# Climate change in the Northern Adelaide Plains and implications for horticulture

## DEWNR Technical report 2013/09

**Government of South Australia**
Department of Environment,
Water and Natural Resources

# Climate change in the Northern Adelaide Plains and implications for horticulture

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September, 2013

DEWNR Technical Note 2013/09

Government of South Australia
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Water and Natural Resources

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ISBN 978-1-922174-32-1

## Preferred way to cite this publication

Pitt, T, Osti, A, Alcoe, D and Green, G, 2013, *Climate change in the Northern Adelaide Plains and implications for horticulture*, DEWNR Technical Note 2013/09, Department of Environment, Water and Natural Resources, Adelaide

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# CONTENTS

## List of Figures

## List of Tables

# 1. INTRODUCTION

The Adelaide and Mount Lofty Ranges (AMLR) Natural Resources Management (NRM) Region is working with key stakeholders to help the NRM sector understand the likely impacts of climate change in the AMLR Region and promote the integration of climate change into short and long-term risk management for sustainable NRM (AMLRNRMB, 2007).

This report is a product of the AMLRNRM Region project *Building Capacity in Adelaide's Food Bowl*, which aims to build knowledge and adaptation capacity amongst horticulturalists in the Northern Adelaide Plains (NAP) in order that horticultural businesses are well prepared to adapt to the impacts of climate change.

The aim of this study is to evaluate the potential impacts of climate change and limited water availability on the irrigated horticulture industry of the NAP. Projections of future climate from a suite of three Global Climate Models (GCMs) have been downscaled from regional-scale model outputs to the local scale of the NAP. The downscaled projections of future climate have been used to identify potential changes in daily temperature and rainfall patterns, and also changes in 'weather event indicators', against which climate-related risks to horticultural crops in the region can be identified.

This study is focussed on indicators of climate change that may affect field-irrigated horticultural crops, and has been limited to those crops that currently occupy the greatest area of irrigated land, namely potatoes, olives, wine grapes, almonds, carrots and lettuce. Other primary industry sectors (e.g. protected horticulture, field crops, livestock etc.) are beyond the scope of this investigation.

This report draws on findings of the Department of Environment, Water and Natural Resources (DEWNR) project *Impacts of Climate Change on Water Resources, Adelaide and Mount Lofty Ranges Natural Resources Management Region* (Alcoe *et al.*, in prep.), in which numerical groundwater models were used to evaluate the potential impacts to groundwater availability under a range of potential future climate scenarios. The climate projection selection and downscaling methods applied in DEWNR's regional *Impacts of Climate change on Water Resources* projects have also been adopted for use in this study.

The main findings of this study include the need to identify new sources of water as the principal strategy to assist growers adapt to a future changing climate. It is also likely that alternative growing systems may need to be considered and new cultivars be explored to aid in the mitigation of the potential impacts of climate change, such as warmer winters and increasing heat, drought, disease and soil salinity.

## *1.1. The Adelaide Plains*

The Adelaide Plains lie between the Western Mount Lofty Ranges and Gulf St Vincent. The main land uses are (1) urban development to the south; (2) horticulture and viticulture across the central extent (i.e. the NAP); and (3) cereal grain cropping and sheep grazing toward the north (Fig. 2). Water resources in the Northern Adelaide Plains (NAP) Prescribed Wells Area (PWA) (Fig. 3) are managed through the NAP PWA water allocation plan. A new water allocation plan for the Adelaide Plains is currently in preparation and will review and incorporate the existing Northern Adelaide Plains water allocation plan, as well as including the Central Adelaide and Dry Creek prescribed wells areas for the first time.

The NAP horticultural district has been a significant producer of high-value horticultural crops since the late 1950's with much of its success attributed to its proximity to the city of Adelaide. The NAP also has high quality, well-drained sandy soils and access to reliable water sources for irrigation. High quality underground water from confined sand and limestone aquifers beneath the plains has supplied NAP irrigators for many years and since 1999 this has been supplemented by tertiary-treated wastewater delivered via a pipeline network from the Bolivar wastewater treatment plant.

These features make the NAP conducive to the production, and efficient distribution, of a wide range of annual market garden crops and perennial tree and vine fruit. However, horticulture in the NAP is vulnerable to the potential impacts of climate change and there is a need for producers to understand the potential implications of climate change for their current and planned cropping systems to assist in making informed investment decisions.

## *1.2. Climate of the Adelaide Plains*

The Adelaide Plains has a Mediterranean-type climate with hot, dry summers and mild, wet winters. The majority of Adelaide's precipitation falls between the months of April to October, although rainfall exceeds potential evapotranspiration only in June and July (Fig 1). Contrastingly, in the Western Mount Lofty Ranges (e.g. Uraidla), rainfall exceeds potential evapotranspiration between April and September. This water deficit is discussed in more detail in Section 3.4.

The marked elevation gradient of the western front of the Mount Lofty Ranges results in a rainfall gradient that follows the prevailing direction of rainfall— i.e. west to east across the plains—from around 400 mm/y near the coast to around 650 mm/y at the foot of the ranges (Fig. 3).

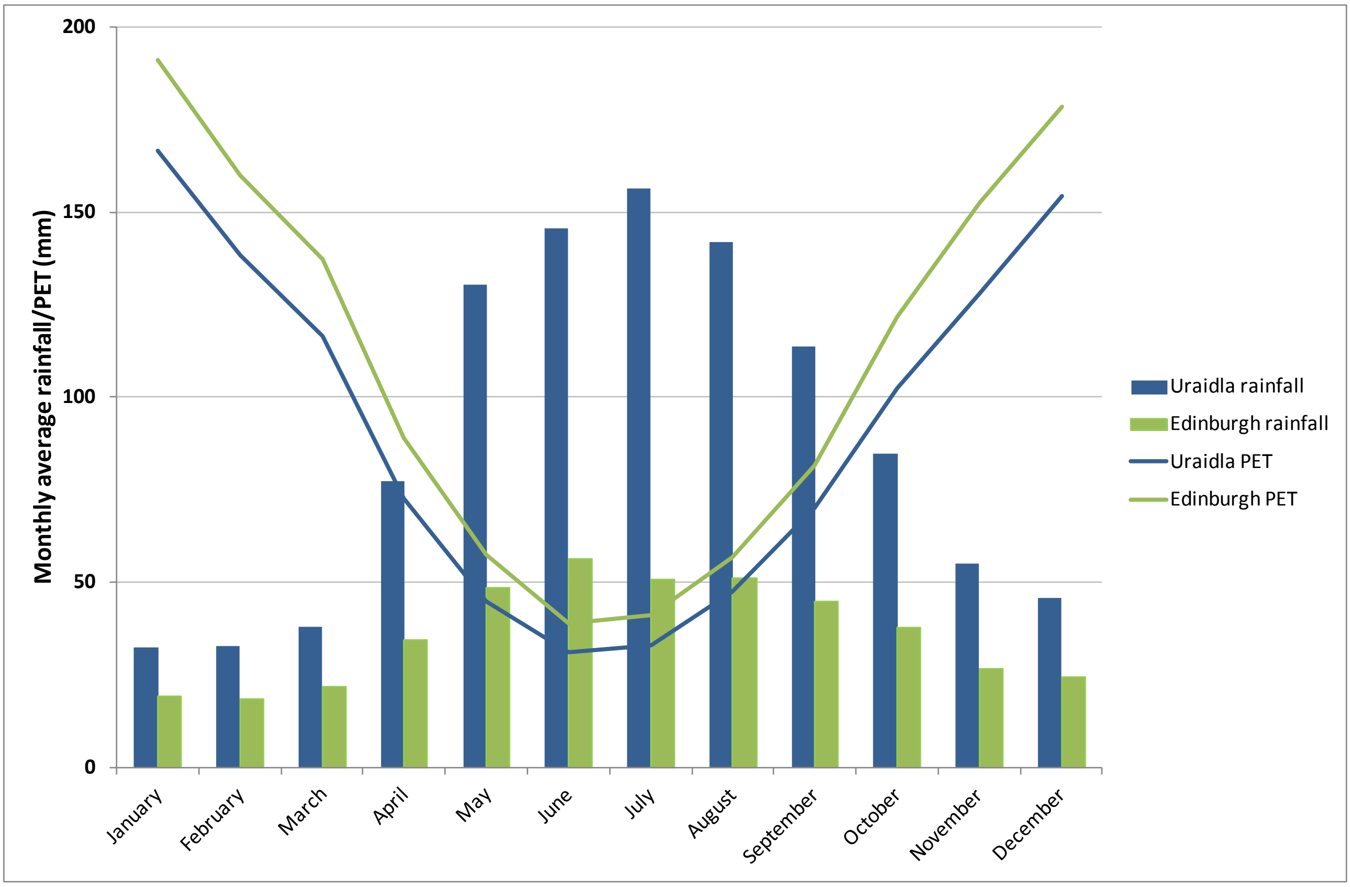
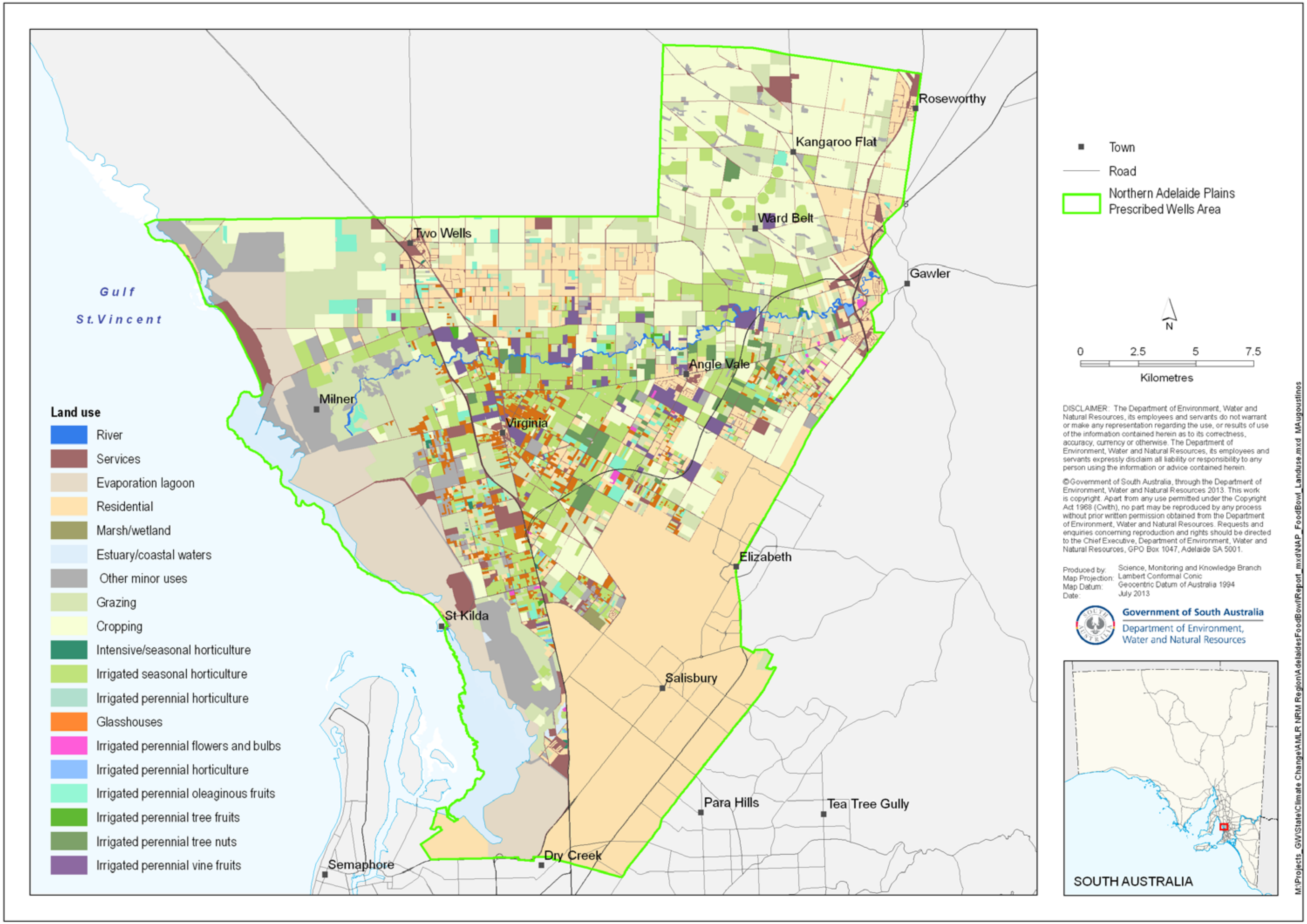
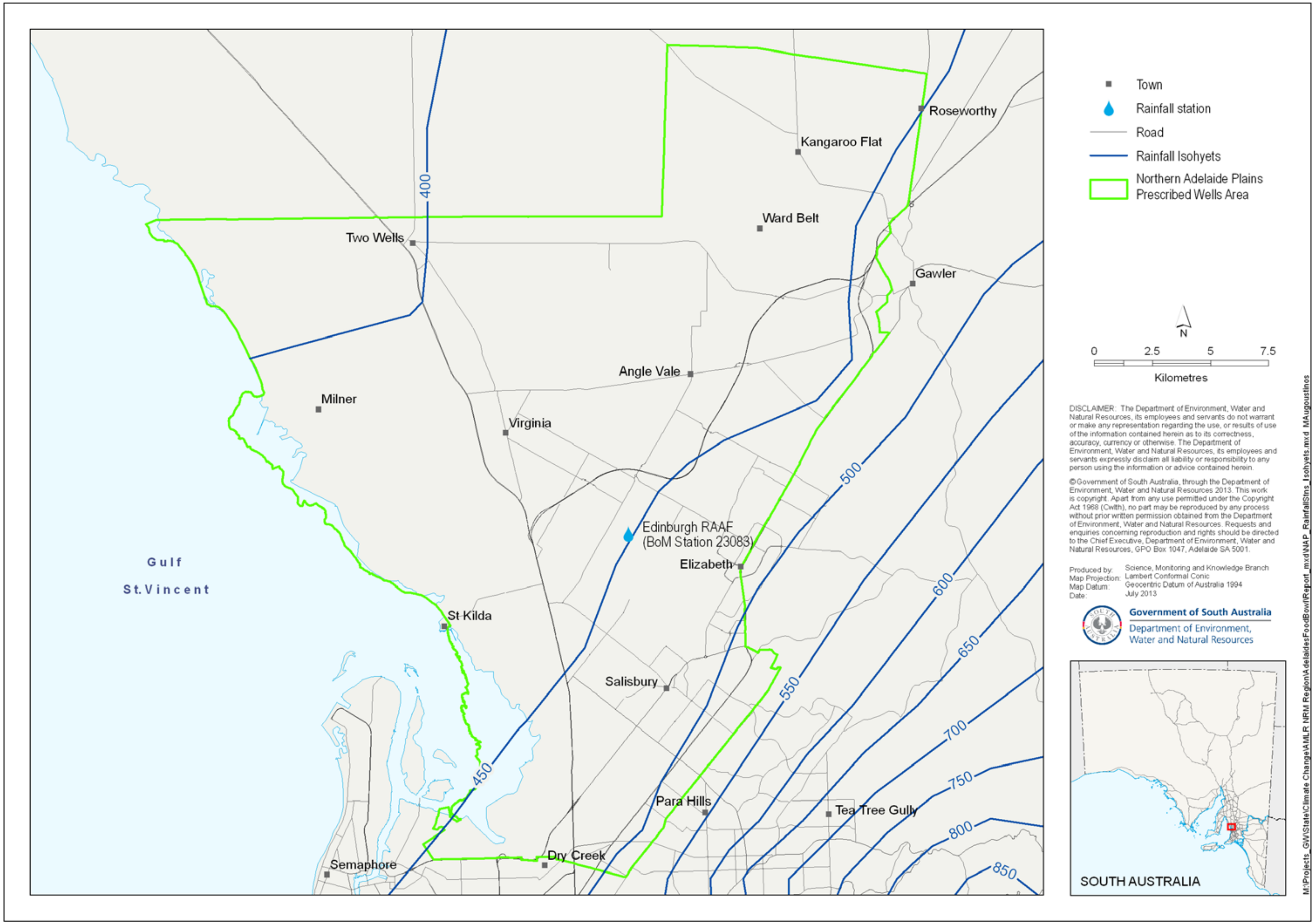


**Figure 1. Average monthly rainfall and potential evapotranspiration for Edinburgh (BoM Station 23083) in the Northern Adelaide Plains for the period 1889–2013, and for Uraidla (BoM Station 23750) in the Western Mount Lofty Ranges for the period 1913–2012. Data source: SILO Climate Data (DSITIA, 2013)**



Produced by: Science, Monitoring and Knowledge Branch
Map Projection: Lambert Conformal Conic
Map Datum: Geocentric Datum of Australia 1994
Date: July 2013

**Figure 2. Land use**



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Produced by: Science, Monitoring and Knowledge Branch
Map Projection: Lambert Conformal Conic
Map Datum: Geocentric Datum of Australia 1994
Date: July 2013

**Figure 3. Location map showing rainfall isohyets**

# 2. METHODS

Global Climate Models (GCMs) are mathematical representations of the physical processes that link together the atmosphere, oceans, land surface and the sun. The output from GCMs differ from weather forecasts in that weather forecasts aim to predict local-scale weather patterns over the time span of a few days, whereas GCMs are used to make regional-scale projections of the trends in climate over time spans of years or decades. In this study, projections of future climate using GCMs requires the regional-scale outputs of GCMs (where the dimensions of output grid cells are typically in the order of hundreds kilometres) to be scaled down such that the data can be used in local-scale models (these require input grid cell sizes typically in the order of a few kilometres).

There is a variety of GCMs that have been developed by various climate research organisations, from which one could select models for use in climate change studies. Rather than applying a large number of GCMs, one approach is to use a small number of GCMs can be selected that 1) represent most of the range of change projected by models and 2) have demonstrated suitable accuracy on the historical climate for the particular geographical location, hence assuming that the projections of future climate will also be representative . There are a number of approaches available to assist in their selection. In this study, the Climate Futures Framework was applied, an approach developed by the Commonwealth Science and Industry Research Organisation (CSIRO). (see section 2.2 and Appendix B)

It is important to note the difference between the terms 'prediction' and 'projection' in climate modelling. A prediction is a forecast of future events based purely on historical observations. For example, a prediction could be based on a simple extrapolation of historical trends. Daily weather forecasts would be considered predictions, because the forecast is based on current atmospheric conditions, and those of the recent past. A projection, however, is an extrapolation of historical trends that is dependent on certain assumptions holding true in the future. In the case of climate science, projections of future climate are made that are dependent, for example, on a particular greenhouse gas emissions scenario playing out in the future.

Because nobody can be certain of which greenhouse gas emissions pathway will play out in the future, climate scientists report climate projections based on a number of possible scenarios of future greenhouse gas emissions and resulting atmospheric concentrations. By considering a number of GCMs and a number of emissions scenarios, a range of climate projections are generated, and these are a reflection of the uncertainty in both the output of the models and in the emissions pathways that might eventuate in the future. In this study, climate projections have been based on three GCMs and two greenhouse gas emissions scenarios (high and low emissions), and the results have been projected out to two future time horizons (2030 and 2050).

This section briefly describes the methods used to generate the climate data used in this study. An expanded discussion explaining these methods is included as appendices at the end of this report, whilst a more-detailed technical description of the methodologies is presented in DEWNR Technical Reports, and these reports are indicated in the discussion that follows.

## 2.1. Climate data downscaling

Global Climate Models (GCMs) are the best tools available for simulating global and regional climate systems, and simulating the changes that may occur due to increases in greenhouse gas concentrations. Generally, these models provide reasonable representations of past trends over large spatial scales for a number of climate variables, such as temperature and air pressure. However, GCM results are too coarse to be adopted directly in local-scale models and consequently, 'downscaling' of the projections to the local weather-station scale is required. A brief summary of the downscaling techniques used to generate the climate data used in this study is presented in Appendix A, and a complete description of the methodology can be found in Gibbs *et al.* (2011). The downscaled data used in this study are at the daily time scale.

## 2.2. Global climate model selection: Climate Futures Framework

The Climate Futures Framework approach involves classifying the projected changes in climate by a range of GCMs into three separate categories (termed Climate Futures) defined by two climate variables – here, the change in annual mean surface temperature and the change in annual average rainfall have been used. Each Climate Future is then assigned a relative likelihood, based on the number of climate models that fall within that category (Clarke et al., 2011). The different Climate Future categories — defined as, for example 'warmer, drier', 'warmer, slightly drier' or 'slightly warmer, slightly drier' category GCMs — can then be used as the basis for further impact assessment. A brief summary of the Climate Futures Framework used to select appropriate GCMs for use in this study is presented in Appendix B, and a complete description of the methodology can be found in Alcoe *et al*. (in prep.).

## 2.3. Potential evapotranspiration

The potential evapotranspiration (PET) of a region is a variable of critical importance to horticulturalists as it directly affects the water requirements of a certain crop type or land use within that region. Of the selected GCMs used in this study, none produce projections of PET, necessitating estimation of PET from the projected data available, namely temperature and humidity. There are many approaches to estimating PET from climate data and, in this study, one approach was selected from a suite of five possible options (Appendix C). The approach used to estimate PET (Option 4) uses maximum temperature and the relative humidity at that temperature. A complete description of the methodology used to estimate PET can be found in Appendix C.

## 2.4. Dormancy breaking periods of 'chilling'

Many perennial crops require a period of 'chilling', through the dormancy period, to trigger flower bud development and a synchronised bud break. For the purpose of this study, the accumulation of chilling hours was assessed between the months of May and September. Two commonly used chilling models were evaluated:

- The accumulation of hours at temperatures <7.2 °C
- The Utah vernalisation model (or Richardson model), designed to account for the relative contribution of different temperatures on chill accumulation (Richardson *et al*., 1974) (Table 1).

Both models required hourly source data. Downscaled daily temperature data was disaggregated to produce the required hourly data, as per the method described by Linvill (1990).

**Table 1. Richardson model showing the relative contribution that different temperatures contribute to chill accumulation**

| Hourly temperature (°C) | Richardson chill units accumulated |
|---|---|
| <1.4 | 0 |
| 1.4 – 2.4 | 0.5 |
| 2.5 – 9.1 | 1 |
| 9.2 – 12.4 | 0.5 |
| 12.5 – 15.9 | 0 |
| 16 – 18 | -0.5 |
| >18 | -1 |

# 3. CLIMATE CHANGE PROJECTIONS FOR THE NORTHERN ADELAIDE PLAINS

The downscaled climate data for future climate scenarios for all three GCMs has been summarised (Tables 2–4) and a number of 'weather event indicators' have been reported. The implications of these changes for horticulture are examined later in this report, where potential climate change impacts to the main crop types are discussed individually and in more detail (Sect. 4).

Each of the tables presented in this section (Tables 2–4) summarises projected climate data for a single GCM – i.e. one table each for (1) the 'most-likely case' or 'warmer and slightly drier' (MIROC-H GCM, (2) the 'worst-case' or 'warmer and drier' (CSIRO mk 3.5 GCM), and (3) the 'best-case', 'slightly warmer, slightly drier' (BCCR GCM) (Appendix B). Although selected as the 'most-likely' GCM, the MIROC-H does project relatively large increases in temperature and thus the results presented herein give reference to all three GCM outputs, resulting in a comprehensive range of potential future outcomes.

## *3.1. High-rainfall and low-rainfall years*

Analyses of changes to average annual rainfall over the 30-year simulation period include projected percentage changes in the number of high and low-rainfall years, characterised by the 80th percentile and 20th percentile average annual rainfall, respectively. By definition, the 80th percentile is the value of annual rainfall totals below which 80% of annual rainfall totals lie. Any year in which the average annual rainfall is projected to be greater than the 80th percentile has been defined to be a high-rainfall year. The same rationale has been applied to the 20th percentile low-rainfall years. Hence, the historic baseline (1990) low (20th percentile) and high (80th percentile) annual average rainfall amounts are respectively 363.4 mm/y and 473.9 mm/y (Tables 2–4). As an example of relative change in high and low-rainfall years, for models run with the 'most-likely case (MIROC-H GCM), and for climate projections for the 2050 A2 scenario (Table 2), the 20th and 80th percentile rainfall amounts are reduced to 354.1 mm and 471.6 mm, respectively. The percentage of years that would have historically been considered low-rainfall years (less than 1990 20th percentile rainfall) increases from 20% to 29% in a 30-year sequence. The number of years that would have historically been considered high-rainfall years (greater than 1990 80th percentile rainfall) reduces from 20% to 17% in a 30-year sequence.

## *3.2. Weather-event indicators*

The 'weather-event indicators' are intended to give an insight into how some of the extremes in climate variables may change in the future. The indicators have been based on generalised climatic vulnerabilities of the main unprotected crop types grown across the NAP.

### 3.2.1. Heatwave

Protracted periods of extreme heat represent a high risk to growers due to potential loss of crop quality and yield as a result of heat damage. Although different crop types have different sensitivities to heat changes with stage of crop development—and indeed different cultivars within a crop type may exhibit variable heat tolerances—a conventional definition of heatwave has been adopted in this study to enable a comparison of the annual occurrence of heatwave events between the 30-year baseline (1990) climate and the climate projections for the future.

There is no universal definition of a heatwave. For the purposes of this study, a heatwave has been defined as a period of at least 5 consecutive days where, on each of those days, the daily maximum temperature exceeds 35 °C. The annual occurrence of heatwaves has then been reported as the number of heatwaves per year. For many biological systems, it is the combination of hot days and hot nights that is important. Consequently, a similar approach has been taken with definition of a heatwave of high overnight minimum temperatures, which is based on the annual occurrence of at least 5 consecutive nights where the overnight minimum temperature exceeds 20 °C. These spells of relatively-high overnight minima have also been reported as the number of occurrences per year.

### 3.2.2. Frost

An index of the risk to crops from frost has been defined as the number of days per year, between May and October, where the daily minimum temperature in the Stevenson screen is less than 1 °C (the temperature nominated by the Bureau of

Meteorology as an indicator of frost risk). Also, the maximum frost-free period (number of consecutive days where the daily minimum temperature is greater than, or equal to, 1 °C) has been calculated. For each of these indices, the percentage change for each scenario from the 1990 baseline period has been reported.

### 3.2.3. Rainfall at harvest

An index of the risk to crops from 'rainfall at harvest' has been defined as the number of rainfall events that occur between February and April, and in which rainfall is greater than 4 mm/day. The percentage change for each scenario from the 1990 baseline period has also been reported. It should be noted that the downscaling approach adopted scales the observed rainfall by different amounts depending on the original rainfall amount and the season. As such, there is no change to the days when rainfall does or does not occur. A more sophisticated approach is required to represent these changes, for example that being developed by the Goyder Institute Project *Developing an Agreed Set of Climate Change Data for South Australia*.

## *3.3.TIME PERIODS FOR PROJECTIONS OF BASELINE AND FUTURE CLIMATES*

Future climate datasets have been projected at the time horizons of 2030 and 2050 and for low and high-emissions scenarios. Climate statistics have been reported as 'average annual' data that have been calculated over a 30-year period. These 30-year periods are centred around the future time horizons of 2030 and 2050. Also reported is the percentage change in climate data between (1) the future time horizons and (2) a 1990 baseline period. The 1990 baseline period is a 30-year climate dataset (1975–2004) comprising historical, measured climate data that has been recorded at the Edinburgh weather station (BoM Station 023083). The projected 2030 and 2050 future climate datasets were downscaled from regional-scale GCM outputs to the Edinburgh weather station locale (Sect. 2.1; Appendix A).

The summary climate data in the following tables have been calculated from GCM projections of daily temperature and daily rainfall.

**Table 2. Changes in climate and 'weather-event indicators' simulated for the Northern Adelaide Plains using input data generated using the MIROC-H GCM (warmer, slightly drier category GCM)**

| **Edinburgh, SA (BOM station 023083)** | **1990[#]** | **MIROC-H ('most-likely' case) GCM** | | | |
|---|---|---|---|---|---|
| | | **2030[#]** | | **2050[#]** | |
| | | **B1** | **A2** | **B1** | **A2** |
| **AVERAGE ANNUAL CLIMATE DATA** | | | | | |
| **Rainfall (mm)** | 423.5 | 412.6 | 406.7 | 412.4 | 402.1 |
| Change from 1990 baseline (%) | | -3 | -4 | -3 | -5 |
| 20th percentile (mm) | 363.4 | 355.2 | 352.2 | 354.1 | 349.6 |
| % of years < 1990 20th percentile | 20 | 23 | 27 | 25 | 30 |
| 80th percentile (mm) | 473.9 | 468.7 | 461.4 | 471.6 | 459.5 |
| % of years > 1990 80th percentile | 20 | 19 | 17 | 19 | 17 |
| **Potential Evapotranspiration (mm)** | 1311.3 | 1352.5 | 1373.9 | 1355.2 | 1391.7 |
| Change from 1990 baseline (%) | | 3 | 5 | 3 | 6 |
| **Maximum Temperature ($T_{Max}$ °C)** | 22.4 | 23.1 | 23.4 | 23.1 | 23.7 |
| Change from 1990 baseline (°C) | | 0.7 | 1.0 | 0.7 | 1.3 |
| **Minimum Temperature ($T_{Min}$ °C)** | 11.0 | 11.5 | 11.8 | 11.6 | 12.0 |
| Change from 1990 baseline (°C) | | 0.5 | 0.8 | 0.6 | 1.0 |
| **Average Temperature ($T_{Ave}$ °C)** | 16.7 | 17.3 | 17.6 | 17.4 | 17.9 |
| Change from 1990 baseline (°C) | | 0.6 | 0.9 | 0.7 | 1.2 |
| **HEATWAVE (Oct – Apr)** | | | | | |
| **Number of days where $T_{Max} > 35$ °C** | 23.7 | 28.0 | 30.4 | 28.5 | 32.8 |
| Change from 1990 baseline (%) | | 18 | 28 | 20 | 38 |
| **Annual occurrences of 5 consecutive days where $T_{Max} > 35$ °C** | 0.9 | 1.1 | 1.3 | 1.1 | 1.4 |
| Change from 1990 baseline (%) | | 19 | 48 | 26 | 56 |
| **Number of days where $T_{Min} > 20$ °C** | 20.5 | 24.3 | 28.1 | 24.7 | 30.3 |
| Change from 1990 baseline (%) | | 18 | 37 | 20 | 48 |
| **Annual occurrences of 5 consecutive nights where $T_{Min} > 20$ °C** | 0.8 | 1.0 | 1.2 | 1.0 | 1.6 |
| Change from 1990 baseline (%) | | 30 | 61 | 35 | 109 |
| **FROST (May – Oct)** | | | | | |
| **Number of days where $T_{Min} < 1$ °C** | 3.8 | 2.8 | 2.8 | 2.8 | 2.7 |
| Change from 1990 baseline (%) | | -27 | -27 | -27 | -30 |
| **Frost free period (days)** | 297.8 | 297.8 | 298.5 | 297.8 | 298.5 |
| Change from 1990 baseline (%) | | 0.0 | 0.2 | 0.0 | 0.2 |
| **RAIN AT HARVEST (Feb - Apr)** | | | | | |
| **Rain events >4 mm/day** | 4.4 | 4.3 | 4.3 | 4.1 | 3.4 |
| Change from 1990 baseline (%) | | -4 | -4 | -8 | -23 |

**[#] Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.3)**

**Table 3. Changes in climate and weather event indicators simulated for the Northern Adelaide Plains using input data generated using the BCCR GCM (slightly warmer, slightly drier category GCM)**

| **Edinburgh, SA (BOM station 023083)** | **1990#** | **BCCR ('best' case) GCM** | | | |
|---|---|---|---|---|---|
| | | **2030#** | | **2050#** | |
| | | **B1** | **A2** | **B1** | **A2** |
| **AVERAGE ANNUAL CLIMATE DATA** | | | | | |
| **Rainfall (mm)** | 423.5 | 404.6 | 395.0 | 403.2 | 387.9 |
| Change from 1990 baseline (%) | | -5 | -7 | -5 | -8 |
| 20th percentile (mm) | 363.4 | 341.2 | 333.2 | 341.6 | 328.7 |
| % of years < 1990 20th percentile | 20 | 28 | 32 | 29 | 36 |
| 80th percentile (mm) | 473.9 | 457.4 | 446.8 | 458.9 | 441.1 |
| % of years > 1990 80th percentile | 20 | 16 | 11 | 17 | 10 |
| **Potential Evapotranspiration (mm)** | 1311.3 | 1346.2 | 1364.6 | 1348.7 | 1379.2 |
| Change from 1990 baseline (%) | | 3 | 4 | 3 | 5 |
| **Maximum Temperature (TMax °C)** | 22.4 | 23.0 | 23.3 | 23.1 | 23.6 |
| Change from 1990 baseline (°C) | | 0.6 | 0.9 | 0.7 | 1.2 |
| **Minimum Temperature (TMin °C)** | 11.0 | 11.6 | 11.9 | 11.6 | 12.1 |
| Change from 1990 baseline (°C) | | 0.6 | 0.9 | 0.6 | 1.1 |
| **Average Temperature (TAve °C)** | 16.7 | 17.3 | 17.6 | 17.3 | 17.8 |
| Change from 1990 baseline (°C) | | 0.6 | 0.9 | 0.6 | 1.1 |
| **HEATWAVE (Oct – Apr)** | | | | | |
| **Number of days where TMax > 35°C** | 23.7 | 27.2 | 29.9 | 27.5 | 31.2 |
| Change from 1990 baseline (%) | | 15 | 26 | 16 | 32 |
| **Annual occurrences of 5 consecutive days where TMax > 35 °C** | 0.9 | 1.0 | 1.3 | 1.0 | 1.4 |
| Change from 1990 baseline (%) | | 15 | 44 | 15 | 52 |
| **Number of nights where TMin > 20 °C** | 20.5 | 25.0 | 28.5 | 25.2 | 31.0 |
| Change from 1990 baseline (%) | | 22 | 39 | 23 | 51 |
| **Annual occurrences of 5 consecutive nights where TMin > 20 °C** | 0.8 | 1.1 | 1.3 | 1.1 | 1.7 |
| Change from 1990 baseline (%) | | 39 | 65 | 39 | 122 |
| **FROST (May – Oct)** | | | | | |
| **Number of days where TMin < 1 °C** | 3.8 | 2.8 | 2.8 | 2.8 | 2.7 |
| Change from 1990 baseline (%) | | -27 | -27 | -27 | -30 |
| **Frost free period (days)** | 297.8 | 297.8 | 298.5 | 297.8 | 298.5 |
| Change from 1990 baseline (%) | | 0.0 | 0.2 | 0.0 | 0.2 |
| **RAIN AT HARVEST (Feb - Apr)** | | | | | |
| **Rain events >4 mm/day** | 4.4 | 4.1 | 4.1 | 4.7 | 4.7 |
| Change from 1990 baseline (%) | | -8 | -8 | 6 | 7 |

**# Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.3)**

**Table 4. Changes in climate and weather event indicators simulated for the Northern Adelaide Plains using input data generated using the CSIRO Mk3.5 GCM (warmer, drier category GCM)**

| Edinburgh, SA (BOM station 023083) | $1990^{\#}$ | CSIRO Mk3.5 ('worst' case) GCM | | | |
|---|---|---|---|---|---|
| | | $2030^{\#}$ | | $2050^{\#}$ | |
| | | B1 | A2 | B1 | A2 |
| **AVERAGE ANNUAL CLIMATE DATA** | | | | | |
| **Rainfall (mm)** | 423.5 | 375.7 | 352.8 | 372.0 | 336.4 |
| Change from 1990 baseline (%) | | -11 | -17 | -12 | -21 |
| 20th percentile (mm) | 363.4 | 316.0 | 297.4 | 313.4 | 279.4 |
| % of years < 1990 20th percentile | 20 | 40 | 53 | 41 | 65 |
| 80th percentile (mm) | 473.9 | 432.1 | 405.5 | 425.5 | 385.1 |
| % of years > 1990 80th percentile | 20 | 9 | 5 | 7 | 4 |
| **Potential Evapotranspiration (mm)** | 1311.3 | 1358.0 | 1382.9 | 1361.3 | 1402.4 |
| Change from 1990 baseline (%) | | 4 | 6 | 4 | 7 |
| **Maximum Temperature ($T_{Max}$ °C)** | 22.4 | 23.2 | 23.7 | 23.3 | 24.0 |
| Change from 1990 baseline (°C) | | 0.8 | 1.3 | 0.9 | 1.6 |
| **Minimum Temperature ($T_{Min}$ °C)** | 11.0 | 11.7 | 12.0 | 11.7 | 12.3 |
| Change from 1990 baseline (°C) | | 0.7 | 1.0 | 0.7 | 1.3 |
| **Average Temperature ($T_{Ave}$ °C)** | 16.7 | 17.5 | 17.8 | 17.5 | 18.2 |
| Change from 1990 baseline (°C) | | 0.8 | 1.1 | 0.8 | 1.5 |
| **HEATWAVE (Oct – Apr)** | | | | | |
| **Number of days where $T_{Max}$ > 35 °C** | 23.7 | 28.7 | 31.9 | 29.6 | 34.8 |
| Change from 1990 baseline (%) | | 21 | 35 | 25 | 47 |
| **Annual occurrences of 5 consecutive days where $T_{Max}$ > 35 °C** | 0.9 | 1.1 | 1.4 | 1.3 | 1.7 |
| Change from 1990 baseline (%) | | 26 | 52 | 44 | 89 |
| **Number of days where $T_{Min}$ > 20 °C** | 20.5 | 26.1 | 30.0 | 26.4 | 32.7 |
| Change from 1990 baseline (%) | | 27 | 47 | 29 | 60 |
| **Annual occurrences of 5 consecutive nights where $T_{Min}$ > 20 °C** | 0.8 | 1.1 | 1.6 | 1.2 | 1.8 |
| Change from 1990 baseline (%) | | 48 | 109 | 57 | 135 |
| **FROST (May – Oct)** | | | | | |
| **Number of days where $T_{Min}$ < 1 °C** | 3.8 | 2.8 | 2.7 | 2.8 | 2.7 |
| Change from 1990 baseline (%) | | -27 | -30 | -27 | -30 |
| **Frost free period (days)** | 297.8 | 297.8 | 298.5 | 297.8 | 298.5 |
| Change from 1990 baseline (%) | | 0.0 | 0.2 | 0.0 | 0.2 |
| **RAIN AT HARVEST (Feb - Apr)** | | | | | |
| **Rain events >4 mm/day** | 4.4 | 4.0 | 3.7 | 3.6 | 4.1 |
| Change from 1990 baseline (%) | | -9 | -17 | -18 | -8 |

**# Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.3)**

### 3.4. Rainfall, potential evapotranspiration and irrigation water deficit

Optimum crop growth can only occur when water is not limiting. The concept of ‘water deficit’ is commonly defined as a shortage of available water through the deficit between the rate of incident rainfall and the rate of potential evapotranspiration. The cumulative water deficit over the course of the water-use year may give an indication of the amount of irrigation that would be required to meet the water deficit. A range of water deficits has been estimated for the average water-use year for the range of projected climates at 2030 and at 2050 and also for the 1990 baseline period (Fig. 4). The range of projected water deficits is a reflection of the uncertainties in different GCMs and also the emissions scenario pathways that might play out in the future, as discussed at the beginning of Section 2.

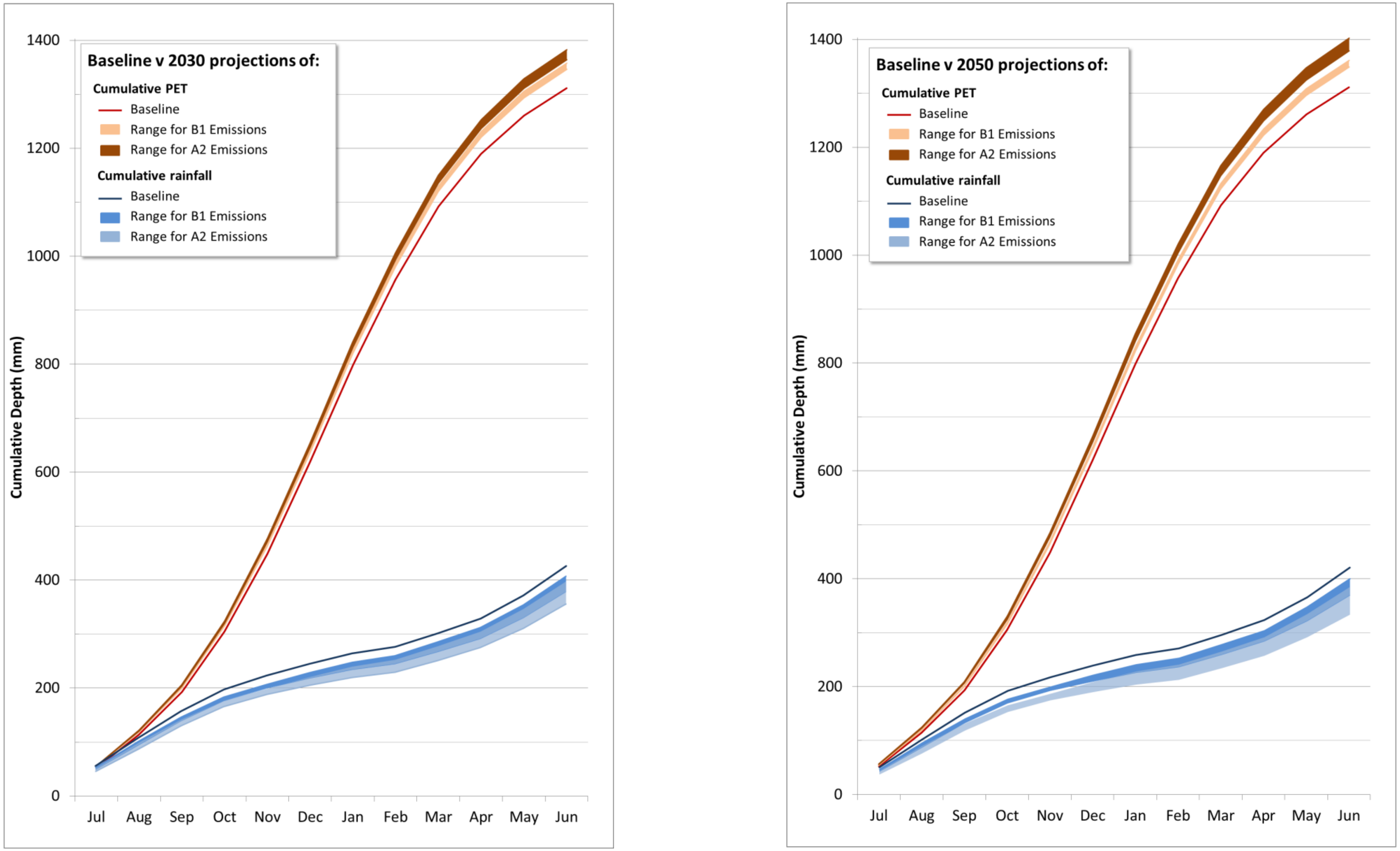

**Figure 4. Comparison of cumulative baseline (1990) rain and PET with the range of 2030 and 2050 GCM projections for B1 and A2 emission scenarios.**

Water deficits have also been presented as average monthly totals (Fig. 5), for the 12 projected future climate scenarios and also for the 1990 baseline period, and are shown only for the irrigation period of September–April. An estimate of the total irrigation water required for the year is presented on the far right of each chart (note the two different scales on each of the two vertical axes).

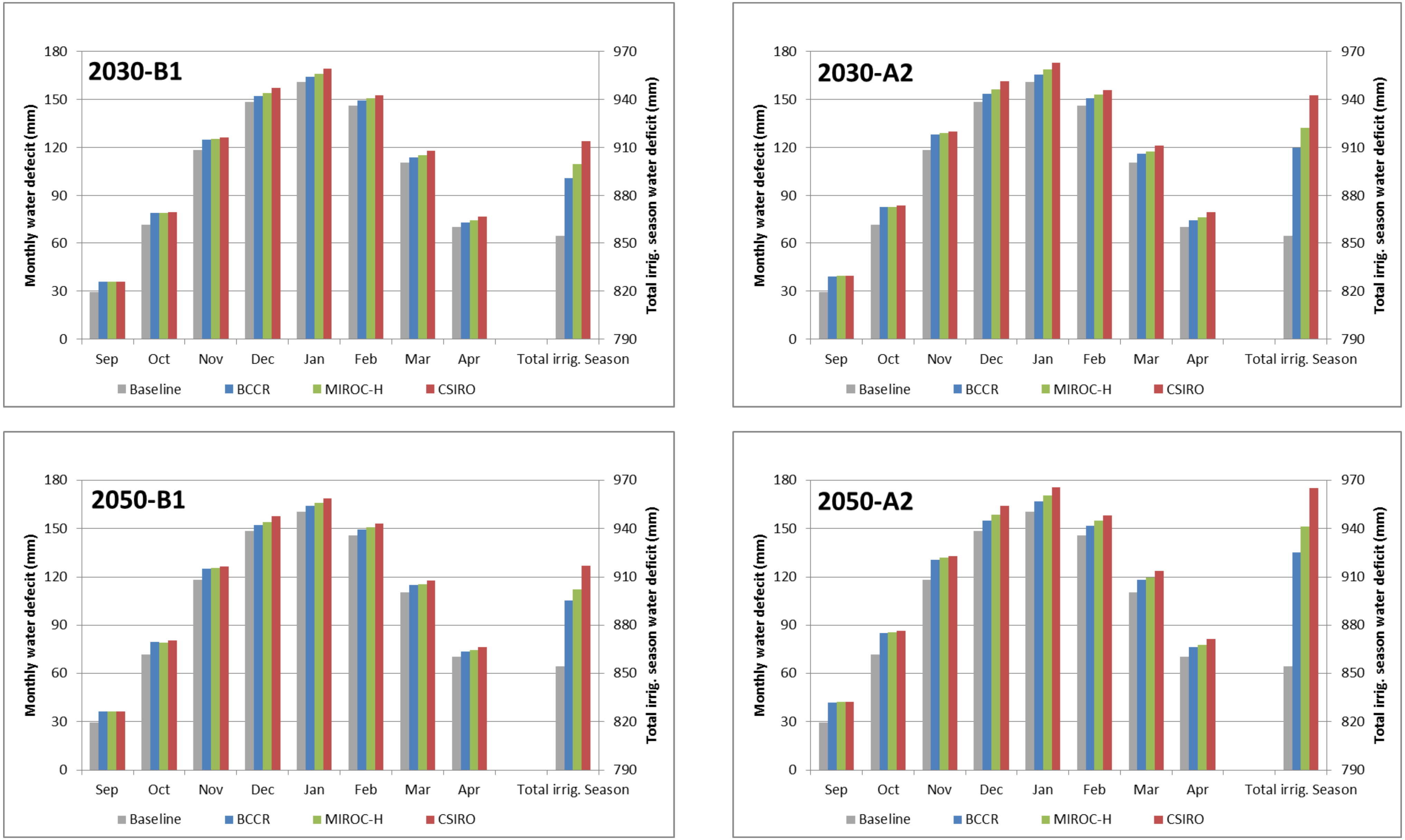

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**Figure 5. Monthly average water deficits (PET minus Rainfall) plus total water deficit through the irrigation season (Sep–Apr) for the BCCR, MIROC-H and CSIRO Mk 3.5 GCMs relative to the 1990-baseline period**

## *3.5. CHILLING*

Many perennial crops require a period of 'chilling', during dormancy, to trigger flower bud development and a synchronised bud break. While chilling requirements are both crop and variety-specific, the response to insufficient chill is consistent across most crops and includes a reduced and protracted bud break which in turn can bring about a cycle of biennial bearing. The projected change in chilling has been evaluated using two different chill accumulation models (Figs 6 and 7). Both models make use of disaggregated hourly observations of daily temperature between May and September. 'Chill hours' are the accumulation of hours where the observed temperature is less than 7.2 °C (Sect. 2.4.). 'Richardson Chill Units' are calculated using a more-complex model, designed to account for the relative contribution of different temperatures on chill accumulation (Sect. 2.4.). While each model accounts for the impact of warming differently, both reflect a reducing trend in chill accumulation, when comparing the 12 future scenarios against the 1990 baseline period.

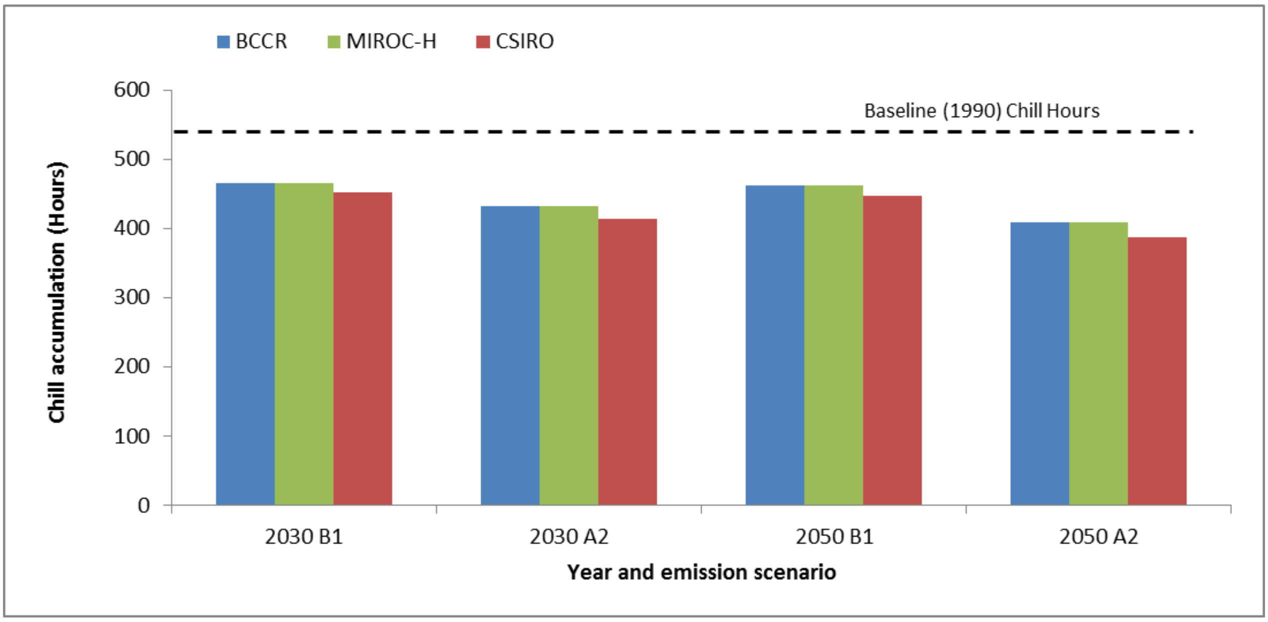


**Figure 6. Projected change in dormancy breaking 'chill hours' (Sect. 2.4). Comparison of baseline (1990) scenario to those of BCCR, MIROC-H and CSIRO Mk 3.5 GCMs at two time horizons and two emission scenarios.**

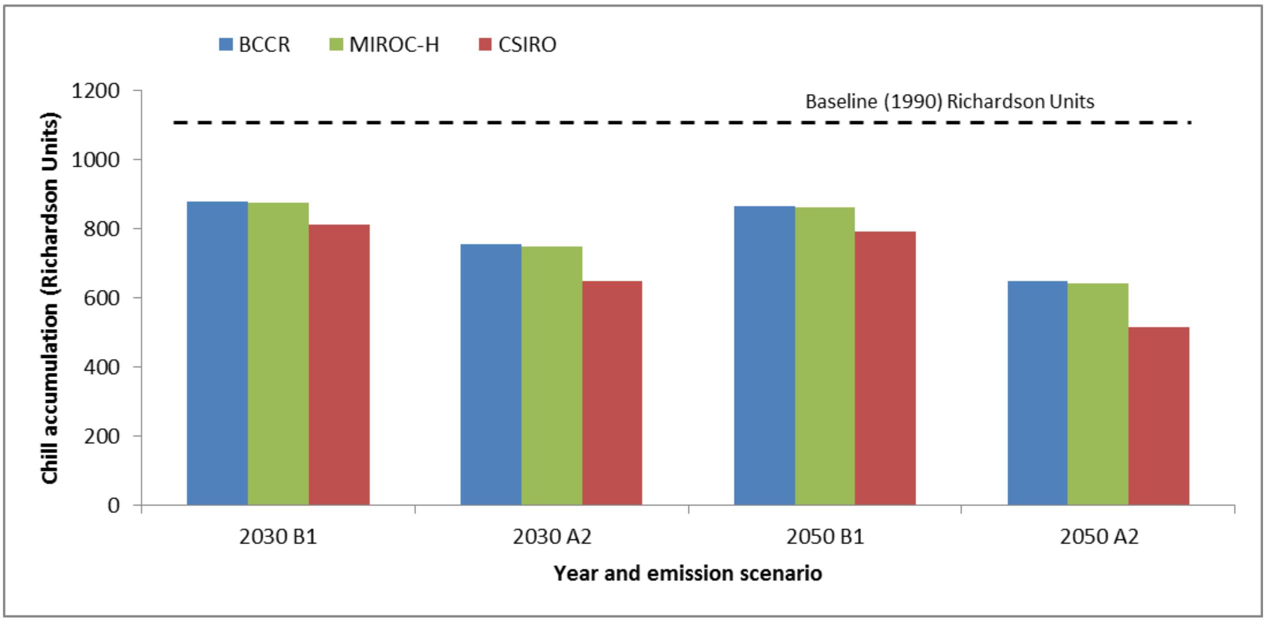


**Figure 7. Projected change in dormancy breaking 'Richardson chill units' (Sect. 2.4). Comparison of baseline (1990) scenario to those of the BCCR, MIROC-H and CSIRO Mk 3.5 GCMs at two time horizons and two emission scenarios.**

# 4. CROP RESPONSE TO PROJECTED CLIMATE CHANGE SCENARIOS

The results tables presented in this section (Tables 5–10) are intended to indicate potential implications of the **direction of change** in the projected future climate of the NAP over the longer term (e.g. increasing heatwave frequency in the future as a result of climate change, and what is the likely impact of this change on a particular crop type). In view of this, the results reported here are based on the MIROC-H GCM under the high-emissions scenario at the more-distant time horizon of 2050. The MIROC-H GCM was selected here as it satisfies the requirements outlined by Clarke *et al*. (2011) necessary for classification as a 'most likely' case GCM (refer Appendix B). An indication of the short-term impacts (i.e. 2030) — or impacts according to the alternative (BCCR, CSIRO Mk3.5) GCMs — can be deduced by reading off projections of climate change from the different GCMs, emissions scenarios and time horizons listed in Tables 2–4 and substituting these data into Tables 5–10.

## *4.1. Potatoes*

The South Australian potato industry occupies approximately 11 900 ha and produces an average annual crop of over 300 000 tonnes (ABS, 2007). The NAP potato growing region is an important part of the SA industry supplying 14% of the state's production. Almost all the NAP crop is marketed as fresh product, making quality as important an issue as yield for local growers. Both yield and quality are closely linked to the prevailing climate.

Temperature influences potato yields both directly, through daily effects on growth rates, and indirectly, through seasonal effects on the length of the crops growth cycle (Kooman, 1994) (Fig. 8). While potatoes are known for their adaptability to a wide range of growing temperatures, particularly during periods of longer day length, their growth slows significantly when the daily average temperature is below 5 °C or above 21 °C (Haverkort & Verhagen, 2008) and their photosynthetic capacity halts completely at temperatures below 2 °C and above 35 °C (Fig. 9). In order to continue cropping in spring and autumn, producers will likely need to source cultivars with growth cycles suited to shorter and warmer winter and longer and hotter summer periods. It is likely that cultivar selection criteria for NAP potato producers will need to include tolerance to reduced water availability and temperature extremes, particularly heat.

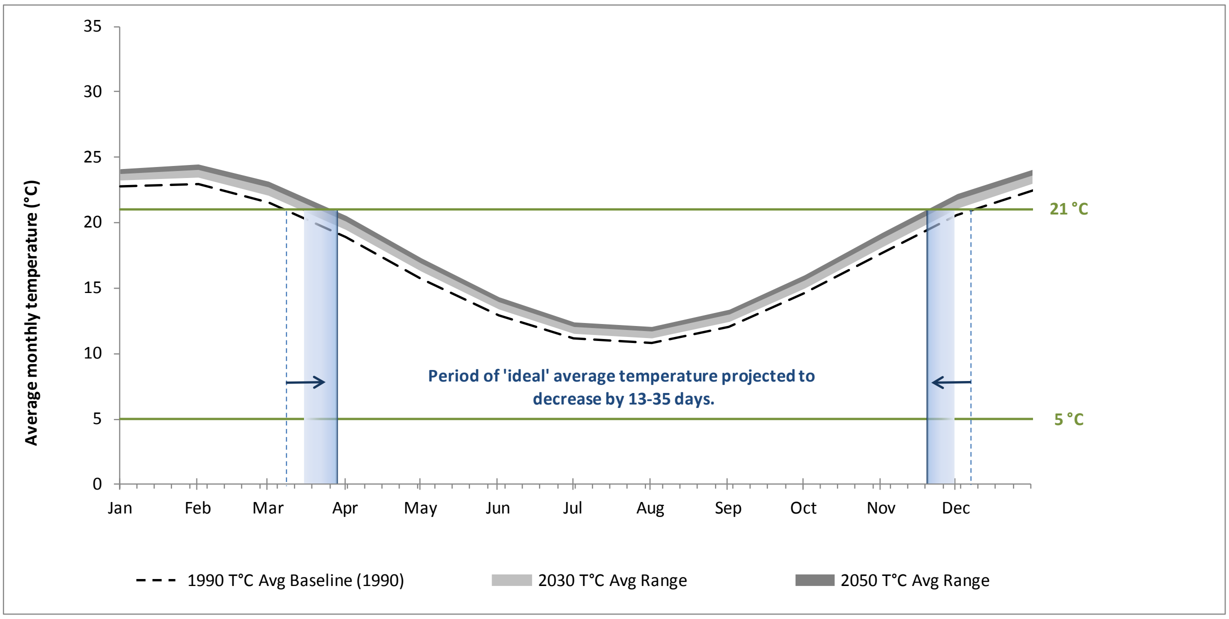


**Figure 8. Effect of projected increase in average monthly $T_{Avg}$ on 'optimum' potato growing conditions**

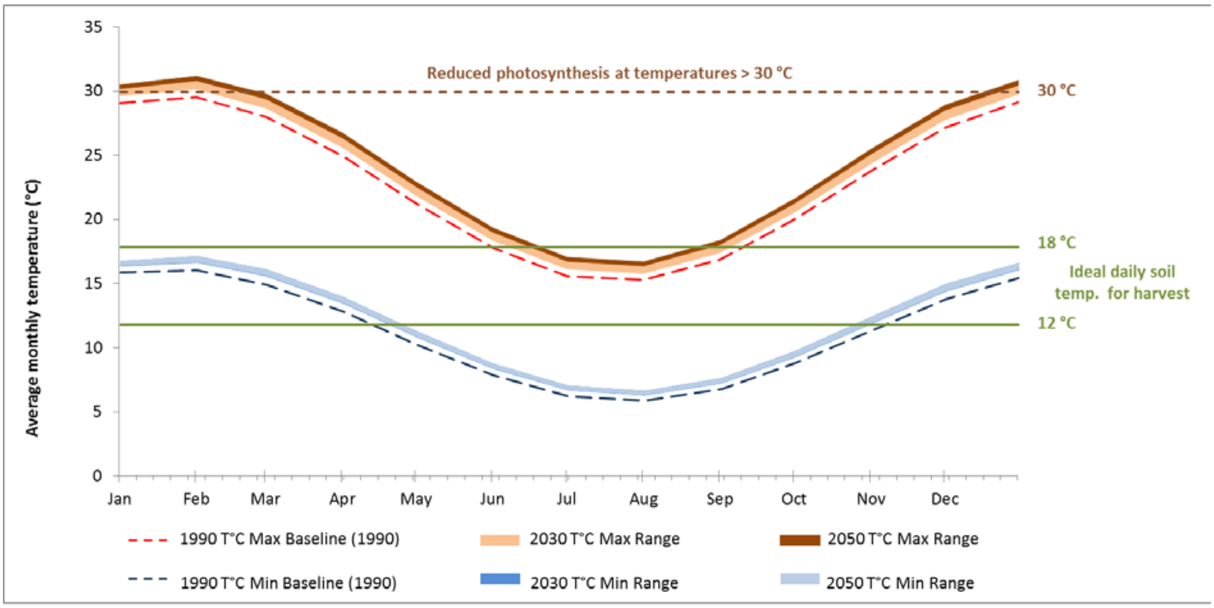


**Figure 9. Average monthly $T_{Max}$ and $T_{Min}$ projections for baseline (1990), 2030 and 2050 climate scenarios with daily thresholds for potato photosynthetic capacity and pre-harvest soil temperature**

**Table 5. Significance of MIROC-H ('most-likely' case) climate projection for NAP Potato production.**

| Climate parameter | 1990 v 2050[4]<br>Change projected by MIROC-H GCM with A2 emission scenario † | Significance for Potato production |
|---|---|---|
| **Mean temperature** | $T_{Avg}$ projected to increase by 7%<br>(1990 = 16.7 °C, 2050 = 17.9 °C) | Length of growth cycle likely to be compressed with potential negative implications on tuber size (Franke *et al.*, 2013).<br>Higher temperatures assumed to favour foliar rather than tuber growth.<br>Optimum growth period, where $T_{Avg}$ = 5-21 °C, projected to decrease by up to 35 days by 2050 (Fig. 8).<br>Current climate allows for spring and autumn cropping (PotatoesSA, 2013). Projected change is likely to favour the autumn cropping period (winter harvest).<br>Greater care may be required when targeting spring crops (summer harvest). For example, there may be an increased dependence on pre-harvest irrigation events to bring soil temperature close to ideal harvest temperature of 12–18 °C. Harvesting outside this range increases bruising and microbiological decays (Johnstone, 2012).<br>The potential shift to warmer growing seasons may increase pest and disease pressure as higher temperatures allow more cycles of pathogen multiplication (Haverkort & Verhagen, 2008). |
| **Extreme heat days [1] & Heatwaves [2]** | Extreme heat days projected to increase by 38%<br>(1990 = 24 days/y, 2050 = 33 days/y)<br>Heatwaves projected to increase by 56%<br>(1990=0.9 events/y, 2050=1.4 events/y) | Photosynthetic capacity reduces when temperatures exceed 30 °C and ceases completely when greater than 35 °C (Franke *et al.*, 2013).<br>Extended periods of high temperatures may increase leaf senescence with deleterious implications for photosynthesis and yield.<br>Tuber initiation may be inhibited at higher temperatures.<br>Increased soil moisture deficits and elevated soil temperatures may be experienced. Both may be exacerbated by reduced leaf cover. |
| **Frost [3]** | Frost events projected to reduce by 30%<br>(1990 = 3.8 days/y, 2050 = 2.8 days/y) | Reduced risk of frost is favourable for this frost sensitive crop. Some potato cultivars present symptoms at temperatures as high as 3 °C (Wale *et al.*, 2008).<br>Plants can recover from exposure to frost, but successive frost events will have negative implications for sizing and quality.<br>Despite a reduced incidence of frost on the NAP, the likelihood of compressed phenology may mean that frost sensitive growth stages remain at risk. |
| **Mean rainfall & PET** | Rainfall projected to reduce by 5%<br>(1990 = 424 mm/y, 2050 = 402 mm/y)<br>PET projected to increase by 6%<br>(1990 =1311 mm/y, 2050 =1392 mm/y) | While potatoes are intolerant to waterlogging, they do require a steady supply of water throughout the growing season.<br>Low soil moisture during tuber initiation results in fewer tubers. Low soil moisture during the bulking phase results in small, misshapen tubers.<br>Low moisture availability also increases the potential for poor quality through secondary growths, scab and hollow heart.<br>Producers will likely need to source additional volumes of irrigation water to satisfy plant water requirements.<br>Soil salinity may become more prominent if increased volumes of low quality water are applied. This may be exacerbated if there is reduced occurrence of winter leaching rain. |

† Refer to Table 2 for more complete description of change projected by the MIROC-H GCM

[1] Extreme heat days = days where $T_{Max}$ >35 °C

[2] Heatwave = five consecutive extreme heat days

[3] Frost events = days where $T_{Min}$ <1 °C

[4] Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.4)

## 4.2. Olives

South Australia's prevailing climate has long been seen as ideal for olive production, particularly given its similarity to that of the Mediterranean Basin where most of the world's olives are grown (Sweeney, 2006). Over 900 ha of the NAP is currently planted to olives, which accounts for more than 20% of the state's planting (ABS, 2007), and is largely operated under small to medium sized holdings of fewer than 10 000 trees. Almost all olives from the NAP region are destined for oil production.

The ideal daily temperature range for olive growth is between 15–34 °C, with performance declining when daily maximum exceeds 40 °C or the daily minimum drops below 5 °C (Taylor & Burt, 2007). Given the tolerance of the olive plant to heat, and its preference for a long hot growing season, the NAP olive industry is likely to remain viable despite the projected increases in temperature (Fig. 10). However, increasing temperatures imply reduced chilling through the dormancy period (Figs 6 & 7). Most olive varieties have low chilling requirements, with average July temperatures below 10-12 °C often being adequate (Kailis & Harris, 2007). Baseline conditions show that the NAP only narrowly meets the chilling requirement for most olive varieties and a warming climate will put further pressure on this chill period (Fig. 11). Furthermore, projections from the MIROC-H GCM under a high-emissions scenario suggest that the frequency of days where the maximum temperatures exceed 40 °C is projected to almost double, from 4.8 days/y in the 1990 baseline period to 9.4 days/y by 2050. Maintaining plant water status through these extreme heat events will be important in producing commercial parcels of fruit.

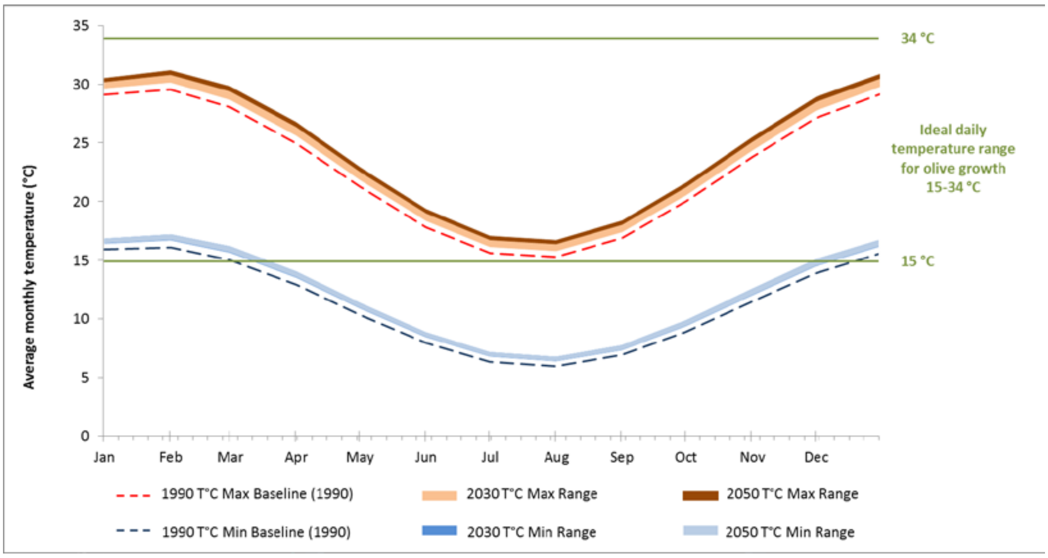


**Figure 10. Average monthly $T_{Max}$ and $T_{Min}$ projections for baseline (1990), 2030 and 2050 climate scenarios with daily temperature thresholds for olive growth. Refer to Table 6 for frequency of daily heat events.**

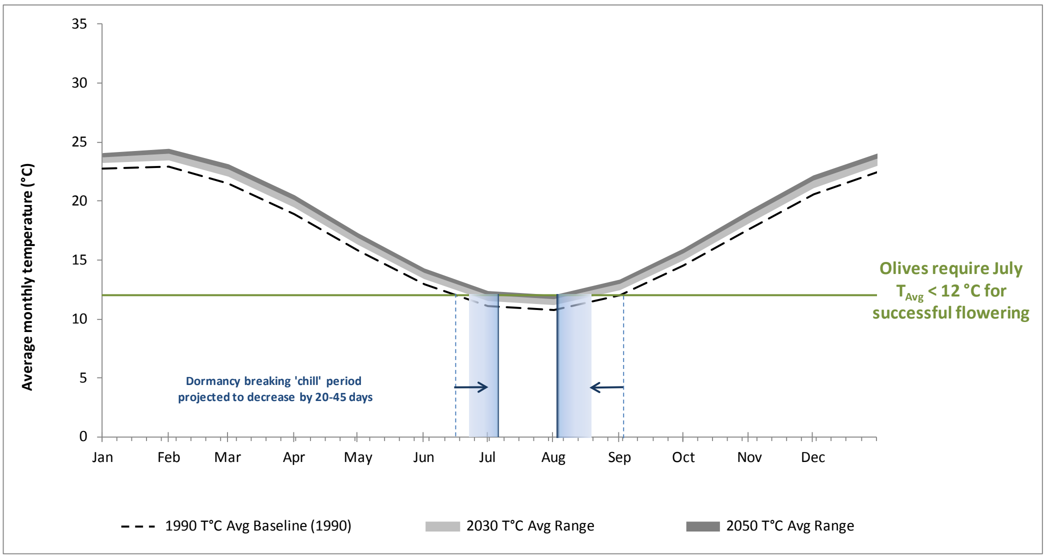


**Figure 11. Projected increase in $T_{Avg}$ is likely to compress the dormancy breaking chill period for olives.**

**Table 6. Significance of MIROC-H ('most-likely' case) climate projection for NAP Olive production.**

| **Climate parameter** | **1990 v 2050[4]**<br>**Change projected by MIROC-H GCM with A2 emission scenario †** | **Significance for Olive production** |
|---|---|---|
| **Mean Temperature** | TAvg projected to increase by 7%<br>(1990 = 16.7 °C, 2050 = 17.9 °C) | Olives are well adapted to warmer climates, ideal temperature range 15- 34 °C (Taylor and Burt, 2007).<br>Temperatures cooler than 10 °C can impede pollination (Kailis and Harris, 2007) and so warmer spring temperatures are likely to improve fruit set.<br>Potential for advanced and compressed phenology if climate warms. Compressed growing season may lead to early harvest. |
| **Extreme heat days [1]**<br>**&**<br>**Heatwaves [2]** | Extreme heat days projected to increase by 38%<br>(1990 = 24 days/y, 2050 = 33 days/y)<br>Heatwaves projected to increase by 56 %<br>(1990=0.9 events/y, 2050=1.4 events/y) | While olives prefer long hot growing season, performance declines at temperatures greater than 40 °C. Such conditions are projected to almost double in frequency by 2050 (1990 = 4.8 days/y >40 °C, 2050 = 9.4 days/y >40 °C)<br>Despite increased frequency of extreme heat days, the tree's adaptability to warmer climates makes the olive one of the crops least susceptible to a projected warming climate.<br>Increased water requirements. |
| **Frost [3]** | Frost events projected to reduce by 30%<br>(1990 = 3.8 days/y, 2050 = 2.8 days/y) | Olives can tolerate severe frosts through dormancy but are particularly sensitive to it during flowering.<br>While the frequency of frost events is projected to decline in the future, the drying climate may increase frost severity.<br>Advancing phenology may result in olives remaining susceptible to frost events, the result being reduced yields. |
| **Chilling** | Dormancy breaking chill period projected to decrease by between 20 and 45 days (Fig 11) | Successful flowering and fruit set requires a period of chilling through dormancy. Average July temperatures below 10-12 °C is adequate for most varieties (Kailis and Harris, 2007).<br>Insufficient chill results in uneven and delayed bud break.<br>Particularly warm winters may see complete bud failure (i.e. increases in July $T_{avg}$ imply an increase in the frequency of years where July Tavg is above 12°C). |
| **Mean rainfall**<br>**&**<br>**PET** | Rainfall projected to reduce by 5%<br>(1990 = 424 mm/y, 2050 = 402 mm/y)<br>PET projected to increase by 6%<br>(1990 =1311 mm/y, 2050 =1392 mm/y) | Projected decreases in rainfall may result in reduced risk from some diseases (e.g. phytophthora root rot, olive leaf spot and anthracnose fruit rot).<br>There may be an increased risk of diseases that favour dry conditions and water stressed plants (eg- charcoal root rot).<br>Reduced rainfall through winter means less opportunity for pre-season filling of soil profile. Adequate soil moisture in spring is essential for flower and fruit set.<br>Extended periods of water stress could impact olive flowering, shoot growth and fruit quality.<br>Producers will need to consider the availability of irrigation water to satisfy potentially increasing plant water requirements.<br>Soil salinity may become more prominent if increased volumes of low quality irrigation water are applied. The issue may be exacerbated if there is a reduced occurrence of winter leaching rain events. |
| **Rain near harvest** | Rain near harvest to reduce by 23%<br>(1990 = 4.4 days, 2050 = 3.4 days) | While unseasonal or extreme rain events are difficult to predict, projections for reduced rainfall through autumn is a favourable trend for olive oil producers. Oil yields can be compromised by high rain in autumn (Taylor and Burt, 2007). |

† Refer to Table 4 for more complete description of change projected by the MIROC-H GCM

[1] Extreme heat days = days where $T_{Max}$ >35 °C

[2] Heatwave = five consecutive extreme heat days

[3] Frost events = days where $T_{Min}$ <1 °C

[4] Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.4)

## 4.3. Grapes

Wine grapes are planted to approximately 600 ha on the NAP. While representing only a small component of the state's total grape crush, the estimated value of the 2013 crush was significant for the region at greater than $3M (PGIBSA, 2013). In 2013, the total intake of grapes from the NAP was over 3800 tonnes, 62% of which were red varietals comprising largely Shiraz (PGIBSA, 2013).

One of the more significant implications of a changing climate for the wine industry is the potential for advanced vine phenology. For recent Australian vintages, advanced phenology has equated to a rate of change in maturity of 9.3 ±2.67 days per °C (Petrie & Sadras, 2008). For NAP vines, this could mean an advancement of up to 18 days by 2050, for the 'worst-case' GCM projection under a high-emissions scenario. The advanced maturity is largely driven by an earlier onset of berry ripening (Sadras & Petrie, 2011) and means that the ripening process is likely to occur during warmer times of the year. Ripening under warmer conditions influences acid levels, the accumulation of sugars as well as complicating the development of berry flavour and colour. These changes imply impacts to the flavour balance and alcohol content of the wine. Advanced maturity also has implications for harvest and winery operations, as production will be impacted by multiple parcels of fruit coming from large plantings of overlapping varieties.

***Powdery mildew case study***

This case study has been included as an example of the type of projection and analysis possible when well defined climatic determinants are available for issues of relevance to crop performance.

While wet weather is not required for the development of powdery mildew, its growth is hastened when relative humidity is >40 %. The ideal temperature range for powdery mildew growth is between 20 and 28 °C. While extreme heat days may slow growth, the cooler nights that follow these hot days are frequently within the ideal temperature range (Magarey, 2010). The result being that a warming climate may favour the development of powdery mildew and related diseases.

The cumulative duration of hours where temperature and humidity met the ideal growing conditions for powdery mildew ($T_{\text{Hourly Avg}}$ 20 – 28 °C, $RH_{\text{Daily Avg}}$ >40 %) were compared between baseline and GCM scenarios. Hourly temperature data was disaggregated, from downscaled GCM data as per the method described by Linvill (1990).

**Table CS1. Average number of hours per day (Oct-Apr) where climatic conditions suit the growth of powdery mildew on grape vines. Projections of three GCM's at two time horizons, 2030 and 2050, and two emission scenarios, B1 and A2.**

| GCM | Baseline (1990) | 2030 | | 2050 | |
|---|---|---|---|---|---|
| | | B1 | A2 | B1 | A2 |
| BCCR (hours/day) | 6.16 | 6.66 | 6.90 | 6.69 | 7.08 |
| Change from baseline (%) | | 8.1 | 12.0 | 8.5 | 14.8 |
| CSIRO Mk3.5 (hours/day) | | 6.78 | 7.06 | 6.81 | 7.31 |
| Change from baseline (%) | | 10.1 | 14.6 | 10.5 | 18.6 |
| MIROC-H (hours/day) | | 6.63 | 6.84 | 6.66 | 7.01 |
| Change from baseline (%) | | 7.5 | 11.0 | 8.1 | 13.8 |

Despite a drying climate, all GCM's projected an increase in the conditions conducive to powdery mildew growth, moving from a baseline of 6.16 hours per day to between 6.63 and 7.31 hours per day per growing season, dependent on GCM scenario. This result highlights the importance of continued vigilance in the application of protective cover sprays from early in the season.

**Table 7. Significance of MIROC-H ('most-likely' case) climate projection for NAP Wine Grape production.**

| **Climate parameter** | **1990 v 2050[5] Change projected by MIROC-H GCM with A2 emission scenario †** | **Significance for Wine Grape production** |
|---|---|---|
| **Mean temperature** | $T_{Avg}$ projected to increase by 7%<br>(1990 = 16.7 °C, 2050 = 17.9 °C) | Potential for advanced and compressed phenology as climate warms. Compressed growing season leading to advanced maturity of about 9 days per degree (Petrie & Sadras, 2008).<br>Changes to the suite of pests and diseases.<br>Warming climate likely to reduce summer populations of light brown apple moth (Braybrook, 2013) which will minimise the potential for bunch rotting fungi such as Botrytis.<br>Most fungal diseases have their greatest economic impact when conditions are warm and humid, particularly close to harvest when chemical treatments cannot be applied. While rain events are difficult to predict, their occurrence in a warming climate may be conducive to a broad spectrum of pathogens. (see powdery mildew case study above). |
| **Extreme heat days [1]**<br>**(Oct-Nov)**<br>**(Feb-Mar)**<br>**Extreme heat nights[2]**<br>**Heatwave[3]** | Extreme heat days projected to increase by 38%<br>(1990 = 24 days/y, 2050 = 33 days/y)<br>Extreme heat days during flowering projected to increase by 74%<br>(1990 = 3.1 days, 2050 = 5.4 days)<br>Extreme heat days during ripening and approaching harvest projected to increase by 38%<br>(1990 = 9.3 days, 2050 = 12.8 days)<br>Extreme heat nights projected to increase by 48%<br>(1990 =20.5 days/y, 2050 = 30.3 days/y)<br>Heatwaves projected to increase by 56%<br>(1990=0.9 events/y, 2050=1.4 events/y) | Extreme heat events have the potential to cause declines in both yield an quality (Hayman *et al.*, 2012).<br>Extreme heat in spring can impact on flowering and result in poor fruit set.<br>Extreme heat in late summer early autumn can impact the ripening and may result in quality issues such as berry shrivel and sunburn.<br>High night-time temperatures complicate the ripening process and have the potential to further increase plant water requirements. The number of days where $T_{Min}$ remains above 20 °C is projected to increase by 48% by 2050. Such conditions, particularly during heatwaves, offer little relief to the vine and may contribute to heat stress (Webb *et al.*, 2010).<br>Increased water requirements. |
| **Frost [4]** | Frost events projected to reduce by 30%<br>(1990 = 3.8 days/y, 2050 = 2.8 days/y) | Despite a reduced incidence of frost on the NAP, the timing of bud break is largely controlled by temperature and is likely to occur earlier. Compressed phenology may mean that frost sensitive growth stages remain at risk. |
| **Chilling** | Chill Hours projected to reduce by 24%<br>(1990 = 541 hours, 2050 = 408 hours)<br>Richardson chill units (CU) projected to reduce by 43%<br>(1990 = 1120 CU, 2050 = 642 CU) | While some grape varieties, such as the table variety 'Thompson Seedless', do not rely on chilling to resume growth, most varieties have a low, but important, chilling requirement (Keller, 2010). In its absence, grapevine buds may show limited, uneven and delayed budburst (Lavee & May, 1997).<br>While the projected change to winter chilling is unlikely to hinder most grape varieties on the NAP, bud break could be more rapid and uniform after cooler winter dormancy. |
| **Mean rainfall & PET** | Rainfall projected to reduce by 5%<br>(1990 = 424 mm/y, 2050 = 402 mm/y)<br>PET projected to increase by 6%<br>(1990 =1311 mm/y, 2050 =1392 mm/y) | Projected reductions in rainfall may reduce the risk from some disease. However, not all require rain for their occurrence (see powdery mildew case study above).<br>Reduced rainfall through winter means less opportunity for pre-season filling of soil profile. Producers may need to consider the availability of irrigation water to satisfy plant water demand<br>Soil salinity may become more prominent if increased volumes of low quality irrigation water are applied. The issue will likely be exacerbated by reduced occurrence of winter rain events. |

† Refer to Table 4 for more complete description of change projected by the MIROC-H GCM

[1] Extreme heat days = days where $T_{Max}$ >35 °C; [2] Extreme heat nights = nights where $T_{Min}$ >20 °C

[3] Heatwave = five consecutive extreme heat days; [4] Frost events = days where $T_{Min}$ <1 °C

[4] Frost events = days where $T_{min}$ <1 °C

[5] Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.4)

## 4.4. Almonds

Almonds are grown on approximately 700 ha of land in the NAP (Fig. 2) (ABS, 2007) which accounts for 2% of the rapidly-growing Australian almond industry.

Almonds are one of many perennial crops that require a period of 'chilling' through the winter dormancy period to trigger flower bud development and a synchronised bud break. Almond chilling requirements are relatively low in comparison to other perennial tree crops, at 400–900 hours below 7.2 °C. While the current NAP climate accommodates this chill requirement, projections for 2030 and 2050 suggest warmer winters may bring chill accumulation closer to the lower end of almond requirements (Fig. 6). Over particularly warm winters, almond growers may experience a reduced and protracted bud break and possibly, a subsequent cycle of biennial bearing. A protracted bud break may also increase the risk of exposure to late frost events and even result in poor synchronisation of 'main-crop' varieties with 'pollinator' varieties. Continued almond production on the NAP would benefit from the availability of self-fertile varieties with low-chill requirements.

Once flower initiation has commenced, the warmer spring period is likely to be advantageous for pollination and nut development, as well as reduced pressure from disease (Fig. 12). The increasing frequency of extreme heat events in summer may have implications for bud initiation, a post-harvest development phase that affects the following year's crop. Increased plant water requirements are very likely if there is a marked increase in mean temperature.

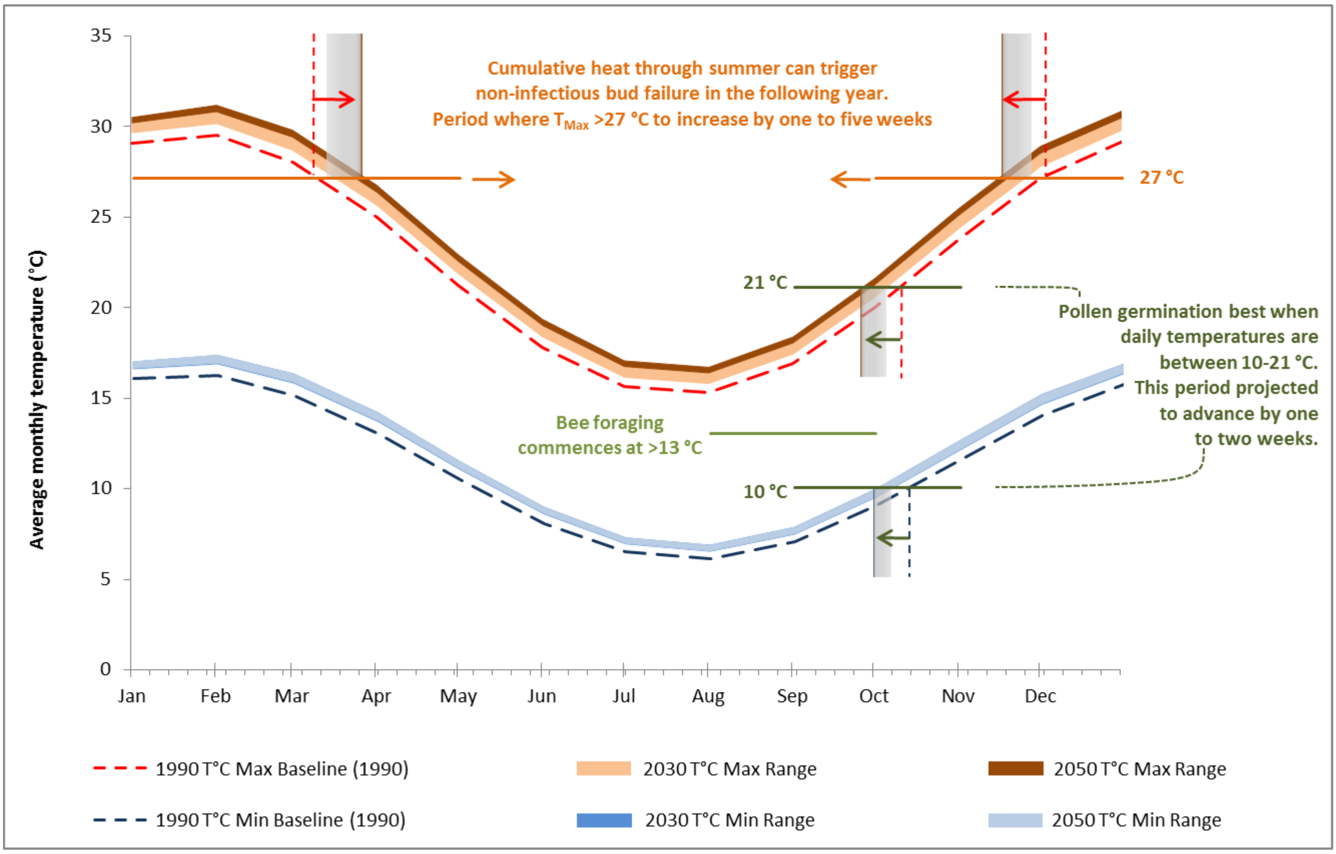


**Figure 12. Average monthly $T_{Max}$ and $T_{Min}$ projections for baseline (1990), 2030 and 2050 climate scenarios. Implications for almond bud initiation in summer and pollination in spring.**

**Table 8. Significance of MIROC-H ('most-likely' case) climate projection for NAP Almond production.**

| Climate parameter | 1990 v 2050[4] Change projected by MIROC-H GCM with A2 emission scenario † | Significance for Almond production |
|---|---|---|
| **Mean temperature** | $T_{Avg}$ projected to increase by 7%<br>(1990 = 16.7 °C, 2050 = 17.9 °C) | Improved conditions for bee foraging, >13 °C, and pollen germination, 10-21 °C (Polito *et al.*, 1996), (Fig. 12).<br>Phenology likely to advance in timing and may negate the abovementioned advantage.<br>Changes to timing of bud break may also have adverse effects on the synchronization of main crop with pollinator varieties.<br>Compressed growing season may lead to earlier harvest |
| **Extreme heat days [1] & Heatwaves [2]** | Extreme heat days projected to increase by 38%<br>(1990 = 24 days/y, 2050 = 33 days/y)<br>Heatwaves projected to increase by 56%<br>(1990=0.9 events/y, 2050=1.4 events/y) | Extreme heat events through the bud initiation phase (Feb–Mar) can result in bud failure in the following year. Cumulative temperatures as low as 27 °C can influence non-infectious bud failure onset and expression (McMichael, 2009).<br>Leaf burn on exposed canopy is likely to be more prevalent when plant water status is low.<br>Likely increased water requirements. |
| **Frost [3]** | Frost events projected to reduce by 30%<br>(1990 = 3.8 days/y, 2050 = 2.8 days/y) | While frost events are projected to decline in their frequency, the drying climate may increase their severity.<br>Advancing phenology is likely to result in almond bud break remaining susceptible to frost. |
| **Chilling** | Chill Hours projected to reduce by 24%<br>(1990 = 541 hours, 2050 = 408 hours)<br>Richardson chill units (CU) projected to reduce by 43%<br>(1990 = 1120 CU, 2050 = 642 CU) | Almonds require 400–900 'chill hours' below 7.2 °C for initiation of bud break. Two projections of chill (chill hours and Richardson units) show significant reductions in winter chilling (Figs 6 & 7).<br>Insufficient chill can result in limited, uneven and delayed bud break. |
| **Mean rainfall & PET** | Rainfall projected to reduce by 5%<br>(1990 = 424 mm/y, 2050 = 402 mm/y)<br>PET projected to increase by 6%<br>(1990 =1311 mm/y, 2050 =1392 mm/y) | Dry seasons are more conducive to pollination and are likely to require less fungal control sprays.<br>Reduced rainfall during summer and autumn can improve conditions for harvest and pickup operations.<br>Reduced rainfall through winter means less opportunity for pre-season filling of soil profile.<br>Producers will need to consider the availability of irrigation water to satisfy potentially increasing plant water requirements.<br>Soil salinity may become more prominent if increased volumes of low quality irrigation water are applied. The issue will be exacerbated by reduced occurrence of winter leaching rain events. |

† Refer to Table 4 for more complete description of change projected by the MIROC-H GCM

[1] Extreme heat days = days where $T_{Max}$ >35 °C

[2] Heatwave = five consecutive extreme heat days

[3] Frost events = days where $T_{Min}$ <1 °C

[4] Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.4)

## 4.5. Carrots

The Adelaide Plains is a significant producer of carrots, over 30 000 t/y, and accounts for almost half the state's processing value. The location of associated packaging and processing facilities on the Adelaide Plains makes the carrot one of the region's most economically important crops.

The carrot is a cool season crop whose optimum growing temperature range is between 10 and 25 °C (Rubatzky *et al.*, 1999) (Fig. 13). Warmer winter temperatures would favour carrot crops on the NAP while warmer summer temperatures may see growers having to avoid the more extreme months. While carrots can continue to grow in warmer conditions, their quality deteriorates during extreme heat events with both flavour and texture being compromised.

A further disadvantage of a warming climate is the tendency for carrots to invest energy into foliage rather than tuber growth. This tendency may be slightly offset in an environment of increasing $CO_2$, which tends to direct a greater partitioning of carbohydrates to the roots. Wurr *et al.* (1998) found that carrots take greatest advantage of additional $CO_2$ at temperatures close to 16 °C.

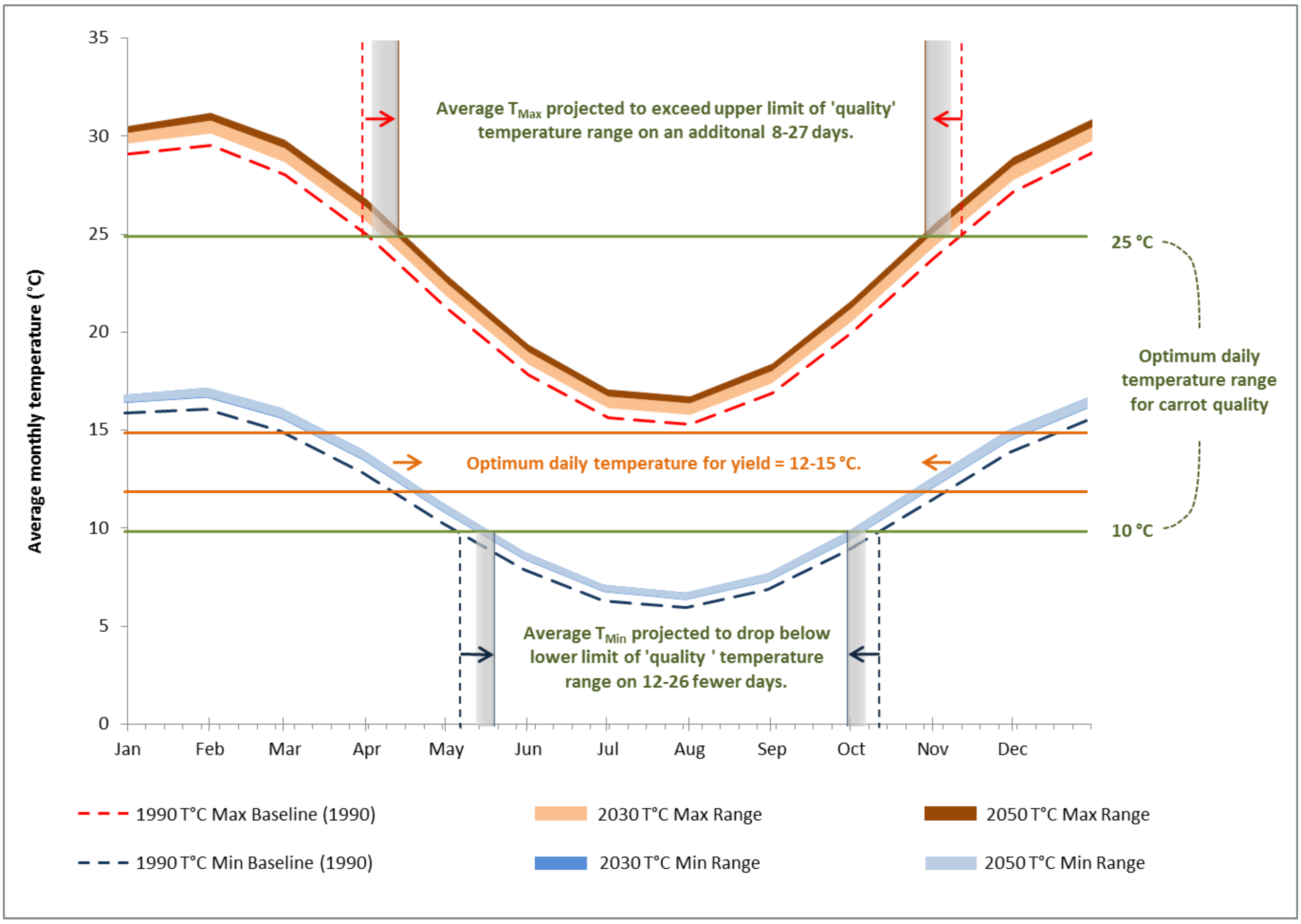


**Figure 13. Average monthly $T_{Max}$ and $T_{Min}$ projections for baseline (1990), 2030 and 2050 climate scenarios with daily temperature thresholds for carrot yield and quality.**

**Table 9. Significance of MIROC-H ('most-likely' case) climate projection for NAP Carrot production.**

| Climate parameter | 1990 v 2050[4] Change projected by MIROC-H GCM with A2 emission scenario † | Significance for Carrot production |
|---|---|---|
| **Mean temperature** | $T_{Avg}$ projected to increase by 7%<br>(1990 = 16.7 °C, 2050 = 17.9 °C) | Greatest yield at temperatures between 12-15 °C. As temperatures increase, leaf growth likely to be favoured over tuber growth (Hole, 1996)<br>The highest quality carrot is produced under growing conditions between 10–25 °C (Rubatzky et al., 1999).<br>While a warming climate could see a shift in the timing of ideal conditions, production is likely to remain viable in all but the hottest months.<br>Warmer soil temperatures are more conducive to pathogen and disease development.<br>Fungal disease may become more prevalent if warm temperatures align with periods of high relative humidity. |
| **Extreme heat days [1] & Heatwaves [2]** | Extreme heat days projected to increase by 38%<br>(1990 = 24 days/y, 2050 = 33 days/y)<br>Heatwaves projected to increase by 56 %<br>(1990=0.9 events/y, 2050=1.4 events/y) | Production during extreme heat can lead to forking, cracking, bitterness and increased fibrous texture (Rubatzky et al., 1999).<br>Likely increased water requirements. |
| **Frost [3]** | Frost events projected to reduce by 30%<br>(1990 = 3.8 days/y, 2050 = 2.8 days/y) | While frost events are projected to decline in frequency, the drying climate may increase their severity.<br>Severe and/or consecutive frosts can cause leaf death<br>Carrots are also prone to cracking at cooler soil temperatures. This will be less of a concern under current projections, particularly if the crown remains covered by soil. |
| **Mean rainfall & PET** | Rainfall projected to reduce by 5%<br>(1990 = 424 mm/y, 2050 = 402 mm/y)<br>PET projected to increase by 6%<br>(1990 =1311 mm/y, 2050 =1392 mm/y) | Carrots require a steady supply of water throughout the growing season.<br>Low water availability results in growth cracks, misshapen tuber and unfavourable flavour/texture.<br>Producers will need to consider the availability of irrigation water to satisfy potentially increasing plant water requirements.<br>Soil salinity may become more prominent if increased volumes of low quality irrigation water are applied. The issue could be exacerbated if there is a reduced occurrence of winter leaching rain events. |

† Refer to Table 4 for more complete description of change projected by the MIROC-H GCM

[1] Extreme heat days = days where $T_{Max}$ >35 °C

[2] Heatwave = five consecutive extreme heat days

[3] Frost events = days where $T_{Min}$ <1 °C

[4] Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.4)

## *4.6. Lettuce*

While gourmet lines of lettuce are increasingly being grown under protected and hydroponic cropping systems, there remains significant acreage of field irrigated lettuce on the NAP, at greater than 350 ha. The relatively short growing period of this crop, combined with the availability of cultivars with differing climatic tolerances, means that NAP lettuce producers have far more flexibility in adapting to climate change than other cropping systems in the district. The period of greatest risk for lettuce producers is likely to be during the seasonal transition between winter and summer cultivars. Warm season cultivars will be more sensitive to frost events and cool season cultivars will be more sensitive to heat.

Lettuce is particularly sensitive to heat in the weeks approaching harvest. Temperatures in excess of 28 °C through this period can result in significant reductions in quality. These conditions are projected to increase under both the 2030 and 2050 GCM scenarios (Fig. 14). Lettuce producers will likely benefit from (1) planting heat-tolerant varieties and (2) considering water availability during an additional month where average maximum temperatures are projected to be over 28 °C.

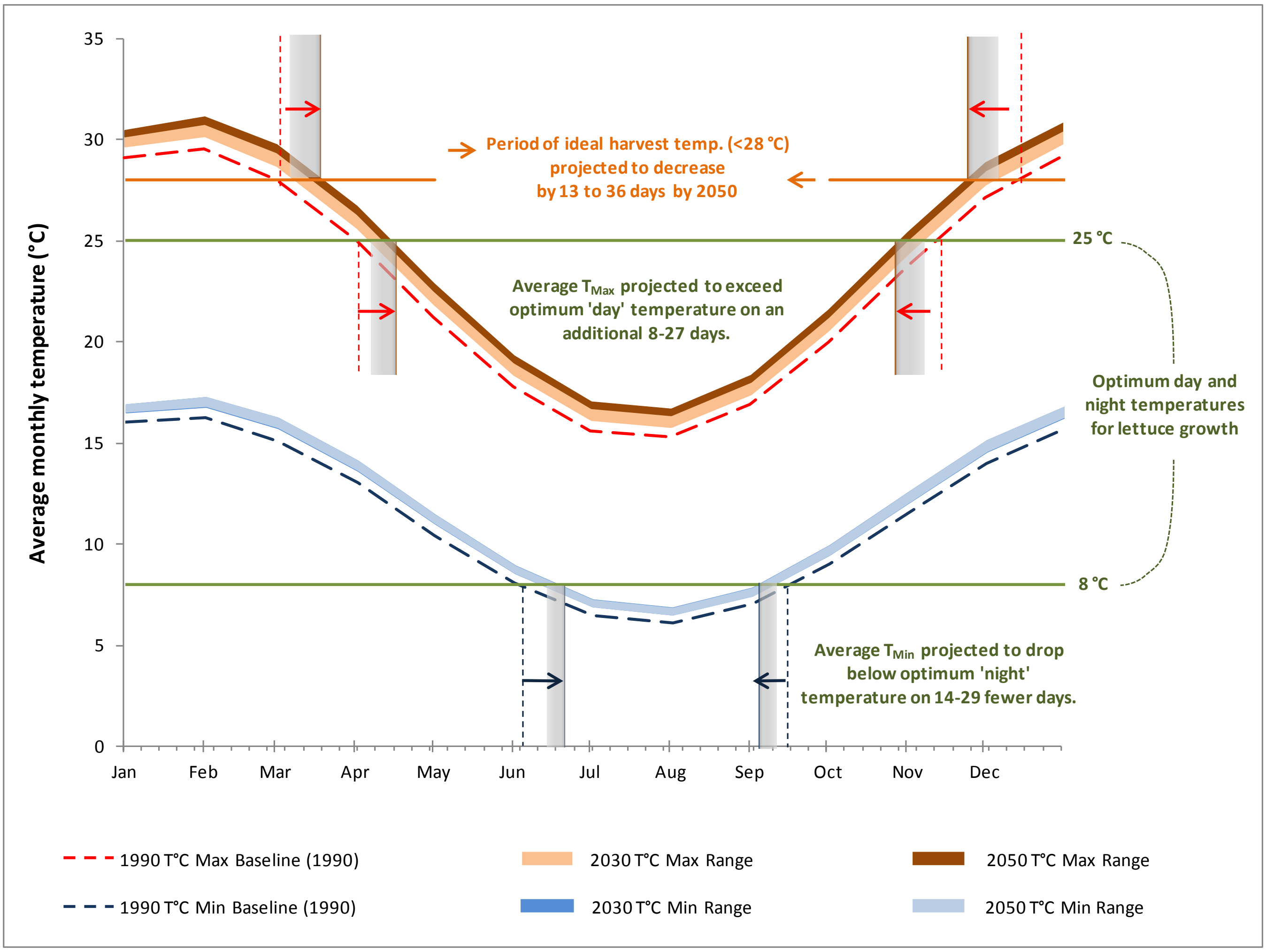


**Figure 14. Average monthly $T_{Max}$ and $T_{Min}$ projections for baseline (1990), 2030 and 2050 climate scenarios with daily temperature thresholds for lettuce growth and quality.**

**Table 10 . Significance of MIROC-H ('most-likely' case) climate projection for NAP Lettuce production.**

| Climate parameter | 1990 v 2050[4] Change projected by MIROC-H GCM with A2 emission scenario † | Significance for Lettuce production |
|---|---|---|
| **Mean temperature** | $T_{Avg}$ projected to increase by 7%<br>(1990 = 16.7 °C, 2050 = 17.9 °C) | Ideal temperature conditions for lettuce growth are 8 °C at night and 25 °C during the day. Lettuce growers are already coping with summer temperatures outside this range. Variety selection, irrigation management and scheduling of growth cycles are likely to be important adaptation strategies for continued production through summer.<br>Lettuce seed germination is best at 0-10 °C (Napier, 2004). While some varieties germinate at higher temperatures, the potential germination period is likely to be constricted as winters warm. The NAP may become more dependent on transplanted seedling product.<br>A warmer, dryer climate is likely to reduce the incidence of diseases such as Sclerotinia and Anthracnose.<br>Warmer winter months may offer greater opportunity for pests, such as silverleaf whitefly, to survive and increase in population size. |
| **Extreme heat days [1] & Heatwaves[2]** | Extreme heat days projected to increase by 38%<br>(1990 = 24 days/y, 2050 = 33 days/y)<br>Heatwaves projected to increase by 56%<br>(1990=0.9 events/y, 2050=1.4 events/y) | Increased temperatures (>28 °C) in the weeks approaching harvest, known as the 'hearting' development phase, may negatively impact product quality (Lovatt *et al*., 1997).<br>Projections of increasing temperatures suggest that increased incidence of daily temperatures >28 °C and a constriction of the suitable harvest period (Fig. 14).<br>As temperatures increase, so too does the opportunity for a wider diurnal temperature range. High diurnal temperatures increase the risk of reduced quality from flower head initiation (bolting). Bolting is most likely to present in plants grown over the summer months as the issue is exacerbated by long days and hot dry conditions. Appropriate cultivar selection may help avoid the issue.<br>Heat near harvest can induce tipburn. Growers may need to harvest early, and compromise weight, to maintain quality.<br>Likely increased water requirements. |
| **Frost [3]** | Frost events projected to reduce by 30%<br>(1990 = 3.8 days/y, 2050 = 2.8 days/y) | While cultivar selection can reduce the impacts of frost, severe and/or consecutive frosts are likely to cause leaf death or allow access to secondary pathogen infections.<br>Growers will need to remain vigilant with frost protection activities despite projections of reduced frost events. |
| **Mean rainfall & PET** | Rainfall projected to reduce by 5%<br>(1990 = 424 mm/y, 2050 = 402 mm/y)<br><br>PET projected to increase by 6%<br>(1990 =1311 mm/y, 2050 =1392 mm/y) | Lettuce must remain free of water stress right up to harvest to ensure maximum yields.<br>The most critical stages are during germination or seedling establishment and head expansion phases.<br>Through the dryer months, producers will need to consider the availability of irrigation water to satisfy potentially increasing plant water requirements.<br>Soil salinity may become more prominent if increased volumes of low quality irrigation water are applied. The issue will be exacerbated by reduced occurrence of winter leaching rain events. |

† Refer to Table 4 for more complete description of change projected by the MIROC-H GCM

[1] Extreme heat days = days where $T_{Max}$ >35 °C; [2] Heatwave = five consecutive extreme heat days

[2] Heatwave = five consecutive extreme heat days

[3] Frost events = days where $T_{Min}$ <1 °C

[4] Amounts stated are annual averages or occurrences in a projected or historic 30-year time period (Sect. 3.4)

## 4.7. Small-acreage crops

The NAP is a diverse horticultural region characterised by many more crops than those listed above. Other prominent plantings include brassicas, onions, tomatoes and a suite of field-grown vegetables.

### 4.7.1. Brassicas

Brassicas, such as broccoli and cauliflower, are particularly sensitive to heat at the critical phenological growth stage of head initiation. For many brassica crops, head initiation is favoured by mean temperatures of around 15-16 °C (Wheeler *et al*., 1995). Excessive heat late in the growing season can also result in reduced quality through uneven floret development in the head (Kaluzewicz et al., 2013).

### 4.7.2. Tomatoes

The most critical phenological stage in the production of tomatoes is the 8 to 13 days prior to flowering (Higashide, 2009). It is difficult to nominate a single temperature threshold for this important development phase given the wide range of tomato cultivars available and their different heat tolerances. Tomato growers on the NAP will need to increase their uptake of heat tolerant varieties. Having said this, most tomatoes on the NAP are produced in glass houses where growers have greater control in defining their micro-climates. Increasing energy demands and the associated costs will become a more prominent consideration for these producers.

### 4.7.3. Onion

*T*he onion is a crop whose phenological stages are driven more by light than by temperature. Increasing temperatures, under a relatively stable photoperiod cycle, are likely to have adverse implications for both yield and quality, most notably in terms of bulb size (Deuter, 2009). Also, harvesting and leaving onions in the field to cure requires temperatures to remain below 30 °C. Alternate curing strategies will become increasingly important.

## 4.8 Additional risks to optimal crop growth

### 4.8.1. Compressed phenology

Most crops will move through their growth cycle more quickly under a warming climate. For producers of seasonal vegetable crops on the NAP, this may bring the opportunity for additional cropping cycles per season through the introduction of earlier and later planting times. For some crops, this will depend on the development of more heat tolerant cultivars.

### 4.8.2. Increased soil temperature

Warmer soils occurring earlier in the season may allow direct seeding techniques rather than the costly process of transplanting greenhouse grown plants (Deuter, 2009). This assumes temperatures remain at the appropriate level for seed germination and that management strategies are in place to account for late frosts.

### 4.8.3. Pollination

Pollination becomes less reliable at higher temperatures in crops such as tomatoes, cucurbits and capsicums.

### 4.8.4. Increased PET and reduced rainfall

The combination of reduced rainfall and increased evapotranspiration have obvious implications for all field-grown crops. Producers will need to ensure they have sufficient allocation of irrigation water, not only to meet plant water requirements through average seasonal conditions but also to manage the increasing frequency of extreme temperature events.

### 4.8.5. Pest and disease activity

While a warmer climate may reduce populations of some pests and diseases, the overriding trend is for their increased survivability and activity. For example, higher temperatures are likely to favour pests such as Diamondback Moth, scale, thrips and mites.

## *4.9. Soil salinity*

Each of the GCM and emission scenarios assessed in this study have projected a widening of the water deficit as a result of increasing PET and declining rainfall (Figs 4 and 5). Analysis projects an increased reliance on irrigation to meet plant water needs (Fig. 5). The availability of additional water for irrigation is one of the most significant limiting factors to continued horticultural production on the NAP. If sufficient water can be secured for irrigation, producers will continue to produce crops that are adaptable to the warming climate.

The NAP is fortunate in that it has access to recycled wastewater from the Bolivar Wastewater Treatment Plant. However, this recycled water contains elevated concentrations of salts (frequently >900 mg/L) compared to rainwater. When applied as irrigation, recycled wastewater imports these salts to the crop's rootzone. As irrigators increase the volumes of recycled wastewater being applied, they also increase the amount of salt being imported into the soil. In a drying climate, rainfall may not always be sufficient to flush these salts from the rootzone. In dry years, rootzone salt levels could rapidly accumulate to levels that impact on the crop's performance (Sect. 3.1 and Tables 2–4).

Measures of salinity tolerance for various crops grown on the NAP are shown in Table 11.

**Table 11. Average rootzone salinity tolerance of various crops grown on the Northern Adelaide Plains. Threshold irrigation water salinities according to soil type and percentage yield loss per dS/m ECse after the threshold is reached (adapted from Unkovich et al., 2004). (se = saturation paste extract)**

| Crop | Average rootzone salinity tolerance ($EC_{se}$ dS/m) | Max irrigation water salinity (dS/m) before yield loss | | | % yield loss / dS $EC_{se}$ |
|---|---|---|---|---|---|
| | | Sandy soil | Loamy soil | Clay soil | |
| Potato | 1.7 | 3.2 | 1.8 | 1.1 | 12.0 |
| Olive | 4.0 | 5.1 | 2.9 | 1.7 | |
| Grape | 1.5 | 3.3 | 1.9 | 1.1 | 9.6 |
| Almond | 1.5 | 2.7 | 1.5 | 0.9 | 19.0 |
| Carrot | 1.0 | 3.3 | 1.2 | 0.7 | 14.0 |
| Lettuce | 1.3 | 3.3 | 1.5 | 0.9 | 13.0 |
| Broccoli | 2.8 | 3.3 | 2.8 | 1.6 | 9.2 |
| Cauliflower | 2.5 | 3.3 | 1.8 | 1.1 | |
| Tomato | 2.3 | 3.5 | 2.0 | 1.2 | 9.9 |
| Cucumber | 2.5 | 3.3 | 2.4 | 1.4 | 13.0 |

Management options include selecting crops and cultivars that have reduced water requirements and/or have a level of salt tolerance. There may also be an argument for additional processing of the water at the point of distribution (Bolivar). Reducing the concentration of salts in the irrigation water would be a costly exercise, but may become more cost effective in the future as demand for high-quality irrigation water increases under a warming climate.

# 5. CONCLUSION

This study provides an overview of the type of scientific analysis available to the NAP's horticultural industries. The results of this study suggest that whilst the timing of crop susceptibility to a changing climate varies, four major responses to climate projections were common to almost all crops: (1) likely compression and/or advancement of growth cycles due to increasing mean temperatures; (2) likely reduced yield and quality due to extreme temperature events (particularly heat), (3) likely increases in the severity of pest and disease events; and (4) likely increasing water deficits due to both reducing rainfall and increasing PET. In general, the future projections for the NAP climate suggest an increase in extreme weather events. However, the wide variety of crops and growing systems on the NAP provide a degree of resilience against extreme events, as not all crops are susceptible at the same time of the year.

## *Impacts of climate change on the horticultural industries*

The main impacts to the horticultural industries of the NAP from a future changing climate are likely to be attributable to:

### Increasing mean temperature and extreme heat days

For annual crops such as potato, lettuce and carrots there will be an increased dependence on cultivars with growth cycles suited to (1) shorter and warmer winters; and (2) longer and hotter summers. For perennial crops such as almonds, grapes and olives, changes in phenology have the potential to impact both yield and quality as critical growth stages occur at hotter times of the year. Further, the reduced availability of winter chilling through dormancy may result in reduced and/or protracted flowering events. While a warmer climate may reduce populations of some pests and diseases, the overriding trend is for their increased survivability over periods where the climate would previously have limited their activity. Higher temperatures are likely to favour pests such as diamondback moth, scale, thrips and mites.

The performance of all crops declines under extreme heat and heatwave conditions. Symptoms can range from reduced photosynthetic activity through to leaf (and whole plant) senescence with implications for yield and quality.

A summary of typical crop response to projected increasing mean temperatures and extreme heat days follows.

**Potatoes:** Shorter growth cycles and higher temperatures that favour increased foliar and reduced tuber growth. While conditions through the spring cropping (summer harvest) period may necessitate greater care, projected temperature changes are likely to make the autumn cropping (winter harvest) period more conducive to potato production. Extreme heat days may result in reduced tuber initiation, leaf senescence and associated yield loss

**Olives:** While winter chilling will satisfy most olive cultivars, those with high chill requirements may display an uneven and protracted bud break, which could extend to complete bud failure, in particularly warm winters. However, given the crop's tolerance to heat, and its preference for a long hot growing season, it is likely to remain viable under projected temperature changes.

**Grapes:** Advanced and compressed phenology leading to earlier harvest dates and potential logistic issues at vintage for larger producers. Earlier maturity also exposes fruit to extreme temperature events and increased risk of compromised quality. Extreme heat days may result in sunburnt and/or shrivelled berries with flavour taints

**Almonds:** Advanced and compressed phenology may have implications on pollination as synchronization of main crop with pollinator varieties shifts. Reduced chilling through dormancy may result in poor or protracted bud break. Heatwaves may reduce flower bud development. Providing plant water needs can be met, and abovementioned issues can be addressed, almonds will remain viable.

**Carrots**: Leaf growth favoured over tuber growth at warmer temperatures. While the timing of ideal growing conditions is projected to shift, production is likely to remain viable in all but the hottest months. Extreme heat days may result in misshapen carrots with poor flavour and texture characteristics.

**Lettuce**: Continued production of field grown lettuce will necessitate increased management in terms of cultivar selection, irrigation management and scheduling of growth cycles. Lettuce producers are likely to be most sensitive to extreme temperature events during the transition periods from cool to warm climate cultivars. Heatwaves may result in tip-burn, bolting and leaf senescence.

## Decreasing rainfall and increasing PET

The combination of reduced rainfall and increased evapotranspiration have significant implications for all field grown crops, as most require a steady supply of water throughout the growing season. Producers of both annual and perennial crops will need to ensure that they have access to sufficient irrigation water to manage the projected increasing water deficit.

## Frost

While frost events are projected to decrease in their frequency, the drying climate may increase frost severity. Also, the advanced phenology of many crops on the NAP will mean that frost sensitive growth stage may remain at risk.

# *Adapting to a future change in climate*

An adequate supply of water that is suitable for irrigation may help ameliorate many of the negative crop responses to the impacts of extreme heat events, and will also promote the continued viability of crops that are best suited to a climate that is warmer than the historic climate of the NAP (e.g. olives and, to a lesser extent, almonds). Securing sources of new water is likely to be one of the principal strategies to help growers adapt to a changing climate in the future. Furthermore, cropping under a changing climate may require producers to more closely monitor climate trends and forecasts when planning their cropping cycles. Growers may also need to invest in the development and use of alternative growing systems and explore new cultivars to help mitigate the potential impacts of climate change, such as warmer winters affecting chilling, increasing heat, drought, disease and salinity.

# APPENDIX A: DOWNSCALING REGIONAL-SCALE GLOBAL CLIMATE MODEL DATA TO THE LOCAL SCALE

Global Climate Models (GCMs) are the best tools available for simulating global and regional climate systems, and simulating the changes that may occur due to increases in greenhouse gas concentrations. Generally, these models provide reasonable representations of past trends over large spatial scales for a number of climate variables, such as temperature and air pressure. However, GCM results are too coarse to be adopted directly in analyses of climate impacts, and downscaling of the projections to the local weather station scale is required. A number of downscaling studies have been undertaken previously in South Australia (e.g. Charles *et al*. 2006 and Charles *et al*. 2009), however they are based on the projections from only one GCM, and do not consider changes to evapotranspiration, only rainfall. Hence, further downscaling of GCM projections is required to provide suitable data for the analysis of impacts that specific to a location and are affected by daily variations in climate variables.

The methods outlined in Gibbs *et al.* (2011) were adopted for this study, to enable daily time-step rainfall data to be generated, incorporating future climate GCM projections appropriate for South Australia. For the downscaling of GCM-projected rainfall, Gibbs *et al.* (2011) demonstrated a daily scaling method to transform the projections simulated by the GCMs, for the different time horizons and emission cases selected to the weather station scale. In a comparison of five downscaling approaches of differing complexity, Chiew *et al*. (2010) concluded that the simple to apply daily scaling method is suitable for hydrological impact assessment studies over large regions, particularly when the main considerations are changes to seasonal and annual catchment water yield. This method allows for variable scaling of rainfall amounts, hence projections that suggest that the largest rainfall events will increase, but the overall average rainfall will decrease, for example, can be incorporated. Adopting an empirical scaling approach such as this allows the range of projections, time horizons and emission scenarios selected to be considered, which would otherwise be unlikely to be feasible if more complex stochastic or dynamic downscaling approaches were implemented. For the downscaling of temperature projections, a simple linear scaling approach was applied, as described by Gibbs *et al.* (2011).

The development of downscaled projected daily PET data for this study is described in Appendix C.

# APPENDIX B: CLIMATE FUTURES FRAMEWORK FOR THE NORTHERN ADELAIDE PLAINS REGION

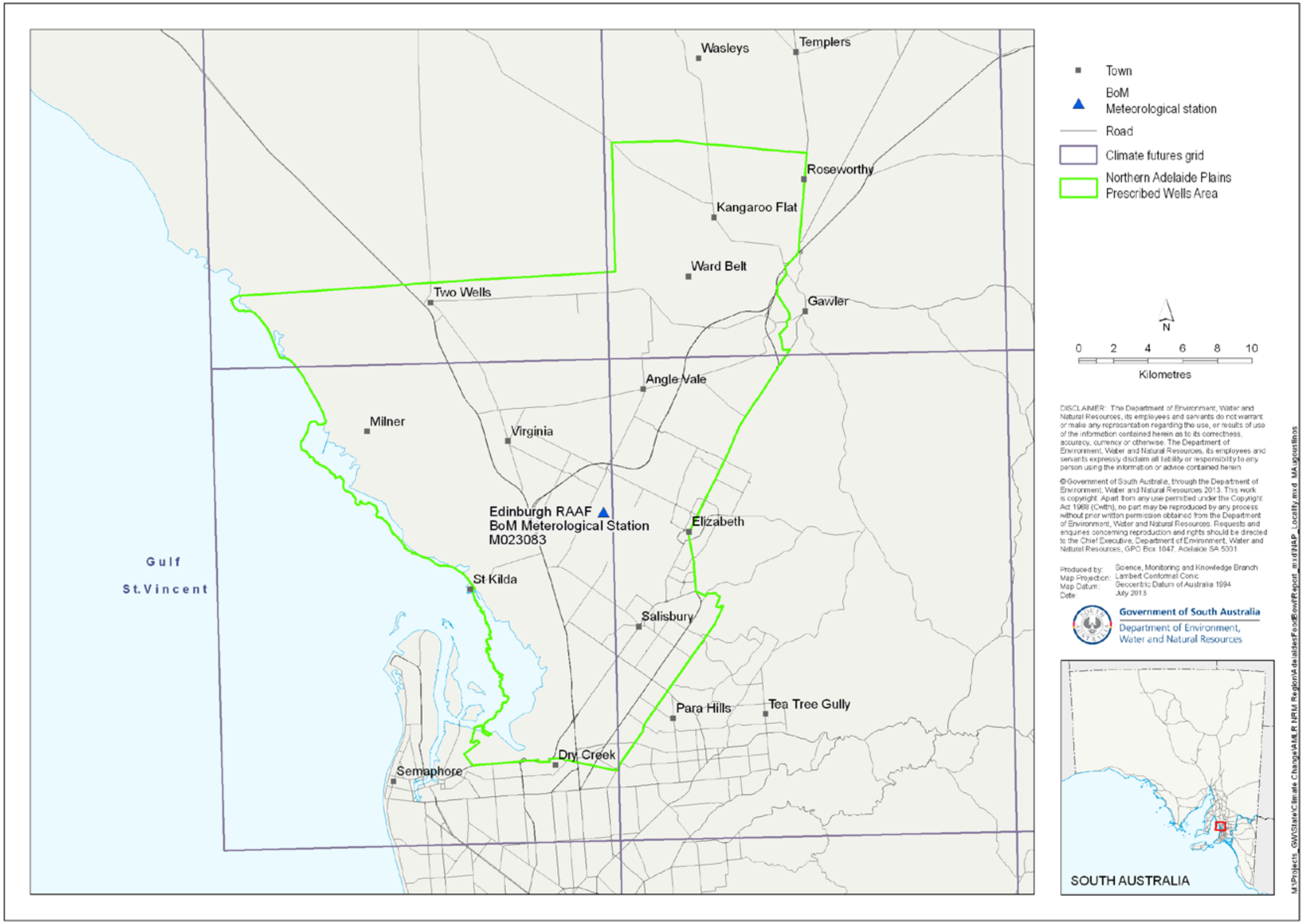
The Climate Futures Framework approach involves classifying the projected changes in climate by the different GCMs into separate categories (termed Climate Futures) defined by two climate variables – typically, the change in annual mean surface temperature and the change in annual average rainfall are used. Each Climate Future is then assigned a relative likelihood, based on the number of climate models that fall within that category (Clarke *et al*., 2011). The different Climate Future categories can then be used as the basis for further impact assessment.

Clarke *et al*. (2011) define a number of Climate Futures categories, including the 'most-likely', 'best' and 'worst' cases. The 'most-likely' case is defined as the category which satisfies all of three criteria; (1) contains the greatest number of models; (2) contains one third of the total number of models; and (3) the number of models must be at least three greater than the next most populous Climate Future. By this definition, it may in some cases be impossible to describe any one of the projected Climate Futures as 'most likely'. The 'best' and 'worst' case Climate Futures definitions are based on the particular risk assessment being undertaken. For example, in an analysis of Perth's climate, Clarke *et al*. (2011) defined the 'best' case as the Climate Future that would result in the highest rainfall and smallest temperature increase (i.e. the wettest and coolest climate) and the 'worst' case was defined as the Climate Future that would result in the least rainfall and highest temperature increase (i.e. the driest and hottest climate). These Climate Futures definitions are considered appropriate for the AMLR NAP region.

Clarke *et al*. (2011) found a strong correlation between change in evapotranspiration and change in mean temperature (0.9 for the Australian region) and as such, it is considered appropriate in the current study to use change in average annual temperature and change in average annual rainfall as the Climate Futures classifying variables. This approach allows all GCMs to be included in the analysis, as all models project changes in temperature, whereas only nine of the 24 models project changes in evapotranspiration. By evaluating both variables concurrently, internal consistency is maintained between the model projections, such that comparisons between the rainfall and temperature changes projected by each GCM are made at the same time. RThe approach of considering only median, 10th and 90th percentile projections for each variable separately (e.g. CSIRO & BoM, 2007) is problematic for impact studies where the combination of temperature and precipitation is important.

Although multiple GCM grid cells overlay the study area, the BoM station location that is most central to the NAP and with appropriate climate data is the Endinburgh RAAF station shown in Figure 15. The analysis was conducted, therefore, on the grid cell in which this station is located. The time horizon of 2050 has been used and both low (B1) and high (A2) emission scenarios have been investigated. For the grid cell and each emissions scenario, the Climate Futures analysis requires the projected changes in mean annual surface temperature (in degrees) and mean annual rainfall (as a percentage) derived from the 12 GCMs' outputs obtained from the OzClim website (CSIRO, 2012). The 12 GCMs were selected from the 24 available as these models were identified as suitable for the South Australian climate by Suppiah et al. (2006). The projected changes were calculated relative to the historic baseline period of 1975–2004.

The projections for temperature and rainfall for the grid cell have been plotted in Figure 16, where each point represents a different GCM output and darker red colours are used to represent the more-likely Climate Futures. Selected GCM outputs have been highlighted. Regular division of the different Climate Futures categories were adopted, every one degree of temperature change, and every 10% reduction in rainfall, starting from a "no change" of ±5%. The naming of the Climate Futures has been chosen subjectively and qualitatively and is only meant to provide some indication of the impacts of the projections.



Produced by: Science, Monitoring and Knowledge Branch
Map Projection: Lambert Conformal Conic
Map Datum: Geocentric Datum of Australia 1994
Date: July 2013

**Figure 15. Map of study area with Climate Futures grid overlay**

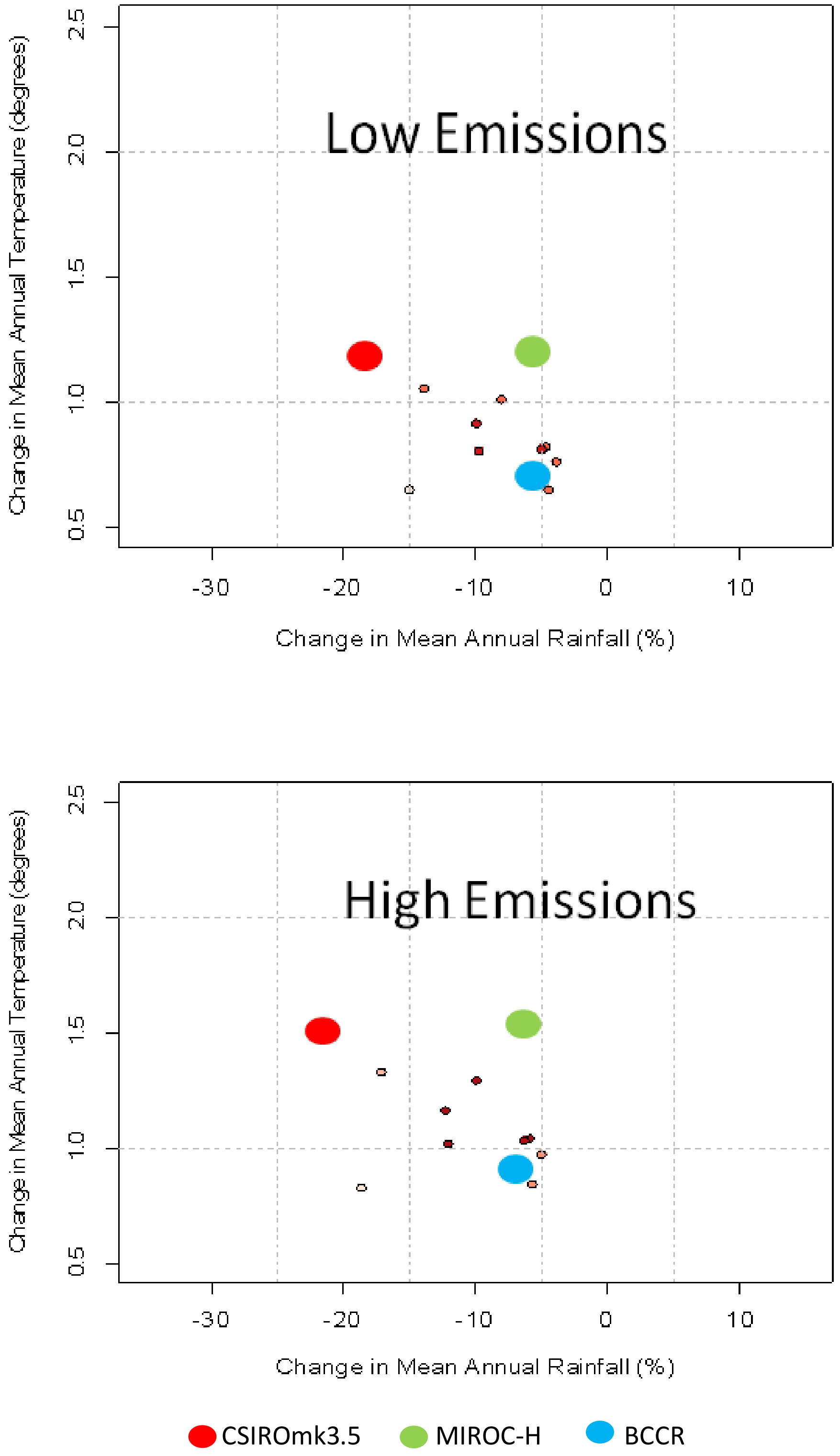


**Figure 16. GCM Projections for Climate Futures grid cell over AMLR NAP Region for 2050**

**Table 12 Climate Future matrix for Climate Futures grid cell over Little Para River catchment for 2050 Low Emissions**

| | | Mean Annual Temperature (° C)<br>Slightly Warmer | Warmer | Hotter |
|---|---|---|---|---|
| Annual Rainfall (%) | | 0.5 to 1 | 1 to 2 | 2 to 3 |
| Much Drier | More than -25 | | | |
| Drier | -15 to -25 | 1 of 12 models | 1 of 12 models | |
| Slightly Drier | -5 to -15 | 4 of 12 models | 3 of 12 models | |
| Little Change | -5 to 5 | 3 of 12 models | | |

**Table 13 Climate Future matrix for Climate Futures grid cell over Little Para River catchment for 2050 High Emissions**

| | | Mean Annual Temperature (° C)<br>Slightly Warmer | Warmer | Hotter |
|---|---|---|---|---|
| Annual Rainfall (%) | | 0.5 to 1 | 1 to 2 | 2 to 3 |
| Much Drier | More than -25 | | | |
| Drier | -15 to -25 | 1 of 12 models | 2 of 12 models | |
| Slightly Drier | -5 to -15 | 3 of 12 models | 6 of 12 models | |
| Little Change | -5 to 5 | | | |

Considering changes to the mean annual temperature, the GCMs project that for 2050 the climate is likely to be slightly warmer for the lower emissions (B1) scenario and warmer for the higher emissions (A2) scenario. The GCMs also project that the future climate is likely to be slightly drier. For the lower emissions scenario, the majority of the remaining GCMs that do not project the future climate to be slightly drier, project little change in rainfall. For the higher emissions scenario, the majority of the remaining GCM projections, project a drier future. This indicates that the GCM projections for the higher emissions scenario generally project a larger reduction in rainfall than the lower emissions scenario.

Of all GCMs considered, the CSIROmk3.5 projects the largest reduction in rainfall for both emission scenarios (Fig. 16). It also predicts the second greatest temperature increase of all GCMs. For these reasons it can be considered the 'worst' case Climate Future under the Climate Futures framework. When establishing the 'best' case, several models are clustered around a 5% reduction in rainfall and 0.75$^0$C increase in temperature in the low emission scenario and a 5% reduction in rainfall and 1$^0$C increase in temperature for the high emission scenario. One of these GCMs is the BCCR, highlighted in blue. Under the low emission scenario, no sub grid satisfies the requirements outlined by Clarke *et al*. (2011) necessary for classification as a 'most likely' GCM. However, under high emissions, the slightly drier and warmer grid cell does meet the requirements and one of the GCMs in that box is the MIROC-H, highlighted in green. Although selected as the 'most-likely' GCM, the MIROC-H does project relatively large increases in temperature and thus the results presented should give reference to all three GCM outputs, presenting readers of this report with a comprehensive range of potential future outcomes.

# APPENDIX C: CALCULATING POTENTIAL EVAPOTRANSPIRATION FROM AVAILABLE FUTURE CLIMATE DATA

Potential evapotranspiration (PET) is a variable of critical importance to horticulturalists as it represents the total idealised water requirements of that region under a certain land use. As PET is dependent on both atmospheric conditions and land use type and cover it is often derived using combinations of very complex formulae. In spite of its importance to land users and perhaps owing to its complexity, most GCMs do not calculate PET. The GCMs selected for inclusion in this report via the Climate Futures approach provide projections of minimum and maximum temperatures, which are variables that are also critical for horticulturalists, so the availability of both these variables were additional criteria for GCM selection. None of the selected GCMs produce projections of PET, necessitating estimation of PET from the projected data available, namely temperature and humidity. Two approaches for estimating PET given observed temperature and humidity were recommended in the literature, specifically the Blaney-Criddle method (Eq 1) and the generic temperature-humidity form (Eq 2) (Xu & Singh, 2002).

$$\boldsymbol{PET = k_m p(0.46T_a + 8.13)} \qquad \text{Eq 1}$$

Where:

$\boldsymbol{k_m}$ = Monthly consumptive use coefficient

$\boldsymbol{p}$ = percentage of total daytime hours

$\boldsymbol{T_a}$ = mean air temperature ($^0$C)

$$\boldsymbol{PET = aDT_a(b - cH)} \qquad \text{Eq 2}$$

Where:

$\boldsymbol{D}$ = day length (hours)

$\boldsymbol{T_a}$ = mean air temperature ($^0$C)

$\boldsymbol{a, b, c}$ are constants

$\boldsymbol{H}$ = Humidity term

Both methods were applied to observed daily data from 1970–2012 for Edinburgh SILO station, with coefficients optimised via a least squares approach when compared to calculated FAO56 (Penman-Monteith PET, see Allen *et al.*, 1994). As the temperature-humidity model requires one temperature and one humidity input, four combinations of these variables were examined. Option 1 uses average temperature and average relative humidity, Option 2 uses average temperature and relative humidity at maximum temperature, Option 3 uses maximum temperature and average relative humidity and Option 4 uses maximum temperature and the relative humidity at that temperature. The results are summarised in Table 14.

## Table 14. Results for Optimisation of PET models

| Method | Option | SSE |
|---|---|---|
| Temperature–Humidity | 1 | 9215 |
| | 2 | 6307 |
| | 3 | 5828 |
| | 4 | 4921 |
| Blaney–Criddle | 5 | 11034 |

Although requiring calibration of three parameters ($a$, $b$, $c$) as opposed to 12 monthly parameters ($k_m$), the temperature-humidity PET relationship outperformed the Blaney-Criddle method for all combinations of temperature and humidity variables. Interestingly, it seems that it is the maximum temperature and relative humidity at that temperature that are the better predictands of PET. Option 4 gives parameter values of $a$ = -0.1766, $b$ = -2.330, $c$ = -0.0147 and was used to calculate the value of PET presented in this report. Implicit in this methodology is the assumption that other variables will not change in the future, or alternatively it can be said that the PET estimates made by these models can be seen as a measure of total water requirement under future climate conditions for the current cropping practices in the region.

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