The Sunraysia Climate for Almond production: Analysis of strengths and challenges.

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Executive Summary

The key climate features of Victoria's Sunraysia region are:

- **An irrigated arid region with low rainfall and high evaporation**
- **A region with strong seasonal pattern of hot summers and cool winters**
- **A warm to hot region with an abundance of heat units**
- **Cool winters with clear cold nights provide moderate levels of chilling units**
- **An irrigated region with the desert to the north that is prone to heatwaves**
- **Clear, still and cold nights are prone to frosts**

These characteristics provide many of the strengths and challenges to almond production.

Future climate

A future climate is likely to be warmer and possibly drier. There is greater confidence in temperature increases than rainfall changes. The uncertainty in the rainfall projections and changes in the seasonality of rainfall may affect the risks of almond production. Preparing for a warmer and more water constrained future climate is recommended.

- **A warming climate will increase mean temperature during the growing season and increase heat units and decrease chill units**
- **There is likely to be an increases in the number and frequency of heatwaves**
- **The number and frequency of frosts is likely to decrease in the longer term**
- **There is likely to be an increase in desirable pollination conditions**
- **There is likely to be an increase in the number of desirable photosynthetic hours in spring but a reduction in summer**
- **There are no clear trends in rainfall but modest increases in evapotranspiration are expected which may increase irrigation requirements**
- **Increased evapotranspiration may enhance drying of fruit before and after harvest**

Climate drivers affect year-to-year variation in climate

Climate drivers influence Mildura's climate, and the weather and climate risks to almond production on a year-to-year basis. These climate drivers include El Niño Southern Oscillation (ENSO) which determines El Niño years and La Niña years, and IOD which determine positive IOD years and negative IOD years. More informed management decisions can be made from knowing how the climate risks are influenced by the climate drivers and the current strength of the climate driver. The Bureau of Meteorology provides up-to-date information on these climate drivers (http://www.bom.gov.au/climate/enso/ and http://www.bom.gov.au/climate/model-summary/).

El Niño years or positive IOD years typically have less rainfall throughout the year. This may

- **Increase the risk of insufficient rainfall in the orchard**
- **Reduce the supply of irrigation water**
- **Increase the irrigation demand as evapotranspiration may also be higher**
- **Reduce the risk of excessively rainy and humid conditions**
- **Have minimal influence on the risk of rainy conditions during harvest**
- **Increase the number of desirable pollination hours in August**

El Niño years or positive IOD years are typically warmer in spring and early summer with higher mean and daily maximum temperature but cooler daily minimum (night) temperature. This may

- **Increase the number and frequency of heatwaves**
- **Hasten developmental growth due to warmer spring and summer temperatures**
- **Decrease the number of undesirable photosynthetic hours in summer leading to reduced carbohydrate gain**
- **Chill accumulation before August is largely unaffected by these climate drivers**
- **Lack of moisture and clear nights can increase the number of frosts**

The opposite of these conditions are more likely in La Niña years and positive IOD years.

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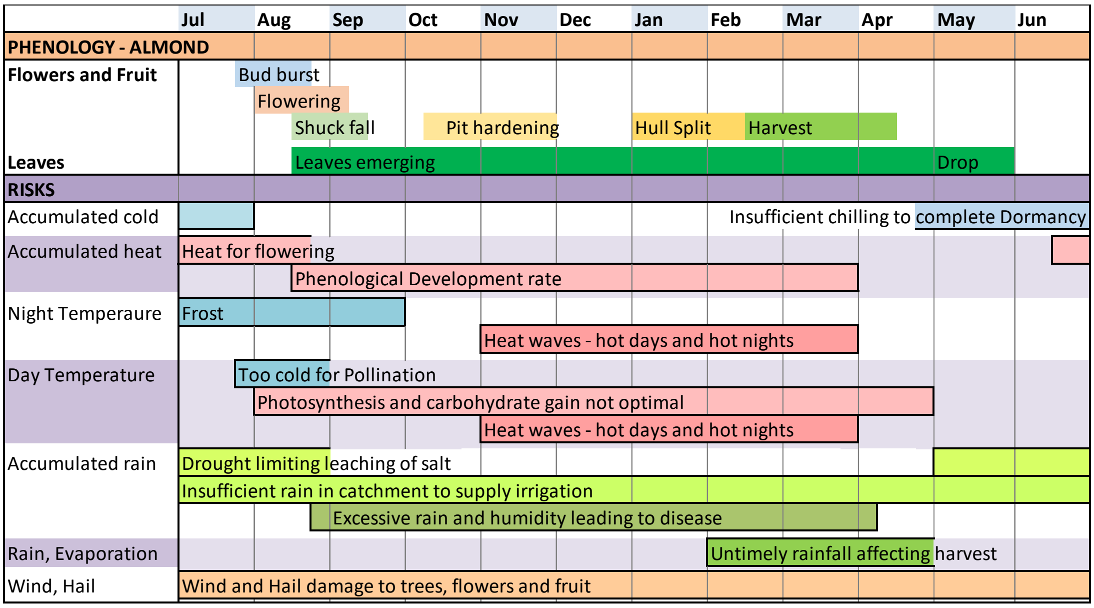
Phenology calendar to assess weather and climate risks to almond production

There are a range of weather and climate risks for almond production. A phenology calendar can be used to identify the weather and climate risks and the time of year that they occur. In a series of meetings with almond growers. The risks were identified and ranked for economic severity based on likelihood of occurrence and likely economic loss.



The phenology and climate risk calendar for almond production in Australia. The identified phenological stages typically commence at the dates shown. The risks identified from undesirable weather and climate events have been amalgamated into broad categories with the shaded periods of the year indicating when the risks impact on production.

Australian almond growers identified a total of 12 risks that could be classified as being related to either temperature, rainfall and evapotranspiration, or wind and hail. Some risks encompassed several weather factors. For example, the risk of rain at harvest (ranked as most important risk), is related to excessive moisture caused by rain and insufficient drying which is best approximated by evapotranspiration, which is itself a complex relationship between elements including incoming solar radiation, wind, temperature and humidity. Other risks such as synchronicity of flowering between pollinators are related to both varieties accumulating their respective chill and heat requirements to flower at similar times. Risks could also be categorised as being related to either single weather events (e.g. rain at harvest, frost or heatwave) or of a longer nature (e.g. insufficient chill or seasonal drought).

Growers' ranking of weather and climate risks to almond production

Rain at harvest (ranked 1). Consistent finding that this is the primary concern. It was ranked a much greater concern for larger operations than small orchards. This risk is much greater in Australia than California. Some recent developments in the cost of drying may reduce this risk.

Heatwaves (ranked 2). Direct cost is extra water and the operational challenge of irrigating before a heatwave. Improved soil structure and increased water holding capacity may improve resilience. Uncertainty on the extent of the damage on yield and quality for current season and next season's crop.

Wind damage (ranked 3). Although relatively rare for major damage across a region, participants assessed there is some wind damage in almost all years.

Non-synchronised flowering (ranked 4). Australian conditions meet the chill requirement for almonds but there is concern on year to year variation of flowering and fruit set due in part to non-synchronised flowering within trees and between main and pollinator varieties.

Rain and Humidity leading to disease (ranked 5). There is concern on current and emerging diseases and pests, and uncertainty about the conditions leading to outbreaks.

Temperature too cold for pollination (ranked 6) and Temperature too warm for pollination (ranked 12).

Although bee activity is weather dependent, improved placement of hives can increase pollination and may overcome periods of adverse weather.

Quantity and quality of irrigation water (Ranked 7). High level of concern on salinity on northern Adelaide Plains but general sense of salinity being managed by policy and engineering in main inland irrigated regions.

Frost (Rank 8). Highly localised. Almonds are susceptible to spring frost damage but in many cases careful site selection has minimised this risk. Frost mitigation fans are increasingly used to overcome potential frost conditions.

Inadequate winter rain (Ranked 9). Because almonds are mostly grown on lighter soils only modest amounts of water can be stored. Improved soil structure and increased water holding capacity may provide a mechanism to store this rainfall. In regions where salinity is a concern winter rainfall is important to leach salts out of the profile.

Hail damage (Ranked 9). Hail is a rare phenomenon that depends on local meteorological conditions.

Warmer spring and summer temperatures (Ranked 11). There is a general confidence that almonds can cope with heat as indicated by successful production of almonds in California's southern central valley which is warmer than Australian growing regions. However Californian soils are typically of higher quality and this may contribute to increased resilience to adverse conditions. Cool springs that slow development are of greater concern.

Managing almond production in a variable and changing climate

Australian almond production, like many horticultural industries, is exposed and sensitive to climate variability and to any future changes in climate. However, the adaptive capacity of the industry will lessen potential impacts to existing climates and to future changes in climate.

Examining the historic trends, year-to-year variations and impact of climate drivers on the risk indices, and exploring the indices in a future climate can tell you about how the risks may change, either beneficially or detrimentally. This can assist with medium and long term planning of orchard operations.

Some climate and weather risks to almond production in Australia are listed below. The table also details the trends in these risks and the year-to-year variation and role of climate drivers during the historic climate. If the climate driver increases or decreases the chance of adverse or of favourable conditions in the coming season then seasonal forecasts of these climate drivers can be a useful management tool.

El Niño years or positive IOD years increase the chance of drier conditions, warmer mean and daily maximum temperature and cooler daily minimum (night) temperatures, and La Niña years or negative IOD years increase the chance of wetter conditions, cooler mean temperature daily maximum temperature and warmer daily minimum (night) temperatures. However it is important to appreciate that not all warm years are El Niño years or positive IOD years and not all cool years are La Niña years or negative IOD years. Similarly not all dry years are El Niño years or positive IOD years and not all wet years are La Niña years or negative IOD years.

Additionally the expectations from climate change science on how the weather and climate risks may change in a future warmer and drier climate are detailed. This can provide a guide to longer term planning.

Some possible adaptation options are provided that the industry could use to respond to and manage the adverse conditions presented by the weather and climate risks.

Climate and weather risk	Trends, variations and expectations from climate science and industry response
Rain at harvest Consistent finding that this is the primary concern. Related to rain and evaporation.	Considerable year-to-year variation in amount of rain, number of raindays and moisture positive days during the harvest season (February to April). Weak relationship indicating El Niño decreasing and La Niña increasing this risk. Projections are inconsistent on changes to rainfall in summer and autumn. Trend in recent decades of increasingly higher evapotranspiration. However the strong seasonal pattern of declining evapotranspiration, and therefore less drying potential, in the autumn months will remain. A warmer climate may hasten plant development pushing harvest to a drier time of year. The industry will need to continue exploring ways of dealing with untimely rain at harvest. Irrigation scheduling offers some potential to modify harvest date. Increased use of weather forecasts to assist with harvest scheduling. Shake and catch harvesting would avoid contact of fruit with wet soil. Improved drying of fruit in stockpiles either through altered covers or actively venting air through stockpiles.
Heatwaves Rated as the second most important concern. and **Warmer spring and summer temperatures** The direct cost is extra water, as warming leads to and increased demand for water requirements	Trend in recent decades of increasingly warmer conditions throughout the year including spring and summer, although with considerable year-to-year variation. Similarly a trend of an increasing number of heatwaves in recent decades, but a considerable year-to-year variation in the number and extent of heatwaves. Warmer conditions and more heatwaves in spring and early summer in El Niño years and positive IOD years. High confidence in warming and of increased heatwaves. There is an acceptance that almonds can cope with heat but there is uncertainty on the threshold temperatures that cause damage to almond crops. These may differ for different processes such as optimising canopy photosynthetic carbon gain, fruit growth and yield; or for developing buds. Bud failure is related to warmer conditions in early summer when buds are developing. More responsive management to crop requirements may be required due to expected faster crop development, and for managing faster lifecycles of pests and diseases. Management may also have to plan for the expected higher evapotranspiration due to the warming climate. Increased use of weather forecasts will be an invaluable management tool for scheduling operations, particularly when planning and implementing responses to heatwaves such as ensuring adequate and timely irrigation. There is a need to continue exploring ways to manage heatwaves and cool canopies through irrigation scheduling; or other means such as leaf surface

	covers that reflect light, or growth regulators that impart heat protection to the crop. Improving soil structure and water holding capacity may increase resilience to heatwaves, and also to generally warmer growth conditions.
Quantity and quality of irrigation water and **Inadequate winter rain to fill profile and leach salts** Rated of medium concern.	Supply of irrigation water is affected by storage and inflows into the main rivers. These vary on a year-to-year basis. There is a general relationship between ENSO and IOD with rainfall in the Murray-Darling basin with less rainfall in El Niño years and positive IOD years. Inflows into Murray-Darling basin river system in a future climate are projected to reduce by 20 to 30% for every 10% decline in rainfall. These declines in inflow would be expected to reduce the availability of water for irrigation. Rainfall in most almond growing regions are generally highly variable, but lower in El Niño years and positive IOD years particularly from August to December. Winter rainfall typically has a stronger relationship with IOD than with ENSO. Evapotranspiration (ETo), particularly during the growing season (September to April) has increased in recent decades. El Niño years and positive IOD years have higher evapotranspiration during the growing season. Irrigation deficit, measured as Evapotranspiration – Rainfall, is higher in El Niño years and positive IOD years. The expected increase in evapotranspiration in future climates may place greater strain on the availability and cost of water. It would be prudent to expect a water constrained future and fluctuations in the quantity and possibly quality of irrigation water. The response to irrigation continues to require attention in the current and future climates when drivers for water loss by plants will change. Altered management practices such as plant spacing, density, pruning or training may affect kernel yield per ML of water applied. Increased understanding of the salt sensitivity of each almond growth stage would indicate if more sensitive stages need to be managed with greater care.
Temperature too cold for pollination Ranked as medium concern.	Pollination is poor if temperatures are below about 15°C and if rain occurs. Pollination conditions during August are typically better in El Niño years and worse in negative IOD years. A warming trend should increase the conditions deemed suitable for pollination as flowering occurs in a cool time of the year.
Insufficient chill accumulation to satisfy flowering Ranked as low concern. and	Chill accumulation prior to August in most almond growing regions is typically above chill portions 40 but with considerable year-to-year variation. The chill requirement of almonds to satisfy dormancy and to flower are considered low with the Nonpareil variety requiring a minimum chill accumulation of 23 chill portions.

	Higher chill years of up to 35 chill portions in California produced higher yields in Nonpareil, suggesting the minimum chill for flowering may not optimise economic return. No indication that ENSO or IOD affect chill accumulation prior to August. A warming climate is modelled to reduce chill accumulation. In most currently warmer almond growing locations a 2°C warmer climate may reduce chill portions to levels approaching those considered insufficient for current main varieties to satisfy dormancy, and considerably below that to optimise yield. It is possible chill accumulation may be promoted using surface covers that reflect sunlight and reduce heating, or sprinklers that enhance evaporative cooling. Rest breaking agents that assist in overcoming dormancy are available for use in some industries.
Non-synchronised flowering Ranked as high concern. Flowering is controlled by chill and heat accumulation that are unique for each variety.	The time of flowering occurs due to a complex interaction of chill accumulation and heat accumulation. A warming climate will independently affect both the accumulation of chill and of heat. The amounts of chill and of heat that are required to achieve flowering are unique to each variety. The synchronicity of flowering between the pollinators and the main varieties that currently exists may not be maintained in a warming climate. Self-fertile varieties should reduce the risk of non-synchronised flowering. It may be possible to increase chill accumulation or to overcome dormancy (details above) of the current varieties in order to maintain synchronicity of flowering.
Frost Almonds are susceptible to spring frosts but careful site selection has minimised this risk.	The date of last frost and the number of frosts after July are highly variable on a year-to-year basis but there are no strong indications that the risk of frosts has changed in recent decades. The number of frosts is affected by ENSO but there is less certainty in the date of last frost. In the long term frost frequency and severity is expected to decrease. However spring frosts may increase in coming decades. Site selection is a major factor that can alter frost risk. Frost can also be managed in several ways such as through air movement (e.g. fans or similar), sprinkler irrigation, soil moisture, ground cover.
Rain and Humidity leading to disease There is uncertainty on the impact of wetter and warmer conditions on the nature of pests and disease. Rated as medium to high concern.	The number of rainy days and of moisture balance positive days from August to April is highly variable on a year-to-year basis. There are typically more rainy days and of moisture balance positive days in spring and early summer in La Niña years and negative IOD years. Projections are unclear on changes to rainfall. There is high confidence of warmer conditions but less certainty about relative humidity. Many horticultural pests and diseases are sensitive to rainfall, temperature and humidity, so the suite of problem species may change in a warmer and drier climate. Managing these is likely to require constant vigilance.

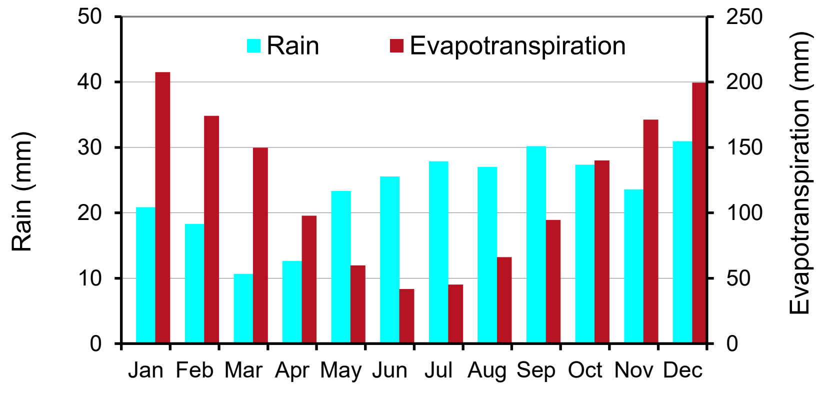
The yearly climate at a glance

Mildura is used here to describe the climate of Victoria's Sunraysia region. Mildura has a warm dry climate with distinct seasonality in temperature and evapotranspiration (ETo) but little seasonality in rainfall. The following figures show the mean monthly values of several climate indices important to almond production. The means were calculated for the period from 1986 to 2005 using daily weather information from the Bureau of Meteorology's Mildura Airport meteorological station (station 76031). The source was patched point data (https://silo.longpaddock.qld.gov.au/).

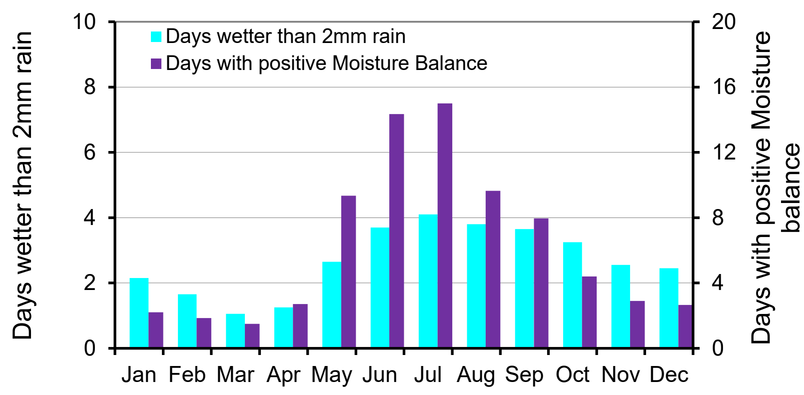
Low rainfall and high evapotranspiration

Rainfall is low in most months with little difference between wetter winter and spring months and drier summer and autumn months.

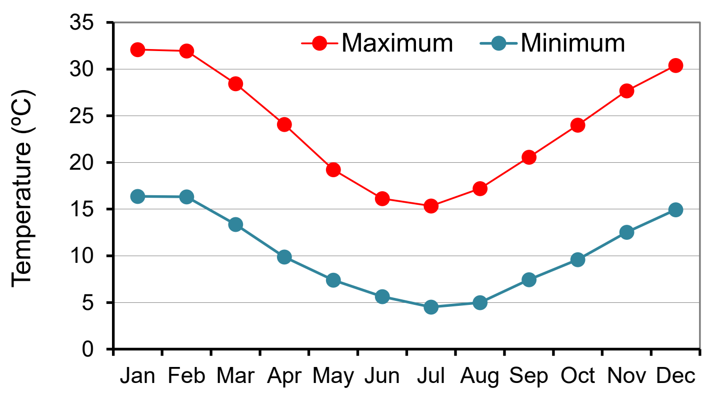
Evaporative demand is seasonal and much higher in summer than in winter.



Days that are wetter such as those having more than 2 mm rain, or those where evapotranspiration does not dry off any fallen rainfall and therefore considered moisture balance positive are more likely in winter than summer.



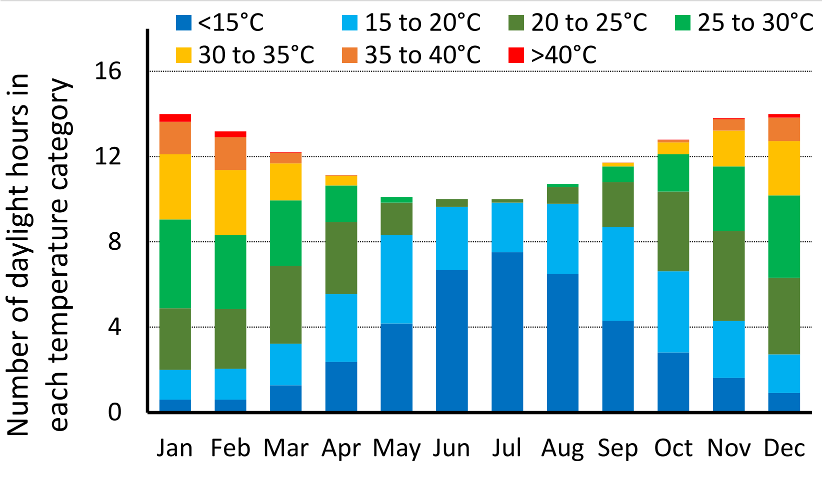
Season pattern of hot summers and cold winters



Summers are characterised by mean monthly maximum temperatures over 30°C and minimum temperatures of about 15°C.

Mean monthly maximum temperatures in winter typically between 15° and 20°C, while minimum temperatures are about 5°C.

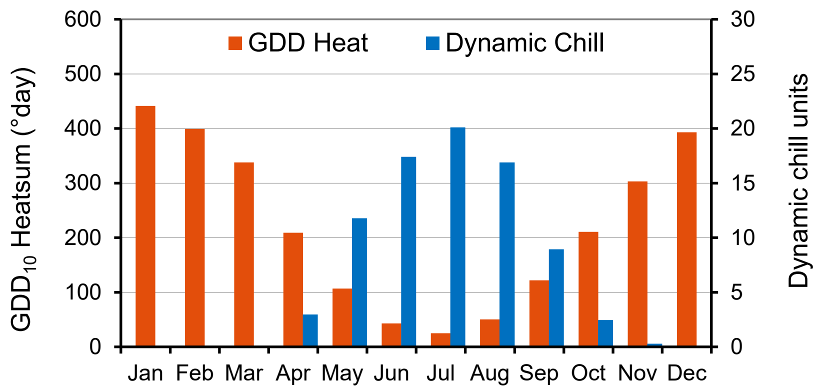
Plenty of daylight hours with temperatures desirable for photosynthesis



Carbon gain by the plant from net photosynthesis is typically greatest at temperatures between 20 and 30°C and declines rapidly when it is warmer than 35°C.

There are many hours per day where high photosynthetic rates are possible, providing the plant has access to water.

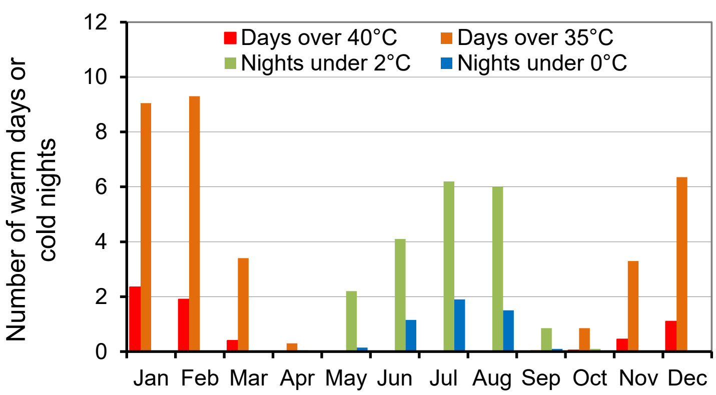
An abundance of heat units and moderate chill units



There is an abundance of heat accumulation, measured here as GDD base 10, in all seasons from spring to autumn.

Chill accumulation, measured here using the Dynamic model, typically commences in late April or early May. While moderate, it is sufficient for many crops, including almonds.

Prone to heatwaves and to frosts



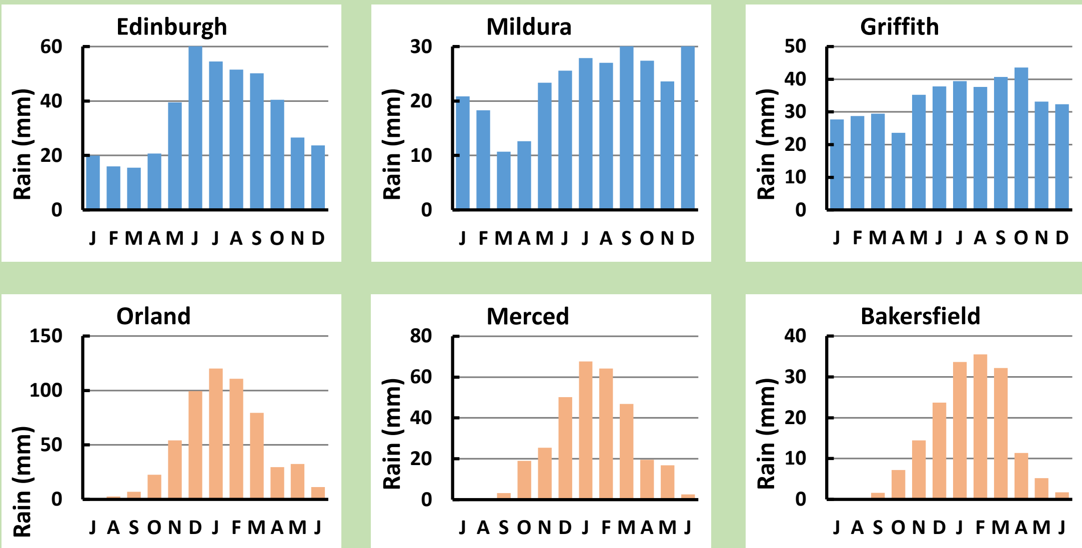
Days warmer than 35°C are common in summer (almost 1 in 3 days). Days hotter than 40°C are much less frequent but not uncommon.

Cold nights can occur from late autumn to early spring, with nights colder than 0°C typically confined to a few occasions per month in May and the winter months. Frost is possible when the screen temperature is colder than 2°C.

How does the Sunraysia compare to other growing regions in Australian and California?

Comparing the climate of your location with other almond growing locations is a useful way to gauge the strengths and challenges of your location.

The Australian almond growing regions extend from milder coastal locations such as Adelaide plains to the hot inland regions. But even the warmest region (Griffith) is cooler than most Californian locations. The most striking difference between Australian and Californian locations is the seasonality of rainfall. Californian locations, particularly the central and southern locations, are strongly Mediterranean with little if any summer rain, whereas most Australian almond growing locations have a more uniform rainfall pattern. The higher rainfall in the Australian harvest season (February to April in Australia and August to October in California) is considered a disadvantage as it affects timing of harvest operations and can reduce yield and quality.



A major difference between Australian and Californian locations is the seasonality in rainfall as seen by these average monthly rainfall graphs. Australia has little monthly variation in rainfall compared to the strongly Mediterranean climate of wet winters and dry summers in California.

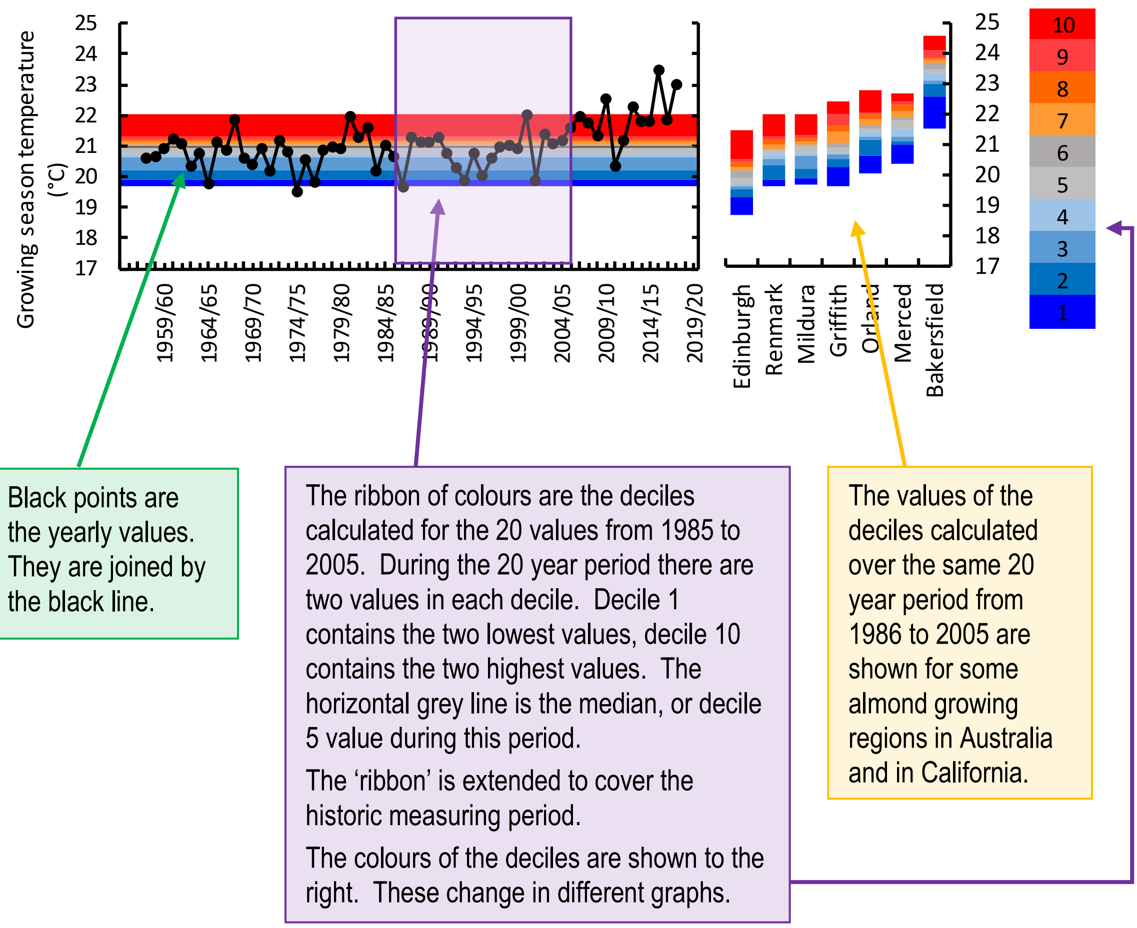
Most of the information we have shown to this point are averages. The following graphs show year-to-year variation in the climate at Mildura from 1957 to 2018 as the black points.

The coloured horizontal ribbons are the deciles calculated from the 20 year period from 1986 to 2005. Decile 1 contains the two lowest values, decile 2 contains the next lowest two values and so no while decile 10 contains the two highest values. The median value is the value which marks the level dividing the ranked data set in half. The median is also known as the 5th decile, decile 5 and the 50th percentile - they are all the same thing.

The colours and deciles are shown to the right. Warm deciles are shown as red, Cool deciles as blue, Wet deciles as green and Dry deciles as brown. Decile 5 is shown as grey and as the solid grey line.

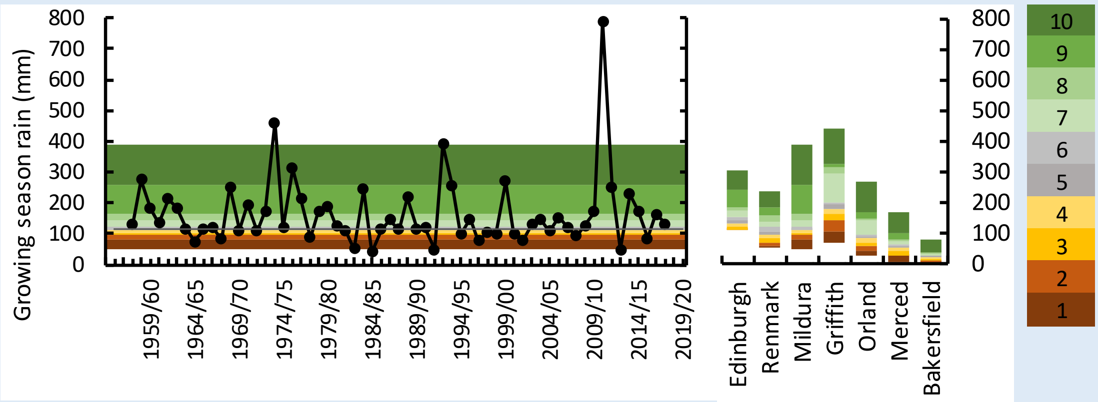
The columns of deciles on the right hand figures can be used to compare almond growing locations in Australia and some almond growing regions in California; Orland in the northern region, Merced in the central region, and Bakersfield in the southern region.

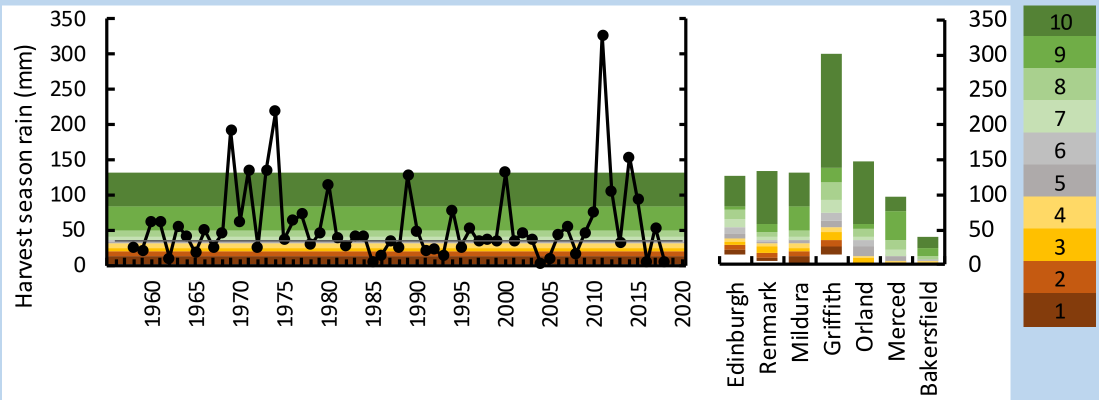
Illustrated guide to the graphs



Trends and variation in rainfall, evapotranspiration and irrigation deficit

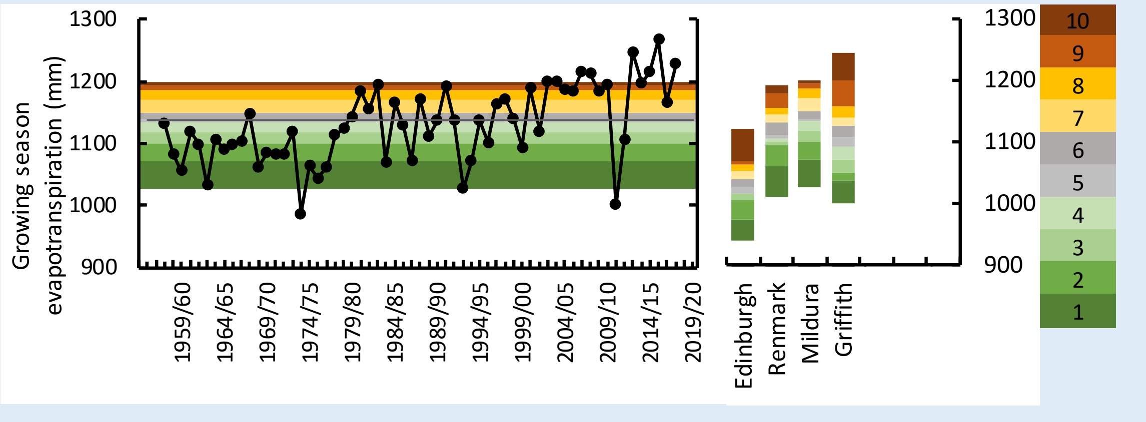
The Sunraysia, like many almond growing regions has low rainfall. While wet years and dry years occur, there is little evidence to date of strong trends in annual or growing season rainfall.





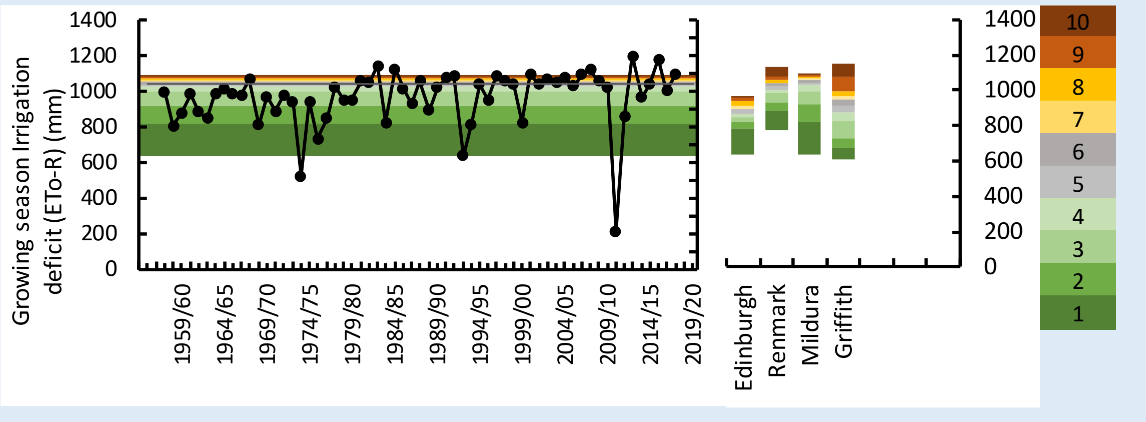
There is considerable year-to-year variation in rainfall. Almonds are grown in both wetter locations in Australia and drier locations in central and southern California. Growing season and Harvest season in Australia were calculated from October to April and February to April; and April to October and August to October in California. *100mm is equivalent to 1ML / ha.*

Like most almond growing regions the evapotranspiration (ETo) in the Sunraysia is much greater than the rainfall. There is a trend of increasing evapotranspiration in recent decades.



Evapotranspiration (ETo) like rainfall shows year-to-year variation, but unlike rainfall there is a trend of increasing evapotranspiration in recent decades. 100mm is equivalent to 1ML / ha.

The demand for irrigation water is related to both the inputs from rainfall and loss from evaporation and transpiration. A basic measure of the demand for water, or irrigation deficit, can be obtained as the difference between evapotranspiration and rainfall (ETo - R). There is a trend of increasing irrigation deficit in recent decades. This trend of increasing irrigation deficit occurs in both the growing season (September to April) and non-growing seasons (May to August).

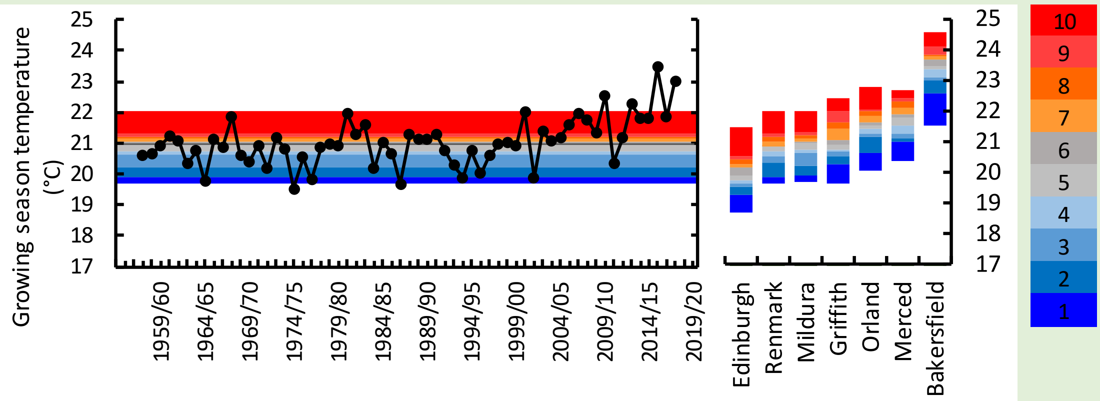


Irrigation demand, measured as the difference between evapotranspiration and rainfall (ETo - R), shows year-to-year variation and an increasing trend in recent decades. 100mm is equivalent to 1ML / ha.

Trends and variation in growing season temperature, heat units and chill units

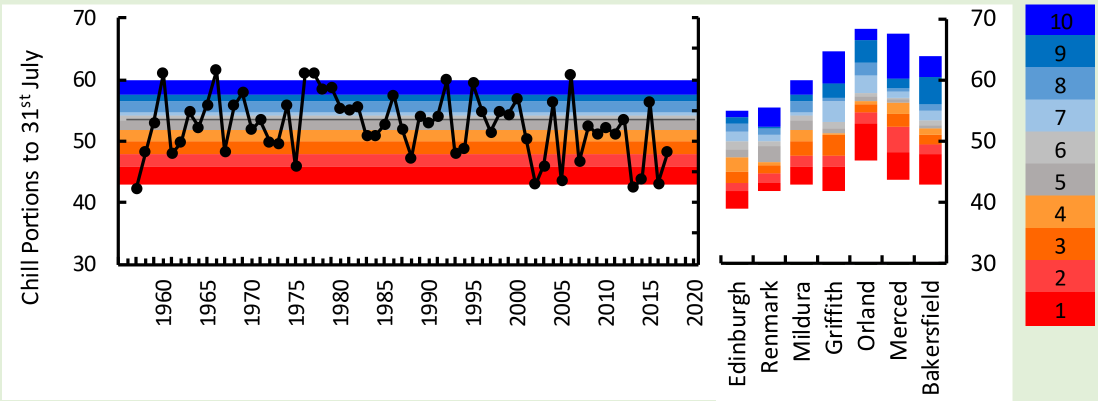
Heat units are strongly related to mean temperature. The mean temperature during the growing season shown below can be a useful substitute for heat accumulation during this same period.

Mildura's mean temperature during the growing season is similar or slightly cooler than other almond growing regions of inland Australia with only Edinburgh in the Adelaide plains being cooler. Australian almond growing regions are typically cooler than those in California. While there is considerable year-to-year variation in temperature with cooler years and warmer years, there is a strong trend of increasingly warmer years in recent decades. This has led to greater heat accumulation.



Mean temperature and therefore heat accumulation during the growing season varies from year-to-year. There is a trend of increasingly warmer conditions with many seasons being warmer than median (decile 6 or above) in the past 20 years. Temperatures in Australian almond growing locations are generally cooler than in Californian almond growing locations.

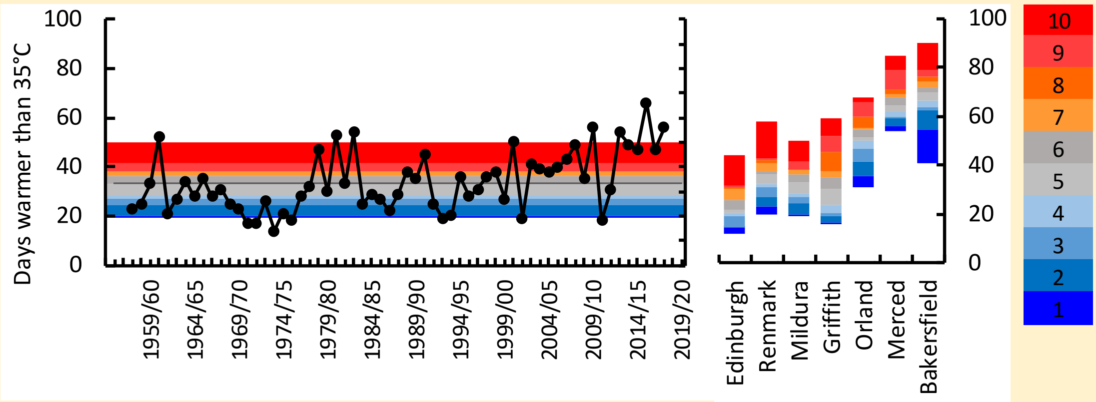
Chill accumulation at Mildura fluctuates from year-to-year but is generally intermediate compared with more inland Australian locations and Californian locations. The figure shows the number of Chill portions measured using the Dynamic model to 31st July for Australian locations (and to 31st January for Californian locations). There have been more below median (decile 5 and less) chill years in the past 20 years and only moderate further warming will be required to decrease chilling in future years to levels lower than that experienced in several decades. However as almonds require only modest chilling (23 chill portions for Nonpareil and less for some other varieties) to satisfy dormancy compared with many deciduous fruit crops, it is likely the chilling requirement of almonds will continue to be satisfied at Mildura for some years.



Chill accumulation at Mildura varies from year-to-year. There have been many more below median (decile 5 and lower) chill years in the past 20 years. Chill accumulation is typically less in more coastal Australian locations. Most Australian almond growing locations generally have less chill than Californian almond growing locations.

Trends and variation in heatwaves and frost potential nights

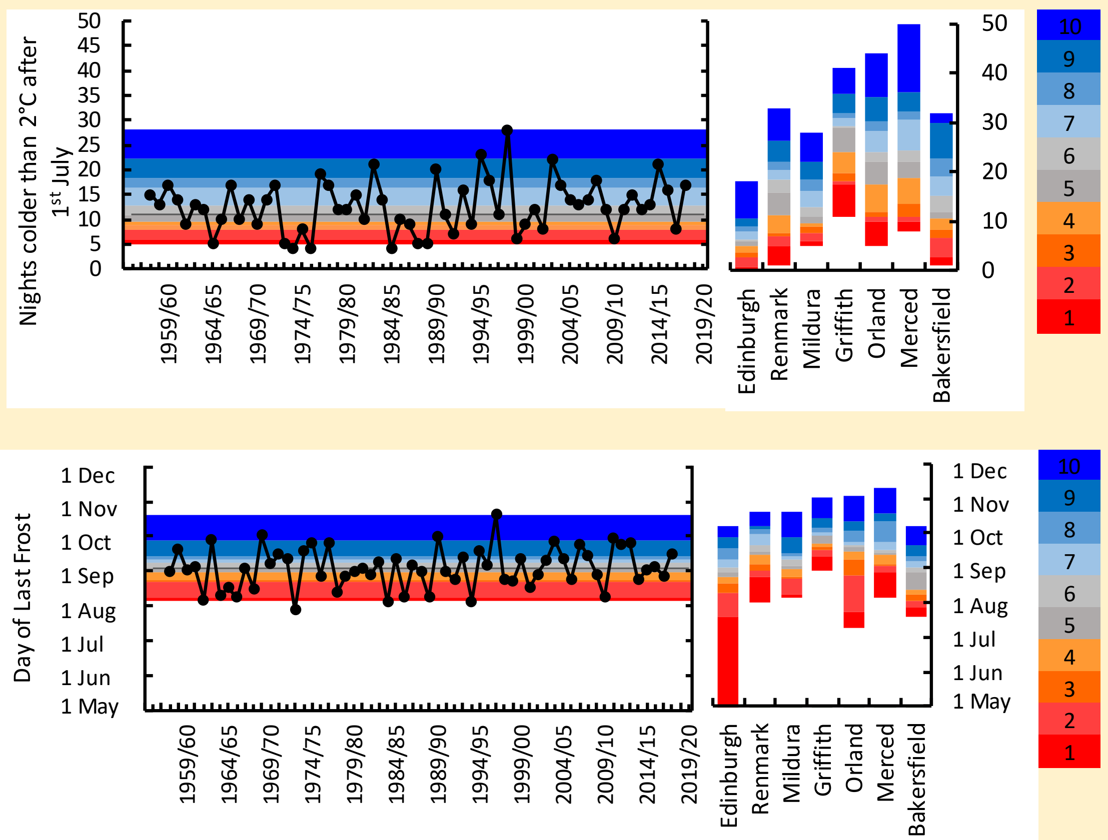
Australian almond growing locations typically experience far fewer hot days than those in California. Mildura experiences about the same number of days hotter than 35°C as Renmark and Griffith, but these are fewer than most Californian locations. The occurrence of these hot days and heatwave conditions has increased in recent decades with most recent years having at least as many hot days as what was a 2 in 10 hot year, that is, decile 9 or 10 during the 20 years period from 1986 to 2005.



The number of hot days over 35°C has increased in recent years but remains lower than in Californian locations.

The potential for frosts was determined by the number of nights cooler than 2°C. The number of frost potential nights after 31st July (after 31st January in Californian locations) was used as this is the time when buds have typically commenced swelling but before flowering. It shows that Mildura has a moderate number of nights cooler than 2°C after 31st July. At first glance this could be considered as unusual in a warming climate, but nighttime minimum temperatures are also related to the dryness of the air and cloud clover, which may both be lower in warmer years. This trend in cold nights and frost over spring is of concern to the grains industry [1].

Minimum temperatures and frost formation has considerable spatial variability which is why site selection is a valuable planning tool when establishing horticultural enterprises. This also means that extrapolation of the frost data from the Mildura Airport meteorological station to local properties should be done with care.



The number of nights sufficiently cold for frosts to potentially occur can be large in some years. Overall the number of cold nights are about as common in the inland Australian almond growing locations as in the Californian locations. The date of the last cold night has considerable year-to-year variation.

1. Crimp S, Baker KS, Kokic P, Jin H, Nicholls N, Howden M. 2015. Bayesian space–time model to analyse frost risk for agriculture in Southeast Australia. *International Journal of Climatology*. **5**: 2092-2108.

How different might a future climate be from what we have experienced?

There is a high degree of confidence amongst scientists studying earth systems that the climate is changing and that humans are the main cause of this change. We can be confident that the Sunraysia will be warmer and that rainfall in the Sunraysia and Murray-Darling Basin will be changed but there is uncertainty on the extent of warming and the exact changes in rainfall. Climate models, or Generalised Circulation Models (GCM's) project the likely future climates and provide information on the extent of warming or changes to rainfall and other parameters such as evaporation, and wind. While there are a range of possible futures conditions, there is general agreement that almond growers should prepare for a warmer and more water constrained future.

The impact of two future climate scenarios are examined to illustrate the likely scale of changes that could be expected. The actual changes may be more or less than those shown. Further details can be found in the recent reports: Climate Change in Australia report (CSIRO and Bureau of Meteorology, 2015, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/).

If greenhouse gas emissions are greatly reduced and follow the moderate emission RCP4.5 scenario it is expected that the climate will be about 1°C warmer by 2050 and 2°C warmer by 2090 than what was experienced during the 20 years period from 1986 to 2005. This 20 year period is known as the base period with climate change projections compared to it. If greenhouse gas emissions follow the higher emission RCP8.5 scenario, warming is projected to be 2°C by 2050.

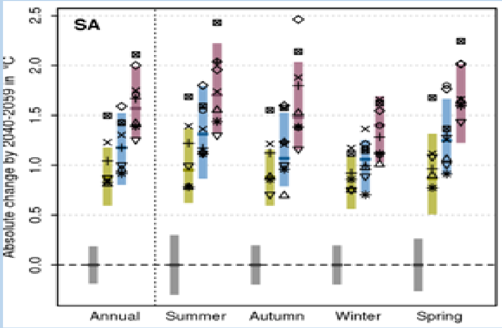
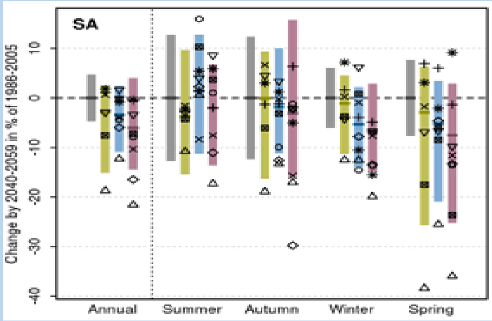
Potential evapotranspiration (ETo) is expected to increase by about 4% per 1°C warming in Southern Australia (CSIRO and Bureau of Meteorology, 2015), although there is uncertainty in the response of ETo to warming [2, 3].

There is greater uncertainty in the projections of rainfall. The high year-to-year and decade to decade variation is projected to continue or even increase. Although different models project either wetter or drier conditions in all seasons, there is high confidence that cool season rainfall will decline towards the later part of the century and there is medium confidence that rainfall will remain unchanged in the warm season. A 20% drier climate and a 10% wetter climate during the growing season are towards the more extreme of the projections for 2050 and 2070. Projected changes in summer rainfall in 2090 vary from about 15% drier to 25% wetter. The 20% wetter climate is shown to illustrate potential impacts on risks associated with rain at harvest.

CSIRO and Bureau of Meteorology 2015, Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia. https://www.climatechangeinaustralia.gov.au/en/publications-library/technical-report/

2. Scheff, J and Frierson, D.M.W. 2014. Scaling potential evapotranspiration with global warming. Journal of Climate. 27: 1539-1558.

3. Snyder, R.L. 2017. Climate change impacts on water use in horticulture. Horticulturae 3:27. doi:10.3390/horticulturae3020027

<table>
<tr><th></th><th>Changes to temperature (absolute change °C)</th><th>Changes to rainfall (% difference)</th></tr>
<tr><td>2050</td><td>
</td><td>
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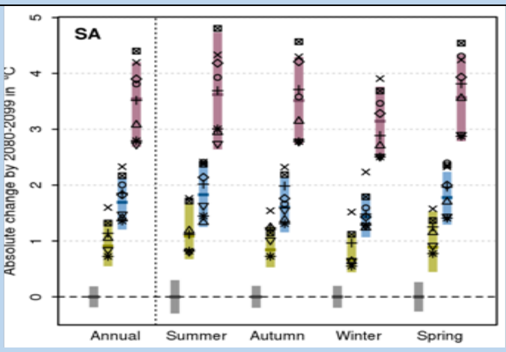
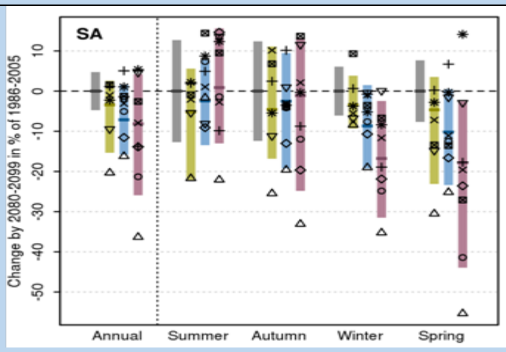
<tr><td>2090</td><td>
</td><td>
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</table>

These figures sourced from Climate Change in Australia report (CSIRO and Bureau of Meteorology, 2015) show the projected change in temperature (°C), and change in rainfall (% change) from those that occurred during the historic 20 year period from 1986-2005 under different GCM models and RCP scenarios for Southern Australia. The changes are shown for the annual period and for each season. The grey bar represents the year-to-year variation during the historic period, while the green, blue and red bars represent the changes projected by 40 different models when different amounts of greenhouse gases enter the atmosphere. The green bar represents RCP2.6 scenario, the blue bar represents RCP4.5, which is towards the lower end of possibilities, and the red bar represents RCP8.5 scenario, which models the largest increase in greenhouse gases entering the atmosphere. Specifically the green, blue and red bars represent the 10th to 90th percentile of 40 CMIP5 models, while the symbols represent projections from eight of the 40 models.

The message from these figures is that the projected change to temperature and rainfall are less dramatic for the 2050 base period (2040 – 2059) than the 2090 base period (2080-2099). Furthermore the projected change to climate are less dramatic when less greenhouse gases enter the atmosphere; that is, RCP8.5 scenario shows larger increases in temperature and reductions in rainfall than RCP4.5 or RCP2.6 scenarios.

By 2050 warming of 2°C is projected in the RCP8.5 scenario, but this is limited to 1°C in the RCP4.5 and RCP2.6 scenarios.

By 2090, warming of 2°C is projected in the RCP4.5 scenario, while the RCP2.6 scenario will maintain the 1°C warmer conditions. However 3°C warming is projected by the RCP8.5 scenario.

Warming is projected to occur in all seasons although winters may warm about 20% less than other seasons; even so warming in winter of 1°C or more is expected by 2050 and 1.5°C or more by 2090.

The extent of drying is more uncertain but so too is the year-to-year variability that occurred in the historic climate (grey bars). Winter and spring rainfall are projected to decline more than summer and autumn rainfall leading to an overall decrease in annual rainfall. The projected changes in rainfall are more extensive in 2090 than 2050, and more extensive when more greenhouse gases enter the atmosphere.

The following bar charts portray indices used to assess the climate risks to almonds in future climates of either 1°C warmer, 2°C warmer, 20% drier, 10% wetter or 20% wetter. The graphs show the expected number of years in these future climate scenarios that fall into the historic deciles. These deciles were calculated using the historic observations during the 20 year period from 1986 to 2005 and form the lower bar on each chart with warm deciles shown as red, Cool deciles as blue, Wet deciles as green and Dry deciles as brown. Deciles 5 and 6 are shown as grey.

In the historic past there was an equal chance of a year being in each decile. The changes in climate shift these chances. For example warming climates will increase the chances of warmer growing seasons indicated by larger number of years in high deciles (more orange and red in the chart) and decrease the chance of cool growing seasons and low decile years (less blues in the chart). Similarly drying conditions will increase the chances of drier seasons indicated by larger number of years in low deciles (more yellow and brown in the chart) and decrease the chance of wet growing seasons and low decile years (less greens in the chart).

The black colour in the bar charts for later periods or with warming or changes to rainfall indicate values that are either warmer, have less chill, more frosts, more evapotranspiration or drier than any experienced during the 20 year period from 1986 to 2005. Similarly the purple colour indicates values that are either cooler, have more chill, fewer frosts, less evapotranspiration or wetter than any experienced during this same period.

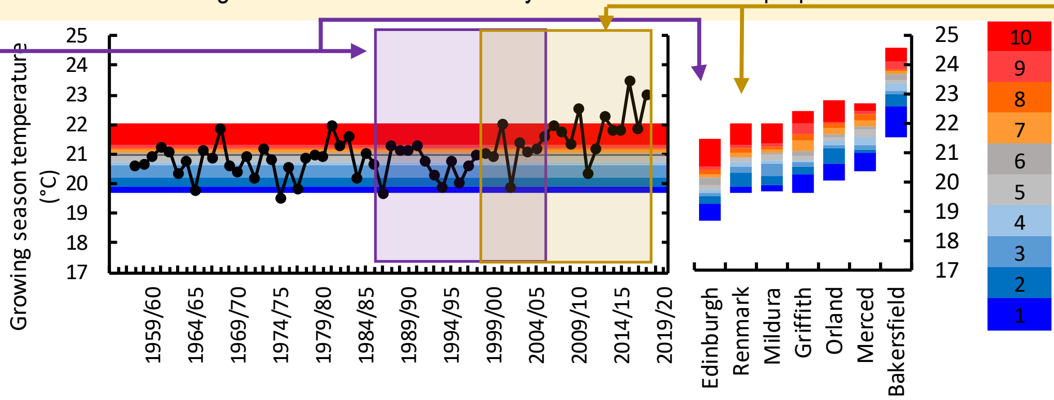
The table next to each graph shows the minimum, median (half the values are lower than this, and half higher) and maximum values in each of the 20 year periods.

Illustrated guide to the graphs

The graphs of historic values form the starting point of figures examining future climate.

The deciles calculated from the 20 years from 1986 to 2005 are used. 10% of the total number of values will be in each decile. For the 20 year period there will be two years in each of the deciles with the lowest two values being in decile 1 and the highest two values in decile 10. These deciles are shown as the ‘ribbon’ of colours underlying the historic values and as the column of colours in the comparison of almond growing regions.

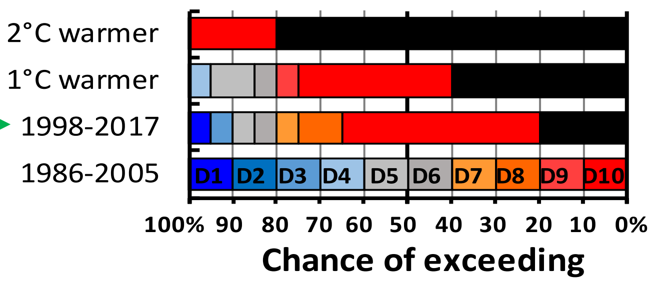
Next the historic values in the 20 year period from 1998 to 2017 are examined. These values are grouped according to the deciles calculated earlier. Unlike the period from 1986 to 2005, there may be more or less than two values in each of those deciles. There may also be values that are higher or lower than any during the 20 year period from 1986 to 2005. Values lower than the historic minimum are classified as being <Min, while those higher than the historic maximum are classified as >Max. For example, when examining indices such as mean temperature there is typically at least one year during 1998 to 2017 that is warmer than any during the period from 1986 to 2005. If there are yearly values in a decile or group then that decile is shown on the column chart. A new maximum value during 1998 to 2017 is indicated by the upper limit of the black section, and a new minimum value during 1998 to 2017 is indicated by the lower limit of the purple section.



The number of values during 1998 to 2017 in each of the deciles and also in the less than minimum (<Min) and more than maximum (>Max) categories during 1986 to 2005 are counted, and these counts converted to a percentage. For example 4 values during 1998 to 2017 above the maximum during 1986 to 2005 would be counted as 4 out of 20 values, or 20% of values in the >Max category. These percentages are shown on the bar charts.

A similar process to the examination of the 1998 to 2017 period is used when examining the impact of a future climate. The projected values in these future climates are calculated as changes from the historic 1986 to 2005 climate, and these values compared to the deciles calculated for the historic 1986 to 2005 climate.

The minimum, median and maximum values in these historic and future periods are shown.

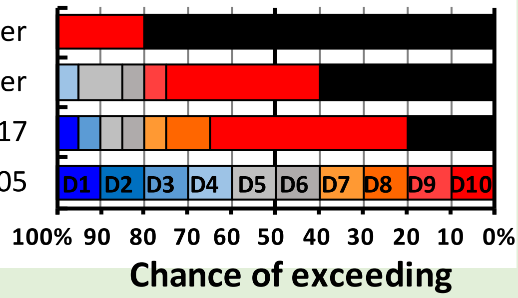


	Minimum	Median	Maximum
2°C warmer	21.7	22.9	24.0
1°C warmer	20.7	21.9	23.0
1998-2017	19.9	21.5	23.5
1986-2005	19.7	20.9	22.0

An increase in growing season temperature and heat units, and a decrease in chill units

Growing season temperature and heat units have already substantially increased in the most recent 20 years (1998 to 2017) compared to the base period (1986 to 2005). Of these most recent 20 years, 80% (16 years) were warmer than the median of the base period, more than half were warmer than decile 9, and 4 years were hotter than any year experienced. Further warming will increase the amount of heat units received. Not surprisingly, there will be very few years with 'below median' heat units in a warmer world. A 1°C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) increases the chance of above median warmer years from 5 in 10 years to 8 or 9 in 10 years, while a 2°C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) would mean every year was as warm or warmer than what was a 1 in 10 hot year with 8 in 10 of these years being warmer than any experienced during the historic period from 1986 to 2005. This new climate would be similar to the historic Bakersfield climate which is among the hottest growing regions in California that had a growing season temperature ranging from cool years of about 21.5°C to hot years of about 24.5°C.

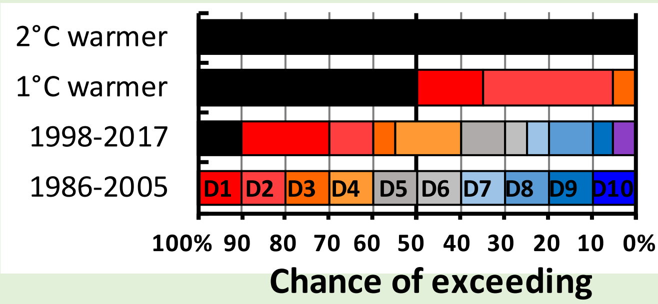
Growing season temperature (°C)



	Minimum	Median	Maximum
2°C warmer	21.7	22.9	24.0
1°C warmer	20.7	21.9	23.0
1998-2017	19.9	21.5	23.5
1986-2005	19.7	20.9	22.0

Chill accumulation in the 20 years from 1998 to 2017 remained similar to those received during the 20 year period from 1986 to 2005. However 1°C warming (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) would mean that every year has 49 or less chill portions which is less than the median during the 20 years from 1986 to 2005 of 51 chill portions. The projected new median of 44 chill portions is similar to the chill received in the lowest chill year in the last 20 years of 42 chill portions. A 2°C warmer world (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) would mean that chill accumulation in every year is likely to be lower than that experienced during the base period or the last 20 years. The projected minimum chill of 30 chill portions is higher than the minimum required for Nonpareil to satisfy dormancy of 23 chill portions suggesting dormancy will continue to be satisfied but this is likely to be later in the year. The impact on flowering is unknown but it is likely to be delayed, and may additionally affect synchronicity of flowering between varieties.

Chill accumulation until 31st July (Dynamic model chill portions)

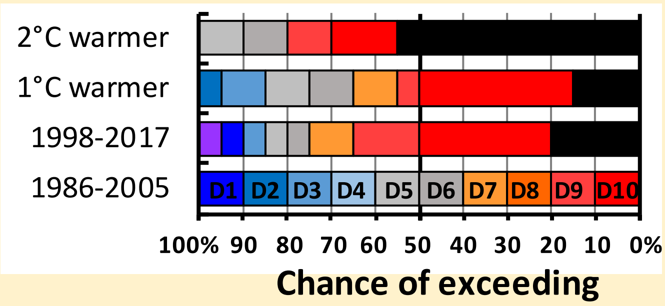


	Minimum	Median	Maximum
2°C warmer	30	37	42
1°C warmer	36	44	49
1998-2017	42	51	61
1986-2005	43	53	60

An increase in heatwaves and a decrease in frosts

The number of days warmer than 35°C in the 20 years from 1998 to 2017 is similar to the number projected to occur if the climate was 1°C warmer (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) than the 20 years from 1986 to 2005. In both instances the median of about 41 warm days per year is similar to what occurred in the hottest 1 in 10 year during the 20 years from 1986 to 2005. Warming by 2°C (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) further increases the projected median number of warm days to 51 per year which is similar to maximum number of hot days during 1986 to 2005. The modelled new minimum number of 31 days warmer than 35°C days in a 2°C warmer climate is only slightly less than the median number of 33 warm days experienced during the 20 year period from 1986 to 2005. Furthermore there will be many years that have more hot days than any experienced during the 20 years from 1986 to 2005. However these projected increased frequencies of hot days is less than what occurred during the 20 years from 1986 to 2005 for many Californian locations such as Merced in central California and Bakersfield in southern California which had a median number of about 70 days per year above 35°C and a maximum of 85 to 90 days per year that were warmer than 35°C.

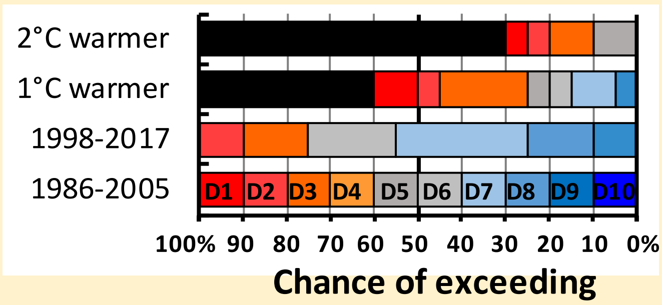
Days warmer than 35°C



	Minimum	Median	Maximum
2°C warmer	31	51	72
1°C warmer	23	42	60
1998-2017	18	41	66
1986-2005	19	33	50

The number of nights that are prone to frost was measured as those colder than 2°C. In most locations there has been little change in the last 20 years from 1998 to 2017 compared to the 20 years from 1986 to 2005. While these colder nights are expected to decrease in coming decades in response to warmer conditions, there are some indications that the number of spring frosts may increase or stay the same depending on the extent of drying in spring. Drier springs will have more clear nights, drier soils and lower humidity which can contribute to frost development.

Nights cooler than 2°C after 1st July

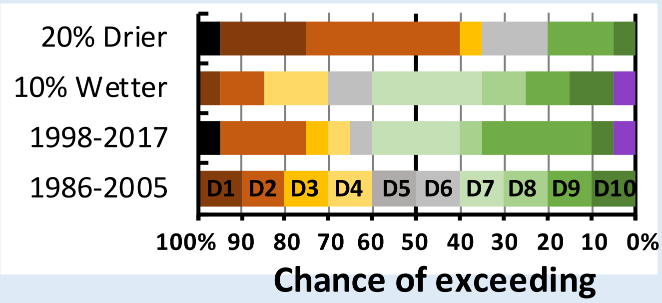


	Minimum	Median	Maximum
2°C warmer	0	3	11
1°C warmer	2	6	19
1998-2017	6	13	28
1986-2005	5	11	28

No clear trend in rainfall but an increase in evapotranspiration and irrigation deficit

A climate that is 10% wetter than the base period from 1986 to 2005 may have a growing season rainfall something like the experiences of the last 20 years apart from the very high rainfalls in 2010-11. Climates that are 20% drier than the base period reduce the chances of above median rainfall (decile 6 denoted by light green colour or higher) from 5 in 10 years to 3 in 10 years, while the new median rainfall may be similar to the current decile 4 years. More concerning is the increased chance of what was a 2 in 10 dry growing season occurring in 6 out of 10 years and some growing seasons being drier than any during the 20 years from 1985 to 2006.

Growing season rain (mm)

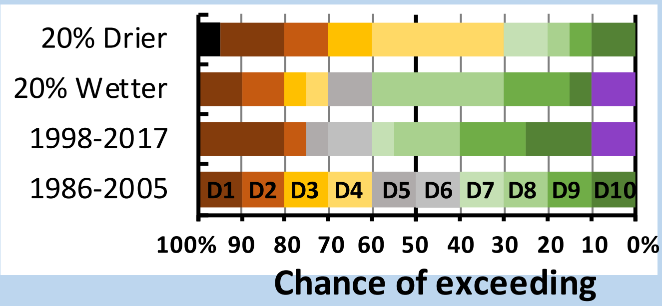


	Minimum	Median	Maximum
20% Drier	40	92	312
10% Wetter	55	127	429
1998-2017	48	128	790
1986-2005	50	115	390

100mm is equivalent to 1ML / ha

Harvest season rainfall that is 20% wetter than the base period of 1986 to 2005 may be similar to that in the 20 years from 1998 to 2017. A 20% drier climate would mean what was an above median wet harvest season (decile 6 or above) that formerly occurred 5 in 10 years would occur in 3 in 10 years.

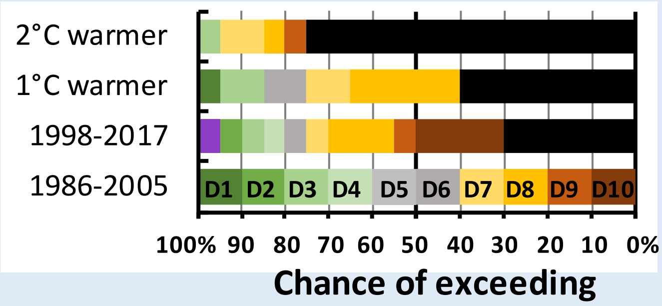
February to April rain (mm)



	Minimum	Median	Maximum
20% Drier	1	27	106
20% Wetter	1	41	158
1998-2017	1	45	327
1986-2005	1	34	132

Evapotranspiration during the growing season in a future climate that is 1°C warmer (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) than the base period and with 4% higher evapotranspiration is projected to be similar or slightly less extreme than evapotranspiration during the 20 years from 1998 to 2017. However the 8% increase in response to a 2°C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) may mean 8 in 10 growing seasons have as great or greater evaporative demand to what was formerly a 1 in 10 year high evapotranspiration growing season with over 7 in 10 of these years having greater evapotranspiration as any year during the base period from 1986 to 2005.

Growing season evapotranspiration (mm)

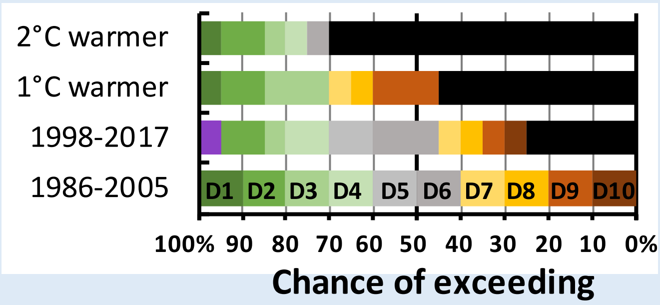


Minimum	Median	Maximum
1109	1229	1296
1068	1184	1248
1001	1188	1267
1027	1138	1200

100mm is equivalent to 1ML / ha

Irrigation deficit, calculated as the difference between evapotranspiration and rainfall (ETo - R) would be expected to increase in a warmer climate. It is understood that this definition of irrigation deficit is simplistic as demand for irrigation will be affected by other factors such as crop factors. Nevertheless this approach can be used as an initial approach to understanding this risk. In these scenarios evapotranspiration was assumed to be 4% higher for each 1°C warming while rainfall was assumed to be unchanged. The irrigation deficit in a 1°C warmer climate would be more extreme than the base period (1986 to 2005) and the recent 20 year period (1998 to 2017) with 7 in 10 years being higher than the former median. In a 2°C warmer climate, what was formerly a 1 in 10 high irrigation deficit growing season is projected to occur in about 7 out of 10 years.

Growing season Irrigation deficit (ETo - R) (mm)



Minimum	Median	Maximum
719	1131	1188
678	1086	1140
211	1049	1200
637	1040	1093

100mm is equivalent to 1ML / ha

How is the climate influenced by ENSO and IOD?

Climate drivers such as ENSO and IOD influence climate on a seasonal basis. Understanding how the weather and climate risks differ in El Niño years and La Niña years or in positive IOD years or negative IOD years can assist with these seasonal management decisions.

An El Niño years or a positive IOD year typically increases the chance of drier conditions, warmer mean and daily maximum temperature and cooler daily minimum (night) temperatures. A La Niña yearsor a negative IOD year typically increases the chance of wetter conditions, cooler mean temperature daily maximum temperature and warmer daily minimum (night) temperatures. However it should be noted that not all warm years are El Niño years or positive IOD years and not all cool years are La Niña years or negative IOD years. Similarly not all dry years are El Niño years or positive IOD years and not all wet years are La Niña years or negative IOD years.

While El Niño Southern Oscillation (ENSO) which determine El Niño years and La Niña years, and IOD which determine positive IOD years and negative IOD years are discrete entities and therefore years can be classified as El Niño and positive IOD, and La Niña and negative IOD, but these conditions are rare. This analysis examines the separate influence of ENSO and of IOD.

The Bureau of Meteorology provides up-to-date information on the Niña 3.4 index, Southern oscillation index (SOI), strength of trade winds and cloudiness which are related to formation of El Niño and La Niña events, and Dipole mode index (DMI, reported as IOD) which is related to formation on negative IOD and positive IOD events (http://www.bom.gov.au/climate/enso/)

Rainfall throughout the year is typically lower in El Niño years or positive IOD years. This may increase the risk of insufficient rainfall in the orchard and of the supply of irrigation water which depends on storage and inflows to the Murray-Darling Basin, and combined with typically higher evapotranspiration may affect irrigation demand. The lower rainfall and higher evapotranspiration reduces the chance of MB+ve days particularly in the spring and early summer which may reduce the risk of disease. However the influence of El Niño or positive IOD is minimal during the harvest season so the risk of rainy conditions during harvest is unaffected. The number of desirable pollination hours in August is likely to be greater in El Niño years and lower in negative IOD years. The opposite of these conditions is more likely in La Niña years and positive IOD years.

Mean daily and maximum temperature during spring and early summer is typically higher in El Niño years or positive IOD years, however daily minimum temperatures can be cooler. This can increase the number and frequency of heatwaves, can hasten developmental rate, and increase undesirable photosynthetic hours thereby reducing carbohydrate gain. Chill accumulation before August is largely unaffected by the climate drivers, but frosts may be more frequent and occur later. The opposite of these conditions is more likely in La Niña years and positive IOD years.

Illustrated guide to the graphs

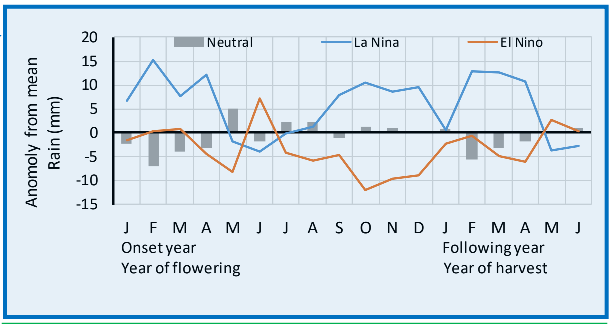
The following figures show the difference (anomoly) of monthly indices in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017 (upper),

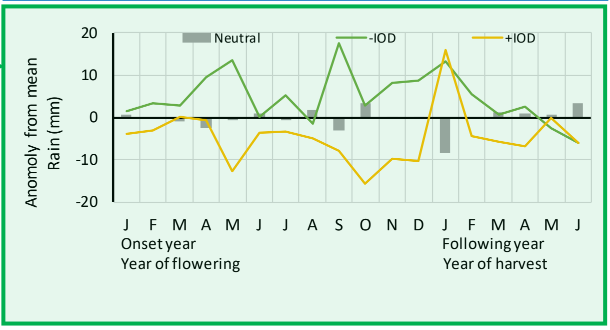
and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017 (lower).

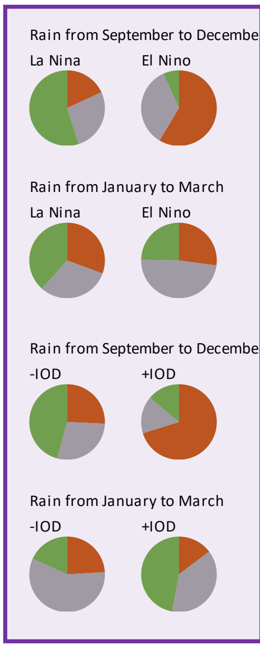
In both instances the average of all years is the zero axis. The monthly averages are shown from January of the year of onset, which is also the year of flowering, until June of the following year, which is the year of harvest.

The pie charts show the chance that the indices in La Niña years and El Niño years or negative IOD years and positive IOD years are in the lowest third of all years (tercile 1), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3). Tercile 1 is coloured brown if the low values or the indices are related to drier conditions such as rainfall; coloured green if the low values or the indices are related to wetter conditions such as irrigation deficit; coloured blue if the low values or the indices are related to cooler conditions such as mean temperature or number of warm days; or coloured red if the low values or the indices are related to warmer conditions such as chill accumulation. Tercile 3 is the alternate colour of tercile 1, that is green if tercile 1 is coloured brown; brown if tercile 1 is coloured green; red if tercile 1 is coloured blue; and blue of tercile 1 is coloured red.

The values of the terciles are shown in the table with years having values between the Minimum and Tercile 1 deemed to be in tercile 1, those having values greater than Tercile 1 up to Tercile 2 deemed to be in tercile 2, and those having values greater than Tercile 2 deemed to be in Tercile 3. The maximum value is also shown.







	mm
Minimum	20
Tercile 1	69
Tercile 2	120
Maximum	388

	mm
Minimum	2
Tercile 1	37
Tercile 2	67
Maximum	444

	mm
Minimum	20
Tercile 1	69
Tercile 2	120
Maximum	388

	mm
Minimum	2
Tercile 1	37
Tercile 2	67
Maximum	444

Less rainfall on orchards and MDB with El Niño and positive IOD

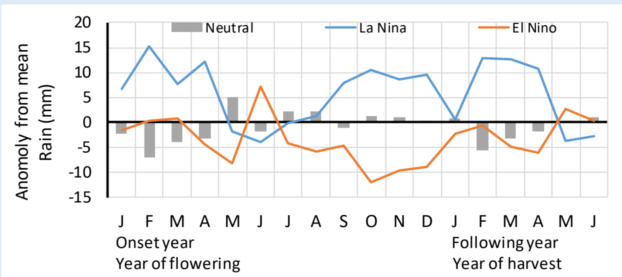
ENSO and IOD influence rainfall throughout the year of flowering, but not the year of harvest. This can be seen on the graphs showing the difference (anomaly) of mean monthly rainfall in the years of onset compared to all years.

The pie charts show there was typically an increased chance of rainfall during September to December in El Niño years or positive IOD years having rainfall in the lower third (tercile 1, brown) and a corresponding chance that La Niña years or negative IOD years having rainfall in the upper third (tercile 3, green). If the climate drivers had no affect then each tercile would contain an equal number of years (about 3 years in 10).

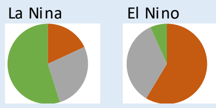
At Mildura rainfall during September to December would be expected to be in the tercile 3 in about 4 to 6 years in 10 during La Niña years or negative IOD years, and in the lowest tercile in 6 or 7 years in 10 in El Niño years or positive IOD years.

Rainfall during January to March of the following year, that is in the year of harvest, was largely unaffected by ENSO and IOD.

The DMI climate driver indices and SOI were significant with rainfall during May to August, while these and the Niño3.4 climate driver indices were significant with rainfall during September to December. Rainfall during the following January to March was not related to the climate indices (see table of correlations).

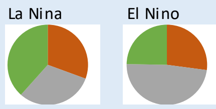


Rain from September to December

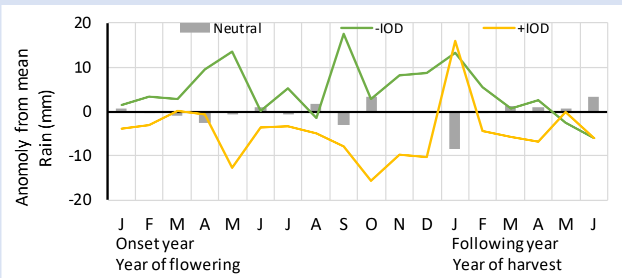


	mm
Minimum	20
Tercile 1	69
Tercile 2	120
Maximum	388

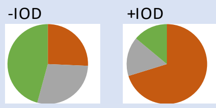
Rain from January to March



	mm
Minimum	2
Tercile 1	37
Tercile 2	67
Maximum	444

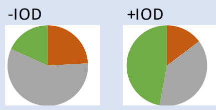


Rain from September to December



	mm
Minimum	20
Tercile 1	69
Tercile 2	120
Maximum	388

Rain from January to March



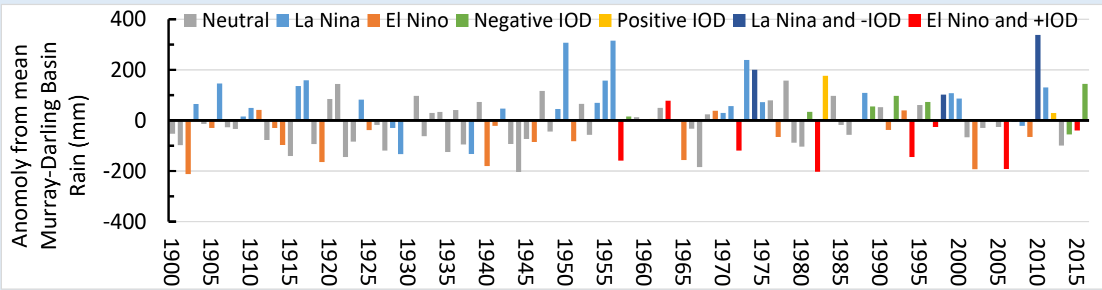
	mm
Minimum	2
Tercile 1	37
Tercile 2	67
Maximum	444

Rainfall was influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year). 100mm is equivalent to 1ML / ha.

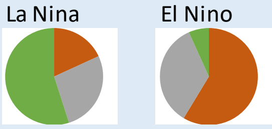
Irrigation water used in almond production in Australia is largely derived from the Murray-Darling Basin. Inflows into the storage system are related to rainfall, but water availability and allocation to irrigation is related to other factors. The figure shows rain in the Murray-Darling Basin (data from Bureau of Meteorology http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries sourced 19 March 2019) categorized by ENSO and IOD event years.

There was a general relationship between ENSO and DMI and rainfall. Annual rainfall would be expected to be in the tercile 3 in about 5 or 6 years in 10 during La Niña years or negative IOD years, and in the lowest tercile in 6 or 7 years in 10 in El Niño years or positive IOD years. These are large changes from the 3 out of 10 years expected in each tercile if the climate drivers did not affect rainfall. The Niño3.4 and the DMI climate driver indices, and SOI were significant with annual rainfall (see table of correlations).

It should be noted that analysis of the drought/dry spell from 1997 to 2009 showed the decline in rainfall was related to a decline in autumn rainfall and that while "ENSO is known to have its maximum impact on rainfall and maximum temperature in spring." and "the IOD can have an impact on rainfall and maximum temperature in winter and spring, there is no significant impact in summer and autumn. Similarly, earlier research by Hendon et al. (2007) suggests that the Southern Annular Mode (SAM) has a significant effect on rainfall and minimum temperature in all seasons except autumn." Rather "SEACI researchers also found a strong relationship between the rainfall in south-eastern Australia and the intensity of the sub-tropical ridge (STR)" (CSIRO, 2010). This suggests the role of climate drivers and of climate change on rainfall in the Murray-Darling Basin and hence inflows and water availability to irrigators is complex and an active area of research.

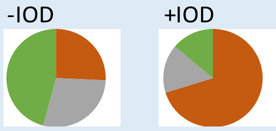


Rain from January to December



	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

Rain from January to December



	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

Rainfall in the Murray-Darling Basin, and hence expected inflow of irrigation water was influenced by ENSO and IOD.

More evapotranspiration and increased irrigation deficit with El Niño and positive IOD

The evapotranspiration response to ENSO and IOD categories occurred in late winter, spring and early summer but not at other times. At these times evapotranspiration was higher in El Niño years or positive IOD years and lower in La Niña years or negative IOD years.

The combined effect of rainfall in the orchard and evapotranspiration from the orchard was assessed as the difference or irrigation deficit (ETo – Rain).

The pie charts show there was an increased chance that greater irrigation deficit (tercile 3, brown) occurred in El Niño years or positive IOD years, and an increased chance that less irrigation deficit (tercile 1, green) in La Niña years or negative IOD years, and that this was most likely to occur in the period between September and December rather than from January to March of the following year. If the climate drivers had no affect then each tercile would contain an equal number of years (about 3 years in 10).

At Mildura there was an increased chance that irrigation deficit during September to December was in the highest tercile in El Niño years or positive IOD years to about 6 or 7 in 10 years. The reverse occurs in La Niña years or negative IOD when irrigation deficit was more likely to be in the lowest third of years. Additionally, in La Niña years or negative IOD years this increased chance of low irrigation deficit can continue into January to March of the following year.

The Niño3.4 and DMI climate driver indices and SOI were significant with irrigation deficit during September to December but only SOI and DMI climate driver indice by HadiSST 1.1 during the following January to March (see table of correlations).

Irrigation deficit was influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year). 100mm is equivalent to 1ML / ha.

Rainy and humid conditions with La Niña and negative IOD

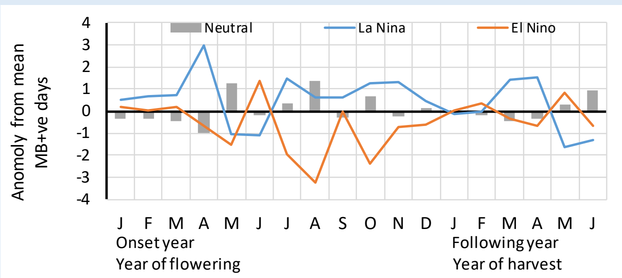
The number of days considered moisture balance positive (MB+ve) was affected more by IOD than by ENSO. As with many indices the impact of ENSO or IOD was stronger during the year of onset than the following year.

The pie charts show there was an increased chance that more MB+ve days (tercile 3, green) occurred between September and December in La Niña years or negative IOD years, and an increased chance of fewer MB+ve days (tercile 1, brown) in El Niño years or positive IOD years. There was minimal effect between January to March of the following year. If the climate drivers had no affect then each tercile would contain an equal number of years (about 3 years in 10).

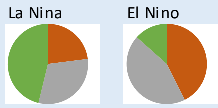
At Mildura an El Niño year or positive IOD year increased the chance that the number of MB+ve days during September to December was in the lowest third of all years (tercile 1) to about 4 to 6 in 10, while also reducing the chance that the number of MB+ve days was in the highest third of all years (tercile 3) to about 1 or 2 in 10. La Niña years or negative IOD years had essentially the reverse effect.

However during January to March of the year following the year of onset, that is the year of harvest, La Niña years increased the likelihood that the number of MB+ve days was in the highest third of all years (tercile 3); while neither El Niño years nor IOD years effected MB+ve days during this period.

The Niño3.4 and DMI climate driver indices and SOI were significant with the number of MB+ve days during September to December but only by DMI climate indices measured by HadISST 1.1 during the following January to March (see table of correlations).

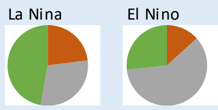


MB+ve days from September to December

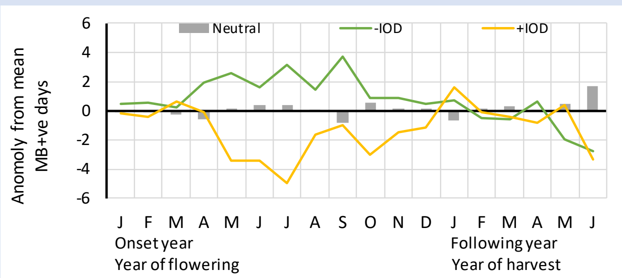


	days
Minimum	3
Tercile 1	10
Tercile 2	19
Maximum	52

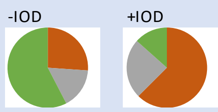
MB+ve days from January to March



	days
Minimum	0
Tercile 1	5
Tercile 2	7
Maximum	22

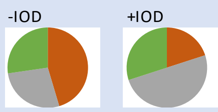


MB+ve days from September to December



	days
Minimum	3
Tercile 1	10
Tercile 2	19
Maximum	52

MB+ve days from January to March



	days
Minimum	0
Tercile 1	5
Tercile 2	7
Maximum	22

Rainy and humid conditions measured by the number of Moisture Balance positive (MB+ve) days were influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year).

Mean temperature and heat units increase with El Niño and positive IOD

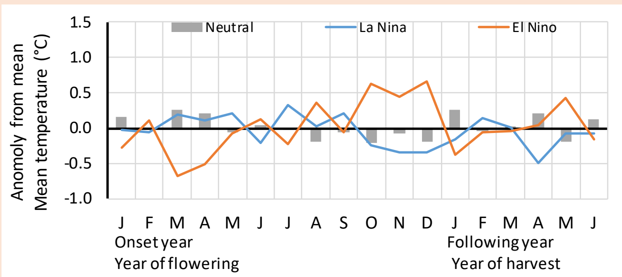
Mean Temperature was influenced by ENSO and IOD mainly in the spring to early summer period of the year of onset. Mean temperature during January to March following the year of onset, that is in the year of harvest, are largely unaffected by ENSO and IOD.

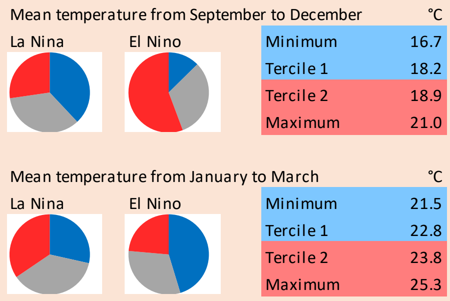
The pie charts show there was typically an increased chance that mean temperature during El Niño years or positive IOD years were in the upper third (tercile 3, red) and a corresponding chance that mean temperature during La Niña years or negative IOD years being in the lower third (tercile 1, blue). If the climate drivers had no affect then each tercile would contain an equal number of years (about 3 years in 10).

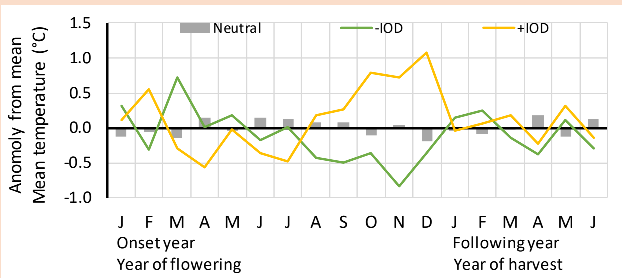
At Mildura mean temperature during September to December was expected to be in tercile 3 in about 4 to 6 or 7 in 10 years during El Niño years or positive IOD years, and in the lowest tercile in 6 or 7 years in 10 in negative IOD event years. La Niña years had minimal impact on mean temperature.

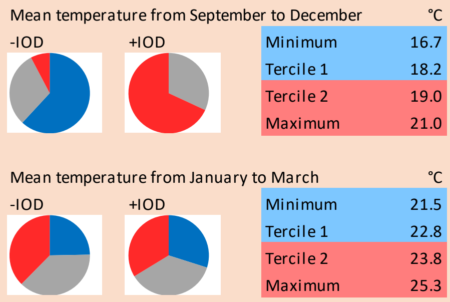
Mean temperature during January to March following the year of onset, that is in the year of harvest, was largely unaffected by ENSO and IOD although with a tendancy that those following El Niño years had a slightly greater chance of being cooler than usual.

The DMI climate driver indices and Niño3.4 climate driver indices by HadISST 1.1 are significant with mean temperature during September to December. SOI was not significantly elated to mean temperature during any period. DMI climate driver indices and the Niño3.4 climate driver indices by HadISST 1.1 significantly affected the date to the measured heat accumulation thresholds (see table of correlations).





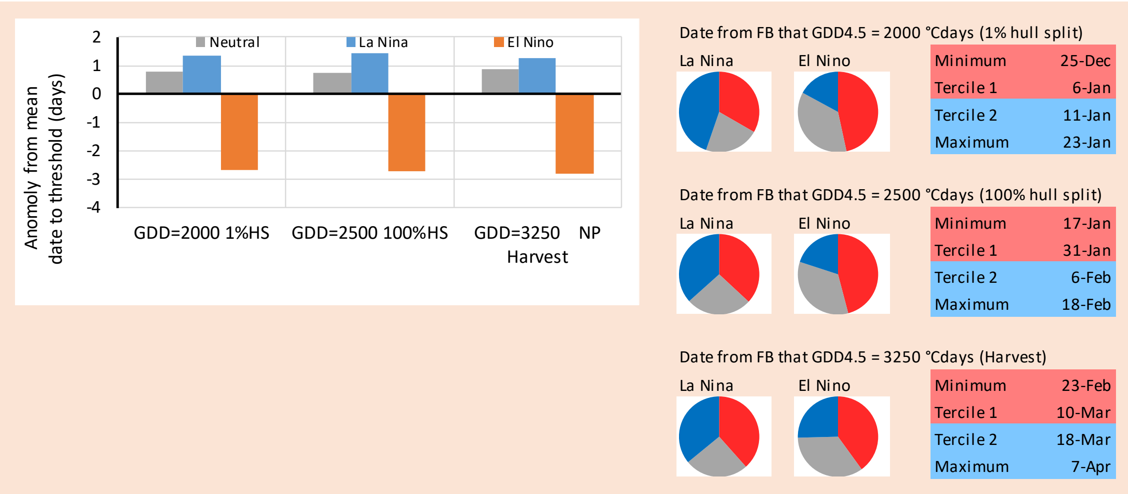


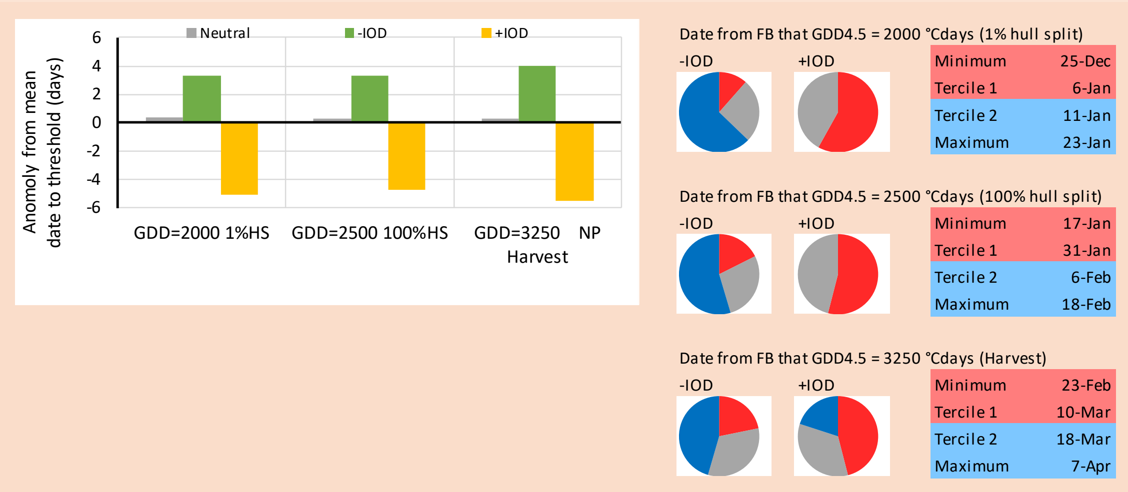


Mean temperature was influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year).

These differences in mean temperature affect the risk of generally warmer conditions advancing growth. The heat accumulation thresholds shown are accumulations from 15th August (taken to represent full bloom) of 2000 °Cdays (taken to represent date of 1% hull split of Nonpareil), 2500 °Cdays (taken to represent date of 100% hull split of nonpareil), and 3250 °Cdays (taken to represent date of harvest of Nonpareil). These heat accumulations are GDD base 4.5°C. The thresholds for Nonpareil development were developed from observations collected during this research project.

El Niño years or positive IOD years advance the rate of development and the thresholds are reached sooner, while La Niña years or negative IOD years retard the rate of development and the heat accumulation thresholds are reached later.





Heat accumulation from date of full bloom (taken to be 15th August) was faster in El Nino years and positive IOD years.

Chill units are largely independent of ENSO and IOD

ENSO and IOD had minimal influence on the accumulation of chill hours after August, and almost none before August. The role of climate drivers on chill accumulation in almonds was likely to be small as chill would likely be satisfied by July with bud burst occurring in July and flowering occurring in August.

Heatwaves are more likely in El Niño years and positive IOD years

The influence of ENSO and IOD on maximum and minimum temperature were similar to the effect on mean temperature (data not shown), however there were differences in the occurrence of extreme hot and extreme cold days.

An El Niño year or positive IOD year had more days warmer than 35 °C during late spring to early summer than La Niña years or negative IOD years.

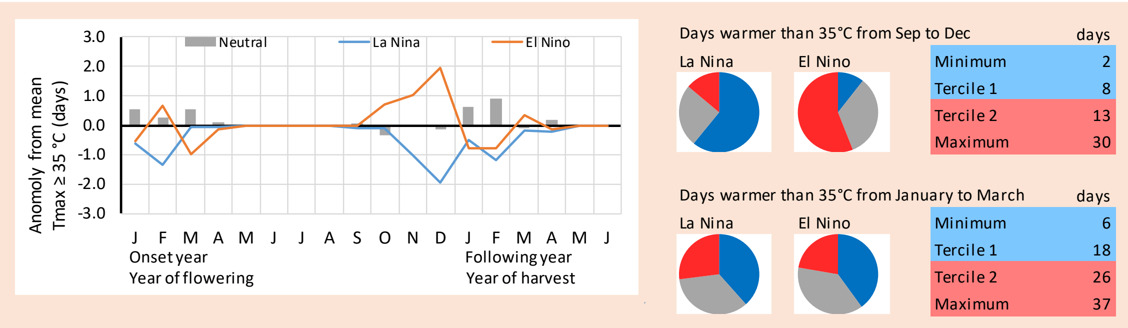
At Mildura there was almost no chance that an El Niño year or positive IOD year will have as few hot days (warmer than 35 °C) during September to December as that which occured in lower third of all years (tercile 1).

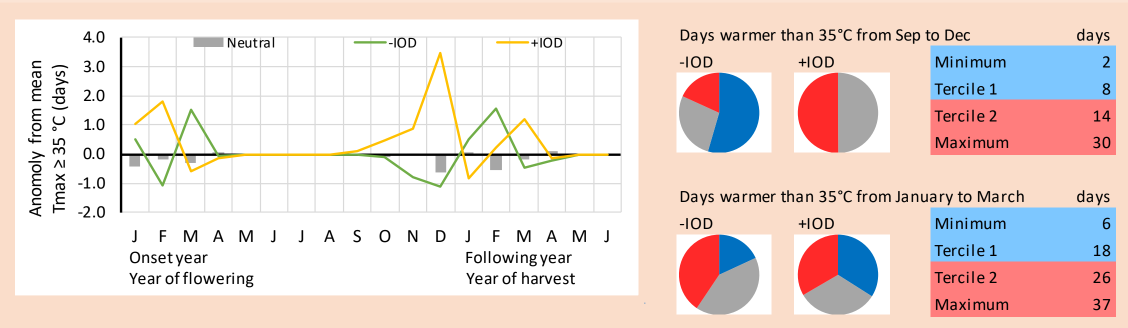
About half the El Niño years or positive IOD years had as many hot days (warmer than 35 °C) as occured in the upper third of all years (tercile 3). The opposite essentially occurred in La Niña years or negative IOD years although the effect was not as dramatic.

The influence of ENSO and IOD did not extend to the January to March period of the following year.

A related indice of the number of daylight hours warmer than 35 °C, which was chosen to represent hours that were not conducive to photosynthesis, behaved very similarly. That is, El Niño years and positive IOD years had a greater chance of having more daylight hours that are too warm for optimal photosynthesis.

Both Niño3.4 climate driver indices, SOI and the DMI climate driver indice measured by HadISST 1.1 significantly affected the number of hot days during September to December. Climate diver indices did not significantly affect the number of hot days during the following January to March period (see table of correlations).





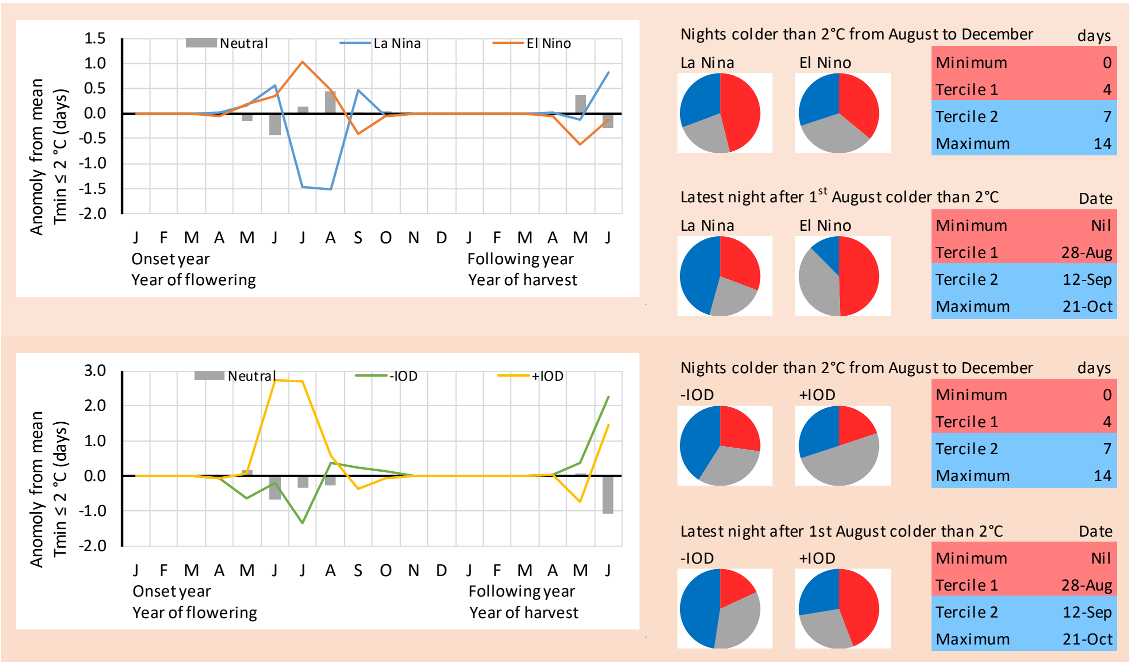
Heatwaves, measured as days warmer than 35 °C were influenced by the time of year and by ENSO and IOD. El Niño years or positive IOD years were likely to have more spring and early summer heatwaves than La Niña years or negative IOD years. Heatwaves in later summer were largely independent of ENSO and IOD.

The number of frosts is affected by ENSO but there is less certainty in the date of last frost.

Minimum temperatures and the number of frosts (nights colder than 2 °C) were related to ENSO and IOD. At Mildura, fewer frosts after 31st July were more likely in La Niña years or negative IOD years.

The date of the last frost was more likely to be earlier (tercile1, red) in El Niño years or positive IOD years while there was an increased chance of it being later (tercile 3, blue) in La Niña years or negative IOD years.

The climate drivers of Niño 3.4 and DMI, or SOI were not significantly related to frost events or date of last frost (see table of correlations).



The number of frost from August to December, and the date of last frost (frost measured as nights colder than 2 °C) was not strongly influenced to ENSO or IOD.

Pollination conditions better with warm dry El Niño years and worse in cooler wetter La Niña years and negative IOD years

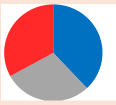
Pollination is a major concern to almond growers. Pollination is poor if temperatures are below about 15 °C and if rain occurs. We calculated the daylight hours in August warmer than 15 °C with no rainfall on that day as an indicator of desirable pollination conditions.

At Mildura there was an indication that El Niño conditions were associated with an increased chance of more desirable pollination hours, while negative IOD years were associated with an increased chance of few desirable pollination hours. This information may assist with decisions related to number of hives.

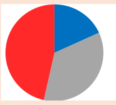
The number of desirable pollination hours was not significantly correlated with Niño 3.4 or DMI climate drivers but was significantly correlated with SOI (see table of correlations).

Daylight hours in August that are warmer than 15°C without rain

La Nina



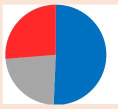
El Nino



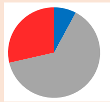
	hours
Minimum	55
Tercile 1	89
Tercile 2	124
Maximum	201

Daylight hours in August that are warmer than 15°C without rain

-IOD



+IOD



	hours
Minimum	55
Tercile 1	89
Tercile 2	124
Maximum	201

Favourable Pollination conditions were influenced by ENSO or IOD.

Table of correlations of the weather and climate indices with the climate drivers indices

	Niño 3.4 HadISST 1.1	Niño 3.4 ERSSTv5	SOI	DMI HadISST 1.1	DMI ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.15	-0.12	0.34	-0.44	-0.35
Rain from September to December	-0.34	-0.30	0.37	-0.26	-0.30
Rain from January to March	-0.17	-0.18	0.25	0.11	0.05
MDB rain from January to December	-0.31	-0.29	0.40	-0.28	-0.33
Evaporation and Irrigation deficit					
Irrigation deficit from September to April	0.38	0.32	-0.43	0.16	0.22
Irrigation deficit from September to December	0.46	0.41	-0.41	0.46	0.41
Irrigation deficit from January to March	0.13	0.06	-0.28	-0.29	-0.16
Rainy and humid conditions					
MB+ve days from September to December	-0.31	-0.29	0.27	-0.40	-0.38
MB+ve days from January to March	-0.08	-0.05	0.17	0.30	0.18
Heat accumulation					
Mean temperature from September to December	0.30	0.21	-0.17	0.53	0.35
Mean temperature from January to March	-0.12	-0.25	0.08	0.19	0.08
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.27	-0.18	0.23	-0.51	-0.38
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.26	-0.15	0.21	-0.48	-0.37
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.16	-0.06	0.04	-0.38	-0.21
Chill accumulation					
Dynamic chill portions accumulated to 31st July	-0.02	0.06	-0.05	-0.19	-0.07
Utah chill units accumulated to 31st July	-0.03	0.07	0.01	-0.29	-0.12
Heatwaves					
Days warmer than 35°C from September to December	0.46	0.38	-0.37	0.39	0.24
Days warmer than 35°C from January to March	0.05	-0.11	-0.14	-0.06	-0.16
Daylight hours warmer than 35°C from September to December	0.44	0.36	-0.33	0.38	0.22
Daylight hours warmer than 35°C from January to March	0.05	-0.09	-0.12	-0.06	-0.13
Frost					
Nights colder than 2°C from August to December	0.07	0.02	-0.15	0.14	-0.04
Latest night after 1st August colder than 2°C	0.04	0.11	0.12	-0.09	0.00
Pollination					
Daylight hours in August that are warmer than 15°C without rain	0.07	-0.05	-0.33	0.09	0.05

The correlation coefficients (r) of the agroclimatic indice with the Niño3.4 and DMI (which determine IOD) climate drivers derived from the ERSSTv5 and from the HadISST 1.1 models, and with SOI. The correlation values are shaded when significantly different at P=0.001 in purple, at P=0.001 as blue and P=0.05 as yellow. Analysis of ENSO and SOI used 1957 to 2017 (61 years) and analysis of DMI used 1960 to 2017 (58 years).

Main points

A phenology calendar linking key phenological development events of almonds and expected weather and climate can be used to identify meteorological risks to almond production.

12 risks were identified including rain at harvest, heatwaves, uncertainty of rainfall and of irrigation water, wet and humid conditions affecting pests and diseases, poor pollination conditions, frosts, chilling and loss of synchronicity of flowering. These risks may be ranked for economic importance.

The risks may be quantified by examining indices calculated from historical weather records. These records can be used to assess not only the risks in an average year, but also their year-to-year variation. This provides insights into the expected range of conditions and the relative importance of different management solutions to address the risks.

Comparison of the indices in different almond growing regions in Australia and in California provides an insight into the relative strengths of the regions, and provides guidance to those regions that may be managing similar climate risks to yourself in the current climate or what you may experience in future climates.

Climate drivers such as ENSO which determine El Niño years and La Niña years, and IOD which determine positive IOD years and negative IOD years affect many of the risks on a year-to-year basis. The current and forecast state of these climate drivers increases the knowledge available to orchard managers when addressing the weather and climate risks.

The severity of the weather and climate risks will change in a future warmer and water constrained future. There is greater certainty of warming than of changes in rainfall. The impact of warming by 1°C (e.g. expected in Southern Australia by 2050 under RCP4.5 or RCP2.6 scenarios) and 2°C (e.g. expected in Southern Australia by 2050 under RCP8.5 or 2090 under RCP4.5 scenarios), and of a 10% and 20% drier climate were examined. The impact of a 20% wetter harvest season was examined owing to the uncertainty of the extent of drying and of changes in the seasonality of rainfall.

Some knowledge gaps and management options for addressing the risks in the current and future climates are identified.