# Assessment of vulnerability to climate change across Australia's wine regions

## FINAL REPORT to

GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

Project Number: **SAR 1002**

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## Contents

## 1. Abstract

The Australian wine industry is exposed and sensitive to a range of weather and climate risks. At the same time there is significant adaptive capacity within the industry. Both the climate risks and the adaptation options differ from region to region and within a region between blocks of vineyards.

Regional workshops were held in Barossa, McLaren Vale, Mornington Peninsula, Yarra Valley, Tasmania, Clare and Limestone Coast. At each workshop climate change projections were presented and a crop calendar was used to identify and prioritise key climate and weather risks. Seven key climate and weather risks were identified. The confidence from climate science of these risks changing, the impact on grapevines from each risk, and management strategies for addressing these risks are discussed. A desktop analysis of climate using regional climate information from 21 sites covering 17 regions provided information on the extent of the risks in the historic climate and how they may change based on two climate models.

## 2. Executive summary

The threat of climate change to the Australian wine industry is likely to come from changes in mean temperature, changes in extreme temperature events and the reduction in quality and quantity of water. Australian wine regions are distinguished by their climate (cool regions, warm regions, hot inland regions). Individual vintages are characterised by the climate. It stands to reason that changes in climate will first influence individual vintages and then overall styles of wine and finally threaten the suitability of a region for grape growing.

A series of regional workshops was held to better understand the potential impacts and to assist viticulturists to prepare for a projected warmer and very possibly drier future.

The regional workshops started with Leanne Webb (CSIRO/University of Melbourne) presenting the science of climate change and regional projections. We then used a grape phenology calendar to identify the risks to viticulture from climate and weather for their region. The confidence from climate science of these risks changing, the impact on grapevines from each risk, and management strategies for addressing these risks were presented.

The process for interpreting a region's vulnerability to climate change included using the region's historic climate to identify the vulnerability that the region had experienced to the risks, and to highlight the variability in recent climate that had been experienced by the region. Recently experienced climate in the region was related to what had been experienced during the World Meteorological Organization's current climate normal period from 1961 to 1990 to highlight the nature of a continually changing climate, while future climate scenarios for the region were produced using a range of models. In both cases the impact on key climate descriptors that are related to the risks were examined. For example Growing Season Temperature (GST) or Growing Degree Days (GDD) are frequently used to determine a variety's suitability to a region or to provide information of a season's ranking (such as cool or warm vintages), while the number of days warmer than a particular threshold of say 35°C can be used to gauge the risk of extreme heat days or heat wave events.

The mean Growing Season Temperature for a climate in 2030 could be 0.5 to 1.3°C warmer depending on the region. These warmer climates would also increase GDD by between 103 to 268 °Cdays depending on the region. These increases are likely to affect phenological development, and the suitability of a variety to the region.

Indicative of warming is the fact that 15 of the 21 locations have experienced 10 or more vintages out of the last 14 vintages since 2000 that have been warmer than average, and in only one location have there been more cooler than average vintages than warmer than average vintages. During this same 14 year period eight locations have experienced three or more vintages warmer than any during the 30 year base period, while only six locations have not experienced a vintage as warm as any during the base period. A projected future climate that is 1°C warmer, which is accepted as very likely for most regions, decreases the chance of what we currently think of as below average GST (the average to cool vintages) to be almost non-existent; and at the same time increasing the above average GST (the average to hot vintages) to what is currently warmer that any vintage during the 30 year period from 1961 to 1990. Larger temperature rises exacerbate these trends. In a practical sense this means there is a higher chance that many future vintages will be as warm as the warm vintages since 2000.

The chance of warmer days in all regions will be higher in future warmer climate but that the actual number of days warmer than critical thresholds will remain lower in cooler regions than in already warm regions. It would also be expected that the chance of a number of consecutive days and/or nights warmer than critical thresholds would be higher in these already warm regions than in the cooler regions. The consequences of these hot days for vines and grape quality will be related to the phenological development stage of the plant. Variety, rootstock and canopy manipulation are likely sources of adaptation options.

The lower confidence surrounding changes in rainfall mean there are larger differences between models for projected rainfall than for temperature. Annual rainfall is projected to decline in 2030 by about a 5% decline in most regions according to a medium impact model, and by a similar amount in Tasmania according to a high impact model. Larger declines in annual rainfall of between 15 and 20% are projected for regions in south eastern mainland Australia. These changes have real and imminent consequences for water supply, both of local water sources (rain fed and stored water) and of externally sourced irrigation water. Summer rainfall is not projected to change thus the risk of more rain leading to increased bunch disease is not expected to change.

The differences in climate within and between regions and seasons highlight the opportunity to explore potential adaptation options to a changing climate. However these climatic differences along with the changes projected in a future climate first need to be identified and explained. All regions are vulnerable in one or more ways to climate change. This research highlights the altered chances of occurrence of some key climate and weather events in a future climate, and suggests some potential management options to reduce the industries exposure to climate risk. It is likely that changes in management to adapt to a future climate that is both warmer and very possibly drier will not always be easy.

Dr Leanne Webb (University of Melbourne/CSIRO) presenting at workshop at Paringa Estate, Mornington Peninsula. 2 September 2011

## 3. Background

The notion of climate change and Australian viticulture is not new. Some researchers have discussed the topic more than 3 decades ago[1]. However the widespread discussion within the industry is relatively recent. This is probably due to three major factors

1. The widespread interest in climate change from the applied research community, the general public and the media which increased through the middle of the last decade possibly peaking around 2005 to 2009
2. The coincidence of a series of heatwaves and the prolonged millennial drought
3. The R&D on climate impacts and climate change from many groups but notable for the early impact was the Melbourne University/CSIRO group (Webb, Barlow and Whetton).

This project was instigated by a request from GWRDC for SARDI climate applications to build on an information kit on climate change at a regional level (GWRDC SAW 06/01). The information kit (Hayman, Leske and Nidumolu) was developed as a partnership between the South Australian Wine Industry Association and SARDI.

The current project built on GWRDC SAW 06/01 and was applied to 17 regions. One of the more significant changes was the use of a crop calendar as a means of identifying and prioritising weather and climate risks in the current climate. Following discussion with Elise Hayes and Michael McCarthy the focus was switched to vulnerability at the level of the vineyard block. This recognised that within a region or even a vineyard it was possible that one variety on a given soil type was quite resilient to a warmer and drier future while an adjacent block was quite vulnerable. Because this project was funded in part by DAFF Australia's Farming Future project we were encouraged to use climate change projection data from the Queensland Centre for Climate Change Excellence. The two models (ECHAM developed in Germany and GDFL developed in USA) utilised in detail in this project were identified by CSIRO as representative of a moderate and high impact on rainfall and temperature in Australia.

Another change from the previous project is that the workshops had a greater emphasis on adaptation. This recognises a general switch in questions from many in the wine grape industry from "What is climate change?" to "What will the impacts be on my enterprise?" to the most important question "What can I do to adapt?".

The phase of impact study and damage reports to adaptation options. For some regions the outcomes of climate change could be positive (e.g. better ripening conditions and less disease) while other regions may be more vulnerable to the impacts of climate change requiring a significant adaptation measures depending on the projected temperature increase, future water resources, vulnerability of varieties, soil types or other factors.

## 4. Project Aims and Performance targets

[1] Dry, P. R. (1988) Climate change and the Australian grape and wine industry. Australian grape grower and wine maker. 300: 14-15. Smart, R.E. (1989) Climate change and the New Zealand wine industry - prospects for the third millennium. Australian and New Zealand Wine Industry Journal, 4: 8-11.

A high level goal for Australia's Farming Future program run by DAFF is to work with primary producers to understand the likely impacts of climate change for their enterprise and region.

The project was designed to address the objectives in the GWRDC 5 Year Plan *"define the opportunities and adapt to the challenges of climate change"* . The project also addresses the key strategy linked to this objective which is to collaborate with other parties to determine and disseminate the effects of climate change on the wine industry.

The original outputs and target activities were as follows:

| Output | Target | Activities |
|---|---|---|
| 1. Conduct case studies for 4 diverse regions | 12/10 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |
| 1. Conduct case studies for 3 additional regions | 03/11 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |
| 1. Conduct case studies for 3 additional regions | 06/11 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |
| 1. Conduct case studies for 6 additional regions | 12/11 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |
| 1. Conduct case studies for 3 additional regions | 03/12 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |
| 1. Conduct case studies for up to 1 additional region | 05/12 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |

Agreed changes on 20 December 2012

| Output | Target | Activities |
|---|---|---|
| 1.Prepare towards workshops and case study regions | 06/11 | Preparation for climate vulnerability workshops across wine regions with workshop trialled in 1 region |
| 2.Conduct case studies for 12 diverse regions | 06/12 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |
| 3.Conduct case studies for 8 diverse regions | 12/12 | Contact and engage with regions. Source and collect data, conduct workshop in each region to pull information together and gain local insight. Develop booklet for each region using toolkit approach. |

# 5. Method

The steps involved in the project included workshops in several major viticultural regions in southern Australia where the risks of weather and climate on viticulture were identified. These are summarised below. An analysis of climate using data from nearby meteorological stations was presented. This analysis included details of weather and climate that posed a risk to production and linked climate and weather to phenological development using a grape phenology calendar.

Seven of the most important climate change factors for viticulture were identified. For each change the confidence from climate science, the impacts on viticulture and the main management options are presented.

A desktop analysis of climate variability was performed for several grape growing regions. Historic data used in this analysis was sourced from SILO as patched point data (http://www.nrw.qld.gov.au/silo/). This desktop analysis included climate change projections for 2030 and 2050 using two of the Generalised Circulation used as part of DAFF Australia's Farming Future project on dryland cropping in southern Australia. Additional climate change projections for the locations of interest were sourced from Ozclim (http://www.csiro.au/ozclim/home.do).

The analysis also showed how different the projections for temperature and rainfall 2030 and 2050 are from the current climate. A number of climate descriptors were presented including Growing Season Temperature (GST), Mean January Temperature (MJT) and growing degree days (base 10) as in viticulture there has been a useful tradition of using these to characterise the climate of a region and to compare regions. Additionally because a future climate will almost certainly be a warmer climate and the impact of high temperatures on grape production we presented information on the number of days warmer than threshold temperatures of 30, 35 and 40°C. (25, 30 and 35°C for Tasmania as the chance of temperatures above 40°C is very low in the Tasmanian localities even with several degrees warming). The projected impact on rainfall was also presented.

These data for vintages since 2000 were presented in detail as this provides a useful link for viticulturists and winemakers to relate experiences during these vintages to measured weather and climate information. Additionally the variability in recent climate can be appreciated.

Because Growing Season Temperature is a widely recognised measure of a sum of the daily weather events during a vintage, we discuss the historic variability in GST including details of the decile value for each vintage's GST. In a stable climate each vintage has equal chance of the GST being in each decile. That is, there is equal chance of cool vintages as there is of warm vintages. We conducted a desktop analysis to show how in a future warmer climate the chance that a vintage's GST will become biased towards warmer vintages, and in many cases GST may become warmer than any experienced.

**24 February 2011 Tasmania:** (Covering 3 districts/regions Tamar Valley, Coal Valley and Eastern Tasmania). Organised with David Sanderson, Wine Industry Tasmania. Presentations by Leanne Webb (Melb Uni and CSIRO), Peter Hayman and involvement from wine grape growers, Tasmanian government on irrigation planning, Greg Holz lead author of Impacts on Agriculture for Climate Futures for Tasmania (Antarctic climate and ecosystems CRC), Caroline Mohammed (Theme leader Climate Adaptation Tasmanian Institute of Agricultural Research TIAR)and Dugald Close, Centre Leader, Perennial Horticulture TIAR. (12 attendees)

**25 August 2011 Limestone Coast** (Covering 4 regions Coonawarra; Robe/Mt Benson; Padthaway and Bordertown). Organised with Dan Newson, Ben Harris and Sue Bell, (Limestone Coast Tech Committee). Presentations by Mardi Longbottom (regional climate, soils, varieties and geology) Hans Loder, Katnook estate (frost protection), Saad Mohamad Hydro-geologist for Dept for Water based at Mt Gambier, Leanne Webb on climate change projections and discussion on vulnerability and climate risks by Peter Hayman. Meeting finished with panel convened by Sue Bell (Bellwether wines). Panel members included all speakers plus Mike Wetherall (Wetherall Vineyards) and Paul Petrie (Treasury Wine Estates)(40 attendees).

**1 September 2011 McLaren Vale** Organised with Jodie Pain McLaren Vale Grape Wine & Tourism Association. Discussion led by Peter Hayman (SARDI) and Leanne Webb (UoM and CSIRO). Local information from Jodie Pain and James Hook. (28 attendees)

**2 September 2011 Mornington Peninsula** Organised with Mornington Peninsula Vignerons Association. Discussion led by Peter Hayman (SARDI) and Leanne Webb (UoM and CSIRO) with local input from Tyson Lewis leader of Mornington Peninsula Vignerons and executive officer, Cheryl Lee. 10 attendees.

**13 September 2011 Yarra Valley**. Steve Crimp climate applications scientist (CSIRO) has a GWRDC funded project on frost in viticulture. At the workshop Steve Crimp used a copy of the spreadsheet and crop calendar developed in this project to assess and rank the weather and climate risks with viticulturists and grape growers. 15 attendees.

**31 May 2011** In addition Peter Hayman contributed to the viticulture component of a workshop at Clare Country Club and a report on climate change vulnerability assessment for Clare and Southern Flinders Ranges where material from this project was used to assess vulnerability and adaptation options. This sub group was attended by 8 viticulturists, including Northern and York NRM employee who was previously a managing viticulturist for Treasury Wine Estate.

**Table 1.** Meteorological stations used in analysis

| Region | Station Name | Station Number |
|---|---|---|
| Barossa | Nuriootpa comparison | 23321 |
| Clare Valley | Clare Post Office | 21014 |
| Langhorne Creek | Strathalbyn | 23747 |
| Limestone Coast - Coonawarra | Coonawarra | 26091 |
| Limestone Coast - Mt Gambier | Mount Gambier | 26021 |
| Limestone Coast - Padthaway | Padthaway | 26089 |
| Limestone Coast - Robe | Robe | 26026 |
| Limestone Coast - Wrattonbully | Naracoorte | 26023 |
| McLaren Vale | Old Noarlunga | 23740 |
| Mornington Peninsula | Mornington | 86079 |
| Riverina - Griffith | Griffith Airport AWS | 75041 |
| Riverina - Wagga Wagga | Wagga Wagga AMO | 72150 |
| Riverland - Loxton | Loxton Research Centre | 24024 |
| Riverland - Renmark | Renmark | 24016 |
| Riverland - Waikerie | Waikerie | 24018 |
| Tasmania - Coal River | Cambridge aerodrome | 94007 |
| Tasmania - East Coast (B) | Bicheno | 92003 |
| Tasmania -East Coast (S) | Swansea Post Office | 92038 |
| Tasmania - North West | Beaconsfield | 91001 |
| Tasmania - Tamar | Launceston | 91049 |
| Yarra Valley | Tarrawarra Monastery | 86364 |

## 6. Results/Discussion

The grape calendar that incorporates weather and climate with phenological development is shown below. The calendar can be modified for specific regions or varieties, although this is not essential when utilizing it for appreciating the relationship between the risks of weather and climate events with crop development and management options.

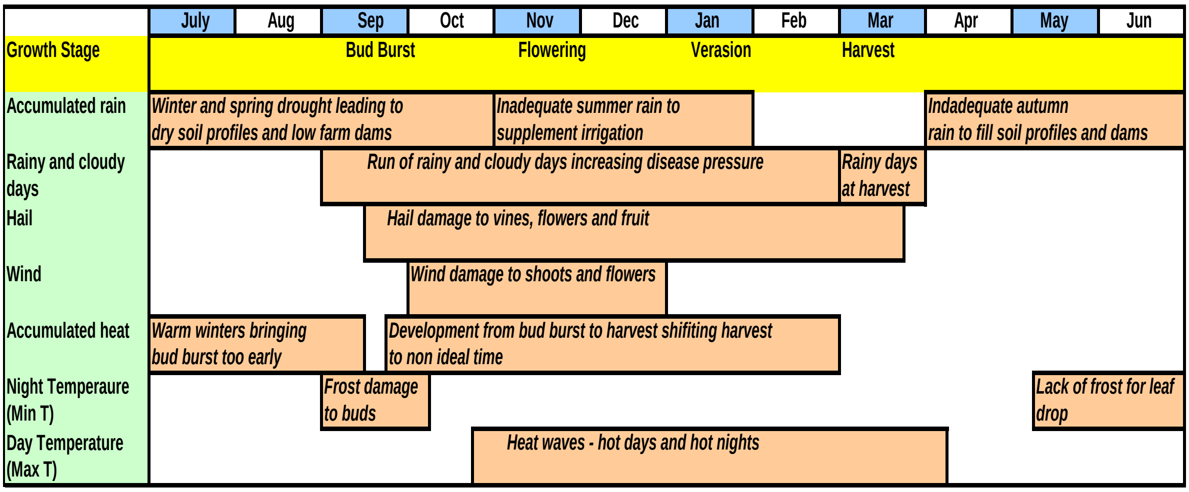



***Figure 1.*** *An example of a crop calendar*

In this project the crop calendar was utilized to explore the potential impact(s) of projected climate change in a warmer drier future. Seven main changes of a future warmer drier climate were identified and their impact on viticulture was examined. These seven changes were:

1. Warmer spring and summer mean temperatures shifting development;
2. Heat waves and extreme high temperature;
3. Frosts and extreme low temperatures;
4. Drought; less autumn, winter and spring rainfall;
5. Irrigation water restricted or of lower quality;
6. Summer rainfall increases;
7. Increased atmospheric carbon dioxide ($CO_2$).

For each change in the following table we have summarised the confidence from climate science, the impacts on viticulture and the main management options.

**Table 2**. The seven main changes of a future warmer drier climate and their impact on viticulture.

**1. Warmer spring and summer mean temperatures shifting development**

| Confidence from climate science | Impact on grapevines | Management strategies |
|---|---|---|
| The high confidence from climate science on general warming means that we should expect more warm vintages than cool vintages.<br><br>There is lower confidence in the seasonal pattern of warming. Although nights have warmed more than days, it is not clear that this will be a strong trend in the future. | A major impact of warmer conditions is to hasten development which, in most cases, will shift ripening to warmer periods.<br><br>There is concern that quicker development leads to de-coupling of sugar and flavour ripening.<br><br>Comments from regional workshops with viticulturists and wine makers suggested that the changes in phenology are more pronounced in the cooler zones than the warmer zones and that this contributed to logistical problems at harvest. | If crop development is determined by temperature alone, it follows that the industry will have to either manage earlier vintages and in many cases, compressed vintages or change to longer season varieties. However, if crop development is determined by the interaction of temperature and management then there may be adaptation opportunities such as managing crop load and pruning.<br><br>Continual monitoring of pests and diseases. Some simple models exist and could be run under climate change projections (eg powdery mildew, Light Brown Apple Moth). |

**2. Heat waves and extreme high temperature**

| Confidence from climate science | Impact on grapevines | Management strategies |
|---|---|---|
| High confidence of general increase in frequency and intensity of heatwaves in summer.<br><br>Lower confidence in the timing of individual synoptic events such as heat waves. | The damage of heatwaves is very dependent on the timing of the heatwave relative to the phenological stage of grapevines. For example, in the Barossa GI, a recent November heatwave had an impact on flowering of Grenache whereas a March heatwave was particularly severe on later red varieties. Similar relationships between timing of heatwaves with respect to the phenological stage of the vines and the subsequent impacts on production would be expected in the other regions. | Canopy management.<br><br>Adequate and timely weather forecasts on chance of heat waves.<br><br>Irrigation regime prior to and after hot days.<br><br>Further sources of information are the Heatwave fact sheet available at the GWRDC website.<br><br>Regional workshops on climate change concerns have raised concerns regarding policies of water remaining unused, if a "use it or lose it" policy is adopted. This could disadvantage efficient managers who were keeping some allocation as insurance for management of heatwave events. |

### 3. Frosts and extreme low temperatures

| Confidence from climate science | Impact on grapevines | Management strategies |
|---|---|---|
| Although warming at night will reduce risk of frost, increased drying may counter this trend.<br><br>Lower confidence in the timing of individual synoptic events such as frosts. | Even if frequency of frost stays the same or decreases, changes in phenology may increase frost risk due to earlier budburst. | Viticulture in frost prone areas has developed sound management practices incorporating:<br><br>Variety choice (later budburst and flowering)<br><br>Management of soil moisture, cover crops and mulch<br><br>Wind breaks, sprinklers and wind turbines. |

### 4. Drought; less autumn, winter and spring rainfall

| Confidence from climate science | Impact on grapevines | Management strategies |
|---|---|---|
| Low to medium confidence in rainfall projections. Generally anticipating drier winters and springs. There is lower confidence in projections for summer.<br><br>Medium to high confidence in an increase in evaporative demand with rising temperatures. Approximately 2 to 3% increase in (ETo) for each 1°C rise in temperature (Lockwood 1999). | There is a large body of scientific work on the impact and management of water stress on viticulture in Australia and much of this is summarised on the GWRDC website for its Soil and Water Initiative.<br><br>Changes in rainfall will alter pests and diseases. | On-site water supply<br><br>Ground works to direct surface water run-off or increase water infiltration<br><br>Varietal and rootstock selection<br><br>Mulching to minimise evaporation<br><br>Management of inter-row cover crop |

### 5. Irrigation water restricted or of lower quality

| Confidence from climate science | Impact on grapevines | Management strategies |
|---|---|---|
| The lower confidence in rainfall projections makes it difficult to be too specific about irrigation. However the projections for flows in the Murray Darling Basin (MDB). (CSIRO Sustainable Yield Project) indicates that runoff is very sensitive to declines in rainfall. A rule of thumb that applies to most inland areas of Australia is that a 10% decline in rainfall may result in a 20 to 30% decline in runoff (Chiew et al 2006). | Quality wine grapes require continuity of supply of high quality water. There is potential for the use of wastewater from towns and wineries, however care is needed if there is insufficient rainfall to leach salts from the profile. | Monitoring the water in the profile across the vineyard to improve understanding of how to manage different soils in various parts of the vineyard.<br><br>Reduce leaks and evaporative losses from dams through design and covers.<br><br>Better use of rainfall during the season through irrigation scheduling and use of weather forecasts to make the most of the rain that falls. Better use of irrigation water through continual improvement to irrigation scheduling and mulching etc.<br><br>Water trade is possible, however volumes transferred are relatively small and there are some restrictions on where water can be transferred.<br><br>Capture and storage of local stormwater, or in-site waste water. |

### 6. Summer rainfall increases

| Confidence from climate science | Impact on grapevines | Management strategies |
|---|---|---|
| Low to medium confidence in rainfall projections.<br><br>Lower confidence in projections for summer. | Altered pests and diseases profile.<br><br>Reduced berry quality. | There are many regions that deal regularly with wet summers so there are opportunities to learn.<br><br>Aspects of the very wet summer of 2010/11 were explained by La Nina and hence it is worthwhile to follow the seasonal forecast for spring and summer. |

7. **Increased atmospheric carbon dioxide ($CO_2$)**

| Confidence from climate science | Impact on grapevines | Management strategies |
|---|---|---|
| Very high confidence. | Uncertainty on many indirect effects and interactions with other stresses.<br><br>A higher concentration of $CO_2$ will have an impact on canopy growth and the transpiration efficiency so hence will change the water balance. We would also expect interaction with heat and frost stress.<br><br>A higher concentration of $CO_2$ may influence ripening processes and both lifecycle of pests and pest damage to grapevines. | Canopy management (e.g. pruning, irrigation regime) to control vine vigour.<br><br>Crop coefficient may need to be revised, leading to altered irrigation regimes.<br><br>Vigilance in pest and disease management. |

**Climate risk – continental perspective and wine regions**

There are many General Circulation Models (GCM) currently available and not surprisingly projections differ between the models. However, it is worth noting even if in a very cursory manner the range in projected changes to climate that is shown by these models. This is worthwhile as no model is perfect, and there is likely to be more confidence in a prediction if many models are indicating a similar result. An analysis of many models can be found in the report *Climate Change in Australia (CSIRO and Bureau of Meteorology 2007)* Available at http://www.climatechangeinaustralia.gov.au

This report indicates that for the grape growing regions in southern Australia, by 2070 there is a very high chance of temperatures increasing by 1°C under all emission scenarios; about a 50:50 chance of a 2°C increase under a medium emission scenario but a high chance under a high emission scenario; and less than 20% chance of a 3°C increase in temperature under a medium emission scenario but about a 50:50 chance under a high emission scenario. Tasmania, compared to mainland Australia, is somewhat protected from the more severe impacts of warming with a high to very high chance of temperatures increasing by 1°C under moderate and high emission scenarios, but about a 50:50 chance of a 2°C increase under a high emission scenario and low chance under a medium emission scenario. Most commentators suggest that the low emission scenario (B1) is increasingly unlikely as emissions are tracking on or above the high emission (A1FI) scenario.

Rainfall changes in southern mainland Australian grape growing regions indicate there is a very high chance of drier conditions expected under all emission scenarios; and about a 50:50 chance of more than 10% drying and conversely about a 50:50 chance of less than 10% drying. In Tasmania there a lower chance of more than 10% drying with most models suggesting between 0 and 10% decrease in rainfall. For southern Australia, including Tasmania, there is less than 10% chance of an increase in annual rainfall under any emission scenario.

The two models (ECHAM developed in Germany and GDFL developed in USA) utilised in detail in this project are recommended by CSIRO as representative of a moderate and high impact on rainfall and temperature in Australia. Importantly the projections by these two models should be read as two possible climate futures that can be used to compare adaptation plans; they should not be read as predictions of the most likely future. The winter and spring rainfall decline of about 10 to 20% by 2030 and about 20 to 40% by 2050 projected for most regions by the high impact model (GFDL) is a more severe drying than most other models. Nevertheless most models show some drying over winter and spring.

The spatial pattern of the warming and drying from the two models for 2030 indicate less warming along the southern coast than inland. The high warming scenario projects mean temperature increasing by less than1°C near coastal southern Australia and between 1 and 2°C once beyond the coastal fringe. Rainfall projections across the continent show more variable changes. Much of the grape producing regions in SA and Victoria are projected to have a smaller reduction in annual rainfall of less than 50 mm in a moderate warming and drying scenario and between 100 mm to 150 mm in a high warming and drying scenario. The rainfall declines have a seasonal pattern with projections of about 10 to 20% reduction in rainfall over winter and spring for most regions. The narrow range of projections in temperature contrasts to the wide spread for rainfall and this difference highlights the high confidence in warming and lower confidence in the changes to rainfall.

### Climate risk for specific wine regions – Growing Season Temperature and Growing degree days

Projected changes in GST and Growing degree days are less for the moderate impact projection than the high impact projection (Table 3). Increases in mean temperature of 0.5 to 1.3°C are projected depending on the model and the region. Because of the close relationship between GST and GDD, increases in GDD of between 103 to 268 °Cdays are projected. These increases are likely to affect phenological development.

**Table 3.** Historic and projected Growing Season Temperature (°C) and Growing Degree Days (°C days) by a medium warming and a high warming model for 2030.

| Region | GST (°C) | | | GDD (°C days) | | |
|---|---|---|---|---|---|---|
| | Historic | 2030 Medium | 2030 High | Historic | 2030 Medium | 2030 High |
| Barossa | 18.3 | 19.0 | 19.2 | 1756 | 1905 | 1958 |
| Clare Valley | 18.5 | 19.2 | 19.5 | 1798 | 1961 | 2019 |
| Langhorne Creek | 18.3 | 18.9 | 19.2 | 1765 | 1892 | 1947 |
| Limestone Coast - Coonawarra | 16.8 | 17.3 | 17.5 | 1439 | 1558 | 1591 |
| Limestone Coast - Mt Gambier | 16.0 | 16.5 | 16.7 | 1289 | 1392 | 1427 |
| Limestone Coast - Padthaway | 17.6 | 18.2 | 18.4 | 1616 | 1741 | 1782 |
| Limestone Coast - Robe | 16.6 | 17.1 | 17.3 | 1399 | 1505 | 1542 |
| Limestone Coast - Wrattonbully | 17.4 | 17.9 | 18.1 | 1568 | 1688 | 1727 |
| McLaren Vale | 18.7 | 19.2 | 19.5 | 1843 | 1963 | 2020 |
| Mornington Peninsula | 17.0 | 17.8 | 17.9 | 1483 | 1648 | 1670 |
| Riverina - Griffith | 21.0 | 22.3 | 22.3 | 2335 | 2603 | 2618 |
| Riverina - Wagga Wagga | 19.8 | 21.0 | 21.1 | 2087 | 2337 | 2346 |
| Riverland - Loxton | 20.0 | 20.8 | 21.1 | 2128 | 2298 | 2356 |
| Riverland - Renmark | 21.2 | 22.1 | 22.3 | 2387 | 2564 | 2620 |
| Riverland - Waikerie | 20.5 | 21.3 | 21.6 | 2224 | 2394 | 2452 |
| Tasmania - Coal River | 15.0 | 15.7 | 15.8 | 1075 | 1221 | 1227 |
| Tasmania - East Coast (B) | 15.3 | 16.2 | 16.1 | 1122 | 1324 | 1286 |
| Tasmania -East Coast (S) | 15.0 | 15.9 | 15.8 | 1074 | 1261 | 1235 |
| Tasmania - North West | 14.9 | 15.6 | 15.7 | 1046 | 1187 | 1214 |
| Tasmania - Tamar | 14.9 | 15.6 | 15.7 | 1049 | 1207 | 1213 |
| Yarra Valley | 17.3 | 18.2 | 18.3 | 1549 | 1734 | 1762 |

Historic data used in this analysis was sourced from SILO as patched point data (http://www.nrw.qld.gov.au/silo/). Climate changed data sourced from DAFF Australia's Farming Future project on dryland cropping in southern Australia. Additional climate change projections for the locations of interest were sourced from Ozclim (http://www.csiro.au/ozclim/home.do). Temperature analysis used data from January 1957 to April 2013. GST – Growing season temperature was deemed to be from 1st October until 30th April. GDD – growing degree days using a threshold of 10°C.

**Climate variability – Growing Season Temperature**

Warming of 1°C does not sound like much considering that the year to year variation between a cool year and a warm year is usually more than 1°C. However a 1°C warmer climate dramatically reduces the odds of experiencing a cooler than average vintage and increasing the odds of experiencing a warmer than average vintage. The average and maximum GST experienced during the 30 year period from the 1961 vintage to the 1990 vintage is shown in Table 4. This table also shows the range in Growing Season Temperature for the middle 8 out of 10 years covering the range from a decile 2 to a decile 9 year is about 1.5°C with the very coolest years (decile 1) and the very hottest years (decile 10) outside this range. The middle 6 out of 10 years calculated as the range from cooler than average decile 3 year to a warmer than average decile 8 year is about 1°C. This means that a 1°C increase in mean temperature would make what was formerly a cooler than average decile 3 year into a warmer than average decile 8 year, and this same 1°C warming is likely to make what was formerly an average year into a warm decile 10 year.

These narrow ranges of historic GST occur in most regions, be that the cooler regions like Tasmania with GST of about 15°C, more moderate regions like the Limestone Coast or southern Victoria with GST of about 16 to 17°C, warmer regions like Langhorne Creek, McLaren Vale, Barossa or Clare Valley with GST of 18 to 19 °C, or hotter regions again like the Riverland or Riverina with GST of 20 to 21°C. Another important point that can be seen in Table 4 is that in the 14 vintages since 2000, there have been more vintages warmer than average then cooler than average in almost all regions. Additionally in many regions there have been a number of vintages warmer than any vintage experienced during the 30 year base period from the 1961 vintage top the 1990 vintage.

Because of this relatively narrow range in historic GST, a future climate that is 1°C warmer dramatically increases the odds of future GST being similar to what we currently think of as a warm vintage compared to a cool vintage. This can be seen in Table 5. For most regions a 1°C increase in temperature decreases the chance of what we currently think of as below average GST (the average to cool vintages) to be almost non-existent; and at the same time increasing the above average GST (the average to hot vintages) to what is currently warmer that any vintage during the 30 year period from 1961 to 1990. Larger temperature rises exacerbate these trends. In a practical sense this means there is a higher chance that many future vintages will be as warm as the warm vintages since 2000. An example of the analysis performed for each region can be seen in Figure 2.

**Table 4.** Variability of Growing Season Temperature calculated using historic data during the 30 year base period from the 1961 vintage to the 1990 vintage. Growing Season Temperature (GST) of an average year, and the range that the middle 8 out of 10 years would be between, calculated as the range from decile 2 to decile 9. The maximum GST is also shown. The number of vintages between 2000 and 2013 (total of 14 vintages) that have been warmer than the average (if no warming then would expect half the vintages to be warmer and half the vintages to be cooler), and also the number of vintages between 2000 and 2013 that have been warmer that any experienced during the 30 year base period.

| Region | 30 year base period (1961 vintage to 1990 vintage) | | | Vintages from 2000 to 2013 | |
|---|---|---|---|---|---|
| | Average | Range | Maximum | Warmer than average | Warmer than maximum |
| Barossa | 18.4 | 17.3 to 18.9 | 19.3 | 12 | 3 |
| Clare Valley | 18.5 | 17.6 to 19.2 | 19.8 | 11 | 0 |
| Langhorne Creek | 18.1 | 17.4 to 18.8 | 19.1 | 13 | 5 |
| Limestone Coast - Coonawarra | 16.9 | 16.2 to 17.6 | 18.0 | 8 | 0 |
| Limestone Coast - Mt Gambier | 16.1 | 15.2 to 16.8 | 17.3 | 11 | 1 |
| Limestone Coast - Padthaway | 17.6 | 17.0 to 18.4 | 18.9 | 10 | 0 |
| Limestone Coast - Robe | 16.6 | 15.9 to 17.4 | 17.6 | 10 | 1 |
| Limestone Coast - Wrattonbully | 17.4 | 16.5 to 18.0 | 18.5 | 9 | 2 |
| McLaren Vale | 18.7 | 17.9 to 19.2 | 19.7 | 13 | 5 |
| Mornington Peninsula | 17.2 | 16.3 to 18.2 | 18.8 | 8 | 0 |
| Riverina - Griffith | 20.8 | 19.7 to 21.5 | 22.0 | 10 | 7 |
| Riverina - Wagga Wagga | 19.7 | 18.4 to 20.6 | 21.4 | 10 | 3 |
| Riverland - Loxton | 20.1 | 19.3 to 20.9 | 21.3 | 10 | 1 |
| Riverland - Renmark | 21.3 | 20.4 to 21.8 | 22.4 | 7 | 2 |
| Riverland - Waikerie | 20.6 | 19.8 to 21.1 | 21.7 | 6 | 1 |
| Tasmania - Coal River | 15.0 | 14.5 to 15.4 | 15.7 | 12 | 4 |
| Tasmania - East Coast (B) | 15.2 | 14.5 to 15.7 | 16.0 | 12 | 4 |
| Tasmania - East Coast (S) | 14.9 | 14.2 to 15.5 | 15.7 | 13 | 4 |
| Tasmania - North West | 14.9 | 14.2 to 15.8 | 16.0 | 11 | 0 |
| Tasmania - Tamar | 14.8 | 14.1 to 15.5 | 15.7 | 12 | 1 |
| Yarra Valley | 17.4 | 16.7 to 18.2 | 18.7 | 8 | 0 |

Temperature analysis used data from January 1957 to 30th April 2013. GST – Growing season temperature was deemed to be from 1st October until 30th April. The 30 year base period used data from 1st October 1960 to commence the 1961 vintage to 30th April 1990 to conclude the 1990 vintage.

**Table 5.** Impact of a 1°C warmer future on percentage of years with GST either cooler than average during 30 year base period; warmer than average but not warmer than maximum during 30 year base period; or warmer than the maximum GST experienced during the 30 year base period.

| Region | Impact of a 1°C warmer future on percentage of years with GST: | | |
|---|---|---|---|
| | Cooler than average during base period | Warmer than average but not warmer than maximum during base period | Warmer than maximum during base period |
| Barossa | 7 | 41 | 52 |
| Clare Valley | 2 | 69 | 29 |
| Langhorne Creek | 1 | 32 | 67 |
| Limestone Coast - Coonawarra | 2 | 69 | 29 |
| Limestone Coast - Mt Gambier | 4 | 58 | 38 |
| Limestone Coast - Padthaway | 5 | 65 | 30 |
| Limestone Coast - Robe | 0 | 46 | 54 |
| Limestone Coast - Wrattonbully | 1 | 29 | 70 |
| McLaren Vale | 5 | 44 | 51 |
| Mornington Peninsula | 12 | 76 | 12 |
| Riverina - Griffith | 5 | 45 | 50 |
| Riverina - Wagga Wagga | 11 | 57 | 32 |
| Riverland - Loxton | 6 | 57 | 37 |
| Riverland - Renmark | 3 | 57 | 40 |
| Riverland - Waikerie | 2 | 25 | 73 |
| Tasmania - Coal River | 4 | 23 | 73 |
| Tasmania - East Coast (B) | 4 | 20 | 76 |
| Tasmania -East Coast (S) | 2 | 18 | 80 |
| Tasmania - North West | 2 | 55 | 43 |
| Tasmania - Tamar | 4 | 30 | 66 |
| Yarra Valley | 8 | 67 | 25 |

Historic data used in this analysis was sourced from SILO as patched point data (http://www.nrw.qld.gov.au/silo/). Climate changed data calculated by addition of 1°C to daily maximum and minimum temperatures. Temperature analysis used data from January 1957 to 30th April 2013. Growing season temperature was deemed to be from 1st October until 30th April. Details of variability in historic GST can be seen in Table 4.

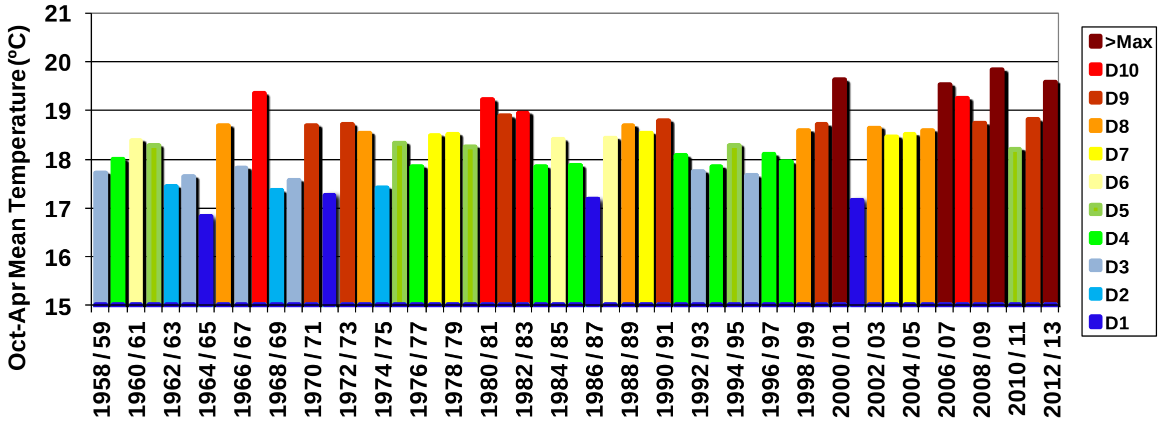
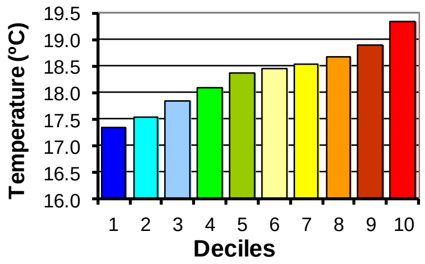
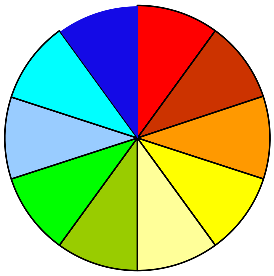


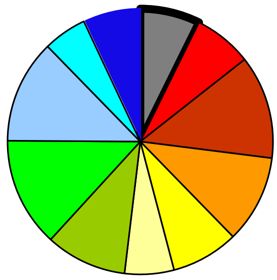

**Figure 2A.** *Mean temperature during each of the 55 growing seasons (1st October to 30th April the following year) from 1958/59 until the most recent growing season of 2012/13. The colour of the bar shows the decile from the 30 year period covering the growing seasons from 1960 / 61 until 1989 / 90 (see bar chart in figure 2B for these values). During this 30 year period, there will be 3 growing seasons in each decile. Cooler growing seasons are coloured blue to green and warmer growing seasons are coloured yellow to red. The three coolest growing seasons during this 30 year period were the vintages in 1965, 1972 and 1987 and the three warmest were the vintages in 1968, 1981 and 1983. If there was no trend in temperature, a viticulturist would expect half the years to be decile 5 or cooler and half the years to be decile 6 or warmer. The right hand side of Figure 2A shows the 14 growing seasons since 1999. The brown bars such as the growing seasons of 2000/01, 2006/07, 2009/10 and 2012/13 are those growing seasons that were hotter than any during the 30 year period. Since 1999, 12 growing seasons were decile 6 or warmer and 8 have been as warm or warmer than decile 9. The coolest vintage was 2002. The meteorological station of Nuriootpa Comparison (station 23321) was used to represent the Barossa. The climate data was obtained from SILO (http://www.nrw.qld.gov.au/silo/) as patched point data.*



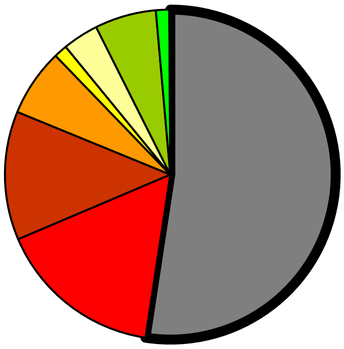

*Values of deciles of Historic record from 1960/61 until 1989/90.*



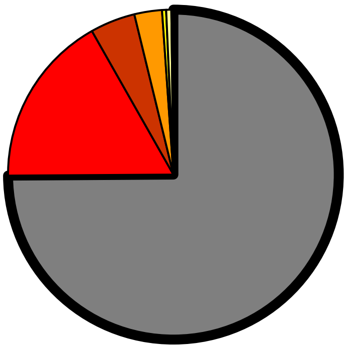
*Deciles in Historic record from 1960/61 until 1989/90*



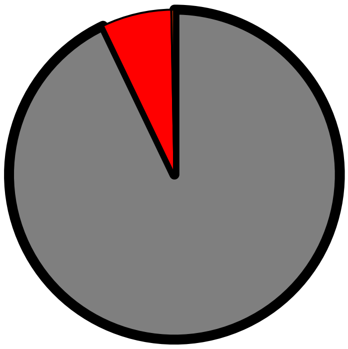
*Historic record from 1958/59 until 2012/13.*



*1°C warmer*



*1.5°C warmer*



*2°C warmer*

***Figure 2B.*** *Bar chart showing the values of each of the ten deciles of GST for the period 1960/61 until 1989/90 as described in Figure 6A. If there was no trend in climate a viticulturist would have equal chance of each colour as shown in the middle pie chart upper row. The right pie chart on the upper row shows the record from the 55 years from summer of 1958/59 to 2012/13. Unsurprisingly the pattern is similar to the 1961 to 1990 pie as 30 of the 55 years are the same. However there is a slight increase in the very warm deciles and decrease in the coolest. There are now 11 sections and the grey indicates growing seasons that are warmer than anything during the 30 year period. The three pie charts on the bottom row represent a future warmer climate of 1°C, 1.5°C and 2°C warmer than the historic record. Increasing warming of 1°C reduces the number of growing seasons in the coolest five deciles (what was previously cooler than average) and now half the growing seasons would be warmer than any in the 30 year period, as indicated by the grey portion of the pie chart. A 1.5°C warmer future would mean that about three in four growing seasons are warmer than any in the 30 year period (grey portion) and that most of the remaining quarter of growing seasons are as warm or warmer than what is currently a 3 in 10 warm growing season. A 2°C warmer future would mean than all growing seasons are as warm as what is now a 1 in 10 hot growing seasons (red portion) with most of these seasons being warmer than any in the 30 year period (grey portion). The meteorological station of Nuriootpa Comparison (station 23321) was used to represent the Barossa. The climate data was obtained from SILO (http://www.nrw.qld.gov.au/silo/) as patched point data. Future warmer climates were generated by adding 1°C, 1.5°C and 2°C to the historic records value for daily maximum and minimum temperature.*

**Climate risk for specific wine regions – Warm days**

Not surprisingly the risk of warm days or heatwaves increases in a warmer climate. This can be seen in Table 6 when comparing the historic climate of many regions, or when examining the impact of a projected warmer climate.

In the historic climate the positive linear equation between the number of days warmer than 30°C and Mean January temperature (MJT) (°C) is

Number of days warmer than 30°C = 10.9 × MJT – 182. $R^2 = 0.96$, n=21

while that for the number of days warmer than 35°C and Mean January Temperature is

Number of days warmer than 35°C = 4.3 × MJT – 74. $R^2 = 0.90$, n=21.

Both relationships show warmer regions have a higher chance of warmer days. Similar highly significant positive linear equations between the average temperature and the chance of a warm day exist in projected future warmer climates. Additionally these same positive relationships between a region's average climate and chances of very warm days, say above 40 or 43°C exist but the relationships are not as significant owing to the rarity of these events. In summary, these relationships support the view that the chance of warmer days will increase in all regions but that the actual number of days warmer than critical thresholds will remain lower in cooler regions than in already warm regions. It would also be expected that the chance of a number of consecutive days and/or nights warmer than critical thresholds would be higher in these already warm regions than in the cooler regions.

**Table 6.** Mean January temperature in the historic climate (°C), and number of days per year warmer than either 30 or 35°C in the historic climate record, and projected for 2030 by a medium warming and a high warming model.

| Region | MJT (°C) | Days warmer than 30°C | | | Days warmer than 35°C | | |
|---|---|---|---|---|---|---|---|
| | | Historic | 2030 Medium | 2030 High | Historic | 2030 Medium | 2030 High |
| Barossa | 21.5 | 51 | 57 | 60 | 17 | 20 | 22 |
| Clare Valley | 21.9 | 59 | 66 | 69 | 19 | 24 | 26 |
| Langhorne Creek | 20.8 | 44 | 48 | 50 | 17 | 20 | 21 |
| Limestone Coast - Coonawarra | 19.5 | 36 | 40 | 40 | 12 | 14 | 14 |
| Limestone Coast - Mt Gambier | 18.4 | 27 | 29 | 29 | 9 | 10 | 11 |
| Limestone Coast - Padthaway | 20.4 | 46 | 50 | 51 | 17 | 19 | 19 |
| Limestone Coast - Robe | 18.3 | 9 | 10 | 10 | 1 | 1 | 1 |
| Limestone Coast - Wrattonbully | 20.2 | 44 | 48 | 49 | 16 | 18 | 19 |
| McLaren Vale | 21.1 | 34 | 37 | 40 | 11 | 12 | 13 |
| Mornington Peninsula | 19.2 | 19 | 23 | 23 | 4 | 6 | 6 |
| Riverina - Griffith | 24.9 | 87 | 102 | 103 | 31 | 42 | 43 |
| Riverina - Wagga Wagga | 24.0 | 70 | 86 | 86 | 21 | 29 | 30 |
| Riverland - Loxton | 23.4 | 76 | 84 | 89 | 30 | 36 | 39 |
| Riverland - Renmark | 24.7 | 84 | 95 | 100 | 36 | 43 | 46 |
| Riverland - Waikerie | 23.8 | 83 | 91 | 96 | 36 | 41 | 44 |
| Tasmania - Coal River | 17.1 | 1 | 2 | 2 | 0 | 0 | 0 |
| Tasmania - East Coast (B) | 17.0 | 3 | 3 | 3 | 0 | 1 | 1 |
| Tasmania -East Coast (S) | 17.0 | 5 | 6 | 6 | 1 | 2 | 1 |
| Tasmania - North West | 17.0 | 0 | 1 | 1 | 0 | 0 | 0 |
| Tasmania - Tamar | 17.4 | 4 | 5 | 6 | 0 | 0 | 0 |
| Yarra Valley | 20.1 | 35 | 41 | 41 | 9 | 12 | 12 |

Historic data used in this analysis was sourced from SILO as patched point data (http://www.nrw.qld.gov.au/silo/). Climate changed data sourced from DAFF Australia's Farming Future project on dryland cropping in southern Australia. Additional climate change projections for the locations of interest were sourced from Ozclim (http://www.csiro.au/ozclim/home.do). Temperature analysis used data from January 1957 to April 2013.

**Climate risk for specific wine regions – Rainfall**

As noted earlier the lower confidence surrounding changes in rainfall means there are larger differences between models for projected rainfall than for temperature. The medium impact model projects comparatively small declines in annual rainfall compared to the higher impact model for all regions (Table 7). Another difference between the projections is the relative uniformity across all regions in rainfall declines projected by the medium impact model compared to the larger variation between regions projected by the high impact model. These rainfall declines are likely to have high impact on viticulture as in most regions viticulture is dependent on filling the soil profile over the previous autumn, winter and spring and then applying modest irrigation over summer, although exceptions exist such as the larger requirement on irrigation water in all seasons in several regions. Summer rainfall can however be detrimental to fruit quality and for disease control, although management options such as canopy manipulation can be practiced. Table 8 shows that summer rainfall is expected to remain similar under both the medium and high impact models.

**Table 7.** Annual rainfall from the historic record and projected for 2030 by a medium warming and a high warming model. The percentage change in annual rainfall for each of the projections is shown in parenthesis. The number of vintages between 2000 and 2013 (total of 14 years) that have been drier than average (if no drying then would expect half the years to be drier and half the years to be wetter).

| | Rainfall (mm) | | | Vintages from 2000 to 2013 drier than average |
|---|---|---|---|---|
| Region | Historic | 2030 Medium | 2030 High | |
| Barossa | 510 | 493 (-3%) | 422 (-17%) | 9 |
| Clare Valley | 633 | 607 (-4%) | 515 (-19%) | 9 |
| Langhorne Creek | 494 | 475 (-4%) | 412 (-17%) | 9 |
| Limestone Coast - Coonawarra | 621 | 585 (-6%) | 526 (-15%) | 10 |
| Limestone Coast - Mt Gambier | 714 | 672 (-6%) | 613 (-14%) | 6 |
| Limestone Coast - Padthaway | 522 | 502 (-4%) | 452 (-13%) | 12 |
| Limestone Coast - Robe | 636 | 596 (-6%) | 541 (-15%) | 8 |
| Limestone Coast - Wrattonbully | 575 | 550 (-4%) | 501 (-13%) | 10 |
| McLaren Vale | 532 | 500 (-6%) | 435 (-18%) | 7 |
| Mornington Peninsula | 731 | 700 (-4%) | 673 (-8%) | 9 |
| Riverina - Griffith | 394 | 374 (-5%) | 355 (-10%) | 9 |
| Riverina - Wagga Wagga | 554 | 519 (-6%) | 492 (-11%) | 10 |
| Riverland - Loxton | 271 | 260 (-4%) | 227 (-16%) | 9 |
| Riverland - Renmark | 255 | 244 (-4%) | 214 (-16%) | 9 |
| Riverland - Waikerie | 259 | 248 (-4%) | 216 (-17%) | 6 |
| Tasmania - Coal River | 526 | 533 (1%) | 517 (-2%) | 9 |
| Tasmania - East Coast (B) | 682 | 712 (4%) | 654 (-4%) | 8 |
| Tasmania -East Coast (S) | 581 | 601 (3%) | 562 (-3%) | 8 |
| Tasmania - North West | 935 | 912 (-2%) | 876 (-6%) | 7 |
| Tasmania - Tamar | 695 | 694 (0%) | 652 (-6%) | 9 |
| Yarra Valley | 915 | 817 (-11%) | 788 (-14%) | 11 |

Rainfall analysis used data from March 1900 to February 2013. Annual rainfall calculated from 1st March each year.

**Table 8.** Summer rainfall from the historic record and projected for 2030 by a medium warming and a high warming model.

| Region | Historic | 2030 Medium | 2030 High |
|---|---|---|---|
| Barossa | 68 | 67 | 62 |
| Clare Valley | 83 | 82 | 74 |
| Langhorne Creek | 70 | 69 | 66 |
| Limestone Coast - Coonawarra | 80 | 81 | 76 |
| Limestone Coast - Mt Gambier | 92 | 93 | 87 |
| Limestone Coast - Padthaway | 68 | 68 | 65 |
| Limestone Coast - Robe | 69 | 69 | 65 |
| Limestone Coast - Wrattonbully | 76 | 77 | 73 |
| McLaren Vale | 62 | 62 | 58 |
| Mornington Peninsula | 140 | 137 | 141 |
| Riverina - Griffith | 89 | 86 | 85 |
| Riverina - Wagga Wagga | 120 | 116 | 118 |
| Riverland - Loxton | 55 | 53 | 49 |
| Riverland - Renmark | 53 | 51 | 46 |
| Riverland - Waikerie | 57 | 55 | 50 |
| Tasmania - Coal River | 136 | 138 | 141 |
| Tasmania - East Coast (B) | 177 | 182 | 180 |
| Tasmania - East Coast (S) | 153 | 156 | 156 |
| Tasmania - North West | 151 | 151 | 152 |
| Tasmania - Tamar | 129 | 130 | 131 |
| Yarra Valley | 191 | 178 | 185 |

Rainfall analysis used data from March 1900 to February 2013. Summer rainfall calculated from 1$^{st}$ December to 28 or 29 February the following year.

**Climate risk for specific wine regions – Evapotranspiration and soil water supply**

Evapotranspiration (ETo) is strongly seasonal in nature due most likely to season changes in incoming solar radiation predominately from longer hours of sunlight. Average daily ETo is high and relatively stable for much of summer (Dec to Feb), and low and relatively stable for much of winter (June to August). (See Figure 3 for example). Peak values in January vary from daily values of about 4 to 4.5 mm/day in more southern and coastal regions; increasing to about 5mm/day for the more inland areas of these southern regions such as most of the Limestone Coast and Yarra Valley, and for coastal regions of less southern regions such as McLaren Vale and Langhorne Creek; close to 6mm/day for more inland and less southern regions including Barossa, Clare Valley, Riverland and Riverina. There is however considerable daily variation in ETo in all regions, with a strong but not perfect relationship with daily maximum temperature (see Figure 4). That is, while it is more likely that warmer days will have a higher ETo, there may be warm days with low ETo, and cooler days with high ETo. A future warmer climate will have moderate impact on ETo, although there is medium to high confidence in an increase in evaporative demand with rising temperatures. An approximation is for a 2 to 3% increase in ETo for each 1°C rise in temperature (Lockwood 1999).

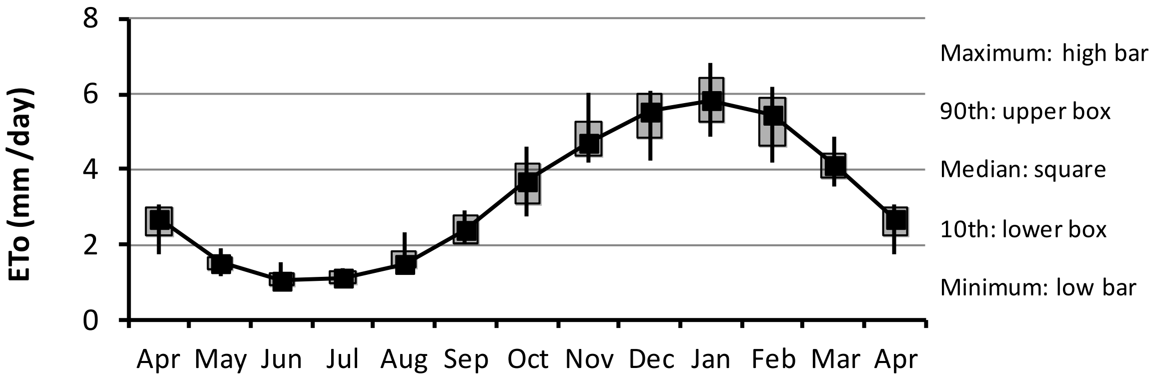



***Figure 3**. Average daily evapotranspiration per month at Nuriootpa. The large symbol (square) represents daily ETo in the average year, the boxes represent daily ETo in 8 out of 10 years, and the vertical lines show the extremes in years with high and low ETo. Daily weather data supplied from SILO. Analysis from 1961 until 1990.*

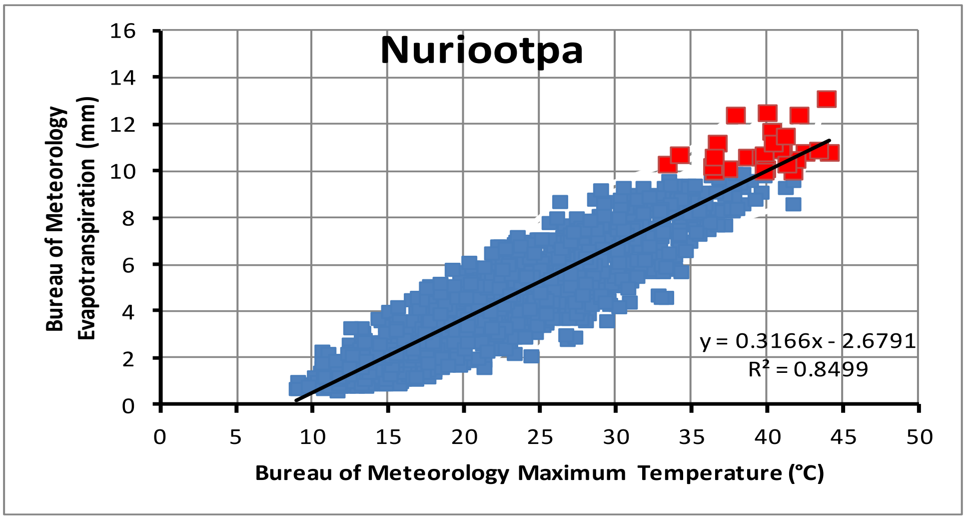



***Figure 4.*** *Daily evapotranspiration (ETo) as a function of daily maximum temperature. All data supplied by the Bureau of Meteorology for period from 1 January 2009 until 6 January 2013. The blue symbols are daily ETo less than 10mm/day; the red symbols are daily ETo greater than 10mm/day. Figure 3 shows that while a general relationship of increasing ETo with warmer daily maximum temperatures does exist, the days with ETo greater than 10 mm (coloured red) do not necessarily occur on the hot heatwave days and can occur on days with maximum temperatures less than 35°C. Concurrently, some hot heatwaves days can have low ETo.*

A practical use for knowledge of daily ETo for a location is in irrigation scheduling. A crop coefficient, Kc, can be applied to relate the water use by the vine to ETo using the formula:

Plant water use = Kc × ETo.

A guide to the maximum number of days between applying irrigation was calculated for soils having readily available water (RAW) of 25, 50, 75 and 100 mm. The calculation was based on the assumption that if the soil was irrigated to 100% field capacity and the grapevine uses a maximum of either 100% of daily evapotranspiration, that is the vine has a crop coefficient (Kc) of 1.0, or 60% of daily evapotranspiration (that is Kc = 0.6) then what is the maximum number of days of actual evapotranspiration that is stored in the soil. That is, what is the maximum number of days where the sum of daily evapotranspiration is less than the RAW of the soil.

A crop coefficient of 1.0 is likely to be an over-estimation of the actual crop coefficient although crop coefficients close to or slightly above 1.0 have been measured although a crop coefficient of 0.6 is probably suitable for most vines (for review see FAO66). Larger crop coefficients occur during peak canopy size but owing to the large variation in canopy structure with pruning and training systems, the relationship between crop coefficient and leaf area index is not unique. However it seems likely that larger canopies will have a larger Kc thus regions that use a large canopy to manage bunch exposure are more likely to have a higher crop coefficient. This analysis is likely to give a very conservative prognosis of the number of days that the 100% filled soil will be able to supply the vine with water. Using a Kc of 0.6 will essentially increase the number of days that the 100% filled soil can supply the vine's water requirements. It is felt that these two crop coefficients – 0.6 and 1.0, should encompass the likely values for mature vines.

Figure 5 shows the days of irrigation that a soil with a RAW of 75mm would contain if the crop coefficient was 1.0. It should be acknowledged that the availability of soil water changes within the total RAW such that water of more filled soils is more readily available than water in less filled soils. The findings indicated the average days of vine water supply are relatively stable for much of summer (Dec to Feb), reflecting the relationship with ETo. For this reason we chose a date of 15 February for more detailed displays of the effect of soil RAW and crop coefficient. These are displayed in Figure 6. The number of days of vine water supply is greater if a lower crop coefficient is used, but soil RAW is an over-riding factor.

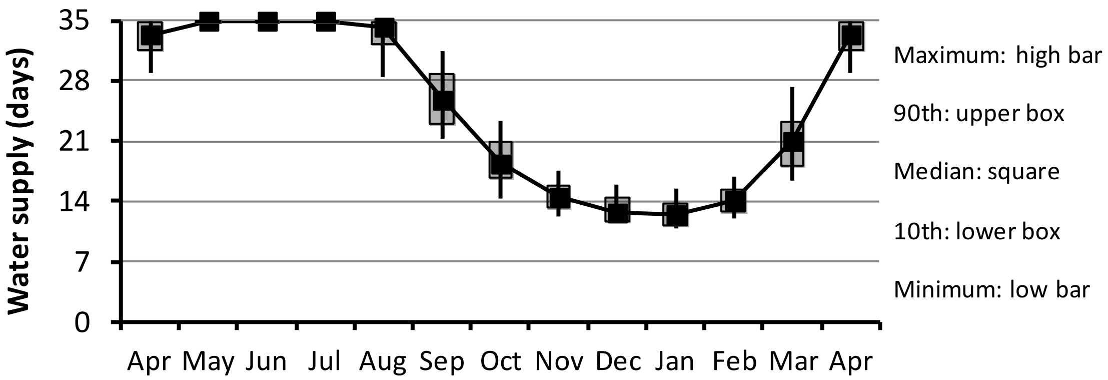



***Figure 5.*** *Average number of days water supply that a 100% filled soil with readily available water of 75mm would hold if the crop coefficient was 1.0. The large symbol (square or circle) represents the number of days supply in the average year, the boxes represent the number of days supply in 8 out of 10 years, and the vertical lines show the extremes in years with high and low ETo. Maximum of 35 days water supply was simulated. Daily weather data supplied from SILO. Analysis from 1961 until 1990.*

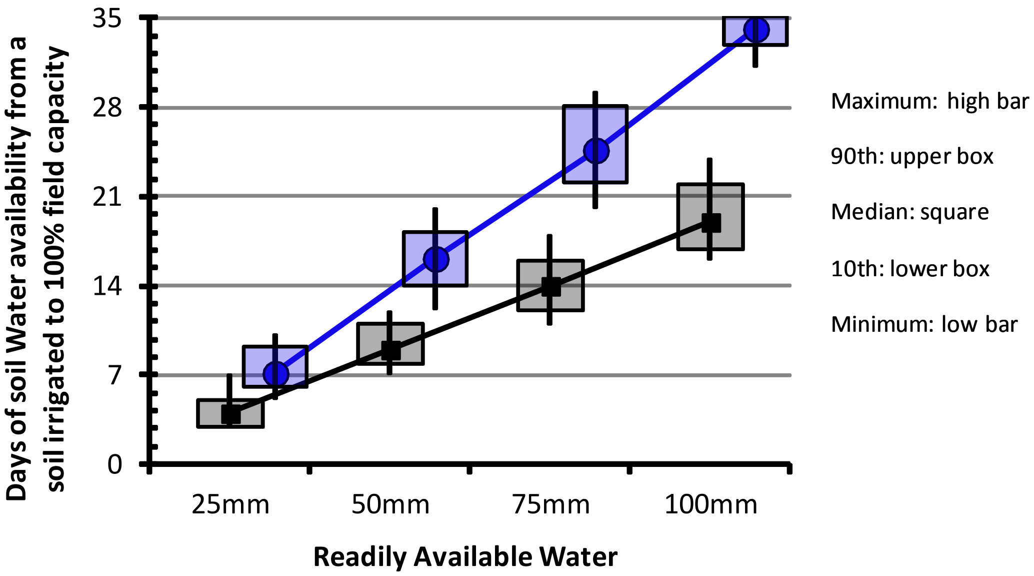



***Figure 6.*** *Days that a fully irrigated soil on 15 February with RAW from 25 to 100mm can supply water requirements to a vine at Nuriootpa. Black lines and boxes when crop coefficient is 1.0; Blue*

*lines and boxes when crop coefficient is 0.6. The large symbol (square or circle) represent days supply in the average year, the boxes represent the days of supply in 8 out of 10 years, and the vertical lines show the extremes in years with high and low ETo. Maximum of 35 days water supply was simulated. Daily weather data supplied from SILO. Data for 30 years of simulation from 1961 to 1990.*

A similar analysis of the amount of stored water in the different regions showed that if a soil with a RAW of 50mm was 100% full on February 15th, then in regions with lower ETo such as those in Tasmania the soil will run out of water between 11 and 17 days if the crop coefficient is 1.0 and if the crop coefficient is 0.6 it will last between 20 and 29 days. For areas with slightly higher average daily ETo such as Padthaway in the northern part of the Limestone Coast (daily ETo in January of 5.2mm) the soil will run out of water between 8 and 13 days if the crop coefficient is 1.0 but it will last between 13 and 21 days if the crop coefficient is 0.6, while at Mt Gambier in the southern part of the Limestone Coast (daily ETo in January of 4.8mm) the soil will run out of water between 8 and 14 days if the crop coefficient is 1.0 and between 15 and 23 days if the crop coefficient is 0.6. Regions such as Griffith in the Riverina with a daily ETo of 6.2mm will run out of water between 6 and 11 days if the crop coefficient is 1.0 and between 12 and 17 days if the crop coefficient is 0.6. An important point of this analysis is that a soil, even if it is not fully irrigated contains the equivalent of many days supply of water, and that while an important management decision to reduce effects of high temperature days or heatwave events is to ensure adequate soil moisture it may not be necessary to ensure soil on all blocks are irrigated to 100% capacity, and that an option may be to categorise limited resources (such as the ability to irrigate within a short time frame) to blocks considered more at risk.

**Varietal selection and choice of rootstocks**

It is generally accepted that different varieties suit different temperatures, and that one management choice viticulturists and winemakers will continue to address is varietal selection for a future warmer climate.  An important part of this process will be to firstly assess how varieties coped with recent warm years and heat events. Another guide is the large amount of literature detailing the suitability of different varieties to a region's climate. One such source is the following table (Table 9) prepared by Jones et al (2005) to determine the relative versatility of each variety, and the relative range of suitable temperatures for these varieties. It is based on an assessment of the temperature for high to premium quality wine production in the world's benchmark region(s) for each variety.  This table can be questioned in the Australian context, as there is little doubt that Chardonnay, for example, performs well across a wider range than that shown; and that successful commercial production of most of the varieties listed occurs outside the ranges noted, across the country. The wine industry has a proven history in adaption to adverse conditions and it is no doubt likely that it will continue to do so.  For this reason it would be expected that regions will continue to produce quality winegrapes and wines for regions warmer than suggested by Table 9.

**Table 9.** The suitability of varieties to growing season temperature

| **Varieties** | **Growing Season Temperature (˚C)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** |
| Pinot Gris | X | X | X | | | | | | | | | |
| Riesling | X | X | X | X | X | | | | | | | |
| Pinot Noir | | X | X | X | | | | | | | | |
| Chardonnay | | X | X | X | X | | | | | | | |
| Sauvignon Blanc | | | X | X | X | X | | | | | | |
| Semillon | | | X | X | X | X | | | | | | |
| Cabernet Franc | | | X | X | X | X | X | | | | | |
| Tempranillo | | | | X | X | X | X | | | | | |
| Merlot | | | | X | X | X | X | | | | | |
| Malbec | | | | X | X | X | X | | | | | |
| Viognier | | | | X | X | X | X | | | | | |
| Shiraz | | | X | X | X | X | X | | | | | |
| Table Grapes | | | | X | X | X | X | X | X | X | X | X |
| Cabernet Sauvignon | | | | X | X | X | X | X | | | | |
| Grenache | | | | X | X | X | X | X | | | | |
| Carignane | | | | | X | X | X | X | | | | |
| Zinfandel | | | | | X | X | X | X | X | | | |
| Nebbiolo | | | | | X | X | X | X | X | | | |
| Raisins | | | | | | X | X | X | X | X | X | X |

One adaption mechanism may be continued use of suitable rootstocks.  Considerable knowledge exists on the tolerance to drought that rootstocks confer to the vine, and this could be expected to also be related to tolerance to high temperature although this is rarely, if ever tested.  Two sources for information relating to rootstocks are Dry (2007) and Whiting (2004).  A brief précis of these is given below.

Drought tolerance of a grapevine can be contingent not only on the scion but also on the rootstock. However a rootstock's drought tolerance is very difficult to ascertain, and there are often contradictory findings. As noted in Dry (2007), a good rule of thumb is to remember that that drought tolerance is related to vine vigour and generally the most vigorous vines (regardless of the rootstock) have the most extensive root systems and are usually the most drought tolerant (Soar, 2004).

Whiting (2004) classifies rootstocks from low, moderate, high or very high tolerance to drought, and also notes suitability is a combination of water availability, climate, soil depth and whether the vineyard is irrigated or not. Whiting (2004) suggests 1103 Paulsen, 99 Richter, 110 Richter, 140 Ruggeri or other *V.berlandieri* × *V.rupestris* rootstocks for shallow soils or limited soil moisture in warm to hot climates; SO4, 5BB Kober, 5C Teleki and other *V.berlandieri* × *V.riparia* rootstocks for medium depth soils with moderate soil moisture in cool climates; and 3309, 3306, 101-14 and Schwarzmann and other *V.riparia* × *V.rupestris* rootstocks for deep soils or ample soil moisture in cool climates.

Dry (2007) provides a table of rootstocks classified as Highly tolerant (Ramsey, 140 Ruggeri), Tolerant (includes 1103 Paulsen, 110 Richter, 99 Richter), Moderately susceptible (includes SO4, 5BB Kober, 5C Teleki), and Susceptible (includes 3309C, 101-14 and Schwarzmann). A recommendation is that growers should use drought tolerant rootstocks if they have soils with less than 50 mm readily available water, currently or expect to have seasons were water availability is restricted, or have areas of vineyard that suffer from loss of yield and quality as a result of not being able to satisfactorily irrigate during periods of peak water use.

Dry (2004) suggests managing rootstocks according to their water requirements. Ramsey, as the most drought tolerant rootstock, should be irrigated less frequently compared to other rootstocks or own roots. Over-irrigating Ramsey may lead to less vigour with subsequent negative effects on quality. Wet years can be an issue as vines can become excessively vigorous. Management options to overcome this excessive vigour could include planting a high water use cover crop to compete with the vine for water. The cover crop can be controlled according to the desired vigour of the vine. 1103 Paulsen, 99 Richter, 110 Richter, 140 Ruggeri have consistently been classified as drought tolerant and with the right management offer potential water savings throughout the growing season. These rootstocks develop large dense root systems and have access to more soil moisture than own roots, and should also be irrigated less frequently than own roots. Like Ramsey, these rootstocks can become overly vigorous in wet years. The rootstocks 5BB Kober, SO4 and 5C Teleki have more extensive root systems in deep soils and therefore higher drought tolerance than own roots. In general these rootstocks have similar water requirements as own roots, but tend to have strong early vegetative growth early in the season and late season leaf loss, therefore irrigation should be applied later or soils should be mulched to avoid this late season water loss. Root systems of 101-14 and Schwarzmann tend to be shallow laterally spreading of low density, and consequently soil water access is minimal, and drought tolerance is poor. An irrigation system of small spacings between drippers and frequent short irrigation applications will ensure irrigation is applied to this root system. Mulching or other practices that retain soil water may provide an additional 'buffer' during periods of high water demand or during heatwaves.

## 7. Outcome/Conclusion

Workshops were held in the Barossa Valley, Clare Valley, Limestone Coast (including representatives from the five regions of Coonawarra, Mt Gambier, Padthaway, Robe and Wrattonbully), Tasmania and McLaren Vale. Detailed climate analysis was conducted for 17 locations.

An analysis of the historic climate variability and expected future warmer drier climate was done for the regions. Two accepted climate projections, and additionally the impact of stepwise increments in temperature were examined. The analyses showed that many if not all regions are likely to have considerably warmer and possibly drier climates in future years. Thus it is prudent to prepare for a warmer future and to consider a more water constrained future. Possible adaption options for seven main climate and /or weather-related risks are discussed. Additionally the level of confidence from climate science of the likelihood of these climate risks occurring are presented to allow industry representatives a more informed choice when considering adaptation options.

The project took a regional and vineyard focus to climate change impacts and adaptation. A strength of the project was the engagement with regional associations. This is the most appropriate way to deal with climate change as adaptation is essentially a regional and local process. Using local information and working with regional associations was the most likely way to be successful as climate change at a national level had been addressed in the years prior to this project.

A challenge of working with regional associations and viticultural officers is the change of personnel, the part-time nature of the job in smaller regions and an understandable focus on the most urgent recent issue. It was particularly apparent that during the very wet summer of 2010/11 growers and regional associations were more focussed on the immediate issue of managing disease and sourcing chemicals. Understandably it is difficult under these circumstances to arrange meetings on adapting to a warmer and drier future in 2030.

The regions did not cover Western Australia although Peter Hayman met with the WA Wine Industry Association, which made the point that the topic of climate change impacts and adaptation has been thoroughly covered in WA (see Glynn Ward: Preparing for a Changing and Variable Climate RT 07/02-2). Some of the information on Climate change adaptation was conducted at state department of primary industry level and the project could have established more contacts with these groups.

## 8. Recommendations

The challenge of finding representative climate stations for many of the important wine grape regions points to the need for better monitoring and positioning of recording stations. There are opportunities for regions to work with the Bureau of Meteorology in a similar way that the Riverland region in South Australia has coordinated measurement stations with the SA MDB NRM board and the SA Bureau of Meteorology.

The list of weather and climate risks identified in this project is not new. However there are continual improvements in the ability of the Bureau of Meteorology to forecast weather events and improvements in the communication of these forecasts with finer spatial resolution. We found that in many cases growers were not fully aware of what was available and the Bureau of Meteorology is open to suggestions for improvements. There are also many opportunities with smart phone and tablet applications that could be explored.

There are shortfalls in knowledge and technology transfer in the broad field of climate change adapted vineyard management practices. More specific topics within this broad field could encompass climate and grape phenology, varietal and rootstock choice, water use management, canopy and bunch management, and grape and wine quality. These research fields have been the subject of R&D but there is still a considerably knowledge gap between what is known and what is being applied.

# 9. Appendix 1: Communication

In addition to the workshops some of the communication activities are as follows

Peter Hayman spoke on climate change impacts and adaptation to most of Yalumba's viticulturists and wine makers at the Viti-Vini conference in Launceston, Tasmania, (September, 2011).

Peter Hayman was invited to present at the ASVO seminar in November 2011 and subsequently submit a paper to the Australian Journal of Grape and Wine Research titled "Characterising the extremely wet summer of 2010/11 in representative wine growing regions of Australia using rainfall, rain days and a simple moisture budget as a wetness indicator". This project is acknowledged in that paper as the primary source of industry questions and ideas for analysis. The ASVO paper has been reviewed but not published.

Peter Hayman and Dane Thomas submitted a paper to the Climate Change Research Strategy for Primary Industries (CCRSPI) conference in Melbourne November 2012 titled "The crop calendar as a Rosetta stone between climate science and the cherry orchard or vineyard."

Peter Hayman used material from the project in the PIARN Master-class in November 2012.

Material from the project was used in a presentation that Peter Hayman and Mike McCarthy gave at the AWRI Vic DPI climate change and viticulture conference at the University of Melbourne in June 2013 and will be used in the Australian Wine Industry Technical Conference in July 2013 in Sydney.

Additional extension material for the regions covered in this report will be developed to summarise the outcomes of the workshops and the analysis of regional climate and its variability.

# 10. Appendix 2: Intellectual Property

No intellectual property has been generated as part of this project.

# 11. Appendix 3: References

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# 12. Appendix 4: Staff

Staff involved in the project include:

Dr Peter Hayman, Climate Applications, SARDI

Dr Dane Thomas, Climate Applications, SARDI

Dr Mike McCarthy, Water Resources, Viticulture and Irrigated crops, SARDI

Dr Leanne Webb CSIRO and University of Melbourne contributed to the workshops by providing an overview of climate science and climate change projections for the region.