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Wine Australia

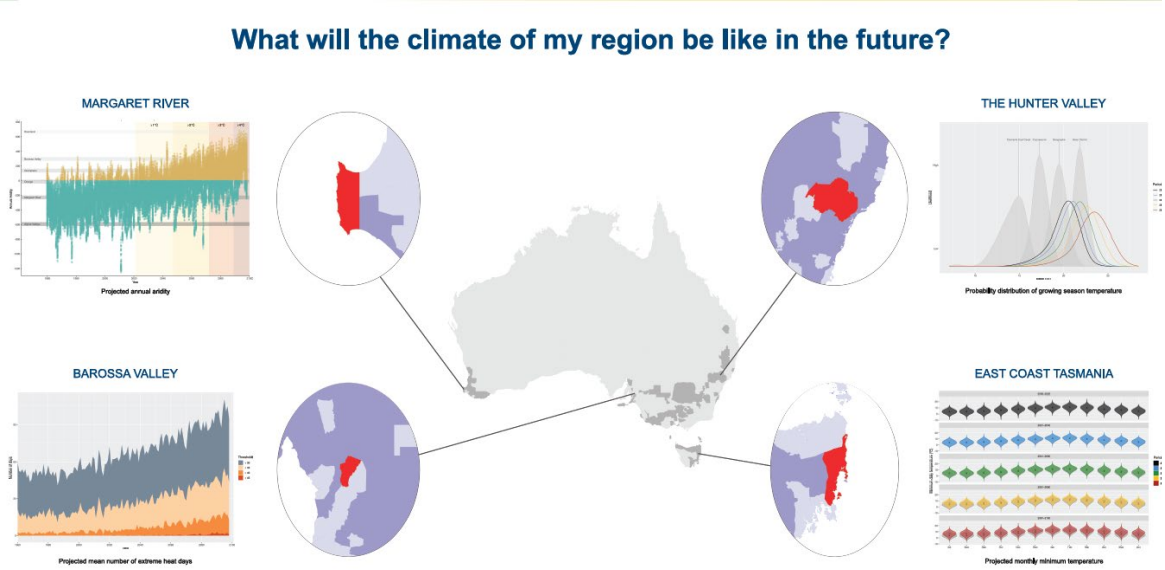
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AUSTRALIA'S WINE FUTURE: Adapting to short-term climate variability and long-term climate change



FINAL REPORT to WINE AUSTRALIA

Project Number: UT 1504

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Research Organisation: **Antarctic Climate & Ecosystems CRC, University of Tasmania**

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AUSTRALIA'S WINE FUTURE: Adapting to short-term climate variability and long-term climate change

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Cover image: An illustration of the fine-scaled climate information presented in *Australia's wine Future. A Climate Atlas*. A total of nineteen different indices are presented in the atlas for each wine region in Australia. The four panels, in clockwise order, represent the changing index of aridity in Margaret River, the changing distribution of the growing season in the Hunter Valley, the projected monthly minimum temperature in east coast Tasmania and the rising number of extreme heat days in the Barossa Valley.

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1. Abstract

Australia's wine future developed tools for Australia's grape growers to manage emerging weather and climate risks for short-term climate cycles and long-term climate change. The project assessed the impacts of short-term climate variability and trends in climate across all Australian wine regions and provided the most up-to-date climate information at the finest resolution available in Australia. Regional climate indices were tailored for particular grape varieties and regions, with the focus on heat accumulation, heatwave and frost. Adaptation options to manage emerging risks in the near future and out to longer-term planning horizons were identified.

2. Executive summary

The project brought together an extensive, multi-disciplinary research team to consider the impact of climate variability and longer-term trends in climate on the wine industry. We generated the finest available climate projections for South-eastern Australia and provided detailed information about how the climate may change in the near, mid and long-term time horizons. In addition to providing climate information, the project focused on how climate information can be used to inform adaptation decisions and identify lessons that might be transferable across regions already managing a range of climate challenges.

2.1. Adaptation and options for managing climate variability

2.1.1. Identification of current weather and climate risks for key regions

Wine growers in six case study regions (Grampians, Hunter Valley, Riverlands, Tasmania, Margaret River and Barossa) were consulted to identify weather and climate risks and the range in market requirements and management options that are currently experienced across Australia. Crop calendars, adjusted for each region, were used to consider weather risks in relation to the timing of grape growth and highlight management responses which could inform adaptation to future challenges. The calendars link the main stages of budburst, flowering, veraison and harvest to the weather and climate risks that occur at specific stages.

The interviews highlighted the very high level of flexibility and responsiveness of vineyard management to climate variability across the Australian wine regions, which offers great opportunities for transferring knowledge necessary for climate adaptation. Many wine regions are likely to be susceptible to climate change, but also have a degree of resilience because inter-annual variability in climate, especially in rainfall, is naturally high in these areas and wine growers have developed a range of short-term management options to minimise the impacts of climate variability on grape and wine quantity and quality.

2.1.2. Adaptation options for key regions

A Decision Analysis approach was used to identify climate sensitive decisions and understand the opportunities and barriers to the use of climate information in informing tactical and strategic decisions in vineyards. Six tactical decisions and seven strategic decisions were highlighted that would benefit from climate information at the seasonal and long-term time horizons.

2.1.3. Identification of analogue regions

Two methods were developed to describe current and future climate analogue regions. The first is a visualisation approach that shows how a region compares to other regions under current and future climate conditions. This climate analogue approach is an intuitive way to understand the local impacts of climate change over time and contextualise decision making. Comparisons between regions provide insights into real impacts of change and allows lessons to be learnt from regions that currently experience the climate conditions

projected for the future. This approach also provides a timeframe for potential adaptation options and could identify the limits to adaptation if there is a time in the future when no analogues remain.

The second approach is a Climate Analogue Tool that can identify similar regions globally on the basis of evaporation, humidity and radiation in addition to temperature and precipitation. It compares the climate on both daily and monthly timescales, to capture differences in extremes and seasonality as well as mean climate conditions. With further refinement and the development of a user-friendly interface, this tool could be widely used to identify future grape varieties and novel adaptation options and provide information about changing global markets.

2.2. Seasonal climate variability

2.2.1. Impact of historical climate drivers on the wine regions

The assessment of the historical impact of El Niño and Indian Ocean Dipole on viticultural climate indices across Australia found several general relationships, although there were strong seasonal and regional differences. The highest correlations with ENSO occurred in Queensland, NSW, ACT, Victoria and parts of the inland rivers irrigation areas, with drier conditions occurring during October to December in El Niño and positive IOD years. These results are consistent with published climate science, which has also shown that the impact of the main climate drivers on rainfall differs across Australia and seasonally (e.g. Risbey et al. 2009).

Changes in the modes of climate drivers may occur with ongoing climate change, but climate scientists are still debating the causes of the changes and the level of confidence in the projections (Cai et al. 2015a).

2.2.2. Development of Seasonal to interannual climate forecasts

The Decadal Climate Forecast Project (DCFP) at CSIRO provided a preliminary assessment of the skill of seasonal to interannual climate forecasts for the wine regions. The first part of this was an assessment of key extreme events such as heatwaves and wet extremes. For a model to have forecast skill it should simulate the distribution of extremes in a similar way to observations, and those extremes should be associated with the same synoptic and large-scale atmospheric circulations in the model and observations.

The DCFP model is broadly successful in simulating the correct distributions and synoptic and large-scale patterns for heatwaves and extreme wet periods. The second part of this work included an assessment of forecast skill for growing degree days (GDD) and cumulative rainfall at selected wine regions. These results showed improved skill relative to climatology (the best that one could do in the absence of a climate forecast) for GDD in the Margaret River and Riverland regions. The improvement in skill covers lead times from about 4 months to 2 years. Examples are presented showing how forecasts of GDD could be applied and visualised at a given point during the season to shape expectations of GDD over the remainder of the year. However, further work is needed to connect forecasts of GDD to viticultural outputs in the wine regions, and to identify windows of time when predictability is potentially higher.

2.3. Projections of future climate change

The best-available dynamically-downscaled regional climate models were used in each region of Australia. A regional climate model was run to provide daily climate data at 5km resolution for 2010-2070 for south-eastern Australia (see Section 9). Over Tasmania, Queensland and Northern NSW the output was at ~10km. Over Western Australia, a secondary statistical downscaling method was applied, to increase the resolution from ~50km to 5km.

The wine sector is likely to face challenges as climate change continues. Temperature increases of 3 to 4℃, relative to 1961-1990, are projected to occur by the end of the century under the high emissions scenario (RCP 8.5), the scenario that we are currently tracking. When superimposed on natural variability, this represents a highly significant change to the climate system, resulting in more frequent and intense extreme events such as heatwaves.

Several trends in future climate are consistently found for wine regions across Australia. Annual temperature and Growing Season Temperature (GST) are projected to increase into the future for every region across Australia. This strong warming trend accelerates towards 2100, with climate change becoming progressively more influential than natural variability after 2020. Aridity is expected to increase in all wine regions across Australia. Fewer Growing Season Frost Risk Days are likely as temperatures continue to rise. More intense heatwaves are expected in many regions, with substantial increases in the Excess Heat Factor (EHF) in some regions. This index describes the severity of acute heat impacts on humans during heat waves, and the results suggest that outdoor work may be restricted in the future in some of Australia's regions. Extremely hot years are likely to occur as much as 30 years earlier than projected by the mean trend. All of these changes will have widespread implications for the wine industry.

We have high confidence in how temperature will change into the future under particular emissions scenarios. The physical drivers of how temperature changes within the climate system are well understood, are valid across large spatial scales and are therefore straightforward to represent within climate models. This allows the models to achieve high levels of skill in the projections they produce. There is strong agreement across the ensemble of climate models we used regarding the rate and magnitude of warming projected into the future. In contrast, rainfall projections are more variable. However, very few simulations indicate increases in rainfall of sufficient magnitude to offset the projected decreases in moisture availability due to evaporation. As a result, all regions are expected to experience increased aridity in the future.

2.4 The Climate Atlas

The main legacy of the project is an online atlas of climate information for all Australian Geographic Indications (GI), providing information to grape growers and wine makers about climate trends for the near, mid and long-term horizons. *Australia's wine Future: A Climate Atlas* will help to answer the question – What will my region's climate look like in the future? This is essential knowledge for making good management decisions and supporting strategic decisions over the longer term such as changing varieties or vineyard sites both within and between regions. The atlas is an important resource that will help the wine industry understand how climate change could affect grape yield, profitability and wine styles across Australia into the future.

Tailored climate indices, identified as being relevant to the wine industry through consultation, were calculated for every GI. Indices representing temperature, rainfall and evaporative demand, and heat and cold extremes are presented, including:

1. Temperature - Growing Season Temperature (GST), Growing Degree Days (GDD);
2. Rainfall and evaporative demand - Annual, Monthly and Seasonal rainfall; Growing Season Rainfall; Number of rainy days during harvest; Annual, Monthly and Seasonal aridity; Number of dry spells before harvest;
3. Heat extremes - extreme heat factor (EHF) during a heatwave; Heatwave duration and intensity; Number of days per year exceeding temperature thresholds (30°C, 35°C, 40°C, 45°C); Frequency of days with high human heat stress;

4. Cold extremes - Number of days at risk of frost during the growing season; Daily minimum temperature; Annual chilling degree days; Number of days per year temperature falls below temperature thresholds (<2°C, <0°C, <-2°C).

In the Climate atlas, future trends in mean climate conditions, variability and extremes are visualised with reference to the current and historical climate. High resolution maps and time series for each region are presented to show the projected change in climate indices over time, highlighting the variability within and across the wine regions of Australia.

The use of fine-scaled climate information enabled the variability within and across Australian wine regions to be visualized. In *Australia's wine Future: A Climate Atlas*, national maps are presented to show the variability across Australia in temperature, rainfall and aridity in observed climate conditions during the period 1997-2017, and the changes in climate that have already occurred since the historical period (1961-1990).

Although the wine sector is likely to face challenges as the climate continues to warm, grape growers are experienced in responding to short-term climate surprises. In the short- to medium-term, adaptation approaches may be learnt from the regions that are currently experiencing the climate conditions that Australia is predicted to see in the future. Fine-scaled climate information tailored for particular sector applications is vital for identifying such adaptation needs, while accounting for climate variability and seasonality within different regional contexts.

3. Background

Over the last century, Australia's climate has warmed by around 1℃, and no regions have been unaffected (CSIRO and Bureau of Meteorology 2018). Hotter average temperatures, hotter summers, longer heatwaves, more frequent bushfires and changes to rainfall intensity and seasonality have already had impacts across the country, and these trends are expected to continue.

Rapid and ongoing climate change has the potential to affect all aspects of the wine industry, including vineyard performance, pest and disease incidence, wine quality and market competitiveness. There is increasing evidence that grape yields and wine quality are already being affected by warmer, drier conditions and increased incidence of heatwaves and bushfires. Challenges such as earlier budburst (Webb et al. 2007), earlier harvest and shorter seasons (Jones and Davis 2000), harvest date compression (Hayhoe et al. 2004) and impacts of high temperatures, extreme events and increased aridity on grape yield and quality are expected to accelerate over the coming decades.

Prior to this project, existing Australia-wide climate projections provided a good basis for understanding the general impacts of climate change, but the information was not tailored for the wine sector or available at sufficiently fine resolution to inform targeted adaptation responses. Previous research into climate change impacts on the Australian wine industry used climate projections at resolutions of 60-250km and focused on changes to mean rainfall and temperature (Webb et al. 2008b, a). This research highlighted the vulnerability of the industry to increasing temperatures and declining rainfall. However, the regional impact of changes in the timing or length of the growing and harvest season, or frequency of heatwaves and drought, was largely unknown.

The uptake of climate change information can be limited when information is delivered at an inappropriate scale or does not address specific industry requirements. Discussions with vineyard managers and wine makers highlighted the need for fine-scale regional projections across Australia and forecasts of inter-annual and decadal climate variability driven by the El Niño-Southern Oscillation and Pacific Decadal Oscillation. Seasonal variability in wine

quality has been associated with climate drivers such as the Southern Oscillation Index (Soar et al. 2008, Jarvis et al. 2018). Understanding the historical impact of El Niño on climate conditions such as heatwaves and droughts is an important step towards identifying current and future weather risks for wine regions across Australia.

The wine sector is likely to face challenges as the climate continues to warm, but, in general, grape growers are experienced in responding to short-term climate surprises. Many wine regions have a degree of resilience because inter-annual variability in climate, especially in rainfall, is naturally high in many parts of Australia. This means that wine growers have developed a range of short-term management options to minimise the impacts of climate variability on grape and wine quantity and quality.

Sharing that experience across regions will be key to supporting the sector in the future. Responses such as changed irrigation and canopy management are commonly employed to combat short-term variability, while decisions about vineyard position, orientation and variety choice may be needed to ensure the long-term viability of vineyards. Fine-scaled climate information tailored for particular sector applications is vital for identifying such adaptation needs.

This information is essential to enable short, medium and long-term planning of management strategies to deal with the challenges of short-term climate cycles and long-term climate change in the vineyard, identified as a priority for R&D investment in 2016–17. Under Priority 2: "*Increasing competitiveness*" and Strategy 4: "*Improving resource management and sustainability*" Wine Australia highlights "*Climate adaptability*" which aims to provide the sector with "information, tools and practical management options to manage the challenges of short-term climate cycles and long-term climate change". The project will increase the competitiveness of the Australian grape and wine industry in both the short and long term.

4. Project Aims and Performance targets

The overall aim was to provide useful information to assist Australian grape growers adapt to a variable and changing climate. The specific objectives listed in the application were to:
1. identify weather risks particularly important to grape growing within different wine regions (e.g. timing of heatwaves, frosts);
2. develop region-specific indices of "heatwave" and variety-specific indices of heat accumulation (e.g. GDD, growing season length);
3. assess the variability and trends in these indices using seasonal and multi-year forecasts and climate projections of near and mid-century conditions;
4. assess the impact of these changes across different phenological stages of grapevines;
5. assess historical and future changes in large scale climate drivers that drive drought and extreme heat in Australia;
6. consolidate available high-resolution climate information in an accessible and useful form to the wine regions of Australia.
7. identify regionally relevant adaptation options to improve the sustainability of each wine region in the short, medium and long-term as climate conditions continue to change;
8. improve understanding and uptake of climate information to empower grape growers to plan for the coming season, future years and decades.

The outputs in the original application are shown in Table 4.1.

Table 4.1: Outputs for the project in the original application

2016–17	Output
a	Communication plan for project, presenting a range of options
b	Standard set of climate indices
c	Database of grape thermal requirements
d	Dataset of Australia-wide climate projections
e	Industry article explaining crop climate calendar
2017–18	**2017–18**
a	Maps of climate suitability for key varieties under current and future climates
b	Report identifying information needs for key climate and weather risks at six case study sites
c	Report on historical analysis of how viticulture climate indices are influenced by ENSO and Indian Ocean Dipole for 23 sites around Australia
d	Assessment of the changes in variety and region specific indices under future climate change
e	1-10 year forecasts of heatwave occurrence across Australia
f	Assessment of the changes in climate drivers under future climate change
2018–19	**Output**
a	Evaluation of weather and climate information
b	Report summarising the effects of heatwave timing and adaptation options on grape growth
c	Report evaluating weather and climate information for viticulturists in the six case study sites
d	Journal papers, industry article and workshop presentations
e	Electronic Atlas with supporting information and adaptation guidance
f	Final report

5. Method

The project was carried out by four research teams, and broadly fell into four logical components:

1. Adaptation and options for managing climate variability
   i) Identification of current weather and climate risks in key regions;
   ii) Adaptation options for key regions;
   iii) Identification of analogue regions
2. Seasonal climate variability
   i) Impact of historical climate drivers on the wine regions
   ii) Development of seasonal to interannual climate forecasts
3. Projections of future climate change
   Production of new fine-scaled climate projections for South Eastern Australia and consolidation of best- available high-resolution climate data across Australia
4. Presentation of projected changes to tailored, region-specific indices in an online atlas.

Each component was led by a different research team, with collaboration from across the other teams. This report will follow this structure, with the methods, results and discussion presented for each section separately. The focus in the main text will be on industry relevant information

and application, and the technical details, such as the climate modelling and validation, will be presented in Appendices 5 and 6.

Following consultation with industry partners we made two changes to the methods.

The first change was that we did not calculate maps of climate suitability for key varieties under current and future climates. After consultation with AWRI partners, it was decided that producing maps of climate suitability for key varieties under current and future climates was unlikely to provide useful information, because there is insufficient information on the interaction between grape quality, vineyard management and climate. Climate suitability maps would therefore underestimate the area in which grapes might potentially be grown in the future, and as a result, wine growers would be unlikely to use the information.

Instead, we developed two approaches to identify analogue climates in wine growing regions of Australia and the world under current and future climate conditions. The first approach is a new model that compares the long-term meteorological data for each wine region and identifies similar regions in Australia and around the world at different time periods, based on important variables for growing grapes (e.g. maximum and minimum temperature, evaporation, rainfall and rainfall seasonality). The second approach is a visualisation tool to identity how a region compares to other Australian regions under current and future climate conditions. These are described in more detail in the relevant sections below (Section 5.3).

The identification of analogue regions will enable vineyard management techniques, such as pruning and timing of irrigation, and potential new varieties from these regions, to be identified at a range of time scales. From discussions with people in the wine industry, we feel that the analogue approach is a more intuitive and useful tool. This approach has been used elsewhere, but currently available models do not provide the flexibility required to incorporate the new fine resolution climate data.

The second change was that grape growth was not modelled under different climate and adaptation options using the growth model DYMEX. This approach was not developed because industry and project partners did not feel that output from a growth model would provide useful information. For it to be realistic, a growth model would need to be very detailed to cover the range in phenological stages of a grapevine, which would be difficult given the lack of robust empirical data. For example, one of the proposed outputs was a database of grape thermal requirements, but after searching the literature, it was found that there was very little robust information that could be applied to Australian conditions and varieties. It was not thought that an overly complicated model would be of interest to grape growers, who understand the complexity of grape growth and the lack of data availability for parameterising such a model.

As an alternative approach to understand changes to potential growth over time, we present Growing Degree Day models based on variety-specific thermal tolerances. Temperature based models such as GDD have been used widely for more many years as indicators of long-term climate suitability for winegrapes (Hall and Jones 2010). They are widely used to optimize harvest and viticultural practices, to improve economic and environmental outcomes, guide the management of grape yield and quality and select suitable sites for grape production (Fila et al. 2012).

However, Growing Degree Days has two main limitations when applied across Australia. Firstly, only accumulating heat after October (assuming no growth over winter) does not account for the effect of warm winter and spring periods, which will be increasingly important under a warming climate. Secondly, limiting the influence of heat to daily values above 10°C does not account for physiological responses that clearly occur at far lower temperatures, especially during the winter/spring period. In response to these limitations, we developed a method that incorporates daily climate values as inputs, accounts for the influence of heat

across the entire growing year (July to June) and reflects the changing physiological demands of grape vines throughout the year. The approach captures the importance of increased heat accumulation prior to October as the climate warms, providing a better representation of the impacts expected to be seen into the future, while also improving the utility of the GDD metric as a measure of heat accumulation within cooler climates (or cooler seasons) as it better reflects the influence of low temperature days relevant to grape-vine phenology.

Additionally, we provide an assessment of changes to the duration and timing of heatwaves in the projections, the results of which can be interpreted in the context of current adaptation options and comparisons across regions. The changes in the projections over time are presented in the electronic atlas.

6. Adaptation and options for managing climate variability

6.1. Identification of current weather and climate risks in key regions

This section was led by Dr Peter Hayman (SARDI) and Paul Petrie (SARDI and AWRI) with input from Tom Remenyi (UTas) and Fiona Kerslake (TIA).

6.1.1 Introduction

Climate change adaptation refers to actions aiming to avoid, manage or reduce the impacts of climate variability and climate change or exploit beneficial opportunities (Noble et al. 2014).

Adaptation includes operational, tactical and strategic management decisions that can be applied at different stages of the growth and production cycle. Adaptation occurs at different timescales to mitigate the impacts of climate change from the short to medium timescales through to longer timescales. Operational adaptations, such as canopy management or mulching, can be used on a short timescale to optimise production without major system changes (Olesen and Bindi 2002). Tactical adaptations, such as water saving or irrigation, can also be applied within the growing season to respond to weather risks. In contrast, strategic adaptations, such as rootstock and variety selection, require longer term planning and greater resources, but may be necessary to respond to emerging climate risks.

Many wine regions have a degree of resilience because inter-annual variability in climate, especially in rainfall, is naturally high in these areas. This means that wine growers have developed a range of short-term management options to minimise the impacts of climate variability on grape and wine quantity and quality. However, under continuing climate change, short-term adaptation options are unlikely to be sufficient in many regions, as the trends projected to occur by mid to late century exceed interannual variability (Lereboullet et al. 2013).

6.1.2 Selection of case study regions

Case study sites were selected in discussion with Wine Australia. These sites cover all states except Queensland and cover the main types of production (warm inland regions (South Australian Riverland) to cool premium (Tasmania)) (Figure 6.1, Table 6.1). The spread of regions also includes those that rely on local (rainfall) vs remote (river) sources of water and regions with low to high growing season rainfall.

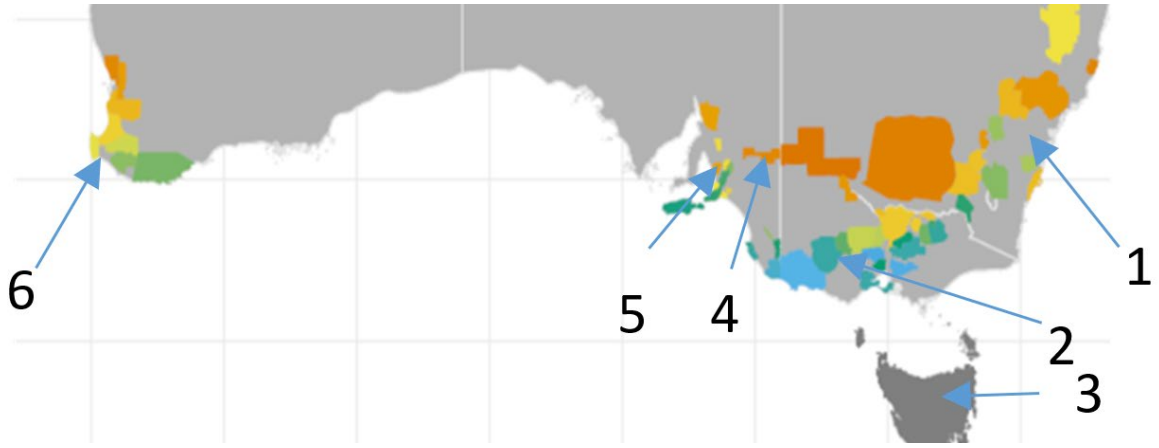


Figure 6.1: Location of six case study regions across Australia

	Case study sites and the associated wine regions	Growing Season Temperature	Rainfall. Wet if > 300mm growing season rain	Irrigation source
1	Hunter Valley, NSW	Hot	Wet	Farm dams
2	Grampians, Vic. (including Pyrenees, Vic.)	Warm	Dry	Primarily farm dams, some recycled water
3	Derwent Valley, Tas.	Cold	Wet	Farm dams
	Cole Valley, Tas.		Dry	Primarily on-farm dams
4	Riverland, SA	Hot	Arid	Murray River
5	Barossa Valley, SA (including Eden Valley, SA)	Warm	Dry	Farm dams and Murray River
6	Margaret River, WA	Mild	Dry	Farm dams

Table 6.1: Case study regions where interviews were conducted and crop calendars were tested.

6.1.3 Crop-climate calendars

The crop-climate calendars were used as part of the interview process in the six case study sites. The first step was to see if all the important risks were identified, then to adjust the timing of the key pheno-stages of budburst, flowering, veraison and maturity. The crop-climate calendar is based on the integrated pest management (IPM) calendars that link the lifecycle of a pest to the development stages of wine grapes. Rather than susceptibility to pests and disease, we are looking at the timing of sensitivity to weather and climate risks. It is important to stress that the calendar is a way to organise information, not to tell growers that frost at bud burst is a problem. The IPM calendar provides context for expert knowledge of pests and disease conveyed to growers whereas the climate crop calendar reverses the flow of information and is primarily a means for climate application researchers to understand the vineyard. Crop climate calendars were developed for 6 sites.

6.1.4 Interviews

We interviewed at least 8 viticulturists from each of the 6 regions. The interviewees were not selected at random or even selected as a representative group. The criterion was to select industry leaders who could provide guidance for the project. We are using a version of key informant interviewing by targeting people who speak from their own experience, but that experience includes aspects of the broader industry. The atlas and information from this project will be made available as widely as possible. However, we recognise that not everyone in the industry is asking for detailed climate information as they may be satisfied with what is currently available and/or have immediate pressures. The selection of the interviewees was on the premise that our target audience is the more technical end of the spectrum.

We used a semi-structured interview which is a qualitative method of inquiry. As a qualitative tool we are purposefully avoiding any quantitative interpretation (e.g. 80% of interviewees see heatwaves as important). The only quantitative analysis is the ranking of risks from the different regions and this was based on the ranking by interviewees (high, medium, low) along with the clarifying discussion with interviewees. As a semi-structured interview, we combined a pre-determined set of open questions (questions that prompt discussion) with the opportunity for the interviewer to further explore particular themes or responses. For a description of the approach see evaluationtoolbox.net.au/index.php.

The interviews were organised around the following questions and we used the same flow of questions in each case.

- What are the strengths and challenges of this region for growing wine grapes?
- Does the crop calendar make sense in terms of the main climate and weather risks and the timing of these risks?
- Taking the list of climate and weather risks, please categorise them into high, medium and low risks.
- What are the main sources of climate and weather information?
- If we categorise decisions on a vineyard into operational decisions that are made daily, tactical decisions that are made through the season and strategic decisions which set the long-term direction for the enterprise? Can we identify some operational decisions that are influenced by weather, some tactical decisions influenced by seasonal outlooks and strategic information influenced by historical climate records and how climate is projected to change?

6.1.5. Climate sensitive decisions and the barriers and opportunities for adoption

The crop-climate calendar was an effective way to identify and rank the main weather and climate risks during the interview. In this project, we aimed to go beyond identifying the risks to discuss climate sensitive decisions, decisions where the outcome is sensitive to climate *and* there is a preferred choice in one climate state (e.g. wetter than average) that is different to other states (drier and average seasonal rainfall).

To assess the questions, we used an established approach in economics and management science called Decision Analysis. This framework identifies who is making the decision, when the decision is made, the choices available to the decision makers and the uncertainty that interacts with the choice to produce the outcome. For example, a grape grower in the Riverland choosing to spray or not to spray for botrytis at cap fall will experience a financial outcome at harvest depending on the price of grapes. Based on the interviews in the case studies we identified 6 tactical decisions that would benefit from climate information at a seasonal time scale and 7 strategic decisions influenced by long-term climate change information. We also considered the opportunities and barriers to the use of seasonal climate information for the tactical decisions and the likely use of climate change projections for the strategic decisions.

6.1.6. Results and Discussion

There was a general agreement that the calendar summarised the main weather and climate risks, the regions differed in the ranking of the risks and the timing of the key phenological stages. With the exception of the Riverland, the diversity of meso-climates within the region due largely to elevation makes it hard to generalise. Furthermore, all regions have a wide diversity of varieties and hence timing of key phenological stages. A consistent approach across frost prone regions was that the frost period should be extended well into November as the later frosts are the most damaging. For South East Australia this was especially the case in 2018 due to widespread frost damage on November 4th and 5th.

The calendar is most applicable at the scale of a vineyard or to a block that has the same variety across a single soil type and is treated as a unit for irrigation and spraying. It is possible to have one section on a vineyard which has a high exposure and/or vulnerability to climate risk while another block is quite resilient. Despite the challenges of generalising, the calendar was an effective tool and the vast majority of interviewees were able to generalise and talk about exceptions.

The overwhelming response from all regions is that people we interviewed had a strengths-based view of their region. This doesn't mean that they overlooked any challenges that were occurring or had recently occurred (e.g. the Millennium drought, grape oversupply, crop protection costs in wet summers). Nor did this positive perspective involve any dismissal of how the challenges would change under projected climates. The strong sense was that the regions had survived past difficulties and would cope with the immediate future challenges. In the case of Tasmania, a warmer future was recognised as bringing advantages.

The opening question of "what is good about growing grapes in this region?" was designed as an ice breaker, however you could see people's faces light up as they spoke with passion about their region. The wine industry has a strong sense of place and which is clear in the marketing slogan of "wine from somewhere" and increasingly "wine from someone".
There are interesting case studies in the climate change literature where viticulturists have included climate change in their consideration of shifting or expanding in Tasmania. These cases have been given substantial media coverage and are valid part of the overall response of the wine industry to climate change. However, it is a simplification. For many in the industry who recognise climate change, shifting regions is not an adaptation option. Part of this relates to scale of operation; a large company may expand into Tasmania whereas a family owned vineyard is less likely to shift. There are exceptions but an overall fining is the confidence that there are changes that can be made within the region. The ranking of the risks is shown in Table 6.2.

Table 6.2: Identified climate risks and their ranking.

		NSW	Vic	Tas	SA	SA	WA	
		Hunter Valley	Grampian Pyrenees	Derwent V Cole V	Riverland	Barossa Eden valle	Margaret River	
	Growing season temperature Wet >300 mm Oct - Apr rainfall	Hot Wet	Warm Dry	Cold Nth Wet Sth Dry	Hot Arid	Warm Dry	Mild Dry	
	Temperature							
Climate extreme	Warmer than normal summer	Not risk	Mod	Not risk	Not risk	High	Mod	#6
Weather extreme	Heatwaves	High	High	Low	High	High	Mod	=#2
Climate extreme	Winter too warm	Not risk	Low	High	Low	Mod	High	#4
Weather extreme	Frost damage	Not risk	High	High	Mod	Mod	Not risk	
	Rainfall							
Climate extreme	Winter spring drought	Mod	High	High	Low	High	Mod	#1
	MDB catchment too dry	N/a	N/a	N/a	High	High	N/a	
Weather extreme	Rain at harvest	Mod	Low	Mod	Low	Low	High	# 5
Climate extreme	Summer too dry - extra irrigation	Low	Low	Low	Not risk	Low	Not risk	#7
Climate extreme	Summer too wet - disease pressure	High	Low	High	High	Mod	High	=#2

The risk that is consistently ranked the highest is drought, either in the region or in the Murray Darling Basin. Wet summers and consequent disease pressure are ranked as a high risk in the wetter regions (Hunter, Tasmania and Margaret River) moderate in the Barossa, low in Grampians but high in the Riverland. These risks include likelihood and consequence; wet summers are uncommon but manageable in Barossa and Grampians. This risk is extremely difficult to manage in the Riverland, a viticulturist from a large company explained that wet summers like 2010/11 led to disease, but apart from the disease “a loss of irrigation as a lever of control of canopy development and vine balance”. Rain at harvest follows a simpler pattern of being a problem in wetter regions and for all regions a dry summer is either welcome or considered a low risk.

Heatwaves were ranked as a major risk in all locations except Tasmania. While all regions recognise that warmer summers will shift maturity, the consequence of this damage is more difficult to pin down. The risk is dismissed in Tasmania where earlier ripening is welcomed. More surprisingly in the hotter regions of the Hunter and Riverland where earlier ripening is also welcomed. In the Riverland earlier ripening is shifting sensitive stages from hot February to equally hot January and hence that crop has less time exposed to heatwaves and perhaps more importantly frees up irrigation resources for other blocks. It is also the case that wineries generally welcome earlier fruit. In the Hunter, the early ripening is thought to provide the grapevine with a longer period to recover, and as with the Riverland the shift is from hot late-summer to hot mid-summer with the added advantage of limiting the chance of rain and disease development. In contrast the shift in time of ripening for the main varieties in the Barossa, Grampians and Margaret River is a shift from milder autumn (March) towards hotter late summer (February).
Warm winters are of concern in Tasmania due to early budburst and hence increasing frost risk. In Margaret River, warm winters are a concern due to lack of vernalisation leading to late and uneven budburst. In the Riverland, Grampians and Barossa a common comment was that the most damaging frost was not immediately after budburst because there was a chance of recovery but when shoots were exposed. The consensus was that changing the time of budburst from warmer winters and/or late pruning would not reduce the damage from late frosts. The November 4th, 2017 frosts were a recent event that influenced the discussion in the Grampians.

Wind is recognised as a problem in the coastal regions of Margaret River and the Hunter,

however, these regions also welcome the role that wind plays in drying the canopy and minimising disease risk. Hail and to a lesser extent frost tend to be highly location specific and are high consequence but low frequency events.

6.2 Adaptation options for key regions

This section was led by Dr Peter Hayman (SARDI) and Paul Petrie (SARDI and AWRI) with input from Tom Remenyi (UTas) and Fiona Kerslake (TIA).

6.2.1. Short-term tactical decisions

The six tactical decisions are briefly described and presented in the format of a payoff matrix with the two choices × two season types leading to four outcomes. Table 6.2.1 summarises the opportunities and barriers to the use of seasonal climate forecasts for each of the decisions.

Decision 1: Use a prophylactic fungicide spray for botrytis bunch rot on a hectare of Chardonnay grapes in the Riverland at 80% cap fall. Assume 20t/ha @ $450t ($9000) and cost of spray applied at $200/ha.

Decision	Season	Outcome
Spray	Wet (rare)	Grower pleased with $200 investment to protect $9000 crop
	Dry (common)	Minor regret of the $200 spray or treat it as insurance. Some concern that this might be contributing to fungicide resistance
Don't spray	Wet (rare)	Major regret with potentially major crop loss
	Dry (common)	Grower pleased or feeling lucky with saving of $200/ha

Decision 2: Purchase extra temporary water from the water market in December (water allocations are based on financial year). Assume a ML of water is worth $400 and in 30% of drier years the ML will increase production by 1.5 t/ha @ $450/tonne.

Decision	Season	Outcome
Purchase	Normal to wet (70% of the time)	Grower regrets $400/ML investment and looking for carryover rules and/or to sell the water. Some growers view the extra water as insurance in case of a late heatwave.
	Driest 30% of years	Grower pleased with $400/ML investment to produce extra $675/ML (1/5 t @ $450/t)
Don't purchase	Normal to wet (70% of the time)	Grower pleased with avoiding the extra cost (but had to endure worry of the chance of a heatwave)
	Driest 30% of years	Major regret due to lost production

Decision 3: Purchase and spread mulch in a vineyard block prior to the growing season

Decision	Season	Outcome
Mulch	Normal to wet (70% of the time)	Grower regrets expense of mulch but thinks of benefits to long-term soil health
	Driest 30% of years	Grower pleased with extra production and soil health benefits from mulch
Don't mulch	Normal to wet (70% of the time)	Grower pleased with cost saving with scarce cash available for other parts of the vineyard or off-farm investment and will consider mulch next year
	Driest 30% of years	Regret due to lost production and/or the extra cost of water

Decision 4: Remove leaves through leaf plucking – the removal of leaves around grape bunches to increase exposure.

Decision	Season	Outcome
Leaf plucking	Normal to wet (70% of the time)	Grower pleased with more effective disease control and sunlight to ripening fruit from leaf plucking
	Driest 30% of years	Major regret due to cost of leaf plucking and loss of quality due to sunburn
Don't leaf pluck	Normal to wet (70% of the time)	Grower regrets disease problems and uneven ripening
	Driest 30% of years	Grower pleased with saved cost and better protection from sunburn

Decision 5: Switch within the season from still to sparking Pinot noir. This will involve an earlier harvest in the vineyard and quicker cash flow from the wine. Assume that there is a premium for grapes harvested for still Pinot noir from the block in question.

Decision	Season	Outcome
Continue with still Pinot noir	Normal to dry (70% of the time)	Grower pleased with premium for quality still Pinot noir
	Wettest 30% of years	Major regret due to downgrading of fruit, extra growing cost and missed opportunity for sparkling
Switch to sparkling	Normal to dry (70% of the time)	Grower regrets missed opportunity for still Pinot noir
	Wettest 30% of years	Grower pleased with saved production cost and returns from sparkling.

Decision 6: Apply sunscreen to grapevines to reduce damage from heatwave.

Decision	Season	Outcome
Apply sunscreen	Normal to cool ripening period (70% of the time)	Grower regrets significant cost of sunscreen
	Hot ripening period 30% of years	Grower pleased with protection provided by sunscreen
Don't apply sunscreen	Normal to cool ripening period (70% of the time)	Grower pleased with saved cost
	Hot ripening period 30% of years	Grower regrets sun burn damage.

Table 6.2.1: The opportunities and barriers to the use of seasonal climate forecasts for each of the six tactical decisions considered.

Decision	Opportunities or reinforcing aspects of adopting seasonal climate forecasts	Barriers or restricting factors to the adoption of seasonal climate forecasts
Prophylactic spray for botrytis bunch rot	Climate post flowering is the primary determinant of disease severity and decision has to be made at flowering.	The decision to spray is seen as insurance because the loss in wet years is so great. A forecast would need to eliminate the chance of wet years.
Purchase temporary water	A high potential value of early information as the price of water can rise rapidly under widespread dry conditions.	The forecast may be overridden by different strategic approaches whereby some growers prefer to have extra water as an insurance policy. There is a potential for the forecast to influence the price of water.
Purchase and spread mulch	The cost of mulch is significant and there are opportunities to be tactical in considering application in any year. Some sources of mulch may be more expensive due to increased demand and reduced supply in a drought.	The regret of not applying mulch is unlikely to be catastrophic if extra water is applied. Some growers will prefer to take a long-term view of soil health and mulching.
Leaf plucking	The optimum choice depends on the climate for the rest of the season. A forecast could influence the extent of leaf plucking, both or more exposed side of the row or to certain varieties.	Serious regret if leaf plucked and a severe heatwave occurs “you can’t put the leaves back on”. Hence there is asymmetry in payoffs from a forecast with a miss costing more than the benefit of a hit.
Switch midseason from still to sparkling Pinot noir	A forecast for wet conditions later in the vintage might influence the decision. The right decision has benefits in the vineyard and winery.	There are many other factors in terms of markets etc that will determine which choice is best. In some cases, the advantages of sparkling are compelling apart from climate risk (early harvest, higher yields, faster cash flow)
Apply sunblock	A decision that can be made in response to shorter term forecast	There are other issues for sunscreen, including questions of effectiveness and not all wineries accepting the fruit.

6.2.2. Longer-term strategic decisions

Longer term strategic examples where climate change projections that are included in the atlas would influence a decision include:

Decisions on permanent water – to take a strategy of leasing or buying where there was a water market and expanding storage in other regions. It is clear that water supply and drought were a major concern for all regions.

Climate change projections of future water supply (rainfall, especially in the non-growing season) and water demand (aridity and heat events) has the potential to assist with planning. A challenge is that future water supply for wine regions that rely on the Murray Darling Basin are dealing with climate risk and policy risk.

Vineyard redesign - row orientation, irrigation design. Although north-south row orientation tends to maximise light interception, the western side is exposed to the hottest afternoon sun. In a warmer, drier climate there may be benefits to East West rows or an angle in between.
There is high confidence in warming and increased heatwaves. The climate change projections may help with planning new vineyards.
Changing varieties – perhaps the most common adaptation to climate change is to change varieties. In cooler regions this involves adopting longer season varieties such as shiraz or cabernet and producing cool climate variants of these well-known varieties. In warmer regions there is an ongoing interest in newer varieties from southern Europe and the large set of varieties tested by CSIRO at Merbein research centre from near Mildura.
The rate and extent of warming is likely to assist in planning future varieties. The analogue approach shown in the atlas is likely to be beneficial in identifying appropriate varieties from within Australia. A climate matching tool to identify varieties from other parts of the world would expand this potential.
Re-locating or opening up new areas. A general principle of climate change is that species shift poleward and uphill. The interest in Tasmania and cooler sites on the mainland are examples where the atlas will be useful, especially when combined with other data such as soils and water availability.
Increase crusher/processing capacity (in response to vintage compression). A commonly reported problem in warmer vintages is vintage compression. Later ripening varieties such as cabernet sauvignon appear to be ripening faster than earlier ripening varieties such as chardonnay. The processing capacity of wineries are always likely to be limiting due to the cost of equipment, much of which is idle for the time outside of vintage. There is a need for more research on the drivers of this change in a warming climate. The atlas and some indication of the possible future rate of warming may help with decision making.
Protective cropping/shading. Table grapes and apples deal with heat waves with permanent shading which has prompted some to ask whether this will be used for premium wine grape production in the future. The primary question is the cost and benefits (improved quality and reduced water use) of these strategies and the likelihood of payoff in the near future. An indication of heatwaves and aridity from the atlas is likely to provide background information.
Fencing/netting (protection from animals, birds). In a region with Mediterranean climate, vineyards are green refuges in a dry hot landscape. This is attractive to introduced and native birds and animals. During a drought the contrast between the grapevines and the surrounding region is even greater. Some vineyards have gone to the expense of fencing exposed blocks. The main drivers for this change are local native vegetation and populations of birds and animals causing the problem. Indications from the atlas of increased aridity will be useful background information.

6.3 Identification of analogue regions

This section was led by Rebecca Harris and Tom Remenyi (ACE CRC).

6.3.1 Background

The climate analogue approach is a climate modelling method that can be used to identify statistically similar climates across space and time. It can identify those regions that are currently climatically similar to the future (projected) climate of a region of interest. It can therefore identify locations in the world where we should be looking to learn from, so we can adapt to the climate conditions that we may be facing at particular periods in the future.

Techniques currently used to mitigate climate variability in an analogue region might be transferable to help adaptation to climate change in the near, and longer, time scales. The approach also provides a timeframe for potential adaptation options and may identify the limits to adaptation if there is a time in the future when no analogues remain.

There are several advantages to the climate analogue approach (Veloz et al. 2012). First, it is an intuitive approach to understanding changing climate conditions over time, providing maps that are easily understood by a broad audience. Results are tailored for specific localities, providing targeted information about the local impacts of climate change. Second, it avoids many of the assumptions about the climatic tolerances of particular species. In contrast to climate suitability or species distribution modelling, it does not require observational data describing the presence of a species. Additionally, it allows the mitigating effects of management to be considered. In the context of wine grapes, for example, it is not just the ability to grow grapes within a climate that is of interest, but the link between climate and grape quality. Finally, the climate analogue approach can easily be applied to new regions to provide information about broad scale change, rather than variety specific detail.

Dunn et al. (2015) surveyed Australian winemakers and found "When making long-term decisions, users in viticulture in Australia would prefer to receive information both about specific variables (particularly as regards extremes) and in the form of climate analogues." They found that those surveyed felt that climate analogues for both domestic and international wine grape growing regions was important to help them contextualise their decision making.

Climate variability is likely to play an important role in adaptation in the short and medium timescales. Many in the wine industry have extensive knowledge and experience in responding to variability. Simple comparisons between regions provide insights into real impacts of change and allows lessons to be learnt from regions that currently experience the climate conditions projected for the future.

6.3.2 Methods

We developed two methods to describe current and future climate analogue regions.
The first, which is presented in the Climate Atlas, is to visualise the climate conditions graphically in relation to other regions with a known current climate.
An example is shown in Figure 6.3.1.

The second method is a climate analogue tool that captures variability in climate at a fine temporal scale. The tool differs from other available climate analogue tools in two important ways. Firstly, it captures the effects of evaporation, humidity and radiation in addition to temperature and precipitation. Secondly, it compares the climate on both daily and monthly timescales, to capture differences in extremes and seasonality as well as mean climate conditions. Previous climate analogue tools, such as CLIMEX (Kriticos et al. 2015) and the Climate Change, Agriculture and Food Security (CCAFS) (Ramírez-Villegas et al. 2011, Koven 2013) and CSIRO climate analogue tools (https://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/analogues-explorer/), use monthly mean values of the climate variables of interest or seasonal averages of temperature and precipitation (e.g. Veloz et al. 2012). Other tools only provide comparisons of current climate conditions (e.g. Climatch (http://data.daff.gov.au:8080/Climatch/climatch.jsp)).

The tool was developed using the R programming language. This was necessary to enable a suite of climate variables to be compared and accommodate continuously varying gridded data. The system was developed using temperature, precipitation and evaporation, but can also incorporate comparisons of humidity and radiation.

The approach compares an array of percentiles (1^{st}-99^{th}) to capture the normal distribution of values, including extremes. An array of monthly mean values is also calculated (from daily data) to capture seasonality. Growing season is offset between the northern and southern hemispheres.

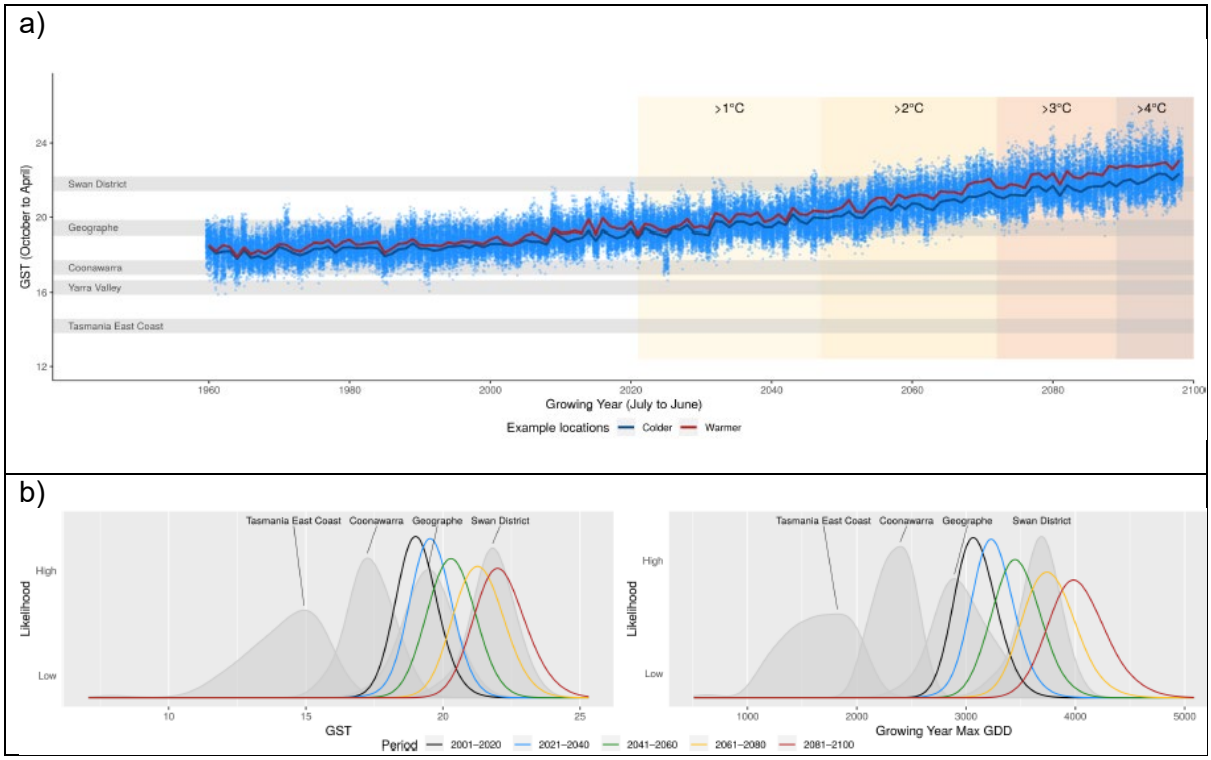


Figure 6.3.1: Examples of climate analogue visualisation in the Climate atlas to provide a comparison between current conditions elsewhere and future conditions in the region of interest, helping to identify future analogue regions. a) Growing Season Temperature (GST) over time, with the horizontal grey bars showing the mean GST value during 1997-2017 in selected regions across Australia. b) Probability distribution of GST for 20-year time periods from 2001 to 2100. Grey shapes represent the probability distribution of GST for contrasting regions during 1997-2017.

Calculating the climate envelopes was a multi-stage process:

1. Determine input climate variables
2. Subset the data based on an input locality or shapefile
3. Calculate statistics for each variable for each period of interest
4. Compare the statistics of each cell in the target region to every other cell in the comparison climate variable grid and return a climatic difference value
5. Determine the climatic difference threshold value for the variable of interest and use this to determine the spatial extent of ‘similarity’ for each input variable
6. Overlay each of the input variables to determine the spatial extent of ‘multivariate similarity’

The data were scaled temporally (all sites at one time) by dividing the mean by the variance to incorporate the variability in the comparison locations.

We used a pre-defined threshold to define the extent to which sites need to be similar to be considered ‘analogous’. Although the choice of threshold is subjective, we chose this approach rather than using a relative threshold, because the latter method is likely to fail when there are few or no analogues to the location of interest. This is not unlikely when considering future climates. Using a pre-defined threshold is also expected to be more accurate when well calibrated (Ramírez-Villegas et al. 2011).

Analogue regions can be identified at a range of periods in the projections, for example, mid-century (2021-2050) or end of century (2071-2100). The tool can be applied globally, to identify analogue regions around the world and within Australia, to determine regions that are currently similar to a region of interest; where similar climates will be found in the future that match the current climate of a region, and what regions are currently climatically similar to the future (projected) climate of a region?

Further development of the tool is required to refine the thresholds and create a more usable interface. The benefits of this is discussed in Section 12.

6.4. Conclusions - Adaptation and options for managing climate variability (now and in the future)

Vineyard management in many Australian wine regions will need to adapt as rainfall patterns change and temperatures and extreme events such as heat waves increase under climate change. These challenges are already occurring in many regions of Australia. As was highlighted in the interviews with growers (Section 6.1), there is widespread awareness of adaptation options that help reduce the impact of weather risks under current conditions. The identification of analogue regions will assist with the transfer of knowledge from regions that already deal with challenging climate conditions to those regions where such conditions are expected to evolve in the near to mid-century timeframes.

7. Seasonal climate variability

Led by Dr Dane Thomas and Peter Hayman (SARDI)

7.1. Impact of historical climate drivers on the wine regions

7.1.1. Background

A range of climate drivers affect weather and climate in different regions of Australia (Risbey et al. 2009, Marshall et al. 2014). These drivers, which include the El Niño/Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM), are influenced on inter-decadal to intra-seasonal timescales by large-scale ocean– atmospheric processes stemming from the surrounding Pacific, Indian and Southern oceans. They influence flooding, drought, storms and bushfire activity (Nicholls et al. 1997, Power et al. 1999, Ummenhofer et al. 2009, Mariani and Fletcher 2016, Taschetto et al. 2016), and make Australia's climate more variable than similar climate zones elsewhere in the world.
ENSO consists of two opposing phases, El Niño and La Niña, and a neutral phase. The El Niño phase generally brings warm, dry weather as atmospheric highs predominate over Australia due to a shift in the Walker Cell circulation associated with the Pacific Ocean basin. Conversely, La Niña is associated with cool, wet weather due to a strengthening of easterly trade winds associated with a canonical Walker Cell. No two El Niño and La Niña events are exactly alike, with variations dependent on the strength and location of the sea surface temperature anomaly, which is related to oceanic and atmospheric circulation patterns. El Niño events tend to last about one year, starting in the Austral winter and peaking in late spring and early summer. In contrast, La Niña events can span multiple years, with multi-year events having more than one peak stage.

Rainfall is mainly affected by ENSO in the winter and spring months (June–November). During El Niño years, the east of Australia tends to have rainfall in the lowest tercile virtually everywhere except the coast east of the Great Dividing Range. During La Niña years, the same regions show increased rainfall. In summer and autumn, the mean El Niño response is weaker. The limited impact of ENSO on South Eastern Australia in autumn means that the recent trend toward a drier climate in this region is unlikely to be related to changes in ENSO (Murphy and Timbal 2008).

Part of the temperature signal related to ENSO comes from the rainfall changes that occur, so that much of the inter-annual temperature variability can be explained by rainfall variations (Nicholls, 2003). This is caused by two factors. Firstly, since lower rainfall is associated with less cloud cover (i.e. higher solar radiation), daily maximum temperatures increase. Secondly, higher mean temperatures result from reduced evaporative cooling when soil moisture is low during dry conditions (Murphy and Timbal 2008).

The Indian Ocean Dipole (IOD) is a phenomenon similar to ENSO which also causes seasonal changes to weather across Australia. It is associated with sustained changes in the difference between sea surface temperatures of the tropical western and eastern Indian Ocean. The IOD can have a significant impact on agriculture, because events generally coincide with the winter crop growing season. As with ENSO, there are three phases of the IOD, positive, negative and neutral. IOD events usually start in May or June, peak between August and October and then rapidly decay when the monsoon arrives in the southern hemisphere towards the end of spring.

The positive phase of the IOD, like El Niño phases, bring warm, dry weather to Australia. IOD negative phases bring cold, wet weather, similar to La Niña (Saji and Yamagata 2003), due to enhanced tropical moisture flux reaching southern and western regions. IOD events are shorter in duration than ENSO events for both phases (Shi et al., 2012). Impacts on air temperature during IOD events were demonstrated to be strongest during Austral spring (Saji et al., 2005), coinciding with the peak time of the IOD event (SajiandYamagata,2003; Meyersetal.,2007), as well as the start of the Australian winegrape growing season."
When El Niño coincides with a positive IOD, the two phenomena can reinforce their dry impacts. Likewise, when La Niña coincides with a negative IOD, the chance of above-average winter–spring rainfall typically increases.

Forecasting the variation in climate over seasonal time scales (3-6 months) is driven by changes in ocean temperature patterns and/or persistent changes in atmospheric circulation. This is different to weather forecasts which essentially use today's weather conditions to forecast weather over the next week and climate change projections which are based on the response of earth systems to changes in radiative forcing over many decades. The main seasonal drivers of Australian climate are shown in Figure 7.1.

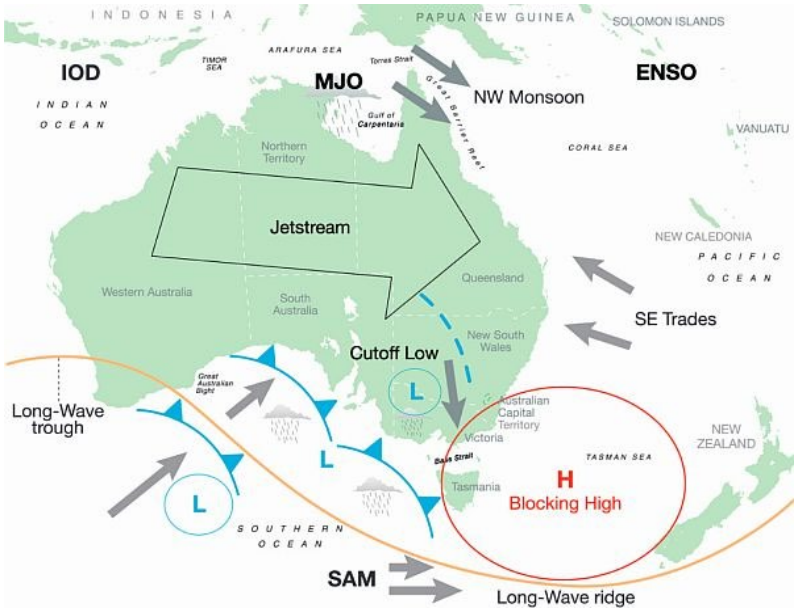


Figure 7.1: Schematic representation of the main drivers of rainfall variability in the Australian region. The dominant features are the IOD, MJO, and ENSO in the tropics, and the SAM and blocking in the extratropics. SOURCE (Risbey et al. 2009).

7.1.2. Methods

In this project, the climate drivers analysed included El Niño Southern Oscillation (ENSO) using the Niño 3.4 index, Indian Ocean Dipole (IOD) and Southern oscillation Index (SOI). Monthly values of the Niño 3.4 and IOD climate drivers were sourced from HadiSST1 data accessed from the Global Climate Observing System (GCOS) Working Group on Surface Pressure (WG-SP) (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/), while monthly values for SOI were sourced from the Bureau of Meteorology (http://www.bom.gov.au/climate/enso/soi/). The categorization of years into ENSO and IOD event years (that is La Niña, El Niño or neutral; and +IOD, -IOD or neutral) was obtained from Bureau of Meteorology.

We focused on text books and review articles to identify appropriate indices that linked climate to viticulture. A set of indices should cover five areas: 1) temperature over the growing season 2) heat extremes 3) frost after budburst 4) some broad indicator of canopy wetness for disease risk 5) an indicator for irrigators that includes rainfall and evaporative demand. A general principle was to err on simpler indices and where possible indices that were either used by the industry or could be readily understood. As an indicator of disease risk we calculated simple moisture budget with a memory or capacity of 10 mm. A moisture positive day was determined by subtracting evaporation from daily rainfall for day 1, if rainfall exceeded evaporation up to 10 mm was carried forward to the next day and evaporation was subtracted from rainfall and carried forward moisture. This index has been used as a simple and transparent way to compare disease risk across vintages and regions.

Spreadsheets were designed to test the indices in Table 7.1 for climate drivers described at the beginning of this section for all the locations in Table 7.2. Results are shown in Tables 7.3 - 7.6.

It is important to note the difference between gridded and station data. A major value proposition of this project is the provision of finer scale gridded climate change projections for wine regions for the atlas. The historical impact of climate drivers such as El Niño Southern Oscillation or the Indian Ocean Dipole was based on point data from meteorological stations (shown in Table 7.2). Climate change projections and seasonal climate forecasts are only available as gridded data. Historical analysis can be conducted on gridded or station data and there are advantages and drawbacks of using either. From previous discussion with wine grape growers, most are familiar with how their vineyard is cooler/warmer, wetter/drier, frostier or less frost prone than the local meteorological station.

7.1.3. Results and Discussion

El Niño Southern Oscillation (ENSO) is the term used to describe the oscillation between the El Niño phase and the La Niña, or opposite, phase. El Niño involves warming of a section of the equatorial Pacific Ocean and La Niña is associated with its cooling. Australia's climate can be related to a particular index of ENSO known as Niño3.4 which measures warming and cooling of a particular region of the equatorial Pacific Ocean. It follows from El Niño being associated with warmer and drier conditions that there will be a positive correlation between Niño3.4 and temperature indices and a negative correlation with rainfall. Indices such as irrigation demand (ETo – rainfall) or moisture budget positive days tend to have a stronger positive correlation than the constituent parts of rainfall and temperature. The increase in ETo is due to the higher daytime temperatures but primarily higher radiation due to less cloud cover. The higher observed frost incidence is also due to the low cloud cover and less moisture. The Indian Ocean Dipole (IOD), an oscillation of sea-surface temperatures in which the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean, has a similar pattern of positive correlation with temperature and negative correlation with rainfall. In general terms the IOD has a stronger relationship with the agro-climatic indices useful to viticulture than Niño 3.4.

The convention in climate science is to list the calendar year that the ENSO and IOD event starts. In contrast the convention in viticulture is to refer to the year that the crop is harvested (vintage year). For the purpose of this analysis the year allocated to the agro-climatic indices was the year of budburst not the year of harvest irrespective of whether the measurement period was solely in the first calendar year, spanned two calendar years, or solely in the second calendar year of the wine grape growing season.

Table 7.1: Agro-climatic indices measured in this analysis.

Agro-climatic indices	**Period**	
Mean temperature	Annual	January to December
Mean temperature	Non-Growing season	May to September
Mean temperature	Growing season	October to April
Mean temperature	Oct-Dec	October to December
Mean temperature	Jan-Mar	January to March
Growing degree days (base10)	Growing season	October to April
Date that 350 GDD attained	Accumulation from 1st October	
Date that 110 GDD attained	Accumulation from 1st October	
Date that 1250 GDD attained	Accumulation from 1st October	
Date that 1500 GDD attained	Accumulation from 1st October	
Sum of Excess Heat Factor	Annual	January to December
Sum of Excess Heat Factor	Growing season	October to April
Sum of Excess Heat Factor	Oct-Dec	October to December
Sum of Excess Heat Factor	Jan-Mar	January to March
Days warmer than 35°C	Growing season	October to April
Days warmer than 35°C	Oct-Dec	October to December
Days warmer than 35°C	Jan-Mar	January to March
Earliest date warmer than 35°C	1st July to 30th June	
Latest date warmer than 35°C	1st July to 30th June	
Days warmer than 95th%ile	Growing season	October to April
Days warmer than 95th%ile	Oct-Dec	October to December
Days warmer than 95th%ile	Jan-Mar	January to March
Earliest date warmer than 95th%ile	1st July to 30th June	
Latest date warmer than 95th%ile	1st July to 30th June	
Days cooler than 0°C	Jan-Dec	January to December
Days cooler than 0°C	Aug-Dec	August to December
Earliest date cooler than 0°C	1st January to 31st December	
Latest date cooler than 0°C	1st January to 31st December	
Rain	Annual	January to December
Rain	Non-Growing season	May to September
Rain	Growing season	October to April
Rain	Oct-Dec	October to December
Rain	Jan-Mar	January to March
Evapotranspiration	Annual	January to December
Evapotranspiration	Non-Growing season	May to September
Evapotranspiration	Growing season	October to April
Evapotranspiration	Oct-Dec	October to December
Evapotranspiration	Jan-Mar	January to March
Evapotranspiration – Rain	Annual	January to December
Evapotranspiration – Rain	Non-Growing season	May to September
Evapotranspiration – Rain	Growing season	October to April
Evapotranspiration – Rain	Oct-Dec	October to December
Evapotranspiration – Rain	Jan-Mar	January to March
Days Moisture Balance +ve (MB+ve)	Growing season	October to April
Days Moisture Balance +ve (MB+ve)	Oct-Dec	October to December
Days Moisture Balance +ve (MB+ve)	Jan-Mar	January to March

The 95th percentile was measured from 1st January 1986 to 31st December 2005.

Table 7.2: The meteorological stations used in the analysis.

Region and Indication	Station name	Number	Lat.	Long.	Elevation (m)
Queensland					
South Burnett	Kingaroy Airport	40922	-26.57	151.84	433
Granite belt	Applethorpe	41175	-28.62	151.95	871
Greater NSW and ACT					
New England	Armidale Airport Aws	56238	-30.53	151.62	1079
Orange	Orange Airport Aws	63303	-33.38	149.13	947
Hunter	Cessnock (Nulkaba)	61242	-32.81	151.35	62
Canberra district	Canberra Airport Comparison	70014	-35.30	149.20	578
Greater Victoria					
Rutherglen	Rutherglen Research	82039	-36.10	146.51	175
Yarra valley	Coldstream	86383	-37.72	145.41	83
Heathcote / Strathbogie	Mangalore Airport	88109	-36.89	145.19	140
Geelong	Avalon Airport	87113	-38.03	144.48	10
Gippsland	Bairnsdale Airport	85279	-37.88	147.57	49
Gippsland	Morwell (Latrobe Valley Airport)	85280	-38.21	146.47	55
Grampians / Pyrenees	Ararat Prison	89085	-37.28	142.98	295
Murray Valley					
Murray valley	Mildura Airport	76031	-34.24	142.09	50
Murray valley	Swan Hill Aerodrome	77094	-35.38	143.54	71
Riverland					
Riverland	Renmark Aero	24048	-34.20	140.68	31
Riverina					
Riverina	Griffith Airport Aws	75041	-34.25	146.07	134
Riverina / Gundagai	Wagga Wagga Amo	72150	-35.16	147.46	212
SA North					
Barossa valley	Nuriootpa Viticultural	23373	-34.48	139.01	275
Clare valley	Clare High School	21131	-33.82	138.59	395
Adelaide plains	Edinburgh Raaf	23083	-34.71	138.62	16
Southern Flinders Ranges	Port Pirie Nyrstar Comparison	21043	-33.17	138.01	2
SA Central	**Station**				

Adelaide hills	Mount Barker	23733	-35.07	138.85	359
Currency Creek	Victor Harbor Comparison	23751	-35.56	138.62	5
Limestone Coast					
Coonawarra	Coonawarra	26091	-37.29	140.83	57
Padthaway	Padthaway South	26100	-36.65	140.52	37
Robe	Robe Comparison	26026	-37.16	139.76	3
Tasmania					
Tasmania	Hobart Airport	94008	-42.83	147.50	4
Tasmania	Launceston Airport Comparison	91104	-41.54	147.20	166
Western Australia					
Swan district/Perth hills	Perth Airport	9021	-31.93	115.98	15
Manjimup	Manjimup	9573	-34.25	116.15	286
Margaret River	Witchcliffe	9746	-34.03	115.10	80
Great southern	Mount Barker	9581	-34.63	117.64	300

Table 7.3: Correlations of Niño3.4 measured using HadISST V1 modelled data with rainfall, evapotranspiration (ETo) and temperature derived climatic indices. Moisture balance positive (MB+ve), mean temperature (Tmean), growing degree days base 10 (GDD), date from 1st July that GDD reached thresholds of 350°C days (GDD350), 1100°C days (GDD1100), 1250°C days (GDD250), 1500°C days (GDD1500), number of days warmer than the 95th percentile (P95), and number and date of frosts measured as minimum temperature cooler than 0°C.

Nina3.4 Correlations (1900-2016)	Cessnock	Launceston	Ararat	Renmark	Nuriootpa	Witchcliffe
Rain (May to Sep)	-0.23	-0.25	-0.25	-0.22	-0.19	-0.33
Rain (Oct to Apr)	-0.29	-0.29	-0.20	-0.30	-0.12	-0.17
Rain (Oct to Dec)	-0.25	-0.38	-0.32	-0.31	-0.25	-0.19
Rain (Jan to Mar)	-0.21	-0.07	0.00	-0.18	0.00	-0.16
ETo (May to Sep)	0.17	0.22	0.22	0.11	0.06	0.14
ETo (Oct to Apr)	0.45	0.19	0.22	0.27	0.21	0.01
ETo (Oct to Dec)	0.39	0.32	0.38	0.41	0.39	0.07
ETo (Jan to Mar)	0.35	0.01	0.00	0.03	-0.05	-0.03
ETo - Rain (May to Sep)	0.24	0.26	0.27	0.20	0.18	0.34
ETo - Rain (Oct to Apr)	0.36	0.29	0.23	0.33	0.19	0.12
ETo - Rain (Oct to Dec)	0.32	0.39	0.38	0.42	0.34	0.17
ETo - Rain (Jan to Mar)	0.25	0.06	0.00	0.14	-0.02	0.10
MB+ve (Oct to Apr)	-0.35	-0.31	-0.22	-0.23	-0.16	-0.20
MB+ve (Oct to Dec)	-0.29	-0.36	-0.33	-0.28	-0.29	-0.26
MB+ve (Jan to Mar)	-0.20	-0.10	-0.04	-0.16	0.04	-0.15
Tmean (May to Sep)	-0.08	-0.06	-0.06	-0.12	-0.11	0.12
Tmean (Oct to Apr)	0.38	0.01	0.08	0.16	0.08	0.08
Tmean (Oct to Dec)	0.31	0.09	0.23	0.30	0.28	0.27
Tmean (Jan to Mar)	0.31	-0.09	-0.10	-0.09	-0.17	-0.06
GDD (Oct to Apr)	0.41	0.06	0.12	0.20	0.12	0.10
Date GDD350	0.15	-0.07	-0.16	0.04	-0.07	-0.16
Date GDD1100	-0.12	0.00	-0.08	-0.18	-0.14	-0.23
Date GDD1250	-0.16	-0.29	-0.07	-0.18	-0.08	-0.21
Date GDD1500	-0.19	0.01	-0.03	-0.16	-0.07	-0.14
Days warmer than P95 (Oct to Dec)	0.42	0.21	0.38	0.30	0.25	0.03
Days warmer than P95 (Jan to Mar)	0.22	0.02	0.02	0.03	-0.09	-0.15
Frost number (Aug to Dec)	0.25	0.09	0.22	0.04	0.21	-0.04
Last Frost	-0.09	0.00	0.05	0.14	0.23	-0.09

Correlations are colour coded: Red indicates >0.5 or <-0.5; Orange indicates >0.4 or <-0.4; Yellow indicates >0.3 or <-0.3; Green indicates >0.2 or <-0.2. A statistically significant result has a r of approximately 0.2 owing to the large sample size (117 years from 1900 to 2016) this significance may not be meaningful.

Table 7.4: Correlations of Indian Ocean Dipole (also known as Dipole Mode Index) measured using HadISST V1 modelled data with rainfall, evapotranspiration (ETo) and temperature derived climatic indices. Moisture balance positive (MB+ve), mean temperature (Tmean), growing degree days base 10 (GDD), date from 1st July that GDD reached thresholds of 350°C days (GDD350), 1100°C days (GDD1100), 1250°C days (GDD250), 1500°C days (GDD1500), number of days warmer than the 95th percentile (P95), and number and date of frosts measured as minimum temperature cooler than 0°C.

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Correlations are colour coded: Red indicates >0.5 or <-0.5; Orange indicates >0.4 or <-0.4; Yellow indicates >0.3 or <-0.3; Green indicates >0.2 or <-0.2. A statistically significant result has a r of approximately 0.2 owing to the large sample size (60 years from 1957 to 2016) this significance may not be meaningful.

Table 7.5: Median value of selected indices and the percentage chance of La Niña (left and bold) or El Niño (right and italics) event years being above the median. Event years from Bureau of Meteorology (http://www.bom.gov.au/climate/enso/). Data from 1900 to 2016.

La Niña, El Niño event years (1900-2016)	Cessnock		Launceston		Ararat		Renmark		Nuriootpa		Witchcliffe	
Rain (May to Sep) mm	208		321		318		122		293		858	
Chance wetter than median	**57**	*41*	**67**	*30*	**50**	*26*	**57**	*33*	**47**	*22*	**63**	*19*
Rain (Oct to Dec) mm	177		150		138		65		104		135	
Chance wetter than median	**67**	*41*	**77**	*15*	**70**	*22*	**63**	*33*	**67**	*37*	**53**	*48*
ETo (Oct to Dec)	431		326		364		504		435		348	
Chance drier than median	**27**	*70*	**43**	*78*	**43**	*74*	**33**	*74*	**33**	*81*	**43**	*52*
ETo - Rain (Oct to Dec) mm	255		176		226		447		328		215	
Chance drier than median	**23**	*63*	**30**	*78*	**30**	*78*	**27**	*85*	**30**	*78*	**47**	*56*
MB+ve days (Oct to Dec)	20		30		24		9		17		26	
Chance more than median	**73**	*37*	**77**	*22*	**77**	*22*	**63**	*30*	**63**	*30*	**67**	*30*
Tmean (Oct to Dec) °C	20.3		13.1		14.6		20.2		17.3		16.5	
Chance warmer than median	**30**	*70*	**47**	*56*	**40**	*59*	**47**	*70*	**40**	*78*	**30**	*63*
Date GDD350	13-Oct		05-Jan		14-Dec		19-Oct		15-Nov		20-Oct	
Chance later than median	**40**	*37*	**50**	*41*	**57**	*41*	**47**	*33*	**50**	*44*	**70**	*33*
Date GDD1100	23-Dec		NA		12-Mar		27-Dec		27-Jan		24-Jan	
Chance later than median	**57**	*26*	**47**	*44*	**43**	*41*	**60**	*33*	**53**	*33*	**60**	*33*
Days warmer than P95 (Oct to Dec)	3		2		3		5		5		4	
Chance more than median	**23**	*78*	**50**	*67*	**37**	*74*	**33**	*67*	**33**	*67*	**60**	*59*
Days warmer than P95 (Jan to Mar)	3		12		11		12		13		14	
Chance more than median	**40**	*67*	**57**	*59*	**47**	*52*	**43**	*59*	**53**	*44*	**60**	*56*
Number of frosts (Aug to Dec)	1		9		6		1		3		0	
Chance more than median	**77**	*70*	**87**	*78*	**80**	*78*	**80**	*70*	**70**	*78*	**83**	*70*

The chances of being different from the median are colour coded: Red indicates >90 or <10; Orange indicates >80 or <20; Yellow indicates >70 or <30; Green indicates >60 or <40.

An explanation of the first line serves as a guide to reading the table. There is a minimal impact of ENSO on Cessnock winter rainfall as shown by the chance of exceeding the median as 57% for La Niña and 41% for El Niño. In Launceston by contrast the impact is stronger with a 67% chance of exceeding the median rainfall in a La Niña and only 30% in El Niño. The deviation from 50 percent chance of exceeding the median is increased when there is a measure of irrigation demand (ETo – Rain) or moisture positive days are calculated. The frost data (last line) should be interpreted with care due to the very low number of frost events.

Table 7.6: Median value of selected indices and the percentage chance of negative IOD (left and bold) or positive IOD (right and italics) event years being above the median. Event years from Bureau of Meteorology (http://www.bom.gov.au/climate/iod/). Data from 1960 to 2016.

-IOD, +IOD event years (1957-2016)	Cessnock		Launceston		Ararat		Renmark		Nuriootpa		Witchcliffe	
Rain (May to Sep) mm	209		321		296		123		292		827	
Chance wetter than median	**73**	*27*	**82**	*27*	**91**	*27*	**82**	*18*	**73**	*18*	**64**	*45*
Rain (Oct to Dec) mm	201		143		131		64		98		132	
Chance wetter than median	**45**	*45*	**64**	*9*	**64**	*0*	**45**	*27*	**64**	*18*	**64**	*36*
ETo (Oct to Dec)	430		328		370		505		435		366	
Chance drier than median	**36**	*55*	**45**	*73*	**36**	*82*	**27**	*82*	**45**	*73*	**36**	*73*
ETo - Rain (Oct to Dec) mm	234		188		247		448		339		237	
Chance drier than median	**55**	*55*	**36**	*91*	**27**	*91*	**45**	*82*	**36**	*82*	**36**	*82*
MB+ve days (Oct to Dec)	23		29		25		9		17		23	
Chance more than median	**64**	*45*	**73**	*9*	**73**	*0*	**55**	*18*	**73**	*18*	**73**	*27*
Tmean (Oct to Dec) °C	20.2		13.2		14.7		20.1		17.1		16.7	
Chance warmer than median	**27**	*73*	**36**	*73*	**36**	*82*	**18**	*82*	**9**	*91*	**36**	*82*
Date GDD350	12-Oct		03-Jan		14-Dec		21-Oct		17-Nov		16-Oct	
Chance later than median	**45**	*73*	**55**	*18*	**73**	*36*	**73**	*36*	**91**	*45*	**55**	*27*
Date GDD1100	22-Dec		NA		05-Mar		28-Dec		30-Jan		21-Jan	
Chance later than median	**64**	*45*	**55**	*36*	**64**	*45*	**91**	*18*	**82**	*36*	**73**	*0*
Days warmer than P95 (Oct to Dec)	12		18		15		15		16		17	
Chance more than median	**18**	*73*	**27**	*82*	**27**	*91*	**36**	*73*	**36**	*82*	**55**	*64*
Days warmer than P95 (Jan to Mar)	5		7		7		7		8		7	
Chance more than median	**5**	*64*	**7**	*55*	**7**	*64*	**7**	*55*	**8**	*64*	**7**	*36*
Number of frosts (Aug to Dec)	1		9		6		1		3		0	
Chance more than median	**45**	*55*	**27**	*73*	**45**	*36*	**64**	*55*	**45**	*55*	**55**	*45*

The chances of being different from the median are colour coded: Red indicates >90 or <10; Orange indicates >80 or <20; Yellow indicates >70 or <30; Green indicates >60 or <40.

To our knowledge, this is the first analysis of the impact of climate drivers on viticultural indices relating to rainfall and evaporation as well as temperature. Not only is there an increase in the demand for water, but the supply of water is likely to be greatly reduced due to the well documented impact of ENSO on runoff and streamflow. The combination of drier soils, less rain and less large rain events in an El Niño tend to amplify the impact of ENSO on runoff and streamflow (Chiew and McMahon 2009, Rice and Emanuel 2017).

The dynamic forecasts in ACCESS –S used the by the Bureau of Meteorology go beyond the statistical relationship between ENSO or IOD and rainfall or temperature. The information from this project will be valuable in the Rural R&D for Profit project Forewarned is Forearmed in which Wine Australia is a partner.

7.1.4. Conclusions

The assessment of the historical relationship between viticultural climate indices and the climate drivers ENSO and Indian Ocean Dipole across Australia found several general relationships between the impact of the climate drivers within geographic regions. For example, drivers were found to have been correlated in the past with both components of the water balance (evapotranspiration and rainfall). The drivers were more closely correlated with positive moisture balance days during October to December compared with the berry ripening period from January to March of the following year. The highest correlations with ENSO occurred in Queensland, NSW, ACT, Victoria and parts of the inland rivers irrigation areas, with fewer than median moisture balance positive days during October to December in El Niño and positive IOD years. Only in Queensland, NSW and ACT, Victoria and parts of the inland rivers irrigation areas were La Niña or negative IOD events associated with more than the median number of moisture balance positive days.

However, the historical relationships showed very high seasonal and regional differences. For example, drivers were found to have been correlated with rainfall from autumn to the initial part of the growing season but minimal relationship from the berry ripening period (January Year 2). In the non-growing season from May to September, IOD was correlated with rainfall in all regions while ENSO was correlated to rainfall in Queensland, NSW, parts of Victoria and WA. During this period, El Niño and positive IOD were related to drier conditions, while La Niña and more negative IOD were historically associated with wetter conditions in all regions (although less so in inland rivers). From October to December rainfall was correlated to ENSO in all regions but only to IOD in the southern regions excluding WA. From January to March of the following year rain had minimal or no relationship with either ENSO or IOD. From October to December, El Niño and positive IOD were related to drier water balance in all regions apart from WA, while La Niña and negative IOD were related to wetter water balance in all regions apart from WA, parts of SA and Tasmania.

These results are consistent with published climate science, which has also shown that the impact of the main climate drivers on rainfall differs across Australia and seasonally (e.g. Risbey et al. 2009).

Changes in the modes of climate drivers may occur with ongoing climate change, but climate scientists are still debating the causes of the changes and the level of confidence in the projections (Cai et al. 2015a). Changes in ENSO are difficult to detect due to the large natural variability present in the climate models and low agreement across models (Chen et al. 2017).

While changes to ENSO driven pulses may have already emerged (Power et al. 1999, McGregor et al. 2013, Ummenhofer et al. 2015), current research suggests that ENSO is unlikely to change significantly in the future. However, the frequency of extreme El Niño events is projected to increase (Wang et al. 2017) as is the atmospheric impact of ENSO events (Cai et al. 2015b) as changes in the background state of the Pacific Ocean allow the meridional collapse of the regions' rainbands onto the equator (Chung et al. 2014). This means that the climatic pulses associated with ENSO events in the future may be larger than those of an event of the same magnitude now. Increasing atmospheric water vapor in combination with intensifying convective events is expected to cause an increase in rainfall associated with ENSO events (Power et al. 2013, Cai et al. 2015a).

Similarly, the characteristics of IOD events might be changing, indicated by recent warming trends in the Indian Ocean (Ihara et al. 2008). By the end of the century the frequency of extreme positive IOD events has been projected to increase, from one event every 17.3 years over the twentieth century to one event every 6.3 years (Cai et al. 2014). 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.

The position of the STR and the latitude of the mid-latitude storm track have shifted in recent decades, and the phase of the SAM has altered. These changes can only be replicated in model experiments when anthropogenic forcings are included (Murphy and Timbal 2008), suggesting that further changes are likely to continue in the future.

8. Development of seasonal to interannual climate forecasts

This section was led by Dr James Risbey (CSIRO)

8.1. Background

Seasonal prediction sits at the boundary between traditional short-term numerical weather prediction (operational weather forecasting) and climate change science. The aim is to predict the climate from around one month (sub-seasonal) to one year in advance. The development of seasonal prediction goes back several decades, but as yet reliable forecasts are not possible. Seasonal predictions are not weather forecasts in the traditional sense but provide a general summary of whether the time period in question is going to be above or below average.

With the development of improved observing system (automatic weather stations and satellites), numerical modelling (enhanced computing capability) and a better understanding of the earth system in general, there have been rapid advances in seasonal prediction over the last twenty years. Predictions rely on the large impacts of climate drivers such as ENSO, which are predictable because of the strong persistence of ENSO, especially in the second half of the calendar year. This field is constantly advancing and has new developments including the recent transition from statistical to dynamical prediction for operational seasonal outlooks by the Australian Bureau of Meteorology (ACCESS-S).

8.2. Methods

The Climate Analysis Forecast Ensemble (CAFE) system, developed by CSIRO's Decadal Climate Forecast Project (DCFP), was used to provide climate forecasts for the wine regions. A detailed description of model improvements, an analysis of the ability of the ACCESS-D control model to simulate heatwaves and rainfall extremes, and an assessment of forecast skill are presented in Appendix 5.

The CAFE forecasts were tested for three wine regions, Margaret River, Hunter, and Riverland. These three regions capture different climate types in the southwest of Western Australia, east coast, and southeast Australia respectively. The climate variables tested at these sites were temperature and precipitation.

8.3. Results and Discussion

The CAFE forecast system has undergone significant improvements over the duration of the Wine Australia project, however forecast skill remains low. Overall, for the wine regions tested (Margaret River, Riverland and the Hunter) the level of forecast skill for cumulative rainfall on lead times out to 2 years is low. For the most part, cumulative rainfall skill is not different from a climatological forecast. While this result is disappointing, it is not different from that obtained for other forecast systems for rainfall on these spatial scales at these lead times. A challenge for climate forecast systems is to identify whether there are windows of skill at some times if/when the climate system becomes more predictable. That is a topic of ongoing research to identify such windows and assess whether there is useful rainfall skill at such times.

The skill results for Growing Degree Days (GDD) are more encouraging and indicate for two of the wine regions (Margaret River and Riverland) that there is more skill than climatology for forecasts issued in some parts of the year. For the Riverland, this skill is evident for forecasts initiated between September and December. This is the time of the year in which El Niño Southern Oscillation (ENSO) events have initiated and provide more skill for the forecast systems. The Riverland is in a part of Australia that benefits from the ENSO teleconnection (Risbey et al., 2009). On the other hand, for Margaret River the skill in GDD is expressed for forecasts initiated between January and July. This is the time of year when forecasts of ENSO have low skill, but Margaret River has no appreciable teleconnection to ENSO. At this time of year, the Margaret River region is much better teleconnected to the

Southern Annular Mode (SAM), although it is not clear whether the SAM is predictable at lead times out to 2 years as examined here. The predictability of SAM and its association with forecast skill in southwest Western Australia will be assessed in future work.

An objective of the forecast assessment is to progress the models and skill to a point where the forecasts provide useful input to the wine industry. In Figure 8.1 and 8.2 below we show example forecast plumes for cumulative rainfall and GDD respectively (for the Hunter and Riverland region). For these forecasts to add value, the ensemble plume of the forecasts needs to be narrower than the expectations from past climate conditions (climatology).

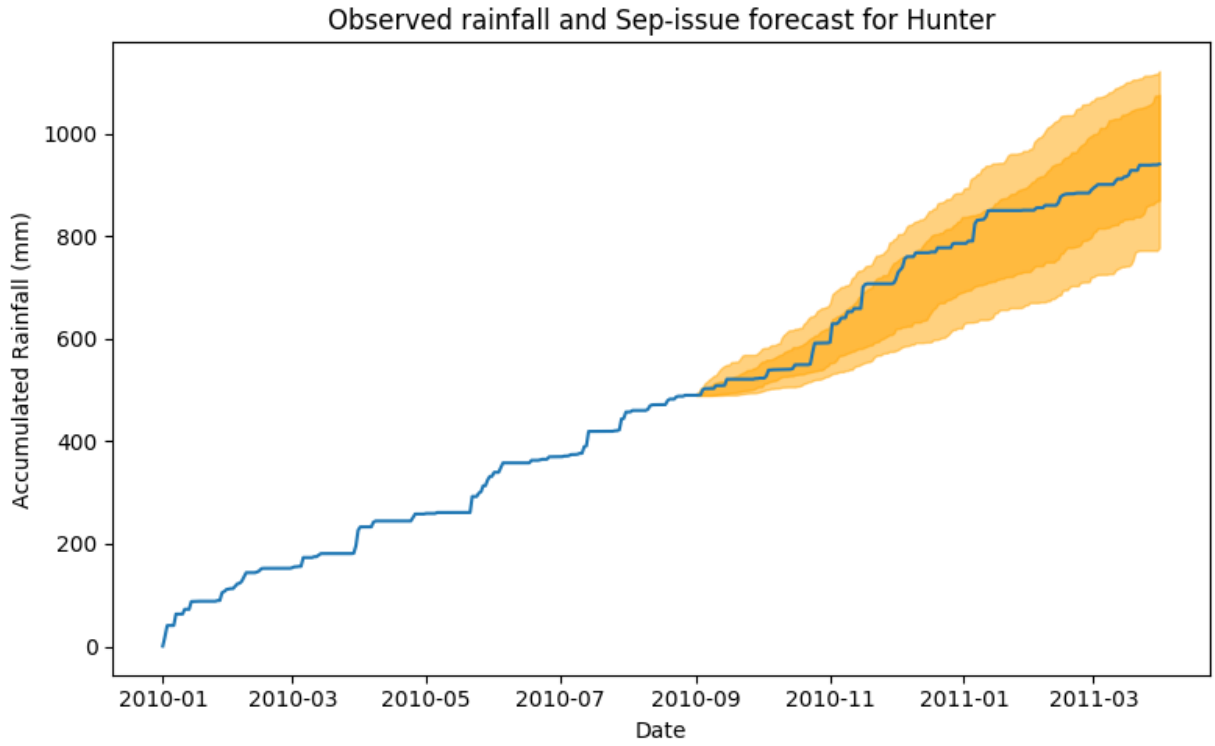


Figure 8.1: Forecast of cumulative rainfall for the Hunter region from September 2010. Yellow plume shows the 10-90 percentile (light shade) and 25-75 percentile (dark shade) ensemble spread in the forecast. The blue line is the observed cumulative rainfall.

In the case of cumulative rainfall (Figure 8.1), the spread of the forecast with time is about the same as the spread from climatology. That is useful in knowing what the set of historical years imply about how the year may finish. However, the forecast itself does not add any value beyond that for rainfall.

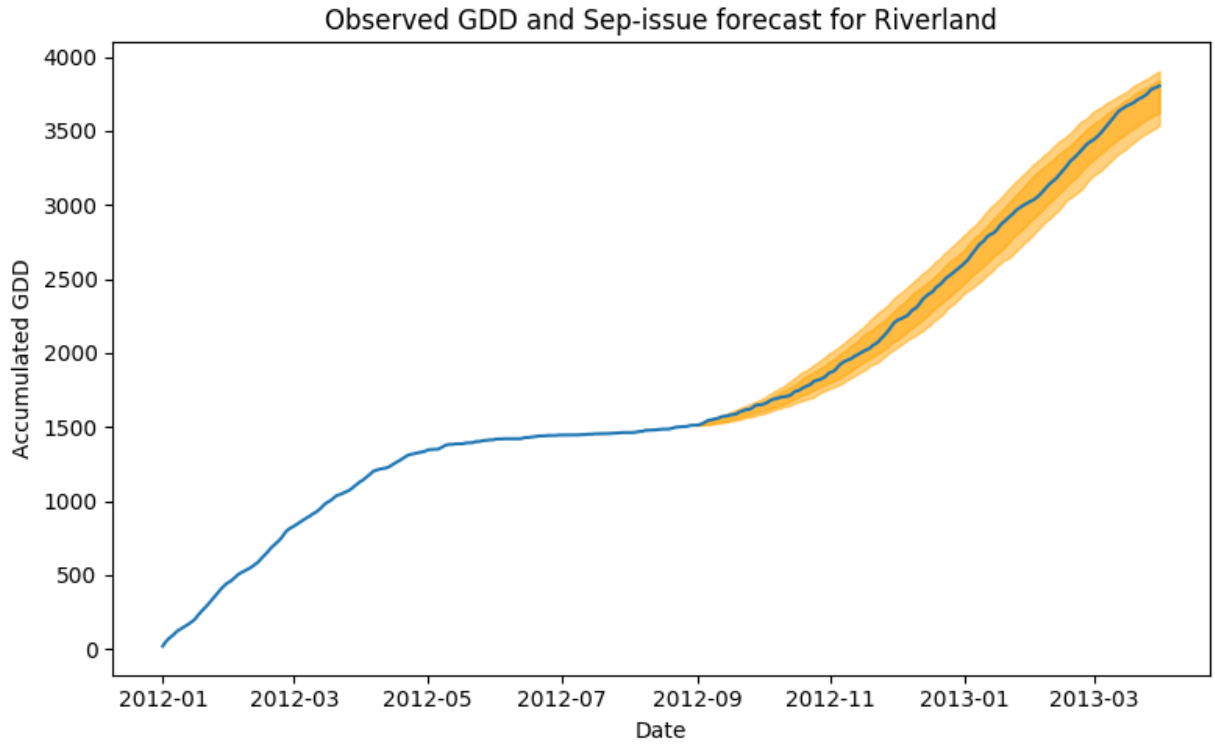


Figure 8.2: Forecast of growing degree days from September 2012 for the Riverland region. Yellow plume shows the 10-90 percentile (light shade) and 25-75 percentile (dark shade) ensemble spread in the forecast. The blue line is the observed GDD.

The example of a GDD forecast for the Riverland region is given in Figure 8.2. In this case the spread of the ensemble plume in the forecast is narrower than the expectations of spread from all historical years (climatology). That is, the forecast is potentially adding value, at least for forecasts initiated from September through December for this region. More work would be needed to establish the utility of skilful forecasts of GDD for the wine industry made at this time of year. That is, how robust is the skill, can it be improved, what decisions can it be related to, and would it improve outcomes from those decisions?

9. Projections of future climate change

9.1 Production of new fine-scaled climate projections for South Eastern Australia and consolidation of best-available high-resolution climate data across Australia.

This section was led by Dr Marcus Thatcher (CSIRO), with input from Dr Tomas Remenyi and Dr Peter Love (ACE CRC).

9.1.1 Background

Global Climate Models typically have a spatial resolution of 50 to 200 km, due to the limitations of current supercomputers. As a result, certain features such as mountain ranges, coastlines, urban areas and storms are poorly represented by GCMs. To address this limitation, Regional Climate Models (RCMs) can be used to provide a higher spatial and temporal climate simulation for SE Australia (e.g. typically between 1 to 50 km resolution). By simulating the climate at these scales, we can expect to better resolve mountains, coastlines and urban areas. We can also expect to better simulate extreme events such as rainfall events that may lead to flooding.

9.1.2. Methods

9.1.2.1. Downscaling to high resolution climate data

Two downscaling methods are statistical downscaling and dynamical downscaling. Statistical downscaling relies on historical statistical relationships between observations and large-scale behaviour of the atmosphere to infer regional scale changes from the large-scale changes in climate. These methods are fast and computationally cheap to run, but do not capture changes in timing and seasonality of weather events, particularly extreme events. Dynamical downscaling is achieved by running a regional climate model to simulate the meteorological processes over a region. This approach incorporates information about orography and land surface conditions (e.g., surface height, coastlines, lakes, and land cover), so can highlight the effect of these factors on regional climate and the climate change signal.

To develop high-resolution climate simulations for Victoria and South East Australia, we used the Conformal Cubic Atmospheric Model (CCAM) developed at CSIRO (McGregor 2005 and McGregor and Dix 2008). CCAM has been used for several regional climate simulations in Australia and South East Asia, including the CORDEX intercomparison experiment, the National Resource Management (NRM) national projections for Australia, the Climate Futures for Tasmania, Climate projections for the Australian Alps and High-resolution projections for Queensland. Unlike most RCMs, CCAM is a global atmospheric model with a variable resolution grid that can be focused over an area of interest. In this way, CCAM can generate a higher resolution climate simulation, but is still coupled to the larger scale atmospheric circulation. Details of CCAM and validation of the new simulations are provided in Appendix 6.

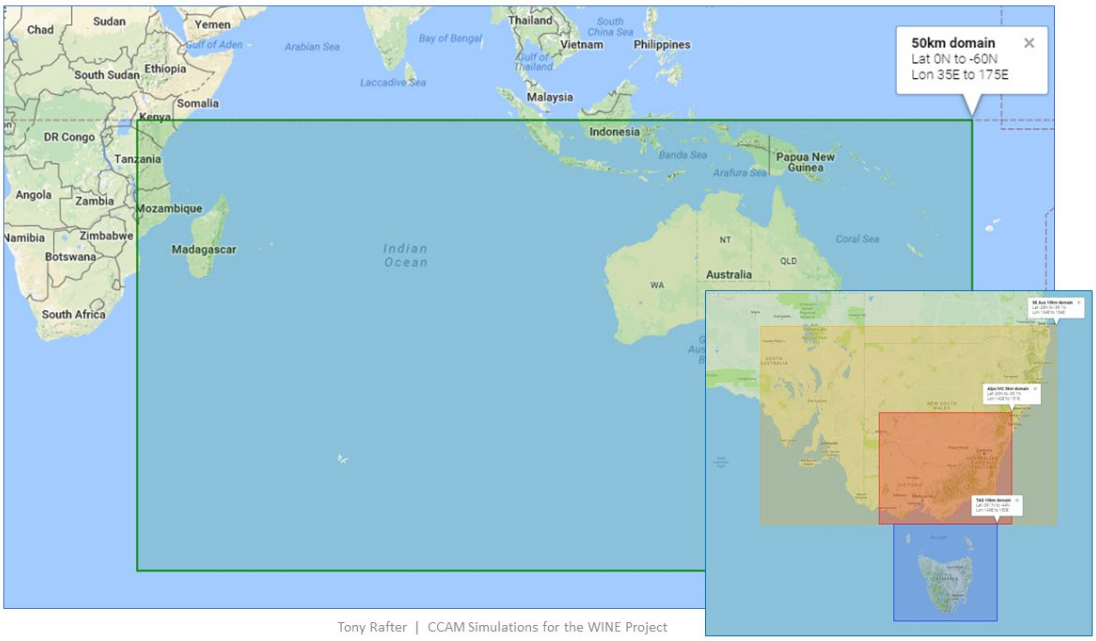
Six GCMs from the CMIP5 archive were downscaled - ACCESS1-0, CNRM-CM5, GFDL-ESM2M, HadGEM2, MIROC5 and NorESM1-M. These models are based on the recommended GCMs for studying Australian climate change from the Climate Change in Australia web portal. The host GCMs for downscaling are selected to show a range of possible climate futures such as changes in the amount of warming and reductions in rainfall (Table 9.1). Because we selectively downscaled GCMs that show a range of possible futures, the downscaled simulations provide scenarios to explore the future climate, rather than an analysis of the most probable future climate. The focus of this project is the high greenhouse gas emission scenario RCP8.5.

The running of new simulations is computationally intensive, so new fine-scale projections were only done for south eastern Australia and Tasmania, where the greatest added value would be achieved over the mountains and coastlines. Figure 9.1 shows the domain of the new simulations.

Host GCM for downscaling	Relevance for downscaling regional climate
ACCESS 1-0	A hot, dry model. Warming exceeds 2.5°C across most of Australia, and >3.5 °C in central Australia. Drying is projected over most areas. This model shows a high skill score with regard to historical climate.
CNRM-CM5	Hot /wet end of range in Southern Australia. It has a good representation of extreme El Niño in CMIP5 evaluations.
GFDL-ESM2M	A hot, very dry model, with warming in central regions exceeding 3.5 °C. Drying is projected across most of the continent, with annual precipitation projected to decline more than 20% in many areas.
HadGEM2-CC	A hot, dry model, with warming typically >2.5 °C and >3.5 °C in central regions. Annual precipitation is projected to increase in central Australia and decline elsewhere including the horticultural zone; Greatest reduction in wind. Maximum consensus for many regions.
MIROC5	A low warming, wet model for Australia and Victoria. Warming does not exceed 3°C, and slight changes in annual precipitation are projected with declines in north-east Queensland and south-west Australia.
NorESM1-M	Low warming, wettest representative model. Warming over most of Australia exceeding 2°C. Little change in annual precipitation is projected, particularly in the south-east, although there is drying in south-west WA.

Table 9.1: List of the six GCMs used for dynamical downscaling and the reason for their selection

For Western Australian regions and South Burnett in Queensland, we investigated the usefulness of using dynamically downscaled simulations available from other archives. We compared these archives for compatibility with key archives we have used for the south-eastern Australian regions with regards to spatial resolution, available variables and both spatial and temporal domain (coverage). In order to be consistent with the rest of Australia, these alternative archives required continuous temporal coverage from the 1960s to 2100. Unfortunately, alternative archives investigated were not continuous. This introduced confusion when visualising many of the outputs, and so could not be used. An alternative approached was adopted that made use of the 50km resolution CCAM outputs, as this model domain was global, and so had coverage over all other Australian regions. However, this coarse resolution provided limited value when investigating the small wine regions. In order to transform the 50km outputs into more valuable forms, these were statistically downscaled down to 5km resolution (using a quantile-quantile bias adjustment method, (Gudmundsson et al. 2013)), based on the Australian Gridded Climate Data product. This produced far more useful, reasonable representations of the regions of interest to the project, providing the best continuous estimates currently available of climatic changes into the future.



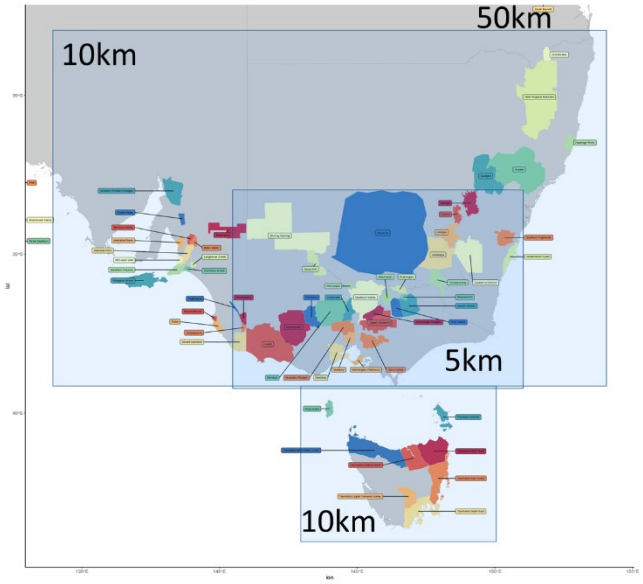


Figure 9.1: The domains of the CCAM simulations showing the different resolutions across Australia, ranging from 5km to 50km.

9.1.2.2. Bias adjustment

Model biases introduce systematic errors which vary from place to place, depending on topography, altitude, latitude and distance from large water bodies. The biases are due to insufficient spatial resolution and the resulting limited representation of meteorological processes (Rauscher et al. 2010). This is not a problem when investigating climate change in terms of the relative changes over time rather than absolute values. However, absolute values are needed for understanding impacts on agriculture, particularly when investigating temperature extremes. The model outputs were therefore bias adjusted before being summarised in the atlas (Christensen et al. 2008).

Bias adjustment is a statistical method that adjusts the climate model output so that it matches the observations over the entire probability distribution. This adjustment is then

applied to each quantile of the probability distribution into the future period, preserving any changes to the distribution projected by the climate models. The raw CFAP2019 ensemble outputs were bias-adjusted using the quantile statistical transformation, which has been widely used for adjusting modelled variables, especially temperature and rainfall (Gudmundsson et al. 2013). Temperature and rainfall were bias adjusted using the qmap package (Gudmundsson et al. 2013) within the R programming language. Observation data inputs were from the Australian Gridded Climate Data product (Jones et al., 2009). An example of the impact bias adjustment can have on the distribution of values is presented in Figure 9.2.

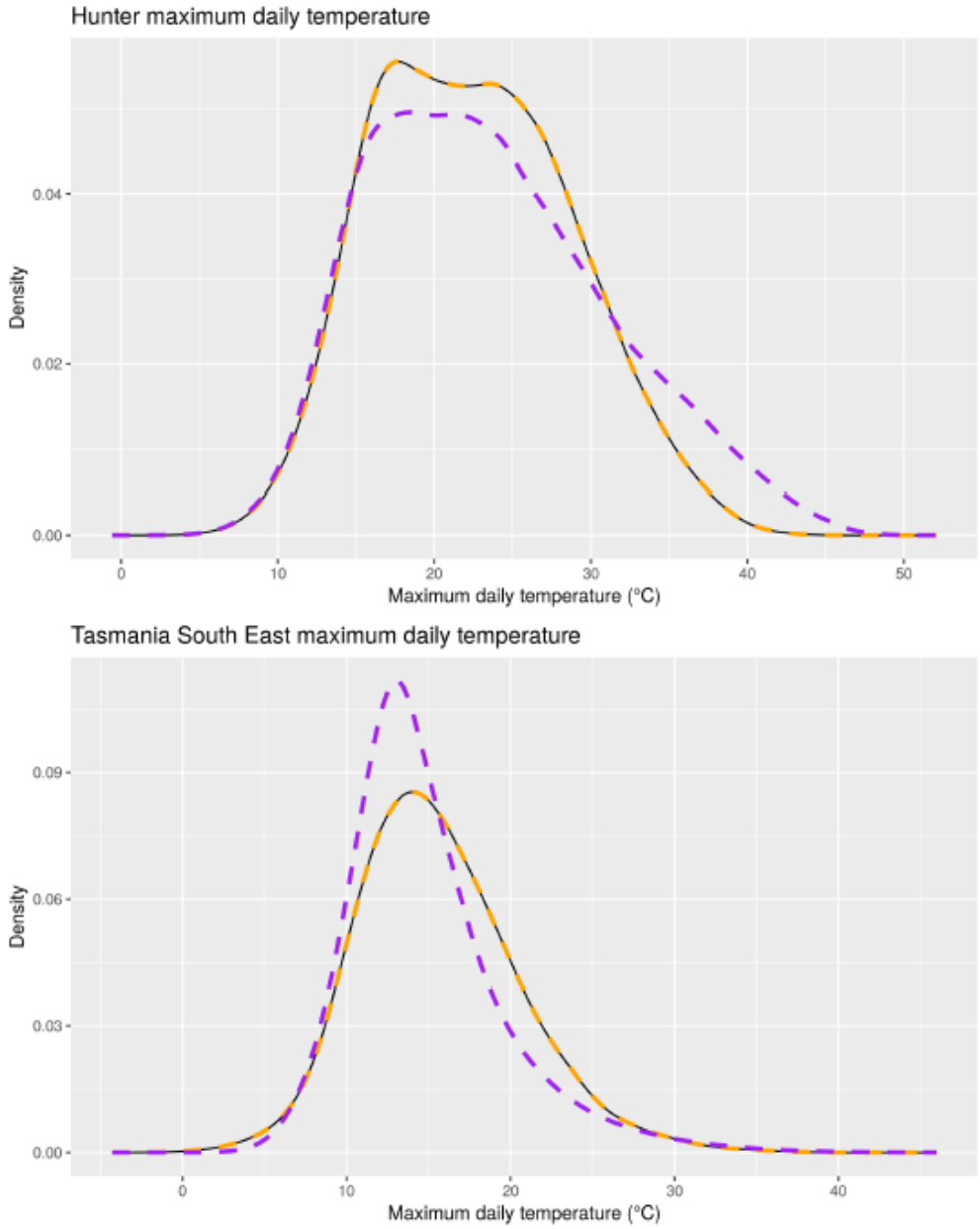


Figure 9.2: Probability distributions of Maximum daily temperature for the period 1961-1990 in two wine regions (top panel Hunter, bottom panel South East Tasmania) before (pink line) and after (orange line) bias-adjustment. The black solid thin lines are the observations (sourced from the Bureau of Meteorology's Australian Gridded Climate Data (AGCD)). The purple dashed lines show the raw output from one climate model (CNRM-CERFACS-CNRM-CM5). The orange lines are bias-adjusted output. Following bias-adjustment, the distribution closely resembles the observed distributions.

9.2 Future trends in climate

Temperature increases of 3 to 4℃, relative to 1961-1990, are projected to occur by the end of the century under the high emissions scenario (RCP 8.5), the scenario that we are currently tracking. When superimposed on natural variability, this represents a highly significant change to the climate system, resulting in more frequent and intense extreme events such as heatwaves.

Given the very large number of wine regions, we have not attempted to summarise the trends projected for each here. The results are presented graphically in the wine atlas. Regional differences are apparent across Australia, reflecting the influence of climate drivers and diverse climatic conditions across the country. For example, Figure 9.3 highlights the range in changes in mean aridity that have already been observed across Australia's wine regions. Similarly, there is a range in future conditions across the regions.

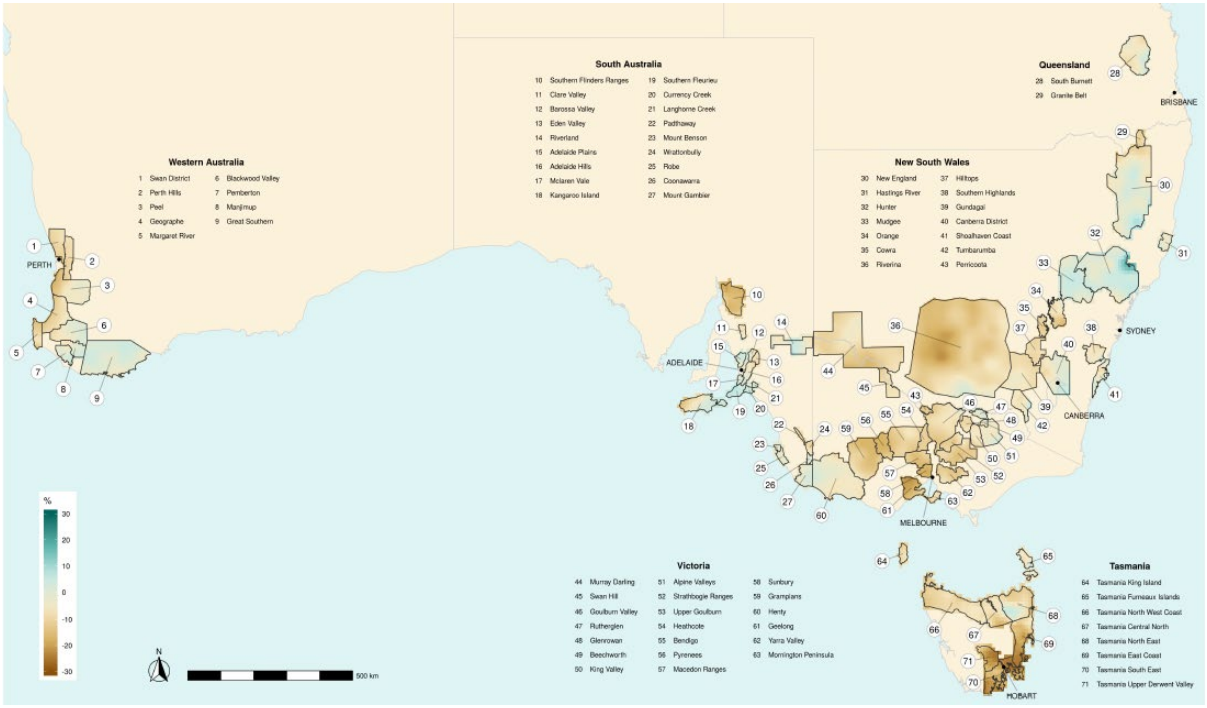


Figure 9.3: Observed percentage change in mean annual aridity between the current (1997-2017) and historical (1961-1990) periods. This shows the change already experienced across the country. Negative values indicate a trend towards drier conditions. Positive values indicate a trend towards wetter conditions.

However, there are several trends in future climate that are consistently found for wine regions across Australia. These are:

1. Annual temperature and Growing Season Temperature (GST) are projected to increase into the future for every region across Australia. This strong warming trend accelerates towards 2100, with climate change becoming progressively more influential than natural variability after 2020.
2. Aridity is expected to increase in all wine regions across Australia.
3. Fewer Growing Season Frost Risk Days are likely as temperatures continue to rise.
4. More intense heatwaves in many regions, with substantial increases in the Excess Heat Factor (EHF) in some regions. This index describes the severity of acute heat impacts on humans during heat waves, and the results suggest that outdoor work may be restricted in the future in some of Australia's regions.
5. Extremely hot years are likely to occur as much as 30 years earlier than projected by the mean trend.

All of these changes have widespread implications for the wine industry.

10. The Climate Atlas

A standard set of climate indices was developed to ensure consistency in the historical analyses, seasonal forecasts and climate projections. A discussion paper was circulated among industry partners for comment, to identify the most relevant, usable indices. The set includes the climate indices most important to describe historical, current and future weather and climate influences on wine grapes across Australia. There are very few industry standards, so national and international literature was reviewed to identify climate indices that may be useful for viticulture. Generally, simpler indices were favoured over more complex measures. However, some new indices needed to be developed to describe heat waves in a way that reflects regional variability.

The core set of indices covers four broad areas: Temperature, Heat extremes, Frost and cold extremes, Rainfall and evaporative demand. Indices representing temperature, rainfall and evaporative demand, and heat and cold extremes are presented, including:

1. Temperature - Growing Season Temperature (GST), Growing Degree Days (GDD);
2. Rainfall and evaporative demand - Annual, Monthly and Seasonal rainfall; Growing Season Rainfall; Number of rainy days during harvest; Annual, Monthly and Seasonal aridity; Number of dry spells before harvest;
3. Heat extremes - extreme heat factor (EHF) during a heatwave; Heatwave duration and intensity; Number of days per year exceeding temperature thresholds (30°C, 35°C, 40°C, 45°C); Frequency of days with high human heat stress;
4. Cold extremes - Number of days at risk of frost during the growing season; Daily minimum temperature; Annual chilling degree days; Number of days per year temperature falls below temperature thresholds (<2°C, <0°C, <-2°C).

These indices were calculated for every Australian Geographic Indication (GI), with the Tasmanian GI separated into eight regions to reflect its climatic diversity (Figure 10.1).

While accepted indices were favoured over more complex measures, some new indices had to be developed to describe heat in a way that reflects regional variability and the warmer conditions expected in the future. Growing Degree Days, for example, has two main limitations of when applied across Australia. Firstly, only accumulating heat after October (assuming no growth over winter) does not account for the effect of warm winter and spring periods, which will be increasingly important under a warming climate. Secondly, limiting the influence of heat to daily values above 10°C does not account for physiological responses that clearly occur at far lower temperatures, especially during the winter/spring period.

In response to these limitations, we developed a method that incorporates daily climate values as inputs, accounts for the influence of heat across the entire growing year (July to June) and reflects the changing physiological demands of grape vines throughout the year. The approach captures the importance of increased heat accumulation prior to October as the climate warms, providing a better representation of the impacts expected to be seen into the future, while also improving the utility of the GDD metric as a measure of heat accumulation within cooler climates (or cooler seasons) as it better reflects the influence of low temperature days relevant to grape-vine phenology.

In addition to the information on Australia's current and future climate, *Australia's Wine Future: A Climate Atlas* provides background information about climate science, climate modelling and emissions scenarios, as well as infographics to summarise the main trends for every wine region across Australia.

Australia's Wine Future: A Climate Atlas will be available for download from the Wine Australia and the Climate Futures Tasmania (http://climatefutures.org.au/) websites.

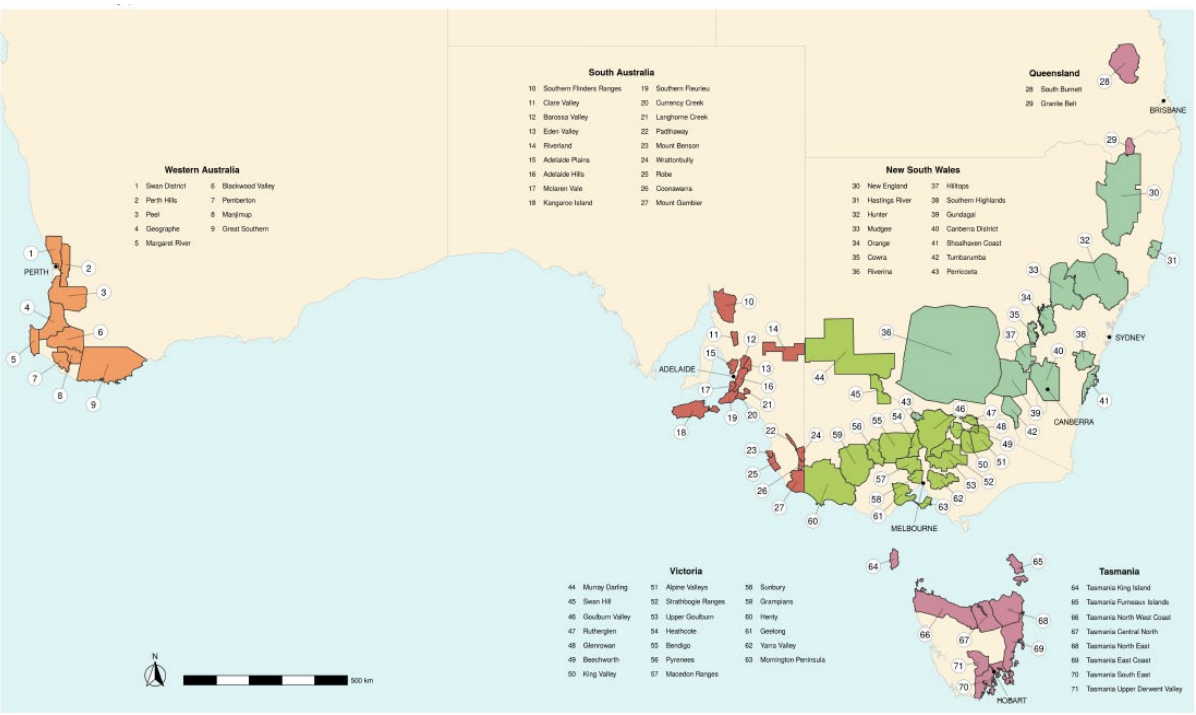


Figure 10.1: The Australian wine regions included in the climate atlas. For mainland Australia they are the Wine Australia Geographical Indications (GI). The Tasmanian GI was divided into eight regions based on Australian Bureau of Meteorology forecast districts, to reflect the climatic diversity across the state.

11. Outcome/Conclusion

The project delivered a wide range of benefits across four broad areas, Adaptation and options for managing climate variability; Seasonal climate variability; Future projections of climate change and the Development of a climate atlas. The benefits and implications of each of these areas of research are detailed in the relevant section, but overall, the project delivered the objectives set out in the application.

The plans to map climate suitability for key varieties and model grape growth under different climate and management conditions were changed following the advice of industry partners and replaced with other approaches that were felt to be more realistic and more likely to provide useful information.

The seasonal prediction component of the project, which aimed to predict the climate from around one month to one year in advance achieved significant improvements over the duration of the project, but, disappointingly, forecast skill remains low. This is a topic of ongoing research by CSIRO. New developments such as the transition to dynamical prediction for operational seasonal outlooks by the Australian Bureau of Meteorology (ACCESS-S) could also provide useful information for the wine sector.

For the first time, Australia's wine sector now has national, fine-scaled climate information, tailored to describe the climate indices most relevant to growing wine grapes across Australia. This is a world first and is likely to bring wide-ranging benefits to grape growers and the sector more widely, as the climate continues to change and adaptation responses become necessary more often, across more of the country.

12. Recommendations

The project identified several areas in which further research would improve our understanding of the impacts of changing climate on grape growth and adaptation:

1. There is a pressing need for more knowledge on the thermal requirements of grape varieties currently grown in Australia and overseas. This knowledge would enable growth under different climatic conditions to be better modelled, incorporating shifts in phenology, and the impacts of different management approaches and timing and intensity of extreme events such as heatwaves and drought.
2. Ongoing development of seasonal forecasting is required to achieve the necessary skill for it to be usable by grape growers.
3. Weather conducive to disease was identified as being important for many grape growers' seasonal planning. In this project we carried out preliminary assessments of the changes to disease indices across Australia, but they could be further refined and added to the online atlas.
4. The Climate Analogue Tool we developed requires further discussion with industry to determine if further refinements would be useful. Discussions of the thresholds used to classify similarity with grape growers in different regions of Australia would be beneficial. Tools such as the Climate Change in Australia tool already exist, but our model builds on the concept in three important ways. Firstly, it captures the effects of evaporation, humidity and radiation in addition to temperature and precipitation. Secondly, it compares the climate on both daily and monthly timescales, to capture differences in extremes and seasonality as well as mean climate conditions. Finally, it can be run globally, not just in Australia. These improvements make it a valuable tool to identify the wine regions around the world that are most climatically similar to the climate conditions that Australian wine regions may experience in the future. The tool is currently run within the R programming language, but a user-friendly interface could be developed to make it accessible to Wine Australia or others in the wine sector. Individuals could then choose the variables, time scales and thresholds they are interested in. This would enable future grape varieties and novel adaptation options to be identified and provide information about changing global markets.

Appendix 1: Communication

A1.1. Tiers of engagement

The communications plan, which was developed in consultation with industry contacts, AWRI partners and Wine Australia, identified three tiers of engagement which we aimed to achieve throughout the project:

1. **Growers and regional viticulturists from the six case study regions** (Hunter Valley, Grampians, Tasmania, Riverland, Barossa and Margaret River). In each of these regions, face to face grower engagement was carried out to learn about weather and climate risk and update the crop calendars.
2. **Next users of climate information**. An important 'next user' is the AWRI who have the responsibility of extension to the wine industry. The project is fortunate to have Paul Petrie and Mark Krstic from AWRI as partners in the project. We also targeted public and private viticultural advisers, wine grape companies and researchers. Other potential 'next users' include NRM groups wishing to support viticulture.
3. **The Australian wine grape industry.** The main legacy of the project is the electronic atlas which will cover all wine growing regions in Australia. The atlas will be available from the Wine Australia website, in addition to the University of Tasmania and Climate Futures websites. Extensive media is planned to coincide with the release of the atlas in November 2019. This will include national and local radio

interviews (ABC rural country hour, ABC local radio) and online and social media engagements.

A1.2. Workshop

A workshop, entitled “NextGen weather and climate information for your wine region”, was run at the Wine Industry Technical Conference in July, 2019. It showcased the latest information on both short and long-term climate trends and encouraged discussion on how this knowledge can be used to better manage vineyards. The draft Climate Atlas was presented and feedback requested for improvements. The workshop was facilitated by Paul Petrie, and included talks by Darren Ray (BOM), Peter Hayman and Dane Thomas (SARDI), Bec Harris and Fiona Kerslake (ACE CRC, UTas).

A1.3. Peer-reviewed papers

Published papers arising from the project:

1. Hayman, Peter; Thomas, Dane and Remenyi, Tom. Climate smart viticulture: Using crop calendars and simple indices *Australian and New Zealand Grapegrower and Winemaker,* No. 643, Aug 2017: 33-34, 36.
2. Risbey, J. S., T. J. O'Kane, D. P. Monselesan, C. L. E. Franzke, and I. Horenko. 2018. On the Dynamics of Austral Heat Waves. *Journal of Geophysical Research*: Atmospheres **123**:38-57.
3. Thomas, D.S. Hayman, P.T. and Petrie P.R. A sensibility test of northern hemisphere phenology models down under. *Crush* 2018 – the grape and wine science symposium Sep 25- Sep 26, 2018, Waite Research Precinct, Adelaide.
4. Tozer, C. R., J. S. Risbey, T. J. O’Kane, D. P. Monselesan, and M. J. Pook. 2018. The Relationship between Wave Trains in the Southern Hemisphere Storm Track and Rainfall Extremes over Tasmania. *Monthly Weather Review* **146**:4201-4230.
5. O’Kane, T. J., P. A. Sandery, D. P. Monselesan, P. Sakov, M. A. Chamberlain, R. J. Matear, M. A. Collier, D. T. Squire, and L. Stevens. 2019. Coupled Data Assimilation and Ensemble Initialization with Application to Multiyear ENSO Prediction. *Journal of Climate* **32**:997-1024
6. Risbey, J. S., D. P. Monselesan, T. J. O'Kane, C. R. Tozer, M. J. Pook, and P. T. Hayman. 2019. Synoptic and Large-Scale Determinants of Extreme Austral Frost Events. *Journal of Applied Meteorology & Climatology* **58**:1103-1124.

A1.4. Industry articles.

1. Harris, R.M.B., Remenyi, T., Rollins, D., Love, P., Earl, N., Bindoff, N. (2020) Australia’s wine future - Climate information for adaptation to change. *Wine & Viticulture Journal 35(1): 42-47*
2. Bec Harris and Tom Remenyi contributed to an industry bulletin written by Sandy Hathaway, an Industry Analyst with Wine Australia. We provided new updated climate data for the (2017 and 2018) regional snapshots and describe how this links to climate variability and ongoing climate trends.
3. Bec Harris was interviewed by Nick Carne in August 2016 and featured as the “Researcher in focus’ in an edition of R&D@Work.
4. Wine Australia RD&E News Article, May 2019. A window into the climate looking glass. https://www.wineaustralia.com/news/articles/a-window-into-the-climate-looking-glass
5. Wine Australia RD&E News Article, September 2018. Weather helps decide whether. https://www.wineaustralia.com/news/articles/weather-helps-decide-whether
6. Wine Australia RD&E News Article, September 2017. The weather data is there; how do we respond. https://www.wineaustralia.com/news/articles/the-weather-data-is-there;-how-do-we-respond

A1.5. Manuscripts in preparation.

Manuscripts for peer-reviewed scientific papers are currently being prepared by all project partners and will continue to be published over 2020-2021. Manuscripts include:

1. Thomas, D., Remenyi, T., Harris, R.M.B., Hayman, P., et al. (In prep) Historical relationships between climate drivers and climate indices. Journal to be decided.
2. Harris, R.M.B; Remenyi, T.; Ratnarajah, L; Kerslake, F., Petrie, P.; Hayman, P., Thomas, D.; Bindoff, N.L. (In prep) Understanding climate analogues to identify climate-ready options for the future. *Climatic Change*
3. Harris, R.M.B; Remenyi, T.; Love, P., Hayman, P., Kerslake, F., Thomas, D., Petrie, P., Bindoff, N. (In prep) Changes in viticultural indices with climate change – implications for adaptation. *The International Journal of Climate Change: Impacts and Responses.*
4. Remenyi, T.; Rollins, D.; Harris, R.M.B (In prep) Re-evaluating temperature-based viticultural indices in the context of a changing climate. *Scientific Reports*
5. Hayman, P.; Thomas, D.; Kerslake, F.; Petrie, P.; Remenyi, T.; Harris, R.M.B. (In prep) How are adaptation decisions affected by forecasts of climate variability and extreme events. Journal to be decided.
6. Thatcher, M., Remenyi, T., Harris, R.M.B. (In prep) Evaluation of the CCAM regional climate modelling over south-eastern Australia.

A1.6. Further communication activities.

1. A roadshow to take the atlas to wine regions around Australia would greatly enhance the uptake of the climate change information in the atlas. Workshops or talks at field days would give grape growers the opportunity to discuss the implications of the changes in climate that are projected for their regions and have any questions about the climate science explained.
2. The online atlas could be updated to make it interactive, which would enable more immersive exploration of the climate data across the wine regions.

Appendix 2: Intellectual Property and/or valuable information arising from the research.

No intellectual property has been generated as part of this project. The climate model output, including the multiyear forecast system and regional climate model simulations, and the information provided in the atlas, are freely available.

Appendix 3: References cited in the report

Cai, W., X.-T. Zheng, E. Weller, M. Collins, T. Cowan, M. Lengaigne, W. Yu, and T. Yamagata. 2013. Projected response of the Indian Ocean Dipole to greenhouse warming. Nature Geoscience **6**:999.

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Appendix 4: All staff engaged on the Project

ACE CRC, University of Tasmania - Dr Rebecca Harris, Dr Tomas Remenyi, Dr Nick Earl, Mr Dean Rollins, Dr Lavenia Ratnarajah, Dr Peter Love, Prof Nathan Bindoff
Tasmanian Institute of Agriculture, University of Tasmania – Dr Fiona Kerslake
SARDI – Dr Peter Hayman, Dane Thomas, Dr Paul Petrie
AWRI – Dr Mark Krstic
CSIRO Oceans and Atmosphere – Dr James Risbey, Dr Marcus Thatcher, Dr Carly Tozer, Dr Tony Rafter, Dr Dougie Squire, Dr Andrew Schepen.

Appendix 5: Details of the Decadal Climate Forecast Project component (DCFP).

Prepared by Dr. James Risbey (CSIRO)

A5.1. Climate model Improvements

The Climate Analysis Forecast Ensemble (CAFE) system, developed by CSIRO's Decadal Climate Forecast Project (DCFP), was used to provide climate forecasts for the wine regions. The system combines a coupled ocean-atmosphere climate model (ACCESS-D) with a state-of-the-art data assimilation and ensemble generation system. Figure A5.1 provides a basic overview of the process used to generate forecasts. The 'control' climate model provides the underlying physics to the system and is performed by running the model without importing any observations. Data assimilation is the process of combining different types of observed data to provide an estimate of the state of the real-world climate system (initial condition). Multiple initial conditions are produced (i.e. an ensemble) from which multiple forecasts can be spawned. Ensembles are used to capture the uncertainty in the forecasting procedure.

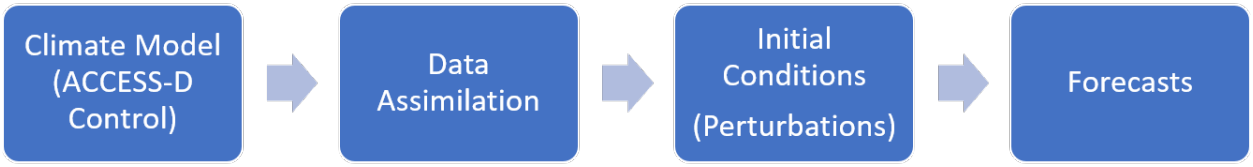


Figure A5.1: Overview of process used to generate forecasts.

The CAFE forecast system has undergone significant improvements during the duration of the Wine Australia project. A full and technical description of these improvements is provided in (O'Kane et al., 2018). The first version of the forecast system contained larger biases in the southern ocean, which have been reduced by taking account of the effect of ocean waves on wind speed in the newer version. The first version was initialized for seasonal to multiyear forecasts by perturbing the tropical ocean everywhere in the tropical zone. In the newer version, the perturbations to the tropical ocean were confined to the region of the tropical thermocline where ENSO dynamics are important. This provided a more targeted set of perturbations that encouraged forecast spread related to the growth of ENSO. Assessments from the newer version of the forecast system are presented here.

During this last year of the project we have also concentrated on generating a large set of ensemble reanalysis products with the forecast system. These are essentially the model's best estimates (guided by observations) of the 3d state of the ocean-atmosphere system for each day since 1960. This reanalysis dataset in turn provides a consistent set of initial conditions for spanning new hindcasts and forecasts. By initialising the next version of CAFE forecasts in this way, we should reduce some of the 'shock' in the forecasts that results from

using less consistent initial conditions. This ‘shock’ is the model’s tendency to move away from the initialised state through time in the forecast and is an important source of forecast errors. These reanalysis products are still being generated and will be available in the next financial year for the next CAFE forecast version.

A5.2. Process verification of heat extremes and rainfall

An important component of climate model development is assessment of the fidelity of the model to simulate the processes driving weather and climate variability, also known as ‘process verification’. Process verification is a key focus of the DCFP and we present here an analysis of the ability of the ACCESS-D control model to simulate multi-day rainfall and temperature extremes.

Extremes at this timescale have the potential to influence wine production. For example, consecutive days of extreme hot temperatures negatively affect grape growth. Additionally, the accumulation of extremes at this timescale lead to seasonal and annual climate anomalies (e.g. an accumulation of very hot/dry days leads to very hot and/or very dry seasons). We present here two case studies – heatwaves in the Riverland region and wet extremes in Tasmania (identified in Figure A5.2). We investigate how well the ACCESS-D model represents both the observed statistics of these extremes and the associated large-scale atmospheric circulation.

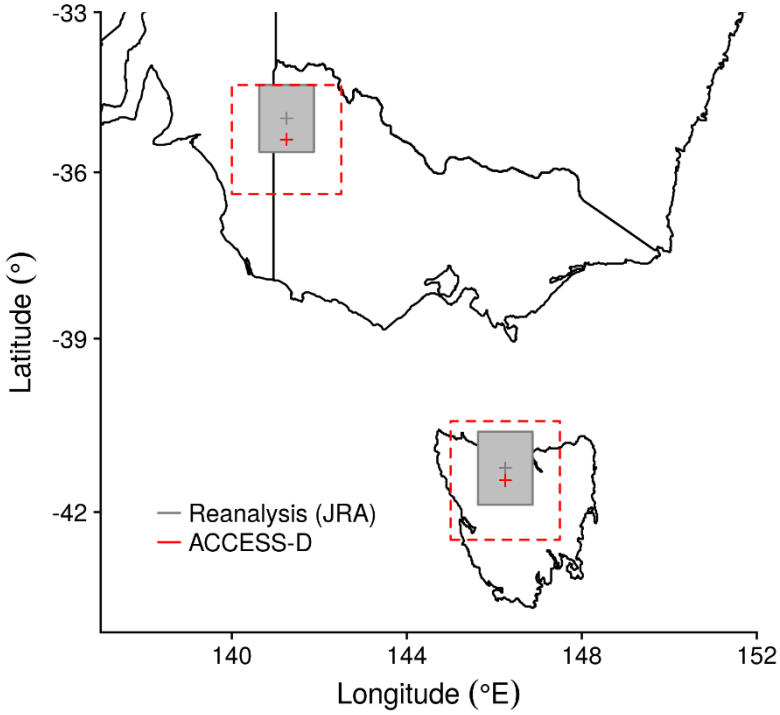


Figure A5.2: Study regions. Red boxes indicate ACCESS-D grid boxes. Grey boxes indicate corresponding JRA grid boxes.

A5.2.1. Data

Observed rainfall and temperature data is provided by the Australian Water Availability Project (AWAP). AWAP provides data on ~5x5km grids. Observed atmospheric data is given by the Japanese 55-year Reanalysis (JRA) product (Kobayashi et al., 2015). We use geopotential height anomalies at 500hPa to represent the atmospheric circulation. Geopotential height approximates the height of a pressure surface (in this case 500hPa) above mean sea-level pressure and shows the presence of high and low pressure systems in the upper atmosphere.

Figure A5.2 shows the model grid box size over the regions of interest (red boxes) and the corresponding JRA grid box size (grey boxes). There is an obvious difference in resolution and so to provide a fair comparison between the ACCESS-D model and observations, we

regridded the model to the same resolution as JRA. Regridding model data is a common approach in model comparison studies. We also extracted all AWAP grids within the relevant JRA grid boxes and created an areal average to be compared to the modelled rainfall and temperature.

A5.2.2. Method

Following preparation of the data we identified heatwaves and wet extremes in the observed and modelled rainfall and temperature data. Temperature extremes are identified as at least 3 days in a row of maximum temperatures greater than the 90th percentile maximum temperature value. The 90th percentile value was determined across a 15-day window to account for seasonality. As a first pass, extreme wet events were identified as consecutive rain days. From this initial list of events we then identified only events with a total rainfall greater than the 95th percentile event magnitude value (i.e. only events with a very large magnitude selected). Further details of event definition are provided in Risbey et al. (2018) and Tozer et al. (2018). We compare the distribution of extremes identified in the modelled and observed data in Section 2.3.

From our lists of heatwaves and wet extremes, we designated the start of each event as 'Day 0' and the ten days before and after Day 0 were then designated as Days -10 to 10. This allows us to look at the onset and decay periods of the extreme events. We then calculated the average of the geopotential height anomalies across each event day. By determining the average of the geopotential height field it is hoped that a common atmospheric circulation pattern can be identified. We compare the patterns we identified for the observed and modelled heatwaves and wet extremes in Section A5.2.3.

A5.2.3. Results and Discussion

We begin by comparing the daily Riverland temperature and Tasmanian rainfall distributed across each month for the observed and model datasets in Figure A5.3. The ACCESS-D model shows very good agreement with the observed Riverland temperature distribution (Figure A5.3a). Both datasets have similar medians and show a similar amount of variability during the year (indicated by the similar sizes of the boxes). For Tasmania rainfall (Figure A5.3b), ACCESS-D shows variability similar to observed, but tends to have higher median rainfall, particularly during the wetter months (April-October).

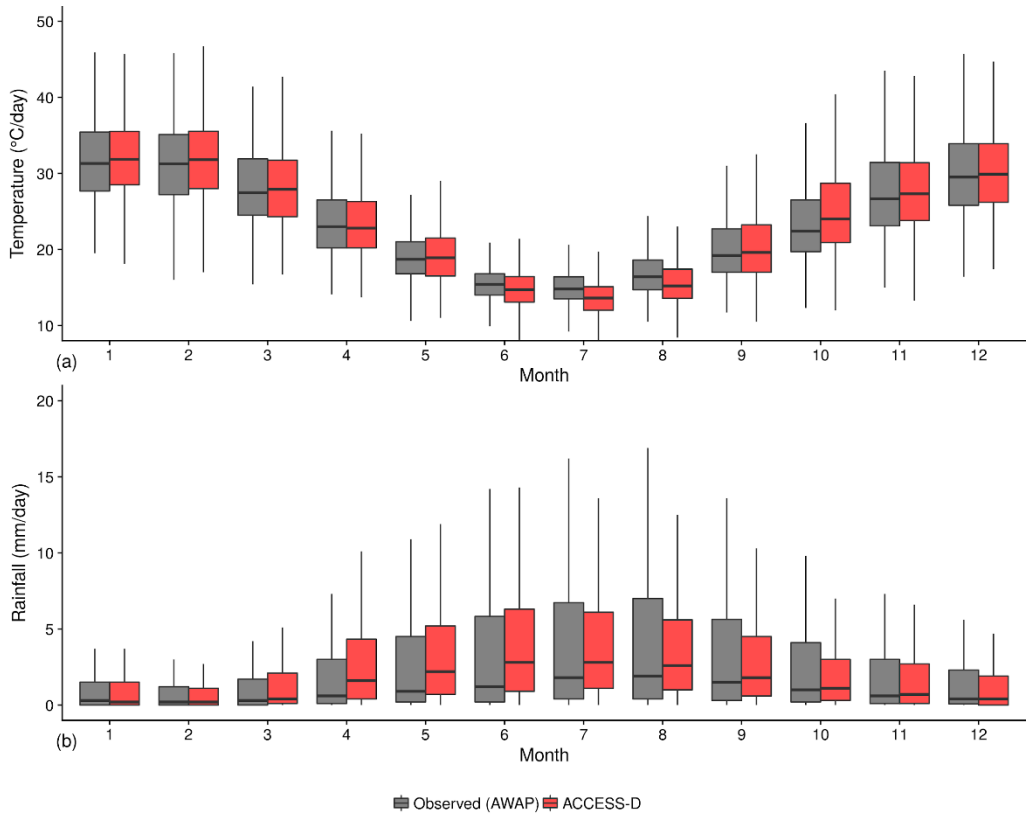


Figure A5.3: Daily Riverland temperature and Tasmania rainfall distributions in each month for observed (AWAP) and ACCESS-D model datasets. Boxes indicate the 25th and 75th percentile range, thick black line indicates median. Whiskers indicate the 5th and 95th percentile range.

We now explore the distribution of extreme events in the observed and modelled datasets where the heatwaves and wet extremes are identified as per the method presented in Section A5.2.2. Figure A5.4 shows the distribution of heatwave duration and magnitude for the observed and modelled datasets. The total number of observed and modelled heatwaves identified across the 40 year analysis period was 137 and 135, respectively. Figure A5.4a shows that both datasets follow a very similar distribution of heat wave duration, though ACCESS-D tends to have longer heat waves, with a maximum of 13 days, compared to 10 days for observed. For heatwave magnitude (Figure A5.4b), modelled heatwaves again closely follow the observed heatwave distribution, noting that these figures include heat waves across the year and so include the seasonal cycle (e.g. mean daily temperature in winter heat waves will be lower than summer heat waves).

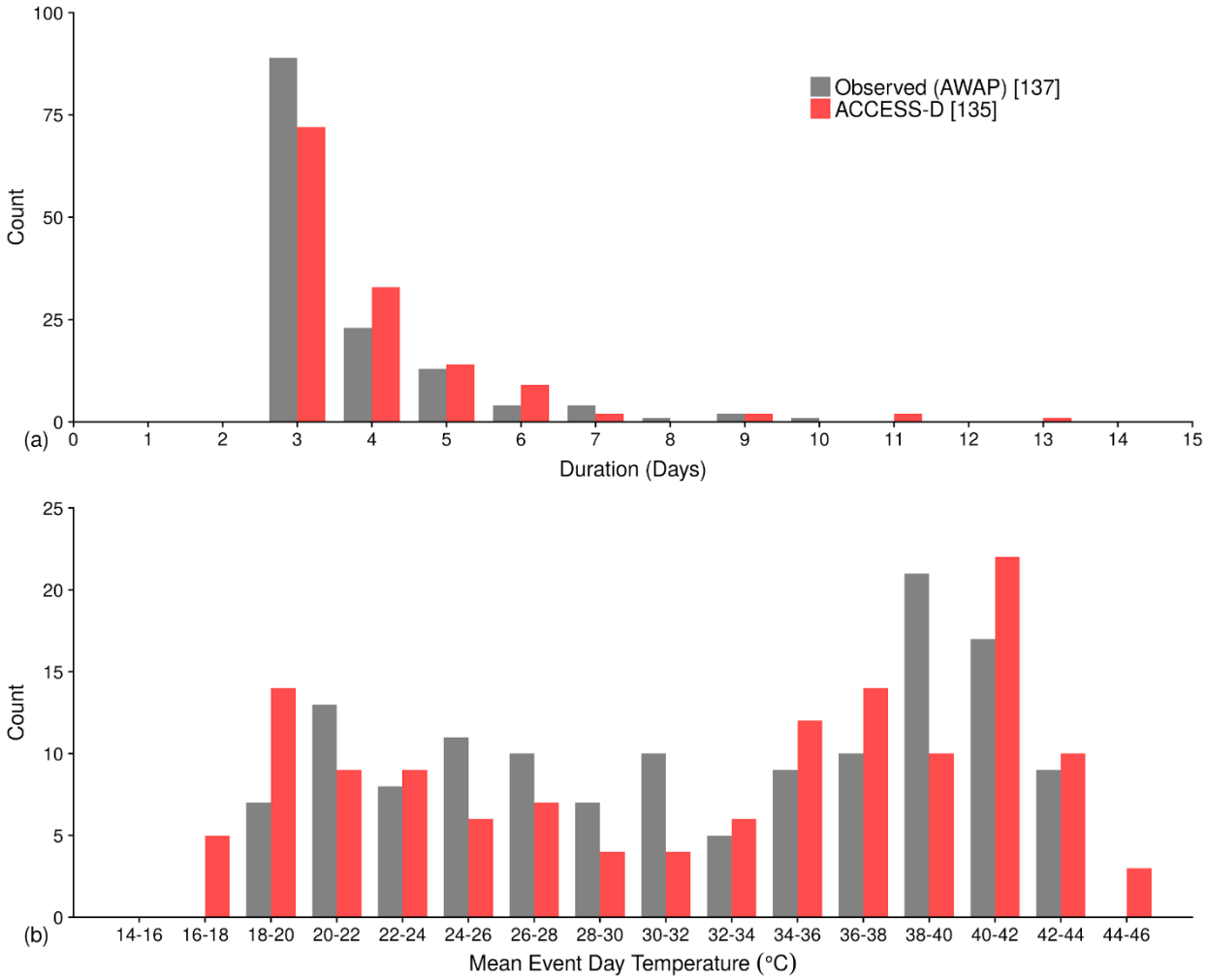


Figure A5.4: Observed and modelled distributions of heatwave (a) duration and (b) magnitude. Bracketed number indicates the total number of wet events identified in the observed and modelled datasets.

Figure A5.5 shows the distribution of wet event duration and magnitude for the observed and modelled datasets. The total number of observed and modelled wet events identified across the 40 year analysis period was 113 and 125, respectively. The distributions of wet event duration (Figure A5.5a) across datasets are remarkably similar, particularly given that no persistence threshold was used to define wet events (the threshold was based on magnitude only). Though it is noted that there is a tendency for longer wet events in the observations. For magnitude, ACCESS-D tends to underestimate observed wet event magnitude. This tends to be a common observation

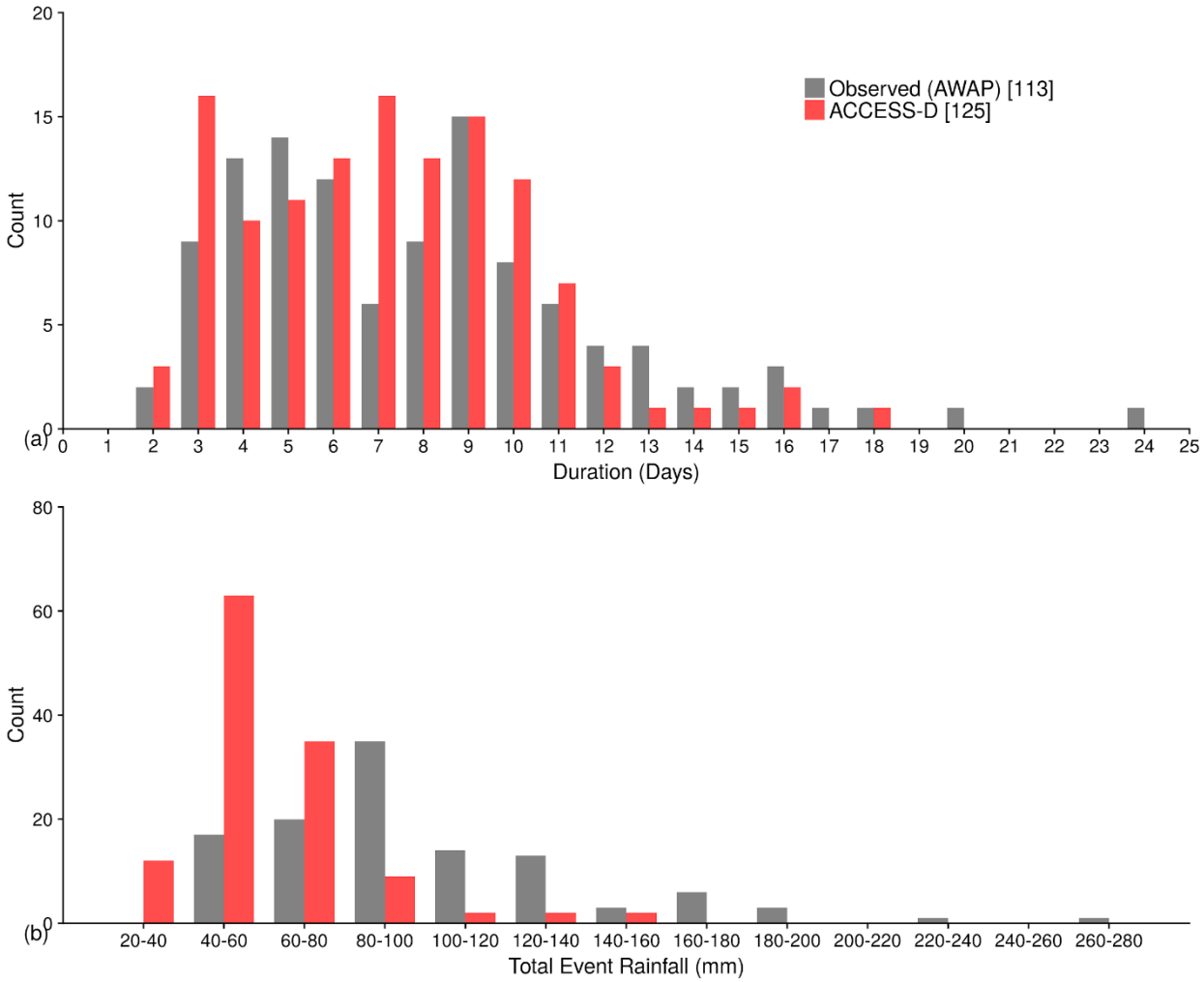


Figure A5.5: Observed and modelled distributions of wet event (a) duration and (b) magnitude. Bracketed number indicates the total number of wet events identified in the observed and modelled datasets.

We now assess the model representation of the atmospheric circulation associated with spring heatwaves in the Riverland and autumn wet events in Tasmania. These seasons are selected based on those presented in Risbey et al. (2018) and Tozer et al. (2018), but we note that similar results were identified for all seasons.

Figure A5.6 presents the circulation associated with heatwaves in observations and the ACCESS-D model for a subset of event days (i.e. days -5, -2, 0, 2, 5). Negative geopotential height anomalies indicate low pressure systems (e.g. cut-off lows) and positive anomalies indicate high pressure systems (e.g. blocking highs). Correlations between the observed and modelled patterns are given in the top right corners of Figure A5.6b. Bold and italic numbers indicate statistically significant correlations. Referring first to the observed results (Figure A5.6a), we see that at Day -5 (i.e. 5 days before the event commences) there is some organisation of low and high pressure systems in the Indian Ocean, west of Australia. The low and high pressure systems appear as alternating systems, one after the other, reminiscent of cars in a train. For this reason they are often referred to as ‘wave-trains’. The wave-train moves eastwards and by Day 0, a large high pressure system has moved over southeast Australia. This high pressure system persists over the region until at least Day 5, in concert with positive temperature anomalies (red shading). The ACCESS-D model can capture the observed circulation relatively well with significant pattern correlations on all days presented. The relationship is particularly strong from Day 0 to Day 5.

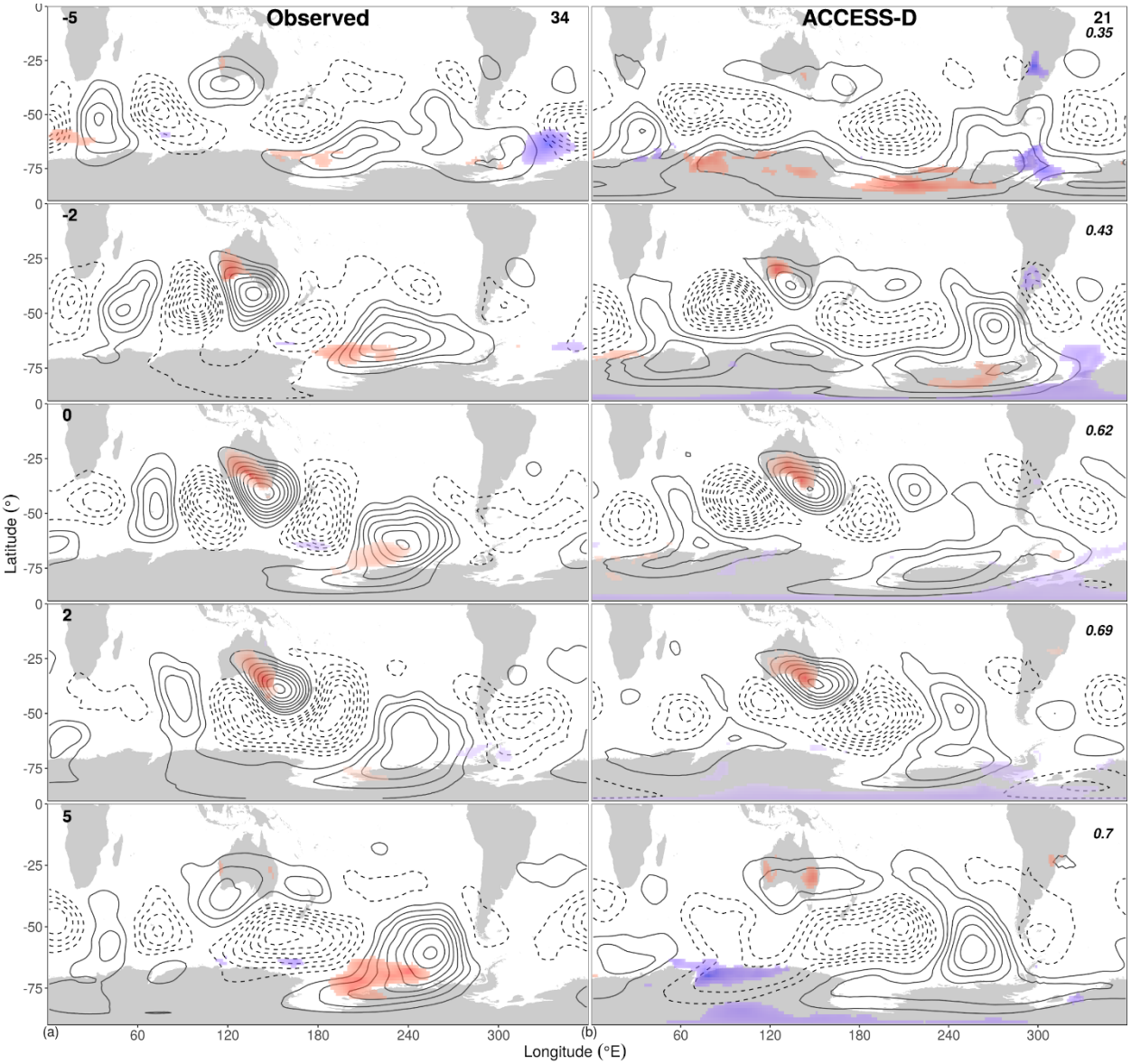


Figure A5.6: Composite (average) geopotential height anomalies and mean surface temperature anomalies for days -5, -2, 0, 2, 5 for Riverland heatwaves (a) Observations and (b) ACCESS-D. Solid (dashed) contours indicate positive (negative) geopotential height anomalies, filtered to only show values > 15 m or < -15 m, with contours every 15 m. High surface temperature anomalies are shown in red and low temperature anomalies shown in red. The event day number is given in the top left corner of (a) and the total number of heat waves given in the top right corner of day -5 for each dataset. Pattern correlation values between observed and ACCESS-D model datasets are given in the top right corner of (b). Bold and italic values indicate values that are greater than the 95th percentile correlation value, which was determined using a Monte Carlo procedure.

A5.2.4 Conclusions of process verification study

We have shown that the ACCESS-D model represents the statistics of heatwaves and the associated atmospheric circulation very well. For wet extremes, there is a tendency for the ACCESS-D model to underestimate the magnitude of the events, though the event duration and associated atmospheric circulation are generally well represented in the model. This is perhaps a surprising result given that climate models are well known to have some issues in their representation of precipitation. Overall the results suggest that the ACCESS-D model can capture temperature and rainfall extremes across southern Australia. This provides some confidence in its use for climate forecasting purposes, since capturing the underlying processes is a necessary condition for forecasting these extremes. However, while this is an important finding, it is not necessarily an indicator of how successfully the model can

forecast extremes. Skilful forecasting also relies on predictability in the climate system and on the alignment of slow circulations between the model and the real world. We now assess the skill of forecasts produced by the CAFE system.

A5.3 Assessment of forecast skill

A set of model hindcasts (forecasts over periods in the past) were generated with the CSIRO CAFE system over the years 2002-2016. The hindcasts were run every month and extended to 2 years lead time. Once a year forecasts were run over 5 years lead time, but as the skill from the forecasts has mostly diminished by the end of the 2nd year, we discuss 2-year leads only. Each forecast consisted of 11 ensemble members. The ensembles are generated from slightly different initial conditions to represent spread in the forecast as lead time increases.

The CAFE forecasts were tested for three of the wine regions in the project; Margaret River, Hunter, and Riverland. These three regions capture different climate types in the southwest of Western Australia, east coast, and southeast Australia respectively. The climate variables tested at these sites are temperature and precipitation. The climate forecast outputs were calibrated to observed data from these regions using the Bayesian Joint Probability (BJP) method (Wang et al., 2009). This method is generally judged to be superior to other approaches such as quantile mapping. The method was applied to monthly output data from the model, from which daily time series with similar statistical attributes to the observed daily data were generated.

The skill of the forecast daily series of temperature and precipitation at each of the three wine region sites was uniformly low. This is not surprising as seasonal to multiyear forecast systems are not designed to have skill on daily time scales. To better match the characteristics of the forecast system, we calculated integrated versions of temperature and rainfall using a cumulative approach. Thus, we calculated growing degree days (GDD) for temperature as the cumulative sum of temperatures above 10C from the 1st of June each year. In a similar manner, we calculated accumulated rainfall as the cumulative rainfall total from the 1st of June each year. For these cumulative variables we calculated skill scores for each wine region as a function of calendar month (from which the forecast commenced) and lead time. The skill score used is the continuous ranked probability skill score (crps), which tests the performance of probability forecasts relative to a climatological forecast (Hersbach, 2000).

Forecast skill is presented in the following figures as a function of forecast start month and lead time. Scores in blue indicate better skill than climatology, while red indicates worse than climatology. The measures of skill are considered more robust when they are consistent with lead time and across neighbouring forecast start months. That is, we interpret large blocks of positive skill as more likely robust, whereas isolated patches of skill are more likely to reflect some skill by chance. The skill results for each wine region are shown below.

A5.3.1 Margaret River

Margaret River provides an example wine region in the west of the country. In this section we assess skill for growing degree days and cumulative rainfall in this region. For Margaret River there is better skill than climatology for forecasts of GDD (Figure A5.7) issued in the first half of the year (January to July forecast starts). For other months and for cumulative precipitation (Figure A5.8) there is little skill relative to climatology.

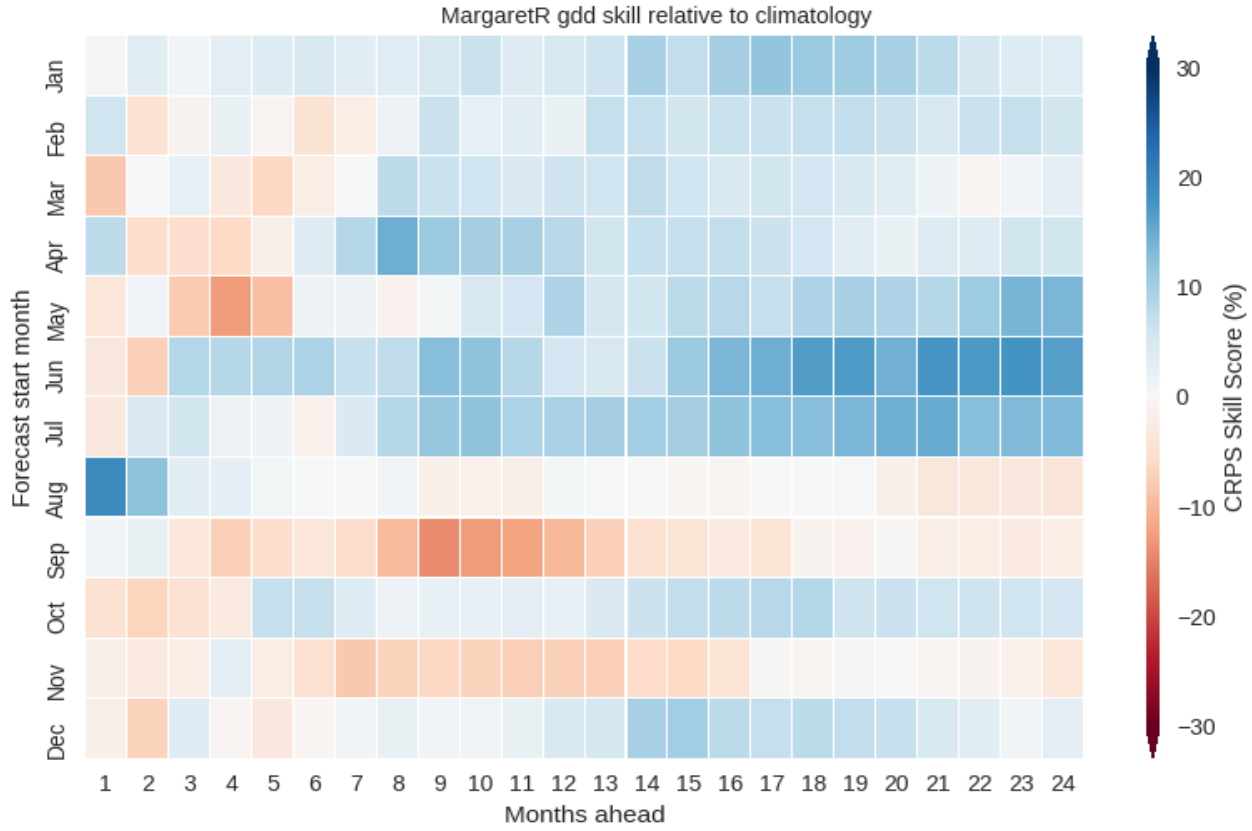


Figure A5.7: Margaret River crps skill score for growing degree days relative to climatology for lead times out to 24 months (x axis) and for each of the calendar month forecast start dates (y axis). Positive skill scores (blue) are better than climatology, while negative skill scores (red) are worse than climatology.

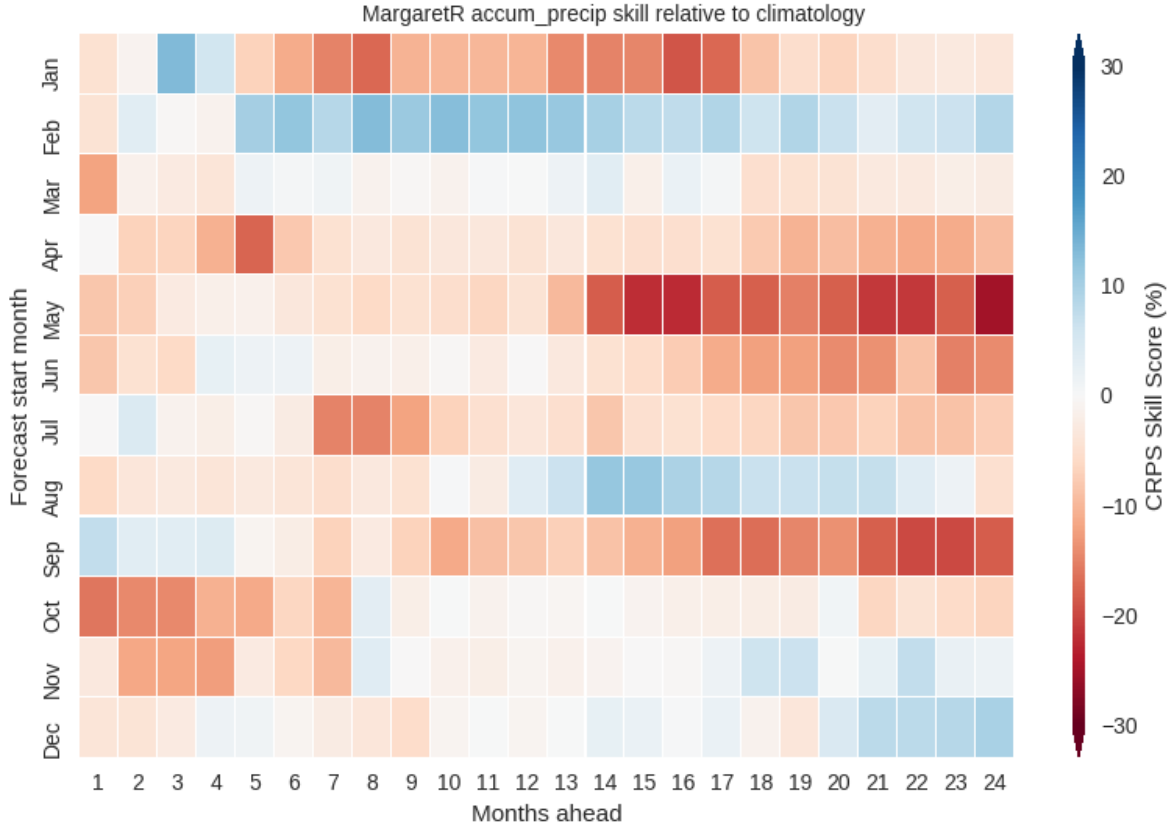


Figure A5.8: As in Figure A5.7 but for Margaret River cumulative rainfall.

A5.3.2 Riverland

The Riverland region sits in southeast Australia and is indicative of model skill for other wine regions in this part of the country. Assessments of Riverland growing degree day and cumulative rainfall skill are presented in Figure A5.9 and Figure A5.10 respectively.

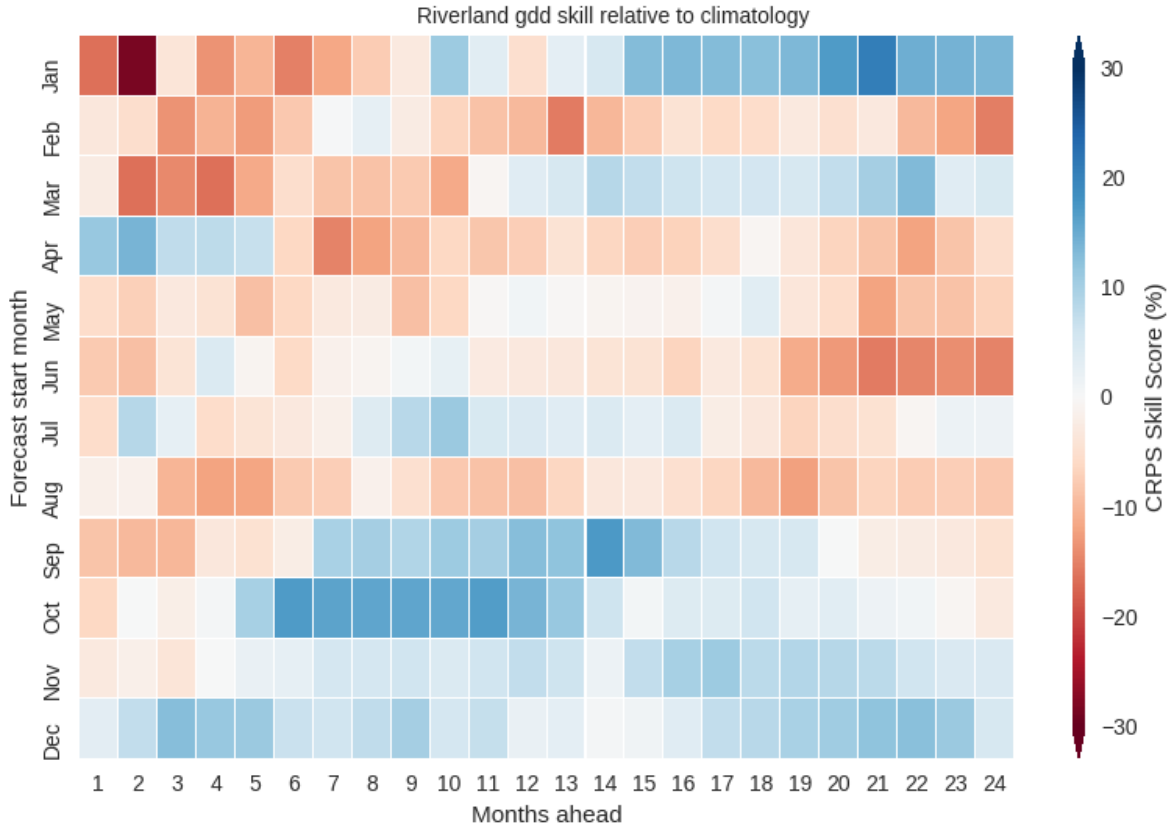


Figure A5.9: As in Figure A5.7, but for Riverland growing degree days.

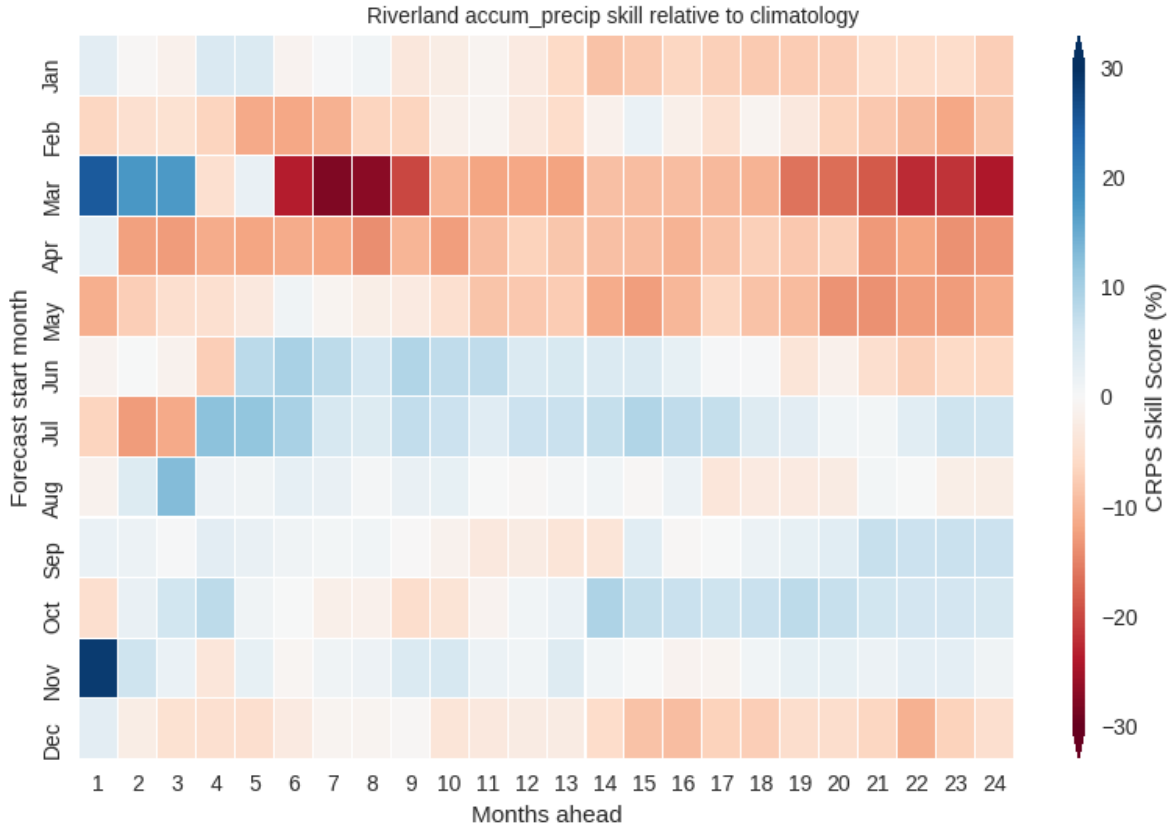


Figure A5.10: As in Figure A5.7 but for Riverland cumulative rainfall.

For the Riverland region there is some skill relative to climatology for forecasts of GDD issued between September and December. The significance of this result is discussed below. For cumulative rainfall there is little or no skill for the Riverland relative to climatology.

A5.3.3 Hunter

The Hunter region is indicative of forecast skill for wine regions on the east coast of Australia. Skill for growing degree days and cumulative rainfall are presented in Figure A5.11 and Figure 72 respectively.

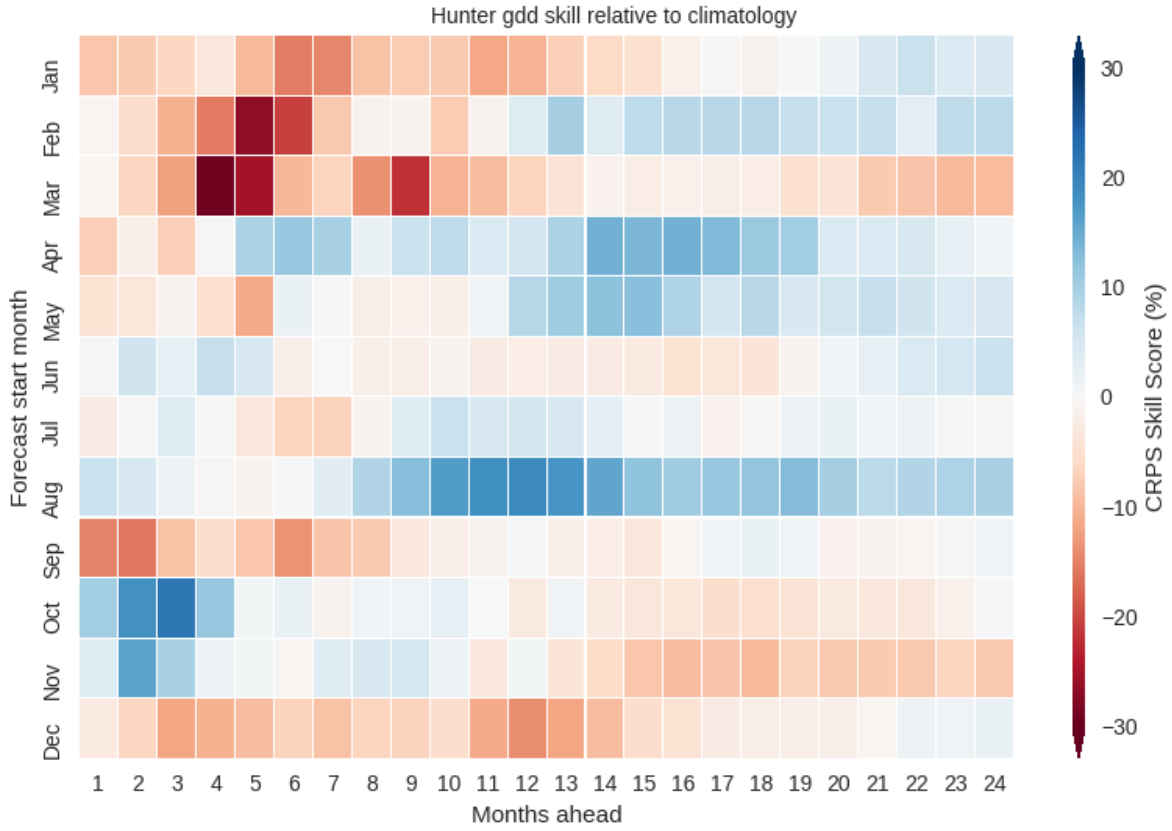


Figure A5.11: As in Figure A5.7, but for Hunter growing degree days.

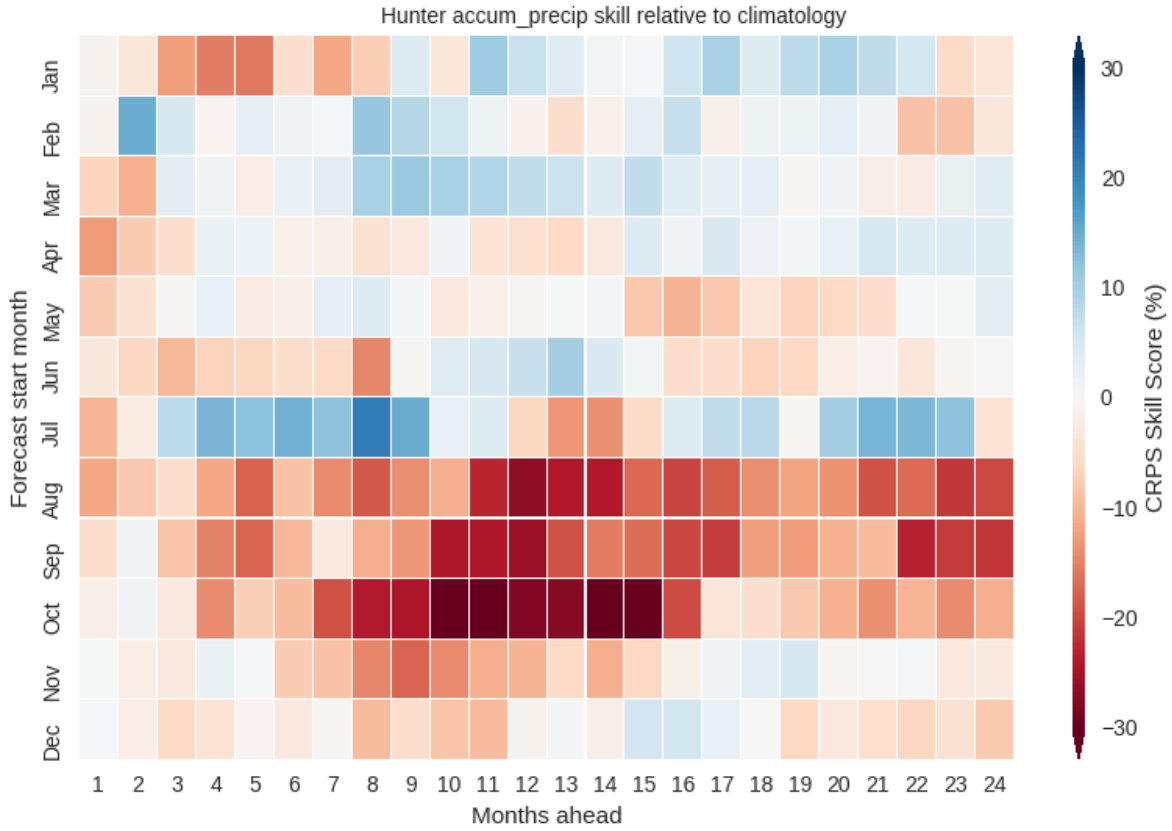


Figure 7: As in Figure A5.7, but for Hunter cumulative rainfall.

For the Hunter region there is little skill relative to climatology for either GDD or cumulative rainfall. There is perhaps some skill for some start months, such as GDD for August starts. However, to have confidence in skill from a single set of forecasts we'd generally like to see that skill reproduced over neighbouring start months as well, as in the Margaret River and Riverland cases.

A5.3.4 Net skill assessment

Overall for these wine regions the level of forecast skill for cumulative rainfall on lead times out to 2 years is low. For the most part, cumulative rainfall skill is not different from a climatological forecast. While this result is disappointing, it is not different from that obtained for other forecast systems for rainfall on these spatial scales at these lead times. A challenge for climate forecast systems is to identify whether there are windows of skill at some times if/when the climate system becomes more predictable. That is a topic of ongoing research to identify such windows and assess whether there is useful rainfall skill at such times.

The skill results for GDD are more encouraging and indicate for two of the wine regions (Margaret River and Riverland) that there is more skill than climatology for forecasts issued in some parts of the year. For the Riverland, this skill is evident for forecasts initiated between September and December. This is the time of the year in which El Niño Southern Oscillation (ENSO) events have initiated and provide more skill for the forecast systems. The Riverland is in a part of Australia that benefits from the ENSO teleconnection (Risbey et al., 2009). On the other hand, for Margaret River the skill in GDD is expressed for forecasts initiated between January and July. This is the time of year when forecasts of ENSO have low skill, but Margaret River has no appreciable teleconnection to ENSO. At this time of year the Margaret River region is much better teleconnected to the Southern Annular Mode (SAM), although it is not clear whether the SAM is predictable at lead times out to 2 years as examined here. The predictability of SAM and its association with forecast skill in southwest Western Australia will be assessed in future work.

A5.3.5 Example climate forecasts

An objective of the forecast assessment is to progress the models and skill to a point where the forecasts provide useful input to the wine industry. In Figures A5.13 and A5.14 below we show example forecast plumes for cumulative rainfall and GDD respectively (for the Hunter and Riverland region). For these forecasts to add value, the ensemble plume of the forecasts needs to be narrower than the expectations from past climate conditions (climatology).

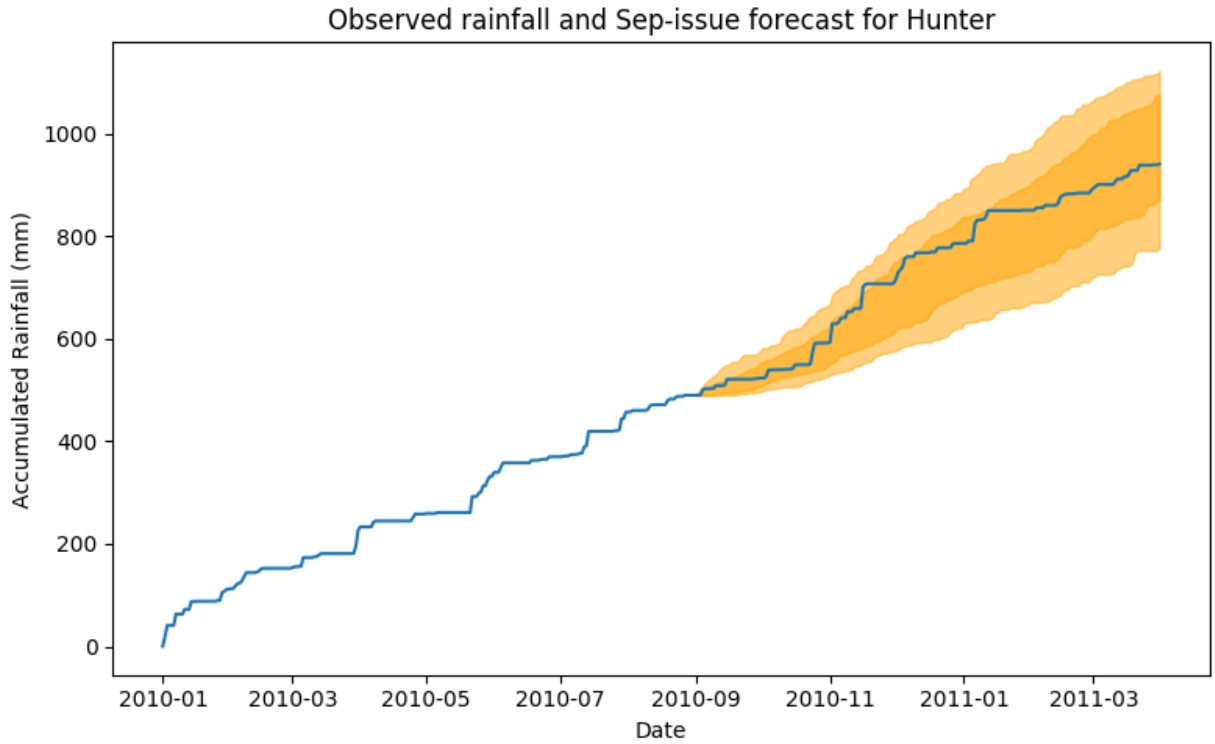


Figure A5.13: Forecast of cumulative rainfall for the Hunter region from September 2010. Yellow plume shows the 10-90 percentile (light shade) and 25-75 percentile (dark shade) ensemble spread in the forecast. The blue line is the observed cumulative rainfall.

In the case of cumulative rainfall (Figure A5.13), the spread of the forecast with time is about the same as the spread from climatology. That is useful in knowing what the set of historical years imply about how the year may finish. However, the forecast itself doesn't add any value beyond that for rainfall.

The example of a GDD forecast for the Riverland region is given in Figure A5.14. In this case the spread of the ensemble plume in the forecast is narrower than the expectations of spread from all historical years (climatology). That is, the forecast is potentially adding value, at least for forecasts initiated from September through December for this region. More work would be needed to establish the utility of skilful forecasts of GDD for the wine industry made at this time of year. That is, how robust is the skill, can it be improved, what decisions can it be related to, and would it improve outcomes from those decisions?

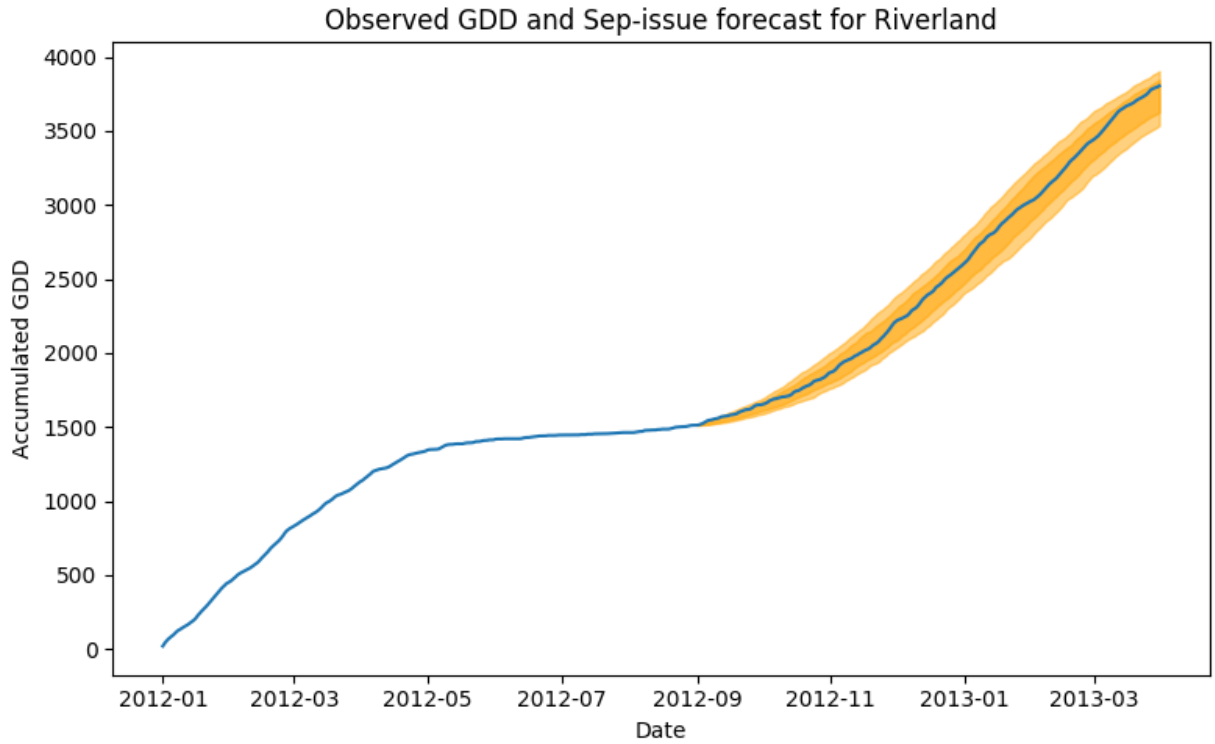


Figure A5.14: Forecast of growing degree days from September 2012 for the Riverland region. Yellow plume shows the 10-90 percentile (light shade) and 25-75 percentile (dark shade) ensemble spread in the forecast. The blue line is the observed GDD.

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Appendix 6: Description and evaluation of the CCAM regional climate modelling

Prepared by Dr. Marcus Thatcher (CSIRO)

A6.1 Climate data sets for developing projections

There are several important data sets when developing regional projections of climate change. Global Climate Models (GCMs) are an important source of information as to how the global climate may change due to global warming and increased greenhouse gas concentrations. Global Climate Models simulate the different components of the Earth system including the atmosphere, ocean, land-surface, sea-ice, aerosols and the carbon cycle. By using prescribed greenhouse gas emission scenarios, GCMs can be used to project large-scale changes in the global climate.

To ensure that the projections of GCMs can be compared in a sensible way, the Coupled Model Intercomparison Project (CMIP) prescribes various scenarios of greenhouse gas emissions that are applied consistently to all GCMs. For the CMIP5 generation of GCMs, greenhouse gas emissions are referred to as Representative Concentration Pathways (RCPs), with examples including RCP2.6, RCP4.5, RCP6 and RCP8.5. The size of the number indicates more energy (in the form of heat) being trapped in the Earth system so that RCP8.5 leads to a significantly warmer future climate than RCP2.6. RCP2.6 is the emission scenario that is closest to a 2ºC warming consistent with the Paris Agreement target. RCP4.5 is sometimes referred to as a medium emission scenario and RCP8.5 is sometimes referred to as a high emission scenario.

Global Climate Model output for CMIP experiments like CMIP5 represent the most diverse range of independent climate models and projections of how the global climate will change. However, the complexity of GCMs results in them having a typical spatial resolution of 50 to 200 km, due to the limitations of current supercomputers. As a result, certain features in the regional climate are often poorly represented by GCMs including mountain ranges, coastlines, urban areas and other atmospheric phenomena such as storms. Downscaling methods are sometimes employed to address this limitation of the GCMs and provide a higher spatial and temporal climate simulation for a region (e.g. typically between 1 to 50 km resolution). Two popular downscaling methods are statistical downscaling and dynamical downscaling. Statistical downscaling relies on historical statistical relationships between observations and large-scale behaviour of the atmosphere. Dynamical downscaling employs Regional Climate Models (RCMs) that are based on modelling techniques that are like those used by GCMs, but with the computing resources focused over a region and with a focus on the atmosphere and land-surface components. In both cases, the downscaling process is informed by large-scale GCM projections, often referred to as a ‘host’ climate model.

A6.2. Description of the CCAM regional climate modelling

To develop high-resolution climate simulations for Victoria and South East Australia, we used the Conformal Cubic Atmospheric Model (CCAM) developed at CSIRO (McGregor 2005 and McGregor and Dix 2008). Unlike most RCMs, CCAM is a global atmospheric model with a variable resolution grid that can be focused over an area of interest (Figure A6.1). In this way, CCAM can generate a higher resolution climate simulation, but is still coupled to the larger scale atmospheric circulation. Formally CCAM is a stretched grid global model, but we will refer to CCAM as an RCM in this report. CCAM includes several sub-models that are useful for simulating the Australian climate, including direct and indirect aerosol feedbacks, the Australian developed Community Atmospheric Biosphere Land Exchange (CABLE) land-surface and carbon cycle model (Kowalczyk 2013), the Urban Climate and Energy Model (UCLEM) for Australian cities (Lipson, M, Thatcher, M, Hart, M and Pitman, A. (2018). A building energy demand and urban land surface model. Quarterly Journal of the Royal Meteorological Society. 144. 1-19.), as well as modern physical

parameterisations for radiation, clouds and rainfall, convection and boundary layer turbulent mixing. CCAM has been used for several regional climate simulations in Australia and South East Asia, including the CORDEX intercomparison experiment, the National Resource Management (NRM) national projections for Australia, the Climate Futures for Tasmania, Climate projections for the Australian Alps and High-resolution projections for Queensland.

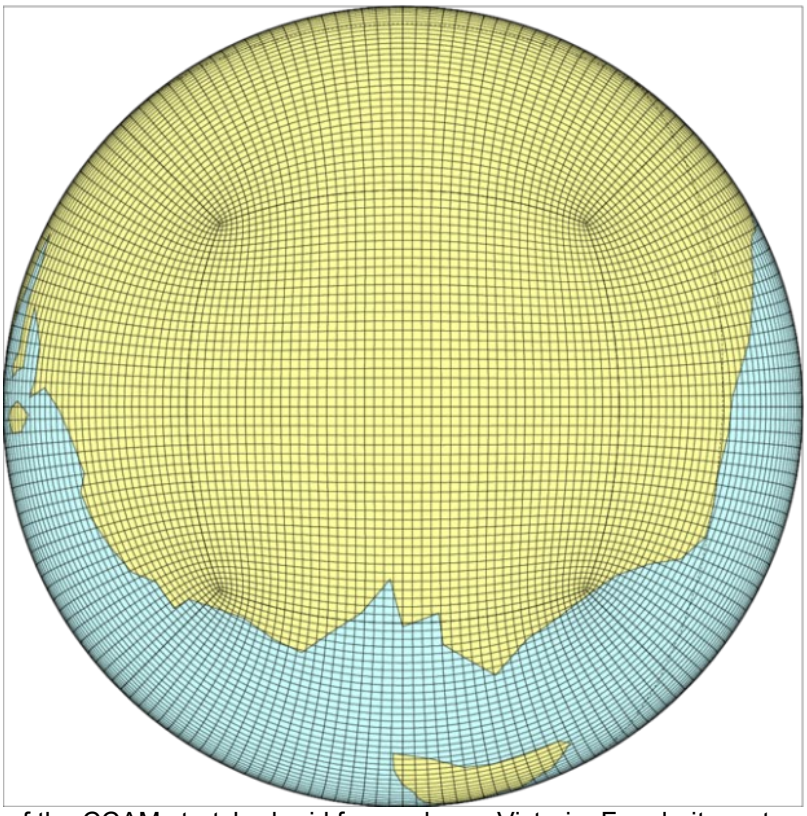


Figure A6.1: Plot of the CCAM stretched grid focused over Victoria. For clarity, not every grid box is shown, but the grid has a 5 km resolution over Victoria and the grid resolution is steadily reduced (i.e., coarser) the further away from this region for the rest of the globe.

For the Victorian projections we downscaled six GCMs from CMIP5, being ACCESS1-0, CNRM-CM5, GFDL-ESM2M, HadGEM2, MIROC5 and NorESM1-M. These models are based on the recommended GCMs for studying Australian climate change from the Climate Change in Australia web portal. The host GCMs for downscaling are selected to show a range of possible climate futures such as changes in the amount of warming and reductions in rainfall (see Table A6.1). Note that because we are selectively downscaling GCMs that show a range of possible futures, the downscaled simulations provide scenarios to explore the future climate, rather than an analysis of the most probable future climate, which lies within the range of downscaled climate. The CCAM model was configured for 35 vertical levels ranging from 20m to 40 km in height, with more vertical levels concentrated in the lower portion of the atmosphere. The CCAM downscaling process is divided into two stages. CCAM simulations are run from 1960 to 2099 for all six GCMs as well as downscaling ERA-Interim reanalyses. ERA-Interim reanalyses represent data sets where observations were assimilated into the atmospheric modelling. As a result, the ERA-Interim data corresponds to the observed weather from 1979 to 2015, although with the atmospheric simulation interpolating gaps in the observations. In this way, we can consider ERA-Interim a useful reference experiment for downscaling the current climate that avoids errors that can arise in GCM simulations.

Host GCM for downscaling	Relevance for downscaling regional climate
ACCESS 1-0	A hot, dry model that is representative of the consensus of GCM projections in northern Victoria
CNRM-CM5	Consistent with the consensus of GCM projections over Victoria
GFDL-ESM2M	A hot, dry model for Victoria
HadGEM2-CC	A hot, dry model for Victoria
MIROC5	A low warming, wet model for Australia and Victoria
NorESM1-M	A low warming, wet model for Victoria

Table A6.1: List of the six GCMs used for dynamical downscaling and the reason for their selection.

The downscaling process used by CCAM for the high-resolution climate simulations involves two stages. The first stage involves taking the projected changes in the Sea Surface Temperatures (SSTs) from the GCMs, correcting the biases and variance on a month-by-month basis relative to the observed SSTs from 1980-2010 (Hoffman et al 2016). The CCAM model is then used to rebuild the atmosphere at a uniformly global 50 km resolution consistent with the corrected SSTs. This removes the first order errors that are present in the GCM output and helps to simulate a more realistic present-day climate. The second stage is to then downscale the 50 km CCAM simulations to 5 km resolution over Victoria using CCAM's stretched grid and scale-selective filters (Thatcher and McGregor 2009). This approach ensures that the regional 5km resolution simulation is consistent with the large-scale behaviour of the global 50 km resolution simulation, but also allows CCAM to add additional information such as extreme events. It is important to note that the SST bias correction process retains the amount of warming represented in the SSTs but can allow CCAM to modify the projections of the GCMs in other respects (e.g., changes in mean sea level pressure or rainfall). When analysing the CCAM projections it can be useful to separate the regional scale changes, the large-scale changes and the differences between the GCM projections so that the processes that explain the changes can be better understood.
The CCAM regional simulations were designed to balance competing needs of finer resolution, larger ensembles of downscaled GCMs and additional emission scenarios. The 5 km resolution simulations are approaching convective spatial scales, where the convective parameterisation in a climate model has a weaker role in the simulation outcomes. By simulating the climate at these scales, we can expect to better resolve mountains, coastlines and urban areas. We can also expect to better simulate extreme rainfall events that may lead to flooding. Finally, the correcting of GCM biases in SSTs can help reduce some errors when simulating the present climate.

A6.3. Evaluation of CCAM simulations

The following section evaluates the CCAM high-resolution climate simulations for the period 1986 to 2005 by comparing the results to observations. In this section we use the Australian Water Availability Project (AWAP) gridded data sets of daily maximum 2 m air temperature, daily minimum 2 m air temperature and daily rainfall. AWAP data is based on interpolated weather station measurements and hence there are some gaps where the station network is less densely populated (e.g., in the Victorian Alps). We also make use of ERA-Interim reanalyses for evaluating the larger-scale performance of CCAM such as mean sea level or winds at 850 hPa. As the ERA-Interim reanalyses are a combination of model simulations with assimilated observations, they are a reasonably accurate representation of the larger-scale behaviour of the atmosphere. The Bureau of Meteorology have also developed the Bureau of Meteorology Australian Regional Reanalysis for Australia (BARRA), which is an important regional reanalysis where the regional atmospheric simulation assimilates regional observations. However, we have not used the BARRA reanalysis in this section as the data set was still being developed at the time of writing.

A6.3.1. Temperature

The CCAM simulation results for average daily maximum 2 m air temperature between 1986 to 2005 are compared to the AWAP observations and the host GCM models in Figure A6.2. The CCAM and GCM results have been averaged over the six downscaled GCMs, although the CCAM results are similar between the different downscaled simulations due to the use of the bias corrected SSTs discussed above. The simulation results indicate that CCAM better represents the temperatures for mountain regions and along the coastline than the GCMs when compared to AWAP. However, there is a warm bias apparent in the CCAM simulations in summer, particularly for eastern Victoria. The spatial pattern of this warm bias is not apparent in the future projected change in daily maximum temperature, suggesting that the issue is related to the diagnoses of the 2 m air temperature for tall vegetation (e.g., forests). Preliminary experiments with CCAM suggest that this error can be removed with a modified calculation of the 2 m air temperature that is more consistent with how weather stations are sited. The CCAM developers will be providing an updated temperature data set once the issue has been resolved. Nevertheless, some caution is advised in interpreting the projected changes in climate for daily maximum temperatures.

The CCAM 5 km simulation results for the daily minimum 2 m air temperature are shown in Figure A6.3, where they are compared to AWAP and the six host GCMs over the time period 1986-2005. In this case the CCAM 5 km resolution simulation results show a significant improvement to daily minimum temperature compared to the host GCMs. The GCMs tend to show a warm bias in the daily minimum temperatures over Victoria that is not apparent in the CCAM simulations. Also, the CCAM 5 km resolution simulations much better represents the colder daily minimum temperatures for alpine regions of Victoria.

Another example of how CCAM has improved the daily minimum temperature can be seen by examining the Urban Heat Island (UHI) for Melbourne. Urban areas result in an increased daily minimum temperature compared to the surrounding natural vegetation of typically 1 to 2^{o}C, depending on the density of the urban area and the amount of green space. Typically, urban areas are not represented in GCMs due to urban areas being poorly resolved. However, regional models like CCAM include special parameterisations to account for the building materials, urban drainage, shadowing effects and changes to air circulation within the urban canyon. Figure A6.4 compares the difference in daily minimum temperature between an inner-city weather station (BoM Melbourne regional office) and three outer city locations (Laverton RAAF, Coldstream and Cranbourne Botanic Gardens) between 1986-2005. The observations at the weather stations show that the Laverton RAAF and Cranbourne Botanic Gardens sites have an average daily minimum temperature that is approximately 2^{o}C cooler than the inner-city BoM Melbourne regional office site. The observed weather station data indicates that the Coldstream daily minimum temperature is 4^{o}C cooler than the inner-city BoM Melbourne regional office. Figure A6.4 shows that CCAM better represents this difference in daily minimum temperatures due to the UHI, correctly projecting a 2^{o}C difference between the inner-city and Laverton and Cranbourne sites but underestimating the temperature difference at the Coldstream site (i.e., CCAM projects an average daily minimum temperature that is too warm at Coldstream). This result for CCAM can be compared to the GCM results which do not simulate any change in daily minimum temperature between the inner-city and outer-city locations.

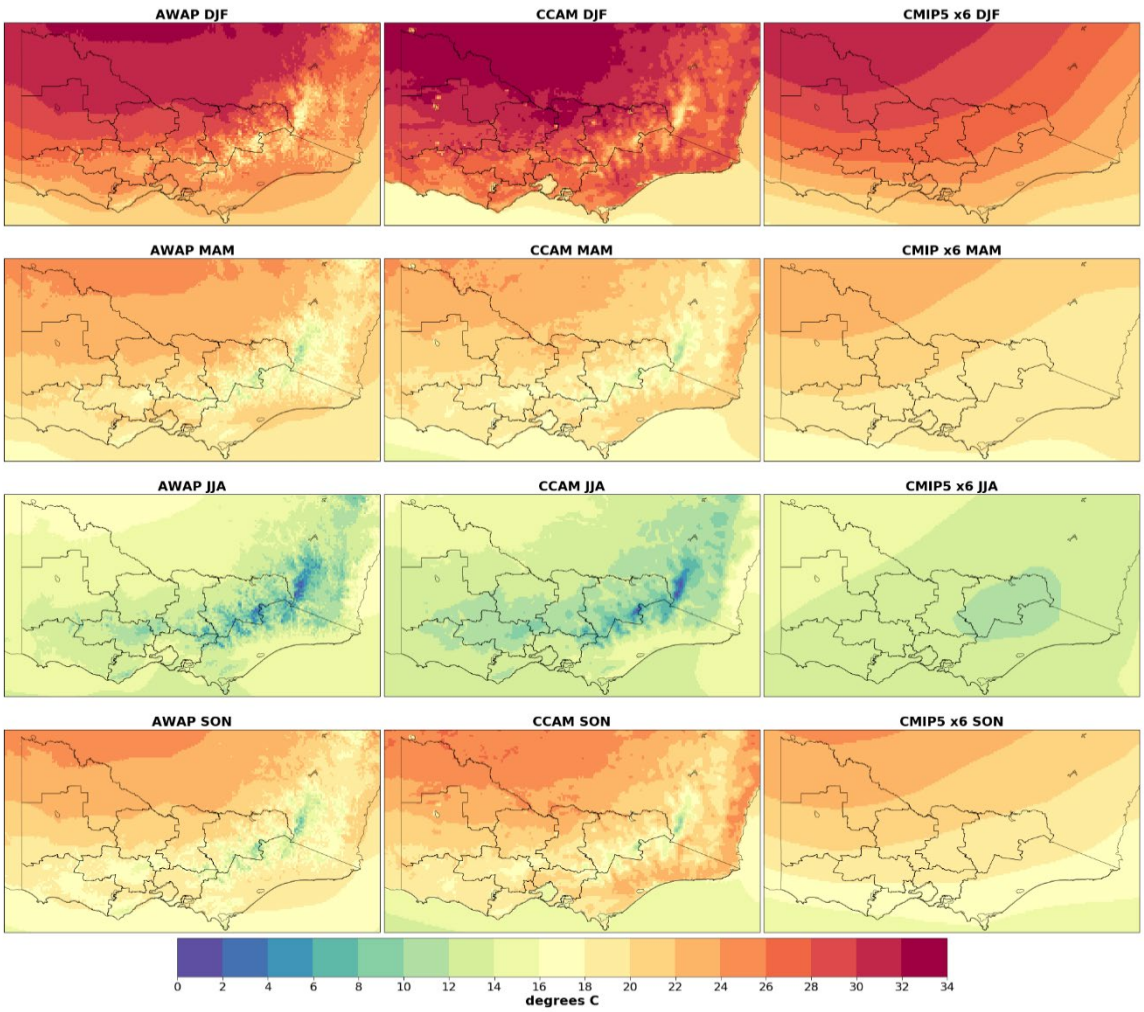


Figure A6.2: Comparison of average daily maximum 2 m air temperature between 1986 to 2005 between AWAP observations (left column), CCAM 5 km resolution simulation (middle column) and host GCM (right column). The CCAM and GCM results are averaged over the six GCMs used for downscaling. The rows from top to bottom correspond to December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON), respectively.

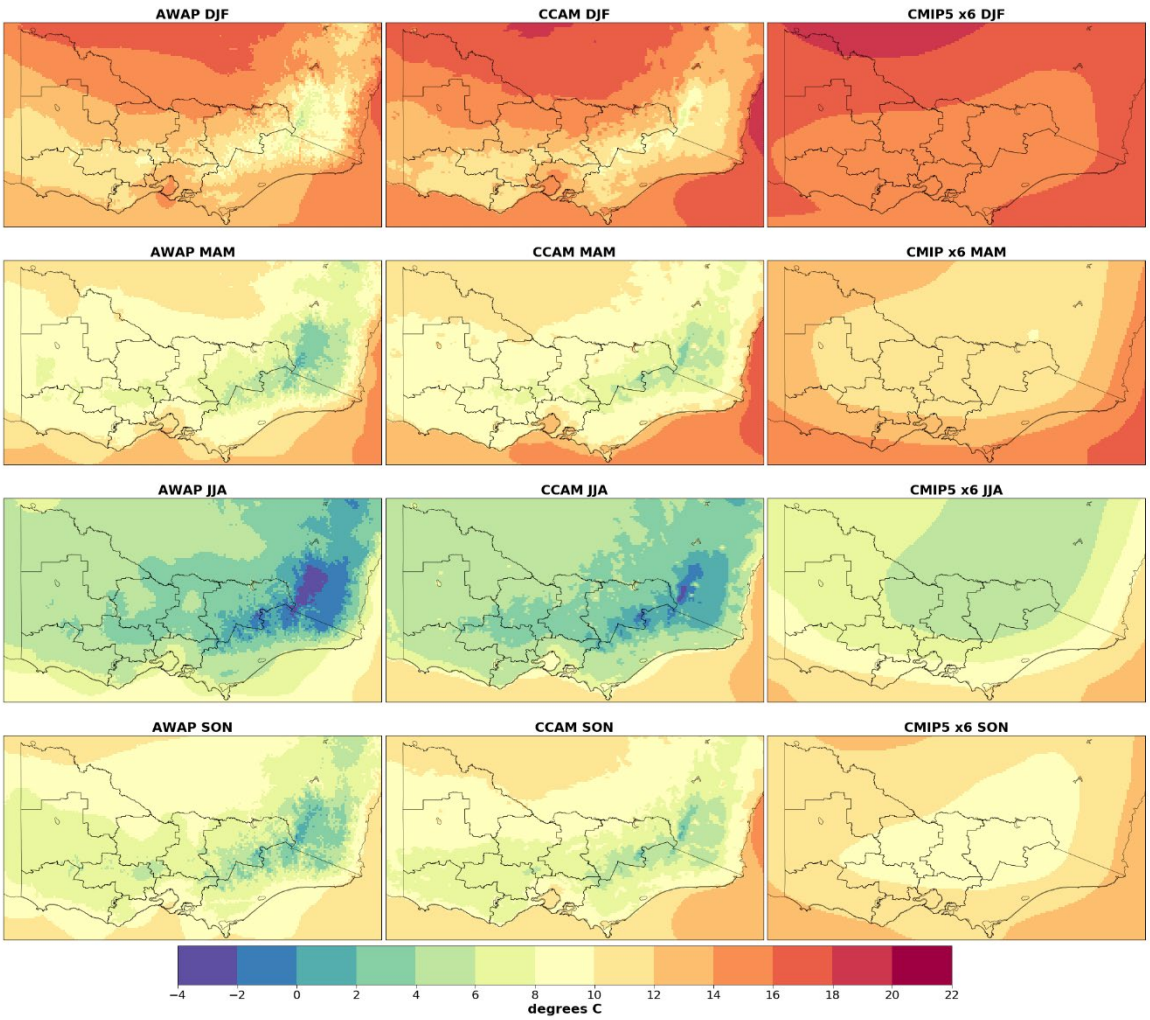


Figure A6.3: Comparison of the daily minimum 2 m air temperature between 1986 to 2005 for AWAP (left column), CCAM averaged over the six downscaled simulations (middle column) and the average of the six host GCMs (right column). The rows from top to bottom correspond to December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON), respectively.

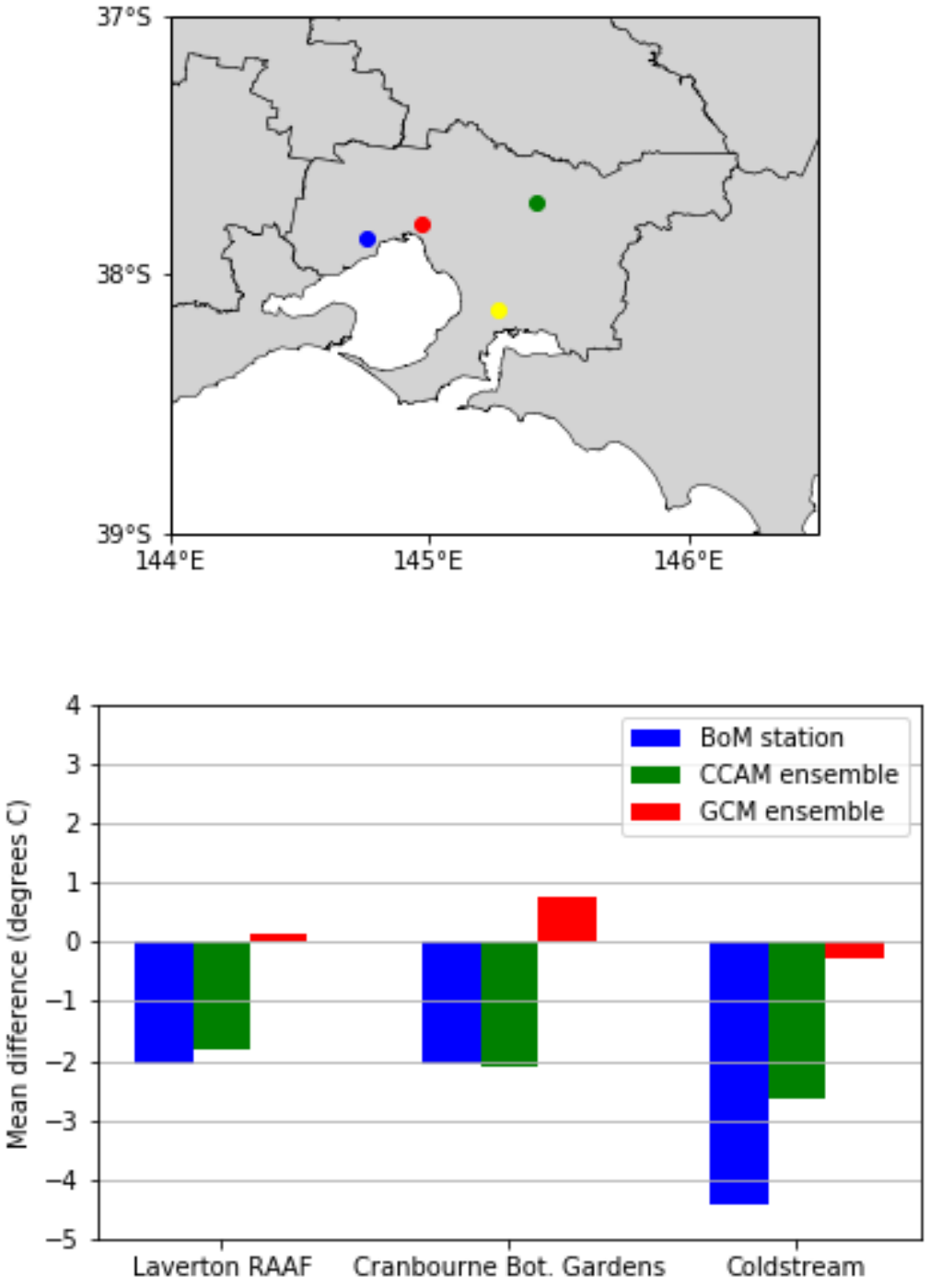


Figure A6.4: Comparison of the Urban Heat Island (UHI) measured as the difference in average daily minimum temperature over 1986-2005 between an inner-city weather station (BoM Melbourne Regional Office – Red dot) and three outer-city weather stations (Laverton RAAF – Blue dot, Coldstream - Green dot and Cranbourne Botanic Gardens – Yellow dot). Location of the weather stations are shown in the top plot and the observed and simulated difference in temperatures between the inner-city site and the three outer city sites is shown in the bottom plot.

A6.3.2. Rainfall

A comparison of the average rainfall simulated for different seasons from 1986-2005 by CCAM with AWAP observations and the host GCMs can be seen in Figure A6.5. The CCAM 5 km resolution simulations can be seen to better represent the average rainfall over the Victorian Alps than the GCMs where the mountains are poorly resolved. CCAM also represents increased rainfall along the southern coastline that was not represented by the GCM simulations. The simulated average rainfall from the CCAM 5 km resolution simulations is higher than what is measured for the AWAP simulations. However, the AWAP simulations can also underestimate the rainfall in mountain regions due to a sparser network of observing stations. The larger scale features in the CCAM simulated rainfall resemble some of the larger scale features in the GCM simulations (e.g., a slightly higher average rainfall in the north west of Victoria in summer and autumn), which reflects some similarities in how rainfall is parametrised in global and regional dynamical climate models. Nevertheless, it is expected that downscaling should improve the distribution of simulated average rainfall which is demonstrated in the CCAM 5 km simulations.

Another aspect where downscaling should improve the simulated climate is extreme rainfall. A comparison of the 99th percentile of daily rainfall between 1986-2005 for AWAP, CCAM and the GCMS is shown in Figure 6. We used the 99th percentile of daily rainfall over the 1986-2005 period as an indicator of CCAM's ability to represent extreme rainfall. The extreme rainfall is overestimated by CCAM when compared to AWAP observations, although CCAM significantly improves on the extreme rainfall from the GCMs which do not represent the high rainfall for the Alpine regions at all. As for average daily rainfall, the AWAP observations may underestimate the size of the extreme rainfall for mountain regions due to a sparser observing network, which is also suggested by comparing the results to BARRA (not shown). Nevertheless, CCAM is able to represent extreme rainfall that could not be captured in the GCM simulations.

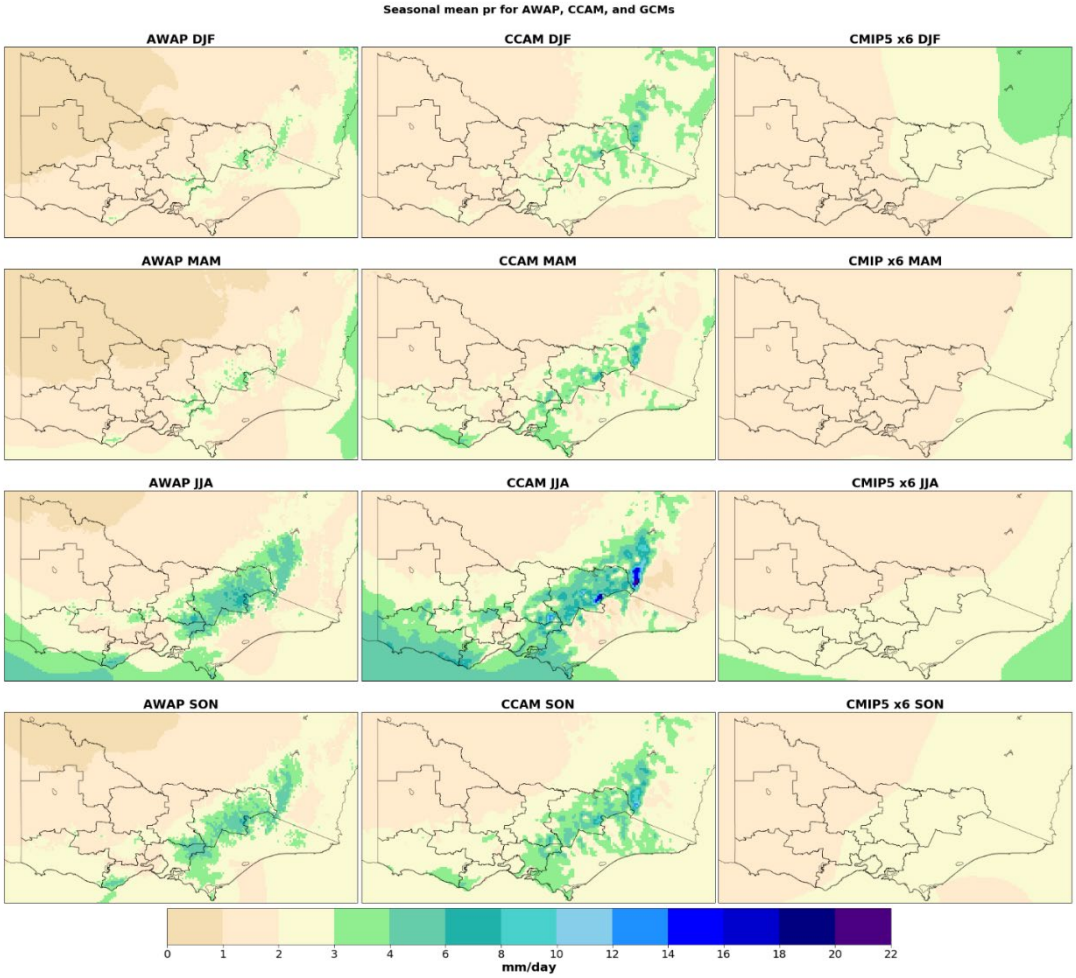


Figure A6.5: Comparison of daily average rainfall from 1986-2005 between AWAP observations (left column), the average of six CCAM 5km simulations (middle column) and the average of the six host GCMS (right column). The rows indicate different seasons with top to bottom showing December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON), respectively.

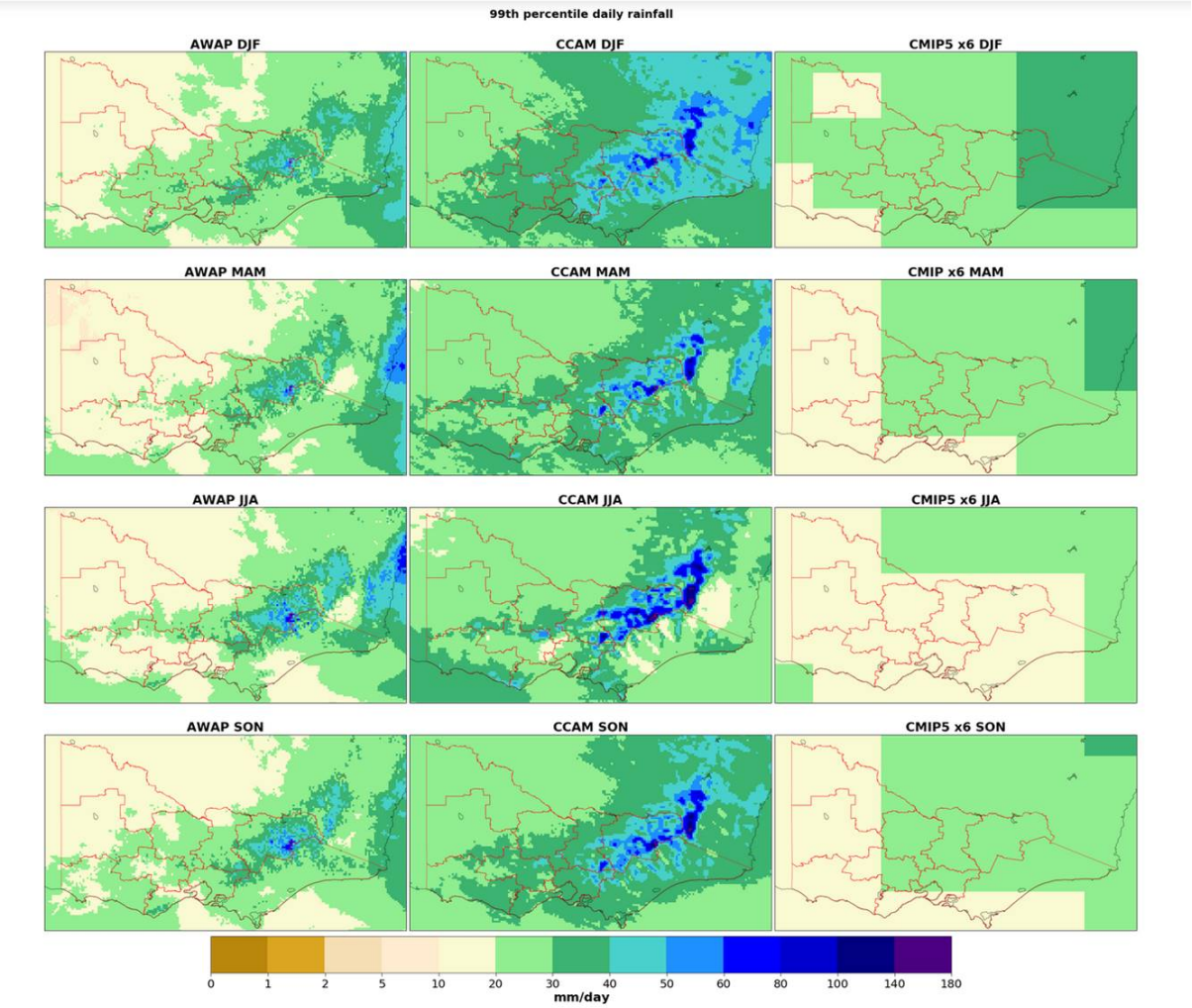


Figure A6.6: Comparison of the 99th percentile of daily rainfall between 1986 and 2005 from AWAP observations (left column), the average of six CCAM simulations (middle column) and the average of six GCMs (right column). The rows indicate different seasons with December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON).

A6.3.3. Mean Sea Level Pressure and 850 hPa winds

Although the use of CCAM simulations is primarily for downscaling the regional climate, it is also important to consider the large-scale behaviour of the CCAM atmospheric simulation. This large-scale behaviour can influence the projections of the climate model simulations and is useful for interpreting the projections of CCAM in the context of the ensemble of CMIP5 GCM projections. As discussed when describing CCAM, the use of bias corrected SSTs can allow CCAM to differ from the host GCM in some respects.

Figure A6.7 compares the simulated Mean Sea Level Pressure (MSLP) averaged between 1986-2005 from the six CCAM 50 km global simulations with respect to ERA-Interim reanalyses and to the average of the six host GCMs. When compared to ERA-Interim, the CCAM 50 km simulations are somewhat too zonal in the MSLP compared to the host GCMs, most noticeable in autumn and winter. This can lead to winds being somewhat too zonal, as indicated with the 850 hPa winds shown in Figure 8. Figure A6.8 compares the average 850 hPa wind speed and direction for different seasons over 1986-2005 between the ERA-Interim reanalyses, the average of the six CCAM 50 km global simulations and the average of the six host GCMs. The 850 hPa winds represent the winds at approximately 1 to 1.5 km above the surface, where ERA-Interim is less influenced by smaller scale mountains. Although the CCAM simulations are a reasonably good representation of the 850 hPa winds, the wind speed is too strong and the wind direction is too zonal in autumn and winter. This result is consistent with the too zonal MSLP results for those seasons. The CCAM simulation

results are still a reasonable representation of the global climate and the projected future changes in climate are physically reasonable. Nevertheless, we can expect some differences in the larger scale changes projected by the CCAM simulations compared to the host GCMs.

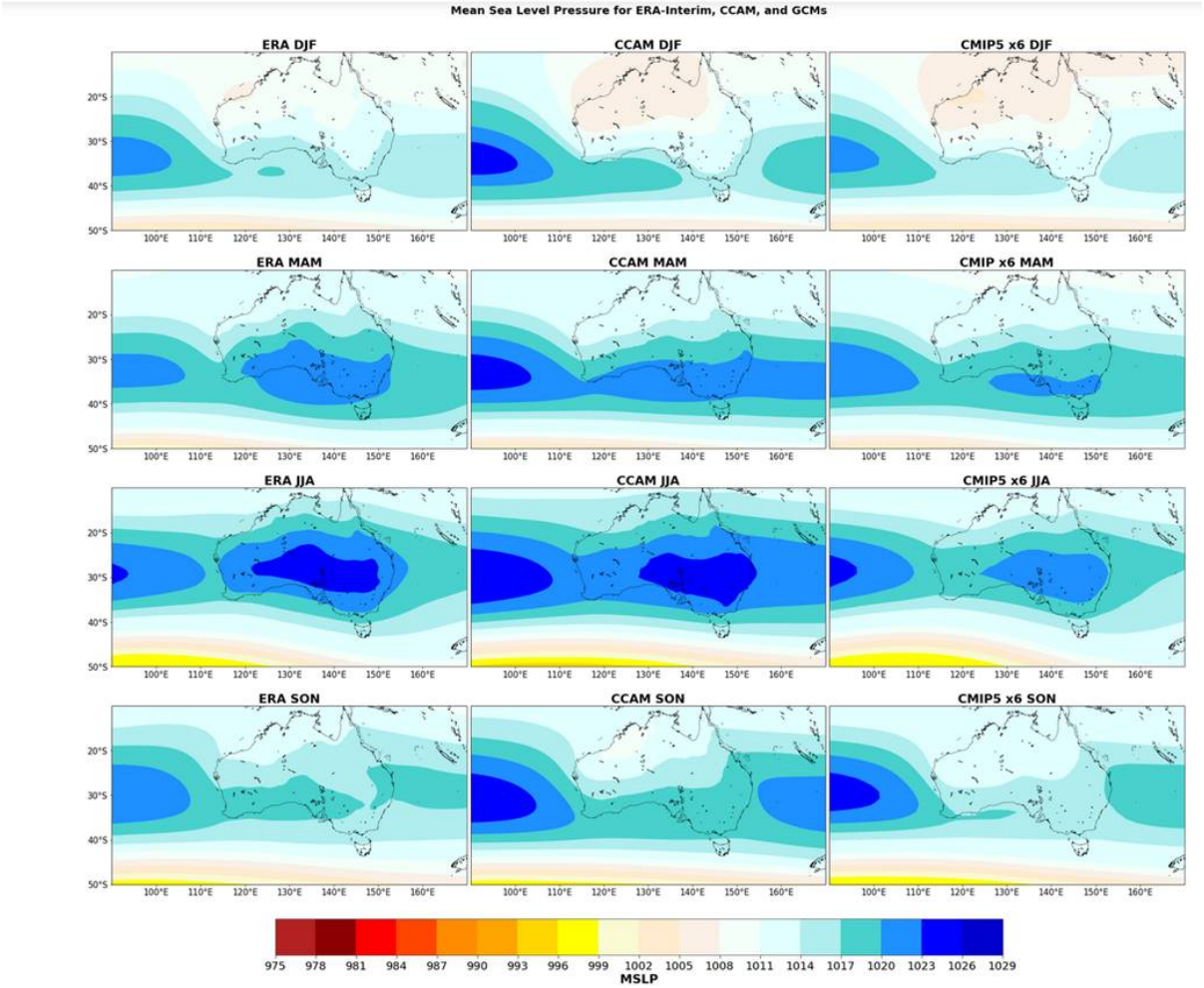


Figure A6.7: Comparison of Mean Sea Level Pressure averaged over 1986-2005 between ERA-Interim reanalyses (left column), the average of the six CCAM 50 km global simulations (middle column) and the average of the six host GCMs (right column). The rows indicate different seasons with December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON).

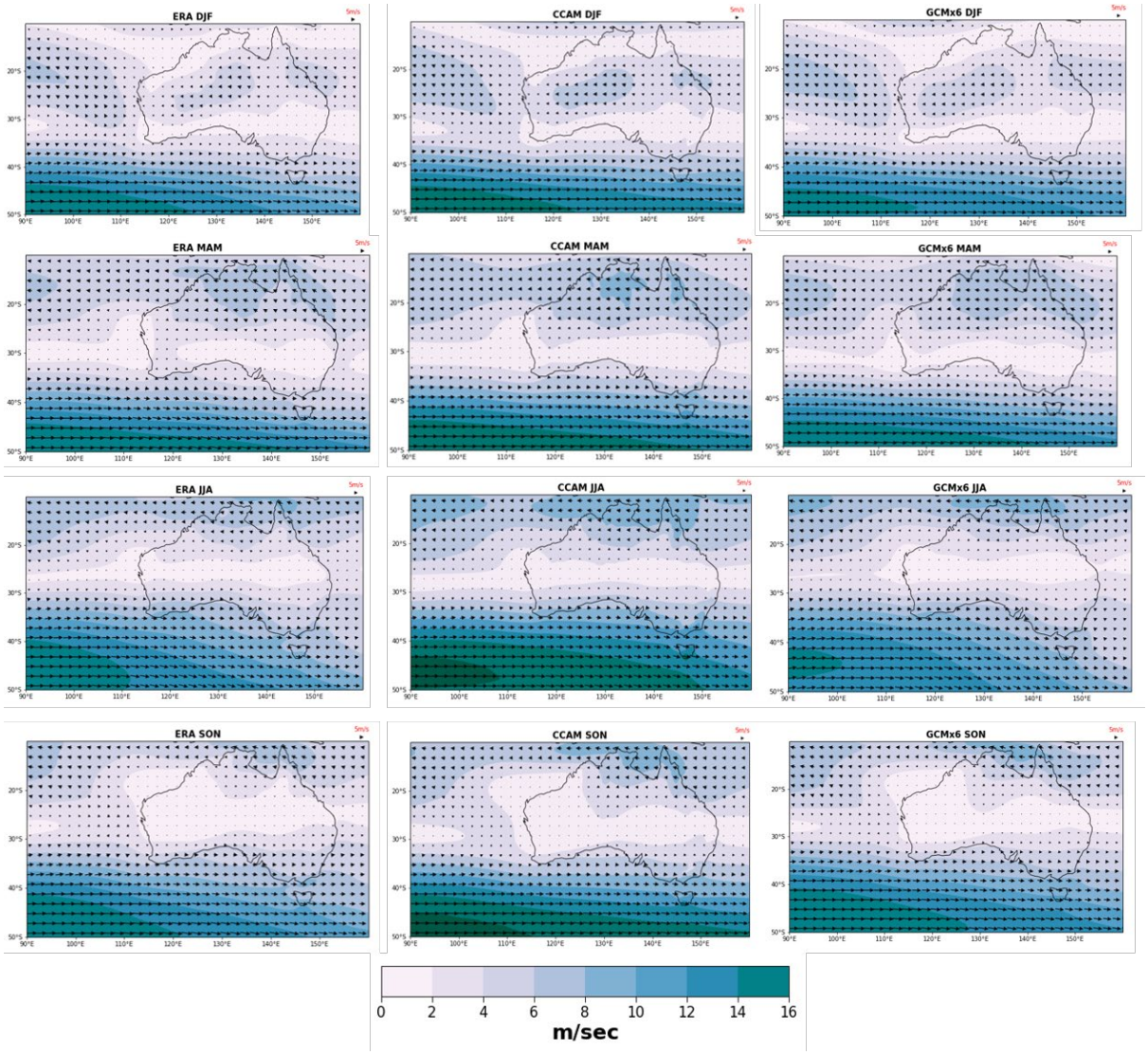


Figure A6.8: Comparison of average wind speed and direction at 850 hPa (approximately 1 to 1.5 km above the surface) between 1986-2005. The ERA-Interim reanalyses are shown on the left column, the average of the six CCAM 50 km simulations in the middle column and the average of the six GCMs on the right column. The rows indicate different seasons for December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON).

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Appendix 7: Copies of published papers arising from the project

The manuscripts are still within copyright period so cannot be attached. All are available from the authors on request.

Appendix 8: Budget reconciliation

Budget statement has been submitted online via AGWA's Clarity Investment Management System.