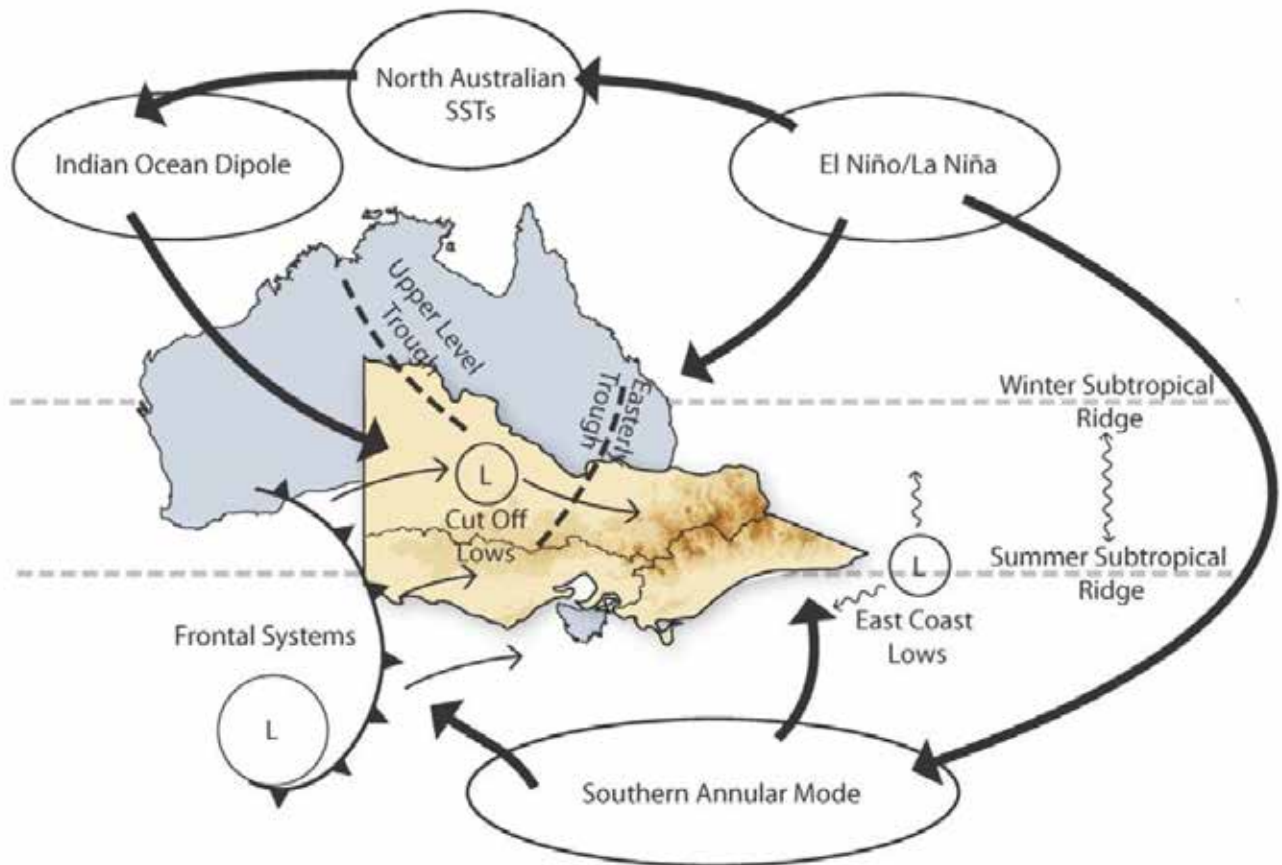


Figure 6. A schematic representation of the main circulation features and drivers of rainfall variability in the Victorian region. Weather systems include fronts, cut-off lows, troughs and east coast lows, that are in part determined by circulation features such as the subtropical ridge and the gradient of sea surface temperatures (SSTs) from north to south. Drivers of variability include the El Niño Southern Oscillation (ENSO) bringing El Niño and La Niña events, the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM), and blocking highs in the Tasman Sea (not shown). Source: VicCI

Along with the changes to the average circulation (the mean state) of the atmosphere, and factors related to a warmer atmosphere, the rainfall variability and averages may also be affected by changes to the drivers of climate variability from year to year. Victoria’s climate is influenced by various processes that create climate ups and downs (sometimes called modes of variability), that then have flow-on effects to Australia. On year-to-year time scales, these include the El Niño Southern Oscillation and Indian Ocean Dipole. While the Southern Annular Mode, the north-south shift of the jet to the south of Australia, varies on both shorter (~10 days) and longer (global warming) time scales. The frequency of blocking highs (or simply ‘blocking’) can also be thought of

as one of these modes. For any given phenomenon, there is considerable noise around the relationship between the cycle and the seasonal climate on the ground, and each event has its’ own character. Therefore, an index of each phenomenon – such as the Southern Oscillation Index (SOI) for the El Niño Southern Oscillation – is a guide to the likelihood of a particular seasonal climate anomaly but not a predetermination. These modes of variability will continue to exert an influence on Victoria’s climate in the future, but climate change may affect their behaviour or their connection to Victoria’s climate. The effects of each feature varies somewhat across Victoria.

### 3.1 El Niño Southern Oscillation

El Niño Southern Oscillation (ENSO) is an irregular cycle in the tropical Pacific Ocean, varying between El Niño, neutral and La Niña events, that has flow-on effects to Australia and many places in the world. Over the entire period 1886–2006, ENSO shows a correlation with rainfall in all or part of Victoria in winter and spring: warmer and drier on average during El Niño conditions, and cooler and wetter during La Niña (Risbey et al. 2009).

El Niño and La Niña events are difficult to predict before autumn of the year they commence; however, the predictability varies from event to event and some are hard to predict even after autumn. Also, the nature of ENSO, and the relationship between ENSO and Victoria's climate, can change over time. Some of these changes are described by a phenomenon termed the Inter-decadal Pacific Oscillation (Timmermann et al. 2018). Climate change due to human emissions may also drive changes to ENSO and its relationship to Victoria's climate, including the possibility of more extreme El Niño and La Niña events (Cai et al. 2015), and a change to the influence on Victorian rainfall (Power et al. 2013); however, there is uncertainty about the future of ENSO due in part to deficiencies of climate models to simulate it with fidelity.

### 3.2 Southern Annular Mode

The Southern Annular Mode (SAM) is a variation in the atmospheric circulation around the southern hemisphere between around 30°S and 60°S. A positive SAM means higher-than-average pressure over the latitudes near Victoria, and a negative SAM indicates the opposite. SAM has the strongest correlation to Victorian rainfall in winter, where a positive SAM indicates typically lower rainfall than average. There is a connection between SAM and some locations in the mid-latitudes in summer, including typically higher than average rainfall in some places but this effect is not marked in most of Victoria. SAM varies from day to day and week to week but can be persistently high or low for a season, affecting the seasonal climate. In addition, trends have been detected in SAM over time. In recent decades there has been a trend towards positive SAM during summer affected by the ozone depletion over Antarctica as well as the increase in greenhouse gases, and trends in other seasons are less clear (e.g. Marshall 2003). The SAM is projected to continue moving towards a more positive mean state, especially under a high emissions scenario, contributing to the rainfall decline in the mid-latitudes including Victoria (e.g. CAWCR 2016; Lim et al. 2016).

### 3.3 Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is an ocean–atmosphere phenomenon in the tropical Indian Ocean to the northwest of Australia that has flow on effects to Victoria's climate. The effect typically peaks in spring but can be seen in May to November. A positive IOD is generally linked to below average rainfall in Victoria, and a negative IOD typically is linked to above average rainfall (Ashok et al. 2003). The effect of IOD can be as large as or even override ENSO (Pepler et al. 2014), and when occurring concurrently the two can reinforce each other – an El Niño and positive IOD contributed to some of the driest June to October periods in Victoria. Strong IOD events are linked to heatwaves and pre-conditioning the environment for damaging bushfires (Cai et al. 2009). In the future, the Indian Ocean is projected to warm, and the IOD may change in nature or the influence Victoria's rainfall may change. Currently, the balance of evidence points towards a shift towards a more positive IOD mean state and more positive IOD events (Cai et al. 2013), meaning an influence towards a drier climate.

### 3.4 Blocking highs

Atmospheric blocking refers to persistent high-pressure systems in a particular location that block the usual atmospheric flow. The frequency and intensity of blocking highs is not the same thing as the average mean sea-level pressure (MSLP) band around the atmosphere, so changes to blocking need to be considered separately from the projected increase of pressure in the mid-latitudes mentioned above. An important centre of blocking is the Tasman Sea. Blocking tends to peak near southeast Australia in winter. Blocking affects Victorian rainfall, particularly in the east, in all seasons (Pook et al. 2013b). The correlation is positive, where more blocking means more rainfall, as blocks are associated with cut-off lows that can bring significant rainfall (Pook et al. 2013a). In future, fewer blocking highs in the Tasman in winter are projected along with a movement in the longitude where most blocks form (e.g. Grose et al. 2017a). The projection of blocking in summer is less clear.

# 4. Model evaluation and confidence

This chapter outlines the process of assessing the confidence in climate projections for Victoria, including the new high-resolution simulations. We cannot assess the climate projections against the future events as we do for weather forecasts, so we must assess the model in the current climate, compare projections from different models and assess our understanding of the relevant processes driving change to gauge the confidence in projections. The new CCAM climate modelling shows some inevitable biases compared to observations, as all climate models do, but is found to be appropriate for assessing regional climate change patterns with confidence.

## 4.1 Confidence

How to best use projections depends on the degree of confidence we have that they are reliable and complete. Projections with higher confidence can inform choices more definitely. In contrast, lower confidence projections 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.

VCP19 follows 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. Climate projections are not assessed in the same way as weather forecasts. Projections are made for a series of ‘what if’ emissions scenarios rather than a single set of inputs. They are estimates of the change in state rather than forecasts of the exact sequence of events. This means they are detailed scenarios of plausible future climates, which is a useful tool to inform decision-making, not a definitive set of results.

Confidence statements applied to a climate projection are determined through an expert elicitation process. This draws on multiple scientific experts’ judgment of its reliability as a guide to the range of change for a given input scenario. For VCP19, we draw upon previous lines of evidence and expert judgments on confidence from previous studies including IPCC assessments, the national climate projections and VicCI. The project also draws on new lines of evidence, such as new model simulations, and also the expert judgement of the project team and technical reference group to refine and add to confidence statements. 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 7).

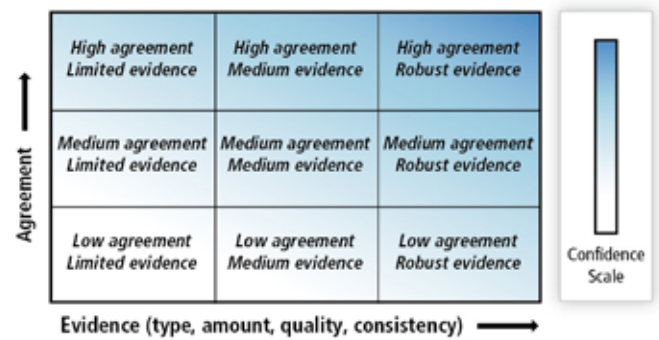


Figure 7. A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases towards the top-right corner as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

Confidence is high when:

- ▶ the processes involved in the change are well understood
- ▶ there is a well-established theoretical basis
- ▶ past trends due to human influence agree with the projected change
- ▶ the relevant Earth system processes that influence climate change are simulated by the models well
- ▶ the models largely agree on the projected change for an appropriately sized ensemble of climate model predictions.

Confidence can be assessed on both the direction of change, and the magnitude of change. For example, confidence may be high in the direction of change but lower in the

magnitude of change. In general, projections of factors more directly related to the energy balance of the Earth and the effect of an enhanced greenhouse effect (e.g. ocean heat, temperature) have higher confidence than those that are primarily related to flow-on effects onto features such as atmospheric circulation (e.g. regional rainfall, frequency of storms).

For VCP19 we have assessed the confidence in the new high-resolution modelling. New insights into how climate change may vary across the regions of Victoria are potentially very valuable, so confidence in this detail needs to be carefully assessed.

For these projections we use all inputs that are available and have not been found to be in error or unacceptable. Rather than use only the new modelling and nothing else, we use all sources of information but put a special focus on the new insights generated by the new modelling. There are cases where other model simulations suggest plausible changes outside the range generated by the new VCP19 runs, and we recommend that these also be considered as they represent plausible projections of climate change. In doing this, we aim to reduce the risk of underestimating the range of projected change. Overreliance on a narrow range of change can lead to maladaptation or maladaptive decisions.

As well as the confidence in the nature of the effect of climate change on the regional climate, the other aspect informing the use of climate projections in decision-making is completeness. Here we will cover three main dimensions of completeness: emissions scenarios, climate response and downscaling methods. The first dimension of completeness is the emissions scenarios, where a range of plausible scenarios should be explored and if one scenario is not included then there needs to be a rationale given. VCP19 reports on a high scenario (RCP8.5) and a moderate scenario (RCP4.5) and includes some information about the ambitious mitigation scenario of meeting the Paris Agreement target of 2°C global warming since pre-industrial times. High-resolution modelling is available for RCP8.5 and RCP4.5. These were chosen as they are more relevant to managing higher risk scenarios through adaptation, but these data should always be placed in the context of their emissions scenario.

The next dimension of completeness is the range of plausible climate response to each scenario. The range of results from a set of GCMs provides our best estimate of the possible response to emissions (noting that this model range may not be a complete and reliable estimate of the response). The project uses the entire set of CMIP5 GCMs alongside

the downscaled outputs. Also, the six models used for downscaling were chosen to be broadly representative of the CMIP5 ensemble in terms of temperature, rainfall and wind-speed change (changes to many other variables are then correlated with these).

The last dimension of completeness is choices of how to process and downscale data. Different methods give different results and a comprehensive intercomparison of global models, downscaling and processing methods is ideal. Currently the only such coordinated downscaling experiment for Australia is the 50 km resolution CORDEX Australasia experiment described in section 2.1. Comparison of the new CCAM 5 km resolution simulations against other downscaling methods available contributed to the assessment of confidence. The primary post-processing method of the CCAM 5 km simulations used was percentile-percentile scaling to form the application ready data sets described in section 2.5.

## 4.2 Model evaluation

Before using climate model output to contribute towards regional climate projections, it is important to evaluate a model's strengths and weaknesses. This evaluation informs the level of confidence in the CCAM projections provided in Chapter 5. In this section the performance of the CCAM regional climate model simulations at 5 km resolution for Victoria is evaluated, with a focus on:

- ▶ a combination of mean temperature and rainfall that is commonly used in climate impact studies
- ▶ extreme rainfall, as this is where the dynamical downscaling can add value to the GCM projections
- ▶ larger-scale features, including mean sea-level pressure and large-scale circulation patterns that reflects CCAM as a single modelling system.

When comparing CCAM's ability to represent regional features, the model evaluation relies on the *Australian Water Availability Project* (AWAP) data sets developed by the Australian Bureau of Meteorology and CSIRO. AWAP provides an approximately 5 km resolution gridded data set of daily maximum near-surface (2 m) air temperature, daily minimum near-surface (2 m) air temperature and daily rainfall, that is based on weather station measurements. AWAP is an important data set for evaluating high-resolution climate simulations, although it does have some limitations. For example, AWAP is based on land-based observations so that information over the ocean is interpolated. Also, some regions have a sparser density of weather stations, such as

for mountain regions, which can lead to some local gaps in the measurements and potentially an underestimate of rainfall in some locations. Large-scale features of the simulated climate are evaluated using the European Centre for Medium-Range Weather Forecasting (ECMWF) ERA-Interim reanalysis data set. This reanalysis product has a resolution of approximately three-quarters of a degree and is based on the assimilation of various observation data sets, including satellite-based measurements, to build a consistent interpretation of the state of the atmosphere at that time. The ECMWF atmospheric model is used to address gaps in the observations when constructing the reanalysis data set. A new ERA-5 data set is being released by ECMWF that will replace ERA-Interim but this was not available at the time the CCAM simulations were conducted. Another data set is the Bureau of Meteorology Atmospheric Regional Reanalysis for Australia (BARRA) which is a regional reanalysis that assimilates observations into the ACCESS weather forecasting model and employs the model to fill in gaps in the observing network. However, we have not conducted an extensive evaluation using BARRA because at the time of writing the data set was incomplete with reduced number of simulation years and the final version of the data set had not been published. Nevertheless, we do comment on features represented by BARRA when relevant to the model evaluation.

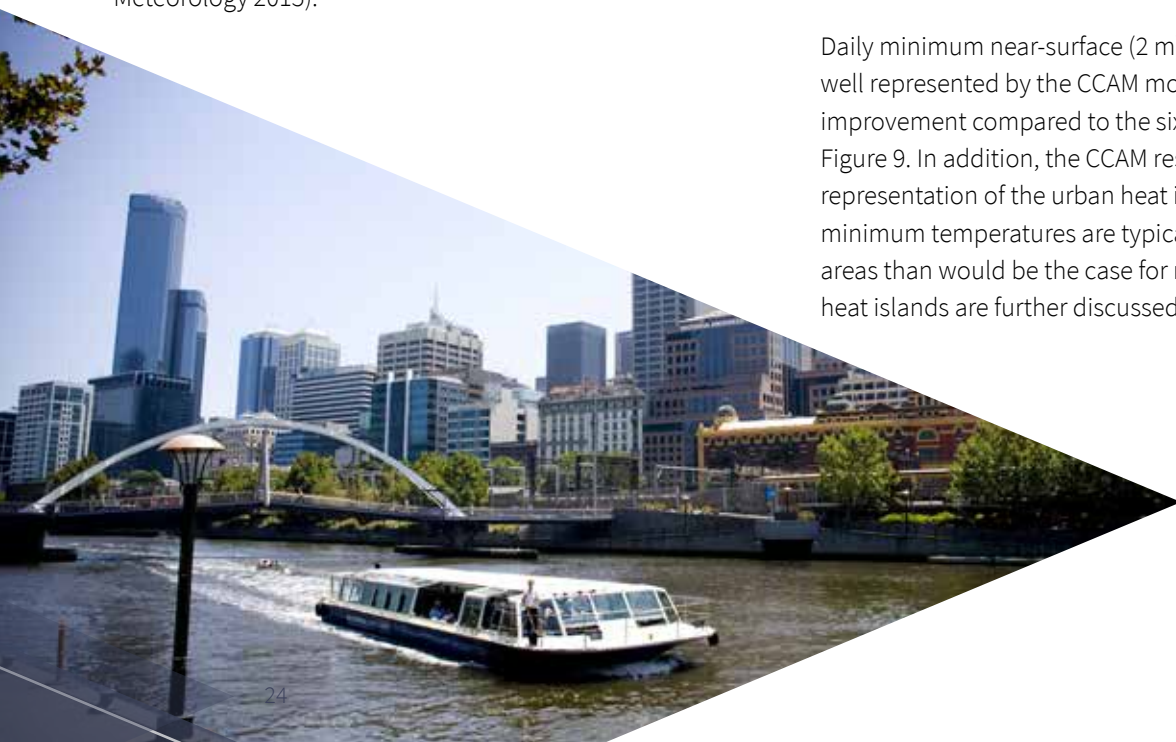
As stated previously, the regional climate model output should be used in combination with the global climate model output. The following analysis compares the downscaled results with the global climate model results as appropriate. Additional information regarding the evaluation of global climate models can also be found in Chapter 5 of the CCIA technical report (CSIRO and Bureau of Meteorology 2015).

#### 4.2.1 Temperature

The results for the daily maximum near-surface (2 m) air temperature (Figure 8) and the daily minimum near-surface (2 m) air temperature (Figure 9) show some of the improvements, as well as some limitations with the downscaled simulations compared to the global climate model results. Note that the AWAP data is based on land-based weather station measurements and can be less reliable over the ocean where the data is interpolated. A bias plot for the daily minimum and maximum temperatures can also be seen in the appendix of this report.

Daily maximum temperature results for CCAM show an improved representation of spatial detail, particularly when representing mountain ranges and, to a lesser extent, coastlines. However, there is also a simulated warm bias (i.e. CCAM compared to AWAP) of several degrees along the east coast of Victoria. This warm bias seems to correspond to forested regions with high vegetation, which may be related to a mismatch between CCAM's calculation of air temperature within the canopy and the observations which are made in clearings. Further investigation is needed to categorically identify the source of the bias in the maximum near-surface (2 m) air temperature. The projected changes in temperature under global warming discussed in Chapter 5 do not appear to be sensitive to the location of these biases, which suggests that the temperature bias does not directly affect the projected changes in temperature. Although all climate models have biases (e.g. see the discussion of minimum temperature below), it appears possible that the problem with the temperature bias could be reliably addressed in a post-processing procedure. If this is the case, then an updated temperature data set will be generated once the problem has been corrected.

Daily minimum near-surface (2 m) air temperatures are well represented by the CCAM model, which shows an improvement compared to the six host GCMs shown in Figure 9. In addition, the CCAM results show a realistic representation of the urban heat island, where daily minimum temperatures are typically 1°C warmer for urban areas than would be the case for natural vegetation. Urban heat islands are further discussed in section 4.2.2.





Seasonal mean tasmax for AWAP, CCAM, and GCMs

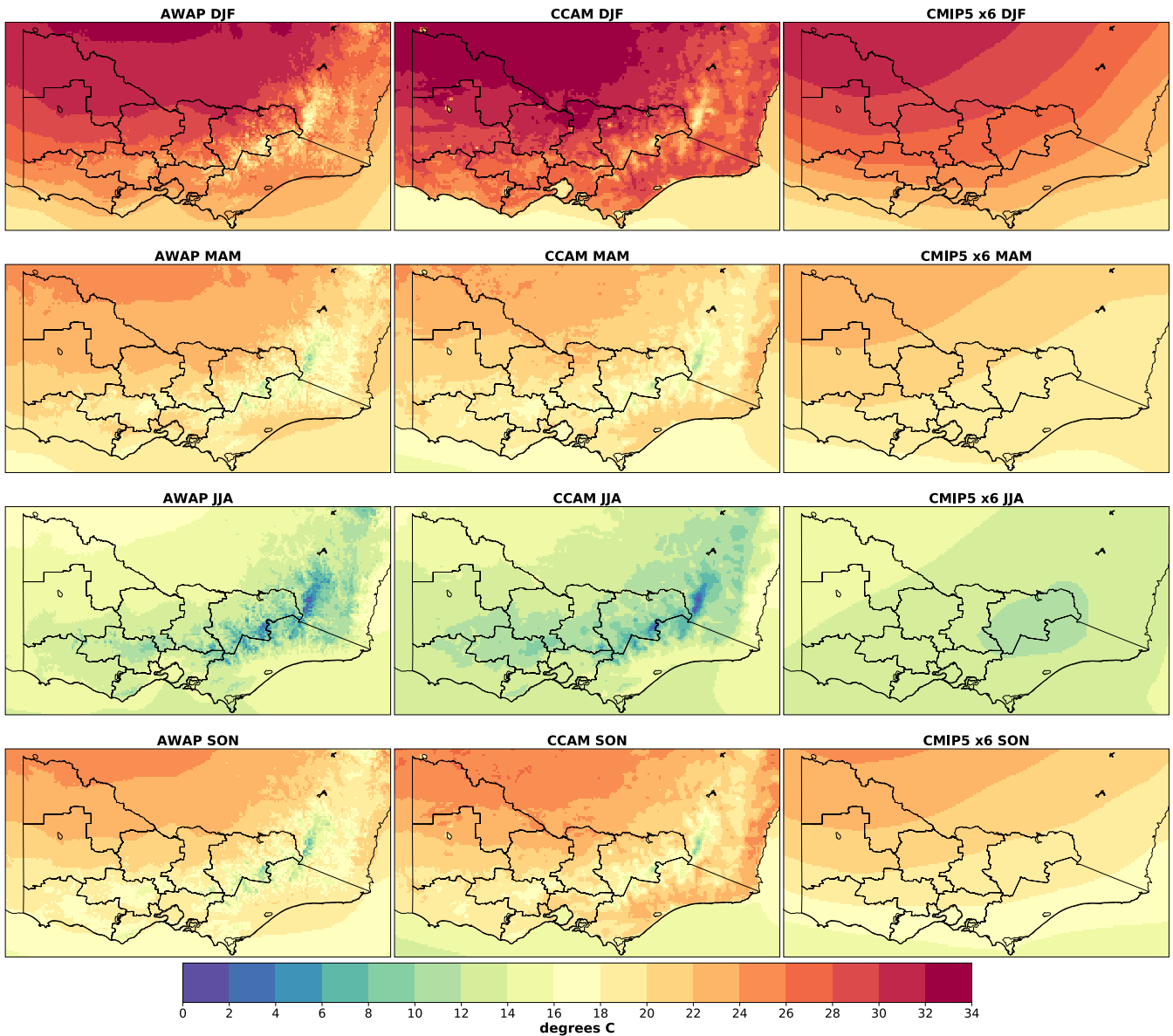


Figure 8. Average daily maximum near-surface (2 m) air temperature ( $^{\circ}\text{C}$ ) from the CCAM 5 km resolution simulations for Victoria for 1986–2005. The left column is the observed climate from the AWAP 5 km gridded climate data set, the middle column is the mean of six CCAM simulations, and the right column is the mean of the six host GCMs. Top row is December to February (DJF), the second row is March to May (MAM), the third row is June to August (JJA) and the fourth row is September to November (SON).

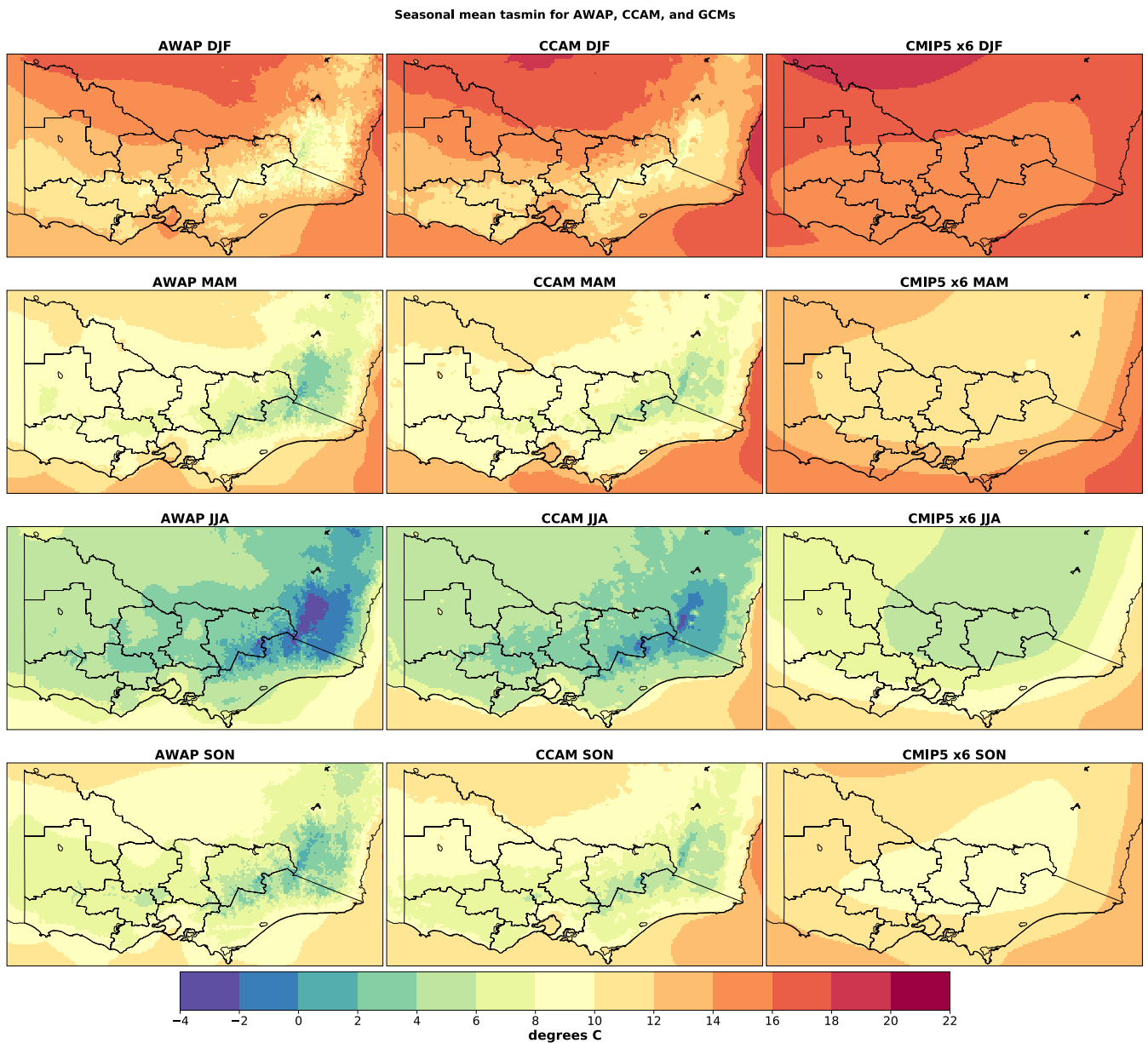


Figure 9. As for Figure 8, but showing average daily minimum near-surface (2 m) air temperature (°C)

### 4.2.2 Urban heat island

One of the potential advantages of using a regional climate model like CCAM is to better represent urban areas that are neither resolved nor parameterised in the host global climate models. The ability of a climate model to simulate urban areas in a realistic way can be assessed by its ability to model the urban heat island (UHI). The UHI refers to the increased daily minimum near-surface (2 m) air temperature in urban areas due to the storage of heat in buildings and roads. Most major Australian cities have an UHI of +1°C to +2°C, depending on the nature of the local built environment. The size of the UHI is usually estimated by comparing measurements of daily minimum temperature from the fringe of the city with that at the city centre, inferring the enhanced warming in daily minimum temperature due to the presence of the city. Although there are other factors which can influence the temperature difference, such as elevation and rainfall, the presence of the urban area is the main factor in determining the difference in daily minimum temperature.

The UHI is estimated by comparing inner-city temperature measurements to the temperatures measured at sites on the fringe of the city. The difference in daily minimum temperature is compared between the inner-city weather station and the outer-city site that approximates the natural vegetation. An example of this approach is shown in Figure 10, where we use the BOM regional office as an inner-city site indicated as a red dot. This inner-city site is then compared to three surrounding sites indicated by Laverton RAAF (blue dot), Coldstream (green dot) and Cranbourne Botanic Gardens (yellow dot). By comparing the differences in these temperatures between each of the three outer-city sites against the BOM regional office, we can estimate the temperature gradient arising due to the presence of the Melbourne urban area.

A comparison of the observations between the inner-city site and the three outer city sites is shown in Figure 11, between observations at weather stations, the simulated climate from CCAM and the simulated climate from the GCMs. This was done by calculating the difference in daily minimum temperature between the inner-city site and the three outer city sites for each day between 1986 and 2005. This difference in minimum temperatures is averaged over time and then shown in Figure 11. The blue bars indicate observed UHI of approximately 2°C warmer between the inner city and Laverton, over 4°C warmer between the inner city and Coldstream, as well as a 2°C difference between the inner city and Cranbourne. We note that the red bars show the CCAM results after downscaling the GCMs, indicating that CCAM correctly simulates the difference in daily minimum temperature between the inner city and Laverton, as well as

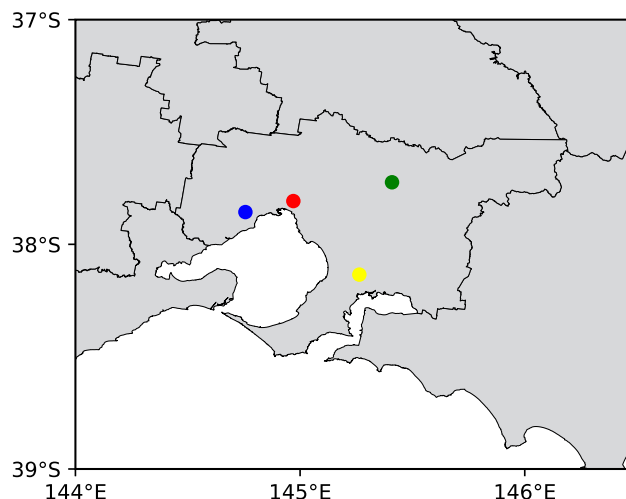


Figure 10. Plot of the locations used to estimate the urban heat island for Melbourne. Dots indicate the location of BOM weather stations: BOM Melbourne Regional Office (red), Laverton RAAF (blue), Coldstream (green) and Cranbourne Botanic Gardens (yellow).

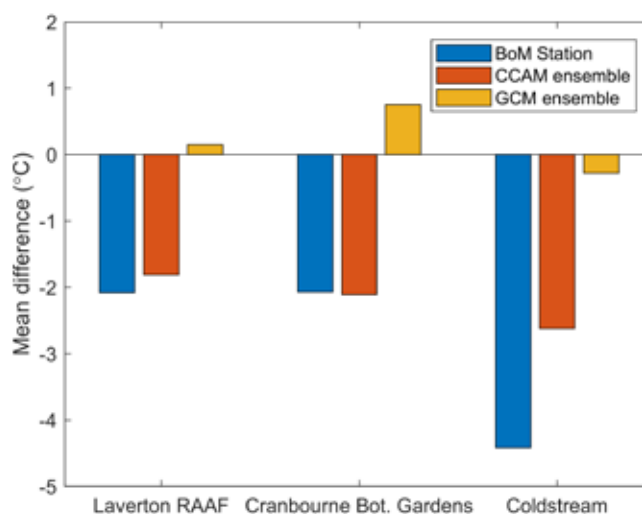


Figure 11. Estimated urban heat island (UHI) averaged over the time period 1986–2005. The UHI is measured as the difference in temperature between the inner-city BOM regional office weather station compared to the three outer-city sites of Laverton RAAF, Coldstream and Cranbourne Botanic Gardens (blue bars). Since the inner-city site is warmer than the outer-city sites due to urban development, we see a negative value for the difference in this plot. The observed data is shown as blue bars and can be compared to the CCAM simulation results (red bars) and the host GCM (orange bars). The results represent the average of the six CCAM simulations and the average of the corresponding six host GCMs that were downscaled by CCAM.

the difference between the inner city and Cranbourne. This is partially a consequence of the UCLEM urban parameterisation (see section 2.2) which represents urban areas in the simulation. CCAM underestimates the difference in minimum temperature between the inner city and Coldstream by effectively overestimating the minimum temperature at Coldstream, resulting in a smaller gradient in temperature between the inner city and Coldstream than was observed. In the case of the GCMs where the temperature data must be interpolated for the locations of the weather stations, the urban area is not resolved and not necessarily parameterised by the climate model (shown as orange bars). Consequently, it is difficult for GCMs to represent the temperature gradient between the inner-city site and the three surrounding outer-city sites. Overall, CCAM simulations show a substantially improved representation of the UHI than the host GCM.

### 4.2.3 Average rainfall

Climate models simulate precipitation, including rain and snow since the precipitation falls as snow when temperature and other atmospheric conditions are conducive. However, throughout this report precipitation is referred to as rainfall, only mentioning snow when relevant (e.g. section 5.3.4).

Spatial and seasonal characteristics of rainfall are particularly difficult for climate models to accurately represent. Notwithstanding, dynamical regional climate models have the potential to improve GCM simulations of rainfall. In part, this is due to better representation of topography such as mountain ranges and coastlines. Seasonal rainfall simulations from CCAM and GCMs compared to observations are shown in Figure 12. A bias plot for average rainfall can also be seen in the appendix to this report.

It is clear from Figure 12 that CCAM better represents rainfall along the Australian Alps compared to the host GCMs. This is due to better representation of the orography of the mountain range. In particular, the CCAM simulations show a rain shadow on the eastern slopes of the Alps, with corresponding enhanced rainfall on the western slopes. There is a tendency to show heavier rainfall over the mountains compared to the AWAP observations. However, AWAP is also known to underestimate daily extremes to some extent due to the lower network density in some alpine regions (Jones et al. 2009). Comparison with the preliminary results from the BARRA reanalysis data sets (not shown) also indicates higher rainfall in the alpine region, when compared to AWAP. Notwithstanding, the CCAM simulated extreme rainfall appears to be higher than the observed rainfall which is partly a limitation of the CCAM cloud microphysics parameterisations. In any event, the representation of rainfall is an improvement on the GCM simulations. This is meaningful for the projected rainfall change discussed in section 5.3. An interesting result shown in Figure 12 is that the larger-scale rainfall in the CCAM simulations is similar to that in the GCMs, but has additional detail for mountains and coastlines that was not represented in the GCM (explored further in section 5.3). This result can be explained by some of the similarities between the cloud microphysics parameterisations in CCAM and the host GCMs. We note that both CCAM and the host GCMs are slightly wetter over Victoria than the observed as depicted in the AWAP data set. For example, the CCAM and GCM simulations never show any regions where the seasonal average rainfall is less than 1 mm/day, although the AWAP observations show this occurs in the northwest part of the state.



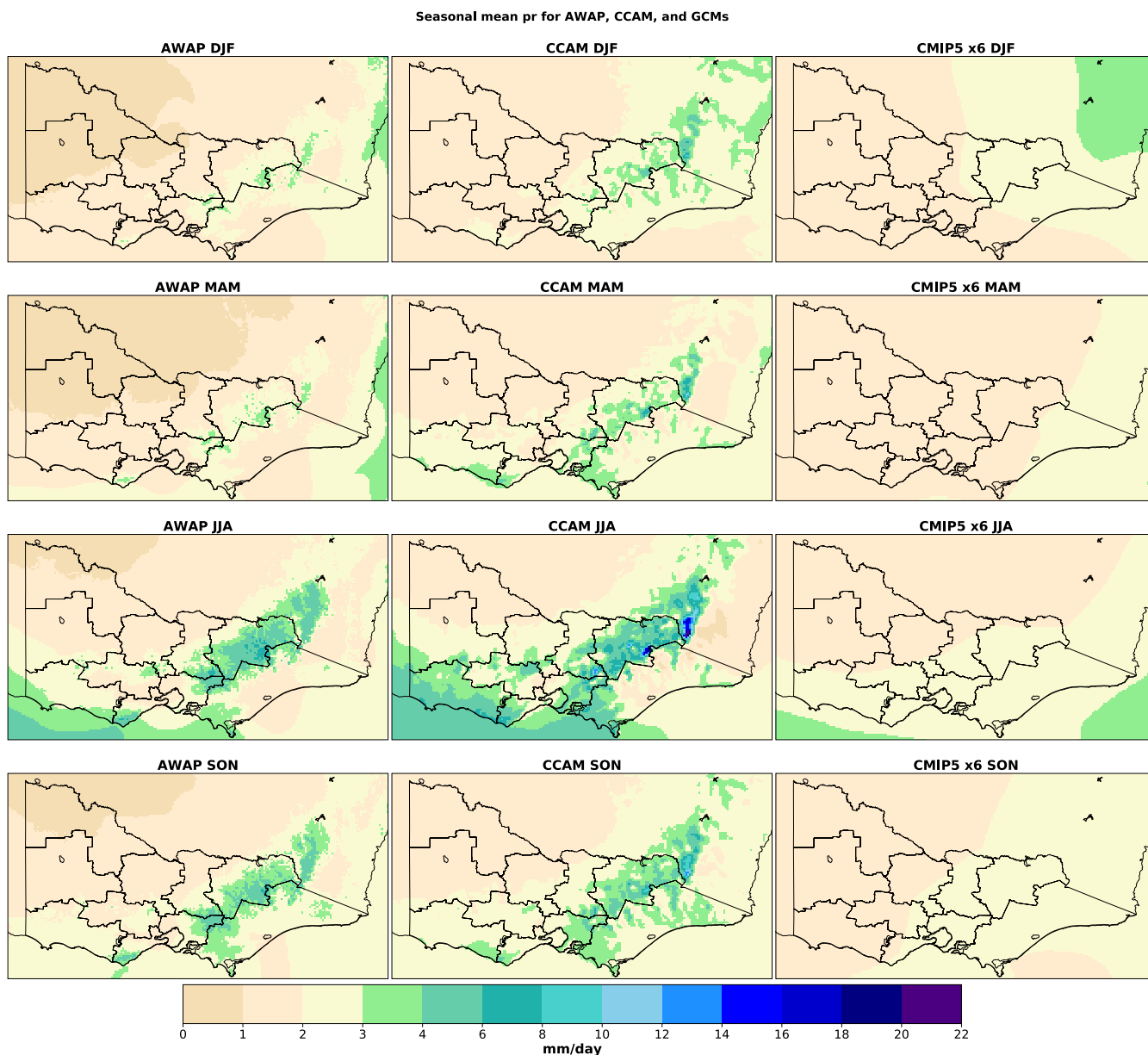


Figure 12. Annual and seasonal mean rainfall for 1986–2005 in the AWAP 5 km gridded climate data set, the mean of six CCAM 5 km simulations, and the mean of the six host GCMs. Top row is December to February (DJF), the second row is March to May (MAM), the third row is June to August (JJA) and the fourth row is September to November (SON).

#### 4.2.4 Extreme rainfall

Extreme rainfall is a key area in which a regional climate model like CCAM has the potential to add important new information not provided by GCMs.

There are several different ways to characterise extreme rainfall, depending on the severity of the event. For simplicity, the 99th percentile of the 1986–2005 rainfall is used as an indicator of how extreme rainfall is simulated by CCAM and by the GCMs. Figure 13 shows the results of

CCAM and the GCMs compared to observations (AWAP) for the 99th percentile of 1986–2005 rainfall. AWAP shows that the largest values for the 99th percentile of rainfall occur over the Australian Alps and the eastern coast of Victoria. This result is reflected in the CCAM downscaled simulations, although the values of rainfall are larger for the CCAM simulations compared to AWAP over the mountain ranges. It is probable that CCAM is overestimating these rainfall events; however, AWAP is known to underestimate extremes (Jones et al. 2009). Nevertheless, the CCAM simulations

still have a noticeably better representation of the 99th percentile rainfall compared to the host GCM. The GCMs do not reproduce the higher 99th percentile rainfall values over the Australian Alps. The GCMs also fail to reproduce the higher 99th percentile rainfall values for the eastern coast. The difference in the CCAM and GCM results can be partially explained by the unresolved mountain ranges in

the GCM, as well as the GCMs relying on their respective convective parameterisations. The extreme rainfall is also better resolved in the downscaled simulations. Although the CCAM simulations are not perfect in their ability to represent extreme rainfall, this is an example where the downscaled simulations have been able to add value compared to the existing GCM data.

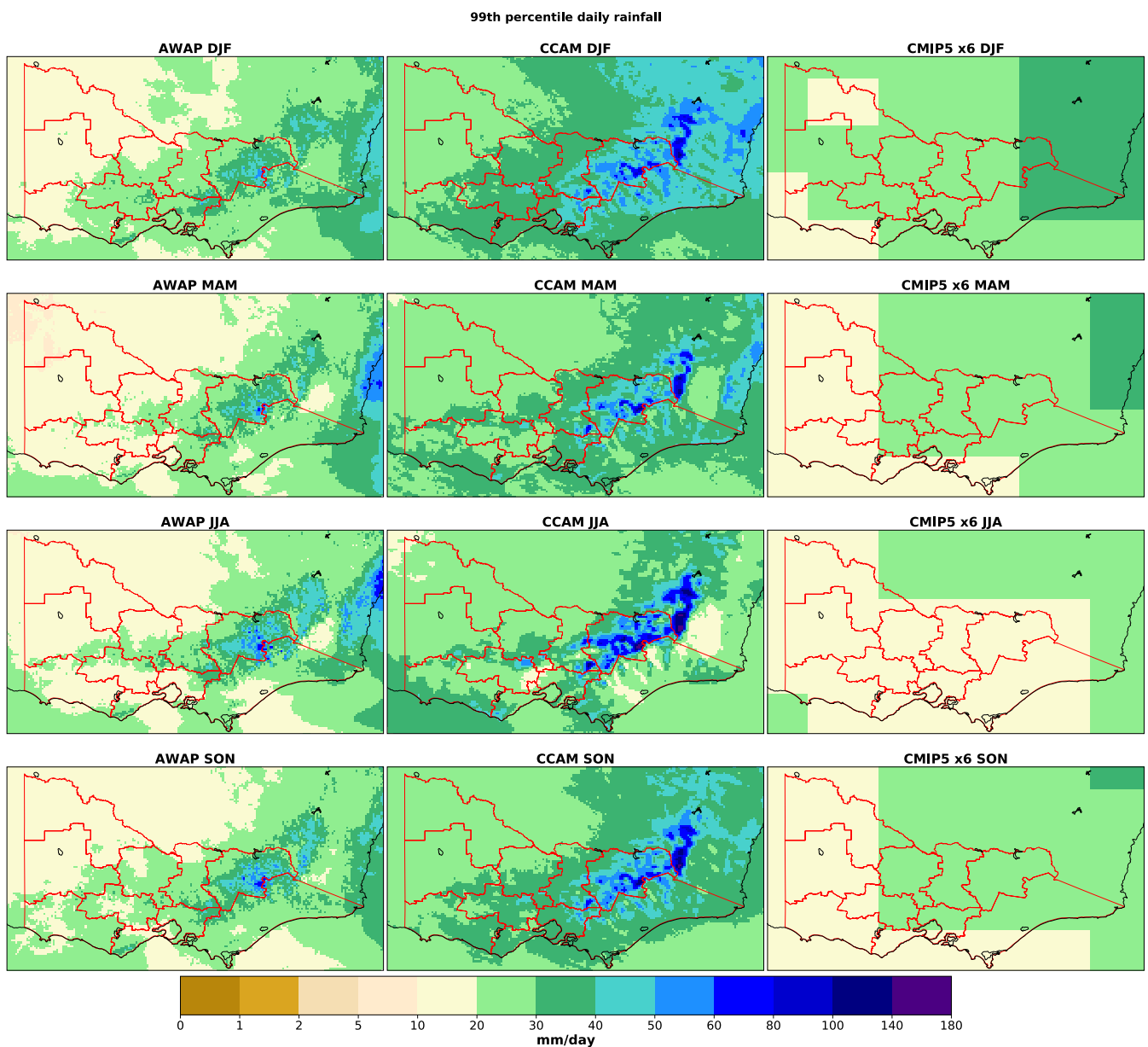


Figure 13. Extreme daily rainfall (99th percentile) for 1986–2005 from the CCAM higher-resolution simulations for Victoria. The left column is the observed climate from the AWAP 5 km gridded climate data set, the middle column is the mean of six CCAM 5 km simulations, and the right column is the mean of the six host GCMs. Top row is December to February (DJF), the second row is March to May (MAM), the third row is June to August (JJA) and the fourth row is September to November (SON).

### 4.2.5 Mean sea-level pressure

Evaluating the simulated mean sea-level pressure (MSLP) can provide an insight into a climate model’s ability to represent the mean circulation. This can often indicate larger-scale issues with the simulation. This is important in the case of the CCAM simulations shown in this report, since CCAM employs the corrected sea surface temperatures (SSTs) from the host GCM (section 2.2). As a result, the simulated MSLP is not constrained by the host GCM and can deviate from the changes projected by the host GCM.

Figure 14 compares the MSLP results from ERA-Interim reanalyses, CCAM 50 km simulations and the host GCMs. As discussed in section 2.2, the CCAM 50 km simulations constrain the larger scale behaviour that is downscaled by the CCAM 5 km simulations and therefore influences the projections of the CCAM 5 km experiments. In this case the ERA-Interim reanalyses are a reasonable representation of the observed MSLP due to the reanalysis simulation being constrained by observations. The 50 km CCAM results are shown because they represent the larger-scale atmospheric circulation that is subsequently downscaled

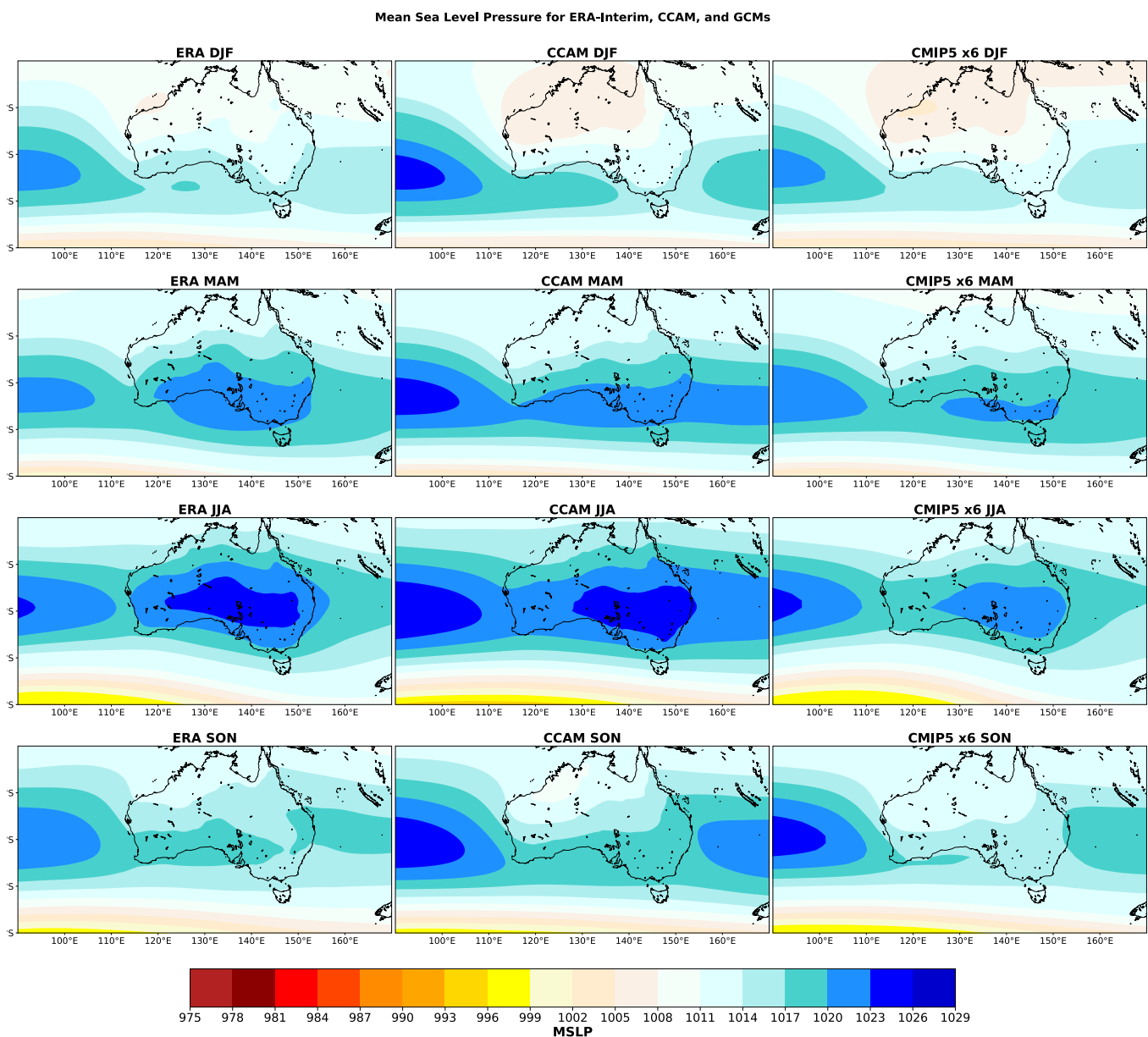


Figure 14. Average mean seasonal sea-level pressure for 1986–2005 in left: the ERA interim reanalysis (ERA); middle: the CCAM simulation averaged over the six downscaled GCMs; and right: average of the six host GCMs. Top row is December to February (DJF), the second row is March to May (MAM), the third row is June to August (JJA) and the fourth row is September to November (SON).

to 5 km resolution over Victoria. When compared to the ERA-Interim reanalyses, the CCAM results for MSLP are too zonal (east-west), with a stronger east-west component, weaker ridges and trough compared to observations. This is most noticeable in autumn (MAM) and winter (JJA) and is one possible cause of the model simulating too much rainfall in autumn. A stronger ridge to the east of Australia is also present in all seasons. In comparison, the GCM host models perform better than CCAM with respect to the simulated MSLP, since the zonal problem is less evident. The differences between the CCAM 50 km and GCMs arise because of the SST bias correction which required the global atmospheric circulation to be reconstructed consistent with the corrected SSTs (see section 2.2). The zonal problem with the CCAM MSLP can influence the dynamical response of the atmosphere under climate change, such as modifying the large-scale winds or large-scale changes to rainfall. This is taken into consideration in the interpretation of the projected changes presented in Chapter 5, and highlights the importance of being mindful of both CCAM and GCM results when looking at projections. This example illustrates some of the issues with using a single modelling system, as the large-scale features in the downscaled CCAM results may be reflective of CCAM as a single modelling system. However, when combined with other downscaling results (e.g. VicCI) and with GCM projections, a more comprehensive projection of the regional climate can be made.

#### 4.2.6 Upper-level wind speed and direction at 850 hPa

Figure 15 shows the average wind speed and average wind vectors at 850 hPa (approximately 1 to 1.5 km above the surface) from ERA-interim, the CCAM 50 km resolution simulations and the six host GCMs interpolated to a common 1.5 x 1.5° lat/lon grid. ERA-Interim is a reasonably accurate depiction on the 850 hPa winds as it is constrained by observations. There is broad agreement among the reanalysis, CCAM and the host GCMs in terms of wind speed and direction for all seasons. However, the CCAM 850 hPa winds are too strong over Victoria in winter. This result is consistent with the mean sea-level pressure being too zonal as described in the section 4.2.5. The implications of this issue with the CCAM simulations are discussed when comparing the results to other models in Chapter 5.

#### 4.2.7 Summary of CCAM evaluation

A common rule of thumb for using climate models is that the better they simulate the current climate then the greater the confidence in the future climate change simulation. Any difference between the modelled current climate and the observed current climate, known as bias, inevitably lowers confidence. However, the question of how much bias is acceptable is in fact complex and depends on the purpose of the model. An evaluation of CCAM downscaling found that it can contribute to the development of regional projections, although there are some deficiencies. The dynamical downscaling successfully captures regional influences on average temperature and rainfall. There is a temperature bias in the daily maximum temperature for eastern Victoria (e.g. Figure 8) which is being addressed by the CCAM developers. This bias is likely to represent an imperfection in how a particular feature of the climate is parameterised in the model, so lowers the confidence in temperature projections to some extent. However, the bias is smaller than many biases in GCMs, and the projected regional changes in temperature do not seem to be spatially correlated with this bias, suggesting the bias does not have a direct effect on the projection of temperature change. Therefore, the temperature results are presented with at least equal confidence as GCM projections.

The urban heat island is noticeably better represented in the CCAM output. Extreme rainfall is much better represented by the dynamical downscaling compared to the GCMs and should add value to the regional projections. Large-scale behaviour of the simulated climate in CCAM is plausible, but has some differences compared to the six host GCMs. Consequently, we should consider changes in the large-scale rainfall may differ from the predictions of the host CMIP5 GCMs. This result emphasises the importance of using the CCAM dynamically downscaled projections of large-scale temperature and rainfall change in conjunction with the GCM output until we have a compelling case to prefer one over the other.



850hPa winds

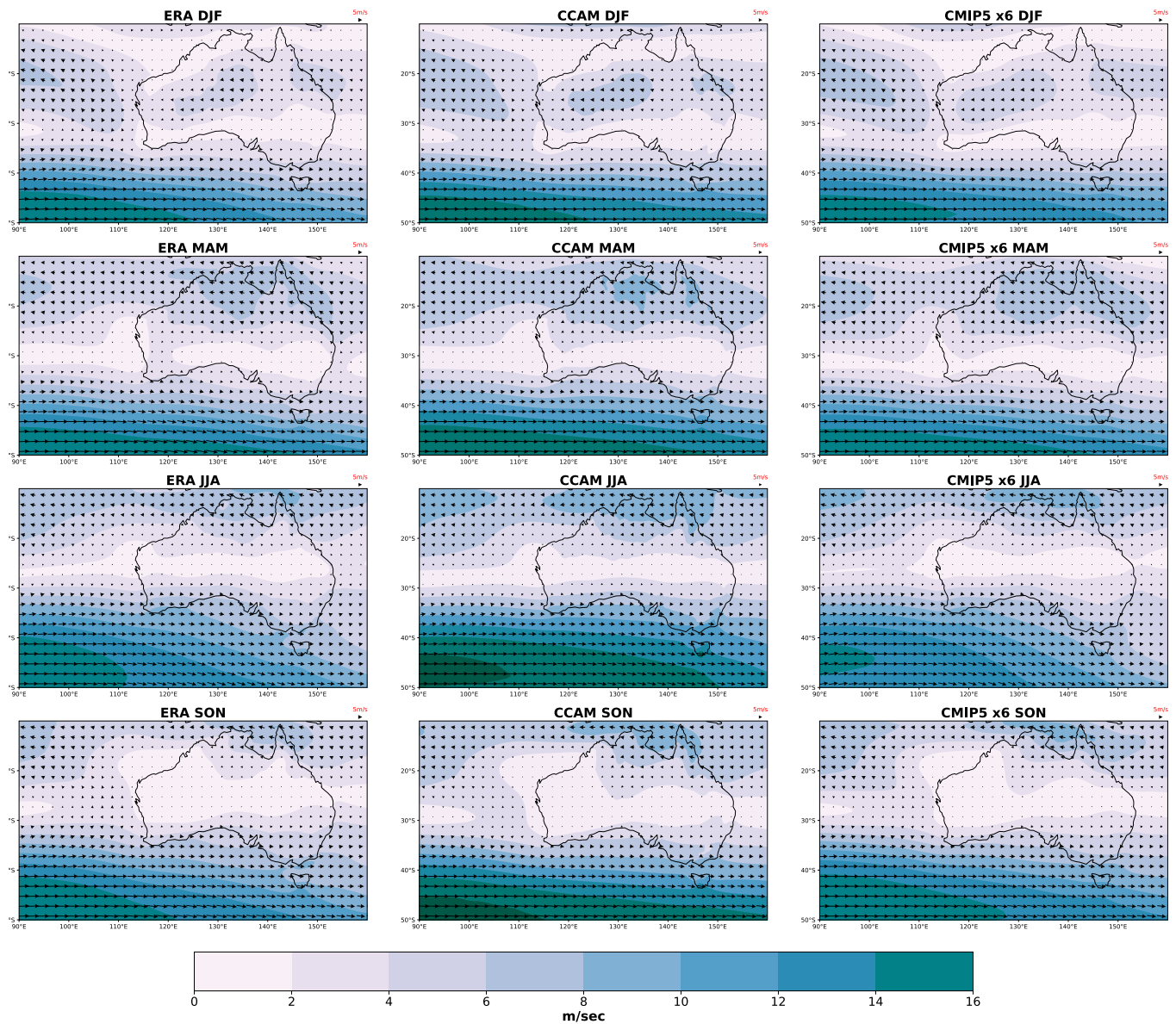


Figure 15. Average wind speed and average wind vectors at 850 hPa (approximately 1 to 1.5 km above the surface) from 1986–2005 for the different seasons, where the speed and direction are shown as vector arrows and the speed is also shown by the colour scale. Left shows ERA-Interim reanalysis (ERA), middle shows CCAM 50 km simulations averaged over the six downscaled GCMs, and right shows the average of the six host GCMs. Top row is December to February (DJF), the second row is March to May (MAM), the third row is June to August (JJA) and the fourth row is September to November (SON).

## 5. Victoria's changing climate

This chapter lays out the observed past changes and projected future changes in many climate variables, including temperature, rainfall, temperature and rainfall extremes, wind and sea level. The chapter reports on the new high-resolution VCP19 climate projections but presents this alongside previous data sources including VicCI. New insights from the high-resolution regional climate modelling, including an enhanced drying over mountain slopes and hotter maximum warming projections are highlighted.

When interpreting climate simulations, it should be noted that projected change can be understood in the three dimensions of climate projections: internal variability, emissions scenario and climate model response. There will be ongoing climate variability through this century, at scales from seconds to decades and beyond. The other two dimensions become progressively more important through time. In this chapter the projected changes in the climate averages and the average incidence of certain climate extremes are described, focused on two main emissions scenarios and four future time periods. The nature of the climate shifts is illustrated by giving the change under a high emission scenario for a far future timeframe.

Changes to the climate have far-reaching and important impacts and present some opportunities. This chapter covers the changes in the averages and extremes of some common climate variables including temperature, rainfall, wind and fire weather. The projections do not explore the impact these changes have, including the social, economic and environmental dimensions.

### 5.1 Climate features and drivers

Human effects such as an enhanced greenhouse effect leading to climate change is projected to drive 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 or timing of the major modes of climate variability may also occur (see Chapter 3). These changes would affect the climate of Victoria in terms of averages, variability and extremes.

Some changes are clearer than others, and the most confident projections are those linked directly to the change in greenhouse gases in the atmosphere, and the warming effect this has. However, a major projection with important implications for Victoria is a weakening and/or southerly movement of the westerly circulation and associated

weather systems. Examples of this include the subtropical jet, the instability in the atmosphere that leads to the growth of weather systems, and the strength and location of the track where weather systems occur in the subtropical jet region. A reduction of blocking events and the movement of the peak of blocking further east away from Australia in winter are also projected. There is a range of projected change in these features, and there is some evidence that the projected change in these features leading to little change in rainfall is less plausible than that leading to a significant rainfall reduction (Grose et al. 2017a; Grose et al. 2019a), and with further evidence we may be able to confidently give a narrower range of plausible change and rule out the wetter end but at the moment the entire range should be considered plausible.

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 is expected to drive an enhanced rainfall reduction on the inland slopes of the Alps (see section 5.3; and Grose et al. 2019b). Further analysis of drivers important to climate change in Victoria are covered in Chapter 3, and in VicCI outputs.

### 5.2 Temperatures

#### 5.2.1 Observed

Mean annual temperature has risen in Victoria in recent decades (Figure 16). The Bureau of Meteorology's official temperature trend data set, ACORN-SATv2 (Trewin 2013), shows the rate of increase is 0.1°C/decade between 1910 and 2018, resulting in an increase of just over 1°C in that period (the exact value is 1.2°C but there is some observed uncertainty around this exact number). There have been many more warm years than cool years in recent decades, and the last year with below-average temperature (using the 1961–1990 baseline) was 1996 (Figure 16). This change is similar to the Australian and global averages of a little over 1°C (Bureau of Meteorology and CSIRO 2019).

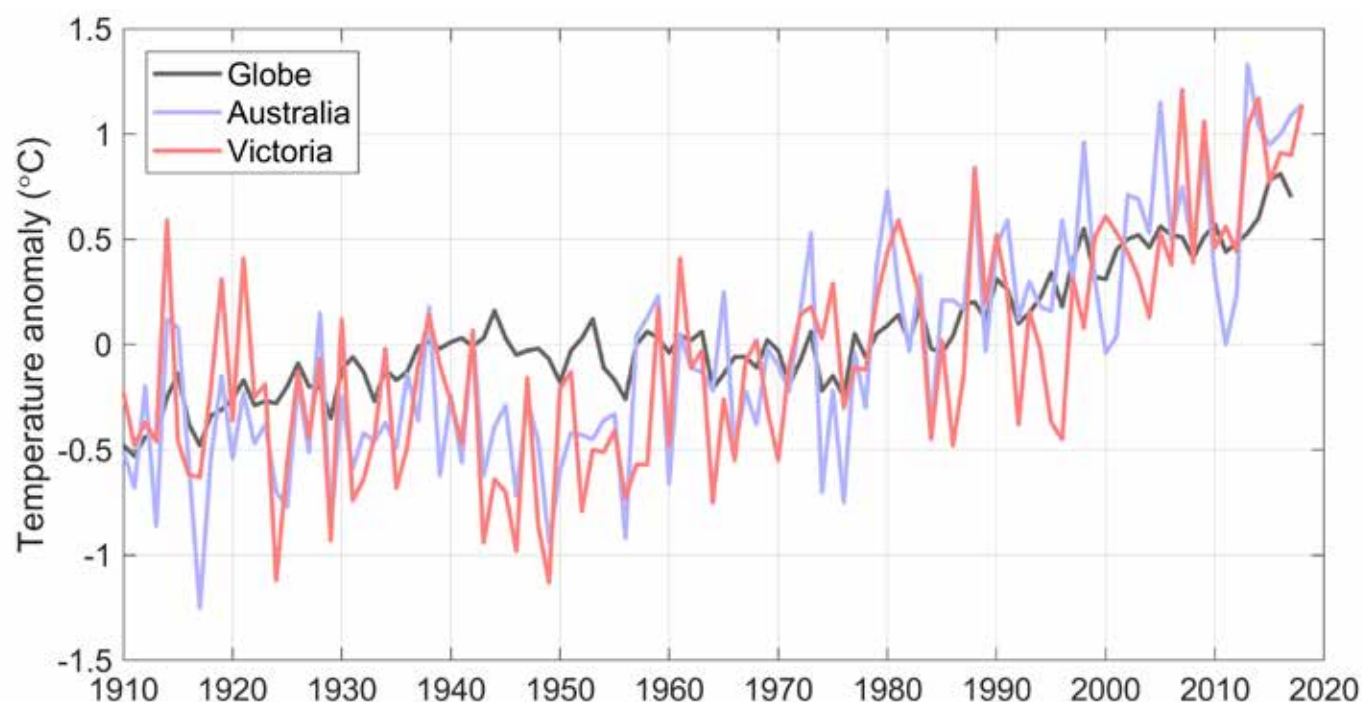


Figure 16. Annual temperature anomaly from the 1961–1990 average for the globe (HadCRUT4 data set), Australia and Victoria (ACORN-SATv2 data set)

The rate of temperature change across Victoria has accelerated in recent decades to  $0.2^{\circ}\text{C}/\text{decade}$  in the period 1950–2018 (Figure 17), at least partly due an acceleration of the enhanced greenhouse effect due to human emissions, but also with a contribution from natural variability. The baseline period used in this report is 1986–2005 (i.e. 20 years, centred on 1995). The warming prior to this was  $0.06^{\circ}\text{C}/\text{decade}$  between 1910 and 1995 (a total increase of  $0.5^{\circ}\text{C}$ ). In the most recent 20 years from 1999 to 2018, the rate of warming was  $0.32^{\circ}\text{C}/\text{decade}$  (solid red line in Figure 17), however the period is too short to be considered a reliable quantification of climate change trend, since variability plays a large role.

The global gridded temperature data sets closely match the changes seen in ACORN-SATv2 in the period since 1910, for example, GISTEM ERSSTv5 (GISTEMP\_Team 2019) and Berkeley (Rohde et al. 2013) indicate  $0.1^{\circ}\text{C}/\text{decade}$  since 1910. These data sets extend before 1910 using interpolation and statistical gap-filling to produce spatial and temporal coverage of this period using very sparse inputs. Therefore, because data prior to 1910 are considerably more limited, changes are more uncertain. The global gridded temperature data sets differ in the patterns of variability and change in the period 1850–1910 (Figure 18). Nonetheless, they broadly agree on some aspects of variability, such as relatively cooler periods in 1850–1870 and 1900–1910, and a relatively warm period in 1880–1900 but still with relatively few years above the 1961–1990 baseline mean.

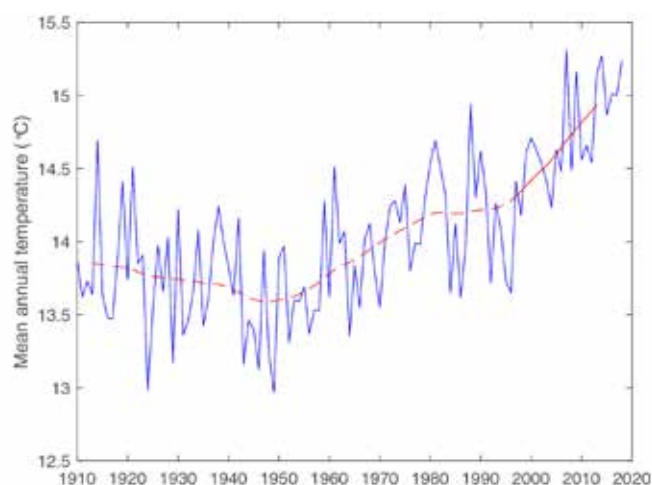


Figure 17. Mean annual temperature of Victoria with an 11-year running average shown in dashed red (the linear trend in the 20 years of 1999–2018 shown as a solid line).



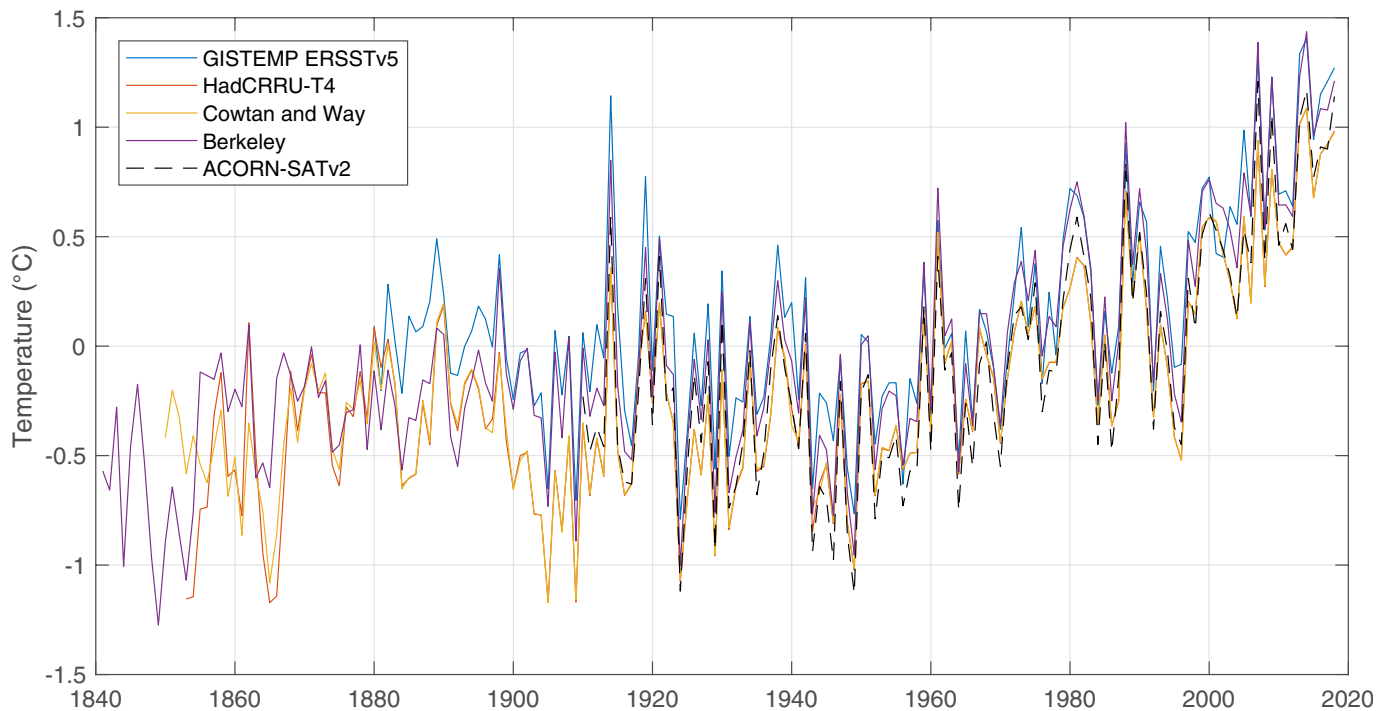


Figure 18. Mean temperature anomaly from 1961–1990 in Victoria in various gridded climate data sets: ACORN-SATv2 (dashed line), showing similar variability and very similar trends as the global temperature data sets kept internationally (GISTEMP, HadCRUT4, Cowtan and Way infilled HadCRUT4, Berkeley). Note that the global gridded data sets are generally on a coarse spatial grid, so Victorian temperature is often derived from a small number of grid cells, explaining some differences in the values for year-to-year variability. Also note there are much larger uncertainties prior to 1910, so the series presented here should be viewed with lower confidence.

### 5.2.2 Near-term temperature change (current to 2030)

The effect of all emissions scenarios is similar by 2030, so they are examined together. Under all plausible scenarios of greenhouse gas emissions (that is, scenarios ranging from ongoing high greenhouse gas emissions through to ambitious mitigation that could mean the world meets the Paris Agreement targets), the projected change in mean annual temperature between 1986–2005 and 2020–2039 is 0.5 to 1.3°C which is broadly consistent in both the CMIP5 global climate models and the VCP19 high-resolution simulations.

As shown in Figure 19 (and conceptually in Figure 4), these projected change values are the difference between the 20-year period 1986–2005 (centred on 1995) and the period 2020–2039 (centred on 2030). Using the recent trend found above (0.32°C/decade) as a guide, we are currently tracking within this projected range at the higher end but change over the relatively short period 1995–2018 is affected by natural variability and is not expected to stay constant until 2030. While the effect of a warming climate is persistently increasing the odds of hotter years and a positive (increasing)

trend in temperature in the long-term, the effect of climate variability is still very important. The temperature trend for 2019–2030 will be influenced by processes of climate variability from year to year and decade to decade (such as the El Niño Southern Oscillation and related processes in the Pacific Ocean). Importantly, not every year will be warmer than the last, and natural variability could create a negligible or even negative trend over this shorter-term timeframe of 11 years, or conversely there could be periods of warming at a greater rate than the long-term trend. Taking model simulations as a guide to the theoretical pattern of warming in Victoria due to greenhouse gases, including the full range of potential climate variability, the linear trend in temperature in 2019–2030 is -0.8 to +1.3°C (median +0.3°C). This suggests that for climate warming and the full range of natural variability, a positive trend is likely, but a negative trend is possible over this short timeframe, or a much higher rate of warming than the long-term trend. Examples of two simulations that show a cooling or rapid warming over this period are shown as a red line in Figure 20. However, this does not account for the actual variability we have had in the observed world and given that we are tracking in the upper range of projections and have not been recently in a period of warming lower than the long-term trend, the possibility of

a rapid warming appears less likely than other possibilities. The prospect of narrowing this estimate by exploiting any predictability in the climate system is known as multi-year to decadal prediction and is a current area of active research (e.g. see the UK MetOffice website for more information <https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal> and for the latest experimental forecasts done around the world: <https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long-range/wmolc-adcp>).

Ongoing warming of the climate, including the average annual temperature of Victoria is given with *very high confidence*, as there is evidence from physical theory, process understanding, acceptable model evaluation, agreement of models with past trends and model agreement. Natural variability of the climate means that this long-term warming of the system may not be clear over short timeframes at the scale of Victoria.

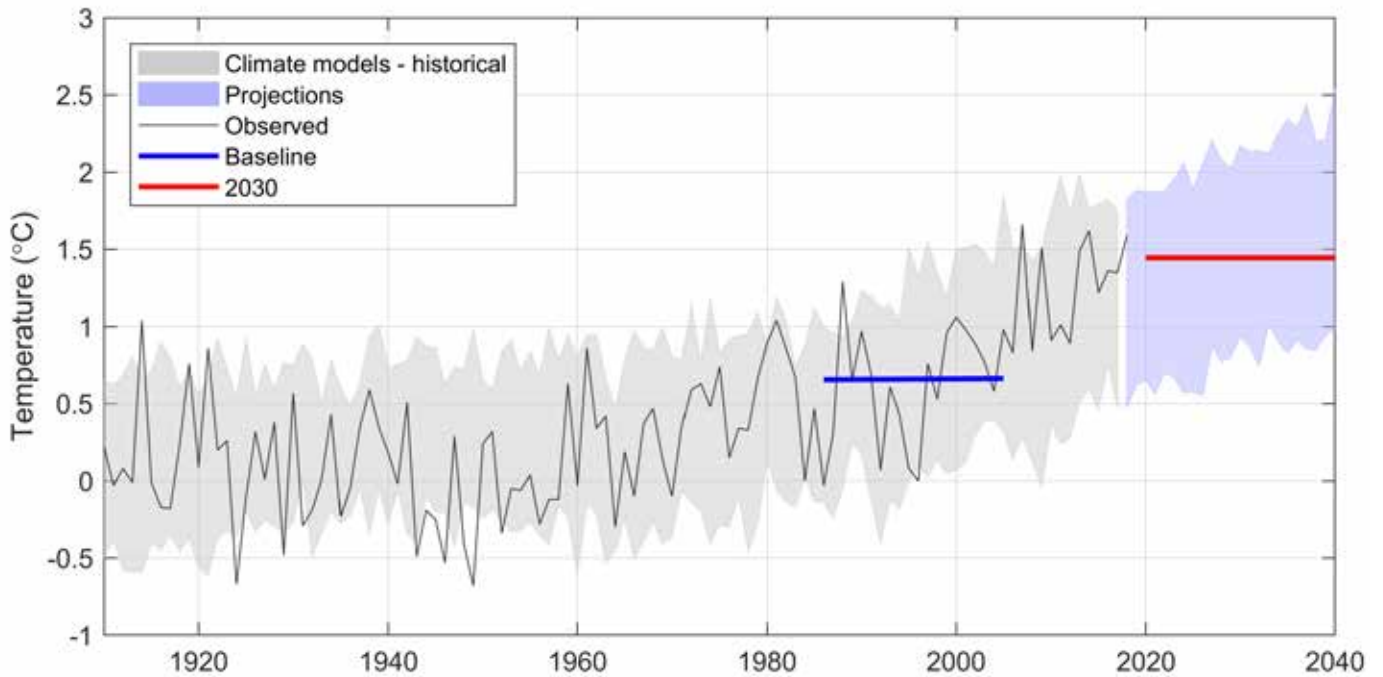


Figure 19. Victorian average annual temperature in observations and global climate model simulations relative to the pre-industrial era (all RCPs are examined together), showing the range among models. Blue and red lines show the average during the 1986–2005 baseline and 2020–2039 projected periods, respectively.

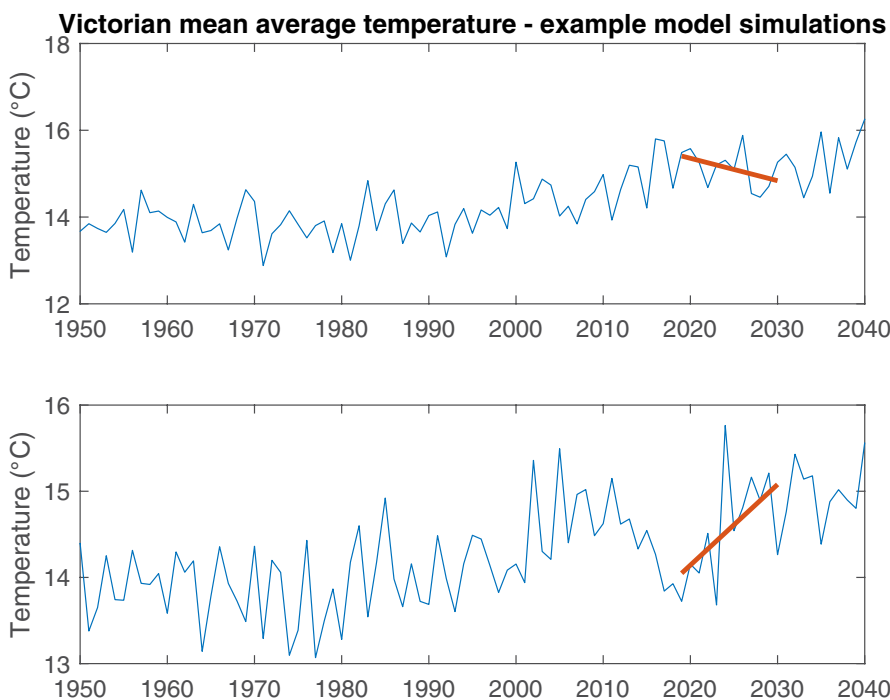


Figure 20. Example time-series from two GCM under RCP8.5 showing how a negative linear trend in temperature (red line; 2019–2030) can occur despite a warming climate, or how the warming may be more rapid than the long-term trend for this short window.

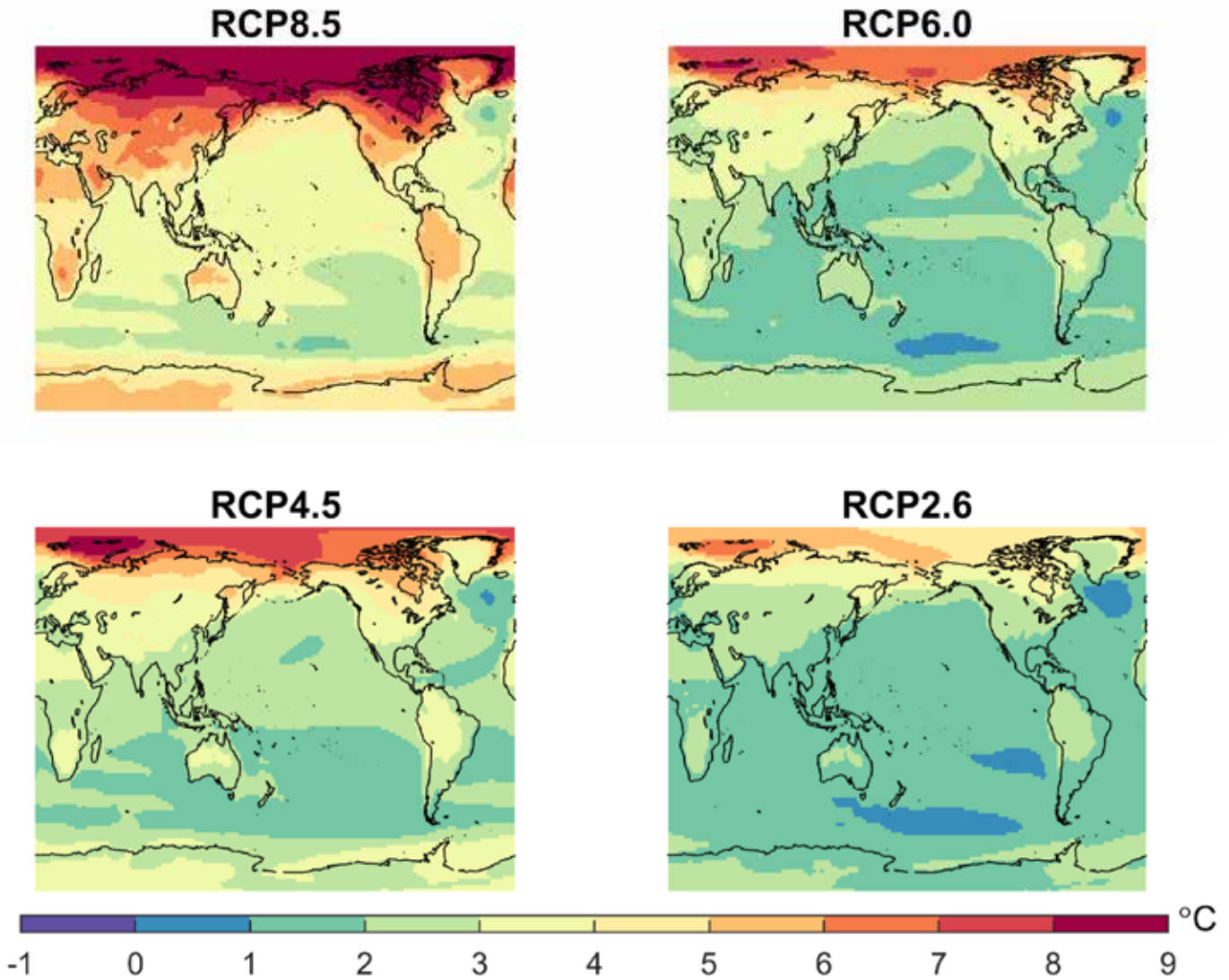


Figure 21. Model average projected change in near-surface (2 m) temperature between 1850–1900 (approximating the pre-industrial baseline) and 2080–2099 from all CMIP5 models under all four RCPs (including the two focused on in VCP19 RCP4.5 and RCP8.5).

### 5.2.3 Temperature change for this century

There are some general features of projected change in temperature that are relevant no matter which greenhouse gas emissions scenario we follow. These spatial patterns can be seen in the projected change under the two RCPs primarily used in this report, RCP4.5 and RCP8.5, as well as the other two RCPs that exist: a very low scenario RCP2.6, and a high scenario RCP6.0. The land regions are projected to warm more than the oceans, and the Arctic is a hot-spot of warming (Figure 21). The Southern Ocean and north Atlantic are areas of lower warming at this time scale. Australia is near the global average, and Victoria is also close to the global average.

The magnitude of warming later in the century depends strongly on the greenhouse gas emissions scenario the world follows. For a given emissions scenario, there is also a range of plausible changes given by the models. For Victoria as a whole, the projected temperature change between 1986 and 2005 and future periods centred on 2030, 2050 and 2070 show a growing difference between the highest RCP8.5 and the very low RCP2.6 (Figure 22). By 2080–2099, the range of change is 0.5 to 1.5°C for RCP2.6, through to 2.8 to 4.3°C under RCP8.5. These changes can be visualised as time-series (Figure 23) and bar plots (Figure 24). Both styles of plot show how the difference between RCPs grows as time progresses. The range among models (as an estimate of the range of climate response) also widens through the century. The very low scenario RCP2.6 is shown here for context, but the focus for projections in general is on the Paris Agreement target rather than RCP2.6 (see next chapter).

An ongoing warming of the climate is given with *very high confidence*, and the ranges of projected change are given with *high confidence*. Confidence is lower for the magnitude than the direction, as it is possible that processes such as climate feedbacks in future may respond outside the range of models due to processes that are currently unclear or poorly understood, creating either a higher or lower projection.

Temperature projections from the pre-industrial period out to 2100 from an example model that is in the mid-range of the models can be visualised using climate stripes (Figure 25). This shows that no future years are projected to be less than the pre-industrial temperature for the rest of the century, and under the higher emissions scenarios beyond around 2050 many years are projected to be above the maximum equivalent threshold for 2°C global warming since pre-industrial set by the Paris Agreement.

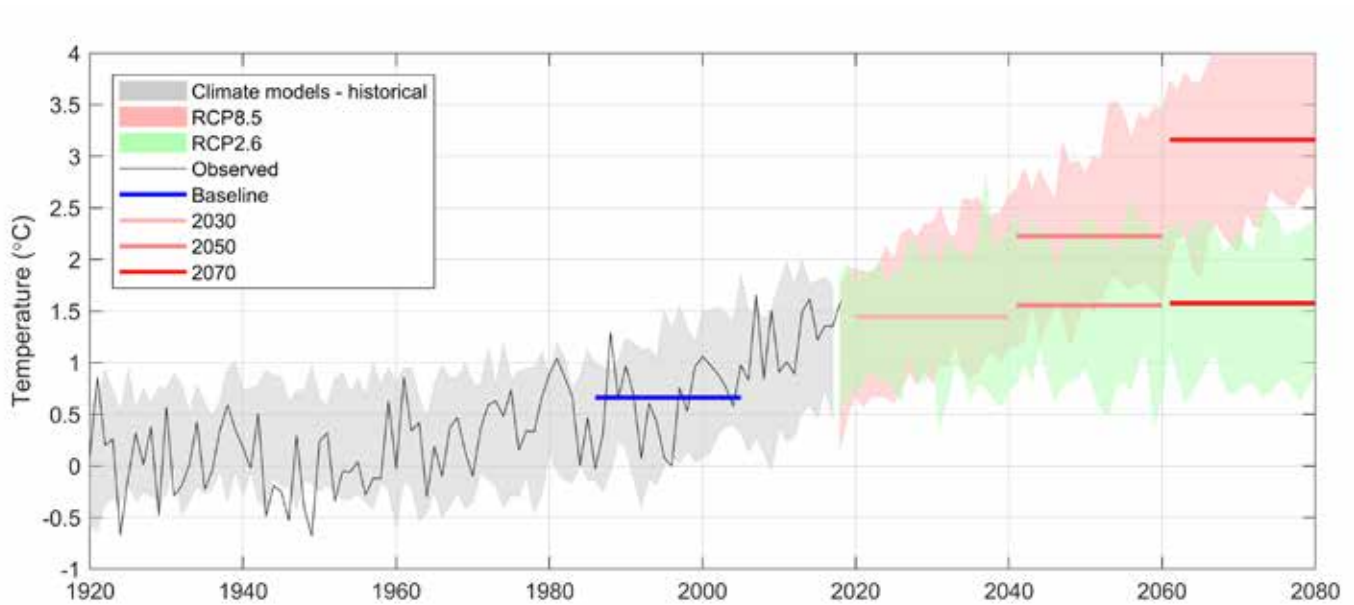
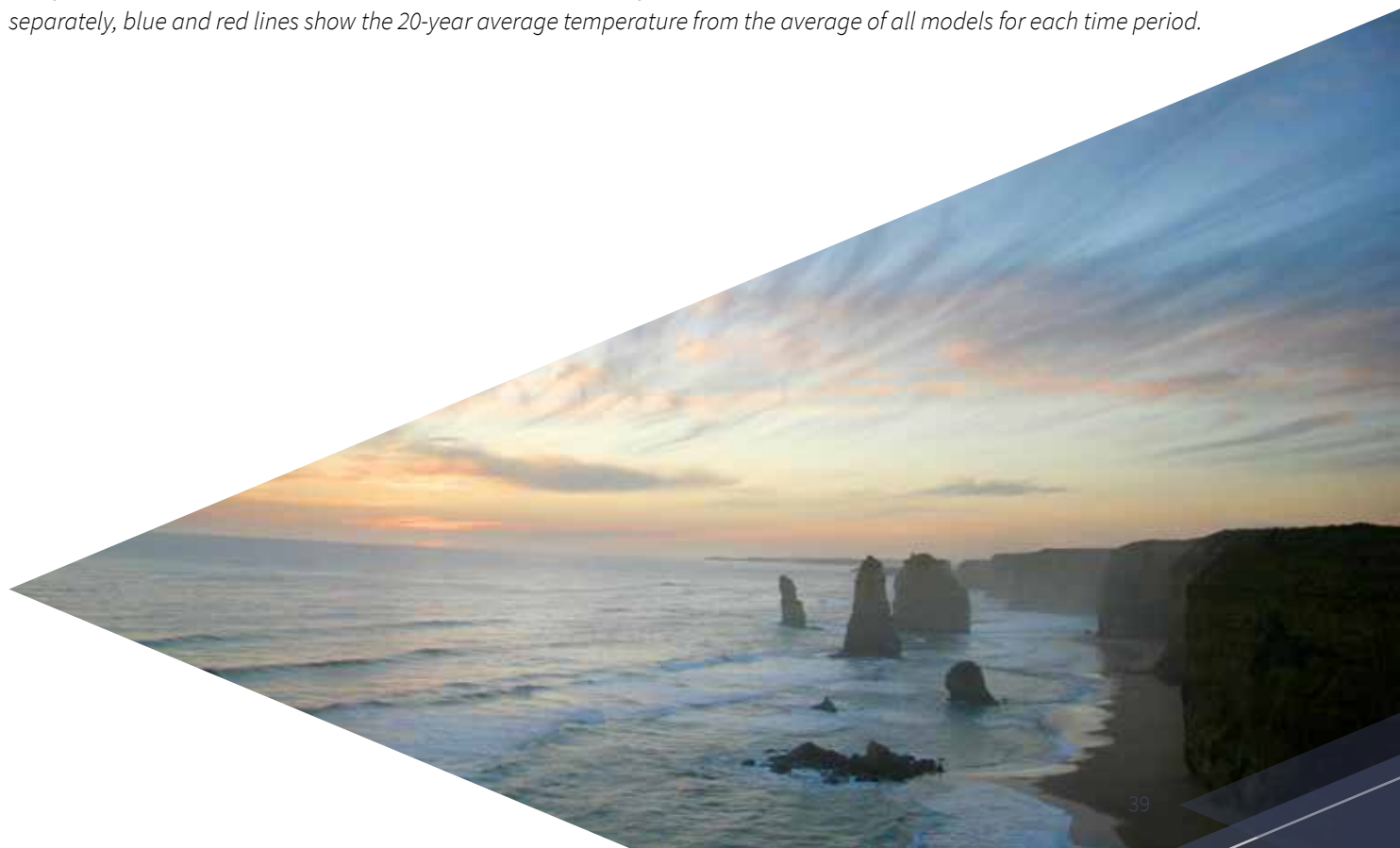


Figure 22. Average annual temperature of Victoria in observations and models relative to pre-industrial era, but in contrast to Figure 19 this plot extends the series to 2080 and shows the highest emissions pathway (RCP8.5) and the lowest (RCP2.6) separately, blue and red lines show the 20-year average temperature from the average of all models for each time period.



## Presentation of area-averaged results

Time-series plots and bar plots both illustrate projected climate change and how the simulated change relates to the current climate.

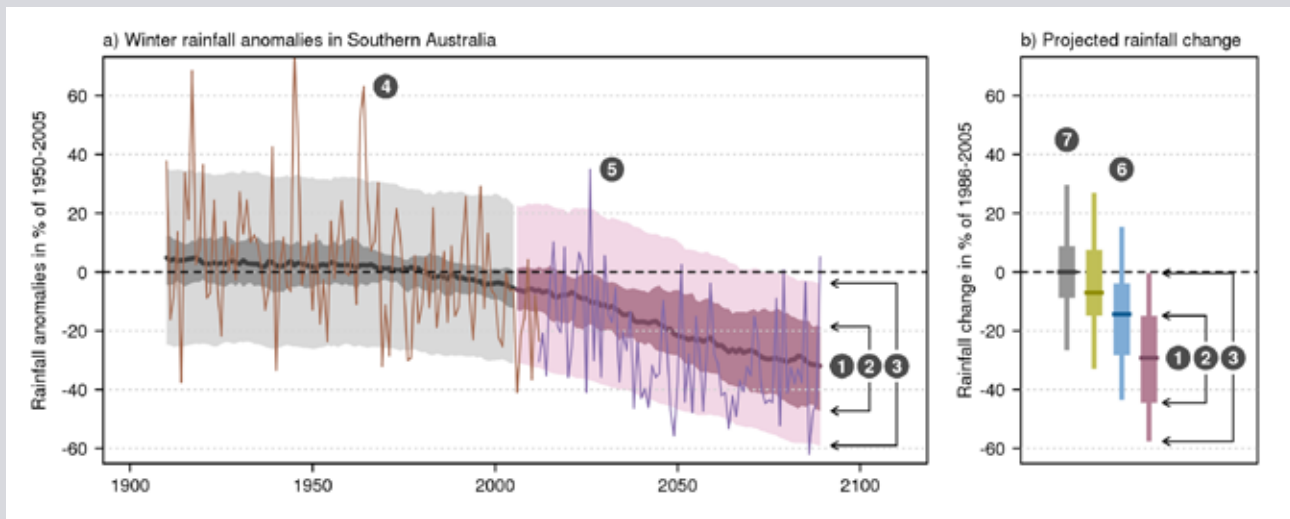


Figure B1. (a) Time series of observed and simulated change and (b) projected change according to different scenarios for winter (JJA) rainfall in southern Australia. Please note the different reference periods used in a and b. For explanations regarding the key elements see text below.

Time-series plots: the range of model results is summarised using the median (1) and 10th to 90th percentile range of the projected change (2) in all available CMIP5 simulations. The change in mean climate is shown as 20-year moving averages (Figure B1(a)). Dark shading (2) indicates the 10th to 90th percentile range for 20-year averages, while light shading (3) indicates change in the 10th to 90th percentile for individual years. Where available, an observed time-series (4) is overlaid to enable comparison between observed variability and simulated model spread. When CMIP5 simulations reliably capture the observed variability, the overlaid observations should fall outside the light-shaded range in about 20 per cent of the years. To illustrate one possible future time-series and the role of year-to-year variability, the time-series of one model simulation is superimposed onto the band representing the model spread (5). Note the 20-year running average series is plotted only from 1910 to 2090.

Bar plots: similar to time-series plots, bar plots also summarise model results using the median (1) and 10th to 90th percentile range of the projected change (2) in all available CMIP5 simulations. The extent of bars (2) indicates the 10th to 90th percentile range for difference in 20-year averages (reference period to a future period), while line segments (3) indicate change in the 20-year average of the 10th and 90th percentile, as calculated from individual years. The projection bar plots enable comparison of model responses to different RCPs (6), where RCP2.6 is green, RCP4.5 is blue and RCP8.5 is purple (Figure B1(b)). The range of natural internal variability without changes in the concentration of atmospheric greenhouse gases and aerosols as prescribed by the RCP scenarios is shown in grey (7). This range is estimated from the spread in projections for the period 2080–99 among simulations differing only in their initial conditions. In the above case, the median projection in all RCPs is for a decrease in winter rainfall. The models agree well on the magnitude of the decrease and therefore the spread in projected changes (coloured bars) is only slightly larger than due to natural internal variability alone (grey bar). In cases where the models do not agree on the magnitude and/or sign of the projected change, the range of projections is much larger than that due to natural internal variability.

Source: CSIRO and Bureau of Meteorology 2015



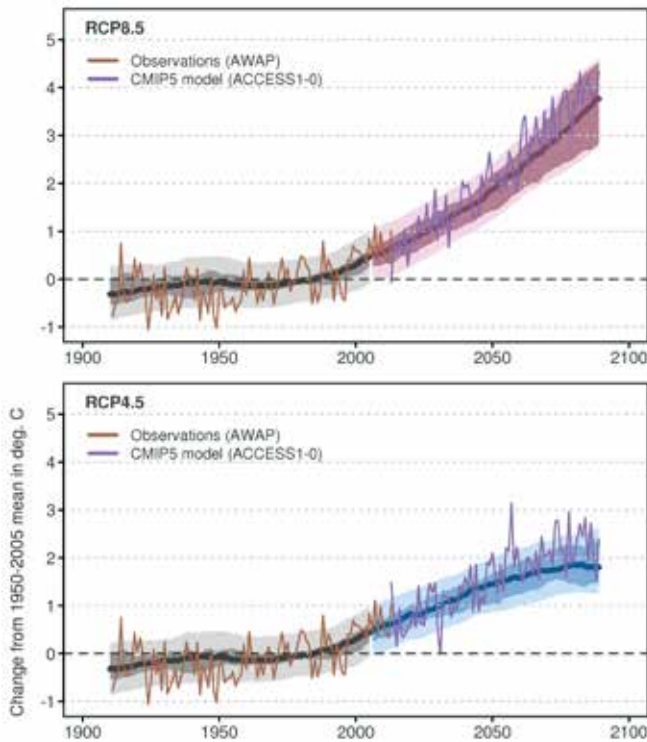


Figure 23. Time series of modelled 20th and 21st century mean annual temperature for Victoria, relative to 1950–2005 for RCP4.5 and RCP8.5 from CMIP5 GCMs. Observed annual temperatures (brown line) and an example model series (purple line) are included on each graph to illustrate variability and change (observed and simulated). For a guide to understanding these graphs, see the box on page 40. Note a different, longer baseline is used here than elsewhere to more clearly illustrate the long-term context of change.

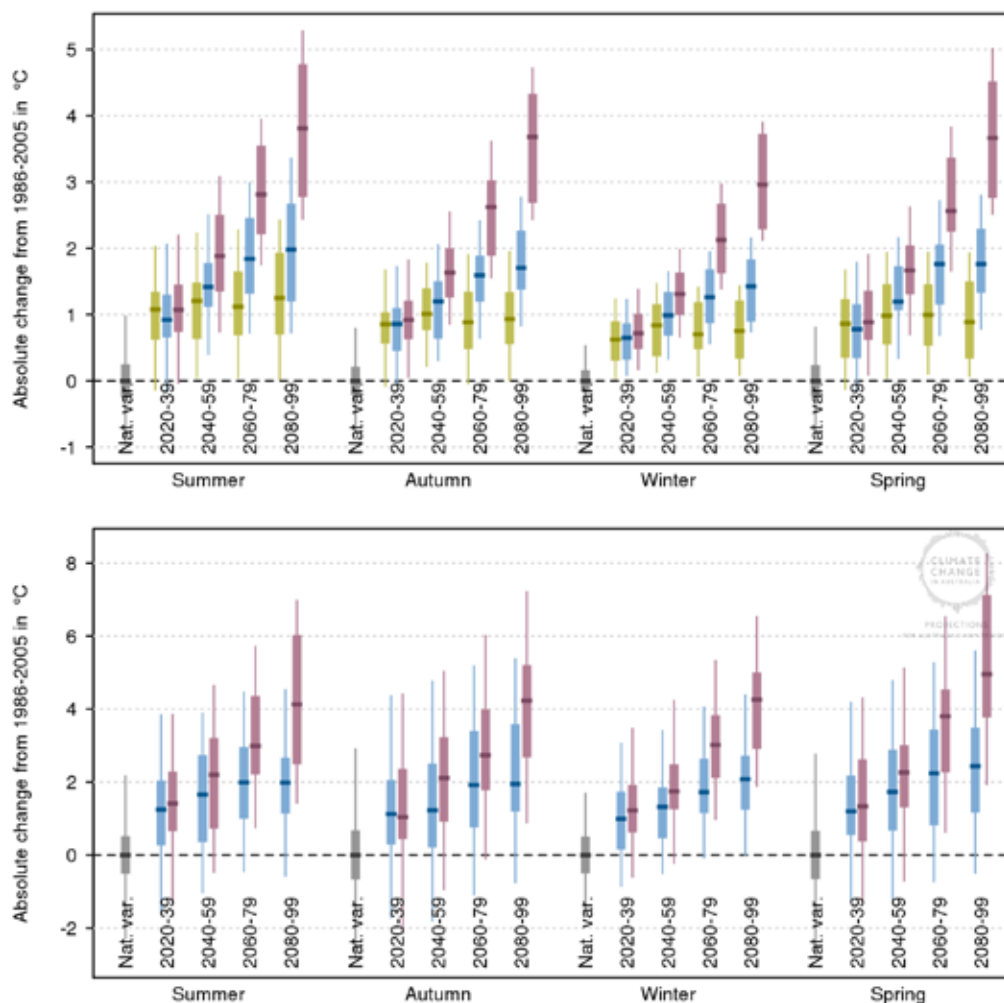


Figure 24. Bar plot of projected change in mean temperature for four future time-periods, relative to 1986–2005 for Victoria. The top panel shows results from 40 CMIP5 GCMs and the bottom: the results from six CCAM simulations for RCP4.5 and RCP8.5. Grey is natural variability only, green is RCP2.6, blue is RCP4.5 and red is RCP8.5. Thick bars show the range of 20-year averages from all models; the dark line shows the median of model results; the thin bar shows the temperature range that year-to-year variability can contribute on top of the longer-term variability and change. For a guide to reading this graph, see the box on page 40.

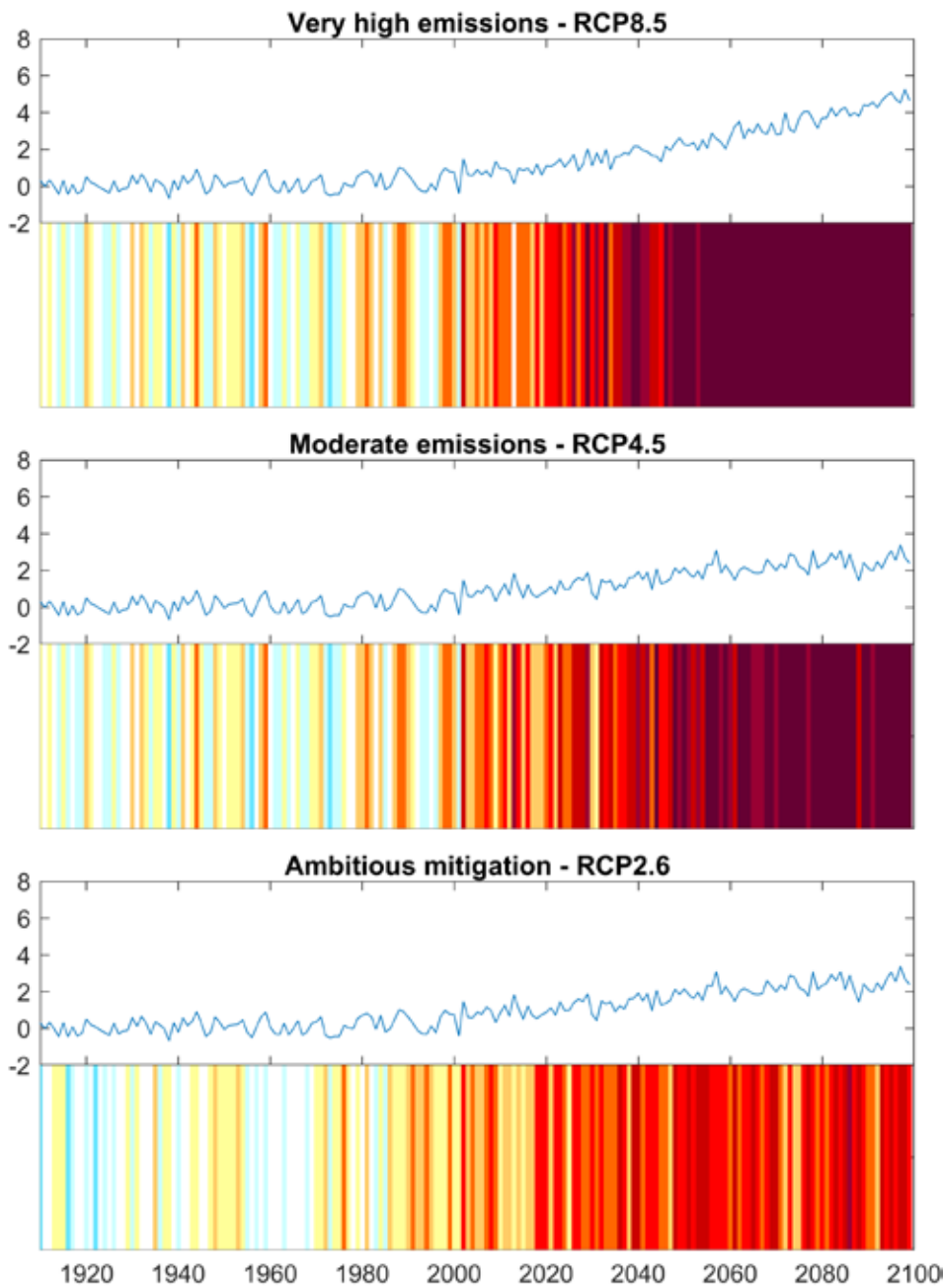


Figure 25. Example series of Victorian average annual temperature relative to 1850–1900 approximating pre-industrial times from a single climate model simulation. The plots include climate stripes as in Figure 1, but the colour scale is different in Figure 1, and tops out at 2.3°C, the higher estimate of what Victoria’s temperature could be at 2°C global warming.

The high-resolution CCAM simulations show a similar range of changes to those from the entire CMIP5 set of simulations, with a few important cases where the upper range of change is higher in CCAM than in GCMs (Table 6). For average annual temperature, most differences in the upper range are less than 0.5°C, but there is one case of 0.7°C by the 2090s (RCP4.5). There are greater differences in some seasons than others (Table 7), where the CCAM simulations show much higher values in spring than the GCMs (up to 1.2°C). The lower bound of the 10th to 90th percentile range is similar in CCAM as the GCMs in all time periods, RCPs and seasons: all within 0.5°C with one exception (0.7°C in spring in RCP4.5).

There are a number of plausible physical explanations for the difference in the upper estimate of projected warming

in CCAM compared to GCMs. The strongest case is where the CCAM projection is drier and hotter than the GCMs for spring. This is plausible since a drier climate is typically associated with warmer temperatures. In addition, the higher-resolution simulation of the response of the land surface to lower rainfall in CCAM could be contributing to warmer temperatures. Confidence in the added value from CCAM compared to the GCMs is given with *medium to high confidence*, as the model evaluation of CCAM was acceptable and there appears to be a physical explanation for the higher values. Therefore, we present a higher hot case for projected change, but this should be used along with the full range of other possibilities, and not used to the exclusion of other inputs.

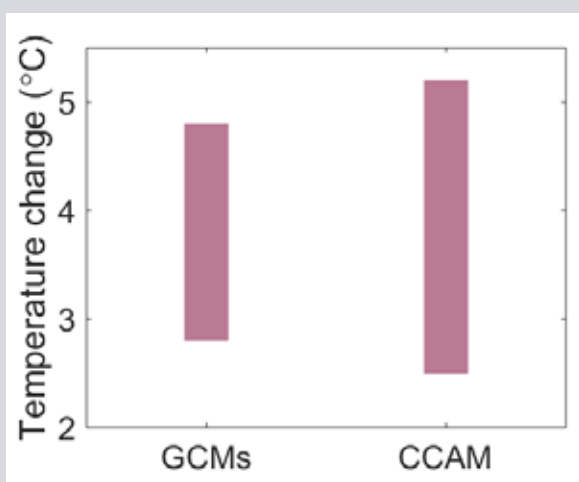
## A plausible hotter ‘hot case’ projection

The high end of projected change is higher in the new simulations than in the GCMs, by up to 0.5°C in the state average, and up to 1°C in some regions.

**Possible reason:** enhanced response of land surface to drying compared to low resolution models

**Seasons:** especially spring and summer

**Regions:** all regions, but especially in the Gippsland, Grampians and Hume regions (the central and southeast of Victoria)



Range of change in summer temperature in 2090 under high emissions (RCP8.5) from the models used as input and the high-resolution downscaling

Table 6. Projected changes to Victorian average annual temperature relative to the 1986–2005 baseline in GCM and CCAM simulations (10th to 90th percentile range of 20-year running average in each period)

	RCP2.6	RCP4.5	RCP8.5
2030 (2020–2039)	GCM: 0.55 to 1.0°C	GCM: 0.6 to 1.0°C CCAM: 0.8 to 1.0°C	GCM: 0.7 to 1.2°C CCAM: 0.9 to 1.3°C
2050 (2040–2059)	GCM: 0.61 to 1.3°C	GCM: 0.85 to 1.5°C CCAM: 0.9 to 1.8°C	GCM: 1.3 to 2.0°C CCAM: 1.4 to 2.4°C
2070 (2060–2079)	GCM: 0.49 to 1.3°C	GCM: 1.3 to 1.9°C CCAM: 1.4 to 2.1°C	GCM: 2.1 to 3.1°C CCAM: 2.2 to 3.5°C
2090 (2080–2099)	GCM: 0.48 to 1.5°C	GCM: 1.3 to 2.2°C CCAM: 1.6 to 2.9°C	GCM: 2.8 to 4.3°C CCAM: 2.6 to 4.7°C

Table 7. Projected change to seasonal temperature around 2090 (2080–2099) relative to the 1986–2005 baseline for each calendar season (e.g. summer is December to February)

	RCP2.6	RCP4.5	RCP8.5
Summer	GCM: 0.7 to 1.9°C	GCM: 1.2 to 2.7°C CCAM: 1.7 to 3.2°C	GCM: 2.8 to 4.8°C CCAM: 2.6 to 5.3°C
Autumn	GCM: 0.55 to 1.3°C	GCM: 1.4 to 2.3°C CCAM: 1.7 to 2.3°C	GCM: 2.7 to 4.3°C CCAM: 2.9 to 4.8°C
Winter	GCM: 0.33 to 1.2°C	GCM: 0.9 to 1.8°C CCAM: 1.2 to 2.5°C	GCM: 2.3 to 3.7°C CCAM: 2.3 to 3.7°C
Spring	GCM: 0.34 to 1.5°C	GCM: 1.3 to 2.3°C CCAM: 2.0 to 3.5°C	GCM: 2.8 to 4.5°C CCAM: 2.8 to 5.6°C

### 5.2.4 Temperature extremes

The new projections show increases in daily maximum and minimum temperatures that are consistent with hotter and more frequent hot days, fewer cold days, more frequent and more intense heatwaves, as well as fewer extreme cold nights.

Temperature-related impacts come from the change in background average temperature as well as the incidence of extremes, either high or low. For some applications, the extremes have more impact than the average. Examples include hot extremes that cause damage to infrastructure and result in heat stress among vulnerable people. But for other applications like agricultural growing conditions, the entire temperature regime is important, that is, the average and the extremes (Harris et al. 2018).

Climate extremes are by definition rare events, so accurately characterising their frequency and intensity is difficult and highly dependent on having a very long climate record. The longer the record, the more 'signal' (extreme events) there will be relative to the 'noise' of the more common everyday events. As Victoria's climate record is just over 100 years in duration, events with say a 1-in-20-year occurrence on average (recurrence interval) are expected to have occurred only five or so times in the entire record. For this reason, it is not appropriate to calculate simple statistics of the observed or simulated extreme events as is done for averages. Instead, extreme distribution fitting and other statistical techniques are used.<sup>3</sup> Here the changes to annual maximum (the average 'hottest day of the year' over a 20-year period) and the 20-year average recurrence interval (ARI20) have been calculated by fitting statistical distributions to the climate data. An ARI20 is expected to be met once every 20 years on average with a randomness on top of this average value, as it is not met regularly every 20 years. Another way of thinking of an ARI20, is that there is a 5% chance of it occurring in any year.

An increase in the average temperature leads to a corresponding increase in hot extreme daily maximum temperatures and a decrease in cold extreme daily minimum temperatures, assuming no change to variability or timing of events. Therefore, the broad framing of changes to extreme temperatures follows directly from the changes to averages in the previous section – changes are projected under all scenarios, with greater change for higher emissions scenarios and further timeframes. The predicted hotter and more

<sup>3</sup> See <https://www.climatechangeinaustralia.gov.au/en/climate-campus/climate-extremes/> for details on extremes and analysis methods

frequent hot days, fewer cold days, more intense heatwaves and fewer extreme cold nights is the most important and relevant message from the projections and is given with *very high confidence*. But within this general framework, there is great interest in the possibility that extremes might change in ways that are different from those expected from the change in the average. This could be due to a change in the nature or timing of the events that bring extremes.

In certain circumstances, we expect the increase in heat extremes such as the ARI20 to increase more or less than the increase in the average. In particular, heat extremes can be amplified by soil moisture–temperature feedbacks, where less rainfall and less evaporative cooling allows hotter temperatures (Seneviratne et al. 2010; Seneviratne et al. 2012). Victoria as a whole is projected to get drier, especially in spring where hot, dry conditions set up a dry landscape for summer heatwaves. Also, the land–sea contrast may change in Australia, meaning greater heat extremes over land compared to over ocean due to changes in the movement of heat from warmer continental interiors (Watterson 2008). A recent example of where heat over land was not dispersed quickly is during the summer of 2018–19 where long hot spells were experienced in many inland locations. The national climate projections (CSIRO and Bureau of Meteorology 2015) indicate that in most regions of Australia, extreme daily maxima are projected to change by a similar amount as the average, but with a few important regional exceptions. Exceptions include southern Victoria, where the extremes projections have a hotter hot end. For example, in the Southern Slopes Victoria West region under RCP8.5 by 2090, the annual average daily maximum temperature is projected to increase by 2.4 to 4.2°C. However, the annual maximum range is 2.5 to 5.8°C and the ARI20 is 2.9 to 6.3°C. This means that the average daily maximum temperature is projected to increase from the value in 1986–2005 (14.3°C) to as much as 18.5°C. In contrast, the annual maximum could increase from 36°C in 1986–2005 to 41.8°C around 2090. The results are different for daily minimum temperature, where the projected changes are similar for the average and extremes, with only small differences for the top of the range.

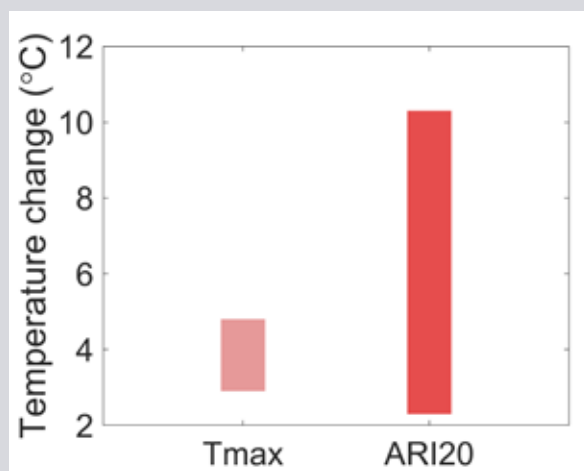
## A plausible projection of hotter heat extremes

Much hotter upper end of projected increase in heat extremes than GCMs projected.

**Possible reason:** as for mean temperature (response to drier climate, resolution of coasts etc.)

**Seasons:** especially winter, but also spring and other seasons

**Regions:** all



Range of change in winter Tmax and ARI20 in 2090 under high emissions (RCP8.5) in Gippsland from the VCP19 simulations

High-resolution CCAM climate simulations developed for VCP19 show a drier rainfall projection than the host models in some regions and seasons, and the response of the land and vegetation to a drier environment is better simulated in VCP19 runs than in GCMs. Also, the land–sea contrast near the coast is better resolved and simulated in VCP19 runs than in GCMs, where GCMs resolves the coast as a few large boxes, whereas CCAM has many cells to simulate the effects of the coast. Changes in extreme temperatures show a strong land–sea contrast with much larger increases over land than ocean. A land–sea contrast is found in all projections, but the difference is more highly resolved in VCP19 runs than in coarser resolution models. These factors are among the likely drivers of differences between the CCAM VCP19 simulations and the host GCMs and suggest the added resolution of CCAM downscaling for VCP19 has potentially produced a more realistic simulation of temperature response. Similar to the GCMs, VCP19 projects a change in both annual maximum and 20-year extreme temperatures with a higher hot end than for average daily maximum temperature in the coastal and metropolitan regions such as Barwon, but not in inland regions such as Mallee (Figure 26 where the 10 high-resolution VCP19 regions are shown using their codes from Table 4). This is consistent with the CCA projections and previous findings, where coastal sub-clusters in southern Victoria showed a stronger enhancement than Murray Basin (CSIRO and Bureau of Meteorology 2015). Notably, the GCMs show a larger increase in ARI20 compared to daily maximum temperatures than the VCP19 runs do. However, striking changes are projected seasonally, with a huge enhancement of daily maximum temperature extremes compared to the change in the average for winter and spring. For example, in the Greater Melbourne region projections for daily maximum temperature in winter by 2090 under RCP8.5 are 2.7 to 4.2°C, but the projection of ARI20 maximum temperatures is 2.3 to 10.0°C. This extreme hot end appears in a single model simulation and for 2090 under high emissions. This model run is CCAM downscaled from HadGEM2-CC and shows extreme drying (by up to 45% in spring), contributing to a land–surface feedback driving hotter hot days. It is unclear if other downscaling methods would replicate this result for Australia at the time of writing, which would have helped determine the level of confidence in this projection. In the absence of additional downscaling results we consider this model simulation is extreme, but physically plausible so is presented as a worst-case scenario to be used in conjunction with the full range of results and scenarios.

The changes projected under high emissions for the far future are extreme compared to the climate we are used to. Under RCP8.5 by 2080–2099, the projections indicate that locations within Victoria could experience days over 55°C in summer, and days over 33°C in winter. An example of the daily maximum temperature in an extreme day in the

2050s for the model with the greatest drying and warming (HadGEM2-CC downscaled by CCAM for VCP19) is shown in Figure 27. Note that the temperatures for Gippsland in this example are elevated due to the temperature bias described in section 4.2.1.

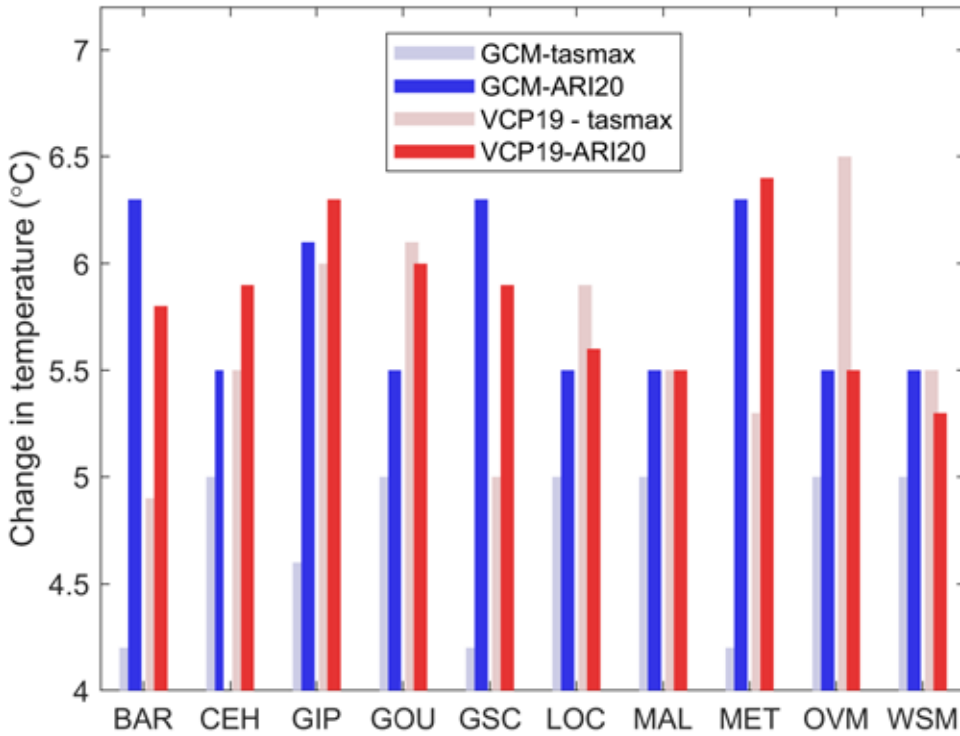


Figure 26. The upper range of projected annual daily maximum temperature change and the 20-year recurrence interval (ARI20) annually for RCP8.5 between 1986–2005 and 2080–2099 for each of the 10 VCP19 regions, the top of bars show the 90th percentile range from GCMs and the highest VCP19 run. The 10 high-resolution VCP19 regions are shown using their codes (see Table 4 for full names)

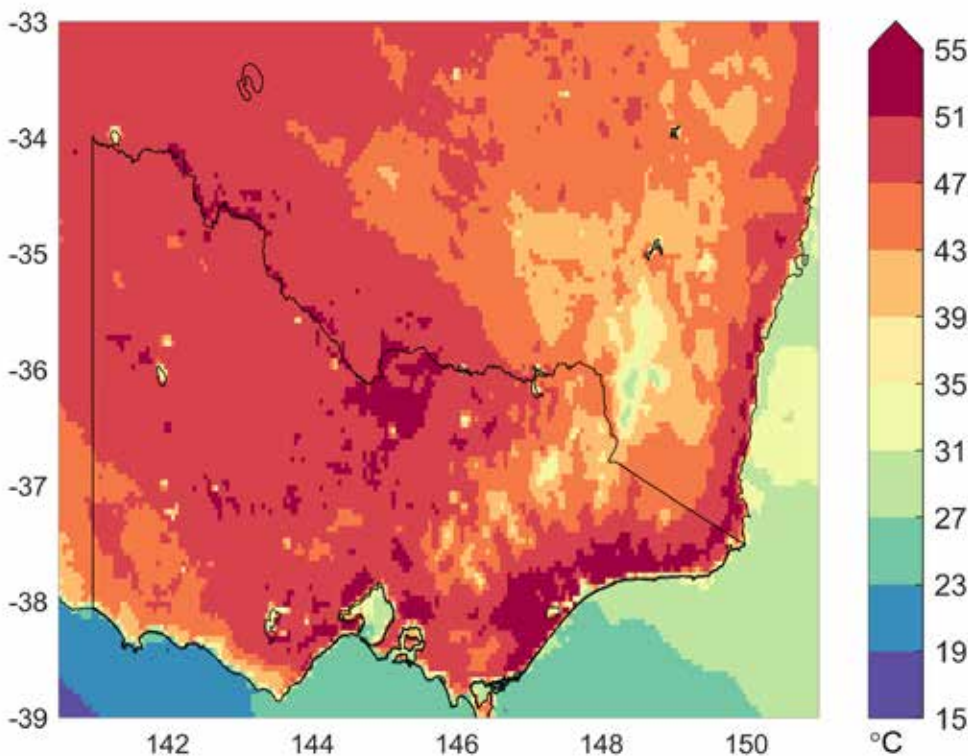


Figure 27. Daily maximum temperature for an example extreme heat day simulated under a very high scenario (RCP8.5, a summer day in the 2050s, HadGEM2-CC model downscaled by CCAM), where Melbourne reaches 50°C, and even higher temperatures inland. There is a warm bias in the simulation associated with the Gippsland region, so the temperature may be artificially elevated near the southeast coast. Note this is not the hottest day in simulations, it is just indicative of a very hot day in the future climate without a historical precedent.

In contrast to daily maximum temperatures, extremes of daily minimum temperature are lower than the change in average temperatures under a high emissions scenario and far future time scale. Dry conditions with clearer skies and less insulating effect of cloud cover are more conducive to heat loss from the Earth’s surface and cold nights, so daily minimum temperatures and specifically the extreme minimums are cooler than if cloud and rainfall stayed the same. The effect on minimum temperatures is present in GCMs and in VCP19 runs and is particularly enhanced in inland regions such as the Mallee (Figure 28).

This effect is also relevant to frosts, where cold, clear nights are projected to persist longer than expected from a change in the average temperature would suggest. This is consistent with past trends, where frosts in some regions, particularly in spring, have in fact increased in frequency despite an increase in the average temperature (Crimp et al. 2016).

### 5.3 Rainfall

Rainfall is one of the less certain projections but is of great interest to almost every sector of the Victorian community. Changes to the climate features described in Chapter 3 (e.g. atmospheric circulation) are the dominant drivers of changes to rainfall in this region, but with some influence from direct effects of a warmer climate (e.g. increased convection). Rainfall variability is high in Victoria, so any trend due to climate change is present amid much natural variability. This can be seen in the difference in the time-series of rainfall compared to temperature in past changes (Figure 29) and also for projected changes in future.

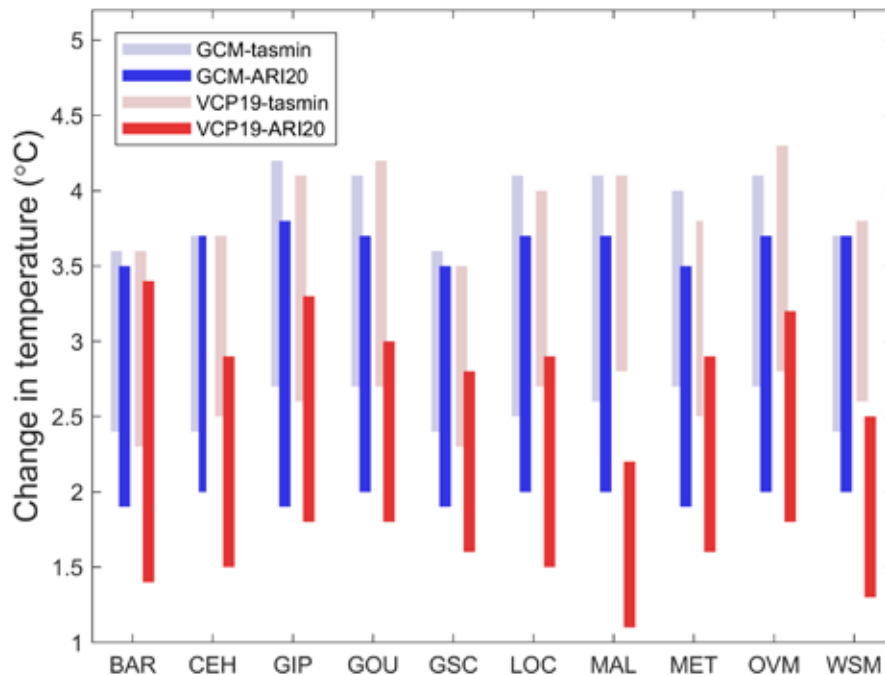


Figure 28. The upper range of projected daily minimum temperature change and the 20-year recurrence interval (ARI20) annually for RCP8.5 between 1986–2005 and 2080–2099 for each of the 10 VCP19 regions, the bars show the full model ranges.

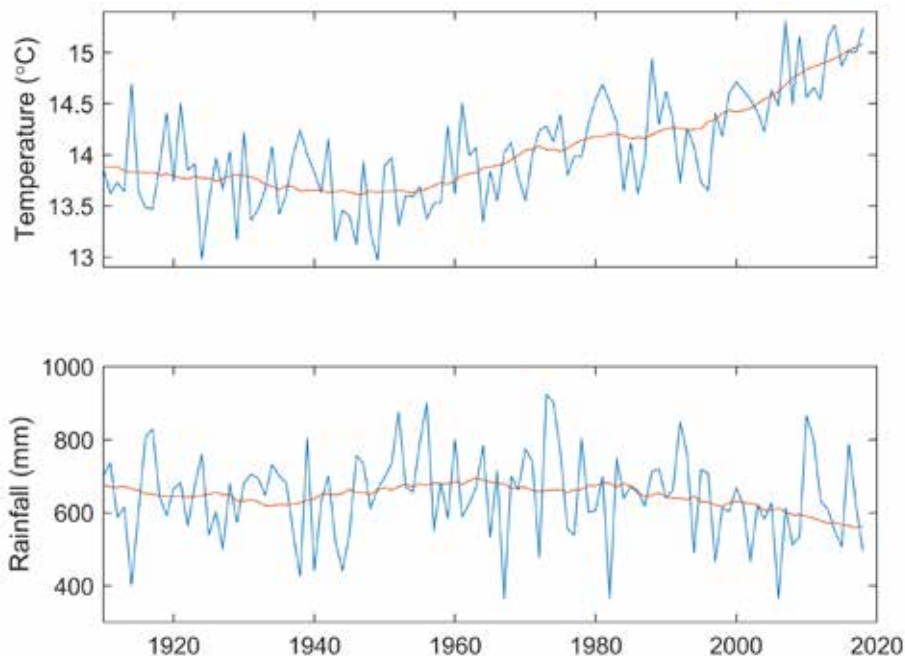


Figure 29. Victorian average annual temperature (top) and rainfall (bottom), showing the clearer trend compared to variability in temperature than in rainfall. Blue line is the annual values, red line is the 11-year running average.

### 5.3.1 Past changes

Using the Bureau of Meteorology’s Australian Water Availability Project (AWAP) gridded climate data set of Jones et al. (2009), there has been a negative trend in rainfall in most seasons in recent decades (Figure 30). Trends are typically larger on the windward slopes of mountains or on the peaks; however, the mean rainfall is generally higher, so changes are not as notable as a proportion (%). Decreases are greater in the cooler seasons (Figure 31). Given that rainfall can have high variability from one decade to another (e.g. Figure 29), the start and end dates of any linear trend can have a strong influence on the result and should be carefully noted when comparing results.

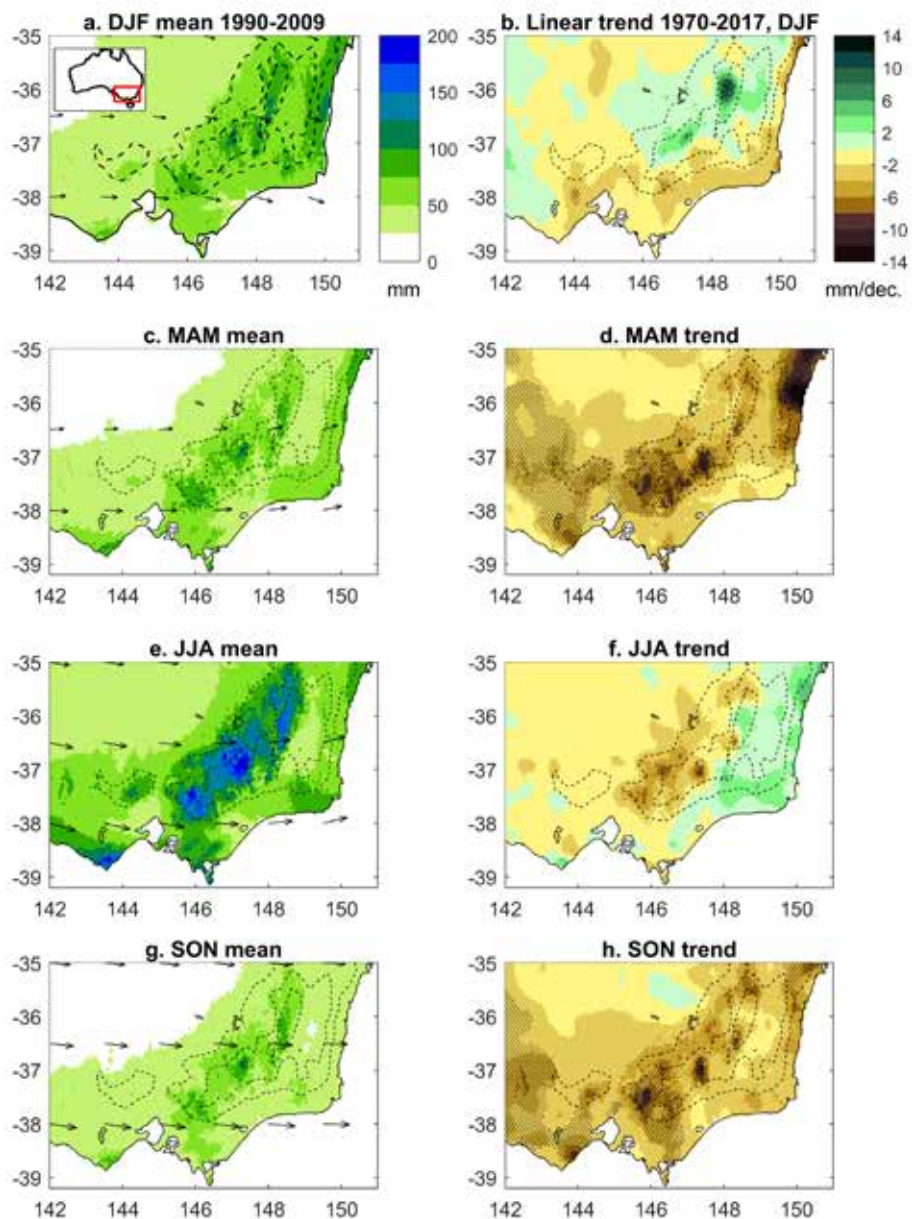


Figure 30. Rainfall mean and trends in the AWAP data set. (a) mean rainfall in 1990–2009 in summer (DJF), inset shows the location of the domain within Australia, vectors show the mean 850 hPa wind; (b) linear trend in mean rainfall in 1970–2017 (mm/decade) in DJF; (c) mean in autumn (MAM); (d) trend in MAM; (e) mean in winter (JJA); (f) trend in JJA; (g) mean in spring (SON); (h) trend in SON. Dashed lines show topography at contours of 400 m, hatching shows statistical significance of the linear trend at the 0.1 level. (Source: Grose et al. 2019b)



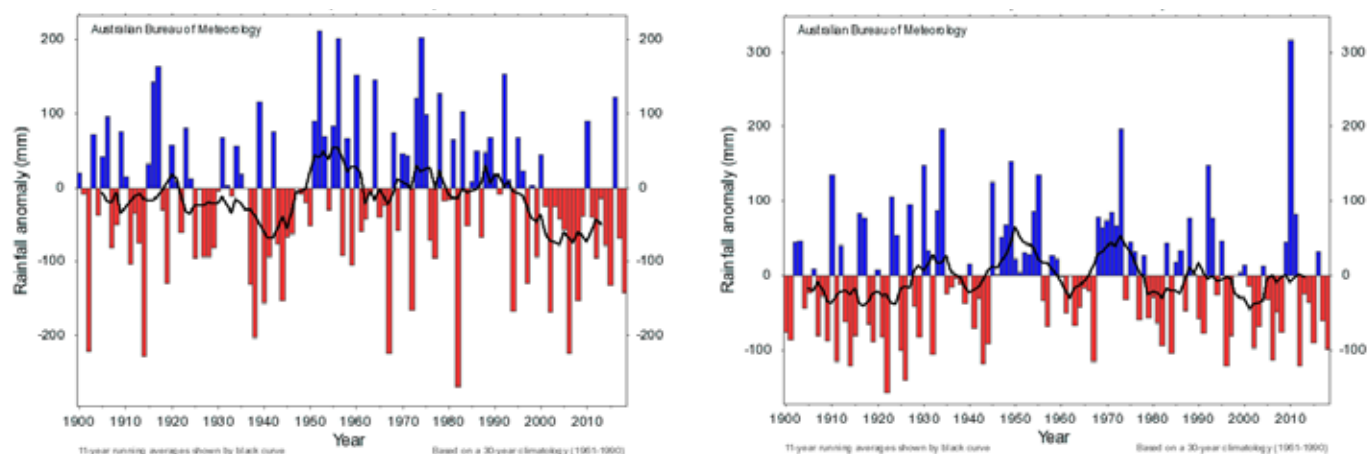


Figure 31. Time-series of Victorian average rainfall for April–October (southern wet season) and November–April (northern wet season) rainfall relative to the 1961–1990 average

### 5.3.2 Projected change – global and Australia

Globally-averaged rainfall is projected to increase as the atmosphere gets warmer. However, there is a large range of changes by region, with some areas projected to get wetter and others drier. There is good physical evidence and agreement between the most recent set of GCMs (CMIP5) for the mid-latitude regions of around 30–45°S to get drier – but with seasonal differences and differences between longitudes (Figure 32). There is high agreement for a decrease in rainfall across much of southern Australia in winter, particularly in the southwest. Victoria is located at the eastern edge of this projected change pattern. In summer, the region of projected rainfall decrease is to the south of Australia, and Victoria sits at a boundary between regions of projected increase and decrease, making it difficult to determine the projected change in summer specifically in Victoria.

Examining the broadscale changes over the Australian region in the GCMs, the 50 km CCAM simulations of VCP19 and various previous downscaling studies, we see how

the model selection and downscaling steps modify the model mean projection of change (Figure 33). The mean of the six GCMs is broadly similar to the full set of GCMs for southeast Australia, although it shows some differences in other parts of Australia. VCP19 high-resolution simulations modify the mean signal of the six GCMs in a few ways. The projected change in northern Australian wet season (mainly DJF and MAM) is drier than the GCMs (results for JJA should be ignored as the change represents a percentage change on top of a very low rainfall amount in the north). VCP19 runs show an enhanced drying over southern Australia in several seasons, including Victoria (in section 5.3.3). Regional patterns linked to mountains and coastlines emerge (also covered in section 5.3.3). Notably, the VCP19 runs do not replicate the broadscale rainfall increase in DJF and MAM found in NRM-CCAM and NARcliM. In the case of CCAM there have been changes to the aerosol feedbacks, convection parameterisation and land-surface model which could account for some of these differences, although the exact reason for the change in the CCAM predictions is still under investigation.

Figure 32. Projected change in average rainfall (%) for the southern hemisphere in calendar seasons of summer (DJF) and winter (JJA) from 45 CMIP5 models between 1986–2005 and 2080–2099 under RCP8.5. Stipples indicate where 80% or more of models agree on the sign of change (i.e. more than 35 of the 45 models).

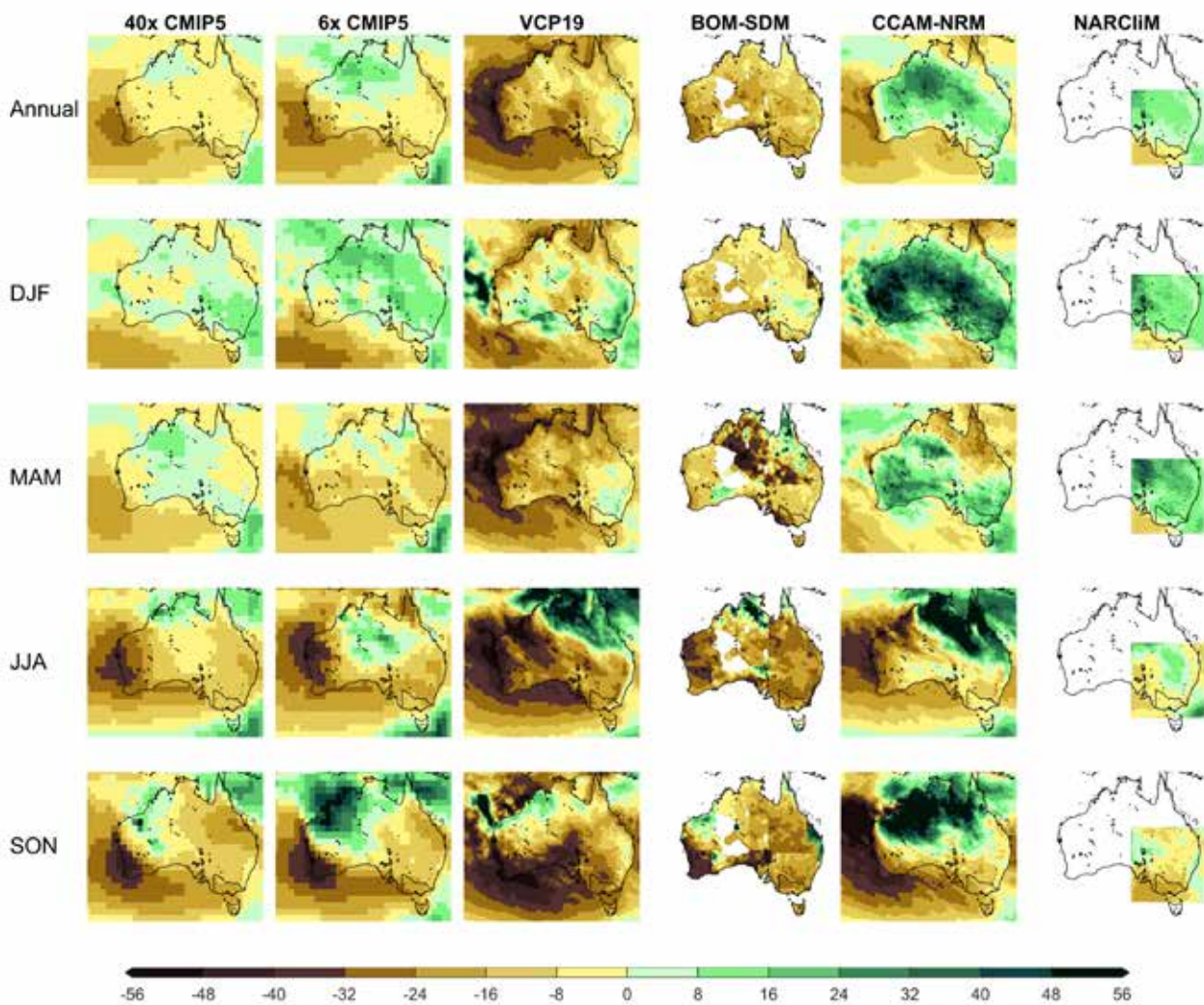
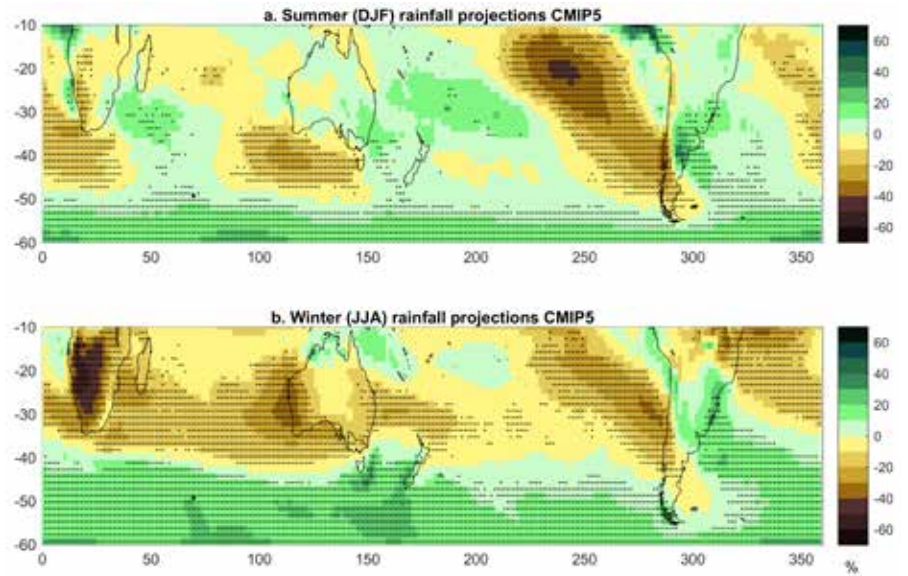


Figure 33. Model mean projected change (%) in average rainfall from different sets of model output: 40 CMIP5 models, the six CMIP5 models used as input to VCP19, the six new CCAM runs for VCP19 (50 km intermediate runs), 23 runs of the Bureau of Meteorology statistical downscaling model (BOM-SDM), six 50-km CCAM runs done previously for the NRM project, and 12 runs from the NARCLiM project. Change is shown for 1986–2005 to 2080–2099 under RCP8.5 except NARCLiM which shows 1990–2009 to 2070–2089 under SRES A2.

### 5.3.3 Projected change – Victoria and sub-regions

There is a range of projected change in average annual Victorian rainfall, but for the majority of CMIP5 GCMs (and hence, the model median) there is a projected decrease (Figure 34, left). The magnitude of the dry end of projections is greater under higher RCPs (compare RCP2.6 to RCP8.5). This is broadly replicated in the new CCAM simulations; however, the median of the six CCAM runs is lower than the GCMs for RCP8.5 by 2100 (Figure 34, right).

When broken down by season the projected decrease is larger, and with greater model agreement, for winter and spring. Changes are smaller, with less model agreement in summer and autumn (Figure 35), again with broad agreement between the CMIP5 GCMs and the new CCAM simulations. Specific differences include the median magnitude of change by late in the century under high emissions – consistently drier in CCAM than CMIP5.

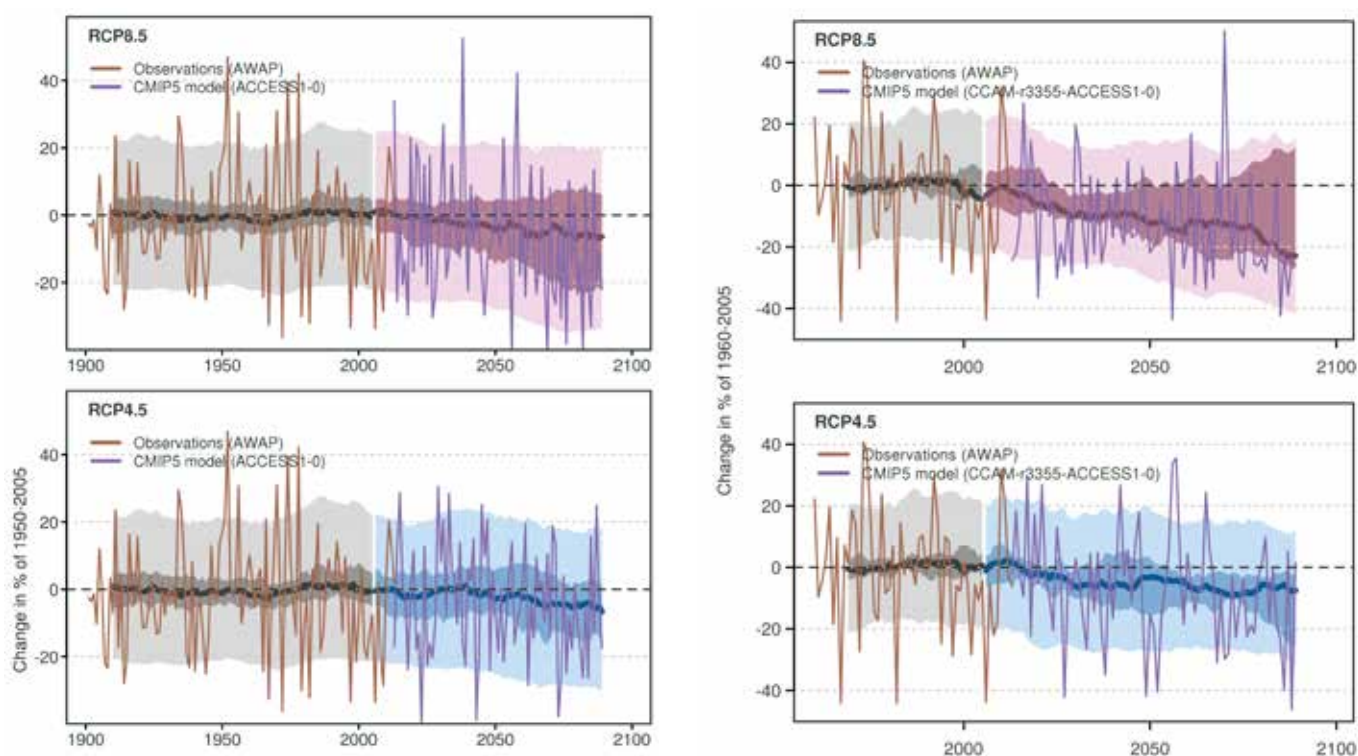


Figure 34. Projected change in Victorian annual average rainfall from CMIP5 (left) and CCAM (right) under different RCPs, showing general agreement for a decrease in rainfall but with a spread of model results and high climate variability (see box on page 40 for details of how to interpret the plots).

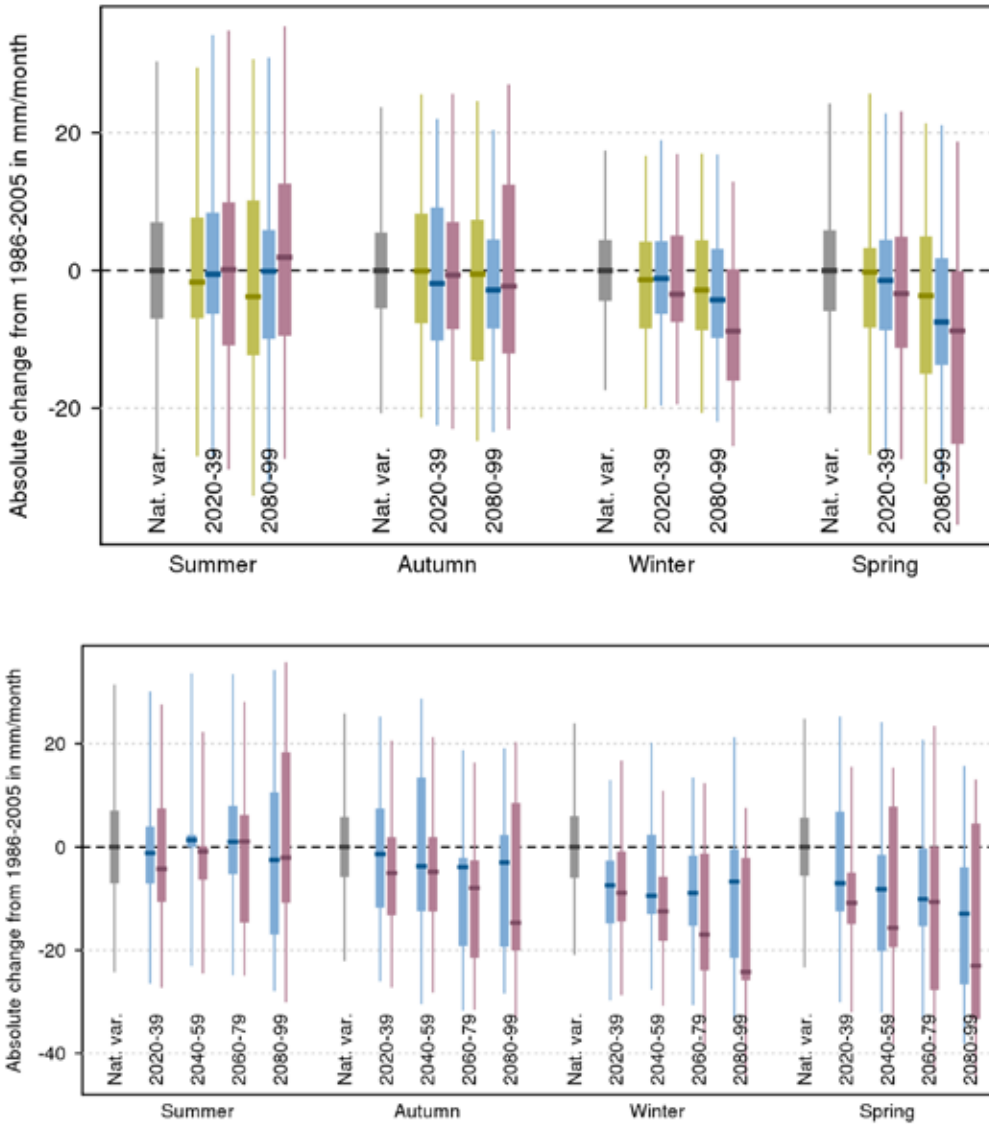


Figure 35. Bar plots of projected change in Victorian average rainfall (mm/month) in the calendar seasons for different future time windows and RCPs from: top: CMIP5 projections for two time periods and three RCPs, and bottom: VCP19 runs for four time periods and two RCPs. Green is RCP2.6, blue is RCP4.5, red is RCP8.5 and grey shows the range of change expected from natural variability alone (see box on page 40 above for details of how to interpret the plots, including bars, stems and dark lines)

Maps of change for individual model projections show the spatial distribution of projected rainfall change through time and by season. Projected change in annual rainfall in each model under the high emissions scenario RCP8.5 (Figure 36) reflects the high model agreement for rainfall decrease through most future periods, with different magnitude of decrease in different models. The plot also shows that the model with the wet projection (NorESM1-M) in fact shows little change or a projected decrease in rainfall through most of the century up until the 2090 time slice. Looking by

season, Figure 37 shows the multi-model average change for the high emissions scenario, towards the end of the 21st century (20-year period centred on 2090 for all ensembles except NARClIM) to illustrate strong change signals and draw out the differences among data sets, seasons and regions. In this case, results from five sets of earlier projections data are compared with the new VCP19 runs (see Table 2 for details of the data sets). The projections from individual runs of VCP19 are shown in Figure 38.

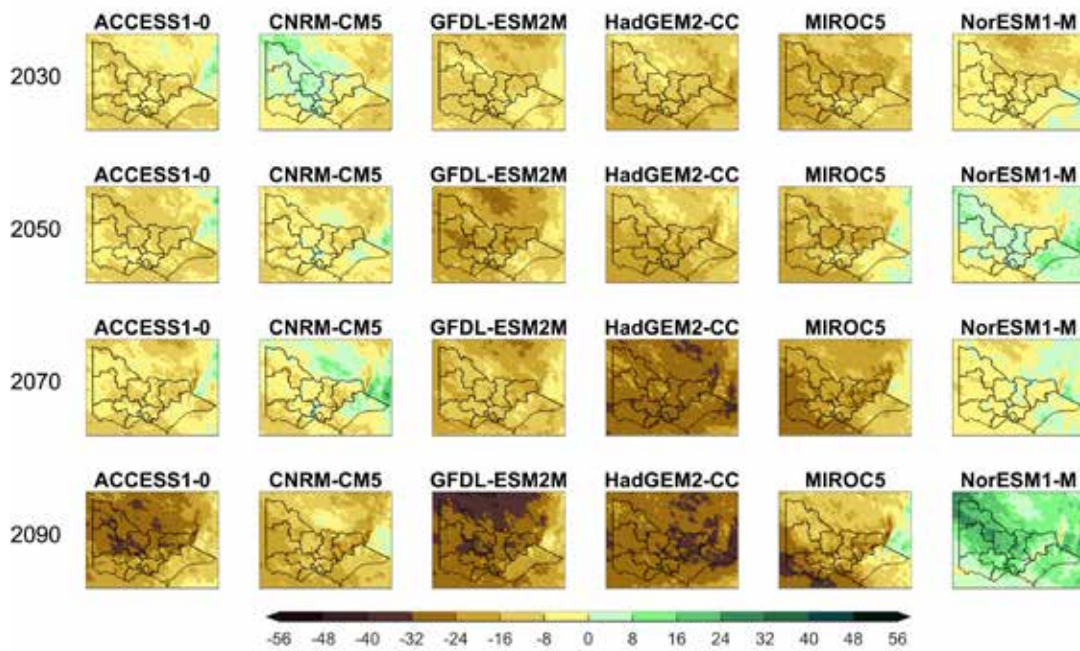


Figure 36. Projected change in annual rainfall (%) under high emissions (RCP8.5) for each of the six VCP19 CCAM simulations between 1986–2005 and four 20-year future periods centred on 2030, 2050, 2070 and 2090 (models are downscaled using CCAM and are labelled using the name of the GCM used as input).

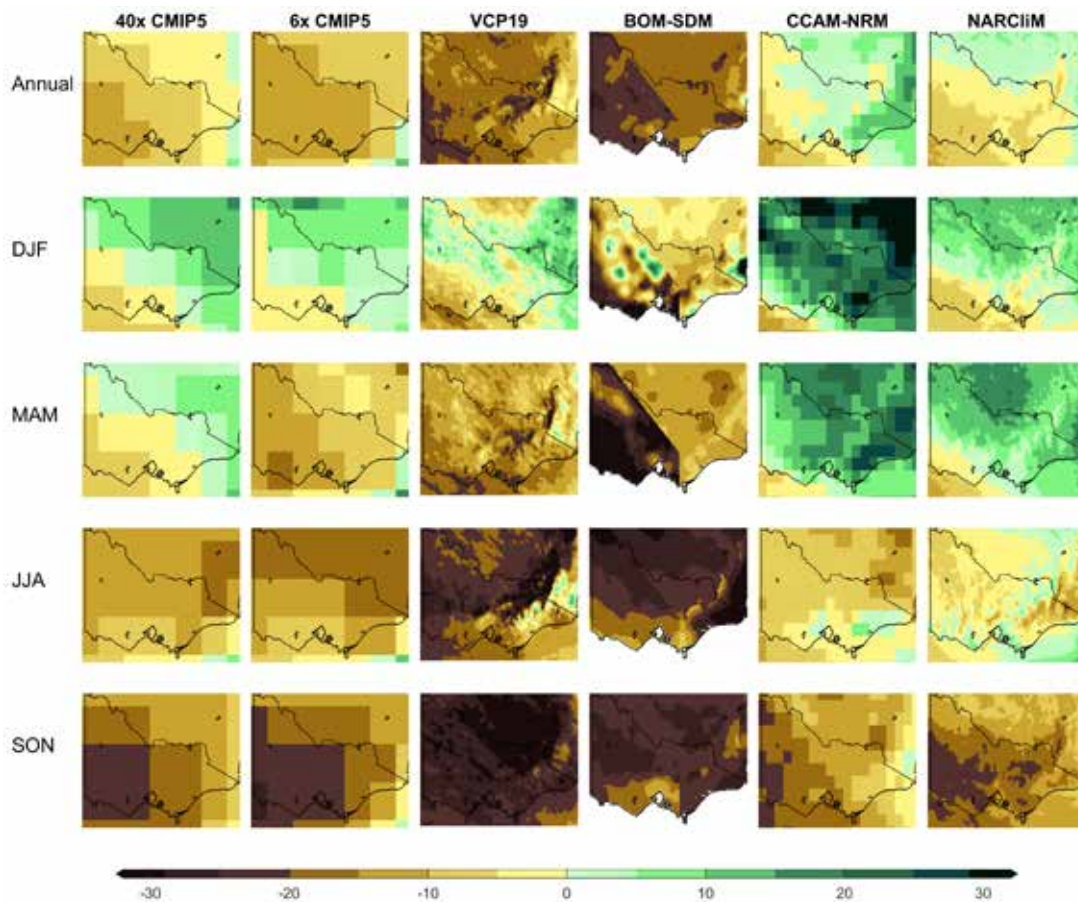


Figure 37. Model mean projected change (%) in annual average rainfall from different sets of model output: 40 CMIP5 models, the six CMIP5 models used as input to VCP19, the six new CCAM runs for VCP19, 23 runs of the Bureau of Meteorology statistical downscaling model (BOM-SDM), six 50-km CCAM runs done previously for the NRM project, and 12 runs from the NARCIiM project. Change is shown for 1986–2005 to 2080–2099 under RCP8.5 except NARCIiM which shows 1990–2009 to 2070–2089 under SRES A2.

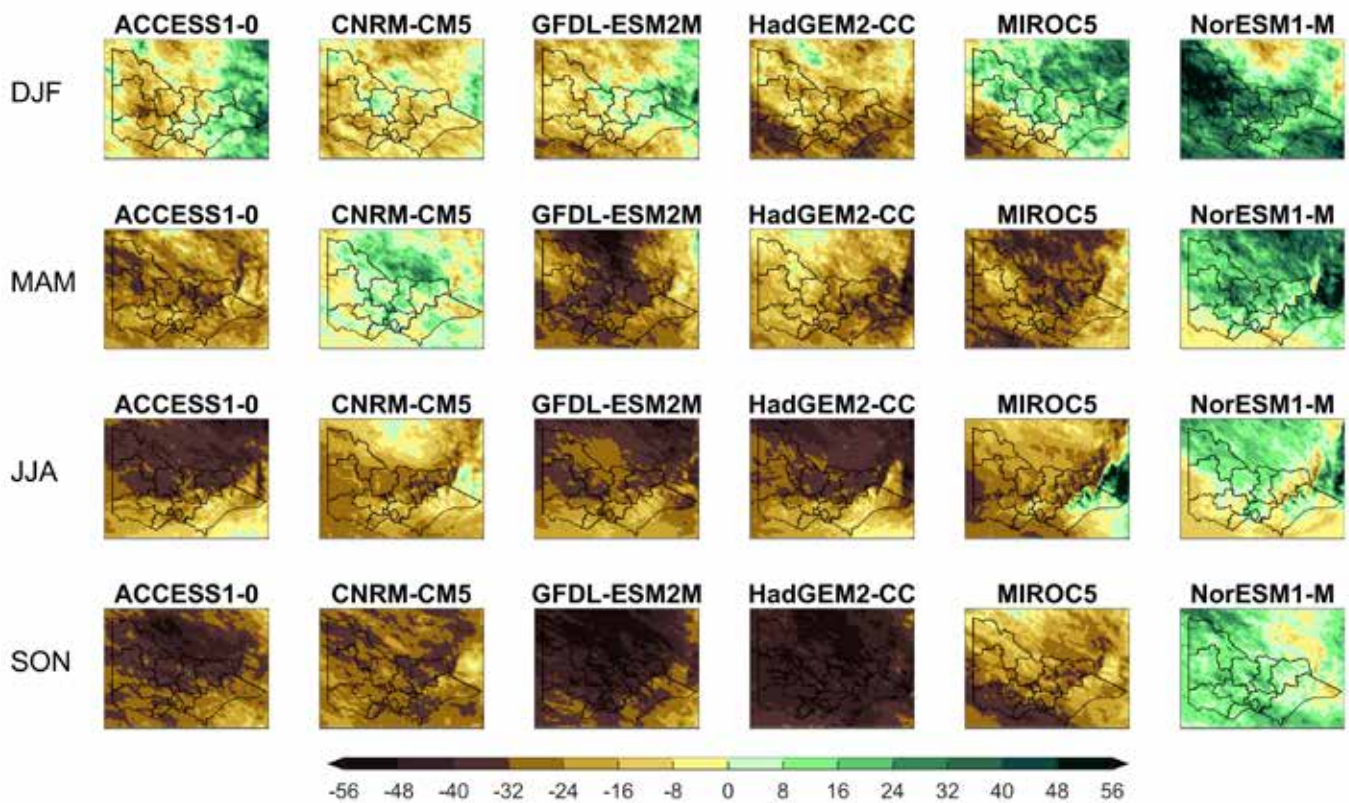


Figure 38. Projected change in rainfall (%) between 1986–2005 and 2080–2099 under RCP8.5 for each calendar season for each of the six VCP19 simulations (models are downscaled using CCAM and are labelled using the name of the GCM used as input).

At the broad scale, the mean of the VCP19 ensemble shows a decrease in annual, summer and autumn rainfall, which is more consistent with CMIP5 and the six host models than the previous dynamically downscaled projections from NRM-CCAM and NARClIM, but not as severe as BOM-SDM. The projected decrease in rainfall from new CCAM in winter and spring is greater than the host models and is comparable to BOM-SDM used for VicCI. Results from individual models show that generally four or five models agree on the sign of change in all instances, with only the simulation using the NorESM1-M model projecting an increase in rainfall in all seasons in this time-slice (noting that previous time-slices are different, see Figure 36). Two models show particularly severe rainfall reductions in spring.

At the regional scale, the VCP19 runs show plausible regional detail in the spatial pattern of change over, and adjacent to, mountains – primarily an enhanced drying on the windward slopes in autumn, winter and spring. There is also, perhaps, increased rainfall over the peaks of the Alps in summer, consistent with work in the European Alps (Giorgi et al. 2016), but this is present mainly north of the Victorian border. See also Grose et al. (2019b) for details about the enhanced drying associated with topography.

These broadscale differences and regional details can be drawn out and the ranges between models in each of the ensembles can be put in context using bar plots for key VCP19 regions for this far future and high emissions scenario. Two interesting and notable cases are shown here, see individual reports for the others. Ovens Murray on the inland slopes of the Alps (Figure 39) shows the enhanced drying in the cool seasons in the VCP19 runs compared to the host models and all of CMIP5, but also shows notable overlap in the model range. The plot shows the difference from previous dynamically downscaled ensembles (NRM-CCAM, NARClIM) is very marked. Differences from BOM-SDM are not notable except in summer.

Individual VCP19 model simulations (marked as dark dots in Figure 39 and Figure 40) show the grouping of models is not even with some strong grouping in some seasons. For example, in spring, there are five simulations that indicate marked drying, but one simulation indicates a wetter future. This is largely related to the host models, chosen to be representative of the complete set of CMIP5 models that show this range, but there is also some effect from the simulation by CCAM as well.

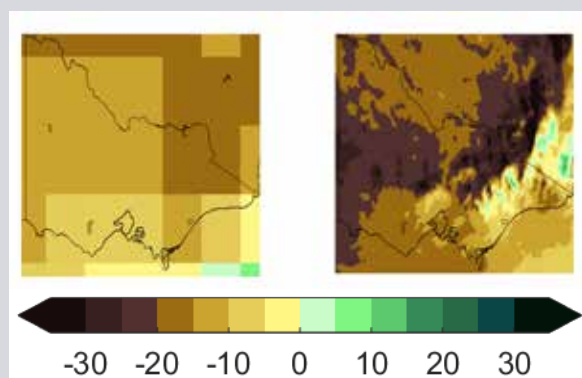
## Enhanced drying on the western slopes of the Alps in cool seasons

By resolving the mountain ranges of Victoria, the new modelling reveals a physically plausible regional pattern of projected rainfall change, with high agreement across models for a greater projected decrease on the western windward slopes and some models indicating little change on the eastern slopes.

**Possible reasons:** physical response of the air flow over mountains in a warmer climate

**Seasons:** autumn, winter and spring

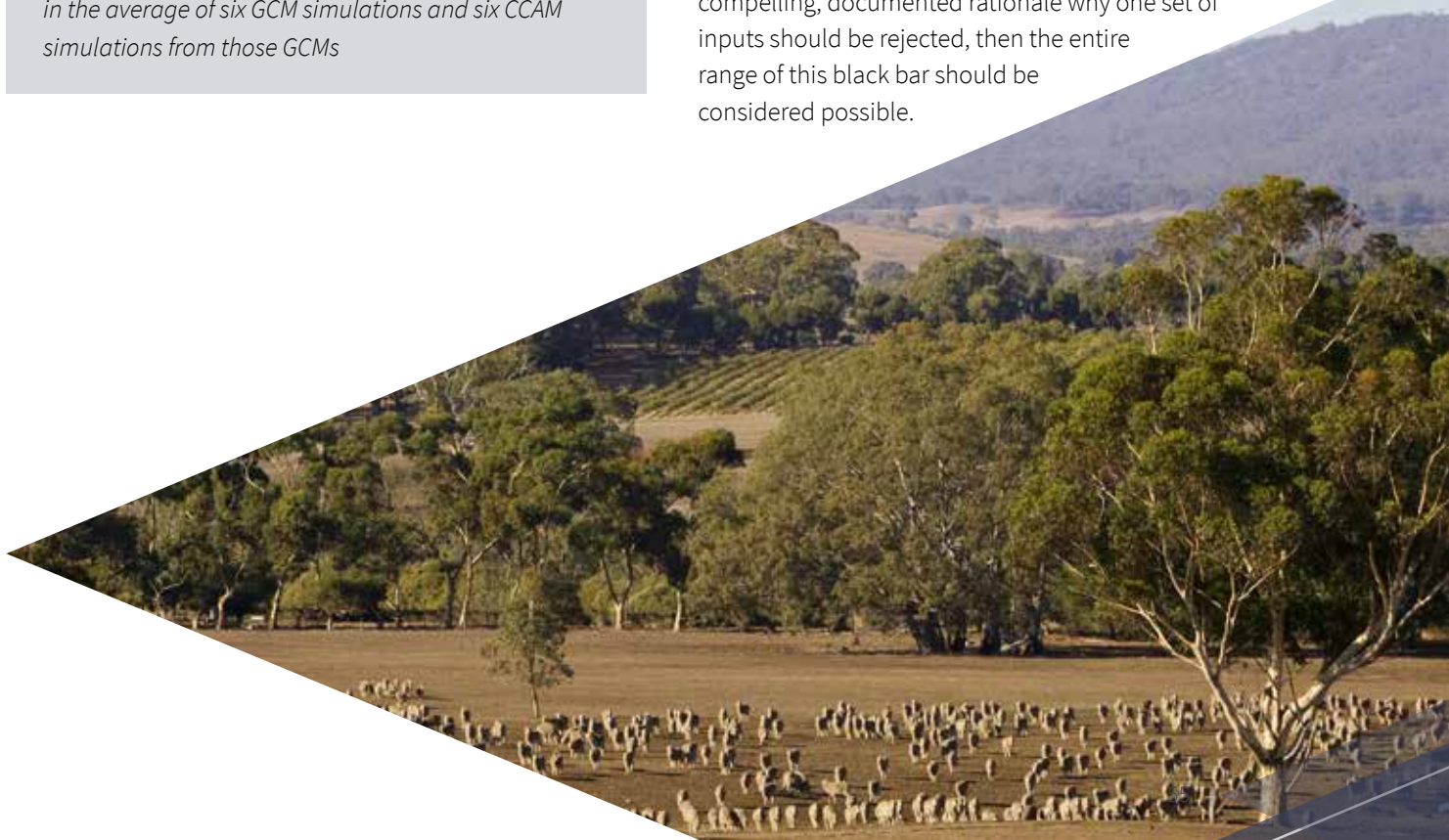
**Regions:** particularly Ovens Murray, but other regions too



*Projected change in winter rainfall – RCP8.5 by 2090, in the average of six GCM simulations and six CCAM simulations from those GCMs*

Grose et al. (2019b) propose that the change in convective rainfall may determine the sign of change in this season inland of the mountains. Such a change will be accounted for in GCMs and dynamical downscaling but not in analogue-based statistical downscaling (e.g. BOM-SDM), which may explain this difference in results. There are notable differences between VCP19 runs and NARClIM, which is likely to be partly due to model selection (the projects used completely different models as input) and also the configurations of the dynamical downscaling models. The ensemble of configurations chosen for the modelling system used in NARClIM are specifically chosen to encompass a wide range of possible rainfall results (e.g. Di Virgilio et al. 2019). Figure 39 shows that the ranges of CMIP5 and the six host models (6xGCMs) are similar, supporting the selection of models as broadly representative in temperature and rainfall change. For the Greater Melbourne region (Figure 40), the results are similar but the differences among ensembles are less pronounced.

An alternative to using any one ensemble in isolation, or considering them all separately, is to produce a combined ensemble distribution of all inputs. This is shown as a black bar in Figure 39 and Figure 40, and uses randomly drawn data from each ensemble, with equal weighting given to each set of inputs, to produce a new statistical sample. See Ekström et al. (2007) for more detail of the methods, and Grose et al. (2015b) for another example of its use. Note that the bar does not cover the entire range of all the bars from input data sets, as the very ends are not shown (the 10th to 90th percentile range is shown). Without a compelling, documented rationale why one set of inputs should be rejected, then the entire range of this black bar should be considered possible.



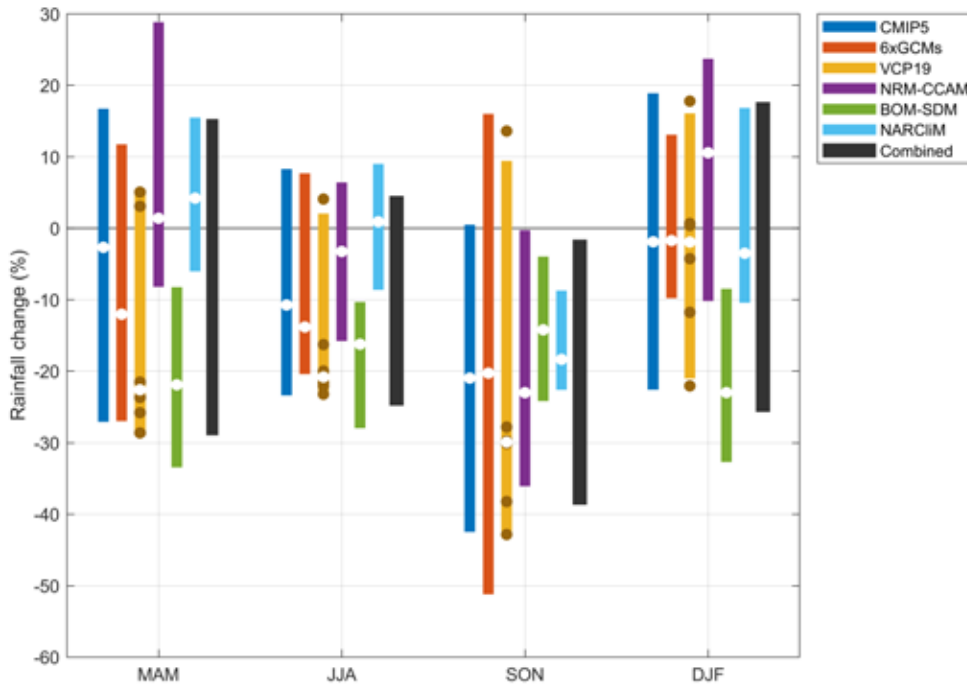


Figure 39. Projected rainfall change for the Ovens Murray (OVM) region, showing the different ranges of projected change for each season from each ensemble of models and a distribution that combines them all (bars show the 10th to 90th percentile range of results, white circle shows the median).

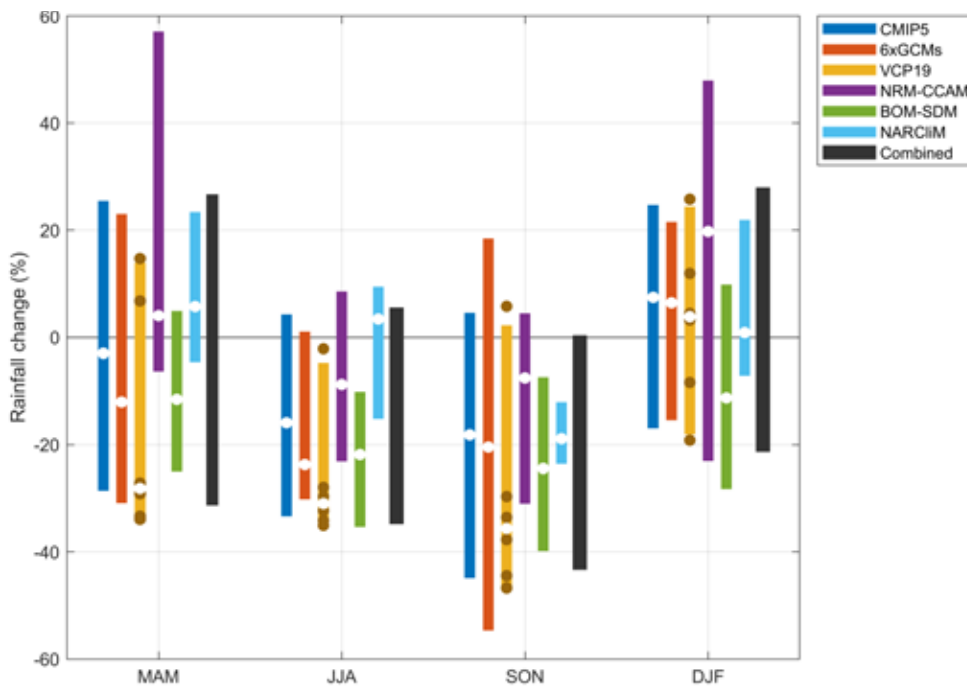


Figure 40. Projected rainfall change for the Greater Melbourne (MET) region, showing the different ranges of projected change for each season from each ensemble of models and a distribution that combines them all (bars show the 10th to 90th percentile range of results, white circle shows the median).



All downscaling approaches are aimed at producing plausible regional projections of a change in the climate. A high level of agreement among different ensembles provides strong evidence that any regional-scale changes are plausible. However, the new VCP19 runs present a different view of future rainfall than previous dynamical downscaling from an earlier (and lower resolution) version of CCAM (the NRM-CCAM runs) and the NARClIM runs, particularly for summer and autumn. The VCP19 runs do agree with previous statistical downscaling (BOM-SDM) in some important aspects while differing in others (e.g. in the most extreme dry projection and the summer projection). This raises the question of why the different ensembles give different results, and if any ensemble should be weighted lower than any other for being less physically plausible or otherwise lower in confidence than the others.

There are two main explanations for a difference between the downscaling ensembles: the choice of host models from which to downscale, and details of the dynamical interactions within the model. The new CCAM results are different from previous CCAM results for a combination of both reasons. The NRM-CCAM used three host models in common with the VCP19 runs but three that were different. This explains some of the difference. The selection of host models used for VCP19 was drawn wholly from the representative set selected by *Climate Change in Australia*. In contrast, NRM-CCAM used only three of these models as hosts. As described in section 2.2, the set of six host models used for the VCP19 runs is broadly representative of the full CMIP5 archive, with some gaps (compare panels in Figure 37, and bars in Figure 39 and Figure 40).

In terms of model design, the version of CCAM used for the VCP19 runs is higher resolution (5 km compared to 50 km for NRM-CCAM) and has had ongoing model development since the version used for the NRM-CCAM simulations. Accordingly, the new version produces different results. The MSLP and circulation response in the CCAM simulations is different than the GCM hosts (see section 5.4), possibly due to a different response to the surface warming pattern, and this may play a role in creating a different rainfall projection. However, we are not able to determine whether the CCAM response is more or less plausible than the GCMs.

The influence of the downscaling model (rather than host model choice) is shown in Figure 41 where autumn rainfall is projected by the ensemble of the three host models that were common to both the NRM-CCAM and VCP19 runs. This shows that the average of the three GCMs (panel a) projects a decrease in rainfall, whereas the average of the three NRM-CCAM runs (panel b) projects a rainfall increase. The average

of the three VCP19 simulations (panel c) projects mainly a decrease in rainfall similar to the host models but with a regional pattern mainly related to topography (a physically plausible pattern, see Grose et al. (2019b)). The average of three BOM-SDM simulations (panel d) projects mainly a decrease in rainfall but with greater magnitude and with some artificial hard boundaries related to the model set up (e.g. the boundary bisecting the Gippsland region).

The added value from the downscaling in the spatial pattern of projected change over mountain regions in response to the topography is presented with *medium to high confidence*, as there is a physical explanation for the difference from GCMs laid out in a peer-reviewed paper (Grose et al. 2019b) and agreement with other modelling systems and recent observed changes. However, the confidence in the broader rainfall projection being reliable is lower, since model agreement is lower.

It is impossible to comprehensively demonstrate which projection is more reliable, since we cannot check against the actual rainfall change to 2090 under that exact emissions scenario. However, the improved representativeness of the host model selection and the similarity of the regional pattern of change with the host models, coupled with physically plausible enhanced regional detail are two lines of evidence supporting the VCP19 projections being physically plausible. In contrast, a case would have to be made that the increases simulated by NRM-CCAM or the greater decreases produced by the BOM-SDM are more physically plausible than other sources of information for them to be used in isolation. To date, such a case has not been made. Therefore, CCAM projections should not be used in isolation and instead the full range of projected change in rainfall (black bars in Figure 39 and Figure 40) should be considered plausible. Also, the median of the six CCAM runs should not be considered as a single ‘best estimate’ of change, particularly for the dry projection in spring. Instead, a scenario-based approach should be taken, sampling from the full range of possibilities, and including cases from CCAM.

Figure 42 further tests the assertion that the projected changes in rainfall in the VCP19 results are consistent with the broader projection of the CMIP5 GCMs, but with added regional detail over mountains and near coasts. Each panel shows the ensemble average for the CMIP5 GCMs over the southeastern corner of Australia, with the VCP19 ensemble averages superimposed over just a rectangle encompassing Victoria. There are relatively few discontinuities between the spatial patterns of change in the two domains, but with higher resolution patterns within the Victorian domain.

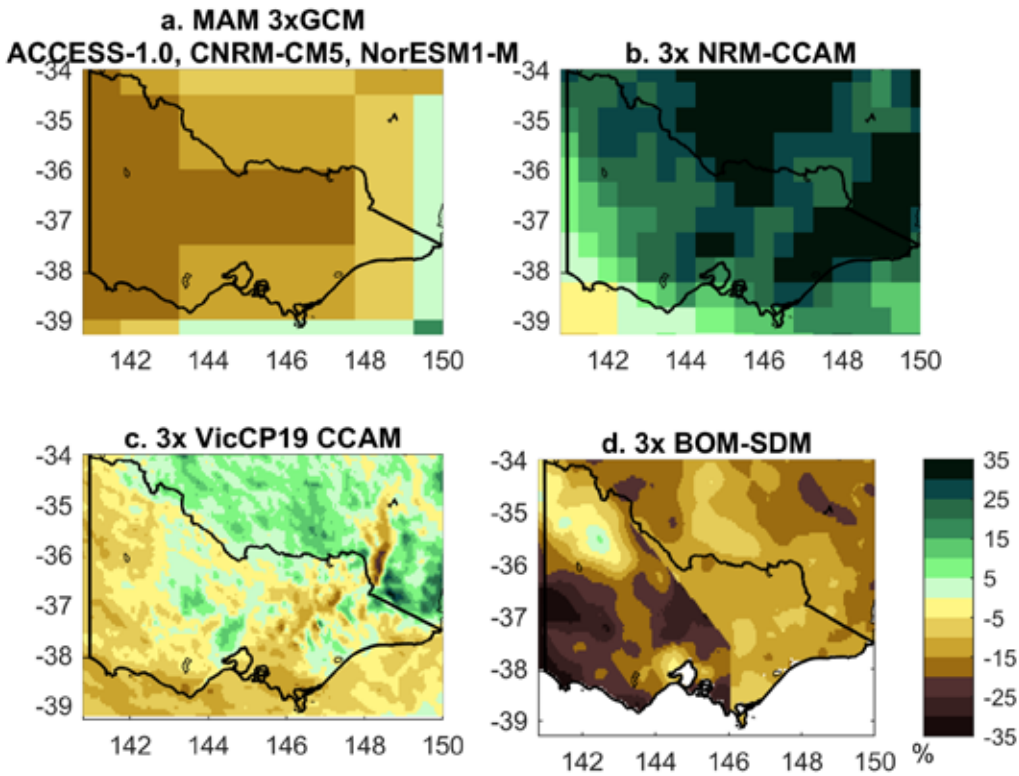


Figure 41. Comparison of the model average projected change in average rainfall between 1986–2005 and 2080–2099 in three GCMs and three downscaling ensembles that use those GCMs as input.

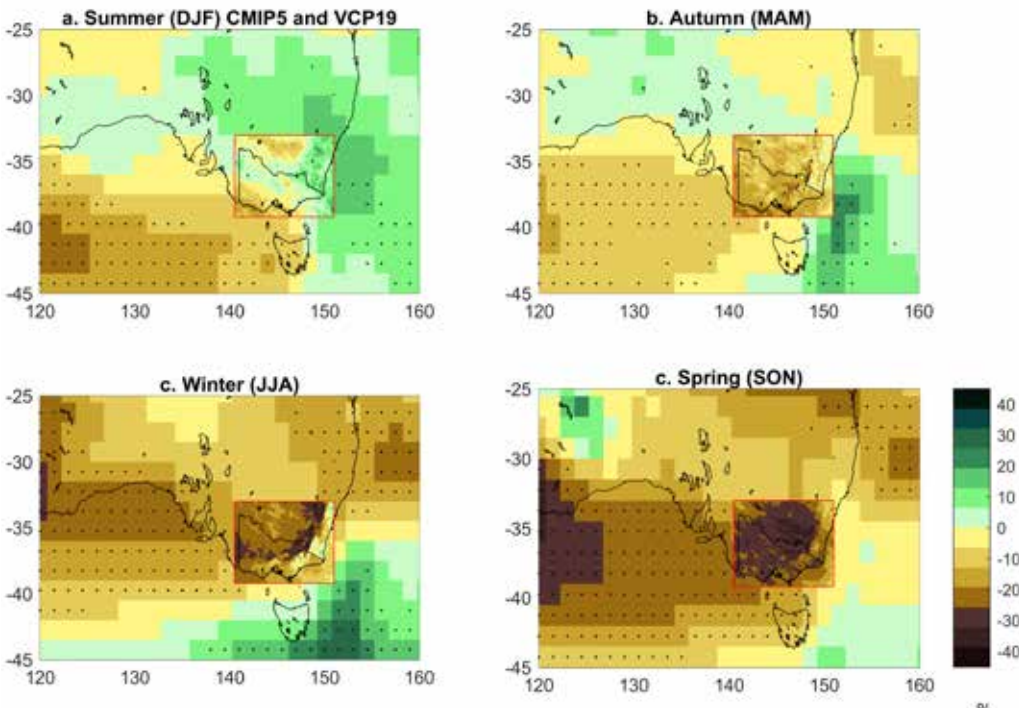


Figure 42. Projected change in rainfall between 1986–2005 and 2080–2099 under RCP8.5 in 45 CMIP5 models over Australia, overlaid with the average of six VCP19 simulations over the Victorian region in four calendar seasons as marked. Stippling is only shown for GCMs and indicates where 80% or more of models agree on the sign of change (more than 35 of the 45 models).

### 5.3.4 Snow

No new analysis of projected changes to snow cover or snow depth is presented here, but a preliminary analysis of the new simulations show they confirm previous findings regarding projected changes to snowfalls and snow cover. Snow depth and the spatial extent of snow cover have been decreasing since the 1950s at many locations in Victoria, with the largest declines during spring. Snow depths are related to temperatures, and the decline is linked to the warming experienced (Davis 2013). In future, snow depths and snow extent are projected to continue decreasing, due to reductions in snowfall and increases in snow melt. The magnitude of the reduction depends on the emissions scenario, where considerable reductions to very low snow cover is projected under a high scenario, but significant reductions even under a moderate scenario. Ski resorts can supplement a lack of natural snow with snow making up to a point, but eventually this can become unviable. 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. For more detailed analysis, see the national climate projections and other previous studies (Nicholls 2005; Hennessy et al. 2008; Bhend et al. 2012; CSIRO and Bureau of Meteorology 2015; Harris et al. 2016).

### 5.3.5 Rainfall extremes

A warmer atmosphere can hold more moisture, so with all else being equal, heavy rainfall at the scale of minutes to a day is expected to increase in most places and seasons as a general response. This has been observed at the continental scale in hourly data, at close to or above the expected rate of about 6.5% per degree of global warming ( $\%^{\circ}\text{C GW}^{-1}$ , (Guerreiro et al. 2018a)). We expect this to be important for hourly to daily rainfall extremes in Victoria both in the current climate and in future. This process can be offset or enhanced by changes to the intensity, frequency or other characteristics of the weather systems that bring heavy rainfall. For example, the future of the strongest cold fronts, thunderstorms, east coast lows or extra-tropical cyclones is important to understanding future extreme rainfall.

In places where average rainfall is projected to decrease slightly, the rainfall from wet days, heavy rainfalls and extreme daily rainfall is still projected to increase under a

high emissions scenario. This was the main finding from the most recent GCM-based projections for southern Australia generally, including Victoria (CSIRO and Bureau of Meteorology 2015). The increase was largest for the rarest extremes. That is, the 1-in-20-year daily rainfall (ARI20) was projected to increase by more than the annual wettest day (calculated over a 20-year period). For example, in the Southern Slopes Victoria West region under a moderate scenario (RCP4.5) by the end of the century, the range of projected change in annual average rainfall was mainly negative (-15 to +3%, median -7%), but the range of ARI20 was mainly positive (-7 to +39%, median of +15%). In comparison, changes to the rainfall on heavy rain days (amount of rainfall on days above the 99th percentile) was projected to increase but with a large range of possibilities (-10 to +76%, median of 18%). Under the lowest scenario (RCP2.6) changes were much less pronounced (and indeed, mean annual rainfall was projected to change less, with a range of -13 to 3%, median of -3%). (For more detail, see CSIRO and Bureau of Meteorology (2015) and the *Climate Change in Australia* website<sup>4</sup>).

The new VCP19 downscaling results support the previous projections for a likely increase in daily rainfall extremes under a high or medium emissions scenario, despite decreases in average rainfall (Figure 43) and with a range of changes possible. This suggests that the higher resolution of atmospheric processes in VCP19 runs (5 km over Victoria compared to 60 km or more in GCMs) does not alter the projection significantly. There is the possible exception in the central regions of Loddon Campaspe (LOC), Goulburn (GOU) and Ovens Murray (OVM) under RCP8.5, where VCP19 runs projected increase in the magnitude of daily rainfall extremes is not as large. This suggests the stronger drying projected by VCP19 runs and the simulated changes to the relevant weather systems result in a lower projection, creating a plausible lower scenario of change.

Given the physical evidence, agreement among models and previous research, an increase in intense rainfall at the hourly to daily scale is projected with *high confidence*, but the magnitude of the change is less certain. It is possible that further new insights could be found using extremely high-resolution modelling (e.g. 1.5 km) that is capable of simulating convection at finer spatial scales.

4 [www.climatechangeinaustralia.gov.au](http://www.climatechangeinaustralia.gov.au)

## Compound extremes

Extreme events in one climate variable (e.g. hot days, very wet days) can have important impacts, but events with the greatest impact are often those with extremes of multiple variables and those that occur simultaneously or in succession, including:

- ▶ extreme storm surge and extreme rainfall and winds occurring as part of an intense low-pressure system
- ▶ a prolonged heatwave and/or extreme heat days during a drought
- ▶ drought and heat leading to higher fire danger
- ▶ a series of extremes with cascading impacts, such as Tasmania experienced in 2015–16 (hot, dry spring and summer, fires, a marine heatwave, floods, then a very wet period).

Climate change will affect the incidence of extremes in different climate variables, but also in the chances of compound events (e.g. sea-level rise and increasing intensity of short-duration rainfall may both increase flood risk in vulnerable estuaries). Modelling compound events is a challenging task for several reasons including the lack of high-quality data sets and is an ongoing area of research.

This projected increase in daily extremes is likely to result in unprecedented events of heavy rainfall and therefore flash flooding. The current record highest daily rainfalls at weather stations anywhere in Victoria are 375 mm at Tanybryn in the Otway Ranges in March 1983, followed by 319 mm at Mount Wellington in June 2007 and 300 mm at Rotamah Island in November 1988. To give a more commensurate comparison to VCP19 runs produced on a grid, these three records in gridded AWAP data do not exceed 209 mm. Figure 44 shows an example very wet day as simulated by the VCP19 modelling under high emissions towards the end of the century. This example shows the possibility that many regions could receive more than 150 mm in 24 hours. It also shows a plausible record daily rainfall in some areas of more than 300 mm. Note that this is not the highest daily event in the projection data but it is representative of a high event.

The projections paint a picture of a drying climate but an increase in daily rainfall extremes. There is also a projected increase in sub-daily extremes, in line with recent trends (Guerreiro et al. 2018b). This has the effect of changing the shape of rainfall intensity, frequency and duration (IFD) curves used in applications such as infrastructure engineering. An increase in the intensity of short duration rainfall (minutes to a day or so) drives an increase in one end of the curve, but a decrease in longer duration rainfall (weeks to months) at the other end of the curve. The response may also be different for the curves for different return periods. Given that projected changes are different for different regions and there is a range of change from different models, the strength and significance of these changes needs to be specifically assessed for any particular application.



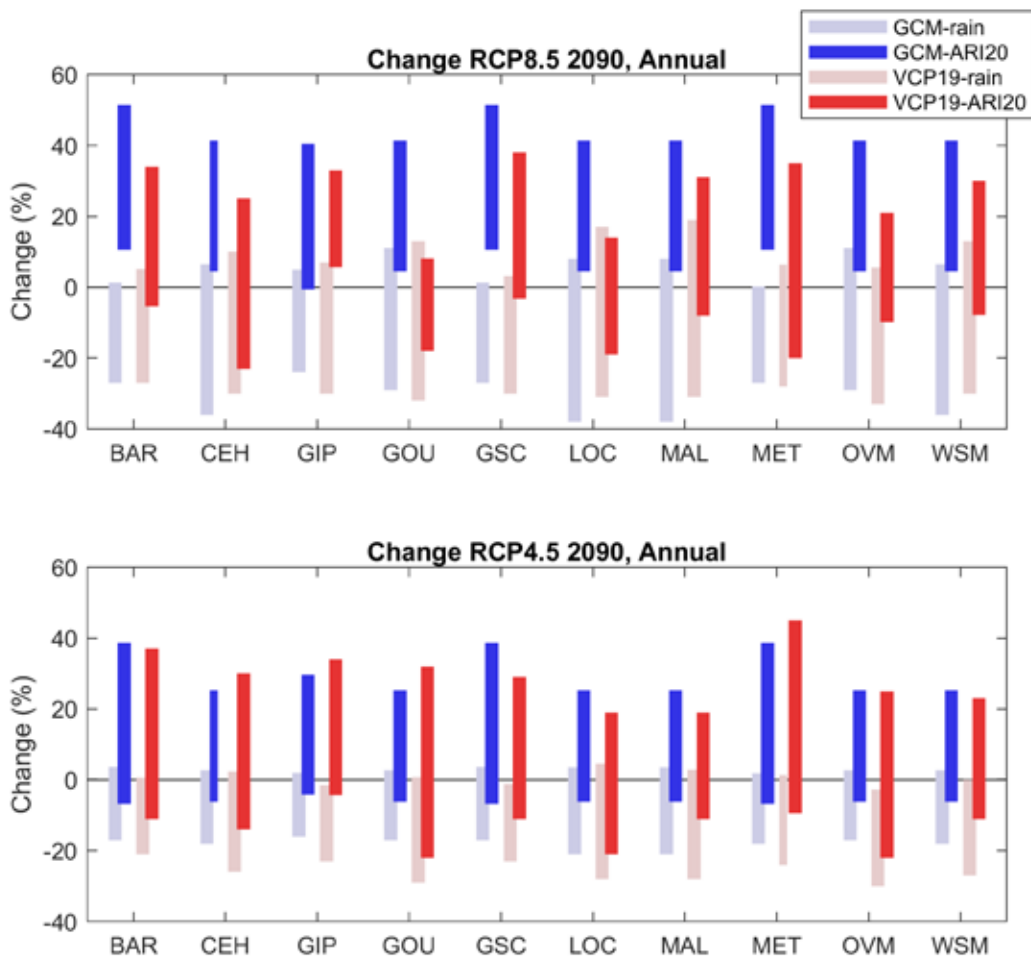


Figure 43. Proportional projected change to average and extreme (ARI20) rainfall between 1986–2005 and 2080–2099 in GCMs and VCP19 runs annually under RCP8.5 and RCP4.5 for the 10 VCP19 regions, showing generally a decrease in rainfall and an increase in extreme rainfall. The 10 high-resolution VCP19 regions are shown using their codes (see Table 4 for full names)

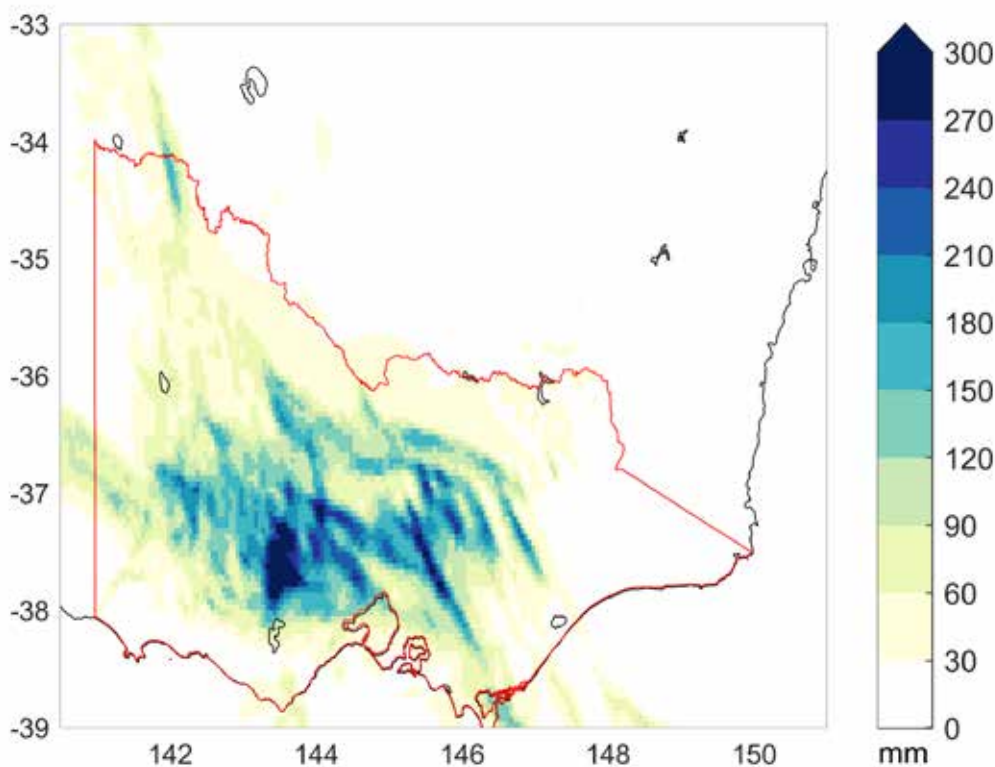


Figure 44. Daily rainfall for an example heavy rainfall day in the far future under the high scenario (2090s under RCP8.5 in the NorESM1-M model downscaled using CCAM). Note this is not the most extreme rainfall event in the simulations, just an example of a very wet event. Also note that extremes are projected to occur in all regions and the locations of the extremes this is just one example event.

### 5.4 Mean sea-level pressure

As the climate warms, mean sea-level pressure (MSLP) is projected to decrease near the south and north poles and increase in the mid-latitude regions such as Victoria. This projected change is consistent with the changes in the broad hemispheric circulation patterns including changes to the Hadley Cell, storm tracks and SAM (Collins et al. 2013). The projected change in MSLP is not uniform around the hemisphere (see Figure 7.2.11 in the national climate projections (CSIRO and Bureau of Meteorology 2015)), and the spatial pattern of change affects the regional climate change experienced at any location. In winter under a high emissions scenario by the end of the century, GCMs project a significant increase in MSLP either side of Australia and

a region of weaker MSLP increase over the south of the continent. In summer, MSLP is projected to increase to the southwest of the continent with little change or even decrease over the continent itself. This pattern is broadly represented in the six GCMs used in these projections (Figure 45). The projected change in MSLP in the average of the six 50 km CCAM simulations using these GCMs as input shows broadly the same pattern as the GCMs, but with a few notable differences. In summer and autumn, the pressure response over land is enhanced, where the MSLP is projected to decrease to a greater degree than the GCMs. This is possibly due to a different response of the CCAM model to the land-ocean contrast in temperature than the GCMs, as found previously (Grose et al. 2015b). In winter, the centre of the peak in increase in MSLP is further east than in the

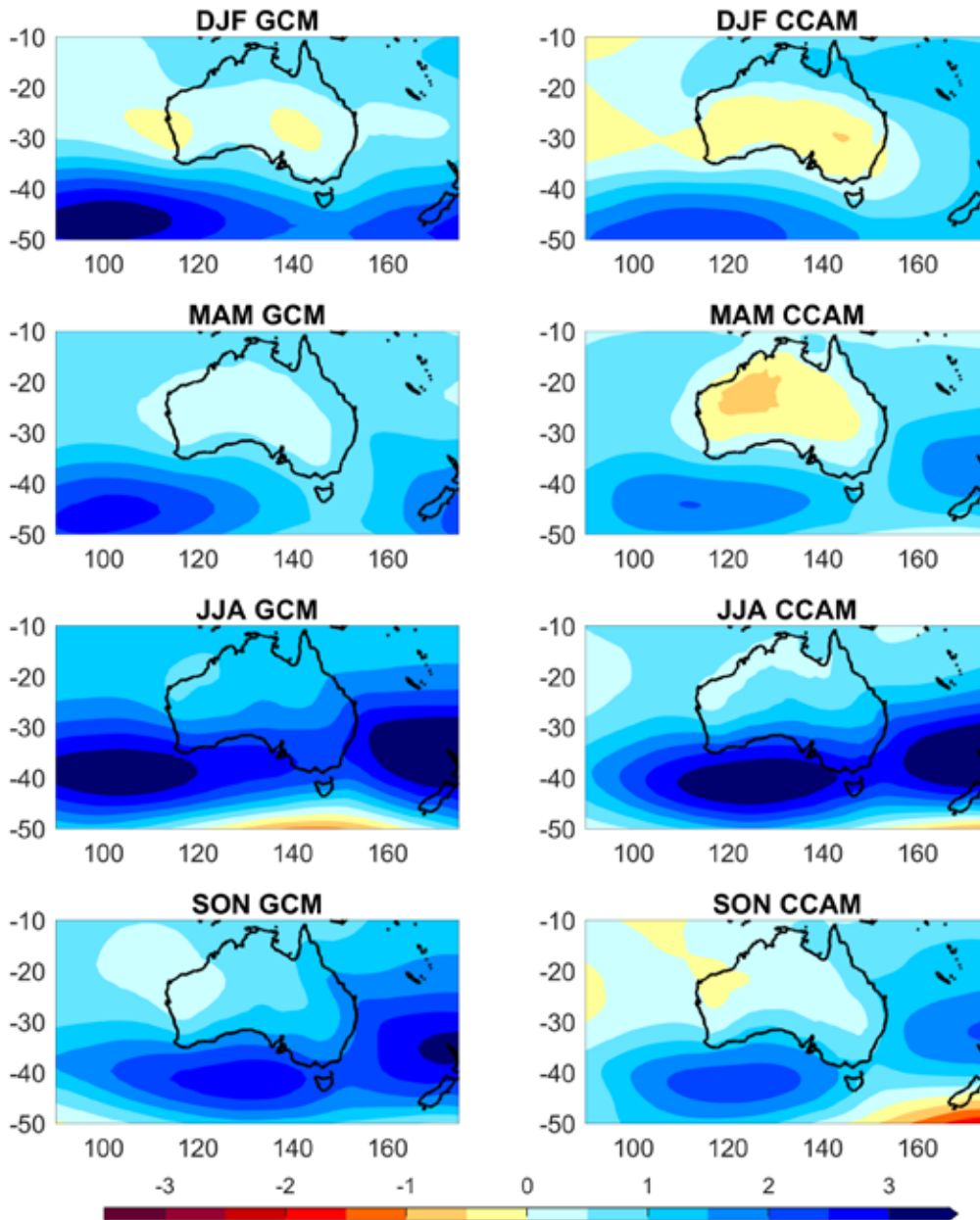


Figure 45. Model-average projected change in mean sea-level pressure (MSLP) in hPa between 1986–2005 and 2080–2099 under a high emissions scenario RCP8.5; left: average of the six GCMs used as input to VCP19; right: six ~50 km CCAM simulations used in VCP19. By calendar season.

GCM hosts, bringing it close to Victoria. These differences are expected to create a different circulation anomaly over the region of southern Australia in CCAM than in the GCMs, and possibly affect the rainfall projection. However, the broadscale rainfall projection is similar between CCAM and the GCMs (see previous section), so this effect may not be significant. It is also not clear whether the difference between the CCAM-simulated change in MSLP compared to the host GCMs less or more physically plausible or realistic than the GCMs, so it is not possible to determine whether it should be seen with lower or higher confidence than the CMIP projection.

## 5.5 Winds and storms

### 5.5.1 Mean winds

Wind patterns are determined by the location and seasonal movement of broad atmospheric circulations and weather systems. During the cool seasons, the subtropical ridge is north of Victoria and experiences dominant westerly circulation, but with periods counter to this mean flow. In summer there is a mixture of circulation patterns over Victoria.

Over the 21st century, westerly 10 m wind speeds in winter are projected to decrease over southern Australia due to weakening circulation, affecting 10 m wind speeds in southern Western Australia. However, this effect is not clearly expressed over Victoria in climate models. The projected changes in 10 m wind speed in all seasons are generally small even under the highest emissions scenarios (<10% magnitude), with low agreement on the strength and direction of change (CSIRO and Bureau of Meteorology 2015).

The new VCP19 simulations are consistent with previous climate model simulations, with projected changes in the 10 m wind speed of less than 10% (mostly less than 5%) even under RCP8.5 by the end of the century, and low agreement on the magnitude or even sign of change in all VCP19 regions. This suggests that average 10 m wind speed over Victoria is unlikely to change significantly over the century.

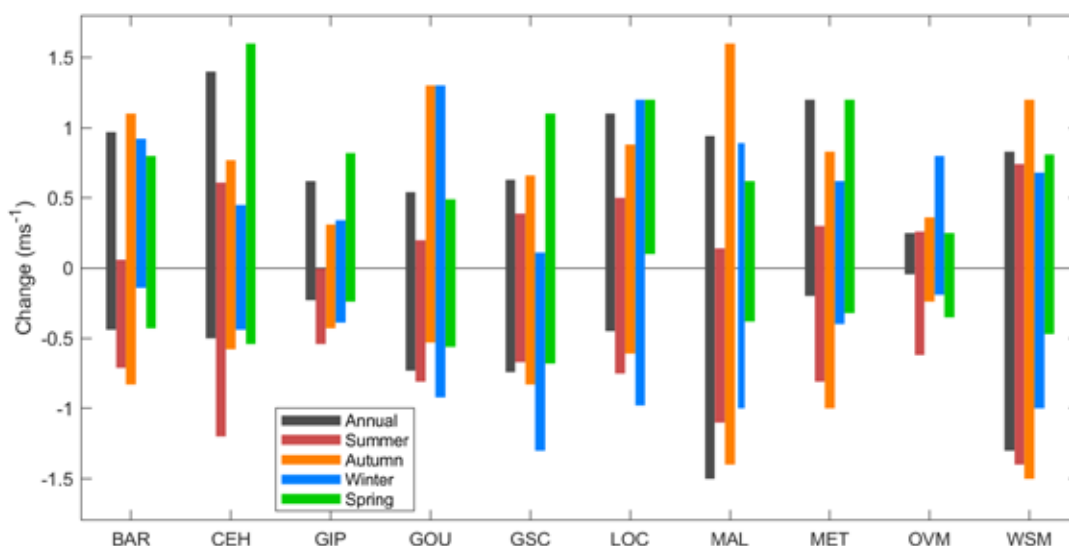
### 5.5.2 Extreme winds

High wind speeds are determined by the same atmospheric circulation and weather systems as mean winds but are modified by surface features like terrain and vegetation. GCMs do not resolve the surface features such as hills and valleys and will poorly resolve the winds associated with the systems that bring strong winds such as thunderstorm downbursts. The 5 km resolution of the VCP19 modelling resolves these features to a much greater extent, so there may be events and highly localised trends in 10 m wind speed that are notable (this requires further specialist analysis and could be the subject of further research).

The national climate projections (CSIRO and Bureau of Meteorology 2015) reported that notable changes in extreme 10 m wind speed in annual maximum and 20-year return period (ARI20) 10 m wind speeds are possible in Victoria, but the magnitude and even the sign of change was uncertain. The model median was for a slight decrease in 20-year return period 10 m wind speed for southern Victoria and the Murray Basin.

The new downscaled results also present a range of changes in extreme 10 m wind speed, but do not show high agreement on magnitude or even sign of change in extreme winds for each VCP19 region (Figure 46).

Figure 46. Projected change in 20-year return period (ARI20) 10 m wind speeds between 1986–2005 and 2080–2099 under RCP8.5 for each VCP19 region. The 10 high-resolution VCP19 regions are shown using their codes (see Table 4 for full names).



Changes in 20-year return period 10 m wind speed are shown in absolute magnitude ( $\text{ms}^{-1}$ ), and the magnitude of change is partly related to differences in the current value (larger changes on larger current values). There are some differences between regions that make sense given current knowledge of climate change. For example, the only region with high agreement on decreased 20-year return period 10 m wind speed in winter is the Great South Coast, which is consistent with reduced westerly circulation known to affect southwest Western Australia and other western coasts.

### 5.5.3 Storms and lightning

Interpreting changes in storms and lightning is a challenge for both GCMs and RCMs. This is because the important processes are also not well resolved by the RCM simulation. Examining the Convective Available Potential Energy (CAPE) can provide an indication of favourable conditions for forming thunderstorms. Projected changes in CAPE can be sensitive to the convective parameterisation used by the atmospheric model, which is an active research area of atmospheric and climate modelling. However, in broad terms the CCAM downscaled results suggest an increase in the favourable conditions for thunderstorm formation under global warming. Further research and additional downscaling experiments by different models will be required to better understand how thunderstorms will change in the future.

## 5.6 Relative humidity

Humidity is a measure of water vapour content in the atmosphere. Humidity near the Earth's surface is important for many processes, including transpiration by plants, fire behaviour and human comfort. There are several measures of humidity, such as specific, absolute and relative humidity. A related measure is dewpoint – the temperature at which water vapour condenses. Humidity is not routinely measured directly, but rather computed from observations of other variables, notably dewpoint. Lucas (2010) reported that there was an increasing trend in Australian averaged dewpoint values between 1957 and 2003. Over that period, dewpoint temperature increased at a rate of approximately  $0.1^\circ\text{C}$  per decade.

Projected changes in relative humidity (the amount of water vapour present in the air as a proportion, expressed in percent, of the maximum possible) are relatively small (Figure 47). Even under high emissions towards the end of the century, relative humidity is expected to show a median change of only  $-6.1\%$  (with a range of  $-8.3$  to  $+0.7\%$ ). While there are regional and seasonal differences, the projected changes are consistently relatively small and mostly show declines.

However, the projections for spring under high emissions around 2090 (Figure 48) show the strongest declines, with a range from  $-1.3$  to  $-13.6\%$ . These changes are broadly consistent with those projected using the CMIP5 GCMs (CSIRO and Bureau of Meteorology 2015).

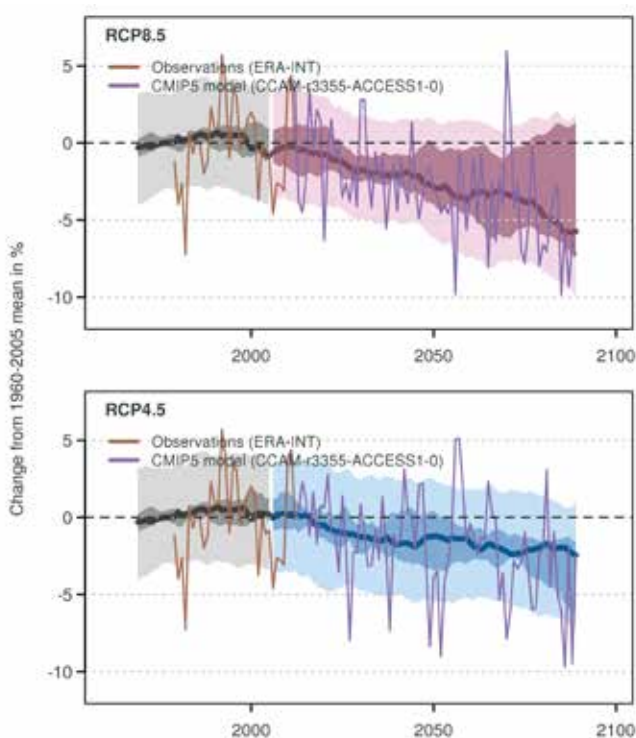


Figure 47. Time-series of relative humidity anomaly (relative to the 1960–2005 mean) from 1960 to 2090 for all of Victoria. Brown line: historic annual averages from ERA-INT; purple line: sample model results from CCAM-ACCESS1-0. For additional details on interpreting this plot, see the box on page 40.



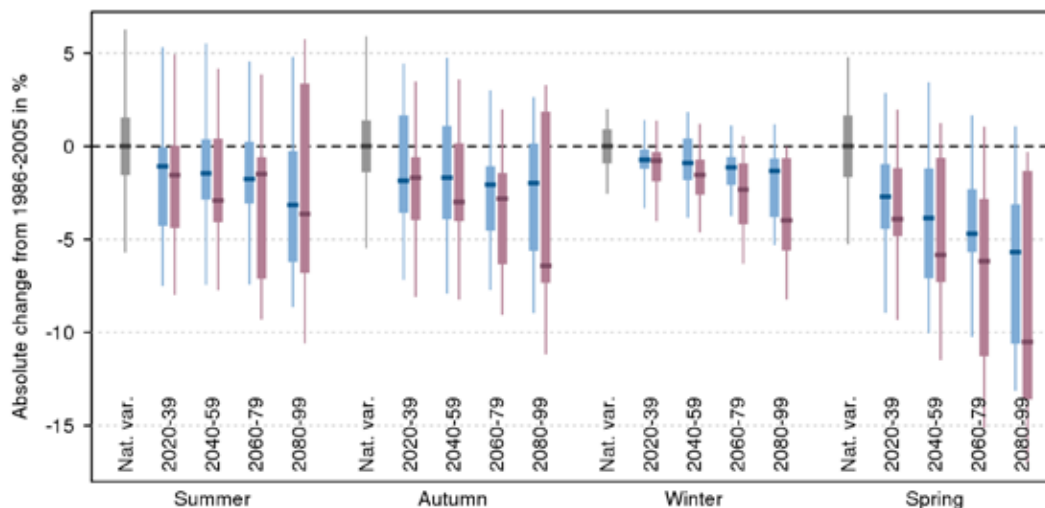


Figure 48. Bar plots of projected change in Victorian average relative humidity (%) in the calendar seasons for different future time windows and RCPs (see box on page 40 for details of how to interpret the plots)

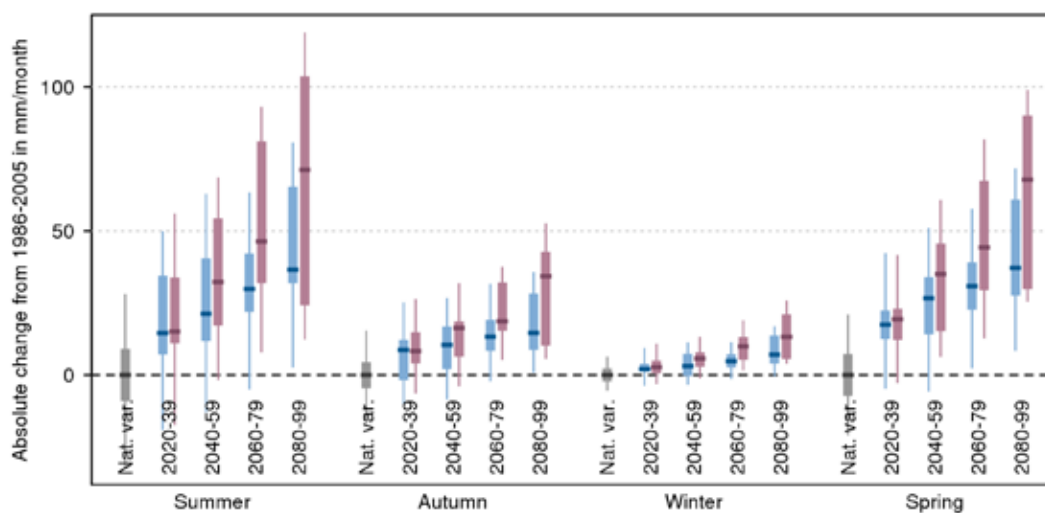


Figure 49. Bar plots of projected change in Victorian average pan evaporation in the calendar seasons for different future time windows and RCPs (see box on page 40 for details of how to interpret the plots).

## 5.7 Evaporation

Like relative humidity, evaporation is important for many applications, including agriculture (transpiration), water management and human health. Here we report on pan evaporation (the evaporative loss from a small body of water). Pan evaporation is modelled directly by CCAM whereas with GCM data, it must be estimated from other variables (see *point potential evapotranspiration* data on the CCIA website).

Pan evaporation is projected to increase overall for Victoria, with the greatest increases in spring and summer (Figure 49). The VCP19 runs show the greatest increases in summer under high emissions towards the end of the century.

## 5.8 Fire weather

As discussed in the *Climate Change in Australia* technical report, the occurrence of fire depends on the availability of fuel, the dryness of the fuel, a form of human or natural ignition, as well as suitable weather conditions. In this section, we estimate changes in the number of fire days using the Forest Fire Danger Index (FFDI) (McArthur 1967). FFDI attempts to account for fire weather (e.g. hot, dry and windy conditions) as well as fuel dryness, as a function of temperature, humidity, wind speed and drought factor. In turn the drought factor is dependent on changing rainfall, leading to changes in soil moisture. FFDI does not account for changes in fuel load, which can also depend on changing rainfall with higher rainfall leading to increased fuel load.

Fire days are defined in this report as days when the FFDI exceeds the 95th percentile of the FFDI for 1986–2005 (i.e. the worst 365 days of FFDI over the 20-year reference period). This approach to defining fire days is based on the analysis used for the National Environmental Science Program (NESP) Earth Systems and Climate Change Hub report, *Climate Change and Bushfires in Australia* (in preparation). Note that the assessment of fire danger in this section is not intended to have a direct correspondence to the fire danger ratings use by the Victorian Government. Rather, this section simply attempts to provide an indication of how the projected changes in climate can influence changes in fire weather. Further work with the Victorian Government will be required to develop a formal assessment of changes in fire danger ratings, considering changes in fire intensity as well as projected changes in the number of fire days.

There have been trends towards higher FFDI yearly-average values in recent decades for southeast and southwest Australia, more incidence of extreme FFDI conditions and a longer fire season including an earlier start in spring (Dowdy 2018). The observed trend in FFDI is also expected to continue into the future under global warming. Figure 50 shows the projected change in fire days between 1986–2005 and 2080–2099 under RCP8.5 for the different CCAM downscaled GCMs, using a definition based on the 95th percentile of FFDI described above. Figure 50 shows that five of the six downscaled simulations by CCAM indicate some

increase in the number of fire days, except for the CCAM projection after downscaling NorESM1-M, which indicates a decrease in the number of days of up to 10 days per year. Note that NorESM1-M is also the only CCAM-downscaled GCM that projected an increase in average rainfall, which has an influence on the changing fire danger under global warming scenarios. The remaining five of the six downscaled CCAM simulations all indicate an increasing number of fire days, with the largest increases occurring in the alpine region of Victoria. For the five downscaled GCMs projecting an increase in fire days, the increase in the alpine regions is typically between 20 to 60 days, except for the CCAM-downscaled HadGEM2-CC that projected an increase of 60 to 90 days. The CCAM-downscaled simulations project a smaller increase in the number of fire days for the non-alpine regions in Victoria, with typical increases between 10 to 25 fire days per year. The CCAM-downscaled HadGEM2-CC experiment projected the most extreme increases of 20 to 40 fire days for central and eastern Victoria, with 40 to 50 additional fire days on the eastern coast of Victoria.

A more detailed analysis based on GCMs, NARCLiM and CCAM is still being developed (see NESP *Climate Change and Bushfires in Australia*, in preparation). However, the majority of CCAM 5km resolution simulations shown here are consistent with the projected average change of the GCM ensemble of typically an increase of 10 to 20 fire days per year for Victoria. However, the downscaled CCAM projections

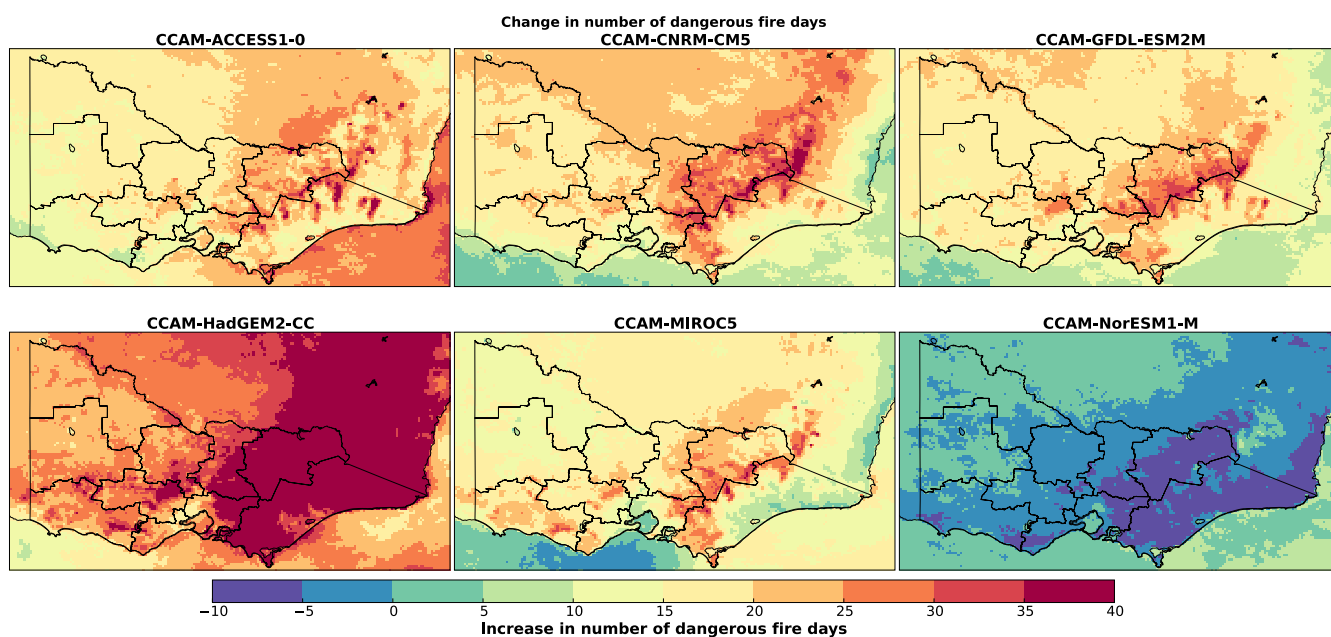


Figure 50. Change in number of fire days per year between 1986–2005 and 2080–2099 under RCP8.5 for the different CCAM downscaled GCMs. Fire days are defined in this report as exceeding the 95th percentile Forest Fire Danger Index (FFDI) for 1986–2005.

have emphasised an increased number of fire days in the alpine regions that can be roughly double the increase in fire days for the non-alpine regions. Further analysis that also includes the other factors that influence fire danger and an analysis more consistent with the Victorian fire ratings will be important for a more complete assessment of changing fire risk.

## 5.9 Sea level

At large spatial scales, sea levels are influenced by changes in ocean density through heating or cooling of the ocean, and by changes in ocean mass through exchanges with the cryosphere (glaciers and ice sheets) and the terrestrial environment such as soil moisture, lakes and groundwater (CSIRO and Bureau of Meteorology 2015). These large-scale influences can be further modified at the regional scale by effects that act over various time-scales. These include long-term processes such as vertical motion of the land in response to the melting of ice sheets (known as glacial isostatic adjustment, GIA) through to shorter time-scales such as year-to-year (interannual) changes in ocean dynamics driven by climate drivers such as ENSO, and seasonal cycles of changes in 10 m winds and the transfer of heat and fresh water between the ocean and the atmosphere (Church et al. 2011a; CSIRO and Bureau of Meteorology 2015).

As ice sheets and glaciers melt, they alter Earth's gravity field which results in sea-level changes that vary geographically (Mitrovica et al. 2011), meaning that relative sea level is not increasing everywhere on the Earth. It is falling in regions of former ice sheets, rising at faster than the global average rates in adjacent regions, and rising slightly less than the global average in many distant regions (CSIRO and Bureau of Meteorology 2015 and references therein).

Measurements of sea level are obtained via tide gauges and, since 1993, by satellite altimeters. Tide gauge data have indicated that globally sea-level rise has occurred at a rate of  $1.7 \pm 0.2$  mm/yr between 1900 and 2010, with higher rates of rise evident since 1993 confirmed by satellite altimeter data (Church and White 2006; Jevrejeva et al. 2006; Jevrejeva et al. 2008; Church et al. 2011b; Ray and Douglas 2011). From 1993 to 2009, global mean sea-level rise (GMSL) occurred at a rate of 2.8 mm/yr from tide gauge data and 3.4 mm/yr from satellite altimeter data.

Sea-level measurements began in Australia in about 1840 at Port Arthur in Tasmania (Hunter et al. 2003), but the two longest sea-level records are at Fort Denison (Sydney) from 1912 and Fremantle (Western Australia) from 1897.

In Victoria, a citizen science project run by CSIRO in recent years has digitised and quality-controlled paper tide gauge records from Williamstown, extending the useable record back to 1872.

Observed rates of sea-level rise for Australia are consistent with global-average values. After accounting for and removing the effects of vertical land movements due to glacial rebound and the effects of natural climate variability and changes in atmospheric pressure, sea levels have risen around the Australian coastline at an average rate of 2.1 mm/yr from 1966–2009 and 3.1 mm/yr from 1993–2009. There is geographic variation in sea-level rise around Australia, but the trend for the Victorian region is similar to the Australian average (Figure 51). Tide gauge and satellite altimeter trends are generally similar for much of Australia, including the Victorian region. The lower trend at the coast compared with offshore for southeastern Australia is thought to be associated with a strengthening of South Pacific Ocean circulation and southward extension of the East Australian Current.

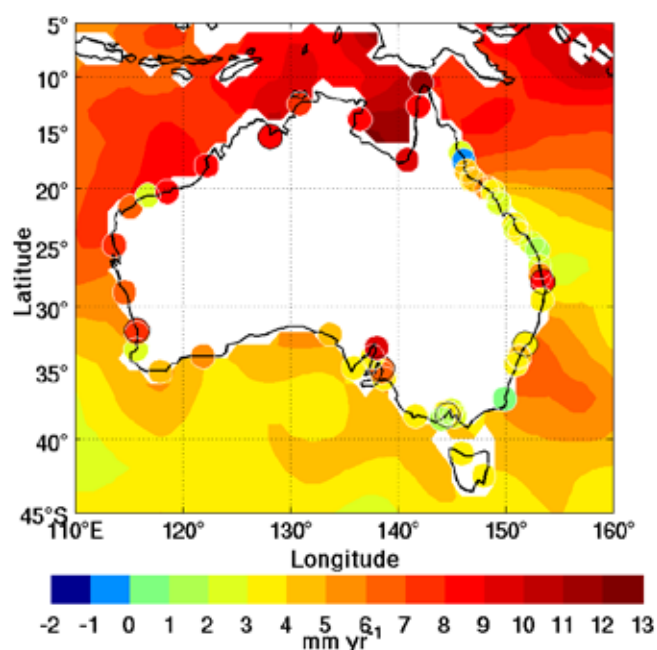


Figure 51. Sea level trends from satellite altimeters (coloured contours) and tide gauges (coloured dots) for 1993 to 2010 after correction for glacial isostatic adjustment. (Source: CSIRO and Bureau of Meteorology 2015)

In the future, the main contributors to sea-level rise are expected to continue to be ocean thermal expansion and loss of glaciers and ice caps, together with loss of ice sheets and changes in the mass of water stored on land. Projections for global mean sea-level rise by the end of the 21st century for RCP2.6 is 0.26–0.55 m (relative to the 1986–2005

baseline), and 0.45–0.82 m under RCP8.5. Projections of sea-level rise for Australia have been made using the methods of Church et al. (2014) and are comparable to the global mean sea-level projections. Projected changes in sea level related to changes in ocean density and circulation (available directly from CMIP5 GCMs) were combined with contributions derived from purpose-built models designed to estimate additional sea level contributions, i.e. from the loss of mass from glaciers, the surface mass balance and the dynamic response of the Greenland and Antarctic ice sheets, changes in land water storage, the mass redistribution from glacier and ice sheet loss and its gravitational response on the ocean, and GIA (CSIRO and Bureau of Meteorology 2015).

National sea-level projections were released in 2015 (CSIRO and Bureau of Meteorology 2015). Tables and maps of projected change under different emissions scenarios and future time periods are available via the *Climate Change in Australia* website<sup>5</sup>. The sea-level data are also available via the *CoastAdapt* website<sup>6</sup> where it has been provided for each coastal council around Australia for four emissions scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) at five time periods (2030, 2050, 2070, 2090, 2100), as well as a rate of sea-level rise for 2100. Projections for key areas in Victoria were also

produced and are available as part of DELWP's *Climate-ready Victoria* brochures<sup>7</sup>. These have been summarised in Table 8 and show projected increases in sea level of around 0.12 m (relative to the baseline period of 1986–2005) by 2030 under medium (RCP4.5) and high (RCP8.5) emissions scenarios. By 2070, the emissions scenario has greater impact, with increases of around 0.32 m under RCP4.5, but up to 0.42 m under RCP8.5. It should be noted that these levels may be higher, depending on the trajectory of Antarctic ice sheet melting in the future (Church et al. 2013). New observations and studies of the role of ice sheet dynamics in future sea-level rise will be quantified in upcoming IPCC assessment reports such as the IPCC Special Report on Oceans and Cryosphere in a Changing Climate (due for release in September 2019).

Sea-level rise not only results in changes in mean sea level, but also contributes to extreme events which are caused by a combination of mean sea level, tides, storm surge, surface waves and coastal geometry. The physical impacts of extreme sea levels on the coast include inundation and erosion. How this might impact Port Phillip Bay in the future is the focus of a DELWP-funded project investigating the likely future hazards of coastal erosion, inundation, and groundwater intrusion. Results will be released in early 2020.

5 [www.climatechangeinaustralia.gov.au](http://www.climatechangeinaustralia.gov.au)

6 <https://coastadapt.com.au/>

7 <https://www.climatechange.vic.gov.au/information-and-resources>

Table 8. Sea-level rise projections (m) relative to the baseline (1986–2005) for key Victorian locations under medium (RCP4.5) and high (RCP8.5) emissions scenarios for 2030 and 2070. Shown are the median values, with the 5th–95th percentile range given in brackets. (Compiled from *Climate-ready Victoria regional data sheets*)

Location	2030 RCP4.5	2030 RCP8.5	2070 RCP4.5	2070 RCP8.5
Geelong	0.12 (0.07–0.16)	0.12 (0.08–0.17)	0.32 (0.20–0.45)	0.40 (0.26–0.54)
Point Lonsdale	0.11 (0.07–0.16)	0.12 (0.08–0.17)	0.32 (0.20–0.45)	0.39 (0.25–0.54)
Cape Otway	0.12 (0.07–0.16)	0.12 (0.08–0.17)	0.32 (0.20–0.45)	0.40 (0.26–0.54)
Port Fairy	0.12 (0.08–0.16)	0.13 (0.08–0.17)	0.33 (0.21–0.46)	0.40 (0.26–0.55)
Portland	0.12 (0.08–0.16)	0.13 (0.08–0.18)	0.34 (0.21–0.46)	0.41 (0.27–0.56)
Inverloch	0.12 (0.07–0.16)	0.12 (0.08–0.17)	0.33 (0.21–0.45)	0.40 (0.27–0.54)
Seaspray	0.12 (0.07–0.16)	0.13 (0.08–0.17)	0.33 (0.21–0.45)	0.40 (0.27–0.55)
Marlo	0.12 (0.08–0.17)	0.13 (0.09–0.18)	0.34 (0.22–0.46)	0.42 (0.29–0.56)
Williamstown	0.11 (0.07–0.16)	0.12 (0.08–0.17)	0.32 (0.20–0.45)	0.39 (0.25–0.54)
Stony Point	0.11 (0.07–0.16)	0.12 (0.08–0.17)	0.32 (0.20–0.45)	0.39 (0.25–0.54)

### 5.10 Step changes

Most climate projections presented in this report give a view of an ongoing climate change signal with climate variability overlaid on it. The climate change signal is presented as a smooth or incremental process, and climate variability is seen as a window or band where the climate varies around this baseline signal. This assumes relative independence of internally-generated climate variability and externally-forced climate change, with a linear combination of the two. However, climate variation and change can appear as steps and jumps rather than a smooth series. The appearance of steps can occur either by an underlying variability and a steadily changing climate combining together to give the appearance of rapid shifts (Figure 52), or true non-linear steps in the climate system (Figure 53). True step changes may be from a rapid transition from one circulation regime to another, also known as a flip between different steady states, such as has been proposed for the southern hemisphere in the late 1970s (Frederiksen and Frederiksen 2011), or from reaching tipping points such as the collapse of ocean circulations, ice sheets or loss of forests (Collins et al. 2013). Here we show an example of temperature, but the same principles also apply to other variables (see also section 5.2.2).

Regardless of the nature of the interaction, the net result is that time-series of climate data can have step change or break points in them. For example, an automated analysis of abrupt change points (detection of where the data do not behave like a linear series) in the mean of Victoria’s average annual temperature observations reveals two break points at 1971 and 1999 (Figure 54). Examining climate models, we see that they also simulate these abrupt changes and break points (Figure 55). The simulated break points do not coincide with observed breakpoints unless it is largely driven by an external forcing such as a major volcanic eruption.

For any change, such as a temperature increase or shift in mean rainfall, the change may appear as a relatively stable regime followed by a step-like change, followed by a relatively stable period, and so on. This is particularly important for considering the near-term climate to 2030: if and when there are step-like changes, these may be much more notable and relevant than the smoother change associated with an underlying signal.

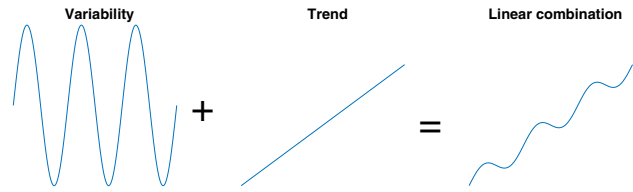


Figure 52. Ongoing variability and a steadily changing climate combining together linearly, creating the appearance of steps.

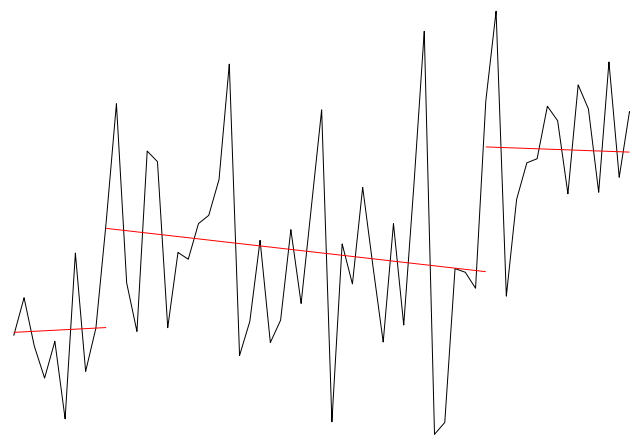
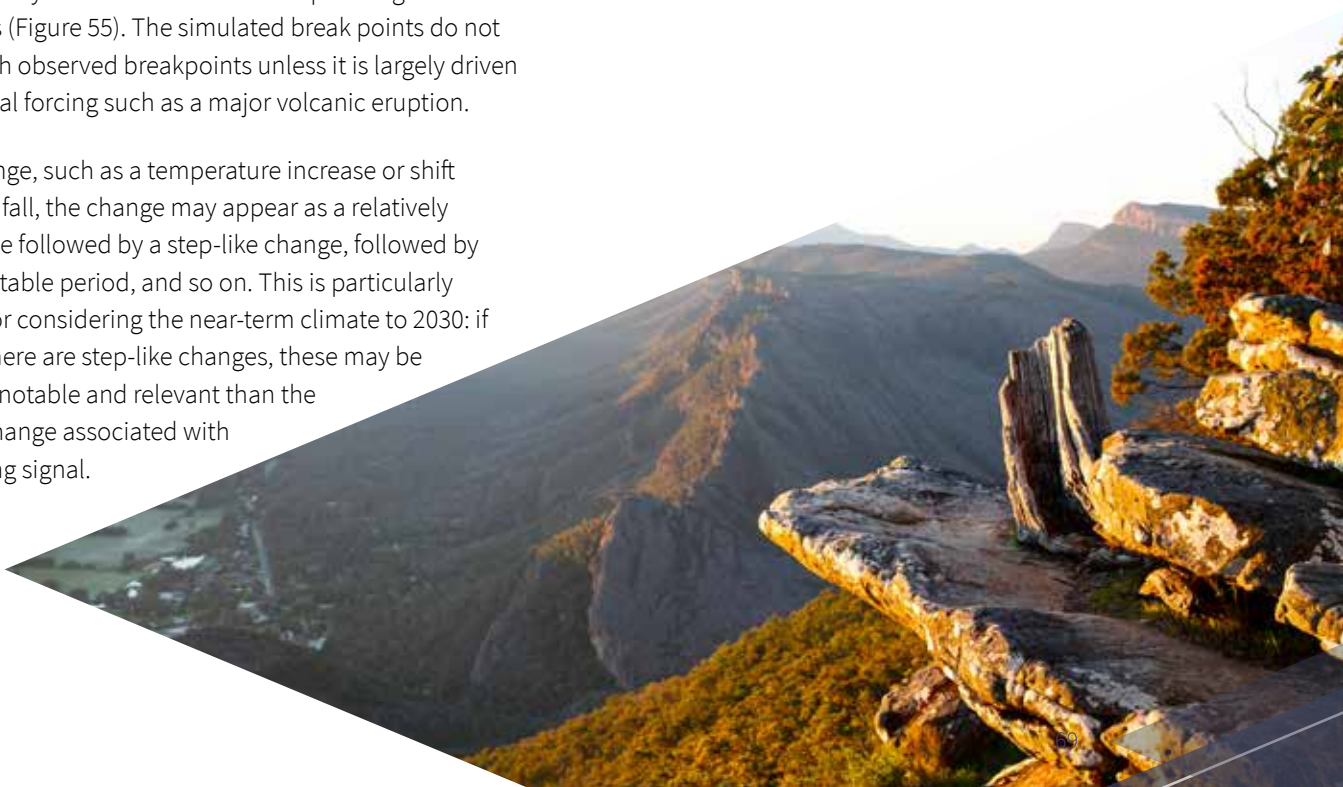


Figure 53. ‘Step changes’ in the climate system that cannot be seen as a combination of variability and a smooth signal (see Jones and Ricketts (2017) for more discussion of this point).



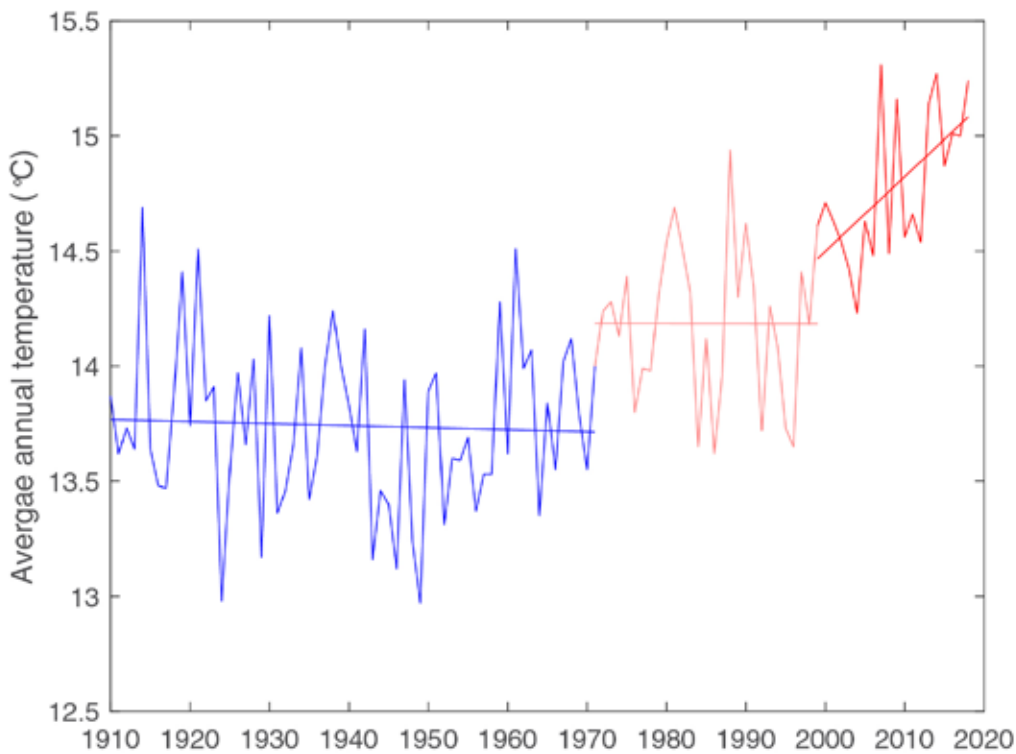


Figure 54. Average annual temperature for Victoria (ACORN-SATv2) showing three eras separated by abrupt change points detected using a breakpoint analysis, and the linear trend in those eras.

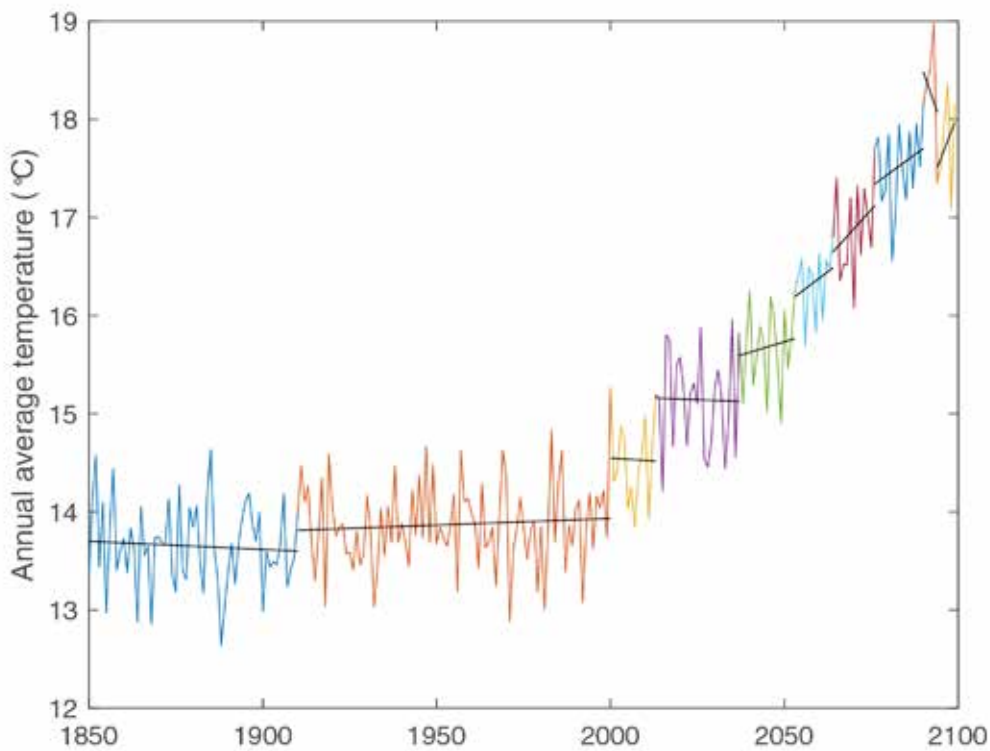


Figure 55. Average annual temperature for Victoria (ACCESS-1.3, RCP8.5) showing 10 eras separated by abrupt change points detected using a breakpoint analysis, and the linear trend in those eras.

## 6. Victoria under the Paris Agreement targets and beyond 2100

This chapter covers projections outside the framework of model projections under RCP greenhouse gas emissions scenarios to 2100, namely change under the Paris Agreement target of 2°C global warming since pre-industrial times and change beyond 2100 (to 2300 and even 3000). Victoria is projected to experience significant change even under the ambitious Paris Agreement target, and how we would reach the target will also strongly affect the future of Victoria. Furthermore, the climate is expected to change long after 2100 especially under the higher emissions scenarios.

### 6.1 Paris Agreement targets – the ambitious ‘best-case’ scenario

The emissions pathway we follow is the largest determinant of change to many variables beyond the next few decades; it makes a larger difference to the temperature, sea level and other variables than the uncertainty in climate response or natural variability. The focus of previous sections has been on emissions scenarios of medium emissions (RCP4.5) and ongoing high emissions (RCP8.5) as plausible scenarios of change to assess impacts and make adaptation plans. However, to make balanced decisions, we need to account for all possibilities of future change, including the best and worst cases.

The Paris Agreement (2015) sets an ambition to keep global mean temperature well below 2°C (relative to pre-industrial times) with the aim to keep it to 1.5°C. This ambitious target is a convenient ‘best case’ in terms of emissions. It differs from the RCP2.6 both in terms of concept and implications. RCP2.6 is a low emissions scenario, for which we calculate a range of plausible climate responses given our current understanding, including a range of global warming amounts. The Paris Agreement targets are specific levels of global warming, and there is uncertainty in the level of emissions needed to get there. Analyses show that very strong mitigation down to zero emissions, as well as greenhouse gas removal, are needed to achieve the target but the exact carbon budget is not clear due to uncertainties in things such as climate sensitivity. Various lines of evidence suggest that the world could reach the 1.5°C Paris Agreement target between 2030 and 2052 if warming continues at the current rate (IPCC 2018).

Using the range of CMIP5 models as a guide, there is a greater than 60% chance of meeting the Paris Agreement target of global warming of 2°C since pre-industrial times under RCP2.6, but a greater than 30% chance of exceeding it. Again, using CMIP5 models as a guide, under the moderate

RCP4.5, 80% of models exceed 2°C global warming by 2100, and for RCP8.5 all models exceed 2°C global warming by 2060. The projected range of change for southern Victorian under RCP2.6 from the national climate projections (CSIRO and Bureau of Meteorology 2015) is 0.5 to 1.4°C under RCP2.6 by 2080–2099 relative to 1986–2005. Adding the warming since 1910 of around 0.5°C warming, plus an estimated 0.2°C prior to this estimated from models, means a total change of around 1.2 to 2.1°C since pre-industrial times (further detail on the equivalent on the target below).

The following discussion uses the Paris Agreement target of 2°C specifically, rather than RCP2.6, since the Paris Agreement has political relevance and provides a simple climate target rather than a spread of results.

#### 6.1.1 Physical changes in Victoria at 2°C global warming

Assuming the world meets the Paris Agreement targets and global warming plateaus at 2°C since pre-industrial with no overshoot, what can Victoria expect? There are a number of different methods to estimate the equivalent warming of the average annual temperature.

First, we can estimate the warming of the average temperature in Victoria compared to the globe in the period 1910–2018 (using ACORN-SATv2 for Victoria, HadCRUT4 for the globe). Over this period, for every 1°C rise in global warming, Victoria warmed by 1.2 to 1.3°C (depending on specific methods used to quantify warming as a linear trend, non-linear smoother or the difference between periods). This suggests that at 2°C global warming, Victoria could expect to be 2.4 to 2.6°C warmer than pre-industrial.

Second we examine the targeted modelling from the BRACE project from the US National Centre for Atmospheric Research (Sanderson et al. 2018), where a set of 15 model simulations were run so that global warming plateaus at

around 2°C, and we can then compare regional changes and patterns. Figure 56 shows when global warming plateaus at around 2°C, in BRACE, Victorian average annual temperature is a little above 2°C, relative to the 1920–1940 baseline (the

historical runs from 1850 indicated change from 1850–1920 of less than 0.1°C). There is regional variation, however (Figure 57) and the changes range from 2.2 to 2.5°C, with a mean of 2.3°C.

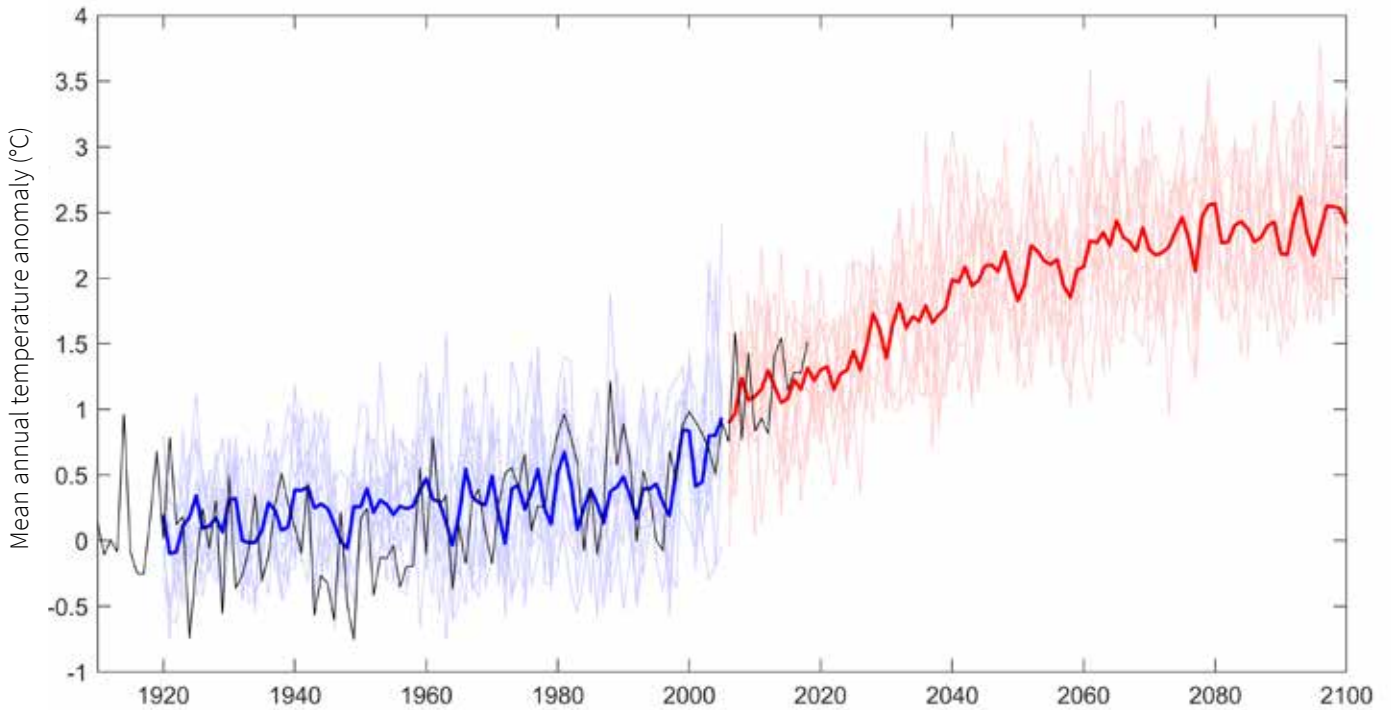


Figure 56. Victorian average annual temperature anomaly (relative to 1920-1940) in 11 simulations under the BRACE program where global mean temperature plateaus at +2°C from the pre-industrial era (blue is historical, red is projected, dark lines are the average off 11 simulations) and ACORN-SAT-v2 (black)

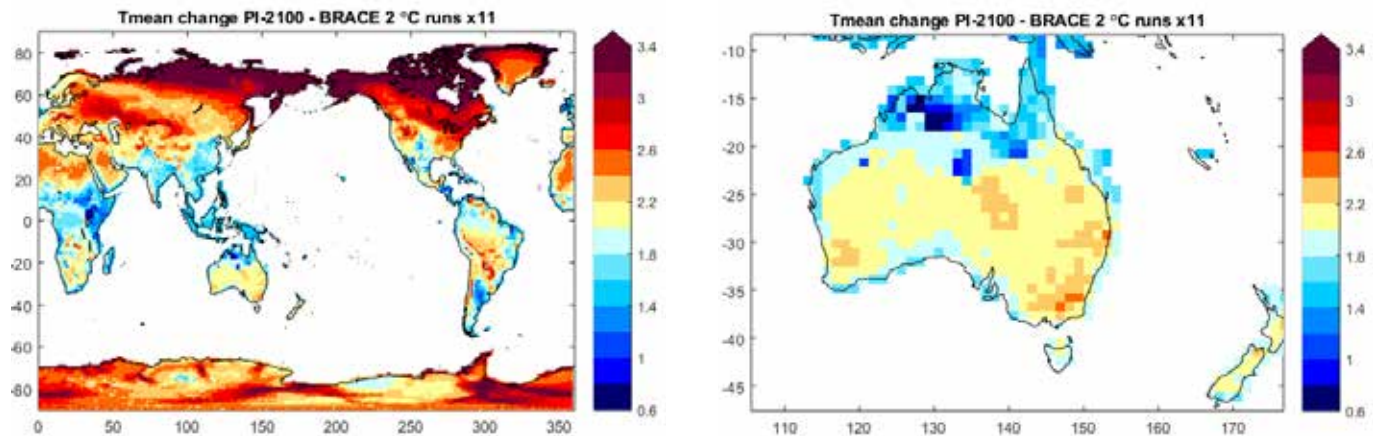


Figure 57. Change in mean annual temperature from pre-industrial era to the end of the 21st century when global mean temperature plateaus at 2°C for land areas in the mean of 11 BRACE simulations (right panel shows detail over Australia). Scale is centred on 2°C to show which areas are projected to warm more than the global average, and which areas less. Note the broad spatial patterns of change are consistent between models (e.g. the Arctic warms by much more than the global average), but some regional details are specific to the BRACE model (e.g. northern Australia warming less than the global average due to increased rainfall imparting a cooling effect).



Lastly we sample a wider set of 16 GCMs<sup>8</sup>, examining the years when each model's decadal average global temperature was 2°C warmer than pre-industrial, using the models, time slices and methods of King et al. (2017). This approach gives a lower estimate of projected change for Victoria at 1.5°C (with values from 1.2 to 2.0°C). This lower estimate from sampling a range of models using different methods is notable and worth further investigation. The higher projection from VCP19 runs compared to the host GCMs suggests that this value might be a little higher once downscaled in some cases.

Therefore, different methods give different estimates, some showing a warming of a little lower than the global average and some a little higher. However, all these values from 1.5 to 2.3°C can be considered to be close to the global average, as they are far lower than values in the hotspots of warming such as the Arctic (with warming two to three times the global average), or areas of minimal warming such as the Southern Ocean (changes of half global warming or less). The results are consistent with the pattern scaling methods used to generate a change per degree of global warming in the Australian climate projections from 2007 (CSIRO and Bureau of Meteorology 2007) and in the IPCC report on 1.5°C (IPCC 2018), which found a similar range.

This warming results in increases in heat extremes that are greater than the mean change and lead to new temperature records under the 2°C target (Lewis et al. 2017). Sampling of GCM models at the relevant global warming target suggests there is a 70–84% increase in the odds of a summer like the 2012–13 'Angry Summer' and a 67–81% increase in the odds of occurrence of the heat conditions during the 2006 drought (King et al. 2017).

Changes to rainfall and rainfall extremes are less clear than for temperature changes at +2°C global warming. Sampling CMIP5 GCMs using the methods above indicate that Victorian rainfall at 2°C global warming since pre-industrial times compared to the recent baseline of 1986–2005 are similar to RCP2.6 projections: annual rainfall -11 to +2%, and winter rainfall -16 to +8%. If the globe meets the even more ambitious target of 1.5°C global warming since pre-industrial, climate changes and associated impacts will be significantly less in several key respects (IPCC 2018), including heatwaves and other temperature extremes.

<sup>8</sup> ACCESS-1.3, BCC-CSM1.1, CanESM2, CCSM4, CESM1-CAM5, CNRM-CM5, CSIRO-Mk3.6, GFDL-CM3, GISS-E2-H, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MRI-CGCM3, NorESM1-M

## 6.2 How we get there matters

If the world meets the Paris Agreement, the exact means by which we get there matters. The mix of methods to keep the global temperature to below 2°C from pre-industrial times makes a big difference to not only the climate, but also the socio-economic world that we will inhabit. Emissions mitigation to zero emissions by 2100 is essential to meet the Paris Agreement target, so any consideration of meeting the target assumes this transition with all that entails (a transition to a net zero carbon economy). Also, all plausible pathways to meet the target use some mix of carbon dioxide removal (BCR), bioenergy with carbon capture and storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector (IPCC 2018). While the global temperature may end up the same, the regional climate change may be different depending on the specific mix of actions taken, and of course the effect of the actions will strongly affect the natural world, human society and economy in different ways. The effect of the mix of action is crucial to consider along with the physical risk of changing climate.

As well as carbon dioxide removal, there is a possibility that some type of climate engineering will be attempted, through techniques such as solar radiation management (e.g. injecting aerosol particles into the stratosphere). The effect of these measures is still very uncertain and is not included in any set of analyses – meaning there is more need to consider climate engineering using a scenario approach, rather than quantitative projections (Knutti 2018). Also, there is the possibility of 'overshoot' and return to 2°C, which results in higher impacts and associated challenges compared to pathways with no or limited overshoot (IPCC 2018).

## 6.3 Worst-case scenarios

Climate model simulations may not present the worst-case scenarios for climate change. Even early climate projections have been tracking quite closely to observations for average annual temperature (Grose et al. 2017b); however, this may not be the case in the future as we move further away from the historical climate. Projections may not capture the full range of change in other climate variables or in extremes (e.g. higher sea-level rise than the current projected range cannot be ruled out). Also, models may not show large enough changes in response to climate drivers, or in other words they may not be sensitive enough. For example, modelled strengthening and southerly movement of the subtropical ridge of high pressure in the Victorian sector is weaker than observed, possibly due to natural variability but possibly due to weaker sensitivity of the processes, meaning that models

may underestimate the associated rainfall change (Grose et al. 2015c). Also, climate projections typically do not include strong non-linear or step changes to the climate.

For these reasons, risk-averse applications may wish to consider a ‘worst-case’ scenario with a storyline that includes stronger or more rapid changes in the climate than in the projections given here. Scenarios are a powerful method of communication and method to start visualising the future (Shepherd et al. 2018). This worst-case scenario can then be used in planning and response exercises, such as in a ‘war-gaming’ framework. For example, for the drought and operational planning scenarios for water planning, DELWP recommend a resampling of baseline climate to create hypothetical droughts more extreme than were observed but potentially possible given conditions in past years, rather than the use of climate model outputs (see DELWP Water: <https://www.water.vic.gov.au/water-for-victoria>).

### 6.4 Change beyond 2100

Climate change does not stop at 2100. We expect to see ongoing changes to the climate after 2100 and even after greenhouse gas concentrations stop rising. A sub-set of CMIP5 GCMs were run to 2300 using the extended trajectory of RCPs known as Extended Concentration Pathways (ECPs) shown in Figure 58. The higher RCPs continue on a high trajectory before plateauing (e.g. ECP12 is an extension of RCP8.5 and reaches  $12 \text{ Wm}^{-2}$  of enhanced greenhouse effect), the lower RCP2.6 shows a decrease in greenhouse forcing as greenhouse gases are removed from the atmosphere. Global changes were presented in the last IPCC assessment report (Collins et al. 2013), and we use the same models and techniques to present projected change over Victoria specifically. Victoria’s temperature response follows the same relationships as for projections to 2100: temperature rise is proportional to the greenhouse gas concentration, and the range of change widens for larger changes as uncertainty in climate feedbacks leads to wider ranges of possible change (Figure 59). A single run from an example model for the year 3000 under the very high ECP12 illustrates changes long after the forcing plateaus (Figure 60). Further warming of over  $2^\circ\text{C}$  occurs as the climate system

slowly moves towards true equilibrium under this much higher greenhouse gas world. Changes over hundreds to thousands of years in the future could be in fact larger than typical model simulations suggest. Models generally only include the faster climate feedbacks in the atmosphere, ocean and ice, whereas over longer time-scales the slower ‘Earth system’ feedbacks become important. These Earth system feedbacks include those linked to melting ice sheets, changes to vegetation zones and the biogeochemistry of the deep ocean and earth. A useful metric of the response of the climate system to forcings is ‘climate sensitivity’, which describes the change in global average near-surface (2 m) temperature to a doubling of  $\text{CO}_2$ . Equilibrium climate sensitivity based on various lines of evidence is thought to likely be between  $1.5$  and  $4.5^\circ\text{C}$ , and this plays out over the scale of decades to centuries (IPCC 2013b). Over longer time-scales the Earth system sensitivity could be up to twice as high. However, this sensitivity depends strongly on the initial state – for example, the shift from the ice age into the current inter-glacial saw a large temperature change partly because of the melting of large ice sheets in the northern hemisphere creating a very large ice-albedo feedback that would not be as large for future warming.

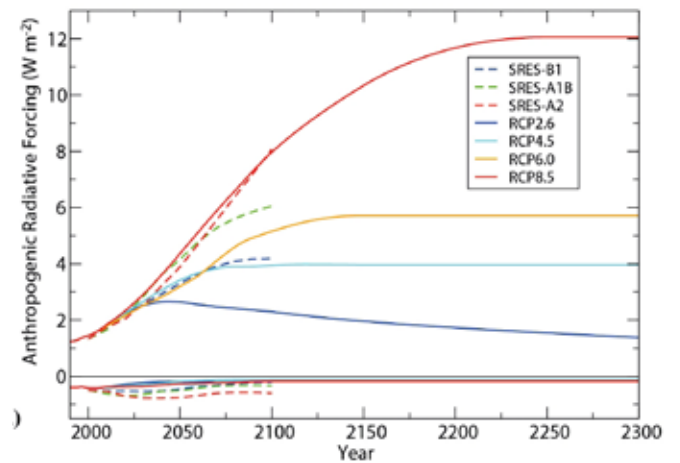


Figure 58. The anthropogenic radiative forcing under the Extended Concentration Pathways, showing greenhouse gas (positive) and anthropogenic aerosol (negative) forcing. The previous generation SRES scenarios are also shown for reference. Source: IPCC AR5 Chapter 12 (Collins et al. 2013)

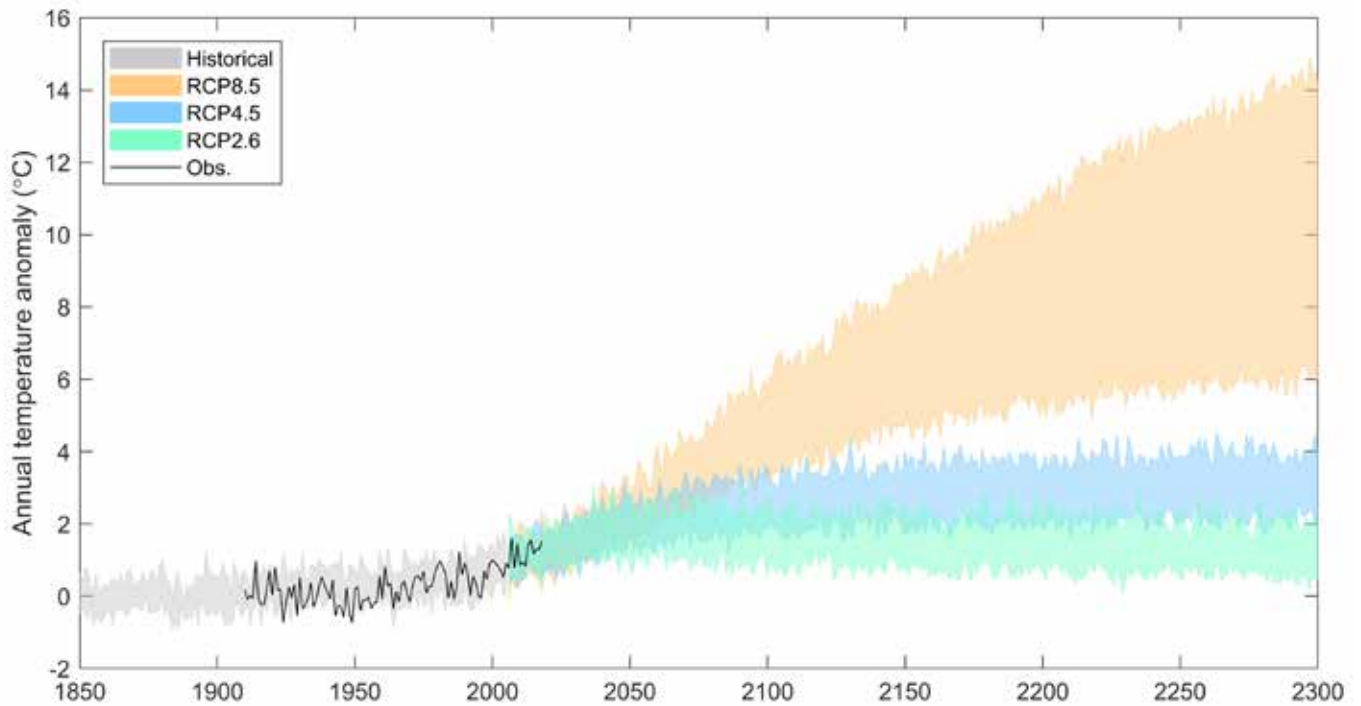


Figure 59. Victorian average annual temperature anomaly from pre-industrial (1850–1900 baseline) from CMIP5 models with data available for all ECPs (15 models)

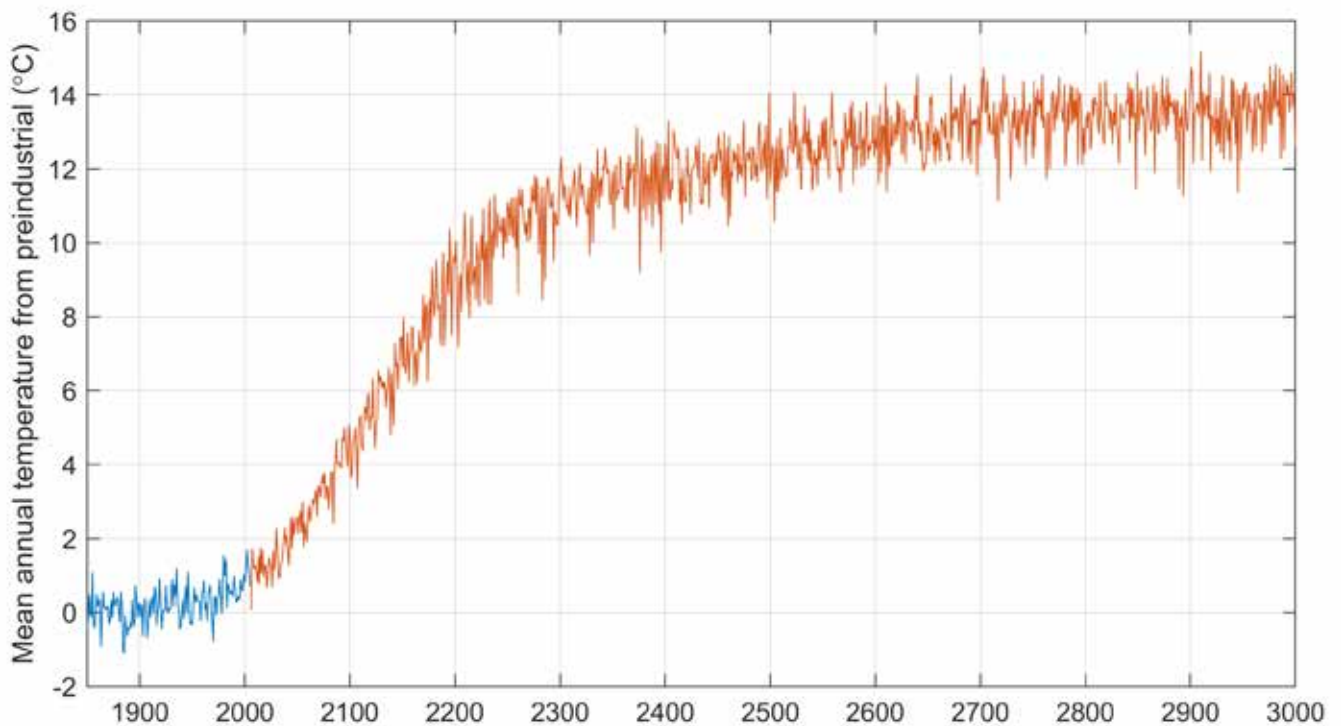
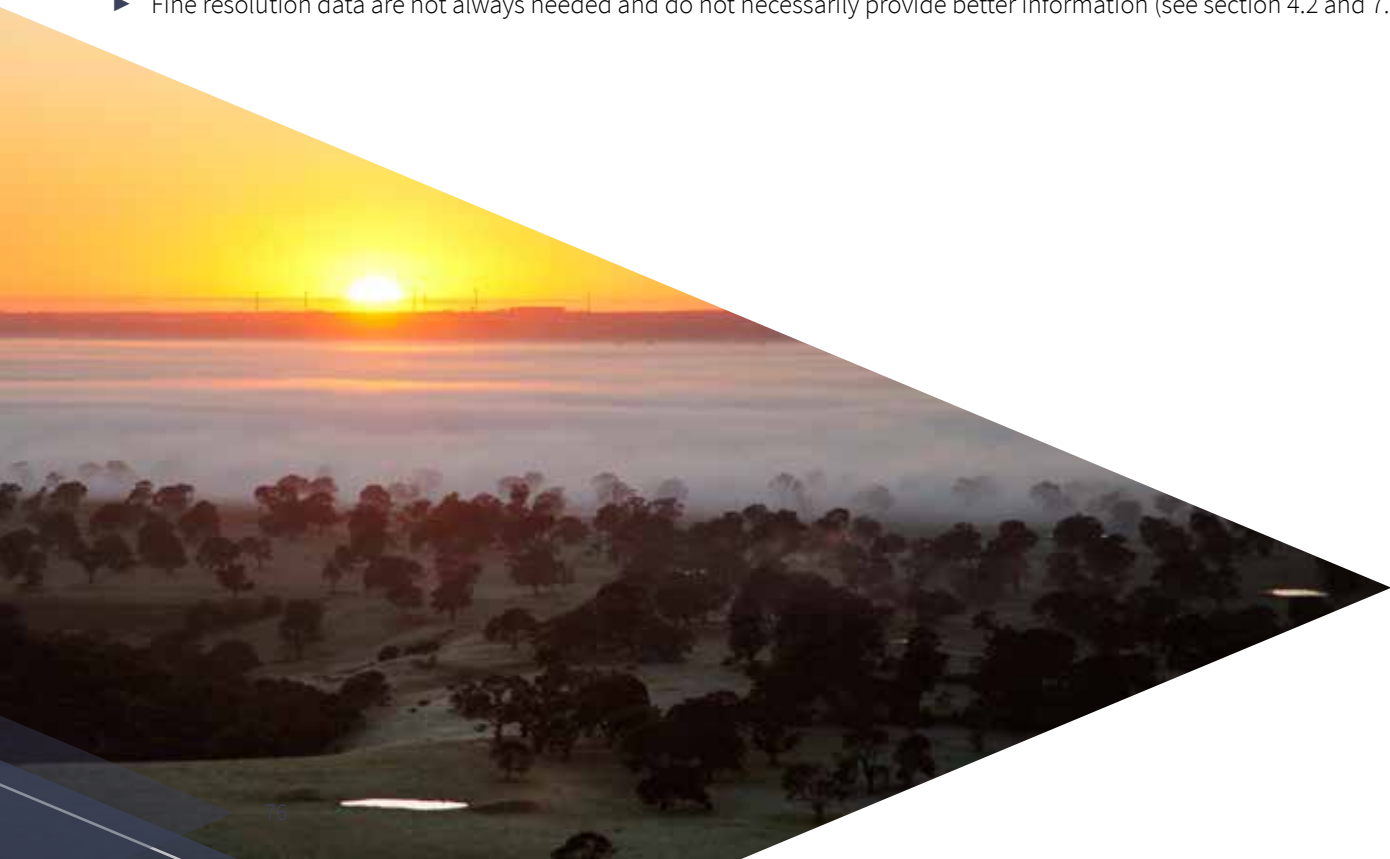


Figure 60. Victorian average annual temperature anomaly from 1850–1900 from a long simulation from a single model (EC-EARTH) from 1850 to 3000 under ECP12 (following RCP8.5 to 2100, and increasing to a radiative forcing of  $12 \text{ Wm}^{-2}$  by 2250, then remaining steady until 3000)

# 7. Guidelines for using Victoria's climate projections

## Key messages

- ▶ Assessing the impact of future climate is complex – plan to allow adequate time for consultation and data collation (see section 7.2).
- ▶ You are likely to need advice and guidance from experts in the field (see section 7.5).
- ▶ Think carefully about the communication needs of your stakeholders – this can influence your choice of climate information (see section 7.1).
- ▶ In most cases, using just the mean or median climate projections will not be appropriate (see section 7.2).
- ▶ In most cases, use a method such as the Climate Futures approach to identify an appropriate subset of models to use in your assessment (see section 7.3).
- ▶ The VCP19 high-resolution data are high quality and add important value to the lower-resolution GCM data in some regions; nevertheless, if GCM results project a high-impact future that is not projected by the VCP19 data, the GCM results should be used unless there is a compelling reason not to.
- ▶ Ensure the ranges of projected change are adequately accounted for in your assessment (see section 7.3)
- ▶ There are multiple sources of uncertainty and there always will be. To deal with this, be sure to evaluate multiple emissions scenarios and explore the full ranges of plausible change from all available data sources (see section 7.3).
- ▶ There is no such thing as a 'most accurate' climate model or 'most likely' emissions scenario. All of the models included in Climate Futures produce climates that are physically plausible for a given emissions scenario. Instead, aim to use a representative subset of the available data (see section 7.3).
- ▶ The climate has always been naturally variable; this variability now occurs on top of climate trends; over short time scales, climate variability will be the largest influence on the climate we experience (see section 5.2.2).
- ▶ Be aware that future climate data have a range of limitations and take this into account (see section 4).
- ▶ Fine resolution data are not always needed and do not necessarily provide better information (see section 4.2 and 7.3).



## 7.1 Getting started

In this section, we provide brief guidance about using climate projections information for the purpose of impact, adaptation and vulnerability (IAV) assessments, as part of the broader response to climate change. The decision tree shown in Figure 61 can help determine which data and information from VCP19 and elsewhere might be useful for a given application.

As shown in Figure 61, not all applications will require access to detailed climate data sets. In addition to this technical report, VCP19 produced a regional report for each of the 10 regions (see Chapter 2) and a range of fact sheets. These are all available as PDF downloads from the VCP19 publications page of the *Climate Change in Australia* website<sup>9</sup>.

<sup>9</sup> <https://www.climatechangeinaustralia.gov.au/en/climate-projections/future-climate/vcp19-publications/>

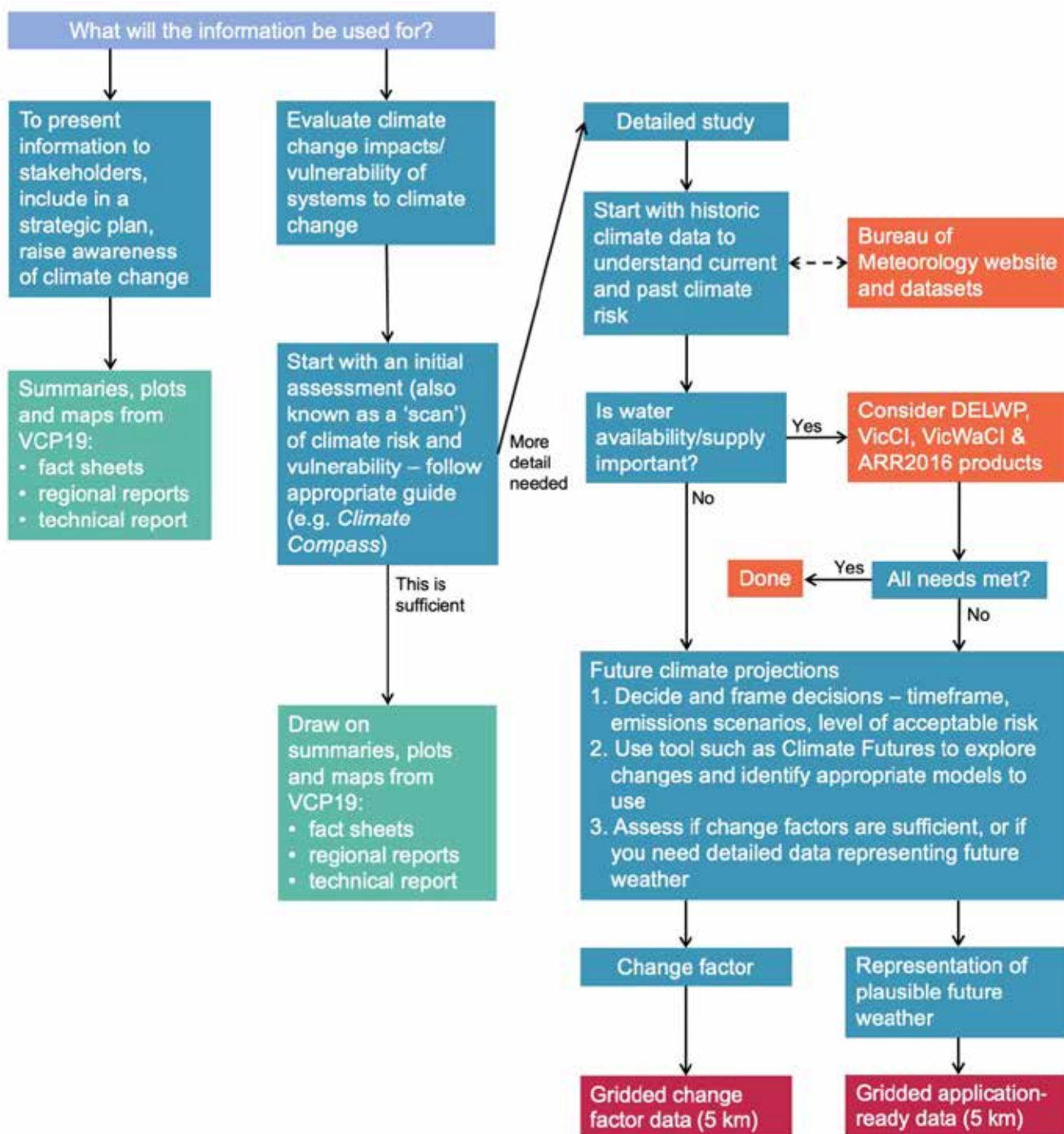


Figure 61. Decision tree for determining which climate data and information from VCP19 (and other sources) might be useful for an application.

## 7.2 Using climate projections in an impact assessment

Establishing plausible future climate conditions (scenarios or projections) is just one of many steps in knowing what climate change means to any application, and what to do in response. To assess the IAV aspects of future climate risk, we need to bring in other knowledge and information, and do further analysis.

Planning for managing future climate risk involves a combination of:

- ▶ ‘Top-down’ analysis – starting by constructing climate projections and feeding them into a chain of analyses such as applied models to understand what this change in the climate means to a downstream application (e.g. feeding rainfall and evaporation into a runoff model to assess changes in water availability and river flows). This top-down chain may include a downscaling step to provide regional insights in the projected changes. The VCP19 project included downscaling for this purpose.
- ▶ ‘Bottom-up’ analysis – assessing the vulnerability and resilience of systems, and pathways to reduce vulnerability and increase the capacity to cope or transform (without consideration of climate projections).

These two approaches can be combined to explore what climate change may mean for a given situation, and the scope and scale of response needed for different scenarios.

As projections of future climate include considerable uncertainties, a simple ‘predict then act’ framework is not suitable. Instead, we must consider the range of possibilities in four main respects:

- ▶ Natural climate variability
- ▶ Emissions scenarios
- ▶ How the climate may respond to increasing greenhouse gases (estimated from a range of models)
- ▶ Understanding the level of confidence that can be applied to each projection and/or model simulation.

Reducing these uncertainties is a global priority for climate research. Nevertheless, uncertainties due to climate variability and emissions uncertainty will always remain. This means impact assessments will always have to deal with a range of plausible future climates.

To deal with these uncertainties, impact assessments should:

1. consider the full range of plausible change as projected by all available climate modelling
2. evaluate multiple emissions scenarios (at least two)
3. account for natural climate variability (which will be superimposed over climate trends)
4. use an objective means (such as the Climate Futures approach described in section 7.3) to select a subset of data that is relevant to the assessment being undertaken.

In addition, some aspects of decision-making are specific to the application, including the time horizon and the tolerance for risk. There are also factors of political will, economic resources and social license to operate that must be considered.

### 7.2.1 Chain of actions

To pursue the top-down part of an IAV assessment, there are a few underpinning principles, and a chain of actions to follow:

1. Before using climate projections, it is important to do relevant background reading, identify relevant stakeholders and determine the appropriate level of stakeholder engagement.
2. Next, determine the need/s for climate change data and information.
3. Obtain appropriate information and/or data (use the decision tree in Figure 61).

The information from VCP19 and similar sources may be enough for basic purposes or raising awareness (the first branch in the decision tree), or it may be the start of further analysis. An initial assessment (sometimes called a ‘first pass assessment’ or ‘scan’) should be done before any detailed analysis. Following a scan, if more detailed information is needed then a detailed study can be scoped and carried out.

All IAV applications, including those in the water domain, should start with an assessment of past and future climate changes and the impact they have – this involves collecting and processing appropriate climate datasets from the Bureau of Meteorology, VCP19, CCIA and others, as well as data sets relevant to the application (e.g. databases of assets, networks and infrastructure).

## Runoff, soil moisture and stream flow

VCP19 has not produced projections of runoff, soil moisture or stream flow. If these are required, the existing DELWP guidelines may be helpful (or mandatory in some cases). At the time of publication, the VicCI and VicWACI projects provided standardised datasets for managing water supply in Victoria (see <https://www.water.vic.gov.au/climate-change>). Like VCP19, these projects were based on a wide-ranging assessment of multiple sources of evidence (and align well with the VCP19 rainfall projections).

Contact DELWP Water and Catchments for further assistance ([HCS.Team@delwp.vic.gov.au](mailto:HCS.Team@delwp.vic.gov.au)).

Once:

1. stakeholders are identified
2. the engagement plan is set
3. historical climate impacts and vulnerability are understood
4. the information needs are assessed
5. the initial scan is completed

then future climate datasets can be collected and climate projections constructed. This is where the Climate Futures tool and the VCP19 datasets may be useful, as described in the next section.

After climate projections have been constructed and used in applied analyses, the results should be interpreted and communicated via appropriate means, and the outcomes assessed. Then the cycle can be repeated, and the scan of needs can start again.

## 7.3 Constructing climate projections – the CSIRO Climate Futures framework

When using climate data sets for IAV assessment, there are four important requirements:

1. The data must be physically plausible, especially when data for multiple climate variables are being used – in other words, they could occur in the real world (this is referred to being ‘internally consistent’).
2. The data must be representative of the range of projections results.
3. The amount of data to be used must be manageable.
4. Information on likelihood or confidence is available.

One mechanism to satisfy these requirements is the Climate Futures framework<sup>10</sup> (Whetton et al. 2012; Clarke et al. 2011). This allows the user to view, compare and select model outputs tailored to the needs of a specific application. The example Climate Futures matrix shown in Figure 62 shows the range of projected changes in winter temperature and rainfall for Gippsland around mid-century (2050s) under high emissions (RCP8.5). The spread of results from multiple climate models is shown on two dimensions divided into categories. The number of models within each category (or ‘climate future’) gives an indication of model agreement on that category.

<sup>10</sup> <https://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-futures-tool/introduction-climate-futures/>

### Climate Compass

The Climate Compass provides guidelines for the Commonwealth public service to manage the risks from a changing climate. Climate Compass describes the three classes of climate change impact assessment in detail:

- ▶ *Scan* – typical starting point, used to obtain a high-level sense of the climate risks that an area or responsibility is exposed to.
- ▶ *Strategy* – a deeper identification, assessment and treatment of risks (may follow a scan cycle).
- ▶ *Project* – a detailed assessment and operational plan for more focused work.

Climate Compass is available at <https://www.environment.gov.au/climate-change/adaptation/publications/climate-compass-climate-risk-management-framework>

Representative climate futures can then be selected, where key cases of interest are defined by the vulnerabilities of the application being considered. A representative model simulation from each key case can then be chosen and the data obtained. In the example matrix shown in Figure 62 (to inform a dairy productivity assessment), a hotter, drier climate is considered the worst case and a future that is less hot but wetter is considered the best available climate future

for this particular application. For another application, the situation is likely to be different.

The *maximum consensus* climate future (where there is the greatest model agreement) is also shown. Understanding where there is the maximum consensus among models is useful. In all circumstances, however, the higher impact but less likely *best* and *worst* cases should also be considered.

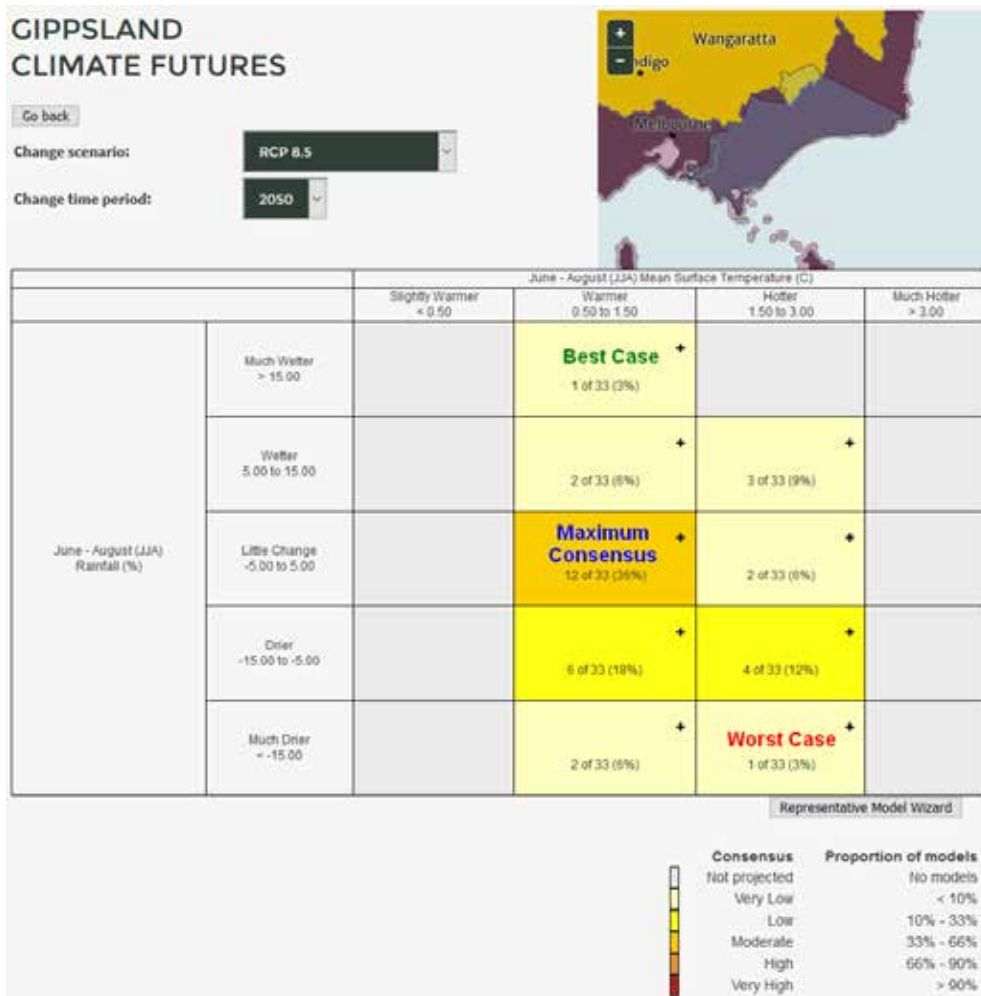


Figure 62. A Climate Futures matrix for Gippsland showing example 'key cases': best, worst and maximum consensus.



The following steps outline the procedure for creating a Climate Futures matrix, using the Climate Futures Toolkit on the *Climate Change in Australia* website. However, this process is complex so you may need to seek help. A good place to start is the *Climate Change in Australia* online training<sup>11</sup>. You can also contact the CSIRO Climate Science Centre<sup>12</sup>.

- ▶ Use the Detailed Projections Tool to generate a Climate Futures matrix to explore the range of change in terms of two classifying variables (because of the correlations among variables, temperature and rainfall are usually best classifiers). Populate the matrix with all the variables and seasons that are important to the impact assessment (e.g. winter rainfall and temperature, and summer minimum temperature are often important for the dairy sector).
- ▶ Use the information on projected changes to identify the ‘key cases’ that are important for the impact assessment. Commonly these are best case, worst case and maximum consensus (e.g. Figure 62). If needed, a simple sensitivity analysis (see section 7.3.1) can be useful to guide this step.
- ▶ Identify a representative model for each key case.
  - Rank the models using the Climate Futures Tool Representative Model Wizard
  - Follow the guidance on the Climate Futures matrix display to reject any models that have been identified as performing poorly for any reason in the region of interest. This is very important since you will be using data from a single model to represent the relevant key case.
- ▶ Obtain the data needed from each model. In many cases, the data will be available on *Climate Change in Australia*, including data from VCP19. However, once the representative models have been identified, the data from those models may be available from a range of sources (take care to ensure data from other sources are comparable to those used by Climate Futures).
- ▶ Input the data into the impact assessment.
- ▶ If using a risk management approach, use the information on model consensus (from the matrix) to guide the assessment of likelihood.

In VCP19, we present data from new high-resolution (5 km) modelling alongside previous modelling datasets – and highlight where the new data add useful insights. When assessing risk, it is important to consider the full range of plausible changes, especially if worst-case or other ‘low probability, high impact’ cases are important to manage or mitigate. The Climate Futures approach makes it easy to choose representative climate futures from across all available data sources.

For Victoria, we suggest using the VCP19 datasets in preference to the GCM datasets *in most instances* (this is because the VCP19 data have been shown to add value to the GCM results). However, if one of the key cases (as described above) is projected only by GCMs, we suggest the GCM results should be used unless there is a compelling reason not to. This is because it is generally more important to evaluate a plausible extreme case than it is to have higher spatial resolution.

A final consideration in model selection is the availability and usability of the necessary data. The range of climate variables and data formats available from GCMs and RCMs varies among models. GCM outputs and detailed dynamically downscaled data sets are available as described below. If other types of data are really needed (e.g. from weather generators or other forms of statistical downscaling), then this can be pursued. These methods, however, can be time-consuming and costly and require specialised skills to produce.

It is vitally important to understand the full range of plausible changes before undertaking a detailed assessment of risk. The Climate Futures approach facilitates this as well as providing a mechanism for objective selection of representative models to use.

<sup>11</sup> <https://www.climatechangeinaustralia.gov.au/en/climate-campus/online-training/>

<sup>12</sup> <https://www.climatechangeinaustralia.gov.au/en/support-and-guidance/contact/>

### 7.3.1 Sensitivity analysis

A sensitivity analysis is a good starting point in an impact assessment process and requires no detailed climate projection inputs.

A sensitivity analysis involves testing the effect of a spectrum of changes to a system – e.g. +1, +2, +3 and +4°C or -20, -10, +10 and +20% rainfall – to look for relationships, sudden changes or thresholds in response to climate changes. The results can in turn be used to define best and worst cases for use in Climate Futures.

For example, if a sensitivity test reveals a threshold of -20% in rainfall where a particular system must transform or face

failure, this can be explored as the worst case in Climate Futures. The chance of reaching this threshold under different RCPs and timeframes across the model range can then be explored.

### 7.3.2 Spatial analogues

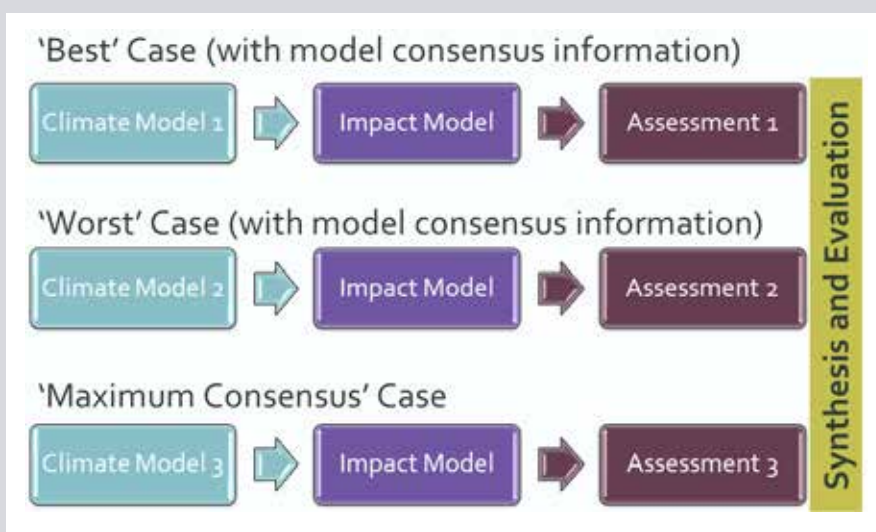
Spatial climate analogues can be another useful tool to start assessing what climate change means by looking at places that currently experience the climate that is projected to occur in the area in question, e.g. Melbourne’s climate becoming more like the current climate of Wangaratta.

A spatial climate analogues tool is available on the *Climate Change in Australia* website<sup>13</sup>.

<sup>13</sup> <https://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/about-analogues/>

## Key steps in developing climate scenarios and identifying data sources

1. Obtain/collate information on the sensitivity of the application to climate influences (e.g. crops are usually sensitive to rainfall, temperatures, evapotranspiration and solar radiation; particular seasons may be important); if necessary, do a simple sensitivity analysis.
2. Determine the type of data needed (e.g. change factors, application-ready daily time-series).
3. Define the key cases of interest, usually best case, worst case and maximum consensus. For example, a worst case for a cropping study is likely to be the hottest and driest future.
4. Generate Climate Futures matrices for the region of interest for all relevant time periods and at least two emissions scenarios (VCP19 data are available for RCP4.5 and RCP8.5); populate the matrix with all variables (and seasons) to which the application is sensitive.
5. Identify the key cases in each matrix.
6. Identify representative models for each key case. (Check the information on model skill; reject any models that demonstrated poor performance in the region of interest.)
7. In general, the VCP19 data should be used. However, if a key case climate future is populated by GCM data only, use the GCM data unless there is a compelling reason not to.
8. Obtain the necessary data from the identified representative models.
9. Complete an impact assessment separately for each case by using the data from the selected model (see figure). The results can then be synthesised and used to inform decision-making.



The 'key cases' approach to impact assessment (after Whetton et al. 2012)

## 7.4 Obtaining VCP19 high-resolution climate data

If the decision tree (Figure 61) recommends a detailed study, and other relevant decisions affirm this course of action, detailed data can be selected and downloaded. Data from VCP19 and host GCMs can be selected and then downloaded from the *Climate Change in Australia* website. This is best done directly from the results page when finishing a Climate Futures selection process. The Climate Futures Tool accounts for the VCP19 regions under ‘detailed projections’, and the Victorian regions can be accessed by selecting the option on the map as shown in Figure 63. It is also possible to access model data directly in netCDF format.

Most applications are sensitive to the biases inherent in climate model output. When obtaining data from the identified representative models (as described in section 7.3), all but the most expert of users should employ either relative change data or the application-ready future data. Both of these types of data are free of model biases and are available from VCP19 (see section 7.5).

In VCP19, application-ready data have been developed from all high resolution six models. This was done by applying the relative change signal from the climate models to an historical dataset. These datasets are explained in more detail in section 2.5. If in doubt, the application-ready

data are usually a more reliable and robust option to apply when using temperature, rainfall, relative humidity, evapotranspiration, wind speed and solar radiation. These application ready data sets have also been used to estimate future exceedances of a range of rainfall and temperature thresholds.

## 7.5 Further resources

The VCP19 pages of the *Climate Change in Australia* website contain additional resources for Victoria. Here you can access a range of climate projections tools and datasets to suit intermediate and expert users. You will also find guidance material and learning resources on climate science, data selection and impact assessment.

- ▶ <https://www.climatechangeinaustralia.gov.au/en/climate-projections/future-climate/victorian-climate-projections-2019/>

For observed data and analyses of climate trends, visit the Bureau of Meteorology Climate Data Online.

- ▶ <http://www.bom.gov.au/climate/data/>

General information on the *Victorian Climate Projections 2019* project is available on the Victorian Government’s climate change website.

- ▶ <http://www.climatechange.vic.gov.au/vcp19>

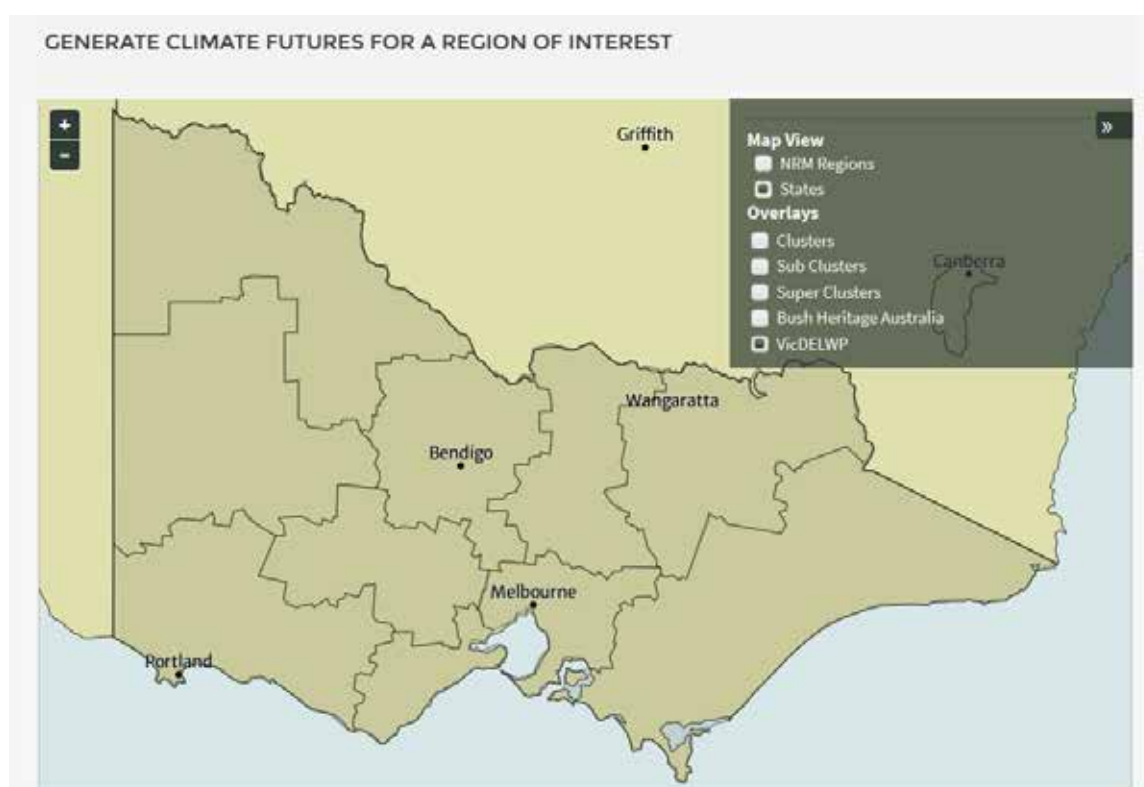


Figure 63. Example from the Climate Futures Tool on the Climate Change in Australia website, showing the VCP19 regions for Victoria.

# Appendix: Bias plots for model evaluation

Figures 64 to 67 show bias plots of the CCAM simulated daily maximum (2 m) air temperature, daily minimum (2 m air temperature), average rainfall and 99th percentile rainfall, corresponding to the figures shown in section 4.2.

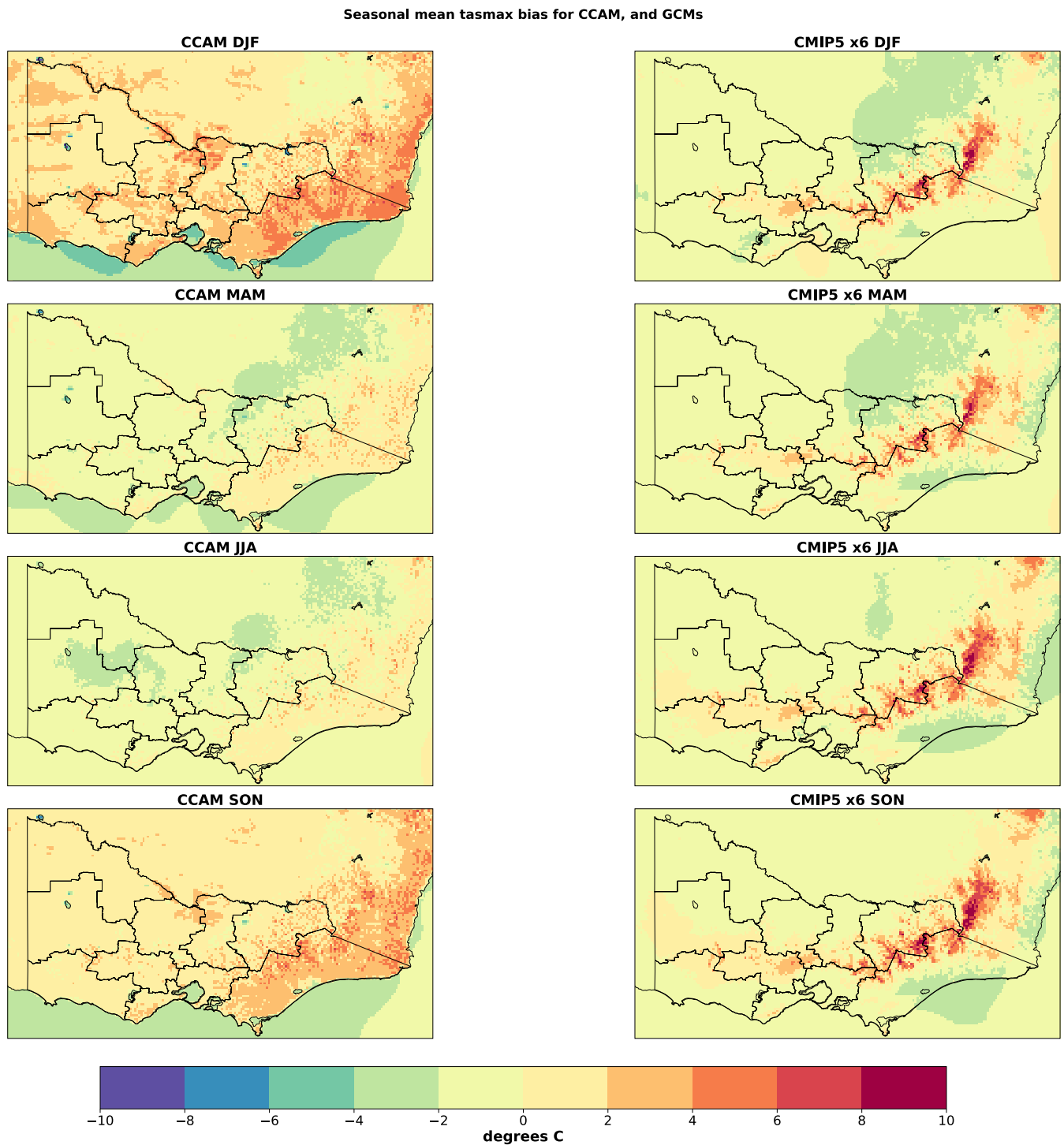


Figure 64. Bias plots for daily (2 m) maximum air temperature corresponding to Figure 8.

Seasonal mean tasmin bias for CCAM, and GCMs

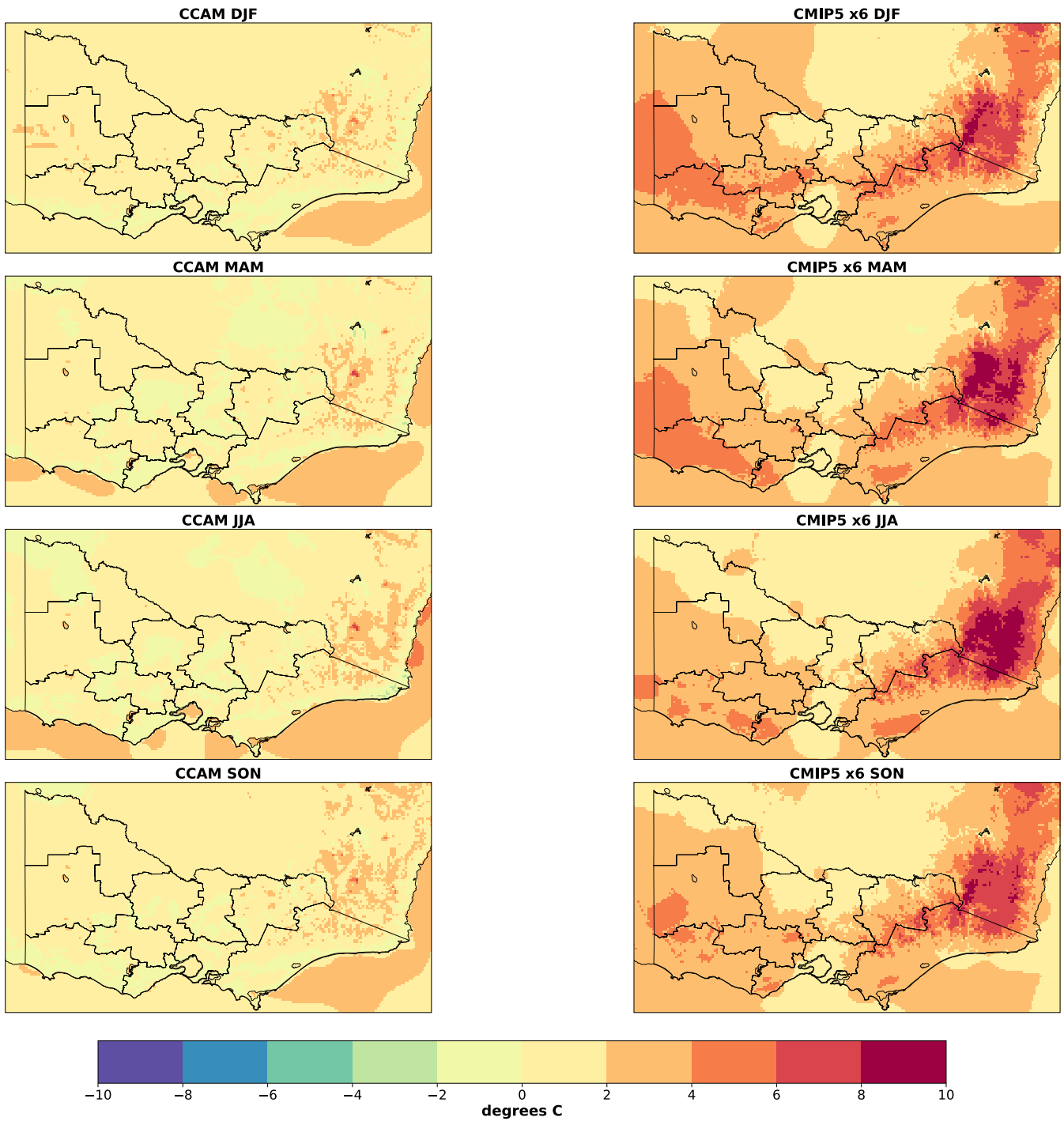


Figure 65. Bias plots for daily (2 m) minimum air temperature corresponding to Figure 9.

Seasonal mean pr bias for CCAM, and GCMs

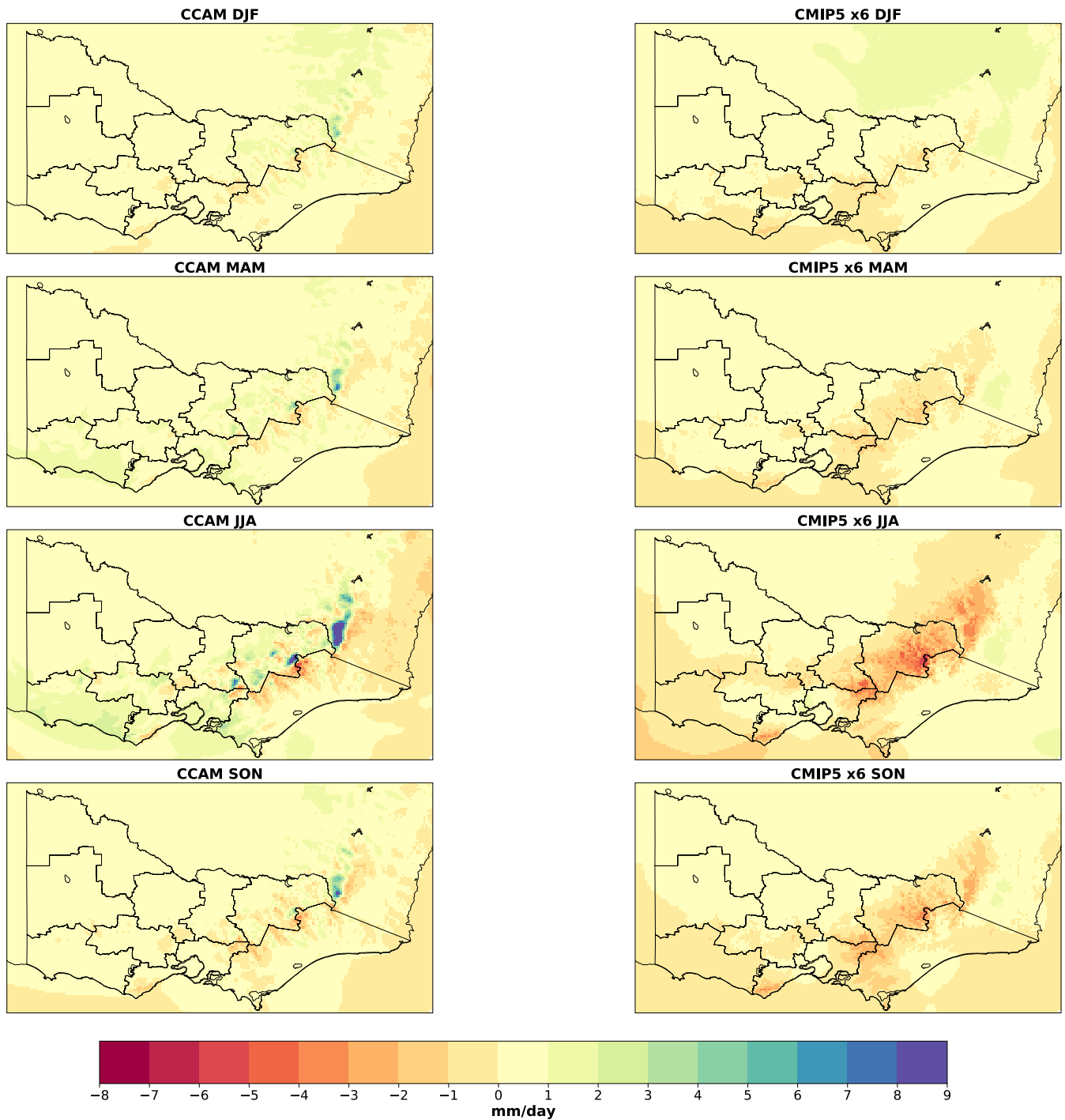


Figure 66. Bias plots for average rainfall in mm/day corresponding to Figure 12.

Seasonal mean 99th percentile rainfall bias for CCAM, and GCMs

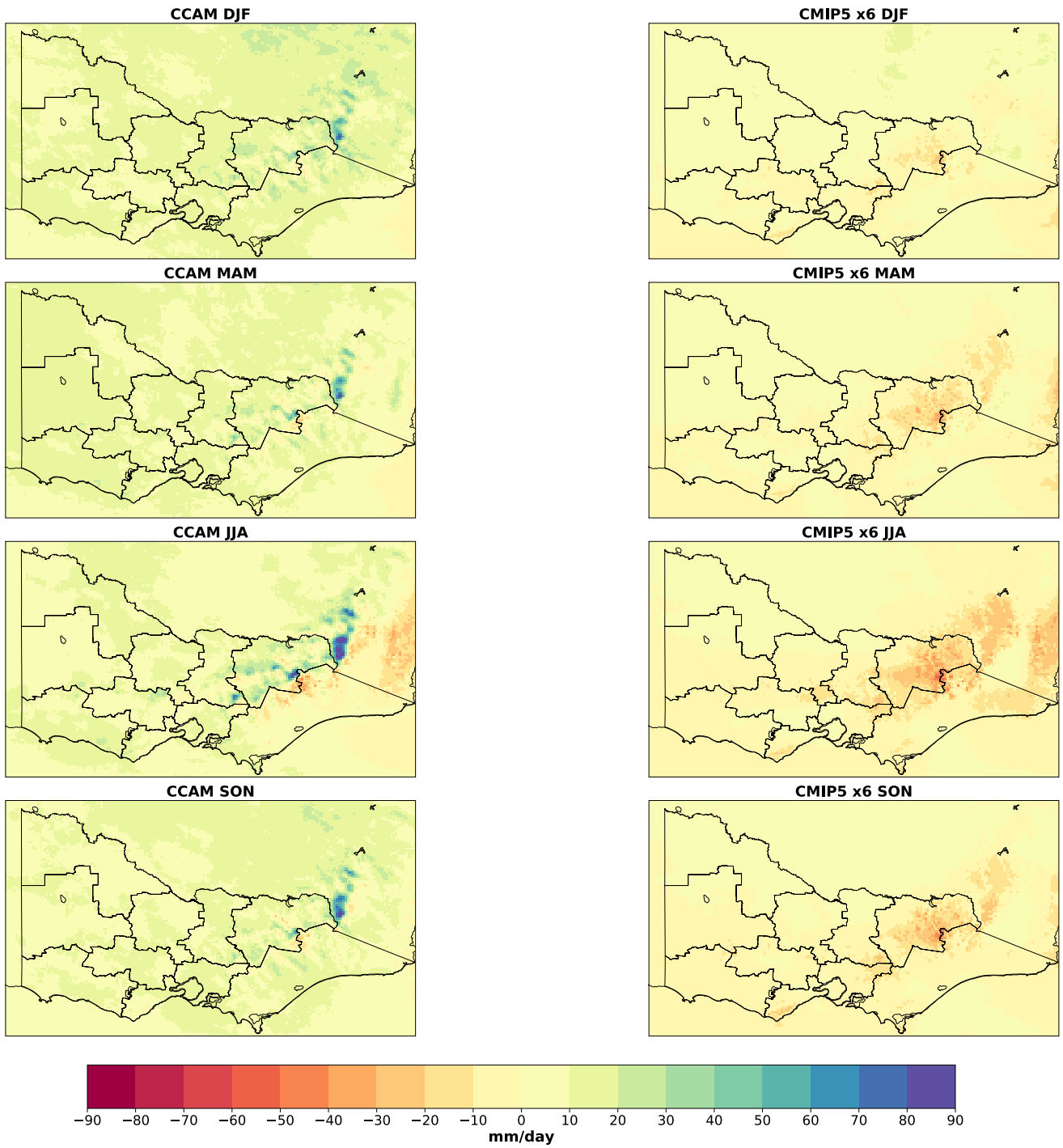


Figure 67. Bias plots for 99th percentile rainfall in mm/day corresponding to Figure 13.

## Shortened forms

Acronym	Definition
BOM	Australian Bureau of Meteorology
CCAM	Conformal Cubic Atmospheric Model
CMIP5	Coupled Model Intercomparison Project phase 5
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DELWP	Department of Environment, Land, Water and Planning
DJF	Summer months – December January February
GCM	Global climate model
IPCC	Intergovernmental Panel on Climate Change
JJA	Winter months – JJA is June July August
MAM	Autumn months – MAM is March April May
RCM	Regional climate model
RCP	Representative Concentration Pathway
SON	Spring months – September October November
Tmax / Tmin	Daily maximum temperature / Daily minimum temperature
VCP19	Victorian Climate Projections 2019
VicCI	Victorian Climate Initiative

## Glossary of terms

The following table provides descriptions of scientific terms that are used in this technical report. Some important terms that may be encountered in further reading are also included.

Term	Description
Adaptation	Changes made to natural or human systems to prepare for actual or expected changes in the climate in order to minimise harm, act on opportunities or cope with the consequences.  <i>Incremental adaptation</i> Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.  <i>Transformational adaptation</i> Adaptation that changes the fundamental attributes of a system in response to climate and its effects.
Aerosol	A suspension of very small solid or liquid particles in the air, residing in the atmosphere for at least several hours.
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.
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen and oxygen with a number of trace gases (e.g. argon, helium) and greenhouse gases (e.g. carbon dioxide, methane, nitrous oxide). The atmosphere also contains aerosols and clouds.



Term	Description
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 <sub>2</sub> )	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	<p>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.</p> <p>Throughout this report, we differentiate between 'climate projection data sets' and 'climate projections':</p> <p><i>Climate projection data set</i> – data relating to future climate, usually obtained from a climate model.</p> <p><i>Climate projection</i> – 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.</p>
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).
CMIP3 and CMIP5	Phases three and five of the Coupled Model Intercomparison Project, which coordinated and archived climate model simulations based on shared model inputs by modelling groups from around the world. The CMIP3 multi-model data set includes projections using SRES emission scenarios. The CMIP5 data set includes projections using the representative concentration pathways.
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. Different methods include dynamical, statistical and empirical downscaling.

Term	Description
El Niño Southern Oscillation (ENSO)	A fluctuation in global scale tropical and subtropical surface pressure, wind, sea surface temperature, and rainfall, and an exchange of air between the southeast Pacific subtropical high and the Indonesian equatorial low. Often measured by the surface pressure anomaly difference between Tahiti and Darwin or the sea surface temperatures in the central and eastern equatorial Pacific. There are three phases: neutral, El Niño and La Niña. During an El Niño event the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the eastern tropical surface temperatures warm, further weakening the trade winds. The opposite occurs during a La Niña event.
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.
Extreme weather	An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations.
Fire weather	Weather conditions conducive to triggering and sustaining wildfires, usually based on a set of indicators and combinations of indicators including temperature, soil moisture, humidity, and wind. Fire weather does not include the presence or absence of fuel load.
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 <sub>2</sub> O), carbon dioxide (CO <sub>2</sub> ), nitrous oxide (N <sub>2</sub> O), methane (CH <sub>4</sub> ) and ozone (O <sub>3</sub> ) are the primary greenhouse gases in the Earth's atmosphere.
Hadley cell/circulation	A direct, thermally driven circulation in the atmosphere consisting of poleward flow in the upper troposphere, descending air into the subtropical high-pressure cells, return flow as part of the trade winds near the surface, and with rising air near the equator in the so-called Inter-Tropical Convergence Zone.
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.
Indian Ocean Dipole (IOD)	Large-scale mode of interannual variability of sea surface temperature in the Indian Ocean. This pattern manifests through a zonal gradient of tropical sea surface temperature, which in its positive phase in September to November shows cooling off Sumatra and warming off Somalia in the west, combined with anomalous easterlies along the equator.
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 ( <a href="https://www.ipcc.ch/about/">https://www.ipcc.ch/about/</a> ).
Jet stream	A narrow and fast-moving westerly air current that circles the globe near the top of the troposphere. The jet streams are related to the global Hadley circulation. In the southern hemisphere the two main jet streams are the polar jet that circles Antarctica at around 60°S and 7–12 km above sea level, and the subtropical jet that passes through the mid-latitudes at around 30°S and 10–16 km above sea level.
Madden Julian Oscillation (MJO)	The largest single component of tropical atmospheric intra-seasonal variability (periods from 30 to 90 days). The MJO propagates eastwards at around 5 ms <sup>-1</sup> in the form of a large-scale coupling between atmospheric circulation and deep convection. As it progresses, it is associated with large regions of both enhanced and suppressed rainfall, mainly over the Indian and western Pacific Oceans.
Monsoon	A tropical and subtropical seasonal reversal in surface winds and associated rainfall caused by differential heating between a continental-scale land mass and the adjacent ocean. Monsoon rains occur mainly over land in summer.

Term	Description
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 90th (or 10th) percentile may be used to refer to the threshold for the upper (or lower) extremes.
Radiative forcing	Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in $\text{Wm}^{-2}$ ) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or the output of the Sun.
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).
Return period	An estimate of the average time interval between occurrences of an event (e.g. flood or extreme rainfall) of a defined size or intensity.
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.
Statistical climate model	A method of downscaling that estimates fine-scale climate information using the statistical relationships with large-scale climate parameters. When used to produce projections of future climate, the large-scale parameters are provided by a GCM. This approach assumes the statistical relationships will remain unchanged under a changing climate. For a recent evaluation of statistical downscaling, see Lanzante et al. (2018).
Subtropical ridge	A belt of high pressure that encircles the globe in the middle latitudes. It is part of the global circulation of the atmosphere. The position of the subtropical ridge plays an important part in the way the weather in Australia varies from season to season.
Southern Annular Mode (SAM)	The leading mode of variability of southern hemisphere geopotential height, which is associated with shifts in the latitude of the mid-latitude jet.
SAM index	A measure of the strength of SAM, otherwise known as the Antarctic Oscillation Index (AOI) is the index is based on mean sea-level pressure around the whole hemisphere at $40^{\circ}\text{S}$ compared to $65^{\circ}\text{S}$ . A positive index means a positive or high phase of the SAM, while a negative index means a negative or low SAM. This index shows a relationship to rainfall variability in some parts of Australia in some seasons.
SRES scenarios	Greenhouse gas emissions scenarios developed by Nakićenović and Swart (2000) in their Special Report on Emissions Scenarios (hence SRES) and used, among others, as a basis for some of the climate projections shown in Chapters 10 and 11 of IPCC (2007) and Chapter 5 of CSIRO and Bureau of Meteorology (2015).
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.
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g. a probability density function) or by qualitative statements (e.g. reflecting the judgment of a team of experts).

For more definitions, see [http://www.ipcc-data.org/guidelines/pages/glossary/glossary\\_a.html](http://www.ipcc-data.org/guidelines/pages/glossary/glossary_a.html)

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