Final Report

Managing Almond Production in a Variable and Changing Climate

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Managing Almond Production in a Variable and Changing Climate – AL14006

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Content

Summary

High quality almond production is sensitive to weather and climate risks including insufficient chill units, heat waves, drought and untimely rainfall. This project conducted a detailed analysis of climate across Australian almond growing regions to identify and prioritise these risks; assess whether the risks are changing from the recent past and what climate science is suggesting about the future; and suggest knowledge gaps in our understanding of the risks and alternative ways to manage the risks. This project also conducted field trials to gain better understanding of the role of climate crop development and yield.

The key activities and grower benefits of the project included:

An interactive crop calendar with key crop development (phenological) growth stages and associated weather and climate risks, which were then ranked for economic importance. This was a useful summary of grower experience and becomes a useful common ground between almond growers, researchers and climate science.

Ranking the risks according to the damage and likelihood showed rain at harvest was considered the most economically damaging risk, followed by heatwaves, non-synchronous flowering, and rain and humidity leading to disease. The supply of irrigation water was ranked as a moderate risk by the industry as a whole but ranked as a major risk in the Riverland and Sunraysia.

Management options were collated for each risk, and included current practices in Australia or overseas that are used to avoid or reduce the impacts of the risk; practices that are being trialed on some properties or are being actively researched; practices that could be researched. These are listed in the Recommendations.

Climate analysis of major locations within each of the three main regions (Riverland, Sunraysia and Riverina) showed warmer conditions in more inland locations with Riverina as the warmest but also the higher summer rainfall. Comparison of Australian sites with almond growing regions in California showed that even in the coming decades of warming, Australian sites will be cooler than the current conditions in southern California. An important difference is the distinctly Mediterranean climate in central and southern California that have much less risk of rain at harvest. These comparisons between sites within Australia and between Australia and California is valuable when interpreting trials and industry experience in the current climate and provides a spatial analogue for adaptation to future climates.

The identified risks are influenced by the major drivers of Australian climate (e.g. ENSO, IOD). This knowledge and information on the current state of the climate drivers (updated in real time from The Bureau of Meteorology) has the potential to assist with management of the risks on a seasonal timescale. ENSO and IOD influence both rainfall and temperature with El Niño years or positive IOD years having less rainfall and warmer mean and daily maximum temperature but cooler daily minimum (night) temperature than La Niña years or negative IOD years. The impact on rainfall is throughout most of the year while the impact on temperature is typically stronger in spring and early summer. The differences in rainfall affect risks associated with insufficient rainfall in the orchard and of the supply of irrigation water, and combined with evapotranspiration affect irrigation demand, rain affecting harvest, and excessively rainy and humid conditions leading to increased risk of diseases. The differences in mean temperature affect risks associated with warmer spring and summer temperatures advancing growth, heatwaves and undesirable photosynthetic hours, frosts, chill accumulation and synchronicity of flowering, and when combined with rainfall, affect desirable pollination hours.

The severity and importance of the risks may change in projected warmer and drier futures. This information can assist with longer term management and planning. There is greater confidence from climate scientists about projected changes in temperature than rainfall. Warmer climates will alter risks associated with temperature: heatwaves, chill accumulation although sufficient chill to satisfy dormancy is expected for some decades, frosts may decline in the medium term but dry atmospheric and soil conditions during spring may increase spring frosts in the short term. The extent of drying is more uncertain. Winter and spring rainfall are projected to decline, while less change is projected for summer and autumn rainfall leading to an overall decrease in annual rainfall. These may affect risks associated with insufficient winter rain and irrigation water, rain and humidity leading to disease and rain at harvest.

The impact of climate on almond yield and crop development was evaluated by monitoring meso-sites in a space as a proxy for time approach to better understand how local climate (meso-climate) impacts on crop development and yield within four orchards (two in the Riverland, two in Sunraysia) over four seasons. A supplementary experiment was conducted on potted plants that were grown in passively solar heated chambers and compared with a control of potted plants exposed to ambient air temperature. Differences in meso-climate existed between

the meso-sites with lower parts of the orchard generally being slightly cooler but only minor differences in crop development and yield were observed. A multi-site and multi-year analysis showed yields were lower when chill accumulation was lower, and on the subsequent years yield following warmer conditions during the period of bud formation.

A photo-standard and an assessment protocol were developed to aid the assessment of crop development. This was essential to ensure consistency in measurement between technical staff. As far as we are aware, this is the first time that international phenology scales were collated and presented with photos and common terms used by the Australian industry. The phenology information from the field trials proved invaluable to producing an Australian almond phenology model that incorporates both predictions of time of flowering, time of fruit maturity and hull-split and time of harvest. The error (RMSE) of the predictions were about 3 to 8 days for flowering and 10 days for hull split and harvest. This model can be used to plan orchard activities in the current year, to assess climate and weather risks in new production areas, or to assess the likely impact of a warmer and more water constrained future on current orchards.

Keywords

Almond; weather; climate; phenology; crop development

Introduction

Australia's current planting of almonds is close to 40,000 ha and earnt $429 million in export income (data for 2017). This has been due to a rapid expansion of the industry in the last decade in the southern Murray-Darling basin irrigation areas in NSW, Victoria and SA. In recognition of this expansion The Australian Almonds Strategic R&D plan 2011-2016 highlighted that the industry faced on-farm agronomic challenges including the prevailing low humidity and high evaporative demand of the growing regions, uncertainty of water security and water availability, and that Australian almonds are grown in regions where predicted changes in climate may have negative impacts. Consequently a greater understanding of climate variability and adaptation was deemed a high priority. This examination was deemed necessary as the rapid expansion of the industry has mean that many almond producers have not been exposed to the full extent of climate and weather risks that can impact production. It is for this reason that it is important to understand the climate and weather risks faced by producers over last decade or so compared to (i) the long term record (and what is reasonably expected to occur), (ii) other parts of world (and faced and managed by producers in these regions), and (iii) climate change projections (and could be reasonably expected to occur in the future).

In addressing these issues this project addressed several major themes. These were 1. Identify and assess risks of climate and weather events, and determine appropriate management options; 2. Field trials to examine the impact of climate and weather on Almond tree physiology; and 3. Examination, collation and evaluation of an Almond phenology model. This evaluation relied on field data of crop development collected during this project.

The management options that were identified consisted of practical solutions which could be explored and also included knowledge gaps which ideally would be explored to more fully understand limitations to almond production. This project did not seek to undertake plant based research to explore these identified management options.

Phenology models can provide greater certainty of key phenological events (typically budburst, flowering, hull split, harvest) and are a useful tool to assist with orchard management including scheduling crop protection activities, pollination management, assessing and scheduling irrigation requirements and operations, planning logistics of harvest, but also as a research tool. For example robust phenology models can be used to explore how dates that a particular phenology may change in a projected warmer climate such as date of flowering, and to determine risks of undesirable weather events in a future warmer climate at these future dates rather than as historic dates.

Methodology

The project reach was national covering four of Australia's five almond production regions that produce 97% of Australian production; these being North Adelaide plains (SA), Riverland (SA), Sunraysia (Vic.) and Riverina (NSW) but not in the Swan region of WA. The target of this research project were almond producers including farm owners and managers and consultants to this industry.

The project encompassed three main themes of Risk assessment and Management options; Tree physiology; and Predictive crop development (phenology) model.

Detailed methods for each theme can be found in the relevant appendices: Appendix 1 for theme 1, Appendix 2 for theme 2, Appendix 3 for theme 3.

Grower input in the form of half-day workshops and follow-up grower surveys were used to collect data that identified and ranked weather and climate risks according to chance of occurrence and economic loss. The workshops were held in the four almond growing regions of North Adelaide plains (SA), Riverland (SA), Sunraysia (Vic.) and Riverina (NSW) but not in the Swan region of WA (The almond production region in WA accounts for 3% of production area). These workshops attracted 36 people including managers from several large almond production companies that account for over 50% of almond orchards. The workshops were followed up with questionnaires sent to all almond growers (using details from Almond Board of Australia) to garner information for a wider audience. A further 16 respondents provided information.

A comprehensive literature review was undertaken to identify management options to address the identified weather and climate risks. The review considered what is known from climate science and the extent of uncertainty in future climate projections, general agronomy, or known from other plants. This review also considered amendments to the typical current practice that are utilized by smaller sub-sections of orchardists, and also preliminary findings from active research trials. The management options that were identified consisted of practical solutions which could be explored and also included knowledge gaps which ideally would be explored to more fully understand limitations to almond production. The project did not seek to undertake plant based research to explore these identified management options, but rather to provide information to others. The information was provided to Horticulture Innovation Australia and to the Almond Board of Australia so future research priorities could be assessed.

The desktop analysis of risks from weather and climate to almond production was done by examining climate indices (agro-climatic indices) that quantify the impact of weather and climate on the previously identified risks. Some risks could be assessed by several agro-climatic indices that in most cases were highly correlated, while few suitable indices would be used for other risks.

The agro-climatic indices were calculated using the historic climate records for locations in each almond growing region. A total of 17 locations were used (4 or 5 in each of the four afore-mentioned regions) with detailed analysis shown for a single location having higher quality meteorological records in each region). Rainfall records since 1900 were used while the period since 1957 was used for temperature records as the quality of temperature observations improved in 1957. The period of the year over which the agro-climatic indices were calculated was based on the information from the phenology calendar. As most almond orchards have been established since 2000, this period of 'grower experience' was placed in context of the long-term climate records.

Australia's climate is influenced by climate drivers with ENSO and IOD being among the most widely recognized in southern Australia (where almond orchards are located). The strength of these climate drivers are used by many industries within the agricultural and horticultural sector for making within-season decisions. The influence of these climate drivers on expected changes from the long-term average of the agro-climatic indices relating to the weather and climate risks was examined.

Examining the agro-climatic indices in a future climate can inform about how the weather and climate risks may change, either beneficially or detrimentally. This can assist with medium and long term planning of orchard operations. There is high confidence that the almond growing regions will be warmer and that local rainfall and that in the Murray Darling Basin will be changed but there is uncertainty on the extent of warming and the exact changes in rainfall. The impact of future climates of either 1°C warmer, 2°C warmer, 20% drier, 10% wetter or 20% wetter were examined to illustrate the likely scale of changes that could be expected. The actual changes may be more or less than those shown, and these changes were chosen to demonstrate likely possible conditions. If greenhouse gas emissions are greatly reduced and follow the moderate emission RCP4.5 pathway it is expected that the climate will be about 1°C warmer by 2050 and 2°C warmer by 2070 than what was experienced during the

20 years period from 1986 to 2005. If greenhouse gas emissions follow the higher emission RCP8.5 pathway, warming of about 2°C by 2050 would be expected. There is greater uncertainty in the projections of rainfall. The high year-to-year and decade to decade variation is expected to continue or to increase. Although different Generalised Circulation Models (GCM's) 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 than changes in warm seasons. 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 the identified most important risk of rain at harvest.

Transfer of the finding of these desktop activities have been achieved through conference proceedings and by booklets (web based downloads available) focusing on each of the four studied almond growing regions.

The tree physiology theme included and field based data collection of plant crop development and yield performance and associated weather data, and potted plant trials where plants were grown under ambient air temperature and in chambers that were passively solar heated. Three to four meso-sites (each having three replicate blocks) along a single elevational slope within the same or similar management units in each of four orchards (Lake Powell, Vic, Lindsay point, Vic. New Residence, SA, Walker Flat, SA) were monitored for meso-climate temperature, crop phenology development (flowering, fruit maturity and hull split) and yield and yield quality. The meso-sites were selected based on elevation as a space-as-proxy-for-time was implemented. This approach which has a more extensive use in ecology than agriculture utilized differences in location to explore differences in weather and climate, and associated plant biodiversity or performance. Within the agricultural context the use of three to four meso-sites within each orchard allowed for a more rapid collection of data relating to climate and performance of the almond plants.

The potted plant trial examined both Nonpareil and Carmel varieties, the two most important varieties accounting for almost 90% of plantings with Australia. Plants were grown in 100 litre pots at Waite, Adelaide under ambient air temperature for two years at which time nine of each variety were placed in passively solar heated chambers (1.6 m * 1.6 m * 1.8 m height) constructed from clear polycarbonate and monitored for a further two years. Temperature was monitored near each plant at 1.2 m height and at three additional heights (0.7 m, 1.6 m, 2.0 m) in eight plants (two of each variety and growth temperature) to examine the extent and influence of warming the entire canopy. Crop development (flowering, fruit maturity and hull-split) and yield characteristics were examined.

All crop development data (commercial orchards and potted plant trial) was utilized to explore the impact of climate on crop development and yield, and also to assess the almond predictive phenology model.

Phenology model development and testing was achieved by firstly a literature review to determine the presence, extent and applicability of phenology models for almonds grown in Australia; evaluating the reliability of these models using field data of temperature and crop development collected during this project; and calculating locally applicable and up to date thresholds for the model using these data in order that the most reliable and robust model would be available to Australian almond growers.

Four models predicting almond flowering were available. These were (i) Prediction of the date of 10% flowering was calculated according to the relationship provided by Pope et al. (2014) based on Californian data; (ii) Prediction of 50% flowering using the relationships provided by Diez et al. (2017) based on Spanish data; (iii) Prediction of 50% flowering using the relationships provided by Rattigan and Hill (1986) and Rattigan and Hill (1987) based on Australian data although unfortunately the thresholds used to progress almond development differed between locations so it was decided to average the thresholds in this model; and (iv) Prediction of 50% flowering using the relationships provided by Alonso et al. (2005) based on Spanish data.

All four flowering models use chill accumulations and heat accumulation that commences on the day after the minimum required chill is accumulated but different forms of chill and heat accumulation are used. Pope et al. (2014) and Diez et al. (2017) used Dynamic Chill Portions and ASYMCUR heat units; Alonso et al. (2005) used Utah Chill units and ASYMCUR heat units; Rattigan and Hill (1986, 1987) used a variation of Utah Chill units and an a variation of ASYMCUR heat units. The progression to 80% flowering (deemed to be Full bloom) and to 50% flowering in the model of flowering based on Pope et al (2014) used a relationship with heat accumulation derived from observations from this research project. The chosen heat accumulation method was the same as that used for the respective flowering models. That is, ASYMCUR for all flowering models except that of Rattigan and Hill (1986, 1987) which used the variation of ASYMCUR.

Models of almond fruit growth and maturity included those by Tombesi et al. (2010) and Connell et al. (2010), both of which used Californian data. The model for 1% Hull Split by Tombesi et al., (2010) was not accurate under Australian conditions as the date of hull split predicted by the Tombesi et al., (2010) model was considerably earlier than actual observations collected during this Research project. The model for 100% Hull split and for Maturity by Connell et al. (2010) was accurate under Australian conditions, but it relied on knowing when 1% Hull Split occurred so was not appropriate in isolation. Like the model for fruit development by Tombesi et al. (2010), the continuous model of almond flowering and fruit growth developed in this project uses heat accumulation to progress development from Full bloom (80% flowering) to 1% Hull Split, then to 100% Hull Split and then to Harvest/Maturity. The thresholds of heat accumulation for these phenology progressions were developed in this research project.

An excel based program for almond phenology was developed for growers. The program allows growers to input local temperature observations and therefore produces predictions of local phenology for use by the almond growers in management decisions. The usefulness of the model relies on accurate measurements of crop phenology development. For this reason two factsheets that describe how to evaluate phenology were developed for growers. Assistance was also provided to the Almond Board of Australia for their development of a grower based tool for recording crop phenology development.

Regular meetings to discuss the project were held with Mr Peter Cavellaro, chair of the Almond Board of Australia's Production committee. This process was an effective and efficient conduit of information as the Production committee oversees a large range of research and development projects, and also provides advice with respect to future priorities for investment in production based research and initiatives to increase yields and better manage risk factors. Additionally regular meetings were held within the scientific research team (D. Thomas, P Hayman, V.Sadras) to plan tasks to facilitate efficient and effective achievement of both short and long term project objectives.

Outputs

The project produced the following outputs.

Theme 1. Identify and assess risks of climate and weather events, and determine appropriate management options produced an assessment of the climate strengths and challenges of Australia's main almond producing regions. This analysis is also detailed in the Thomas and Hayman (2019) (Appendix 1) and more briefly described below. In addition to the Thomas and Hayman (2019) report, six booklets each focusing on a location within the four main almond producing regions of Riverina, Sunraysia, Riverland / MurrayLands and North Adelaide Plains were produced.

A major output from this theme is the consolidation of new learning from this project on climate risks to almond production in Australia. These include:

A phenology calendar developed in conjunction with almond producers in a series of workshops.

These workshops also identified and ranked weather and climate risks according to economic importance.

Agro-climatic indices were analysed in order to quantify these risks.

The severity and trends of the risk indices were examined in the historic climate and compared to other almond growing regions within Australia and in California. This use of spatial analogues facilitates learning from other regions in managing for current or future climate conditions at your location. This analysis showed:

- Mean annual, spring and summer temperatures vary considerably between almond growing locations, with largest differences being in mean summer temperature. Across the Australian almond growing regions the climate is cooler in the coastal locations such as the Adelaide plains and Murraylands and warmest in the inland and more northern locations (Griffith), but even Griffith is cooler than most Californian locations.
- The analysis of historic trends in the indices showed a trend of increasingly warm conditions in all locations. The rate of increase in mean annual temperature per decade (calculated from 1957 to 2014) is up to 0.3°C per decade and averaging 0.13°C per decade across the locations examined. This is consistent with Bureau of Meteorology climate analysis from high quality stations. While there is considerable year-to-year variation in temperature with cooler years and warmer years, there was a strong trend of increasingly warmer years in recent decades resulting in a corresponding change in indices related to temperature such as mean growing season temperature (mean temperature from October to April) and heat accumulation. For example, at Renmark 16 of the 19 years since 2000 have been warmer than average.
- Heat accumulation is required to achieve flowering and subsequent growth and development. It was strongly related to mean annual temperature. Heat accumulation from July is likely to be useful to complete ecodormancy and 'force' flowering, and along with chill accumulation it therefore related to the risks of **Insufficient chilling for synchronized flowering** or **Pollinators not flowering in synchronicity.** Heat accumulation at other times is likely to be useful for further development, with faster development being related to higher heat accumulation and is related to the risk of **Generally warmer conditions advancing growth.** Pest pressure is also expected to increase as heat accumulation increases as the rate of development of pests can be related to temperature and heat accumulation..
- Temperature conditions desirable to biomass accumulation and growth may also be examined by photosynthetically desirable hours. 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 was considerable seasonal variation in the number of daylight hours per day that are conducive to high photosynthetic rates, with excessively warm conditions occurring on average only for small amounts per day. However, there will be considerable daily variation in the number of desirable photosynthetic hours owing to the fluctuations in weather.
- Risk from temperature extremes by **Frost**, **Heatwaves** or **Temperatures being too cold for pollination** change during the year, vary between almond growing locations, and are related to mean annual temperature. Risks from high temperature are larger in more inland regions but overall are less in Australia than in California. Risks from poor pollination conditions are higher in more inland conditions and these are comparable with Californian locations.
- Owing to the close relationship between temperature and the number of extreme days, as for the trend in growing season temperature there was also a trend of an increasingly greater number of warmer days (*e.g.*

the number of days per year warmer than 35°C), but also a greater number of very cold nights that increases the risk of frosts. For example, at Renmark 15 of the 19 years since 2000 had a higher than average number of days warmer than 35°C, while at Mildura 15 of the 19 years since 2000 had a higher than average number of days colder than 2°C. 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. It should also be remembered that the number of days where the minimal temperature is cooler than 2°C per year is very low and small changes of only one or two additional days per year can have a large impact on which decile that year is categorized into. This trend in cold nights and frost over spring is of concern to the grains industry (Crimp *et al*. 2015, Zheng *et al*. 2015).

- There was little trend in the number of bee flight (potential pollination) hours, although the temperature component of this indice (hours warmer than 15°C did increase), the indice was reduced by the occurrence of raindays in August which had no historical trend.
- The amount of chill accumulated addresses the risk of **Insufficient chilling for synchronized flowering** or **Pollinators not flowering in synchronicity.** Chill accumulation varies considerably each month. Almonds require a minimum of 23 chill portions to satisfy dormancy requirements, and as flowering occurs in August the chill accumulated until 31st July was calculated although chill continues in August and can occur as late as October. Other reports show Nonpareil almonds require approximately 400 Utah chill hours. Chill portions are more strongly related to mean winter temperature than mean annual temperature but also show a decline with increasing mean annual temperature. The historic trend in the amount of chill accumulated showed there has been a downward trend in the amount of chill accumulated with 13 of the 19 years since 2000 at Mildura having lower than average chill accumulation. The decline in chill accumulation is expected to continue at a faster rate as the climate becomes warmer. That is, for each successive 1 °C warmer climate, there will be an increasingly larger decline in chill accumulation. The average chill and that received during the warmest year and the highest 10% of years (corresponding to the lowest chill and 10th percentile of chill) is higher in inland locations. While the average chill was similar in Californian locations to most inland Australian locations, the minimum amount of chill and that received in warm years, especially at Bakersfield in southern California, can be less than that received in coastal Australian locations.
- Several risks are associated with rainfall. These include risk of **Insufficient rainfall on the orchard,** risk of **Insufficient irrigation water,** risk of **Rainy days at harvest,** risk of **Excessively rainy and humid conditions leading to increased risk of diseases,** and as such are related both to rain and to evapotranspiration.
- Rainfall, unlike evapotranspiration of Australian almond growing locations is essentially aseasonal with similar rainfall occurring in each month. Monthly Rainfall rarely exceeds ETo but approaches ETo only in the Winter months. 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 harvest season (February to April in Australia and August to October in California) is usually considered a disadvantage as it affects timing of harvest operations and can reduce yield and quality.
- Many almond growing regions have low rainfall and high evapotranspiration and while wet years and dry years occur there is little evidence to date of strong trends in rainfall although there is a trend towards higher evapotranspiration. For example growing season evapotranspiration at Renmark has been higher than average in 16 of the 19 years since 2000, while slightly more than half these years have had higher than average growing season rainfall and slightly less than half have had higher than average annual rainfall. The demand for irrigation water is related 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 (ETo - R) 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). These provide a guide to the risk of **Insufficient rainfall on the orchard.**
- The risk of **Insufficient irrigation water** is related to inflows into the major catchments, water storage and also to water policy. Inflows into Murray-Darling Basin river system are projected to reduce by 20 to 30% for every 10% decline in rainfall (Chiew, 2006). This would be expected to reduce the availability of water available for irrigation. The expected increase in evapotranspiration may place greater strain on the

availability and cost of water.

- Rainy and non-drying conditions, the later measured as moisture balance positive days (MB+ve) during the harvest window (February to April in Australia) are an indicator of the risk of **Rain affecting harvest**. Conditions considered to increase the risk of rain at harvest are generally less desirable as summer ends and autumn progresses in Australia, and less desirable than in California. The long term trends in these indices shows the long term trends of these indices during the growing season, which could be used to assess the risk of **Excessively rainy and humid conditions leading to increased risk of diseases.**
- The use of rainy days and MB+ve days to assess the risk of rain at harvest or of **Excessively rainy and humid conditions leading to increased risk of diseases** was chosen for simplicity of these indices. Other indices to assess leaf wetness are available but complex to calculate. There was generally high agreement between the two models used to calculate leaf wetness (dew point and hours of relative humidity greater than 90%). The number of hours per day of wet leaf declined with increasing mean annual temperature for locations cooler than 17°C, but showed no further declines for locations warmer than 17°C. Leaf wetness was less in locations with higher evapotranspiration, but was poorly related to mean annual rainfall. The number of rain days was related to leaf wetness only when examined for the period from October to April so could be an indication of disease pressure, but not from February to April so was unlikely to be a good indicator of the risk of rain or non-drying conditions at harvest. In other words, leaf wetness near harvest (February to April) was poorly related to the number of rainy days. However, wetter locations also had a larger number of days considered moisture balance positive (not shown). The index of the number of moisture balance positive days increased as the number of days with either 2 or 5mm rain increased, and decreased as Evapotranspiration of a location decreased.
- Taken together the relationships of indices with mean temperature suggest warmer locations or increasingly warmer conditions may be associated with increased risks of heatwaves, increased evaporative demand and demand for irrigation water, increased risk of insufficient chill but reduced risk of poor pollination conditions and of frost (although it is understood that the risk of frost may increase in the short term as drier conditions frequently lead to greater risk of frost). There is considerable year-to-year variation in indices related to rainfall and little indication of strong long term trends. However it should be noted that global circulation models used to project future climates in response to increased greenhouse gases indicate the seasonality of rainfall is likely to change and that rainfall is likely to decline.

The impact of climate drivers such as El Niño Southern Oscillation index (ENSO) and Indian Ocean Dipole (IOD) were examined to determine relationships with the agro-climatic indices and therefore able to provide an indication of altered chance of the severity of the risks in years when the climate drivers were positive or negative, that is if negative IOD years, positive IOD years, El Niño years or La Niña 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 Niña 3.4, Southern oscillation index (SOI), strength of trade winds and cloudiness which are related to formation of El Niño and La Niña events, and IOD which is related to formation on negative and positive IOD events (http://www.bom.gov.au/climate/enso/). http://www.bom.gov.au/climate/model-summary/ provides an overview of several climate models that can be used to assess NINO3.4 and IOD climate drivers.

A brief summary of the influence of ENSO and IOD on the climate in the almond growing regions is that an El Niño 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 year or 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. There can be however an increased chance that El Niño years or positive IOD years result in warmer mean and daily maximum temperature and cooler daily minimum (night) temperatures and drier conditions, and an increased chance that La Niña years or negative IOD years result in cooler mean temperature daily maximum temperature and warmer daily minimum (night) temperatures and wetter conditions.

ENSO and IOD influence both rainfall and temperature with El Niño years or positive IOD years having less rainfall and warmer mean and daily maximum temperature but cooler daily minimum (night) temperature than La Niña years or negative IOD years. The impact on rainfall is throughout the year while the impact on temperature is typically stronger in spring and early summer. The duration of months that IOD influences daily maximum and minimum temperatures can be as long or longer than when ENSO influences daily maximum and minimum temperatures, with the impact of ENSO on daily minimum (night) temperatures being mainly restricted to winter. The differences in rainfall affect risks associated with **insufficient rainfall in the orchard** and of the **supply of irrigation water**, and combined with evapotranspiration affect **irrigation demand**, **rain affecting harvest**, and **excessively rainy and humid conditions leading to increased risk of diseases**. For example rainfall in the Murray-Darling Basin catchment is lower in El Niño years or positive IOD years and this may influence inflow and irrigation water availability in this and following years. Because rainfall is lower and Evapotranspiration is higher in El Niño years or positive IOD years there is likely to be an increased demand for irrigation in these years. This may affect management decisions concerning purchase or irrigation water. However the lower rainfall and higher evapotranspiration reduces the chance of MB+ve days particularly in the spring and early summer but less so during the following years harvest season which may reduce the risk of excessively rainy and humid conditions leading to increased risk of diseases during the event year, but is likely to have minimal influence on the risk of rainy conditions during harvest. Specific findings were:

- Rainfall throughout the year was influenced by ENSO and IOD and there was typically an increased chance of El Niño years or positive IOD years having rainfall in the lower third and a corresponding chance that La Niña years or negative IOD years having rainfall in the upper third. Rainfall during the following January to March, that is in the year of harvest was largely unaffected by ENSO and negative IOD but would be expected to be higher in those years with positive IOD years during the year of flowering. The ENSO and the DMI indices, and SOI were generally significant with rainfall during September to December but not rainfall during January to March.
- 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. There is 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 compared to the long term average of 3 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. The ENSO and the DMI indices and SOI were significant with annual rainfall.
- The evapotranspiration response to ENSO and DMI categories showed that differences occur 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 was assessed as the difference or irrigation deficit (ETo – Rain). There was an increased chance that greater irrigation deficit occurs in El Niño years or positive IOD years, and that this is most likely to occur in the period between September and December rather than from January to March of the following year. The reverse occurs in La Niña years or negative IOD years 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 ENSO and the DMI indices and SOI were generally significant with irrigation deficit, particularly during September to December.
- The number of days considered moisture balance positive (MB+ve) was affected more by DMI than by ENSO. As with many indices the impact of ENSO or IOD was stronger during the event year than the following year. This meant that ENSO or IOD was likely to have a greater influence on the risk of excessively rainy and humid conditions leading to increased risk of diseases during the event year, but was likely to have minimal influence on the risk of rainy conditions during harvest. An El Niño year or positive IOD year increases the chance that the number of MB+ve days during September to December was in the lowest third of all years while also correspondingly reducing the chance that the number of MB+ve days was in the highest third of all years. La Niña years or negative IOD years have essentially the reverse effect. However during January to March of the following year La Niña increases while negative IOD decreases the likelihood that the number of MB+ve days was in the highest third of all years (tercile 3); while neither El Niño nor positive IOD effects MB+ve days during this period. The ENSO and the DMI indices and SOI were generally significant with the number of MB+ve days during September to December but not during January to March.

The differences in mean temperature affect risks associated with **warmer spring and summer temperatures advancing growth**, **heatwaves** and undesirable photosynthetic hours, **frosts**, **chill accumulation** and **synchronicity of flowering**, and when combined with rainfall affect desirable **pollination hours**. For example warmer than usual mean temperatures occur during September to December in El Niño or positive IOD event years and this can affect heat accumulation and development rate, but also the chance of heatwaves and the loss of desirable photosynthetic hours thus limiting the extent of carbohydrate accumulation. Greater irrigation may be required to alleviate heat stress in these conditions. Chill accumulation before August is largely unaffected by the climate drivers, but frosts may be more frequent and occur later, suggesting strategic decisions relating to frost mitigation may be warranted.

- Mean Temperature was influenced by ENSO and DMI (which measures IOD) mainly in the spring to early summer period with mean temperature during January to March following the event year, that is in the year of harvest, being largely unaffected by ENSO and DMI. There was typically an increased chance that mean temperature during El Niño years or positive IOD years was in the upper third of years and a corresponding chance that mean temperature during La Niña years or negative IOD years being in the lower third of years. La Niña years had minimal impact on mean temperature. Mean temperature during the following January to March, that is in the year of harvest was largely unaffected by ENSO and DMI. The ENSO and DMI were generally significant with mean temperature during September to December but not during January to March.
- These differences in mean temperature affect the risk of generally warmer conditions advancing growth. El Niño years or positive IOD years advance the rate of development and the thresholds were reached sooner, while La Niña years or negative IOD years retard the rate of development and the heat accumulation thresholds were reached later.
- The influence of ENSO and DMI on maximum and minimum temperature were similar to the effect on mean temperature, however there were differences in the occurrence of extreme hot and extreme cold days. An El Niño year or positive IOD year typically has more days warmer than 35°C during late spring to early summer than La Niña years or negative IOD years. The chance that an El Niño year or positive IOD year had as few days warmer than 35 °C as the lower third of all years (tercile 1) during September to December was essentially nil at many locations. The opposite essentially occurred in La Niña years or negative IOD years although the effect was not as dramatic. The correlation of the climate drivers and SOI on the indices was significant. The influence of event years and climate drivers does not extend to the January to March period of the following year.
- ENSO and DMI had minimal influence on the accumulation of chill hours after August, and almost none before August. Therefore 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).
- Pollination conditions are thought to be unfavourable if temperatures are below about 15 °C and if rain occurs. This indice was not well correlated with climate drivers but was correlated with SOI. However 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.

An important aspect of the climate analysis is the examination of the impact on the identified risks in a warmer and water constrained future as a consequence of climate change. This analysis provides information pertinent to longer term management and investment decisions for the almond industry. A future climate is likely to be warmer and possibly drier although there is greater uncertainty in the rainfall projections and changes in the seasonality of rainfall may affect the risks of almond production. A warming climate will increase mean temperature during the growing season and increase heat units and a decrease in chill units. There will be a change in the average hours per day that are considered photosynthetically desirable. There will be an increase in heatwaves and a decrease in frosts. There are also likely to be an increase in desirable pollination conditions. There are no clearly defined trends in rainfall but an increase in evapotranspiration is expected, and this will affect irrigation requirements and also the risk of rain at harvest. Specific findings were:

- In general across all the almond growing locations examined the growing season mean temperature and heat units have increased in the 20 years from 1998 to 2017 with about three quarters of all years being warmer than the median, and several years receiving more than the historic maximum during 1986 to 2005.

Further warming will increase the amount of heat units received and not surprisingly the projections indicate there will be very few years with 'below median' heat units in a warmer world. In general 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 more years in 10 years, while a 2°C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) would mean almost every year was as warm or warmer than what was a 1 in 10 hot year with over half the years being warmer than any experienced during the historic period from 1986 to 2005. This new climate would be similar or hotter than the historic climate at Bakersfield, California which is among that states hottest growing regions.

- Chill accumulation for most of the almond growing locations examined was similar or slightly lower during the 20 years from 1998 to 2017 to those received during the 20 year period from 1986 to 2005. However chill accumulation declines in response to 1°C warming (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) and all locations have less chill than the former median amount of chill. In other words, the 50% of years that had high chilling are projected not to occur in a 1°C warmer climate. A 2°C warmer world (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) would mean that for almost all locations the chill accumulation in every year is likely to be lower than that experienced during the base period or the last 20 years, while in a few locations there may be some years where the chill accumulation is as low as that which would be received in a formerly very warm and low chill accumulation year. Of concern is that the reportedly minimum chill to satisfy Nonpareil's dormancy requirements of 23 chill portions is projected to occur in only some locations with a 2°C warmer climate. However chill accumulation can continue in August meaning that accumulation of sufficient chill may continue to be achieved but it is unknown how flowering may be affected although it is likely to be at a later time of year.
- The warmer climate is projected to alter the number of days with extreme temperature leading to 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 for most locations was 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. Warming by 2°C further increases the projected median number of warm days to about the same amount that occurs in the hottest 8 in 10 years. The projected new minimum number of days warmer than 35°C days in a 2°C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) is about the same as the median number of warm days experienced during the 20 year period from 1986 to 2005. In this 2 °C warmer climate 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 are likely to remain 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.
- 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 comparted to the 20 years from 1986 to 2005. Frost is a complex phenomenon. While there is very high confidence of warming at night which should reduce frost in the long run, frost damage in the almond industry are radiation frosts and the reduced cloud cover associated with increased drying may mean the number of spring frosts may increase or stay the same depending on the extent of drying in spring. It is thought that in the near term (e.g. 2030) the annual chance of frost and year-to-year variability and relationship with climate drivers will remain unchanged. In the longer term the potential for frost is likely to decline.
- There is no clear trend in rainfall but there has been an increase in evapotranspiration and irrigation deficit. Projections and therefore changes to risks associated with for rainfall are less confident. It is expected that the natural annual variation and seasonal patterns of rainfall will remain the dominant factors in the near future but there is high confidence of a decline in autumn and spring rainfall in southern Australia in the longer term. There is good scientific understanding of drivers of hydrology and the relative uncertainty under climate change projections. However the impact on runoff to catchments is partially understood as plants grow differently across catchments with higher carbon dioxide, warmer and possibly drier conditions. Consequently it is thought the amount of irrigation supply and its' quality may decline, while the expected increase in evapotranspiration with warming may place greater strain on availability and cost of water.
- 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 from 5 in 10 years to

about 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 3 in 10 dry growing season becoming the new median and some growing seasons being drier than any during the 20 years from 1985 to 2006.

- Evapotranspiration during the growing season in a future climate that is 1 °C warmer 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 while a 1 °C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) is projected to increase evapotranspiration by 4%, the 8% increase in response to a 2 °C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) may result in about 8 in 10 growing seasons have as great or greater evaporative demand to that which occurred in the highest 2 in 10 year growing seasons.
- 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.
- 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 as indicated by both the amount of rainfall and the number of days that could be classed as moisture balance positive. A climate that is 20% drier during the harvest season would mean about 3 in 10 years are as problematic as the current median year but wet harvest seasons are likely to continue to occur.

Importantly for each of the identified weather and climate risks a detailed understanding of how the risks affect the almond crop provided an initial basis for detailing areas of knowledge gaps (or knowledge uncertainty) from crop physiology and from climate science that require examination. Furthermore a detailed list of management options to address the identified risks were developed.

A summary of the outputs can be seen in Table 1.

The Bureau of Meteorology are aware of these weather and climate risks. This will be beneficial to the Almond industry as future products from the Bureau of Meteorology may be able to be tailored to industry requirements.

Conclusions from Theme 1 were that 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 detailed, as are the trends in these risks and the year-to-year variation and role of climate drivers during the historic climate. It is important to appreciate that while 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 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. However 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.

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.

Table 1. Summary of climate and weather risks to almond production in Australia with details the trends in these risks and the year-to-year variation and role of climate drivers during the historic climate.

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**	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.
The direct cost is extra water, as warming leads to and increased demand for water requirements	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.

Non-synchronised flowering Ranked as high concern. Flowering is controlled by chill and heat accumulation that are unique for each variety.	Rest breaking agents that assist in overcoming dormancy are available for use in some industries. 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.

Theme 2. Field trials to examine the impact of climate and weather on Almond tree physiology produced two factsheets, one detailing a crop development photoscale, and another detailing assessment methodology to determine flowering and hull split in almonds. These factsheets are available at https://industry.australianalmonds.com.au/research-topics/orchard-management/

and

https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/phenology-standard-for-almonds/

https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/assessing-phenology-of-almonds/

The field trials undertaken for this theme also found that meso-climates do exist within the meso-sites within an orchard; and that the lower elevation meso-sites generally had cooler daily minimum and daily maximum temperature but local topography and perhaps row orientation affected this general relationship. It also established that the canopy itself can modify the climate with leafier canopies (due to growth and development or tree density) tending to be cooler but also less windy.

Crop development (phenology) was relatively stable between meso-sites in any year and location, but an analysis of all meso-sites and years showed flowering was earlier when chill accumulation was higher (that is in colder winters); and hull split occurred earlier when growing season temperature was higher (that is, when spring and summer was hotter).

Yield and its components differed between the meso-sites, but not in a consistent manner, with no meso-site having consistently higher or lower yields with the four year average yield not different between any meso-site within an individual orchard. However there was an overall positive relationship between crackout and yield at all orchards implying the %shell and hull were reduced when trees retained more fruit and therefore had higher yields.

The relationship between yield and temperature is not conclusive. Warmer growing seasons benefited yield. However in some orchards a larger number of hot days reduced yield, and warmer conditions during the period of bud formation reduced yield from these buds. Yield was also positively related to a greater accumulation of chill implying colder winters with greater chill accumulation are beneficial to yield.

Another important output from this theme were the observed climate and phenology at each of the meso-sites which was used when developing and testing the phenology model (see Theme 3).

Detailed outputs from these trials can be found in Appendix 2.

Theme 3. Examination, collation and evaluation of an Almond phenology model produced a literature review detailing combined chill and heat summation model(s) of phenology with a focus on Almond specific models and related *Prunus* crops (Appendix 4). This showed that although there is no unified phenology model for almonds that explains the influence of environment on the development of all the major phenological stages, phenology models largely based on temperature exist for several stages of Almond production.

The output for this themes aspect involving collation and examination of an almond phenology model established that models for these individual stages can be successfully amalgamated to form a continuous model, and that these can be tested under Australian conditions. The discrete models, and in particular the flowering, flower progression and nut maturation models were able to predict phenological development with remarkable accuracy and precision, although the ability of the continuous model to accurately predict phenology declined as the development stages progressed as errors became exacerbated. This difference in the models ability to predict phenology in a new location (Australia) compared to California where the discrete models were developed highlights that both the discrete and the continuous models could be used by managers to assist orchard operations and by researchers. Detailed outputs from these phenology models can be found in Appendix 3.

A final step was the development of an excel based version of the phenology models developed during this project (Appendix 5).

Outcomes

Outcomes of this research included:

The almond industry has a better understanding of the priorities of weather and climate risks to almond production in Australia. Importantly the Bureau of Meteorology have a greater awareness of these weather and climate risks. These improved links between the orchard and The Bureau of Meteorology will be beneficial to the Almond industry as future products from the Bureau of Meteorology may be able to be tailored to industry requirements.

The almond industry is better informed about:

- the severity of weather and climate risks in the historic climate and of any recent trends in the severity of weather and climate risks in different growing regions within Australia and with other main almond producing regions in California.
- the role of major climate drivers in altering the likelihood of weather and climate risks.
- the likely severity of weather and climate risks in future climates.

There is a more informed understanding of within orchard variability in climate and yield. Findings that meso-climates exist allows for the option of their use as monitoring sites, and increases the awareness of understanding and accounting for within orchard variability when making management decisions.

The cooler temperatures within the orchard with higher density highlights the possible benefit of increasing tree density in adaptation to a warmer climate.

Findings that although the meso-climates exist but these related poorly to changes in phenology and yield highlight the importance of multi-year field trials, and imply that biennial bearing may be contributing to these findings, and importantly within the industry as a whole. This would have implications to the year to year management of an orchard.

The multiyear and multi-location analysis of these field trials highlighted possible challenged for the industry. For example this analysis showed flowering was earlier when chill accumulation was higher (that is in colder winters) but importantly yield was also positively related to a greater accumulation of chill implying colder winters with greater chill accumulation are beneficial to yield. Warming climates will reduce chill accumulation.

In contrast this same analysis showed that warmer growing seasons benefited yield, although in some orchards a larger number of hot days reduced yield. The relationship between yield and within season temperature was not conclusive as it was also found that warmer conditions during the period of bud formation reduced yield from these buds in the following growth cycle.

The use of passively heated chambers provided some insights into the role of temperature but these data also suffered from possible biennial bearing of trees and larger than desired between tree variability. Overall passively solar heated chambers do provide a heated environment but this heating occurs largely during sunlight hours. This means difference in chill accumulation can be small.

There is an improved understanding and comparison of the different phenology scales used by Researchers and Industry. This allows more accurate transfer of knowledge between the sectors (research, industry) and industries in different localities that may use different scales. Detailing the methodology for assessing phenology facilitates a common standard of data to be collected. This assists researchers and also producers, and benefits the phenology data collection workbooks developed by the Almond Board of Australia.

The user operated phenology model (excel spreadsheet) allows orchardists to schedule operations based on phenology with greater certainty. The model progresses crop development using temperature, an easily obtained measure in most orchards, and allows for user correction of phenology predictions based on actual observations provided by the orchardists.

Monitoring and evaluation

The project excelled in its performance to provide the Australian almond industry with the three themes of this project: to assess the current climate and weather related risks and evaluate how these risks may change in a water and dryer climate; to develop a phenology model for almonds; and to undertake field research to evaluate the role of climate on phenology and yield.

A key evaluation question relating to the projects effectiveness was to determine if the project has developed and provided new information and/or technology to the almond industry. The project provided both these. The phenology model (excel file) has been provided to Hort Innovation. This model has been calibrated to the Australian industry and allows growers to track the development stage which assists with orchard management and scheduling. The most up to date version (V2) is included as an attachment to this report and replaces the older version (provided January 2017). The model has been trialed by representatives of the Australian Almond Industry. This version is approved by SARDI and may be provided to the almond industry. The Almond Board of Australia is willing to host the excel file on their website for grower download.

New information has also been provided in the form of two factsheets that describe how to evaluate phenology. Draft copies of these factsheets were provided to representatives of the Almond industry for reviewing for accuracy, readability and presentation style that were incorporated into the final versions. These factsheets are available on Horticulture Innovation Australia's website and the Almond Board of Australia's website for grower download; and complement a recently developed excel based tool for growers to record and monitor flowering in the orchards.

The third area of new information that has been provided to the almond industry are the booklets detailing the strengths and challenges of the climate and weather for the almond growing regions that provide an historic context of the indices that describe the climate and weather risks along with the role of the major climate drivers (ENSO, IOD) in altering the year-to-year variability, and the projected impact of a warmer and drier future climate on these indices. This information can be used in planning for the current season and also when assessing near – term and longer - term investment strategies. Draft copies of these booklets were provided to representatives of the Almond industry for review and incorporation of information and presentation style in the final versions.

These booklets and the detailed list of management options that identify knowledge gaps relating to identified weather and climate risks (provided in May 2016) are examples of this project meeting the needs of the Almond industry to plan for climate variability and adaption. This was an area identified by the almond industry as high priority. The identification of a knowledge gap as also being a management option is based on the premise that some information on the subject is available and that it may be possible to use this information to examine the impact of an altered management practice. The management options were discussed at grower workshops, and a more detailed list presented to representatives of the Almond Board of Australia. This was done to provide growers and the Almond Board of these risks and relative importance, of current scientific understanding and practical methods that could be implemented to alleviate risks.

A further evaluation was to engage with levy payers through at least three learning styles. This was achieved through

1. workshops and questionnaires that reached over 50 growers;

2. through presentations of information at annual regional meetings were updates and highlights are presented (these are well attended by growers and regularly attract over 50 however no attendance records collected);

3. factsheets and booklets (mentioned above) that are available on-line;

4. presentations of research at annual conferences including Activated Almond R&D forum October 2015, Biennual Australian Almond Conference – 2014, 2016, 2018 – all of which are attended by over 200 people, two presentations at the ISHS VII International Symposium on Almonds and Pistachios, November 5-9, 2017 which was attended by growers and both national and international researchers.

The overall project was evaluated by an independent mid-term review (March 2017).

Recommendations

The links established between the almond industry and The Bureau of Meteorology should be utilized more fully. The provision of existing information and the potential of new products tailored to the industries requirements would greatly benefit the industry.

The observations suggesting a degree of alternate / biennial bearing in the almond trees should be explored in greater detail, and methods developed to reduce its extent. This would assist with crop management and greater certainty of annual crop yields and assist marketing.

Experimentally exploring the impact of climate change in almonds requires a more complex approach than the passively solar heated chambers used in this project. Future research into examining the impact of warmer and drier climates on almonds could involve experimental systems using rainout shelters, more sophisticated passively heated chambers, or active heating or incorporating the impact of elevated CO_2 as have been used in other crops. This is important as a higher concentration of CO_2 is likely to impact on the transpiration efficiency and canopy growth hence will change the water balance and to interact with stresses such as heat waves and frost.

It is recommended that this list of potential actions be prioritized by considering economic importance in both the current and future climate(s), and the be explored more fully using a combination of national and international research and farm trials. While almonds may experience a number of weather and climate related risks in the current climate and it is likely these will remain in a future climate, the ranking of economic importance of the risks in the current climate may not reflect the ranking of economic importance of the risks in a future climate because the severity and likelihood of the risk event may change. This is because climate scientists are much more certain of the extent of warming and hence changes to risks associated with temperature (apart from those associated with frost), than changes in rainfall and hence risks associated with rainfall. That is, some risks associated with temperature may increase in economic importance.

Risks associated with temperature

Heatwaves (Ranked 2) and **Warmer spring and summer temperatures (Ranked 11)**

These risks are related to changes in mean temperature, in extreme high temperature, changes in evapotranspiration and changes to wind. There is very high confidence of a gradual rise in mean temperature, and that the number and severity of heatwaves will increase in future years. Heatwaves are typically managed by applying more irrigation which imposes an economic cost through cost of water and pumping. See recommendations relating to risks associated with availability of water for more details.

- The industry should explore the suitability of management options used in other crops. This includes overhead/within canopy evaporative cooling, altered canopy management (self-shading of sensitive organs), reducing solar radiation through netting or reflective sprays applied to leaves or fruit.
- Higher density orchards were found to have fewer extreme hot days, and hot days during bud development were related to lower yields in the following crop cycle. The benefits of high density orchards in mitigating detrimental impacts of hot weather conditions should be explored more fully and in a number of different locations and years.
- The reliability, use and value of short and longer term forecasts of coming heatwaves (temperature) and associated evapotranspiration is unknown.
- Greater understanding of the thresholds of temperature that cause damage should be explored. This includes damage to developing buds and loss of carbohydrate gain through reduced photosynthesis. Information is lacking on the role of irrigation, soil water and evapotranspiration on mediating the impacts. This will focus operational decisions to best alleviate the impacts.

Non-synchronised flowering (Ranked 4) and **Low Chill accumulation (Ranked 12)**

Chill accumulation will decline in a warmer future, but will remain above the critical threshold of about 23 chill portions to complete dormancy in almonds. However recent findings from this research indicate yield is strongly related to chill accumulation, so this risk may be more important than previously recognized.

- It may be possible to increase chill accumulation through use of evaporative cooling, application to buds of kaolin or other reflecting agents to decrease bud temperature, or partially overcome chilling requirements using rest breaking agents. The impact on yield should be explored.

- The synchronicity of flowering and hence cross-pollination between varieties in a warming climate are unknown. This could be examined by developing flowering models of the different varieties.
- Self-fertile varieties should overcome non-synchronicity between pollinators. Yield and crop management practices for these varieties need to be explored.
- It may be possible to alter management practices to increase the chance of synchronous flowering through use of evaporative cooling to increase chill accumulation; application to buds of kaolin or other reflecting agents to decrease bud temperature and therefore increase chill accumulation; timing and efficacy of rest breaking agents.

Temperature too cold for Pollination (Ranked 6) and Temperature too warm for Pollination (Ranked 13)

An increase in daily temperature during the pollination period (August) will reduce risks associated with pollination temperature being too low. The current occurrence of temperature being too high for pollination are very low and likely to remain low in coming decades.

- The risk of poor pollination is likely more related to availability of sufficient high quality hives. Artificial pollination of almonds is possible, albeit costly, and requires a source of pollen that has to be collected, stored and applied. However these studies have been of short duration and require further examination to confirm results.
- Fertilization processes in the flower are generally well understood but may require further investigation. It is known that these processes are affected by temperature and it is generally accepted that there is a broad temperature range. It is unknown how general warming will affect the efficiency of these processes.

Frost (Rank 8)

The relationship between minimum temperature measured in a Stevenson screen often located some distance from the orchard, and those experienced by the plant in the almond orchard are not well understood. Factors such as topography, and wind will influence orchard temperatures. Site selection is a major management tool.

- Greater understanding of the interaction between climate and weather affecting chance of frost and of climate affecting phenology is required. The sensitivity of plants, specifically buds and flowers to low temperatures is reasonably well understood, but there is poor understanding of when these organs are present (i.e. phenology poorly understood).

Risks associated with rainfall and humidity

Rain at harvest (Ranked 1)

This risk is related to rainfall and evapotranspiration. As a consequence, the risk of moisture increase as the harvest window progresses into autumn. The projected increase in evapotranspiration suggests a future climate may cause this risk to decline, but is likely to remain as a major risk for the industry.

- Methods to move the harvest window to an earlier period in the current climate are partially understood. Irrigation management can be used although additional understanding is required to avoid yield losses. Other options such as hormones that enhance fruit desiccation and abscission but retain leaves should be explored. The success of any method will require greater understanding of fruit maturation, potential yield losses through reduced carbohydrate gain, and advances in kernel drying procedures.
- The industry should continue to explore changing harvesting equipment to a mechanised shake and catch method would avoid issues of undesirable soil moisture (apart from traffic-ability and compaction). This change may also allow for changes to improving soil structure or topography
- The industry should continue to explore improved drying practices of nuts and kernels. These include examination of types of tarpaulin covers. Other options include use of active (powered) driers. The rate of drying or temperature used for drying may affect quality.
- The risk of rain at harvest may be able to be partially reduced through operational logistics deciding whether to harvest or not based on weather forecasts, or of moving harvesting equipment between orchards based partially on weather (short term forecasts) of chance of rain in the near term. This approach would be

driven by economics and could follow the existing guidelines of when to harvest based on rain or chance of rain such as those currently used or those developed by the Californian industry. It would also require additional understanding of drying properties of different soil types, and the interaction between wet soil and fruit drying.

Rain and Humidity leading to disease (Ranked 4)

This risk is likely to be related to changes in rainfall, humidity, temperature and evapotranspiration. While there is uncertainty for rainfall, there is a high degree of confidence in warming. The impact on disease pressure is uncertain.

- The appropriate climate index for this risk is unknown and may differ depending on the disease or pest in question. Many horticultural pests and diseases are very sensitive to rainfall, humidity and temperature (both day and night temperature). Models of the responses of some pests and diseases to weather and climate exist and could be explored under climate change projections. While these models would indicate the progression of a pest or disease they do not indicate that the pest or disease is present and will cause damage.

Availability of irrigation water, and its quality (Ranked 7) and **Inadequate winter rain (Ranked 9)**

These risks are related to changes in rainfall and to changes in evapotranspiration.

- The infrastructure must be available to supply the water to the irrigators under a potentially increased demand, such as to alleviate impacts of heatwaves.
- The response to irrigation continues to require examination in the current and future climates when drivers of water loss from plants will change, and different management practices may be utilised such as plant spacing, pruning or training).
- Improving utilisation of existing rain fall may be possible by improving soil structure thereby increasing water holding capacity. Improving soil structure is typically achieved through incorporation of biomass. This may increase risks associated with orchard floor hygiene and kernel quality.
- Almond are considered sensitive to salinity with some Californian orchards showing marginal leaf burn, yield decline and other obvious signs of excess salinity in the root zone which may be compounded by deficit irrigation and declining groundwater quality as water table levels drop. Research into salinity issues of almond trees such as use of saline irrigation water, salt leaching from soils, salt exclusion and tolerance of root stocks and scions, and of saline water applied at different phenological stages on growth and yield are in their infancy and should be continued.

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Intellectual property, commercialisation and confidentiality

No project IP, project outputs, commercialisation or confidentiality issues to report

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Appendices

Appendix 1. Thomas and Hayman, 2019. Identifying and managing risks to Australian almond production in current and future climates

Appendix 2. Methods and Outputs from Theme 2: Field trials to examine the impact of climate and weather on Almond tree physiology

Appendix 3. Methods and Outputs from Theme 3: Examination, collation and evaluation of an Almond phenology model

Appendix 4. Literature review detailing combined chill, heat summation model(s) of phenology with focus on Almond specific models, and also related crops such as peach and other *Prunus* species.

Appendix 5. Excel spreadsheet

Identifying and managing risks to Australian almond production in current and future climates

Dane Thomas, Peter Hayman

SARDI, Adelaide, Australia

21 May 2019

Hort Innovation Strategic levy investment | ALMOND FUND | SOUTH AUSTRALIA | Government of South Australia Primary Industries and Regions SA | SARDI South Australian Research and Development Institute

Executive Summary

- 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. Further details of knowledge gaps and management options are detailed in Activity 2. Identify knowledge gaps relating to the identified risks, and suggest Management Options

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	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.
The direct cost is extra water, as warming leads to and increased demand for water requirements	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.

Further details of the risks, management options and knowledge gaps can be found in Activity 2 Identify knowledge gaps relating to the identified risks, and suggest Management Options

Identifying and managing risks to Australian almond production in current and future climates

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This report comprises Theme 1 of Projects AL14006 Managing almond production in a variable and changing climate (Horticulture Innovation Australia) and Project IRSP-R1-006 Managing almond production in a variable and changing climate (South Australian River Murray Sustainability Program Industry-Led Research Sub-Program)

Disclaimer

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Table of Contents

Activity 1. Workshops to identify and rank weather and climate risks

Methods

Workshops were held with almond producers during May 2015 at Virginia (SA), Renmark (SA), Mildura (Vic) and Griffith (NSW). A total of 36 participants attended these workshops. The workshops were followed up with questionnaires sent to all almond growers (using details from Almond Board of Australia) to garner information for a wider audience. A further 16 respondents provided information.

During these workshops participants assisted with the developed of a phenology calendar where the main phenological stages of almond development and the usual timing that these occurred in their orchards were identified. Participants then identified weather and climate risks that affect the economic viability of almond production. These risks were prioritized by the participants according to perceived typical economic importance calculated as the product of economic loss by the meteorological event and chance of occurrence of the meteorological event. Rankings of the risks were produced for each region and for the industry as a whole. Risks with the lowest ranking number were the most economically important.

Results

Workshops were held with almond producers during May 2015 at Virginia (SA), Renmark (SA), Mildura (Vic) and Griffith (NSW). A total of 36 participants attended these workshops. The workshops were followed up with questionnaires sent to all almond growers (using details from Almond Board of Australia) to garner information for a wider audience. A further 16 respondents provided information.

During these workshops participants assisted with the developed of a phenology calendar where the main phenological stages of almond development and the usual timing that these occurred in their orchards were identified. The usual timing was similar between regions. An example of the phenology calendar is shown below (Figure 1). The development of the phenology calendar preceded the identification and prioritisation of weather and climate risks that affect the economic viability of almond production; and discussion of possible management options to address these risks.

A total of 12 risks were identified that could be classified as being related to either temperature, rainfall and evapotranspiration, or wind and hail (Table 1). Some risks encompassed several weather factors. For example, the risk of rain at harvest, 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 events (e.g. rain at harvest, frost or heatwave) or of a longer nature (insufficient irrigation water). The risk of wet and rainy conditions at harvest was considered the most important risk.

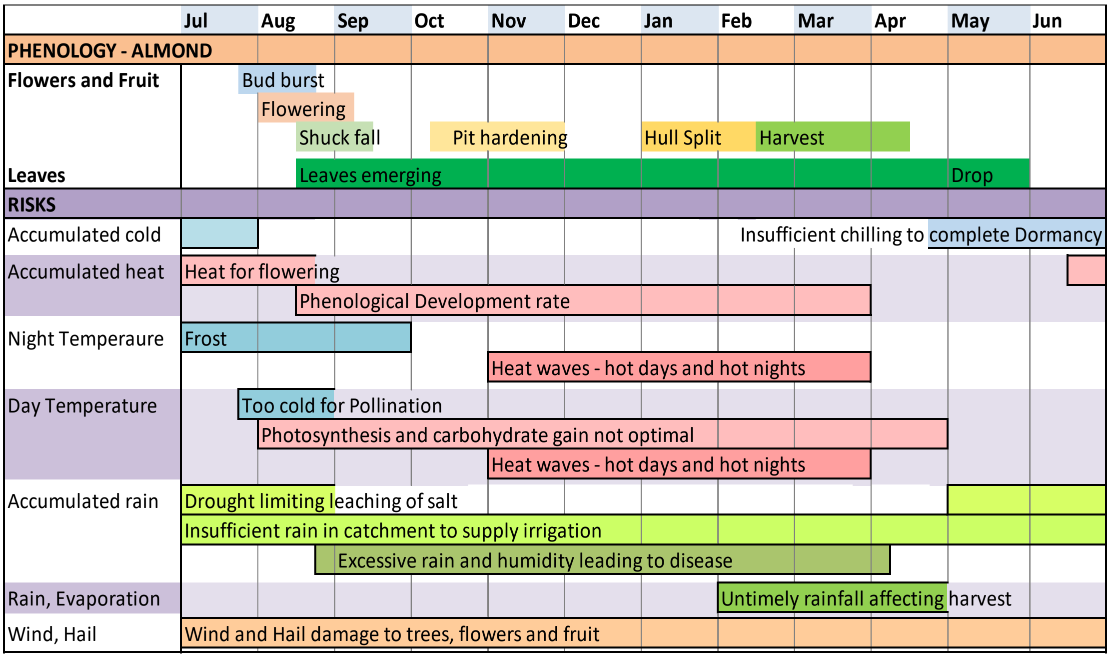


Figure 1. The phenology calendar for almond production in Australia along with the main weather and climate risks. The identified phenological stages typically commence at the dates shown. The identified weather and climate risks have been amalgamated into broad categories. The shaded periods of the year indicate when the undesired weather and climate events are considered to impact on the identified weather and climate risks.

Table 1. The ranking of weather and climate risks to almond production for the industry as a whole and for each growing region. A low ranking indicates the risks is considered more important. Those risks shown in bold are the most important four risks for the industry and for each region.

Risk	ALL	Virginia	Riverland	Sunraysia	Riverina
Rain at harvest	1	6	1	1	1
Heatwaves	2	1	4	2	9
Wind	3	4	2	6	4
Non-Synchronized flowering	4	9	5	6	2
Rain and Humidity leading to disease	4	7	6	5	5
Too cold for pollination	6	2	11	6	3
Insufficient irrigation water	7	11	2	3	7
Frost	8	10	10	3	7
Inadequate winter rain	9	5	7	12	11
Hail	9	8	8	9	10
Warm Spring and Summer	11	11	9	10	6
Insufficient chilling	12	3	11	11	12

Risks related to rain and humidity

Rainy days during harvest operations (harvesting, drying and storage) was ranked the number 1 (highest) risk by participants in all workshops apart from Virginia where it was ranked 6. The economic loss was thought to be 15% or higher everywhere except by growers at the Virginia workshop where it was 5%. The chance of this level of economic loss occurring was thought to be 75% or greater by growers at the Mildura and Griffith workshops but less than 10% by growers at the two SA workshops. There was an indication that although this risk is important to all producers, it may be considered less severe by smaller producers. This was because the scale of these operations allowed greater flexibility with timing of harvest operations to avoid the impacts of rain at harvest or during the period immediately after harvest when the concern focusses on ensuring the fruit dry adequately and is stored under conditions that do not promote pathogen infection. The ranking of the risk of rain at harvest was ranked similarly by the questionnaire respondents as by the participants at the workshops.

Excessively rainy and humid conditions leading to increased risk of diseases was ranked a high to medium risk in all regions (rankings of between 5 and 7). Economic losses were considered to be 10% or less, although it was recognized that this could occur either infrequently (1 in 10 years) or with regularity (1 in 2 years). The risk of rainy and humid conditions leading to disease was ranked as a more important risk in the questionnaires than the workshops, signifying that this risk could be considered more important than previously indicated.

The risk of insufficient rainfall in the catchments that supply the irrigation water was considered a high risk by growers who attended the Renmark workshop (second after rainy days at harvest) and by those who attended the Mildura workshop (rank of 3). This risk was rated lower by those who attended the workshops at Griffith (rank of 7) and Virginia (rank of 17) as these locations rely more heavily on groundwater for irrigation, and additionally in Virginia this can also be supplemented with treated water. In contrast the risk of inadequate rain at the orchard was considered a minor risk by participants at the Mildura and Griffith workshops (rankings of 12 and 11 respectively) but considered of greater importance by participants at Renmark and Virginia (ranked as 7 and 5 respectively). The reason for this is probably related to the importance that growers in these regions place on this rain flushing salts that have been concentrated in the root zone as a consequence of lower quality irrigation water. The differences between Griffith, Mildura and Renmark can be explained by their relative position in the Murray-Darling Basin.

These two risks of insufficient irrigation water and insufficient winter rainfall on the orchard were generally ranked differently in the questionnaires than the workshops. The risk of insufficient irrigation water was generally considered of almost equal importance (change in rankings of about 3 units and considered both more and less important than in the workshops); while the risks of insufficient winter rainfall on the orchard were generally considered of similar or more important by the respondents to the questionnaires as in the workshops. However, in both cases the rankings of these two risks across all regions were similar or identical in the questionnaires and in the workshops.

A further risk identified by participants at the Virginia workshop was of high and variable salt content and hence low water quality of the treated water (reclaimed water from Bolivar treatment plant) that can be used as an irrigation source. The importance of water quality as a weather and climate risk was not examined at the other locations (workshops in these locations were held prior to the Virginia workshop).

Risks related to Temperature

Growers at all locations except those who attended the workshop at Virginia rated the risk of not receiving sufficient chill units for synchronized flowering as a lower risk than the risk of pollinators not flowering in synchronicity. This was similar to the responses from the questionnaires. The risk of not receiving sufficient chill units for synchronized flowering was considered an unlikely occurrence everywhere except by growers at the Virginia workshop where it was considered to occur in 1 in 5 years. The economic loss to growers in the Virginia of not receiving sufficient chill units for synchronized flowering was considered to be 15%. This risk was rated as 3 by producers in the Virginia region but greater than 11 elsewhere. As almonds have a relatively low requirement for chill compared to most stone fruit, the general conclusion is that there is adequate chill in the inland regions.

The risk of pollinators not flowering in synchronicity was rated very differently by participants at the different workshops. Those at Griffith thought it a high chance and high impact risk; those at Mildura and Renmark thought it a lower chance but high impact risk; while those at Virginia thought it a low chance and low impact risk. The chance of pollinators not flowering in synchronicity was thought to occur in half the years by growers at the Griffith workshop but in 10% or fewer years elsewhere. The economic loss of pollinators not flowering in synchronicity was rated highly at more than 20% by growers except by those who attended the Virginia workshop who rated the economic loss at 3%. This could be because growers in the Virginia region use a greater number of pollinators in their orchards, whereas it is common to use only 3 cultivars (nonpareil and two pollinators e.g. carmel and either price, peerless or monterey) in other regions.

Frosts were rated as having less than 10% economic loss, (1% in Virginia and Griffith) but were thought of as occurring with high regularity by attendees of the workshops at Mildura and Griffith (over half the years) but thought to be infrequent events by attendees at the two SA workshops (1 in 20 year or less). This meant that frost damage to buds and blossom was considered a low risk by participants at the two SA workshops (ranked as 10) but a high risk by those who attended the workshops at Mildura (ranked as 3) and a medium risk by those who attended the workshop at Griffith (ranked as 7). The participants at Mildura noted frosts are typically managed with fans, but as the use of fans is a cost then the economic loss by frosts to growing almonds resulted in a high risk rating. There were reports of some orchards using helicopters to mix the warmer air above the orchard to minimise frosts in the Mildura region. The participants at the Griffith workshop noted frosts are very localized and are actively managed with sprinklers or fans.

The risk of temperature being too low for pollination was rated high in by workshops participants all locations except those from the Renmark workshop where it was rated as low. Participants at the Renmark workshop thought the economic loss of low temperature was low (less than 1%) while participants at other locations rated at between 10 and 25%. The participants at the Renmark workshop also rated the chance of this level of economic loss was rare (1 in 20 years) while participants at other locations thought it occurred at between 1 in 4 and 1 in 6 years.

The risk of temperature being too high for pollination by bees was not considered to ever occur by all participants in the workshops and the questionnaires.

The risk of it being too hot for ideal growth and development was rated lower than the risk of heatwaves by participants at all workshops except those at Griffith. The risk of it being too hot was rated as having a low economic impact (<5%) but it was thought this level of impact may occur in up to 1 in 4 years. In contrast the economic loss from a heatwaves was considered higher, and in addition the chance of this occurring was also considered to be more frequent. Questionnaire respondents ranked the risk of a warm spring and summer as more important than the workshops participants, but the risks of heatwaves as less important that the workshop participants. Respondents in the workshops noted that hotter years were possibly more favourable as it was thought the risk of rain at harvest was lower.

Risks related to wind and hail

These risks were ranked similarly in the questionnaires and the workshops. Wind damage to flowers, fruit and branches was ranked as one that is highly likely to occur but having a low economic impact. This meant that it ranked at about 4 to 6 by growers at all workshops apart from those at Renmark who ranked it as the second most important risk.

Activity 2. Identify knowledge gaps relating to the identified risks, and suggest Management Options

Methods

Discussions during the workshops also focused on possible management options to address these risks. Following these discussions a comprehensive literature review was undertaken to identify management options to address the identified weather and climate risks. The review considered what is known from climate science and the extent of uncertainty in future climate projections, general agronomy, or known from other plants. This review also considered amendments to the typical current practice that are utilized by smaller sub-sections of orchardists, and also preliminary findings from active research trials. The management options that were identified consisted of practical solutions which could be explored and also included knowledge gaps which ideally would be explored to more fully understand limitations to almond production. The project did not seek to undertake plant based research to explore these identified management options, but rather to provide information to others. The information was provided to Horticulture Innovation Australia and to the Almond Board of Australia so future research priorities could be assessed.

Results

The identification of a knowledge gap as also being a management option is based on the premise that some information on the subject is available and that it may be possible to use this information to examine the impact of an altered management practice.

Risks related to rain and humidity

Risk: Rain at harvest (Ranked 1)

This risk is related to changes to rainfall and evapotranspiration.

Rain at harvest was rated as the most important risk. The economic losses from rain at harvest are varied. They relate to lost wages from the inability to perform the harvest operations (down-time); additional wage, fuel costs associated with spreading / turn over of windrows to facilitate drying of moist fruit; cost of artificial drying of fruit (if this option used); management associated with possible separation of stockpiles of wet and dry fruit; potential yield losses due to staining/ browning of kernel; increased infection of hull rot which can reduce yield as fruit cannot be shaken (lost yield in infection year), death of spurs (lost yield in later years) and also due to presence of infected fruit on tree being a source of inoculum and an over-wintering for this and other diseases and pests; loss of product due to moist fruit becoming infected with afflotoxin or salmonella.

In terms of weather and climate, this risk is likely to be a more complex than simply rain, and possibly be an interaction of moisture availability and duration, and involve both high rain and lower evapotranspiration. A management option for reducing the risks associated with undesirable rain at harvest that may be more easily implemented is additional use of weather forecasts in decision making of daily operations involved in the harvesting process. This like other management options can involve a complex interaction of decisions and trade-offs, in part because of the in-exact understanding of this risk.

While rainfall is relatively stable in all months (but generally lower in summer), there is a more dramatic decline in evapotranspiration from January onwards. As a consequence, the risk of moisture increase as the harvest window progresses into autumn. The uncertainty of projected changes to rainfall and seasonality of rainfall suggest these risks may or may not change. The projected increase in evapotranspiration suggests a future climate may cause this risk to decline.

Nevertheless this is likely to remain as a major risk for the industry.

The projections of a warmer spring and summer may hasten plant growth and development hence shift harvest to an earlier period that has a higher evapotranspiration and similar or lower rainfall. This would also reduce this risks associated with rain at harvest.

Knowledge Gap 1.1. A more comprehensive climate index for this risk is required. It is likely to involve rainfall, evapotranspiration and to be associated with an interaction of moisture balance of the fruit while it is on the tree, the soil when it is on the ground, and the fruit after it is harvested.

Knowledge Gap 1.2. A warmer climate may also hasten development and move the harvest to an earlier and naturally higher evaporation period, although the exact response of a warmer climate on phenology is unknown.

Knowledge Gap 1.3 – Management Option. Methods to move the harvest window to an earlier period in the current climate are partially understood. Irrigation can be used to some extent (some additional understanding is required) but methods such as application of chemicals to allow fruit desiccation and abscission but retain leaves are not. The success of any method will require greater understanding of fruit maturation, potential yield losses through reduced carbohydrate gain, changes to visual defects, and advances in kernel drying procedures.

Knowledge Gap 1.4 – Management Option. The risk of rain at harvest may be able to be partially reduced through operational logistics deciding whether to harvest or not based on weather forecasts, or of moving harvesting equipment between orchards based partially on weather (short term forecasts) of chance of rain in the near term. This approach would be driven by economics and could follow the existing guidelines of when to harvest based on rain or chance of rain such as those currently used or those developed by the Californian industry. It would also require additional understanding of drying properties of different soil types, and the interaction between wet soil and fruit drying.

Knowledge Gap 1.5 – Management Option. Changing harvesting equipment to a mechanised shake and catch method would avoid issues of undesirable soil moisture (apart from traffic-ability and compaction). This change may also allow for changes to improving soil structure or topography

Knowledge Gap 1.6– Management Option. Improved drying practices of nuts and kernels is being examined. These include examination of types of tarpaulin covers. Other options include use of active (powered) driers. The rate of drying or temperature used for drying may affect quality.

Risk: Rain and Humidity leading to disease (Ranked 4)

This risk is likely to be related to changes in rainfall, humidity, temperature and evapotranspiration. While there is uncertainty for rainfall, there is a high degree of confidence in warming. The impact on disease pressure is uncertain.

Knowledge Gap 5.1. The appropriate climate index for this risk is unknown and may differ depending on the disease (or pest) in question. Many horticultural pests and diseases are very sensitive to rainfall, humidity and temperature (both day and night temperature). Some simple models of pests and diseases exist and could be run under climate change projections. While these models would indicate the progression of a pest or disease they do not indicate that the pest or disease is present and will cause damage.

Risk: Availability of irrigation water, and its quality (Ranked 7)

This risk is related to changes in rainfall. It is also related to changes in evapotranspiration. This risk is closely related to the risk of inadequate winter rain and should be examined in conjunction with that risk.

There is good scientific understanding of drivers of hydrology and the relative uncertainty under climate change projections. A major limit to the accuracy of projections will be the challenge of simulating daily rainfall. A second limit is how runoff will be affected as plants grow differently across catchments with higher carbon dioxide, warmer and possibly drier conditions. The ability to purchase water is a management solution that assists in addressing this risk. The economic cost and benefit of individual situations will be a factor.

The infrastructure must be available to supply the water to the irrigators under a potentially increased demand (to alleviate impacts of heatwaves).

Knowledge Gap 7.1 – Management Option. The response to irrigation continues to require examination in the current and future climates when drivers of water loss from plants will change, and different management practices may be utilised (for example plant spacing, pruning or training).

Knowledge Gap 7.2 – Management Option. Almond are considered sensitive to salinity. However only growers in North Adelaide Plains who utilise treated water identified it as a risk to production. This is despite salinity being identified as a risk to almond production in California with some orchards showing marginal leaf burn, yield decline and other obvious signs of excess salinity in the root zone. This damage is often compounded by deficit irrigation and declining groundwater quality as water table levels drop. Salt is a natural part of the Murray-Darling Basin system with groundwater discharges to the River Murray delivering salts to the river. Salt removal is currently managed through salt interception schemes and via flows of saline water to the sea.

Research into salinity issues of almond trees such as use of saline irrigation water, salt leaching from soils, salt exclusion and tolerance of root stocks and scions, and of saline water applied at different phenological stages on growth and yield are in their infancy.

Knowledge Gap 7.3. A higher concentration of CO_2 is likely to impact on the transpiration efficiency and canopy growth hence will change the water balance and to interact with this risk and knowledge gaps identified above.

Risk: Inadequate winter rain (Ranked 9).

This risk is related to changes in rainfall. It is also related to changes in evapotranspiration. This risk is closely related to the risk of quantity and quality of irrigation water.

There is uncertainly from climate science on projected mean changes in rainfall although it is expected that the natural annual variation and seasonal patterns of rainfall will remain the dominant factors in the near future but there is high confidence of a decline in autumn and spring rainfall in southern Australia in the longer term. The amount of irrigation supply and its' quality may decline. The expected increase in evapotranspiration with warming may place greater strain on availability and cost of water.

Knowledge Gap 9.1 – Management Option. Improving utilisation of existing rain fall may be possible.

Redirecting rain falling on the inter-row to the base of the plants where irrigation is currently applied could make better use of available rainfall. The premise of this approach is that this rainfall is not currently being utilised and/or that there are no roots currently in the inter-row that make use of this water. This should be explored as the rainfall falling on the inter-row may already be utilized by the plant. Physical changes to the soil shape (mounding) or use of covers on the soil surface or sub-surface to impede downward water flow are possible, but are likely to affect current harvesting practices (shaking nuts onto ground then blowing and sweeping fallen nuts up) or to be costly to implement.

Knowledge Gap 9.2 – Management Option. Improving soil structure thereby increasing water holding capacity may allow greater utilisation of rain. Improving soil structure is typically achieved through incorporation of biomass. This may increase risks associated with orchard floor hygiene and kernel quality.

Knowledge Gap 9.3. A higher concentration of CO_2 is likely to impact on the transpiration efficiency and canopy growth hence will change the water balance and to interact with this risk.

Risks related to temperature

Risk: Heatwaves (Ranked 2)

This risk is related to changes in extreme high temperature. It is also related to changes in evapotranspiration and changes to wind. There is very high confidence that the number and severity of heatwaves will increase in future years.

Heatwaves are considered a risk due to impacts on bud development that form the following years growth. Heatwaves may enhance desiccation of fruit that can reduce yield (fruit typically sold to processors at 5% kernel moisture). Kernels that are too dry are more prone to damage during the shelling process which lowers their value.

Heatwaves are typically managed by applying more irrigation which imposes an economic cost through cost of water and pumping. See Risks associated with availability of water for more details.

Knowledge Gap 2.1 – Management Option. There is uncertainty on the threshold temperature (day and night) that causes damage to photosynthetic machinery and carbohydrate gain for the current crop, and the impact on bud quality which may affect subsequent crops. In addition to threshold temperatures, more information is needed on damage functions for different phenological stage(s) of physiological processes and the role of irrigation/soil water/evapotranspiration on mediating the impacts.

Knowledge Gap 2.2 – Management Option. Applicability of Management Options used in other crops for almonds. This includes overhead/within canopy evaporative cooling, altered canopy management (self-shading of sensitive organs), reducing solar radiation through netting or reflective sprays applied to leaves or fruit.

Knowledge Gap 2.3 – Management Option. The reliability, use and value of short and longer term forecasts of coming heatwaves (temperature) and associated evapotranspiration is unknown.

Knowledge Gap 2.4. The interaction with CO_2 on the transpiration efficiency and canopy growth hence impact on water balance. There are likely to be CO_2 interactions with other stresses such as heat waves and frost.

Risk: Non-synchronised flowering (Ranked 4) and Low Chill accumulation (Ranked 12)

These risks are related to changes in mean temperature. There is very high confidence that chill accumulation will decline. It is unknown how the risk of non-synchronous flowering of pollinator varieties will be affected.

One of the most obvious impacts of climate change for almond will be the expected continued rise in temperatures and hence a reduction in chill accumulation. Fortunately almonds require very little chill compared with many other deciduous fruit-tree species and are therefore more tolerant of the projected decline in chill accumulation, and would therefore be expected to receive sufficient chill to complete dormancy and allow flowering of each of the commercial varieties.

Knowledge Gap 4.1. Although models of flowering time have been developed for some varieties of commercial importance to Australia, these models have not been evaluated in Australia.

Knowledge Gap 4.2. Additionally flowering models have not been developed for several important varieties used in Australia, thus the responses of these varieties to a warming climate are unknown. This is of some concern as currently and very likely in to the near future the almond industry relies on varieties that require cross-pollination. The concern is that even though sufficient chill is likely to continue to be accumulated to allow completion of dormancy and progression of flowering of each individual variety, there is no guarantee that the flowering times of the individual varieties will continue to align such that cross-pollination is achieved.

Knowledge Gap 4.3 – Management Option. It may be possible to alter management practices to increase the chance of synchronous flowering through use of evaporative cooling to increase chill accumulation; application to buds of kaolin or other reflecting agents to decrease bud temperature and therefore increase chill accumulation; timing and efficacy of rest breaking agents.

Knowledge Gap 4.4 – Management Option. Self-fertile varieties could overcome non-synchronicity between pollinators.

Risk: Temperature too cold for Pollination (Ranked 6) and Temperature too warm for Pollination (Ranked 13)

This risk is related to changes in mean temperature. There is very high confidence of an increase in mean temperature. An increase in daily temperature during the pollination period (August) will reduce risks associated with pollination temperature being too low.

The current occurrence of temperature being too high for pollination are very low, and although these will increase in a warmer climate the relative increase in occurrence of temperature being too high is much less than the increased occurrence of desirable conditions (that is those times when temperature is currently too low will increase to become desirable for pollination).

Recent research on bee pollination has shown gains in pollination can be made through hive management and placement.

Knowledge Gap 6.1. Artificial pollination is possible, albeit costly, and requires a source of pollen that has to be collected, stored and applied.

Knowledge Gap 6.2 – Management Option. Recent research on self-fertile varieties has shown pollination is possible without bees. However these studies have been of short duration and require further examination to confirm results.

Knowledge Gap 6.3 – Management Option. Fertilization processes in the flower are generally well understood but may require further investigation. It is known that these processes are affected by temperature and it is generally accepted that there is a broad temperature range. It is unknown how general warming will affect the efficiency of these processes.

Risk: Frost (Rank 8)

There is very high confidence of warming at night which should reduce frost in the long run. However frost damage in the almond industry are radiation frosts and the reduced cloud cover associated with increased drying may counter this trend. It is thought that in the near term (e.g. 2030) the annual chance of frost and year-to-year variability and relationship with climate drivers will remain unchanged. In the longer term the potential for frost is thought to decline.

Knowledge Gap 8.1 – Management Option. The relationship between minimum temperature measured in a Stevenson screen often located some distance from the orchard, and those experienced by the plant in the almond orchard are not well understood. For example a minimum temperature of 2°C is often used to represent frost potential but a frost may not eventuate. Factors such as topography, and wind will influence orchard temperatures. Site selection is a major management issue that can be used to alter frost risk.

Knowledge Gap 2. Greater understanding of the interaction between climate and weather affecting chance of frost and of climate affecting phenology is required. The sensitivity of plants, specifically buds and flowers to low temperatures is reasonably well understood, but there is poor understanding of when these organs are present (i.e. phenology poorly understood).

Knowledge Gap 8.3 – Management Option. Frost risk can be managed through site selection, air movement (e.g. frost fans, helicopters), sprinkler irrigation, soil moisture, ground cover management; or use of later flowering varieties (that are also self-compatible, have desirable separation of harvest date, and desirable yield and kernel quality).

Knowledge Gap 8.4. A higher concentration of CO_2 is likely to impact on the transpiration efficiency and canopy growth hence will change the water balance and to interact with frost stress.

Risk: Warmer spring and summer temperatures (Ranked 11)

This risk is related to changes in mean temperature. There is very high confidence that mean temperature will increase.

Global warming is likely to result in a slow shift in the climate in each growing district that may impact on production. There is also uncertainty on the elasticity (or tolerance) of individual varieties to heat. There are likely to be interactions between varieties, temperature and irrigation regimes.

Knowledge Gap 11.1. The impact of warmer temperature on phenology is unknown. Flowering time may change (impacts risk of frost and synchronisation of flowering). Fruit maturation and time of hull split may be advanced from late summer/early autumn into warmer periods of summer. This shift to a period of higher evapotranspiration could be advantageous to harvesting which can be limited by excessive rain although the interaction of rain with evapotranspiration is likely to be a more meaningful measure of risk.

Knowledge Gap 11.2. There is a lack of understanding on the nature and importance of the trade-off in early fruit development between dimensional growth (which determines kernel size) and rate of growth. It is possible that warmer temperatures speed growth which leads to smaller kernels. Kernel size is important, but there a further complex trade-off within the tree between number of kernels and weight of the individual kernels.

Knowledge Gap 11.3. The response of phenology and almond fruit growth to heat accumulation is imperfectly understood and requires further examination, both in terms of the development of existing models and the transferability of these models to Australian locations. For example will warmer conditions allow kernels continue to accumulate carbohydrates for a longer period or will it lead to earlier hull split and maturity?

Knowledge Gap 11.4. A higher concentration of CO_2 is likely to impact on the transpiration efficiency and canopy growth hence will change the water balance and to interact with this risk and knowledge gaps identified above.

Risks related to wind and hail

Risk: Wind damage (Ranked 3)

The intensity of wind is strongly modified by terrain and vegetation. It is not possible to resolve the small scale meteorological phenomena that contribute to extreme winds. It is likely the risk of wind damage will remain unchanged and be an ongoing feature of orchard location and design.

Risk: Hail damage (Ranked 9)

Hail is a comparatively rare phenomenon that depends on local meteorological conditions. It is unknown how the risk of hail may change in a future climate.

Activity 3. Cost-benefit analysis of some management options

Methods

The use of weather forecasts in addressing the highest ranked risk of rainfall at harvest was examined. The intent of this work was not to provide a tool of trade that would be used as part of routine decision making. Rather it was to structure the decision problem and use the insights to confirm or challenge the rules of thumb used in the complex real world of harvest time in the orchard.

Rain at harvest is a major risk to almond production. Harvesting of almonds in Australia typically occurs from February and can continue to mid April or later in some years. Owing to the requirement of fruit pollination there will be at least two varieties of almonds planted in alternate rows, but as these fruit have different sales prices and marketing options they mature and are harvested at different times. It is essential that fruit of the different varieties remain separated during the harvest and post-harvest procedures; and all fruit of the highest value nonpareil variety must to harvested prior to the harvesting process (shaking) of the pollinator trees (typically carmel and one other variety in Australia) as shaking of the nonpareil trees also knocks fruit off the lower value pollinator trees thereby causing contamination. This means the harvest window of a particular variety is considerably less than the February to April period.

The usual procedure is to delay shaking fruit from the trees on rainy days as wet fruit dry quicker if they remain on the tree. This would be related to greater exposure to wind and sunlight to aid the drying process. Fruit take longer to dry once harvested because they may also be in contact with wet soil and because they may be covered by wet leaves that fall during the harvesting procedure.

Small amounts of rain are usually considered more of an annoyance than a major hindrance. Additional costs may be incurred because harvested fruit may need to be 'conditioned' in the field to aid the drying process in a process that exposes and turns the fruit. A typical procedure is to separate the fruit from the wet leaves and wet soil but replace the fruit on the orchard floor for further drying. This procedure and turning-over of fruit may be repeated as required until the kernel has dried to the required moisture content suitable for hulling and shelling (typically 5% moisture).

Larger amounts of rain, or increased frequency of rainy days exacerbates the difficulties as harvest of fruit from the trees can be delayed potentially leading not only to greater chance of contamination by pollinator varieties but also as rainy and less evaporative conditions are more likely as the year progresses, and because collection of harvested fruit from the orchard floor may be delayed which increases the potential for losses by pathogens (bacterial and fungal).

As indicated in a previous activity of this project there are a number of potential management options: The use weather forecasts to delay harvest was examined as an exercise of cost:benefit analysis.

Results

The use weather forecasts to delay harvest to address the risk of rain at harvest was examined as an exercise of cost:benefit analysis.

Economic analysis of weather or climate sensitive decisions requires a situation where the manager of the system has to make a decision prior to the weather unfolding and the preferred option differs depending on the weather event.

As shown in Figure 2, the decision to shake or delay fits this criteria. As conventional with decision trees, a square is a decision node (to shake or delay and leave the fruit on the tree) and a circle is a chance node representing different states of nature, in this case, weather in the three days after shaking. The outcome is a combination of the decision and the weather, but is also dependent on preceding conditions. The outcomes are colour coded where dark green is a good/ideal outcome dark red is an undesirable outcome and the lighter colours represent intermediate outcomes.

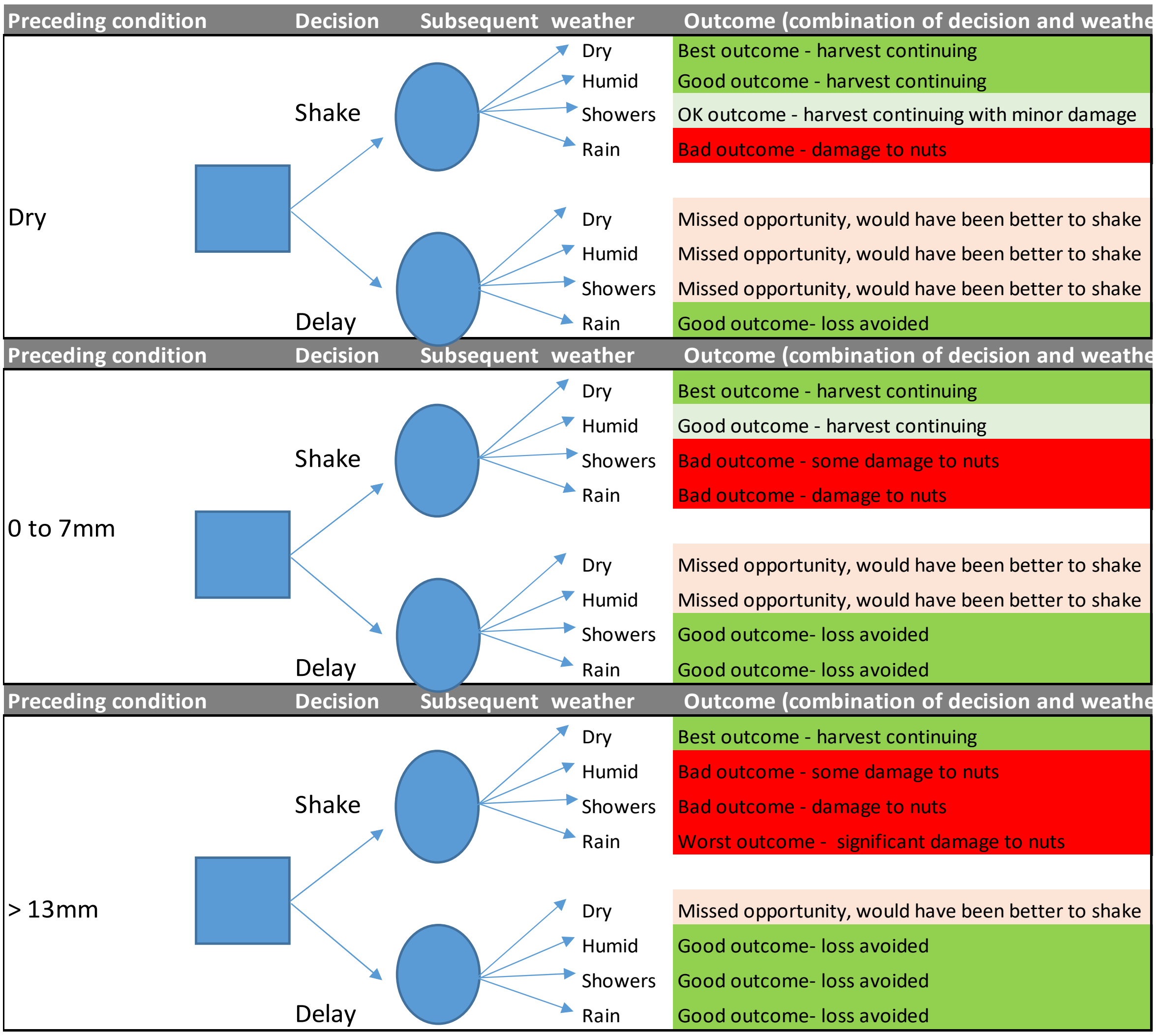


Figure 2. Decision trees based on table 36.1 from Reil et al. 1996. A quantitative approach to the decision to shake or delay by including the percent loss, the cost of delay and probabilities of future weather being dry or raining will be examined later. However, as suggested by Anderson et al. 2015 insights on the decision problem can be drawn out from simply structuring the decision, states of nature and outcomes. The structure highlights the truism that a 'good' decision (as opposed to a lucky decision) may not always lead to a desirable outcome.

Other insights include: The preceding weather has a large influence on the decision, with dry preceding conditions favouring shake and wet favouring a delay. In one sense this is stating the obvious, however it highlights the point that the value of knowledge of future rainfall is sensitive to current conditions. Furthermore an optimistic decision maker is considering the best outcome and will always shake. A highly conservative decision maker who is avoiding the worst outcome will always delay. The shake option is the higher return but also higher risk option. Perhaps the most important insight is that it is difficult to weigh the options without some estimate of the loss in profit due to leaving the fruit on the tree and the extra cost of the delay in harvest. According to economic spreadsheet for almond industry the cost of harvest is about $1000 per hectare. If damage is estimated to be 2%, and yield is 3.2 t/ha at $8.00 per kg, then the switching point to delay is when the extra cost of delay will be more than 51% ($512). This is based on

Loss $/ha = % damage × income $/ha,

where

Income $/ha = t/ha × price per t

Assuming 2% damage of 3.2t/ha @ $8.00 kg = $512

Cost $/ha = % cost of delaying harvest X cost of harvest $/ha

A rational decision maker will always take action if, and only if Loss > Cost

The relationship between damage and cost of delay is illustrated in Figure 3 (a to d).

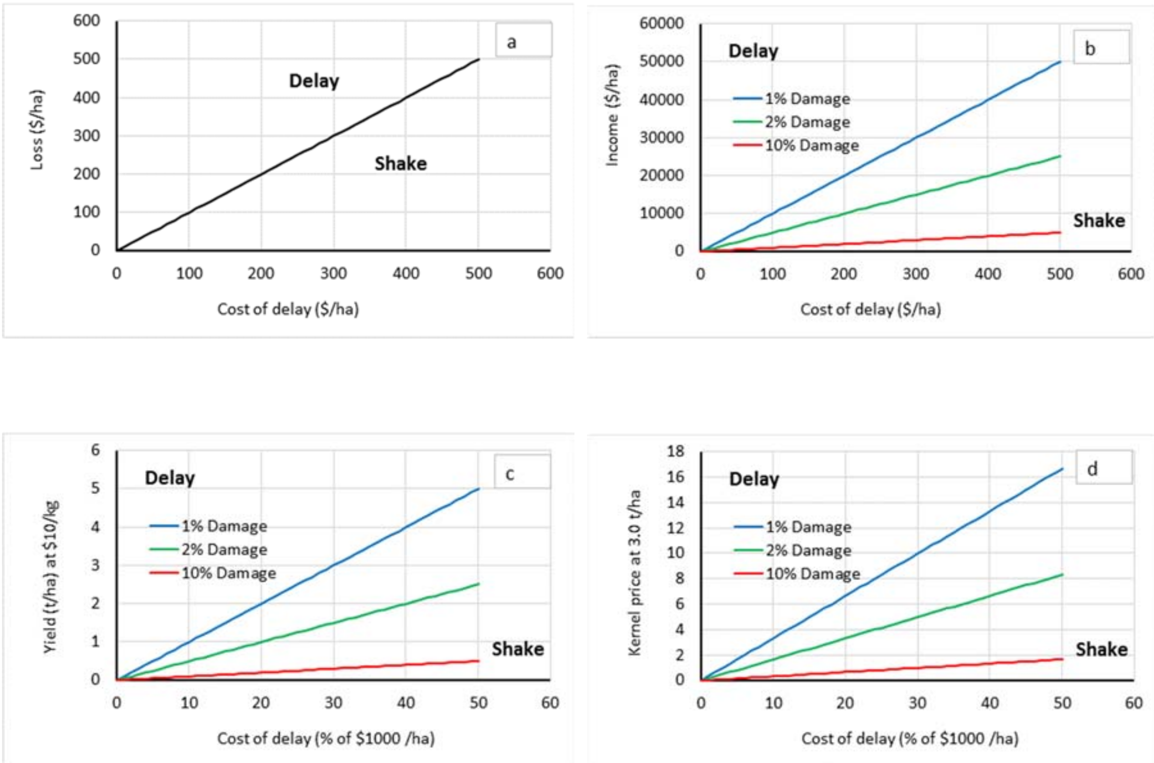


Figure 3 the relationship between Income and cost of delay for different levels of damage. Points above the line are conditions where the preferred option is to shake and points below the line are where the preferred option is delay. All figures are essentially the same graph. Figure (a) illustrates the relationship between Loss and Cost, Figure (b) the Y axis is changed to Income ($/ha) and the switch point between delay and shake is shown for 1% 2% and 10% damage, (c) changes the x axis to % additional cost of harvest due to delay and the y axis to yield @ $10 kg and (d) uses the y axis for a range of kernel prices.

The simple message from Figure 3a shows that if the cost of delay is low and/or the loss is high the best option is to delay whereas if the cost of delay is high and loss is low the best option is to shake. Figure 3b shows that as the estimate of percent damage from rainfall increases, the best option is to delay. Figures 3c and 3d can be used with the x axis of % cost of delay which is likely to be somewhere between 10% and 50% of harvest proceeding as normal. This will depend on many factors, however a possible thought experiment is to ask "if a fuel company provided contaminated fuel and the grower was seeking damages due to a delay in harvest, what might be a reasonable cost of the delay"? Because Figures 3c and 3d show a breakdown of the income to yield and price they indicate that the higher the price or yield, the more likely it is that delay becomes the preferred option.

Figure 4 shows a decision tree representation of the decision to shake or delay assuming no damage if dry, 0.5% damage if humid, 1% damage if showers and 2% damage if rain in the following 3 days. Figure 4a shows the decision tree without a forecast the long term climatological odds and figure 4b shows the decision tree if a forecast is used. The likelihood of weather events at harvest without a forecast are the long term averages and can be illustrated by an 80% chance of dry, 10% chance of humid, 5% chance of showers and 5% chance of rain. The probability weighted average is shown above the decision node as $-51/ha for shaking and $-200/ha for delaying. Further assumptions are a yield of 3.2 t/ha @ $8.00 kg and a harvest cost of $1000 and cost of delay as 20% of harvest cost ($200).

Following the assumptions and logic contained in figure 4a the preferred option is to shake because the long term average loss will only be $51 which is about a quarter of the cost of delay. However a weather forecast that changes the likelihood of rainfall will alter the preferred option (figure 4b). In this case the preferred option is to delay because the increased likelihood of showers and rain has led to greater likelihood of loss.

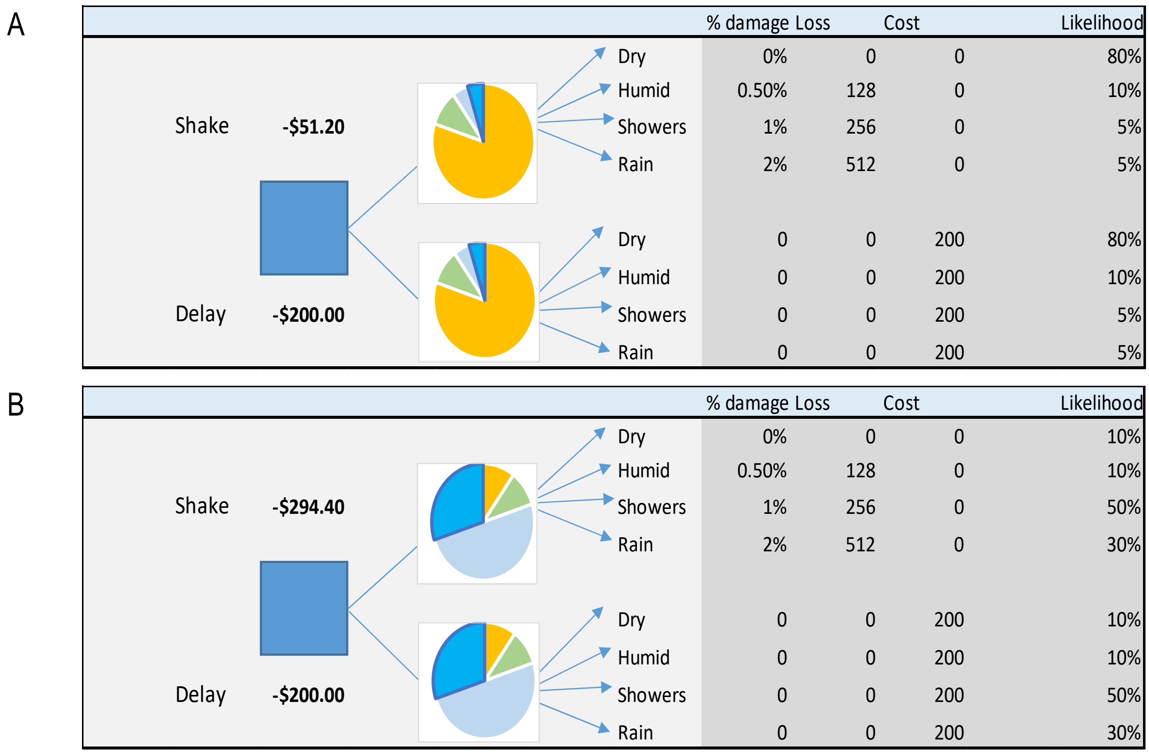


Figure 4. A decision tree to explore the economic loss due to damage from weather events when the likelihood of these undesirable weather events is not based on a forecast, i.e. they are based on long term average conditions; and when the likelihood of these undesirable weather events is based on a weather forecast.

Activity 4. Analysis of the historic weather and climate associated with these risks

Methods

The approach used was to firstly examine the historic values of indices (both specialist agroclimate indices which will be detailed later, and more readily available general climate indices) for 17 locations within Australia's almond growing regions and three regions in California. The historical weather data for the Australian locations (Table 2) was sourced from SILO https://silo.longpaddock.qld.gov.au/as patched point data. Weather data for the locations in California was sourced from the California climate data archive (https://calclim.dri.edu/). The period(s) that these agroclimate indices were calculated were assumed from the phenology calendar. It should be noted that there was usually insufficient information to provide specific thresholds for most indices above or below which the risk was mitigated or enhanced. It may be assumed that risks will be increased if the undesirable weather or climate conditions are exceeded more frequently. Table 3 shows Mean Annual Temperature (°C), Mean Annual Rainfall (mm), and Mean Annual evapotranspiration (mm) at the stations used in analysis.

Historical data from 1957 to 2014 was used to calculate and correlate long-term averages of the specialized agroclimate indices with the more readily available general climate indices in order to determine if it was possible to obtain approximations of the specialized agroclimate indices by these general climate indices. This would allow orchardists to obtain approximations of the specialized agroclimate indices for other locations by obtaining the general climate indices. This approach also served to examine if redundancy existed within agroclimate indices that could be used to examine an identified weather or climate risk. Furthermore the analysis serves as a useful indication of future conditions if it can be assume that space can be used as a proxy for time. That is, can the historic conditions in a warmer location serve as an indicator of what an historically cooler location may transform into under future warmer conditions. This approach has a longer history in ecological research than agricultural and horticultural research, but is a valid approach to exploring the impact of future climate conditions.

Detailed analysis for a fewer number of indices (general climate and agroclimate) and a selected number of locations that had higher quality weather data (minimum of one location per region) are detailed in booklets of climate strengths and challenges of each region (see attachments). This analysis examined a longer the same historical period from 1957 to 2018 and placed years into deciles to examine the seasonal variability in the indices and risks. Deciles are a method of showing how a particular year ranks with other values. The 20 year period from 1986 to 2005 was used to calculate the deciles. This 20 year period was chosen as it is the base period used in the latest IPCC report on climate change (https://www.ipcc.ch/assessment-report/ar5/). To calculate deciles, the 20 years were ranked and divided into ten parts each containing two years. The values of the deciles are those that demarcate one group of ten parts from another. Decile 1 contains the lowest 10% of values, which in this case is the lowest 2 values; decile 5 or the 50% percentile or the median is the point dividing the values into two equal groups; while decile 9 or the 90th percentile, means that 90 % values will be at or below this figure and the two highest values will be in decile 10 (See http://www.bom.gov.au/climate/cdo/about/about-stats.shtml for more information).

General climate indices were associated with the year of flowering, while agroclimate indices were associated with the year or flowering and year of harvest. This was required as in Australia, as with most perennial tree and vine crops, the almond growing season begins in winter of year 'x' when budburst and flowering occurs and continues until late summer or autumn of year 'x + 1' when harvest occurs. That is, trees flowering in August 2018 would be harvested in early 2019. This season would be denoted as "x/x+1". For clarification, the general climate indices such as mean annual temperature (MAT) or mean annual rain (MAR) were associated with the year of flowering; while the agroclimate indices were associated with the year of flowering / year of harvest. For example, when describing the general and agroclimate indices associated with trees flowering in August 2018 and harvested in early 2019 (that is the 2018/19 season), mean annual temperature or rainfall would be from January 2018 to December 2018, chill accumulation for flowering would be that occurring from March 2018 to July 2018, growing season temperature or rainfall would be associated with the period from September 2018 to April 2019, harvest season rain would be from February 2019 to April 2019.

Table 2. The meteorological stations used in this analysis.

Station	Number	Latitude, longitude	Elevation (m)	Commencing year. Rainfall, Temperature
North Adelaide Plains and Hills				
Adelaide (Kent Town)	23090	-34.921, 138.622	48	1977, 1977
Edinburgh RAAF	*23083*	-34.711, 138.622	16	1972, 1972
Mclaren Vale # *	23729	-35.220, 138.541	65	1938,!!
Strathalbyn #& *	23747	-35.256, 138.890	70	1861, 1957
Riverland				
Loxton Research Centre	24024	-34.439, 140.598	30	1984, 1984
Murray Bridge Comparison	24521	-35.123, 139.259	33	1885, 1966
Nildottie #&	24547	-34.676, 139.651	41	1965, 1965
*Renmark # **	*24016*	-34.171, 140.749	20	1889, 1957
Waikerie (Golden Heights) #	24041	-34.194, 139.938	65	1968, 1968
Sunraysia				
Mildura Airport	*76031*	-34.236, 142.087	50	1946, 1946
Robinvale Consolidated School #	76125	-34.600, 142.783	49	1970, 1970
Swan Hill Post Office # *	77042	-35.341, 143.553	70	1884, 1960
Balranald (RSL)	49002	-34.640, 143.561	61	1879, 1967
Riverina				
Griffith Airport Aws	*75041*	-34.249, 146.070	134	1958, 1970
Hay (Miller Street) # *	75031	-34.519, 144.855	93	1877, 1957
Hillston Airport	75032	-33.492, 145.525	122	1881, 1957
Narrandera Golf Club # *	74221	-34.733, 146.559	173	1969, 1970
California				
Orland	46506	39.75, 122.20		
Merced	45532	37.18, 120.50		
Bakersfield	40442	35.42, 119.05		

# denotes the some or all of weather elements are no longer being observed. & rainfall continues to be observed. * denotes a Bureau of Meteorological station that records both rainfall and temperature has opened within 10km. !! denotes station has never observed temperature. Stations in italics denote those used in more detailed analysis.

Table 3. Mean Annual Temperature (°C), Mean Annual Rainfall (mm), and Mean Annual evapotranspiration (mm) at the stations used in analysis. The average is shown with the numbers in parenthesis being the minimum and maximum; and the 25th and 75th percentile. Temperature and Evapotranspiration are calculate from 1957 to 2014 while rainfall is calculated from 1900 to 2014.

	Mean Annual Temperature (°C)	Mean Annual Rainfall (mm)	Mean Annual Evapotranspiration (mm
North Adelaide Plains and Hills			
Adelaide (Kent Town)	17.0 (15.6 - 18.3; 16.6 - 17.4)	548 (266 - 883; 472 - 629)	1306 (1168 - 1443; 1266 - 1347)
Edinburgh RAAF	16.8 (15.8 - 17.8; 16.4 - 17.1)	432 (229 - 674; 360 - 504)	1304 (1168 - 1408; 1263 - 1338)
Mclaren Vale	16.2 (15.0 - 17.4; 15.8 - 16.5)	555 (290 - 812; 480 - 616)	1189 (1044 - 1317; 1156 - 1216)
Strathalbyn	15.7 (14.7 - 16.8; 15.3 - 16.0)	493 (241 - 879; 427 - 557)	1184 (1063 - 1290; 1150 - 1218)
Riverland			
Loxton Research Centre	16.5 (15.4 - 17.5; 16.3 - 16.8)	265 (83 - 537; 216 - 306)	1377 (1199 - 1525; 1333 - 1426)
Murray Bridge Comparison	16.3 (15.6 - 17.5; 16.1 - 16.7)	349 (136 - 674; 281 - 397)	1262 (1093 - 1388; 1224 - 1303)
Nildottie	16.7 (15.7 - 17.6; 16.3 - 16.9)	265 (116 - 540; 218 - 304)	1338 (1162 - 1456; 1303 - 1377)
Renmark	17.5 (16.9 - 18.3; 17.2 - 17.8)	257 (90 - 517; 210 - 293)	1447 (1287 - 1567; 1407 - 1486)
Waikerie (Golden Heights)	16.8 (15.9 - 17.5; 16.5 - 17.0)	268 (96 - 545; 216 - 315)	1392 (1216 - 1501; 1357 - 1441)
Sunraysia			
Mildura Airport	17.1 (16.2 - 18.3; 16.7 - 17.4)	280 (103 - 657; 214 - 327)	1435 (1259 - 1579; 1376 - 1486)
Robinvale Consolidated School	17.1 (16.1 - 18.3; 16.6 - 17.4)	301 (89 - 647; 238 - 367)	1427 (1187 - 1567; 1373 - 1476)
Swan Hill Post Office	16.5 (15.6 - 17.4; 16.2 - 16.7)	345 (140 - 736; 271 - 412)	1364 (1219 - 1493; 1311 - 1415)
Balranald (RSL)	17.1 (16.2 - 18.3; 16.7 - 17.3)	326 (122 - 692; 252 - 383)	1427 (1279 - 1582; 1371 - 1472)
Riverina			
Griffith Airport Aws	16.8 (15.7 - 18.4; 16.4 - 17.2)	395 (149 - 719; 308 - 473)	1388 (1222 - 1585; 1323 - 1452)
Hay (Miller Street)	17.3 (16.5 - 18.7; 17.0 - 17.6)	366 (157 - 837; 274 - 427)	1432 (1242 - 1573; 1387 - 1476)
Hillston Airport	17.7 (16.7 - 19.0; 17.3 - 18.1)	367 (101 - 820; 285 - 444)	1459 (1266 - 1620; 1396 - 1515)
Narrandera Golf Club	16.6 (15.5 - 17.8; 16.3 - 17.0)	446 (176 - 913; 353 - 514)	1359 (1187 - 1539; 1300 - 1412)

General climate or specialized agroclimate indices used to assess each weather and climate risk to almond production are detailed below. The period(s) that these agroclimate indices were calculated were assumed from the phenology calendar. It should be noted that there was usually insufficient information to provide specific thresholds for most indices above or below which the risk was mitigated or enhanced. It may be assumed that risks will be increased if the undesirable weather or climate conditions are exceeded more frequently.

Risks related to temperature

Frosts

Frost will affect plants at most if not all stages of growth, with the critical temperature and duration that this temperature must be maintained affecting the extent of damage. Later phenological stages are more sensitive to frosts (see Snyder and Connell, 1996).

Frost formation is affected by a series of factors including low cloud coverage, low humidity, low surface winds, topography and location. Temperature is an *indicator* of frost, not that frost will occur. Temperature observations are made in a shelter (Stevenson screen) at a height of approximately 1.2 m above the ground. These observations are then used to approximate the conditions at surface level. An observed temperature of 2.2°C at 1.2 m height indicates that the temperature at the ground surface is approaching 0°C (http://www.bom.gov.au/climate/map/frost/what-is-frost.shtml). However because the sensitive organs on an almond plant are located some distance above the ground surface, which may be warmer than the ground surface during the night period, and because the temperature required to damage almonds if typically less than 0°C (Snyder and Connell, 1996) the critical temperature for frost risk may be lower.

The number of days per month when daily minimum temperature was less than 2 °C and less than 0 °C provided an indication of the risk of frost at each location.

The date of the last night when daily minimum temperature was less than 2 °C and less than 0 °C was used to determine the date of last frost.

Heatwaves and hot spells

Many growers did not rate the risks from heatwaves as high providing there was adequate irrigation. However, there is anecdotal and published literature suggesting damage to crops can occur from heatwaves and excessively warm conditions. This damage may be observed by an increased incidence of non-infectious bud failure (or witches broom) that is associated with high temperature in late spring and summer when the buds are developing, or by a reduction in kernel weight associated with high temperature during the final stages of growth. This could be mediated through a reduction in photosynthesis and carbohydrate gain by the tree.

In addition there is the possibility that high temperatures during the initial phase of fruit growth could restrict kernel size because rates of fruit growth cannot keep up with rates of fruit development as although fruit growth rate is typically enhanced by higher temperatures, the duration of this rapid growth is reduced such that final dimensions are reduced as occurs in peach (Lopez and Dejong, 2007and as noted by Doll (2013) where it was proposed higher temperatures will favour respiration over photosynthesis and reduce the supply of carbohydrate to developing fruit thus reducing kernel size.

The thresholds of temperature and duration of exceedance and associated damage to yield are poorly understood. It is likely that indices such as number of days when daily maximum temperature exceeds systematic thresholds are a useful indicator of potential stress and damage to the almond plant and crop. This is important given the likelihood of more frequent and intense heatwaves in the future.

The number of days per year and per month when daily maximum temperature was warmer than 35 °C and warmer than 40 °C provided an indication of the risk of heatwaves at each location.

Temperature being too cold for pollination.

The temperature threshold for possible bee flight was set to 15°C. This was based on grower observations and acceptance that 15°C was required for bee activity, and more formally by the measure of Good bee hours defined in University of California Regional Almond Variety Trials (http://fruitsandnuts.ucdavis.edu/dsadditions/Regional_Almond_Variety_Trials/ sourced 30 October 2015) as temperature warmer or equal to 15°C, wind speed less than or equal to 10mph, and no rain.

We calculated indices for possible bee flight based on the number of days when daily maximum temperature exceeded 15°C, by the number of daylight hours when temperature was warmer than 15°C, and by the number of daylight hours when temperature was warmer than 15°C and there had been no rainfall recorded for that day. We used interpolated hourly temperatures calculated from daily minimum and maximum temperature when calculating these later indices. Daylight hours were assumed to be from sunrise to sunset as calculated previously according to latitude and day of year. The latter indice assumed any rain during the 24 hour period was detrimental to bee flight. As we did not have access to wind speed data we could not include wind speed in the indice.

Temperature being too hot for pollination.

Temperatures warmer than 28°C are considered too warm for bee flight. At all locations the average number of days warmer than 28°C was zero in July and less than 1 in August indicating this risk was sufficiently low to be considered as inconsequential in the current climate.

Insufficient chilling for synchronized flowering or Pollinators not flowering in synchronicity.

These risks are related as both refer to the risks of the main variety (Nonpareil) and its pollinators (*e.g.* Carmel, Price, Peerless, Monteray etc.) not flowering in synchronicity. Within a tree or variety, a set amount of chilling must be achieved for buds to proceed through dormancy thereby enabling flowering to occur and commence in a synchronized manner. Due to the requirement of cross pollination, the different varieties must flower at the same time. Recent analysis has shown that budburst and flowering in almonds can be estimated by both the accumulation of chill and the accumulation of heat such that less heat accumulation is required to ‘force’ flowering if more chill accumulation has occurred (See Pope *et al*., 2014). In other words, chill accumulation must be achieved by all varieties to proceed through dormancy, and the relative amounts of chill accumulation and heat accumulation received by each individual variety must be matched such that flowering of the varieties occur at the same time.

Both chill accumulation and heat accumulation can be measured by many indices (see section *Generally warmer conditions advancing growth* for methods of calculating heat accumulation). There is no globally accepted method of measuring chill with several standard models developed for calculating chill accumulation. Chill was calculated for five widely used chill models: 0 to 7.2°C model (Weinberger, 1950), Utah model (Richardson *et al.*, 1974), modified Utah (Linvill, 1990), Positive Utah model (Linsley-Noakes *et al.,* 1994) and the Dynamic model (Fishman *et al.,* 1987a, b). The dynamic model (Fishman *et al*. 1987a, b) is considered the most biologically accurate model. It assumes that chill results from a two-step process where cold temperatures initially form an intermediate product in the buds and warm temperatures can destroy this intermediate product. When a certain quantity of the intermediate product has accumulated, it is transformed irreversibly into a chill portion, which can no longer be destroyed.

All chill models require hourly temperature. These were calculated from daily minimum and maximum temperatures according to methods based on Linvill (1990). The calculations incorporate a sine function for daytime heating which assumes that the maximum temperature occurs two hours after solar noon and minimum temperature occurs at sunrise (eqn. 1).

$T(t) = Tmin + (Tmax - Tmin)\sin(\pi t/(D+4))$ (eqn. 1)

Where T(t) is the temperature at time t hours after sunrise, Tmax and Tmin are daily maximum and minimum temperature and D is the daylength in hours.

Equation 1 can be used to calculate hourly temperatures from sunrise to sunset. The temperature at sunset (Ts) can be estimated by solving equation 1 for t = D. The variation in daylength can be calculated for calendar date and latitude. Temperature between sunset and sunrise of the following morning can be calculated from a logarithmic function describing night-time cooling, assuming the minimum temperature of the following day occurs at sunrise (eqn. 2).

$T(t') = Ts - \ln(t') * (Ts - Tmin) / \ln(24-D)$ (eqn. 2)

Where T(t') is the temperature at time T > 1 hour after sunset.

There is limited conversion between chill models as shown by Luedeling and Brown (2011) and Luedeling (2012) study into the comparability of chill models on a global scale. Darbyshire *et al.* (2011) support this global assessment in an Australian setting.

The risk of insufficient chill accumulation was assessed by the chilling per month and for the period to 31st July as almonds typically flower in early August so chill after this date could be considered unnecessary.

Generally warmer conditions advancing growth.

This risk was considered of minor importance by almond producers. Warmer than usual conditions may impact production through the general advancement of growth and development of the almond, an increase in the number of days with sub-optimal carbohydrate production (as respiration losses may increase faster than net photosynthesis), or an increase in pest reproduction rates (which are temperature related). A hastened development was thought by some almond producers to be of benefit as harvest may be earlier in the year when the risks of rain at harvest would be reduced.

Climate indices such as mean temperature and the heat accumulation indice of growing degree days (GDD) calculated over annual, seasonal and monthly periods were used to assess this risk.

$$GDD = \sum_{d=1}^{n} \max[\frac{(Tmax+Tmin)}{2} - b, 0] \quad \text{(eqn. 3)}$$

Where b is a threshold temperature below which no heat can be accumulated. A typical value of b used by many horticultural industries is 10°C, although a value of 4.5°C was used by Richardson et al., 1975 and subsequently by others examining flowering in almonds (e.g. Pope et al 2014). Another variant of GDD used by the horticulture industry in California (amongst other locations and industries) are single and double sine and triangle methods (see Zalom et al., 1983), with the single sine method used by Tombesi et al. (2010) when modelling hull split of almonds.

Heat accumulation may also be calculated using hourly temperatures as growing degree hours (GDH). The forcing model of (Anderson *et al.,* 1986) was used to calculate GDH. The model assumes that heat accumulates between the base temperature (Tb, set to 4°C) and the critical temperature (Tc set to 36°C) with optimum accumulation at the optimum temperature (To set to 25°C).

The equation for GDH between the base and the optimum temperature is:

$GDH = FA/2 \times (1 + \cos(\pi + \pi (T-Tb)/(To-Tb)))$. (eqn. 4)

The equation for GDH between the optimum and the maximum temperature is:

$$GDH = FA \times (1 + \cos(\pi/2 + \pi/2\,(T-T_o)/(T_c-T_o))), \quad \text{(eqn. 5)}$$

where $A = T_o - T_b$, and F is a factor of stress (assumed to be 1 unless the plant is under stress).

We calculated GDD base 10 in the initial analysis.

We used GDD base 4.5 when modelling almond fruit growth and maturity in a phenology model developed in the third theme of this project. Those modelled dates of the phenostages have been used in this report.

Desirable photosynthetic hours were calculated from hourly temperatures (interpolation method described above) and those occurring during daylight hours (daylength calculated as described above) were categorized into those that could be considered too cold (below 20°C), optimal (between 20 and 35°C) or too warm (above 35°C) for optimum photosynthesis.

Risks related to rain and humidity

Rainy days during harvest operations (harvesting, drying and storage).

This risk is related both to the ease of harvesting operations and also to the increased risk of spoilage from diseases if the fruit is moist after harvest. Consequently both rainfall and the drying conditions following the rainfall are important. The risk was assessed through a series of elements including the amount and number of days when rainfall exceeded a threshold (assumed to be 2mm), the number of days when daily evapotranspiration (ETo) is below set thresholds, and the number of days when the moisture balance is positive (MB+ve). A day was calculated as being moisture balance positive if a reservoir of rainfall (set to a maximum of 10 mm to allow for runoff and drainage) was not removed through ETo on the same and subsequent days.

MB(today) = Min[MB(yesterday) + R – ETo, 10] (eqn. 6)

In addition to these indices we also examined two indices of modelled hours of leaf wetness. The first is the RH model (LwRH) which initiates the onset of leaf wetness when the relative humidity is greater than or equal to 90%, and the wetness period ends when the value drops below the 90% threshold. The second is the dew point depression model (LwDPD), which measures the onset of leaf wetness if the difference between the measured air temperature and the dew point temperature is less than 2°C and the end of the wetness period occurs when this difference exceeds 4.3°C (Gillespie *et al.,* 1993). These indices were calculated for each month with the period from 1st February to 30th April deemed to be the harvest season.

> It should be noted that ETo is calculated using the Penman-Monteith equation, as recommended by Allen *et al.* (1998) in the United Nations Food and Agriculture Organisation Irrigation and Drainage paper 56 (FAO56). ETo from SILO assumes a wind speed of 2m/s. ETo calculated by the Bureau of Meteorology uses measured wind speed when available but this wind speed is typically measured at heights exceeding 2 m and may need to be adjusted to wind speed modelled at a height of 2 m. This may create artefacts as noted by the Bureau of Meteorology "*A local comparison of the Bureau ET_0 values against measurement by other weather stations using direct wind measurements at 2 metres above ground level indicated that the Bureau values can be up to 20% higher*." (Bureau of Meteorology "About Evapotranspiration" http://www.bom.gov.au/watl/eto/about.shtml sourced 22 October 2015). Additionally the Bureau of Meteorology's ET_0 values are for the period midnight to midnight and may differ from those that have been calculated using the standard meteorological day, which is for the 24 hours from 9am.
>
> It is worth noting this additional information provided by The Bureau of Meteorology. "*Please note that local environmental factors such as hills or nearby water bodies can also impact ET_0 values, so ET_0 at locations away from Bureau of Meteorology automatic weather stations may vary considerably, and some local knowledge and calibration between the station and the location of interest may be required to help with decision making at the property level. In some cases where alternative weather station information is available on-farm then some local calibration of the ET_0 values provided by the Bureau should be possible.*" (Bureau of Meteorology "About Evapotranspiration" http://www.bom.gov.au/watl/eto/about.shtml sourced 22 October 2015).

Hourly %relative humidity was interpolated from daily data. The SILO dataset provide values of daily minimum and maximum temperature along with the %RH at these temperatures. The vapour pressure in the ambient air (Ea) under the conditions of daily maximum temperature and its %RH and under the condition of daily minimum temperature and its %RH were calculated by first calculating the saturated vapour pressure at each temperature (Es) using equation 7, then calculating the Ea as a proportion of this value according to equation 8.

Saturated vapour pressure (Es) was calculated according to the August-Roche-Magnus formula using equation 3 where temperature (T) is in °celcius.

Es = $6.1094\exp(\frac{17.625T}{T+243.04})$ (eqn. 7)

The vapour pressure in the ambient air at the respective %RH (Ea) was calculated as the proportion of these values using equation 8.

Ea = (%RH/100) * Es (eqn.8)

The vapour pressure in the ambient air (Ea) were constant at both daily maximum and daily minimum temperatures. This meant that Ea could be assumed to be constant between these times (that is at sunrise when daily minimum temperature is assumed to occur, and at 2 hours past solar noon when daily maximum temperature is assumed to occur). We further assumed that Ea remained constant until sunset, such that Ea for the hour between sunrise and sunset of each day could be calculated from the daily maximum temperature and its respective %RH. The values of Ea between sunset and the following sunrise were assumed to be the average of Ea calculated on the day sunset occurred and the following day when sunrise occurred.

The %RH at each hour could then be calculated from the saturated vapour pressure at each interpolated hourly temperature (Es) and the vapour pressure in the ambient air (Ea) at that time.

Dew point (Td) at each hour was calculated using equation 8.

Td =243.04 × {ln(RH/100)+[(17.625×T)/(243.04+T)]}/{17.625-ln(RH/100)-[(17.625×T)/(243.04+T)]} (eqn. 9)

Where T is temperature (°C) and RH is relative humidity

Excessively rainy and humid conditions leading to increased risk of diseases.

Disease susceptibility models typically rely on a measure of free moisture and suitable temperatures (for example see http://www.ipm.ucdavis.edu/DISEASE/DATABASE/diseasemodeldatabase.html for summary of several models for specific diseases) while pest models typically rely on temperature (for examples see http://www.ipm.ucdavis.edu/MODELS/index.html).

Evaluation of the risk of Excessively rainy and humid conditions leading to increased risks of diseases, was examined the same indices as used to evaluate the risk of rainy days during harvest but for the entire growing season.

Insufficient rainfall on the orchard.

This risk is related to insufficient rainfall in the catchments (Risk 10) that supply the irrigation water as both provide the necessary water for plant growth. However rainfall on the orchard may also serve other purposes such as leaching of salts. The risk was measured by the amount of rainfall but also by ETo as a measure of water loss.

Insufficient rainfall in the catchments that supply the irrigation water.

Analysis of this risk involves inflow into the river system and storage volumes. Almonds are a high water use crop and as a perennial, require a consistent supply of water. The amount of water available to irrigators is a complex relationship between drought, water policy and the water market. These later aspects will not be examined in this milestone, but the climate risk of insufficient rainfall creates a shortage in inflows and storage volumes which triggers policy responses and sharp increases in the price of water. It should be noted that runoff is very sensitive to declines in rainfall.

A rule of thumb that applies to most inland areas of Australia is that a 10% decline in rainfall may result in a 20 to 30% decline in runoff (Chiew 2006).

Risks related to wind and hail

Wind or hail damage to flowers, fruit or trees

This risk could not be assessed due to insufficient information that can be obtained on the fine spatial scale necessary to assess orchards. However it should be noted hail is a rare event and as such is poorly predicted. Climate projections for the mean speed of non-cyclonic winds are uncertain with both increases and decrease projected. If the speed of wind gusts, which are most typically associated with damage, remain a constant proportion of wind speed as in the historical record then the strength of wind gusts and hence chance of damage may similarly increase or decrease depending on the projections of wind speed. As such the risk of wind damage cannot be assessed with any certainty.

Results

The weather and climate indices relating to historic long term averages over yearly or seasonal time periods were used to examine if it was possible to obtain approximations of the specialized agroclimate indices by the general climate indices; if it would be feasible to use a space-for-time approach to approximating risks in future climates; and if there was redundancy in the specialized agroclimate indices. Indices measured over shorter time periods (*e.g.* months) and the historic year-to-year variation and any trends also provide useful information for assessing the risks. An example of these monthly values and historic year-to-year values of several indices for one sample location is provided in this report. Detailed information for one representative location in each of the four almond growing regions is provided in the appendices of this report and also in the booklets detailing climate strengths and challenges of each region.

Risks related to temperature

Mean annual, spring and summer temperatures vary considerably between almond growing locations, with largest differences being in mean summer temperature (Figure 5). Across the Australian almond growing regions the climate is cooler in the coastal locations such as the Adelaide plains and Murraylands and warmest in the inland and more northern locations (Griffith), but even Griffith is cooler than most Californian locations. Figure 6 shows the average monthly values at Renmark, SA of daily maximum temperature and daily mean temperature; and the strongly related indices of heat accumulation.

The analysis of historic trends in the indices shows a trend of increasingly warm conditions in all locations. The rate of increase in mean annual temperature per decade (calculated from 1957 to 2014) is up to 0.3 °C per decade and averaging 0.13°C per decade across the locations examined. This is consistent with Bureau of Meteorology climate analysis from high quality stations. 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 resulting in a corresponding change in indices related to temperature such as mean growing season temperature (mean temperature from October to April) and heat accumulation. Figure 7 shows how the year-to-year variation in the climate at Renmark 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. Warm deciles are shown in red and cool deciles in blue. Decile 5 and 6 are shown as grey with the junction being the median or middle value. Since 2000, 16 of the 19 years have been warmer than average. 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. See text box for a guide to interpreting these figures.

Heat accumulation is required to achieve flowering and subsequent growth and development. It is strongly related to mean annual temperature (Figure 8). Heat accumulation from July is likely to be useful to complete ecodormancy and 'force' flowering, and along with chill accumulation it therefore related to the risks of Insufficient chilling for synchronized flowering or Pollinators not flowering in synchronicity. Heat accumulation at other times is likely to be useful for further development, with faster development being related to higher heat accumulation and is related to the risk of Generally warmer conditions advancing growth. Pest pressure is also expected to increase as heat accumulation increases as the rate of development of pests can be related to temperature and heat accumulation.

Two methods have been used to calculate heat accumulation. Growing degree days (GDD) is the simplest. We have used a base temperature of 10°C and no maximum temperature cutoff. There are many variants of GDD. Growing degree hours (GDH) assumes that the optimal temperature is 25°C and that between 4°C and 25°C and 25°C and 36°C a reduced amount of heat will accumulate, but that temperatures below 4°C or above 36°C are not useful to growth.

Temperature conditions desirable to biomass accumulation and growth may also be examined by photosynthetically desirable hours. 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 is considerable seasonal variation in the number of daylight hours per day that are conducive to high photosynthetic rates, with excessively warm conditions occurring on average only for small amounts per day. Figure 9 shows long term averages at Renmark. However, there will be considerable daily variation in the number of desirable photosynthetic hours owing to the fluctuations in weather.

Risk from temperature extremes by Frost, Heatwaves or Temperatures being too cold for pollination change during the year (figure 10); vary between almond growing locations (figure 11); and are related to mean annual temperature (figure 12). These risks are shown as daily minimum temperature of 2 °C or cooler during July to September for frost; daily maximum temperature of 35 °C or above for heatwaves; and daily maximum temperatures cooler than 13 °C or warmer than 28 °C in August for Poor pollination conditions. Risks from high temperature are larger in more inland regions and are less in Australia than in California. Risks from poor pollination conditions are higher in more inland conditions and these are comparable with Californian locations. Risks from frost are greater in inland locations.

Owing to the close relationship between temperature and the number of extreme days, as for the trend in growing season temperature there was also a trend of an increasingly greater number of warmer days (*e.g.* the number of days per year warmer than 35°C is shown), but also a greater number of very cold nights that increases the risk of frosts (figure 13). At Renmark 15 of the 19 years since 2000 had a higher than average number of days warmer than 35 °C, while at Mildura 15 of the 19 years since 2000 had a higher than average number of days colder than 2°C. 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. It should also be remembered that the number of days where the minimal temperature is cooler than 2°C per year is very low and small changes of only one or two additional days per year can have a large impact on which decile that year is categorized into. This trend in cold nights and frost over spring is of concern to the grains industry (Crimp *et al*. 2015, Zheng *et al*. 2015).

There was little trend in the number of bee flight (potential pollination) hours, although the temperature component of this indice (hours warmer than 15 °C did increase), the indice was reduced by the occurrence of raindays in August which had no historical trend (figure 14).

The amount of chill accumulated addresses the risk of Insufficient chilling for synchronized flowering or Pollinators not flowering in synchronicity. Chill accumulation varies considerably each month as shown by the average monthly accumulation at Renmark, SA (figure 15). Almonds require a minimum of 23 chill portions to satisfy dormancy requirements, and as flowering occurs in August the chill accumulated until 31st July was calculated although chill continues in August and can occur as late as October. Other reports show Nonpareil almonds require approximately 400 Utah chill hours. The seasonal variation in the amount of chilling received from May to July for almond growing locations is shown in figure 16 while the relationship of chill accumulation calculated by the Dynamic model and mean temperature is shown in figure 17. Chill portions are more strongly related to mean winter temperature than mean annual temperature (figure 17) but also show a decline with increasing mean annual temperature. The average chill and that received during the warmest year and the highest 10% of years (corresponding to the lowest chill and 10th percentile of chill) is higher in inland locations (figure 16). While the average chill is similar in Californian locations to most inland Australian locations, the minimum amount of chill and that received in warm years, especially at Bakersfield in southern California, can be less than that received in coastal Australian locations.

The historic trend in the amount of chill accumulated is shown in figure 18. There has been a downward trend in the amount of chill accumulated with 13 of the 19 years since 2000 at Mildura having lower than average chill accumulation. The decline in chill accumulation is expected to continue at a faster rate as the climate becomes warmer. That is, for each successive 1 °C warmer climate, there will be an increasingly larger decline in chill accumulation.

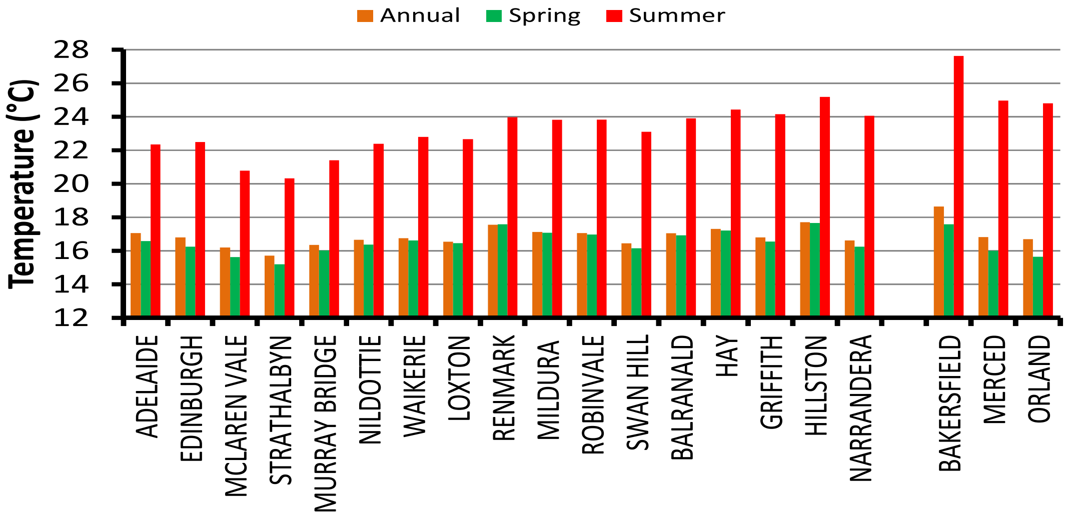


Figure 5. Seasonal mean temperature at selected almond growing locations.

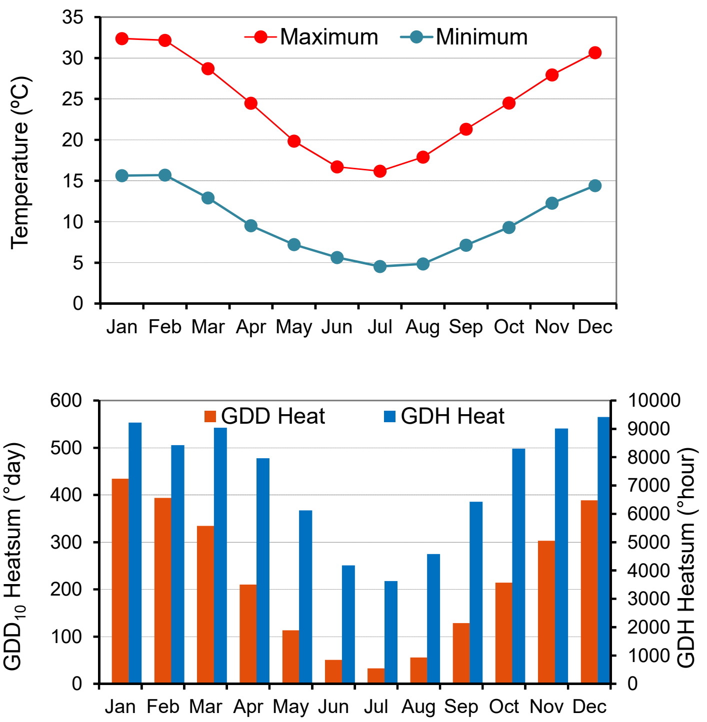


Figure 6. Average monthly maximum and minimum temperature and heat accumulation at Renmark, SA. Data from 1986 to 2005.

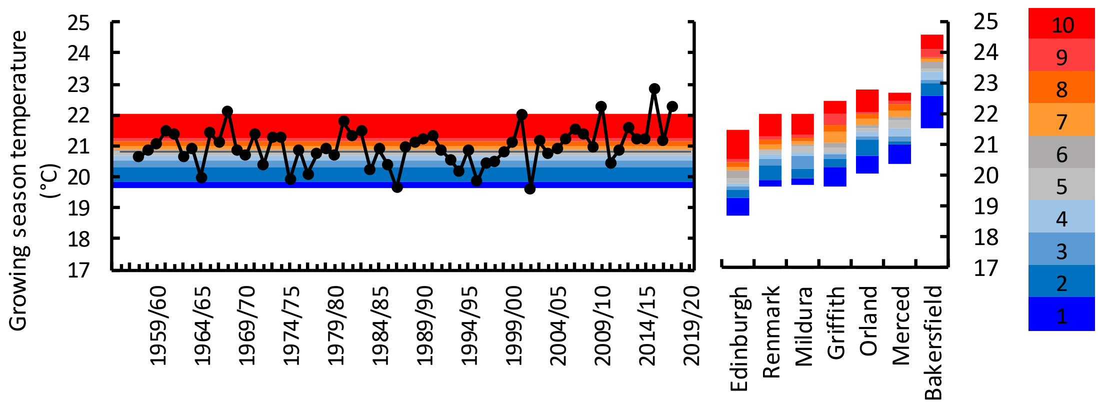


Figure 7. Historic growing season temperature at Renmark. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.

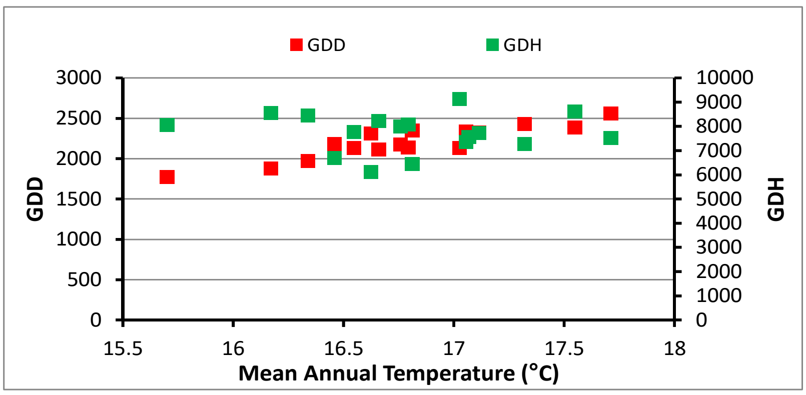


Figure 8. The relationship between long term averages of mean annual temperatures and heat accumulation calculated as GDD base 10 and GDH (calculated according to ASYMCUR, see Anderson et al. 1986).

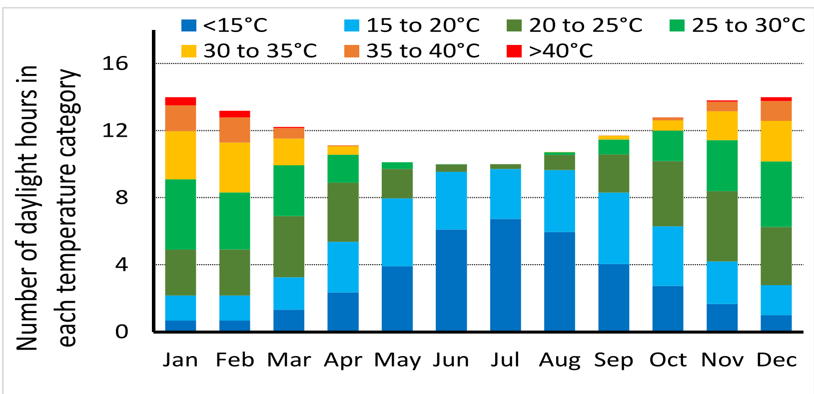


Figure 9. Average number of daylight hours per day in each temperature category at Renmark, SA. Carbon gain by the plant from net Photosynthesis is typically greatest at temperatures between 20 and 30°C and declines rapidly when it is warmer than 35°C.Data from 1986 to 2005.

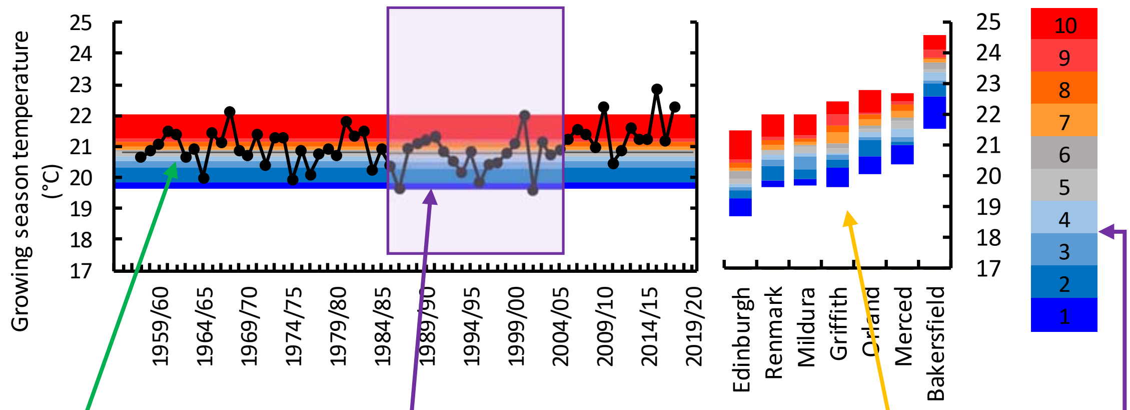
Illustrated guide to figures

The following graphs show year-to-year variation in the climate at Renmark 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.



Black points are the yearly values. They are joined by the black line.

The ribbon of colours are the deciles calculated for the 20 values from 1985 to 2005. During the 20 year period there are two values in each decile. Decile 1 contains the two lowest values, decile 10 contains the two highest values. The horizontal grey line is the median, or decile 5 value during this period.

The 'ribbon' is extended to cover the historic measuring period.

The colours of the deciles are shown to the right. These change in different graphs.

The values of the deciles calculated over the same 20 year period from 1986 to 2005 are shown for some almond growing regions in Australia and in California.

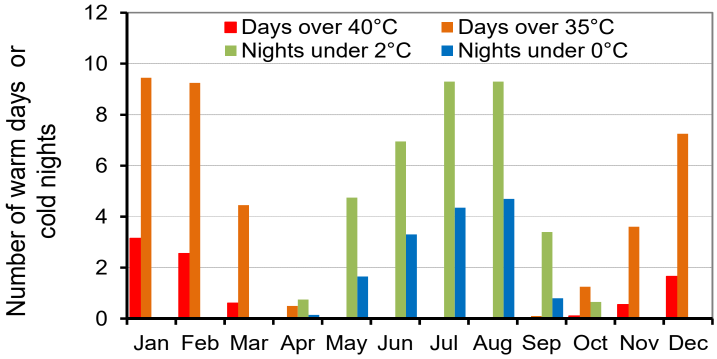


Figure 10. The number of extreme warm days or cold nights per month at Loxton, SA. Data from 1986 to 2005.

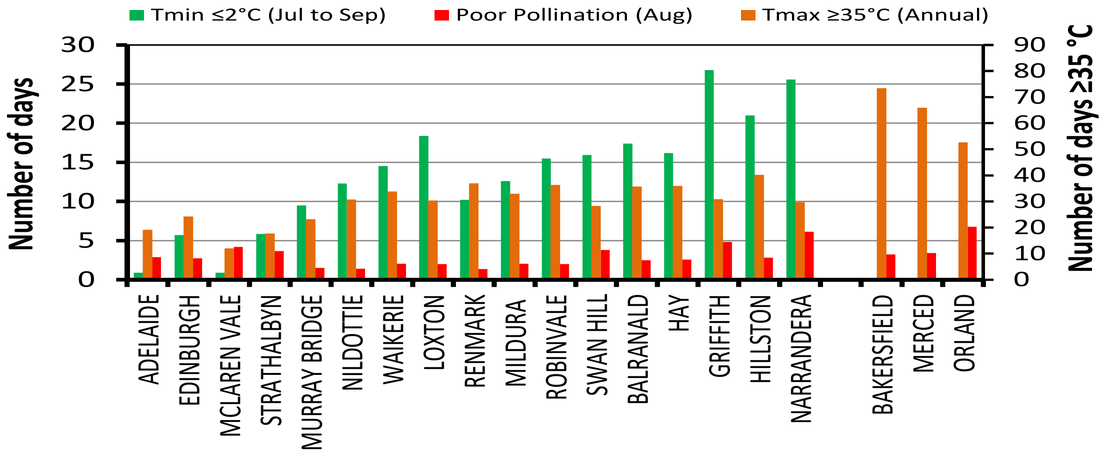


Figure 11. Number of days when daily minimum temperature was ≤2°C during July to September (Australian locations only, January to March for Californian locations), days during August (February for Californian locations) when daily maximum temperature was cooler than 13 °C or warmer than 28 °C, and days per year when daily maximum temperature was ≥35°C.

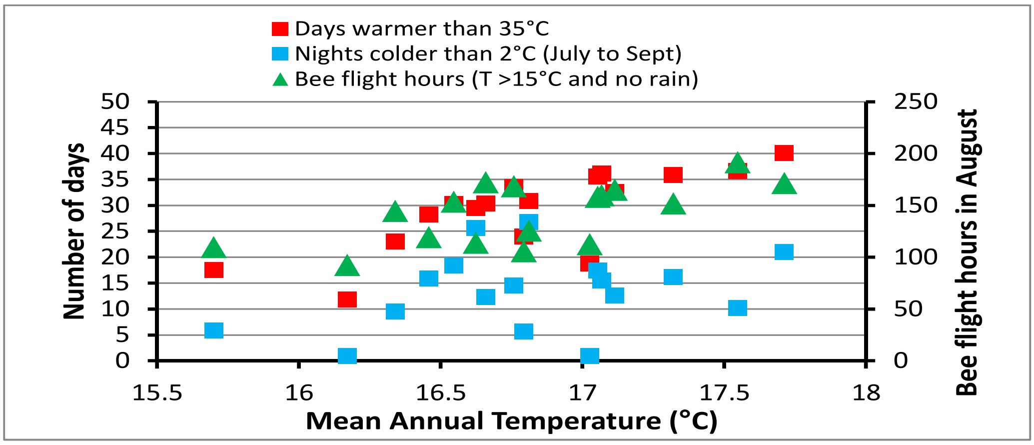


Figure 12. Mean annual temperature is related to the number of days per year warmer than 35 °C or colder than 2 °C from July to September; or number of hours considered satisfactory for bee flight (daylight hours warmer than 15 °C with no rain).

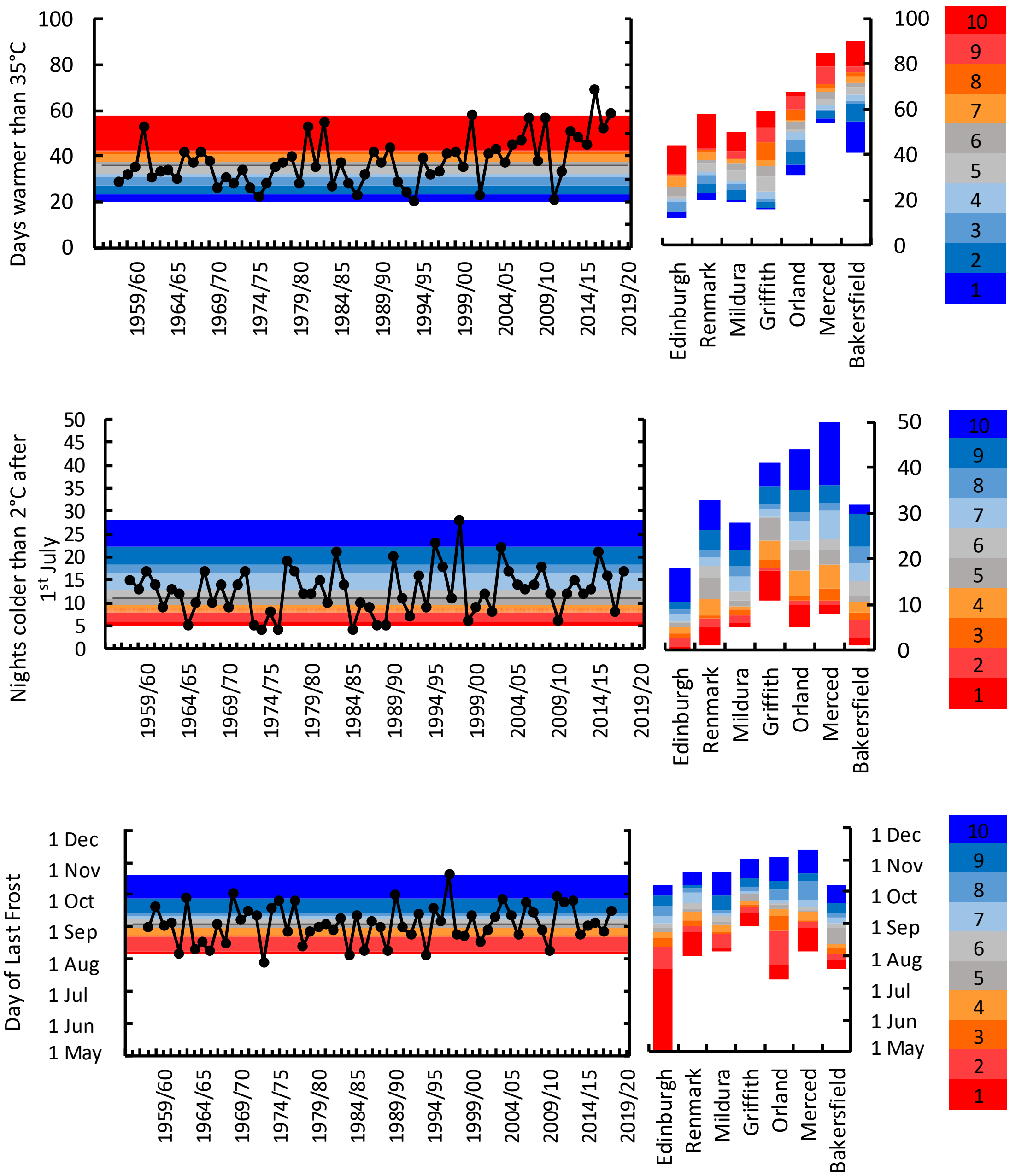


Figure 13. Historic tends in days warmer than 35 °C at Renmark, SA; and of days colder than 2 °C after 1st July at Mildura, Vic. and the last day of the year when this occurred.

Yearly values are shown as black points. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.

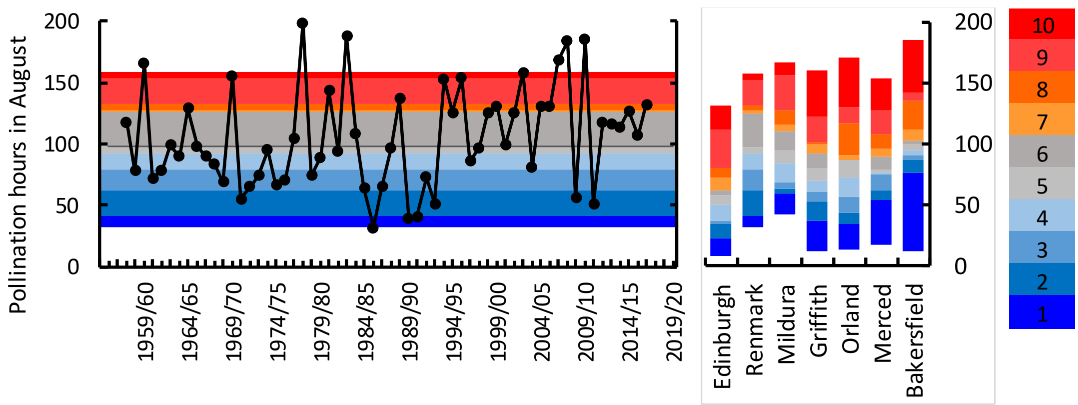


Figure 14. Historic tends in pollination hours at Renmark, SA. Yearly values are shown as black points. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.

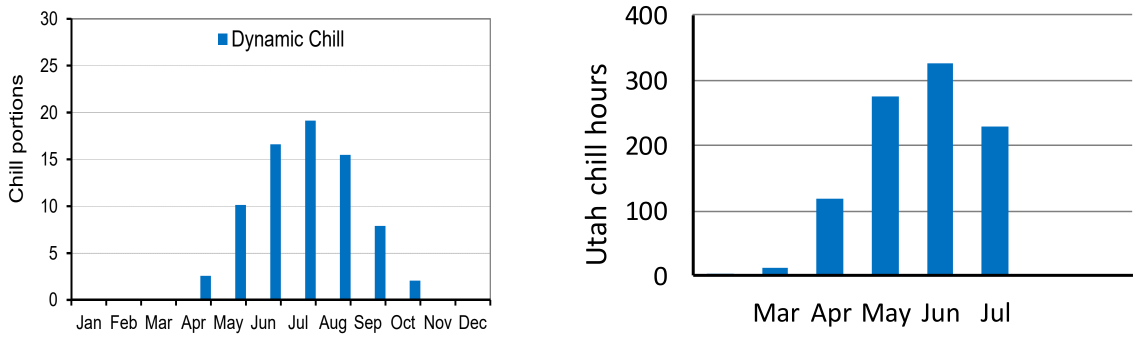


Figure 15. The amount of chill accumulated is seasonal as shown by the average monthly accumulation at Renmark, SA of Dynamic chill portions and Utah chill hours. Data of Utah chill hours after august are not shown. Data from 1986 to 2005.

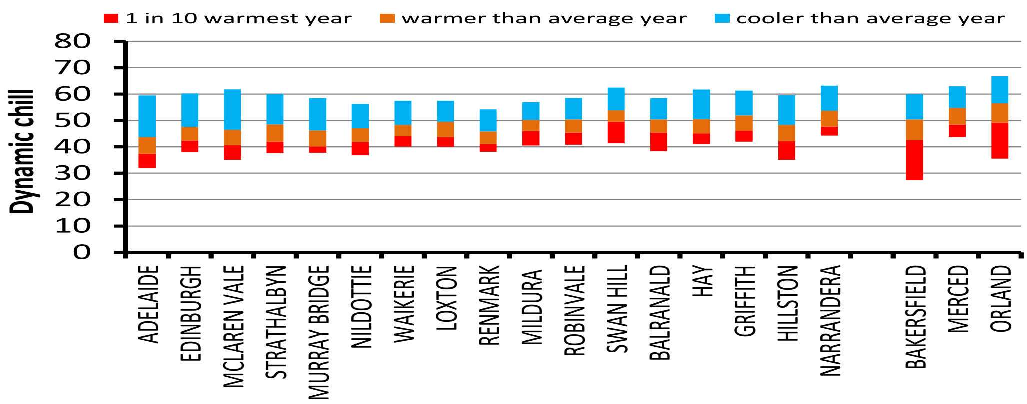


Figure 16. Dynamic chill calculated from May to July (November to January for Californian locations). The red bar shows the range from the lowest on record to the 10th percentile (10% of years have chill in this range); the orange bar shows the range from the 10th percentile to the average, and the blue bar shows the range of higher than average chill. The minimum value of chill should be considered when assessing the risk of insufficient chilling.

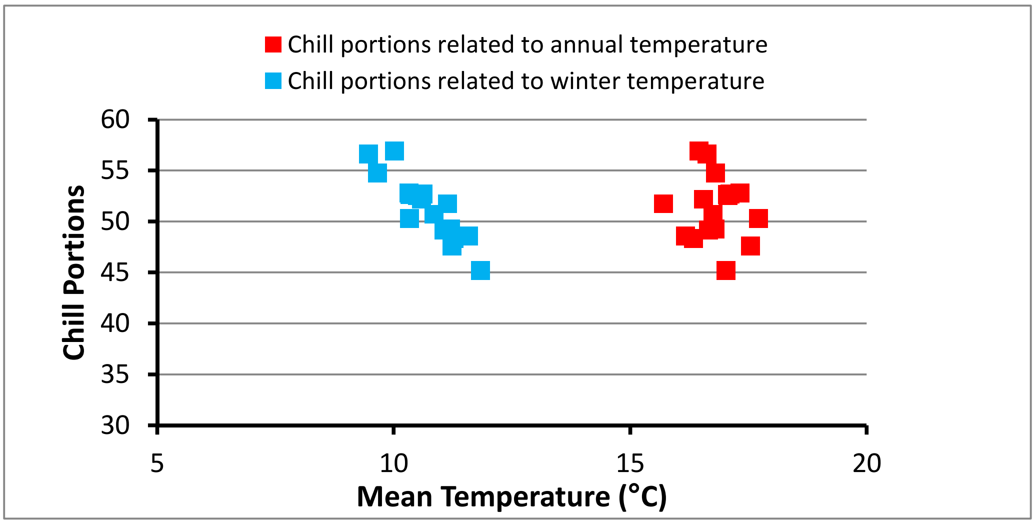


Figure 17. Chill accumulation shown as a function of mean annual temperature (red) or mean winter temperature (blue).

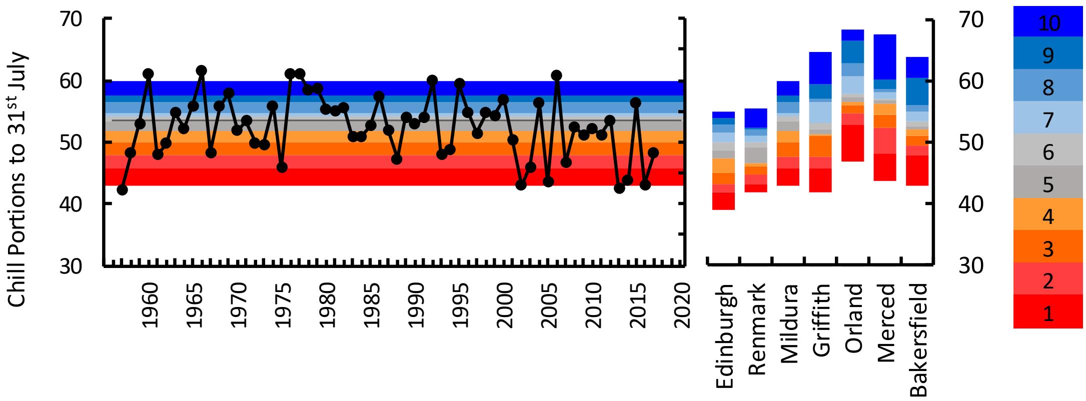


Figure 18. Chill accumulated until 31st July at Mildura, Vic. Yearly values are shown as black points. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.

Risks related to rain and humidity

Several risks are associated with rainfall. These include risk of Insufficient rainfall on the orchard, risk of Insufficient irrigation water, risk of Rainy days at harvest, risk of Excessively rainy and humid conditions leading to increased risk of diseases, and as such are related both to rain and to evapotranspiration.

Rainfall, unlike evapotranspiration of Australian almond growing locations is essentially aseasonal with similar rainfall occurring in each month (figure 19). Monthly Rainfall rarely exceeds ETo but approaches ETo only in the Winter months (figure 20). The most striking difference between Australian and Californian locations is the seasonality of rainfall (Figures 19, 20, 21). 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 harvest season (February to April in Australia and August to October in California) is usually considered a disadvantage as it affects timing of harvest operations and can reduce yield and quality.

Many almond growing regions have low rainfall and high evapotranspiration and while wet years and dry years occur there is little evidence to date of strong trends in rainfall although there is a trend towards higher evapotranspiration (figure 22, 23). Growing season evapotranspiration at Renmark has been higher than average in 16 of the 19 years since 2000, while slightly more than half these years have had higher than average growing season rainfall and slightly less than half have had higher than average annual rainfall. The demand for irrigation water is related 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 (ETo - R) 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) (figure 24). These provide a guide to the risk of Insufficient rainfall on the orchard.

The risk of Insufficient irrigation water is related to inflows into the major catchments, water storage and also to water policy. Figure 25 shows annual inflows in to the Murray system and storage of the major dams. Inflows into Murray-Darling Basin river system are projected to reduce by 20 to 30% for every 10% decline in rainfall (Chiew, 2006). This would be expected to reduce the availability of water available for irrigation. The expected increase in evapotranspiration may place greater strain on the availability and cost of water.

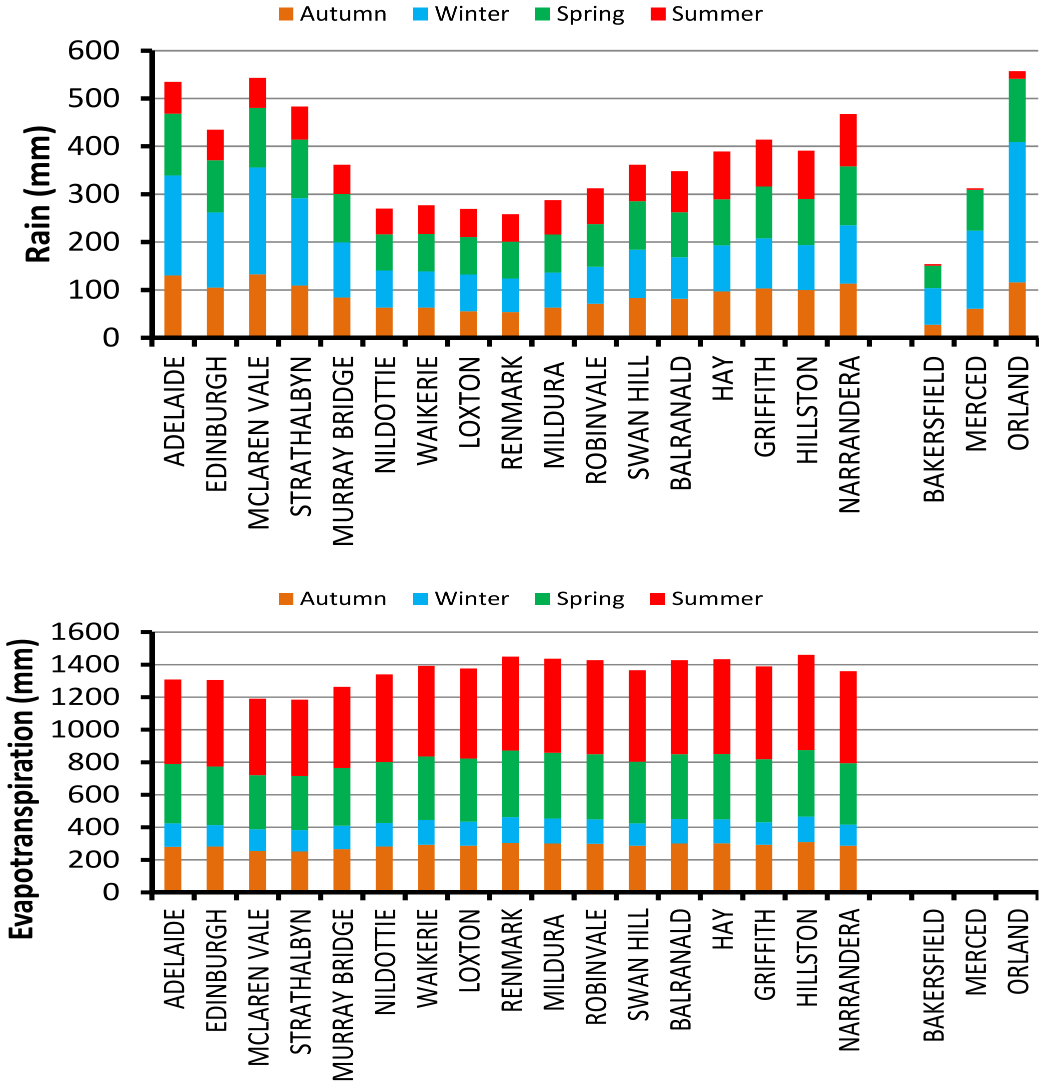


Figure 19. Seasonal rainfall and evapotranspiration at selected almond growing locations.

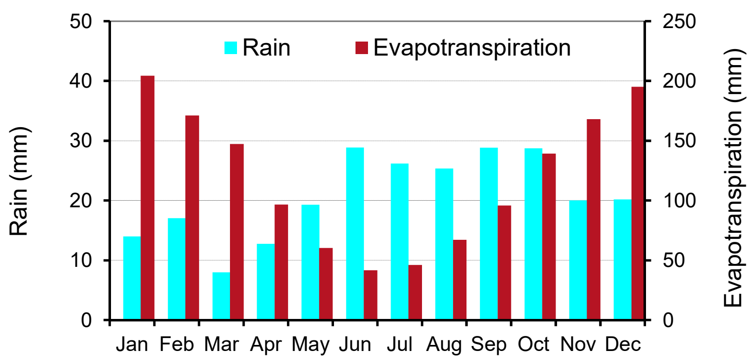


Figure 20. Monthly rainfall and evapotranspiration at Renmark, SA. Data from 1986 to 2005.

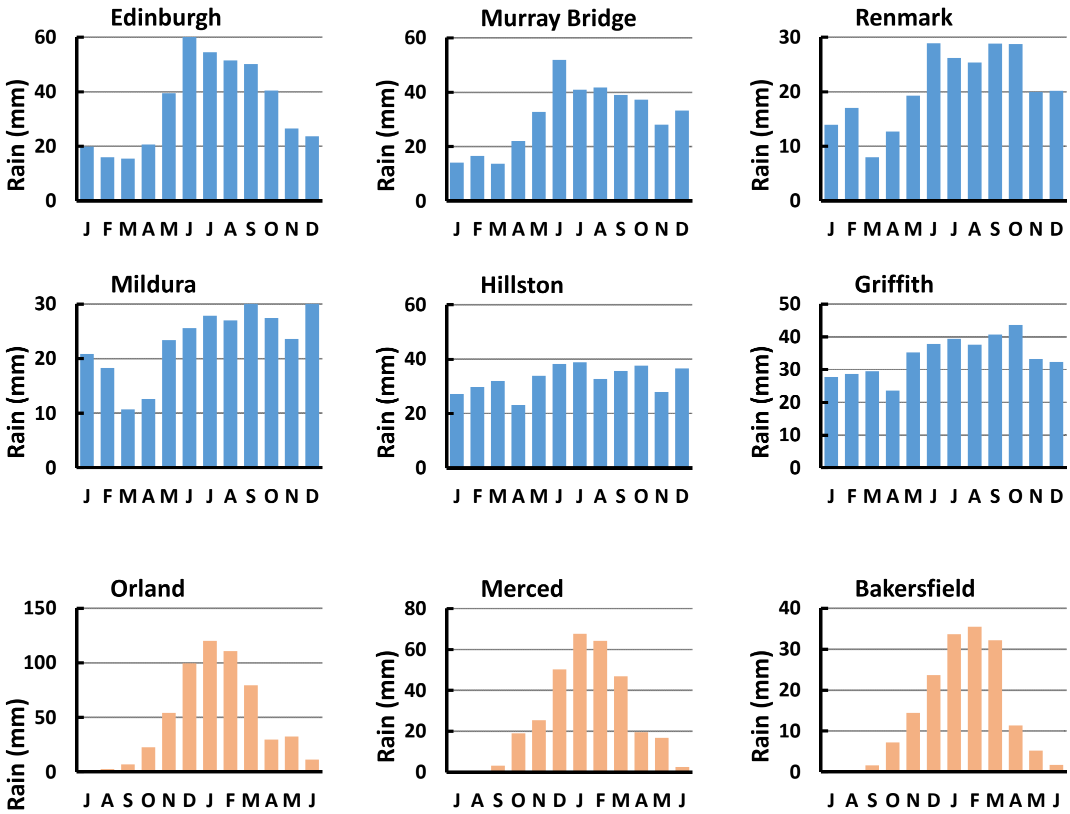


Figure 21. A major difference between Australian and Californian locations is the seasonality in rainfall as seen by these average monthly rainfall graphs. Australia has little monthly variation in rainfall compared to the strongly Mediterranean climate of wet winters and dry summers in California.

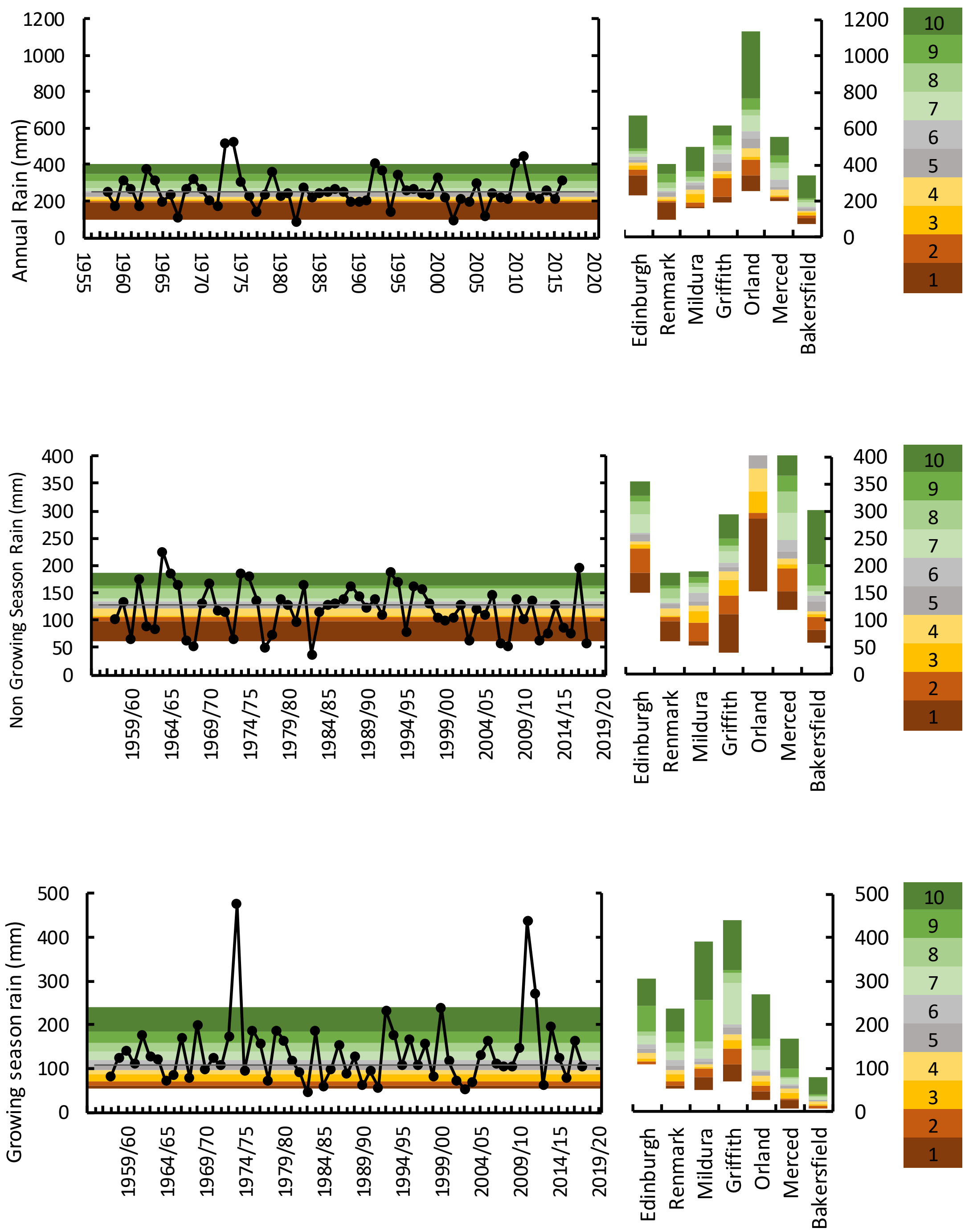


Figure 22. Annual, non-growing season (May to August) and growing season (September to April) rainfall at Renmark, SA. Yearly values are shown as black. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.

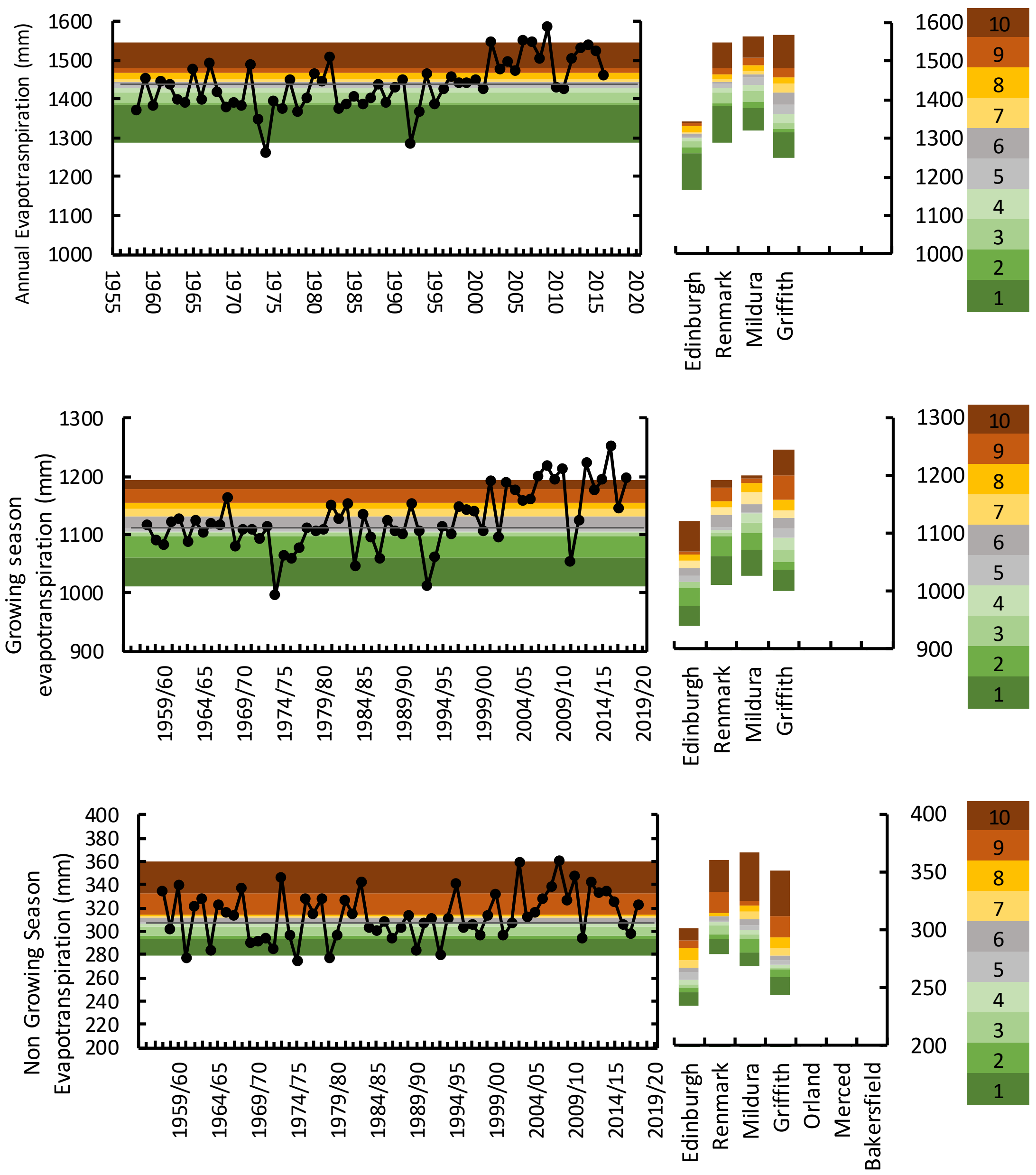
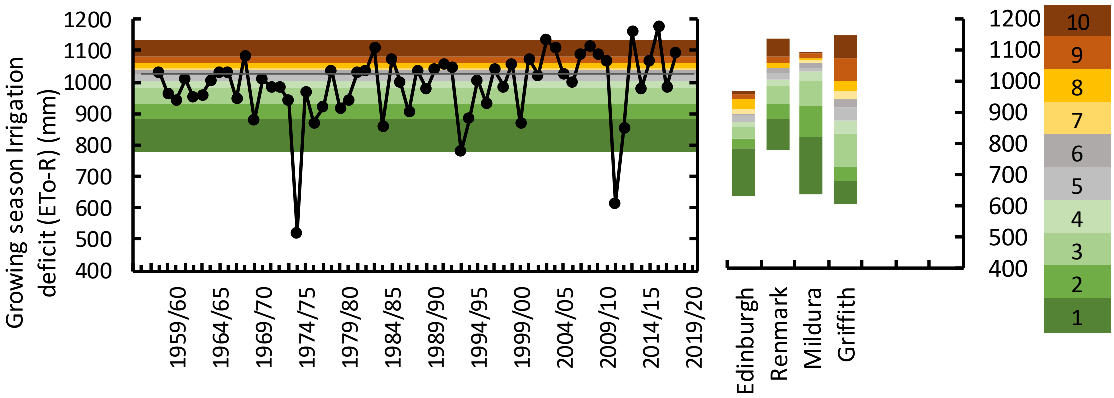


Figure 23. Annual, non-growing season (May to August) and growing season (September to April) evapotranspiration at Renmark, SA. Yearly values are shown as black. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.



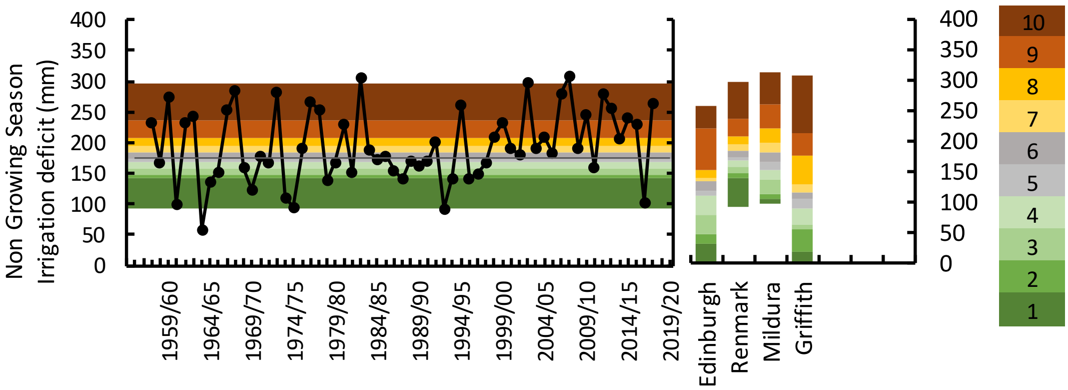
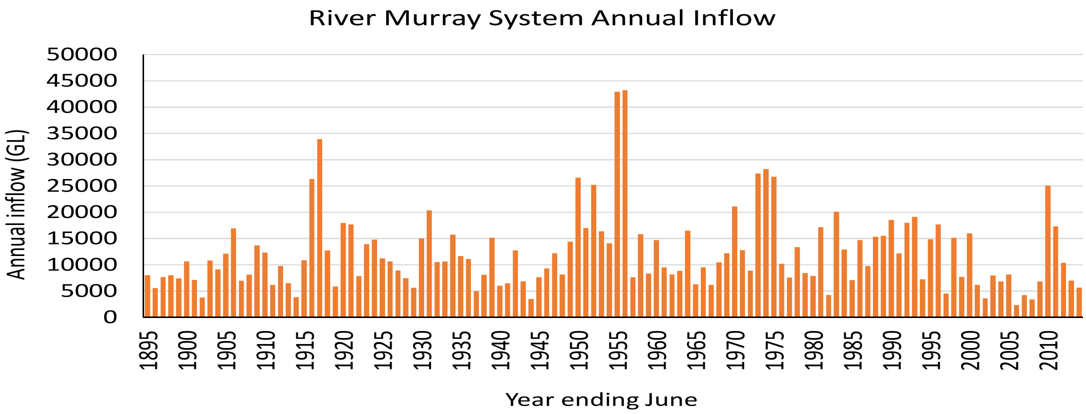


Figure 24. Annual, non-growing season (May to August) and growing season (September to April) irrigation deficit at Renmark, SA. Yearly values are shown as black. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.



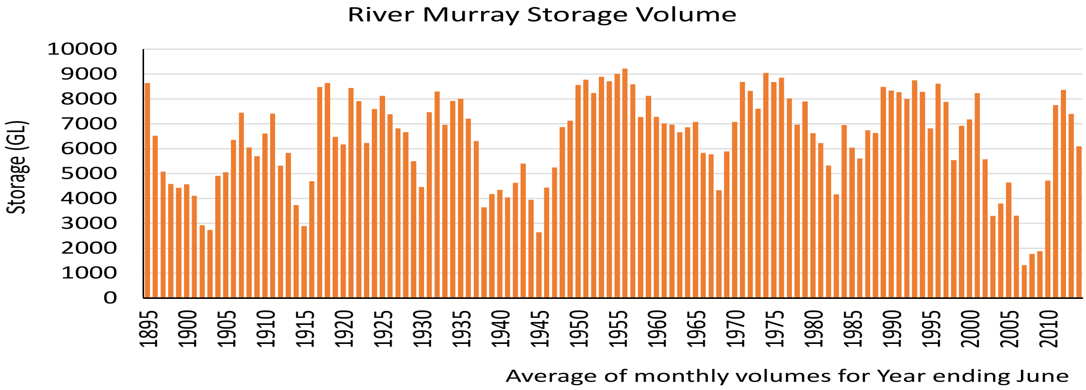


Figure 25. Annual inflow volume into the Murray system and annual storage volume for Dartmouth, Hume, Lake Victoria and Menindee. The data from 07/1895 to 06/2009 is from the Murray Darling Basin Authorities Basin Plan modelling scenarios (number 845), while data from 07/2009 onwards is the best available observed data. The modelling scenario used (#845) is the scenario presenting the baseline for the Basin Plan, which is based on June 2009 development conditions. The modelling has been described in the Hydrologic Modelling report (http://www.mdba.gov.au/kid/files/1949-Hydrologic-Modelling-Report.pdf). This is consistent with the baseline scenario for which data are provided on the website: http://www.mdba.gov.au/kid/kid-view.php?key=eBOXpE69xM4v/O76NJeKy1kOXFxGKWs*INeQeAuRfi0=

Data supplied by MDBA (November 2015).

Rainy and non-drying conditions, the later measured as moisture balance positive days (MB+ve) during the harvest window (February to April in Australia) are an indicator of the risk of Rain affecting harvest. These conditions are shown in figure 26. Conditions considered to increase the risk of rain at harvest are generally less desirable as summer ends and autumn progresses in Australia, and less desirable than in California. The long term trends in these indices are shown in figure 27. Figure 27 also shows the long term trends of these indices during the growing season, which could be used to assess the risk of Excessively rainy and humid conditions leading to increased risk of diseases.

The use of rainy days and MB+ve days to assess the risk of rain at harvest or of Excessively rainy and humid conditions leading to increased risk of diseases was chosen for simplicity of these indices. Other indices to assess leaf wetness are available but complex to calculate. Figure 28 shows there was generally high agreement between the two models used to calculate leaf wetness (dew point and hours of relative humidity greater than 90%). The number of hours per day of wet leaf declined with increasing mean annual temperature for locations cooler than 17°C, but showed no further declines for locations warmer than 17°C. Leaf wetness was less in locations with higher evapotranspiration, but was poorly related to mean annual rainfall. Figure 29 shows that the number of days with rain above either 2mm or 5mm was larger in locations that had higher mean annual rain. The number of rain days was related to leaf wetness only when examined for the period from October to April so could be an indication of disease pressure, but not from February to April so was unlikely to be a good indicator of the risk of rain or non-drying conditions at harvest. In other words, leaf wetness near harvest (February to April) was poorly related to the number of rainy days. However, wetter locations also had a larger number of days considered moisture balance positive (not shown). The index of the number of moisture balance positive days increased as the number of days with either 2 or 5mm rain increased, and decreased as Evapotranspiration of a location decreased.

Taken together the relationships of indices with mean temperature suggest warmer locations or increasingly warmer conditions may be associated with increased risks of heatwaves, increased evaporative demand and demand for irrigation water, increased risk of insufficient chill but reduced risk of poor pollination conditions and of frost (although it is understood that the risk of frost may increase in the short term as drier conditions frequently lead to greater risk of frost). There is considerable year-to-year variation in indices related to rainfall and little indication of strong long term trends. However it should be noted that global circulation models used to project future climates in response to increased greenhouse gases indicate the seasonality of rainfall is likely to change and that rainfall is likely to decline. The following is quoted from the Climate Change in Australia summary for the Murray Basin subcluster https://www.climatechangeinaustralia.gov.au/en/climate-projections/future-climate/regional-climate-change-explorer/clusters/?current=MBC&tooltip=true&popup=true, sourced 26 February 2019)

> By late in the century (2090), less rainfall is projected during the cool season, with *high confidence*. There is *medium confidence* that rainfall will remain unchanged in the warm season. For the near future natural variability is projected to dominate any projected changes.
>
> PAST RAINFALL TRENDS
>
> The Murray Basin experienced notable prolonged periods of extensive drying in the early 20th century, but annual rainfall shows no long-term trend between 1910 and 2013.
>
> RAINFALL PROJECTIONS
>
> In the near future (2030) natural variability is projected to predominate over trends due to greenhouse gas emissions. Late in the century (2090) cool season (April to October) rainfall is projected to decline under both an intermediate (RCP4.5) and high (RCP8.5) emission scenario.

In the warm season (November to March), little change, increases and decreases of rainfall are projected by different models. The magnitude of projected changes for late in the century (2090) span approximately -40 to +5 percent in winter and -15 to +25 percent in summer for a high emissions case (RCP8.5).

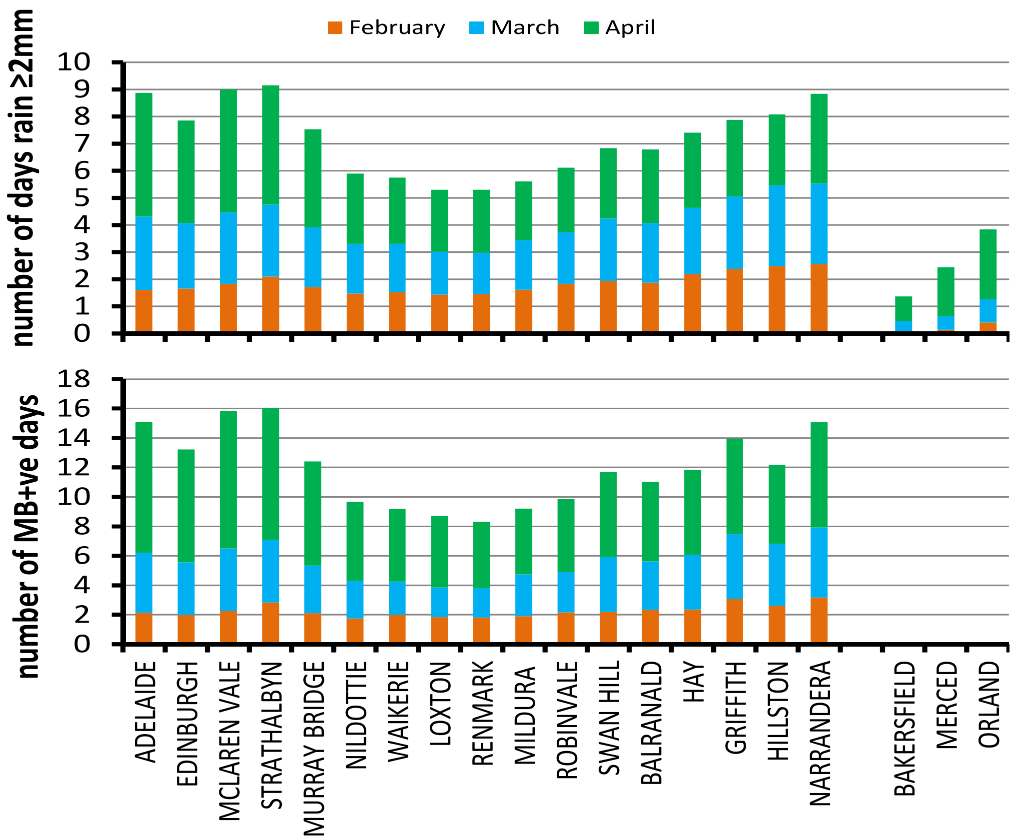


Figure 26. Number of days when rainfall exceeds 2mm during February to April (August to October in Californian locations), and the number of days considered moisture balance positive (MB+ve) are shown. MB+ve days not shown for Californian locations.

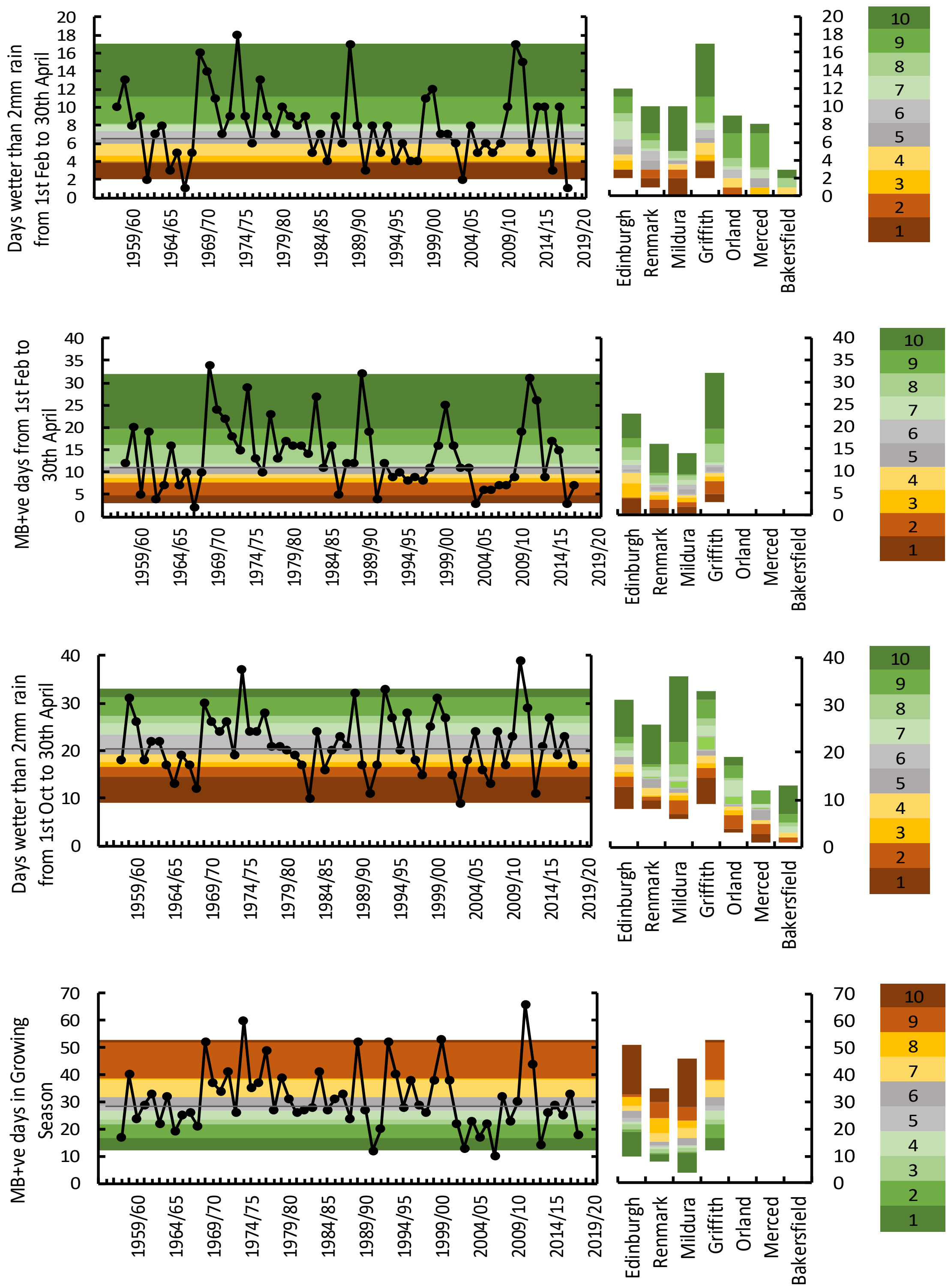
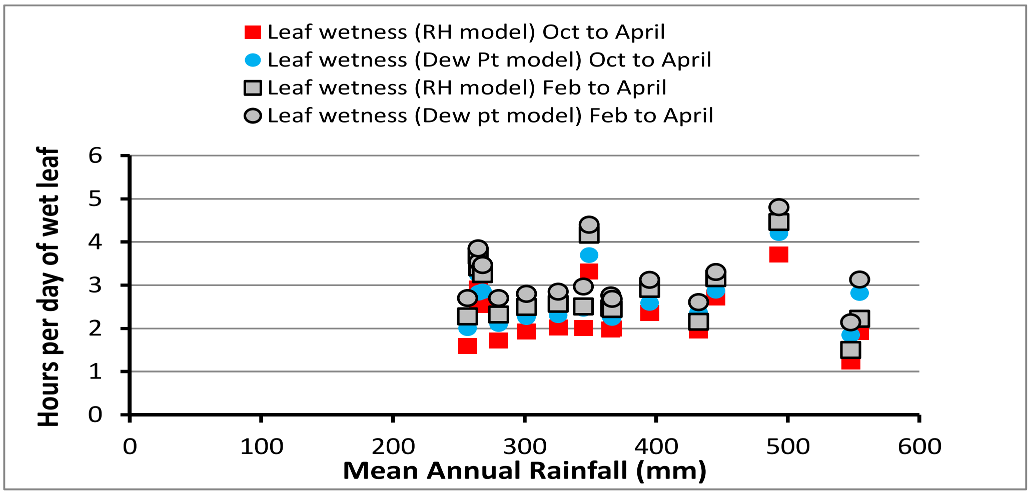


Figure 27. The number of days during the harvest window (February to April) that have more than 2mm rainfall or are considered moisture balance positive at Griffith, NSW. These indices can be calculated over the growing season as an indicator of disease pressure. The ribbon indicates the deciles calculated from 1986 to 2005 with colours of each decile indicated by the bar situated to the right side of the figure and the horizontal grey line showing the value of decile 5 (median value). The values of deciles in other almond growing regions are shown on the right hand graph.



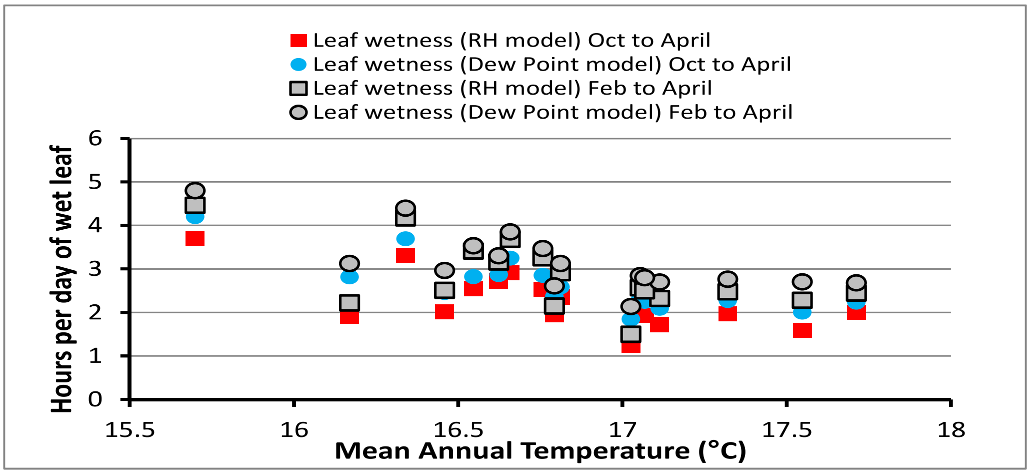
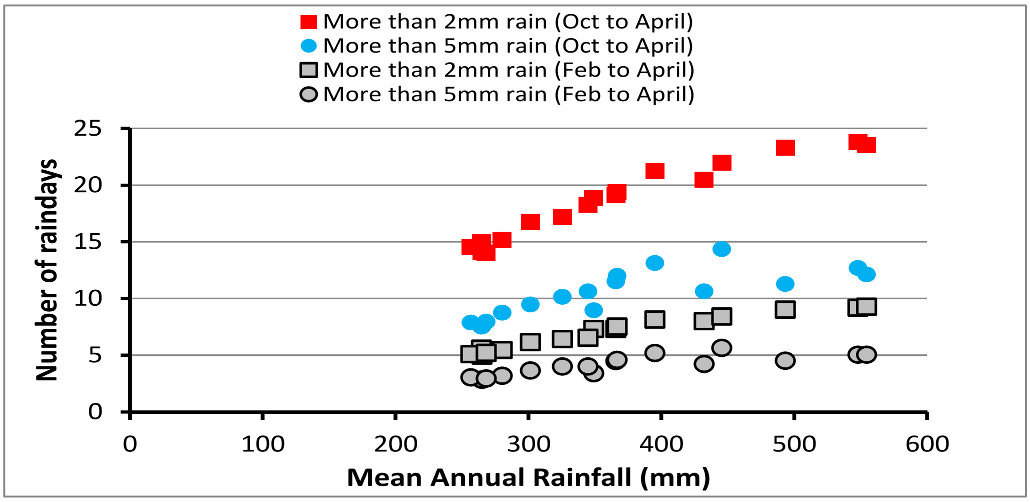


Figure 28. Leaf wetness generally decreased with increasing temperature and increased with increasing rainfall.



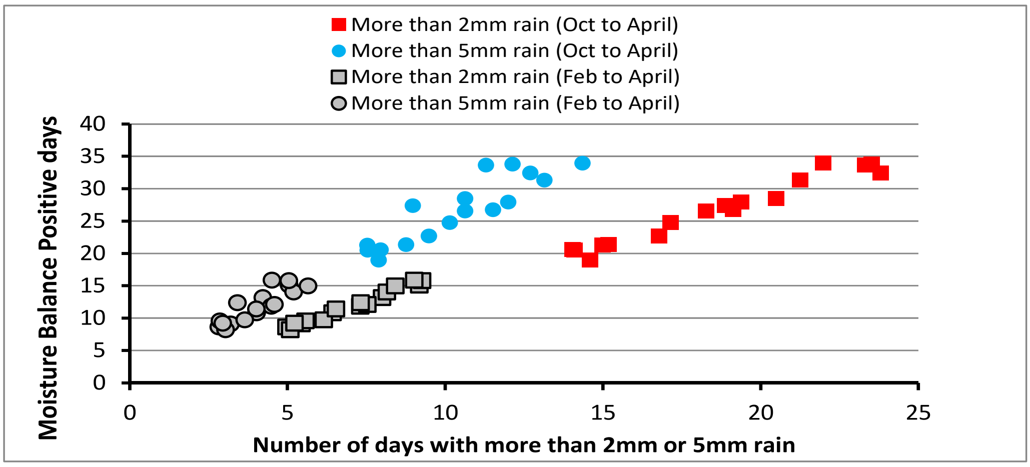


Figure 29. Locations with higher rainfall had more days with rain (upper) and also more days considered moisture balance positive (not shown). Moisture balance positive days were related to the number of raindays (middle) and also evapotranspiration (lower).

Additional analysis of rainy days near harvest in almond producing regions

This analysis of major almond producing regions includes Edinburgh (in North Adelaide plains), Renmark (in Riverland), Mildura (in Sunraysia) and Hillston (in Riverina), and three location in California. For the analysis of Australian locations daily rainfall was obtained from SILO from 1900 to 2015. The number of rainy days above set thresholds and total rainfall (mm) in each month and from January of each year were analysed. The figures (figure 30 to 36) show the median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 116 year period from 1900 to 2015; and for the year 2011. This year was chosen as a comparison owing to how wet it was and because rain caused great difficulties to the harvesting process was in that year.

Just how extraordinary the frequency of rainy days and total rainfall was in 2011 can be appreciated by examining the analysis of Mildura in particular. While the number of days with rainfall greater than 2.5 mm is approximates the 90th percentile (only 1 in 10 years has more rainy days), the number of days with higher rainfall 10 mm or more is essentially the maximum on record. The number of wet days of more than 20mm, or very wet days of more than 40mm, and total rainfall is the maximum and much greater than the 90th percentile. This year was wet even by historic standards, and would have been exacerbated by wet conditions since October in the previous year. A similar situation occurred at Renmark and Edinburgh and although 2011 did not set the record as often, it was usually equal to or above the 90th percentile. At Hillston, the very wet days of rainfall greater than 40mm did not occur in 2011, but the number of days wetter than 10 mm and 2.5mm were above the 90th percentile and total rainfall close to the 90th percentile. The heavier soil (higher clay content) at Hillston would have added to difficulties of adhering to the fruit, soil drying, and trafficability for machinery.

In comparison the frequency of rain and total rainfall in the months near harvest in Californian almond growing regions is minor particularly in southern and central regions. As harvest in California is typically from August to October the cumulative number of rainy days and total rainfall was calculated from 1 July in each year. This showed that for three example areas (Colusa in north, Modesto in central region, and Bakersfield in south) there were much fewer number of rainy days, particularly those wetter than 20 mm and less total rainfall than locations in Australia, which again highlights this risk is more important to Australian production and one that has to be solved through local ingenuity.

Mildura, Vic

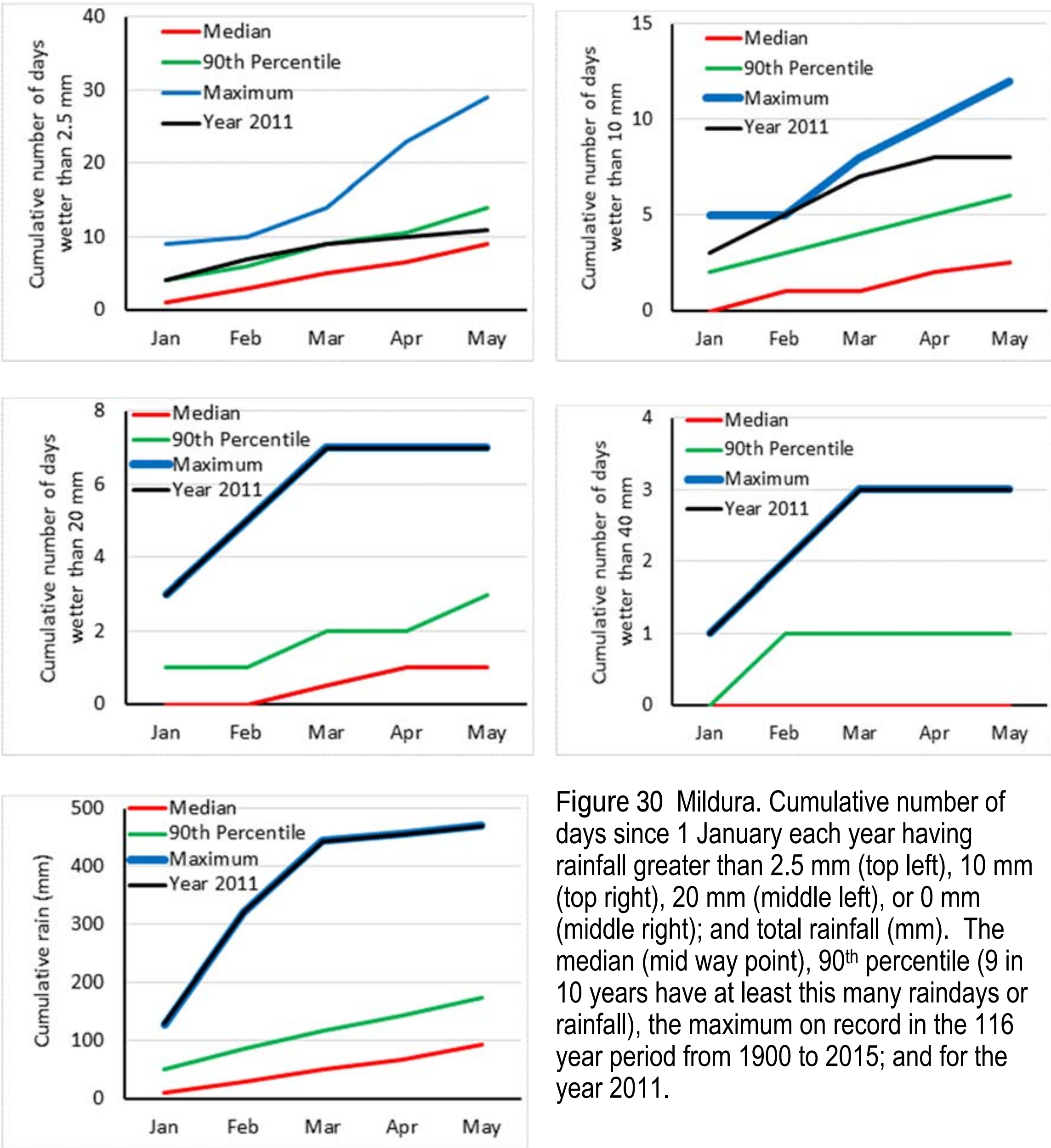
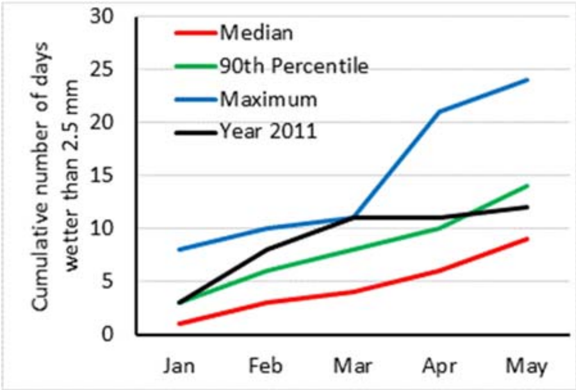
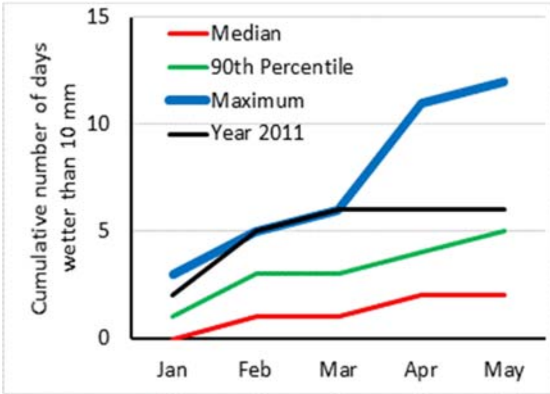
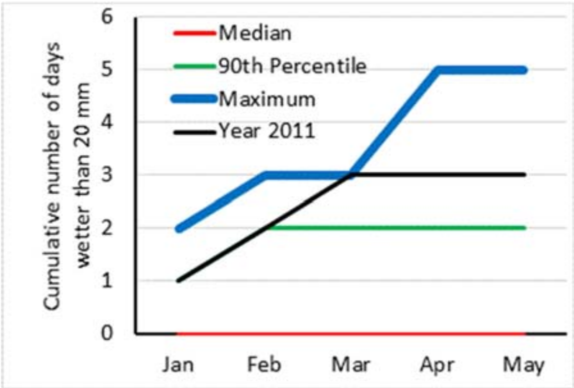


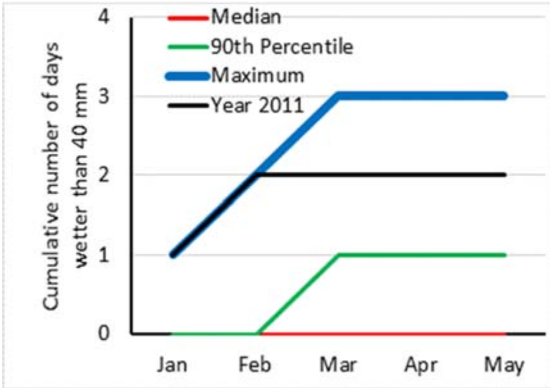
Figure 30 Mildura. Cumulative number of days since 1 January each year having rainfall greater than 2.5 mm (top left), 10 mm (top right), 20 mm (middle left), or 0 mm (middle right); and total rainfall (mm). The median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 116 year period from 1900 to 2015; and for the year 2011.

Renmark, SA









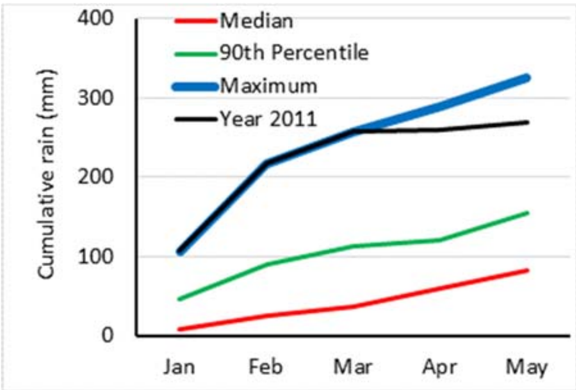
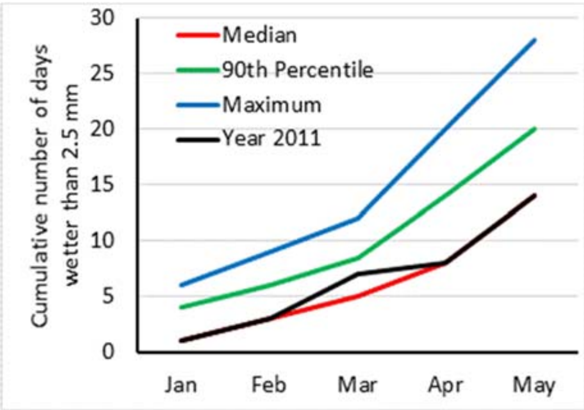
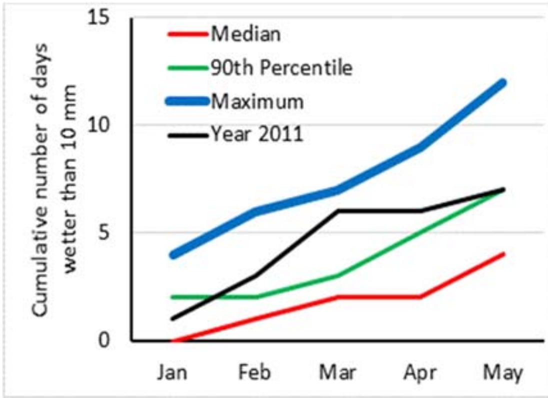
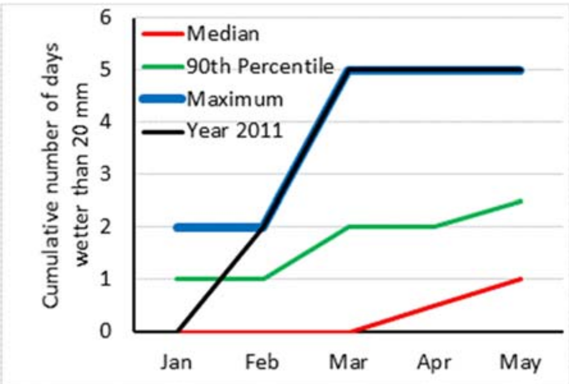


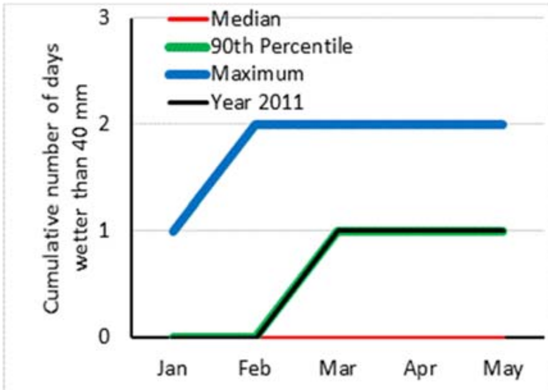
Figure 31 Renmark. Cumulative number of days since 1 January each year having rainfall greater than 2.5 mm (top left), 10 mm (top right), 20 mm (middle left), or 0 mm (middle right); and total rainfall (mm). The median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 116 year period from 1900 to 2015; and for the year 2011.

Edinburgh, SA









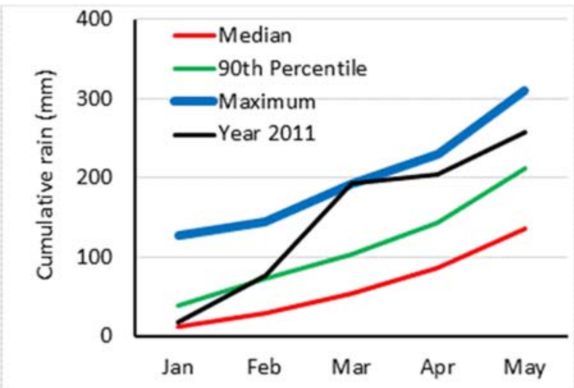
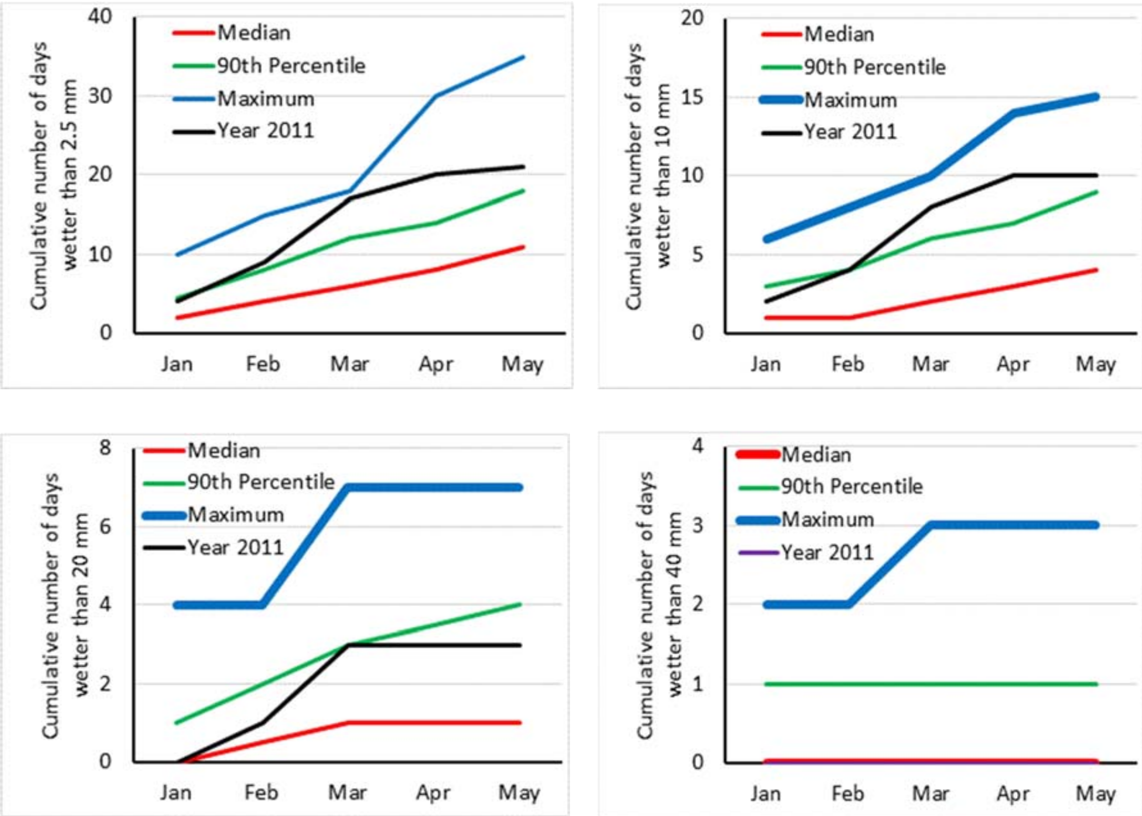


Figure 32 Edinburgh. Cumulative number of days since 1 January each year having rainfall greater than 2.5 mm (top left), 10 mm (top right), 20 mm (middle left), or 0 mm (middle right); and total rainfall (mm). The median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 116 year period from 1900 to 2015; and for the year 2011.

Hillston, NSW



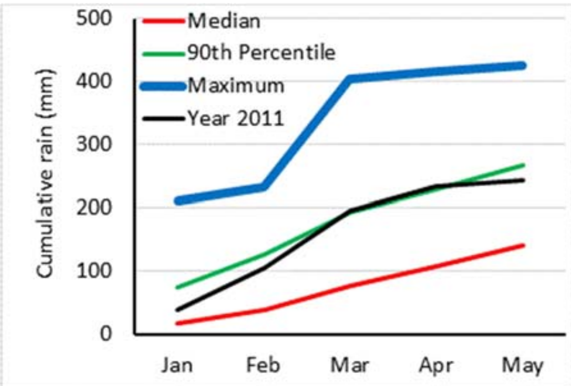
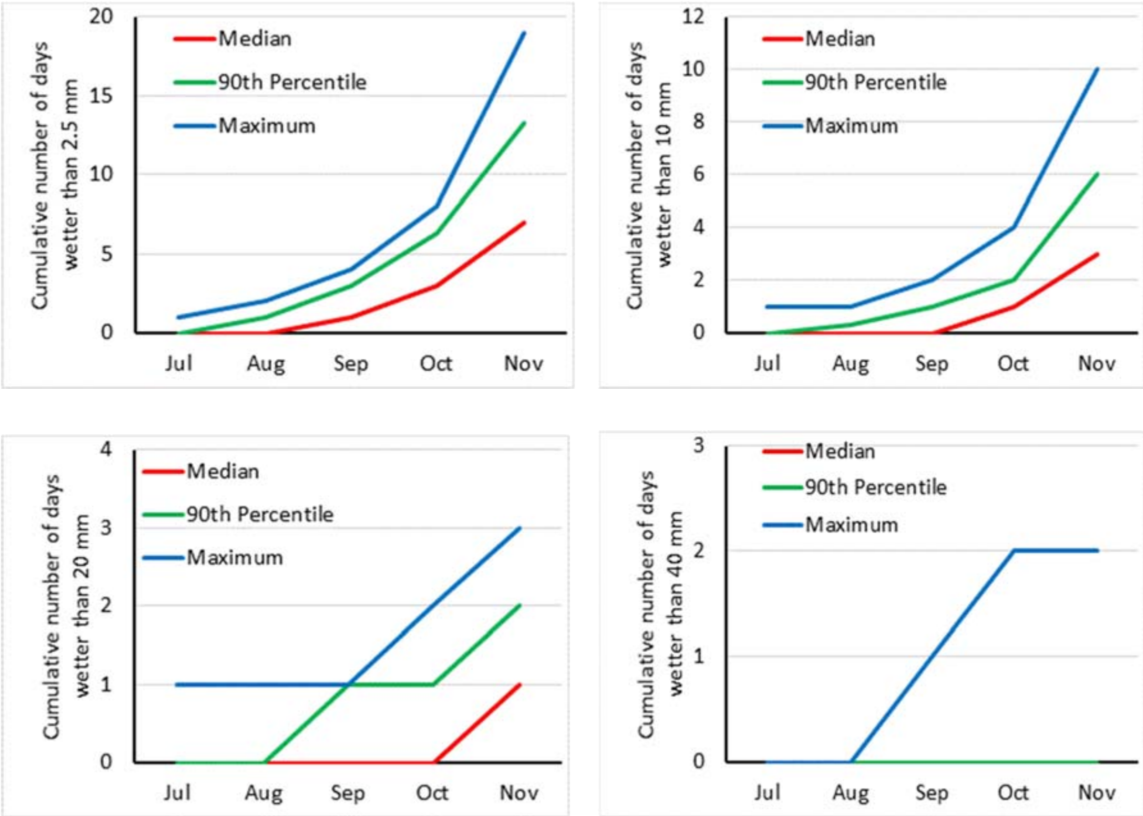


Figure 33 Hillston. Cumulative number of days since 1 January each year having rainfall greater than 2.5 mm (top left), 10 mm (top right), 20 mm (middle left), or 0 mm (middle right); and total rainfall (mm). The median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 116 year period from 1900 to 2015; and for the year 2011.

Colusa, California



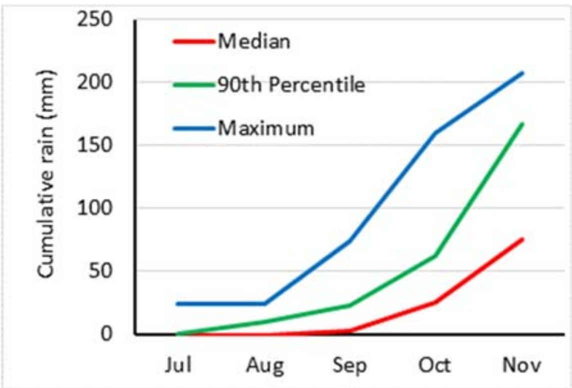
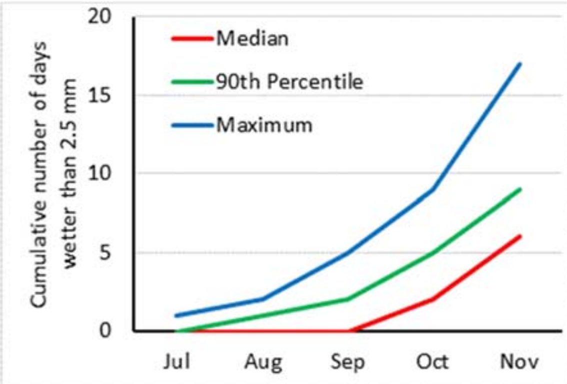
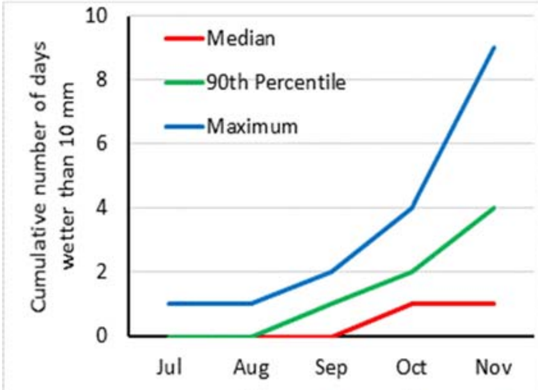
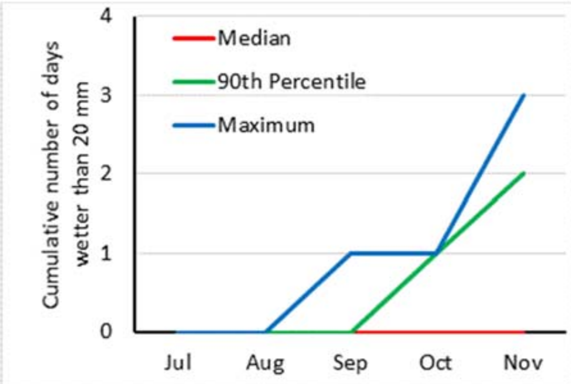


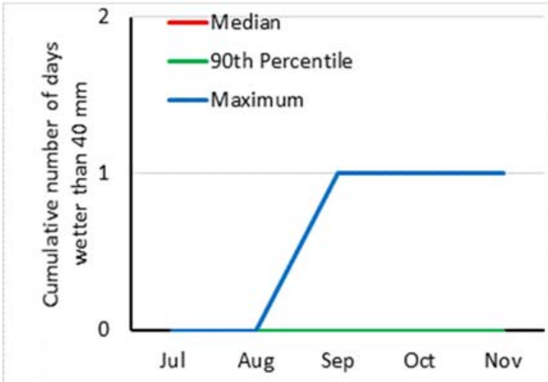
Figure 34 Colusa, California. Cumulative number of days since 1 July each year having rainfall greater than 2.5 mm (top left), 10 mm (top right), 20 mm (middle left), or 0 mm (middle right); and total rainfall (mm). The median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 57 year period from 1957 to 2014.

Modesto, California









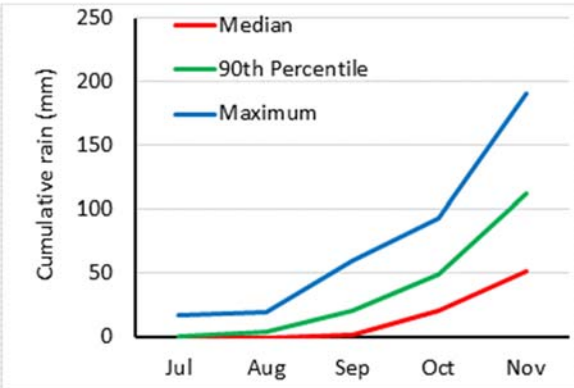


Figure 35 Modesto, California. Cumulative number of days since 1 July each year having rainfall greater than 2.5 mm (top left), 10 mm (top right), 20 mm (middle left), or 0 mm (middle right); and total rainfall (mm). The median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 57 year period from 1957 to 2014.

Bakersfield, California

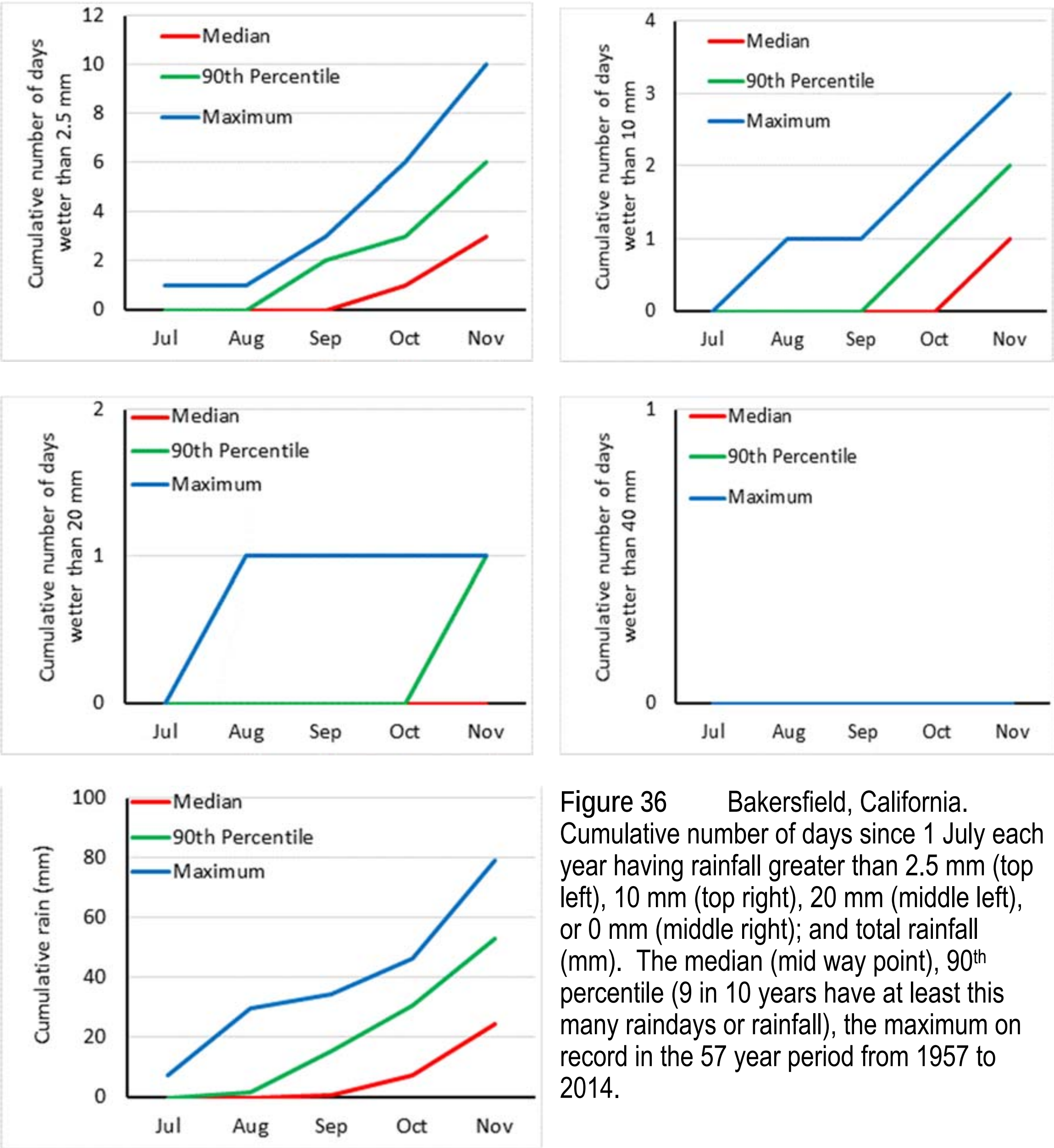


Figure 36 Bakersfield, California. Cumulative number of days since 1 July each year having rainfall greater than 2.5 mm (top left), 10 mm (top right), 20 mm (middle left), or 0 mm (middle right); and total rainfall (mm). The median (mid way point), 90th percentile (9 in 10 years have at least this many raindays or rainfall), the maximum on record in the 57 year period from 1957 to 2014.

Activity 5. The major climate drivers of these risks, and how these may change in projected warmer and drier future

Methods

Climate drivers

Australia's climate displays considerable annual variability. There are many climatic influences on Australia’s climate that can be related to the weather or climate elements associated with the risks to almond production. The Bureau of Meteorology’s Water and the Land section (http://www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml?bookmark=introduction#page-top) and Climate Kelpie (http://www.climatekelpie.com.au/) detail the climate drivers and synoptic features that can affect the risks to almond production. These climate drivers and synoptic features are inter-related.

The El Niño -Southern Oscillation (ENSO) is the dominant driver of climate variability on seasonal or inter-annual time scales for Australia. A general feature is that an El Niño - Southern Oscillation will be associated with less rainfall, but may also be related to warmer temperatures, shift in temperature extremes, increased frost risk, reduced tropical cyclone numbers with later monsoon onset. A La Niña will be associated with more rain. A positive Indian Ocean Dipole (IOD) will also be associated with less rain. The analysis of risks to almond production will focus on these two climate drivers.

The associations of other climate drivers may be summarized as a positive phase of the Southern Annual Mode (SAM) in winter will be associated with more rain but less rain in summer. Additionally temperatures, especially extreme temperatures are influenced by blocking highs, which prevent the westerly movement of weather systems. Blocking highs can have a wide range of impacts depending on their location and strength. A blocking high can produce a hot spell, a cold spell, dry conditions or wet conditions depending on its location and the systems around it. Blocking highs can also be associated with greater probabilities of fog and frost occurrence. Table 4 (adapted from Climate Kelpie) summarise the main climate drivers in synoptic features that influence weather and climate in southern Australia.

The importance of ENSO and the Dipole mode index (DMI), which determines the IOD phase, on the general climate and specialized agroclimate indices was examined by firstly determining if values in La Niña or El Niño or positive IOD or negative IOD years were more or less likely to occur in the lower, middle or upper terciles of all years during the historic period. The historic period from 1957 to 2017 was used when assessing ENSO, while the period from 1960 to 2017 was used when assessing IOD. This information can be used by managers to assess the altered chance of values for the indices being much lower, much higher or about the same in years that are categorized as La Niña or El Niño, or positive IOD or negative IOD. That is, if the value of the indice is related to ENSO or IOD years then orchard managers can adjust management according to seasonal forecasts. For example, if it is known that rainfall is reduced in an El Niño year then demand for irrigation water could be higher than usual. 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/)

ENSO and DMI (and hence IOD) are related to sea surface temperature (SST) between different parts of the Pacific Ocean and Indian Ocean respectively. These SST values can be obtained by various means with several models available. Likewise various criteria can be used to categorize years or seasons into those considered neutral or in warmer or cooler phases (warmer phases result in El Niño events or positive IOD phases, and cooler phases result in La Niña events or negative

IOD phases). This has led to differences between meteorological agencies and within the literature in the categorization of years or seasons into neutral, warmer and cooler phases (See review by McGregor and Ebi, 2018 and also Meyers et al., 2007; Cai et al., 2009; Ummenhofer et al., 2009; Perkins et al., 2015; Jarvis et al., 2018 for different categorization methods and event years). The Australian Bureau of Meteorology defines the ENSO phases of El Niño events and La Niña events based on SST anomalies in the Niño 3 and Niño 3.4 regions in addition to strength of trade winds over the western or central equatorial Pacific for the previous 3 to 4 months and the Southern Oscillation Index (SOI) that measures the mean sea level pressure difference between Tahiti and Darwin.

For this study the Australian Bureau of Meteorology official record was used to categorise ENSO into La Niña events or El Niño event years, or by IOD into either positive IOD phases or negative IOD phases (http://www.bom.gov.au/climate/enso/ and http://www.bom.gov.au/climate/iod/). Data from 1957 to 2017 was used for ENSO and from 1960 to 2017 for IOD. These are displayed in figure 37. In similarity to the analysis of the historic weather and climate associated with the risks (above), the general climate and agroclimate indices were categorized based on the occurrence of an ENSO or IOD event year during the flowering year rather than the associated harvest year. For example, the ENSO classification of La Niña event in 2015/16 was classified as a 2015 event year and associated with the almond flowering year of 2015 and harvest year in 2016.

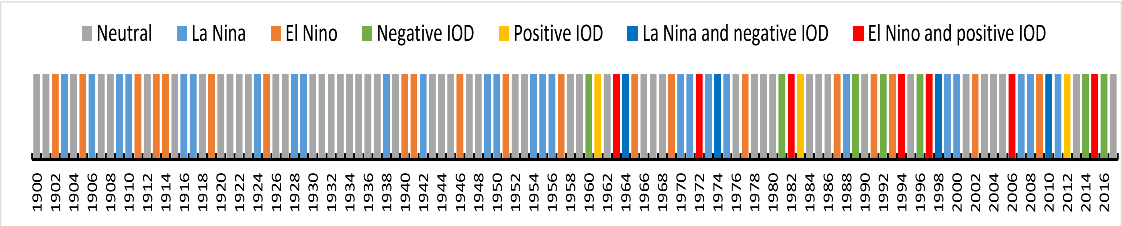


Figure 37. Categorisation of years according to the Australian Bureau of Meteorology. ENSO categories of La Niña years and El Niño years are shown from 1900, while positive IOD years and negative IOD years are shown from 1960. Years may be categorized as La Niña and negative IOD or as El Niño and negative IOD.

Secondly the impact of climate drivers was examined by correlating indices of ENSO (namely Niño 3.4) or DMI with the calculated general climate and agroclimate indices. The monthly values of indices of Niño 3.4 and DMI were obtained from the Hadley Centre Global Sea Ice and Sea Surface Temperature data (HadISST 1) (Rayner et al., 2003) specifically HadiSST 1.1); and from the Extended Reconstructed Sea Surface Temperature (ERSST) dataset version 5 (Huang et al., 2017) where anomalies were relative to 1961 to 1990 (data sourced from https://climexp.knmi.nl/). The monthly values of the Southern Oscillation index (SOI) were obtained from the Bureau of meteorology (http://www.bom.gov.au/climate/current/soi2.shtml). These are Troup SOI which is the standardised anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin. Data are based on means and standard deviations calculated over the period 1933 to 1992 inclusive. The indices of climate drivers (2 of each Niño 3.4 and DMI, and 2 of SOI) were correlated with the specific agroclimate indices or general climate indices using the same calendar periods as the specific agroclimate indices or general climate indices. Note these calendar periods may differ from those used in previous analysis.

Table 4. The main climate drivers and synoptic features that affect weather and climate in NSW, South Australia and Victoria. Adapted from Climate Kelpie (http://www.climatekelpie.com.au/understand-climate/weather-and-climate-drivers)

Climatic driver or Synoptic feature	Potential effect	Period of activity (and region)
El Niño - Southern Oscillation	El Niño associated with less rain	May - November
	La Niña associated with more rain	May - April (NSW), May - November (SA, Vic.)
Indian Ocean Dipole	Positive IOD associated with less rain	May - November (NSW); June - November (SA, Vic.)
	Negative IOD associated with more rain	
Southern Annular Mode	Negative phase associated with more rain	winter
		winter
	Positive phase associated with less rain Positive phase associated with more rain	spring in NSW; spring/summer (SA, Vic.)
Sub-tropical ridge	frontal activity	winter
	fine and dry	summer
Frontal systems	heavy rainfall and strong, winds	March - October (NSW) All year (SA, Vic.) but more frequent in winter (SA)
Cut-off lows	rainfall with strong, gusty winds	March - October (NSW) All year (SA, Vic.)
Cloud bands	rainfall	March - October (NSW) April - September (SA, Vic.)
Blocking highs	Variable conditions (temperature/rainfall) depending on the strength and position of the high pressure system. Hot and dry conditions in SA and Vic. if the high is in the Tasman Sea. Fog and/or frost if the high is centred near or over the region.	

Future climates

A further way of assessing the weather and climate risk profile of almonds grown in Australia is to examine the general and agroclimate risk indices in future climates. This provides indications of how the risks may change in the future, either beneficially or detrimentally. This can assist with medium and long term planning of orchard operations.

The possible impact of climate change on the risks was examined by recalculating the general and agroclimate indices using modified climates obtained from Generalised Circulation Models (GCM's) which project the likely future climates. However the effect of human induced climate change is uncertain, and that this uncertainty extends to how the risk indices change. The uncertainty exists for several reasons including:

- the future rate that greenhouse gases enter the atmosphere. These are examined by exploring the different Representative Concentration Pathways (RCP's), with RCP2.6 scenario representing the least increase in greenhouse gases although RCP4.5 scenario is typically the most benign RCP examined of intermediate emissions, and RCP8.5 scenario representing a high emissions of greenhouse gases. RCP6.5 scenario may also be examined.
- the part of the weather system examined (e.g. temperature, precipitation…). There is uncertainty surrounding the understanding of climate science, climate systems and it's representation in climate models. There is more confidence in temperature than rainfall, and there is most confidence in mean changes than changes in extremes.
- the location on earth and the natural year-to-year variation in weather and climate.
- GCM variability. That is, the models behave differently.

Table 5, sourced from Climate Change in Australia (http://www.climatechangeinaustralia.gov.au/) shows the level of similarity between projections by GCM's, and illustrates that a warmer future climate is likely, particularly under higher emissions of greenhouse gases, but that a range of possibilities exist. Additionally there is greater uncertainty on the impact to rainfall but overall a more water constrained future is likely for the current Almond growing regions.

We examined the impact of future climate change by examining future climates that were discrete step-wise increase in temperature or decreases in rainfall (denoted by some as a storyline approach) rather than projections by specific models. These steps were warming of both daily minimum and daily maximum temperatures by 0.5°C, 1°C, 1.5°C and 2°C; reduction in daily rainfall by 10% and 20%, increase in daily summer and autumn rainfall by 10% and 20%; increase in daily evapotranspiration by 4% per 1°C in temperatures. Potential evapotranspiration is expected to increase by about 4% per 1°C warmer climate (data sourced from figures within CSIRO and Bureau of Meteorology (2015) although there is uncertainty in the extent of change with increased warming (Scheff and Frierson, 2014; Snyder, 2017).

Figure 38, which was also 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 RCP 2.6 scenario, the blue bar represents RCP4.5 scenario, 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 10^{th} to 90^{th} percentile of 40 CMIP5 models, while the symbols represent projections from eight of the 40 models.

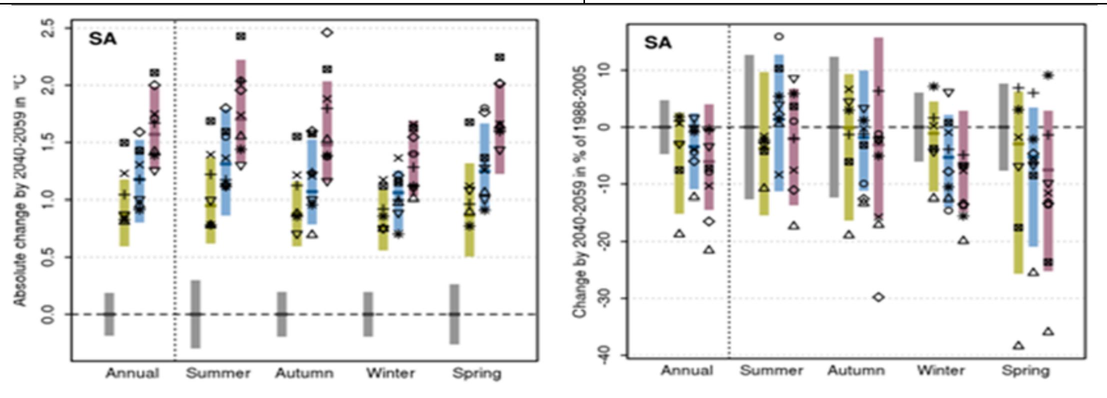
The message from these figures is that the projected change to temperature and rainfall are less dramatic for the 2050 base period (2040 – 2059) than the 2090 base period (2080-2099). Furthermore the projected change to climate are less dramatic when less greenhouse gases enter the atmosphere; that is RCP8.5 scenario shows larger increases in temperature and reductions in rainfall than RCP4.5 scenario or RCP2.6 scenario. Warming of 2°C is projected by 2050 in the RCP8.5 scenario, but by 1°C in the RCP4.5 and RCP2.6 scenario.

RCP4.5 scenario projects warming by 2°C by 2090, while the RCP2.6 scenario will maintain the 1°C warmer conditions. The RCP8.5 scenario is projected to increase temperature by 3°C or more by 2090. Warming is projected to be about 20% less in winter than other seasons, although warming of 1°C 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, while little change is expected in 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.

	Changes to temperature (absolute change °C)	Changes to rainfall (% difference)
A		
B		

A



B

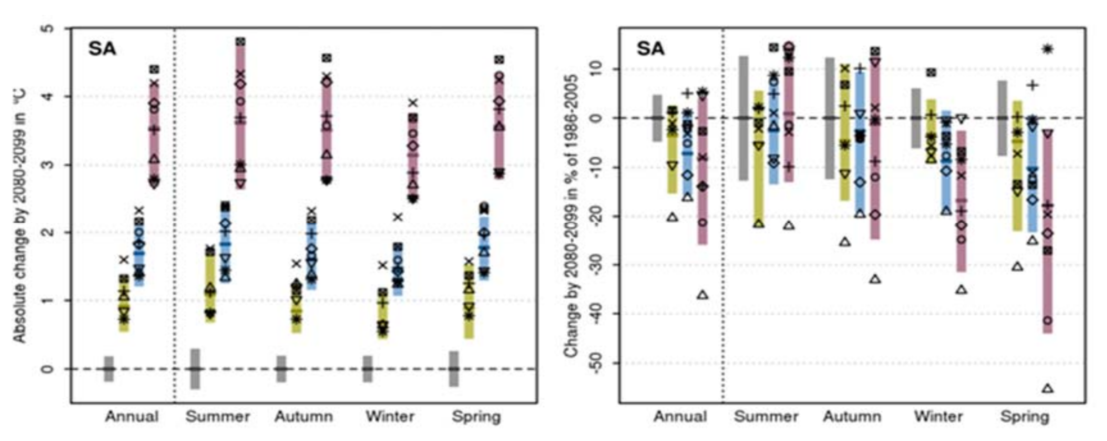


Figure 38. Projected changes in temperature (°C) (Left) and rainfall (% change) (Right) for A. 2050 and B.2090 for Southern Australia. Data for annual, Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). Bars represent the 10th to 90th percentile of 20-year running mean of 40 CMIP5 models: Historic (grey), RCP2.6 (green), RCP4.5 (blue), and RCP8.5 (purple). Superimposed on the bars are eight selected models: ACCESS1.0 (circle), GFDL-ESM2M (triangle up), CNRM-CM5 (plus), CESM1-CAM5 (cross), HADGEM2-CC (diamond), MIROC5 (triangle down), CANESM2 (square), and NORESM1-M (star). Figures sourced from CSIRO and Bureau of Meteorology (2015)

Table 5. Number of models with projections in each category of changes in temperature and changes in rainfall in the annual period and each season in 2050 and 2070 under the RCP4.5 and RCP8.5 scenarios. Projected area is the Murray Basin.
The shading denotes the proportion of models with orange indicating moderate agreement with between 33 and 66% of models in the category, yellow indicating low agreement with between 10 and 33% of models in the category, fawn indicating very low agreement with less than 10% of models in the category.

	Annual			Summer			Autumn			Winter			Spring		
	Warmer 0 to 1.5°C	Hotter 1.5 to 3.0°C	Much hotter >3.0°C	Warmer 0 to 1.5°C	Hotter 1.5 to 3.0°C	Much hotter >3.0°C	Warmer 0 to 1.5°C	Hotter 1.5 to 3.0°C	Much hotter >3.0°C	Warmer 0 to 1.5°C	Hotter 1.5 to 3.0°C	Much hotter >3.0°C	Warmer 0 to 1.5°C	Hotter 1.5 to 3.0°C	Much hotter >3.0°C
2050 RCP4.5 (Intermediate emissions															
Much wetter (>15%)				2	5		3							1	
Wetter (5 to 15%)	6	1		10	6		7	2		7			8	1	
Little change (-5 to 5%)	22	4		8	5		13	5		16			6	6	
Drier (-15 to 5%)	6	6		3	2		9	1		17	1		9	7	
Much drier (<15%)		1			5		1	5		3	2		3	5	
2050 RCP8.5 (high emissions)															
Much wetter (>15%)				2	6		7	3					1		
Wetter (5 to 15%)	2	9		2	6		2	7		5	6		1	5	
Little change (-5 to 5%)	8	13		4	13		5	5		10	5		4	8	
Drier (-15 to 5%)		12		1	7	1	2	12		10	5		4	12	
Much drier (<15%)		4			6			5		3	4			13	

2070 RCP4.5 (Intermediate emissions															
Much wetter (>15%)				2	4		7	3					1	1	
Wetter (5 to 15%)	7	3		3	7		6	3			4		2	1	
Little change (-5 to 5%)	7	12		5	11		3	6			14	1	8	13	
Drier (-15 to 5%)	2	11			5		2	8			13		1	6	
Much drier (<15%)		4			7		2	6			14	2		13	
2070 RCP8.5 (high emissions)															
Much wetter (>15%)				1	4	8	1	5	2					2	
Wetter (5 to 15%)		9	1		8	3		9	3		4			7	1
Little change (-5 to 5%)		12	7		8	6		7	3		14	1		6	4
Drier (-15 to 5%)		7	4		4	1		8	2		13			5	3
Much drier (<15%)		4	4			5		5	3		14	2		4	16
2090 RCP4.5 (Intermediate emissions															
Much wetter (>15%)		1		1	5		2	3							
Wetter (5 to 15%)		1		1	8	1	5	8		2	4		1	4	
Little change (-5 to 5%)	7	17		5	12		4	7		8	11		6	6	
Drier (-15 to 5%)	4	9		1	7		1	7		10	6		1	14	
Much drier (<15%)		7		1	4	1	1	8		2	7			14	
2090 RCP8.5 (high emissions)															
Much wetter (>15%)		1	1		2	12		5	8					2	
Wetter (5 to 15%)		4	4		1	12		1	8		3			2	3
Little change (-5 to 5%)		2	11		2	7		2	7		7	5		1	7
Drier (-15 to 5%)		3	9		1	8		1	5		4	8		2	9
Much drier (<15%)			13			3			11		6	15			22

Results

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.

The Bureau of Meteorology provides up-to-date information on Niña 3.4, Southern oscillation index (SOI), strength of trade winds and cloudiness which are related to formation of El Niño events and La Niña events, and IOD which is related to formation of negative IOD events and positive IOD events (http://www.bom.gov.au/climate/enso/). http://www.bom.gov.au/climate/model-summary/ provides an overview of several climate models that can be used to assess NINO3.4 and IOD climate drivers.

While El Niño Southern Oscillation (ENSO) which determine El Niño and La Niña years, and IOD which determine positive IOD 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.

A brief summary of the influence of ENSO and IOD on the climate in the almond growing regions is that an El Niño 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 or 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. There can be however an increased chance that El Niño years or positive IOD years result in warmer mean and daily maximum temperature and cooler daily minimum (night) temperatures and drier conditions, and an increased chance that La Niña years or negative IOD years result in cooler mean temperature daily maximum temperature and warmer daily minimum (night) temperatures and wetter conditions. Table 6 shows the correlations of of the climate indices with ENSO and the DMI indices measured by both the ERSSTv5 and HadISST 1.1 models, and SOI.

ENSO and IOD influence both rainfall and temperature (figures 39, 43), with El Niño years or positive IOD years having less rainfall and warmer mean and daily maximum temperature but cooler daily minimum (night) temperature than La Niña years or negative IOD years. The impact on rainfall is throughout the year while the impact on temperature is typically stronger in spring and early summer. The duration of months that IOD influences daily maximum and minimum temperatures can be as long or longer than when ENSO influences daily maximum and minimum temperatures, with the impact of ENSO on daily minimum (night) temperatures being mainly restricted to winter. The differences in rainfall affect risks associated with insufficient rainfall in the orchard and of the supply of irrigation water (figure 40), and combined with evapotranspiration affect irrigation demand (figure 41), rain affecting harvest (figure 42), and excessively rainy and humid conditions leading to increased risk of diseases (figure 42). For example rainfall in the Murray-Darling Basin catchment is lower in El Niño years or positive IOD years and this may influence inflow and irrigation water availability in this and following years. Because rainfall is lower and Evapotranspiration is higher in El Niño years or positive IOD years there is likely to be an increased demand for irrigation in these years. This may affect management decisions concerning purchase or irrigation water. However the lower rainfall and higher evapotranspiration reduces the chance of MB+ve days particularly in the spring and early summer but less so during the following years harvest season which may reduce the risk of excessively rainy and humid conditions leading to increased risk of diseases during the event year, but is likely to have minimal influence on the risk of rainy conditions during harvest.

The differences in mean temperature affect risks associated with warmer spring and summer temperatures advancing growth (figure 43), heatwaves (figure 44) and undesirable photosynthetic hours (figure 44), frosts (figure 45), chill accumulation (figure 46) and synchronicity of flowering, and when combined with rainfall affect desirable pollination hours (figure 47). For example warmer than usual mean temperatures occur during September to December in El Niño years or positive IOD years and this can affect heat accumulation and development rate, but also the chance of heatwaves and the loss of desirable photosynthetic hours thus limiting the extent of carbohydrate accumulation. Greater irrigation may be required to alleviate heat stress in these conditions. Chill accumulation before August is largely unaffected by the climate drivers, but frosts may be more frequent and occur later, suggesting strategic decisions relating to frost mitigation may be warranted.

Illustrated guide of 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).

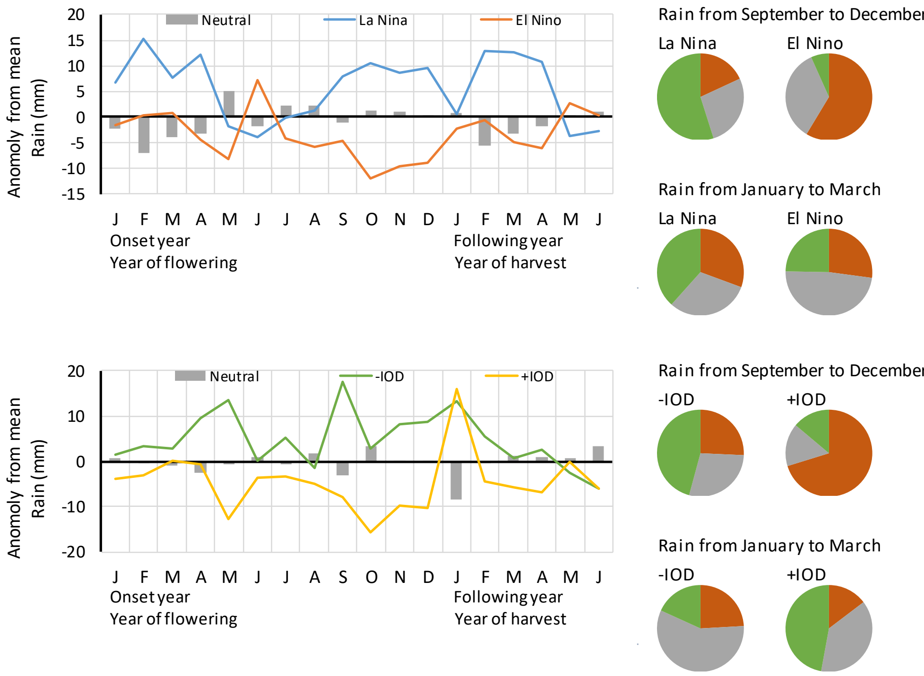
In both instances the average of all years is the zero axis. The monthly averages are shown from January of the year of onset, which is also the year of flowering, until June of the following year, which is the year of harvest.

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.

Risks related to rain and humidity

Rainfall throughout the year was influenced by ENSO and IOD as seen by the graphs showing the difference (anomaly) of mean monthly rainfall in event years compared to all years (figure 39). The pie charts show there was typically an increased chance of 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). In figure 39, showing rainfall at Mildura, rainfall during September to December was in the tercile 3 in about 6 years in 10 compared to the long term average of 3 in 10 during La Niña yeasr 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 the following January to March, that is in the year of harvest was largely unaffected by ENSO and negative IOD years but would be expected to be higher in yeasr following positive IOD years during the year of flowering. Table 6 shows that the ENSO and the DMI indices measured by both the ERSSTv5 and HadISST 1.1 models, and SOI were significant with rainfall during September to December but not rainfall during January to March.



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

Figure 39. The anomoly of monthly rainfall at Mildura, NSW in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017, and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017.

The pie charts show the chance that the rain between September to December and between January and March of the following year 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- shown in brown), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in green).

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. Figure 40 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 DMI event years. There is 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 compared to the long term average of 3 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. The ENSO and the DMI indices measured by both the ERSSTv5 and HadISST 1.1 models, and SOI were significant with annual rainfall. 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 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 more complex than previously recognised.

Table 6 shows that the ENSO and the DMI indices measured by both the ERSSTv5 and HadISST 1.1 models, and SOI were significant with rainfall during September to December but not rainfall during January to March.

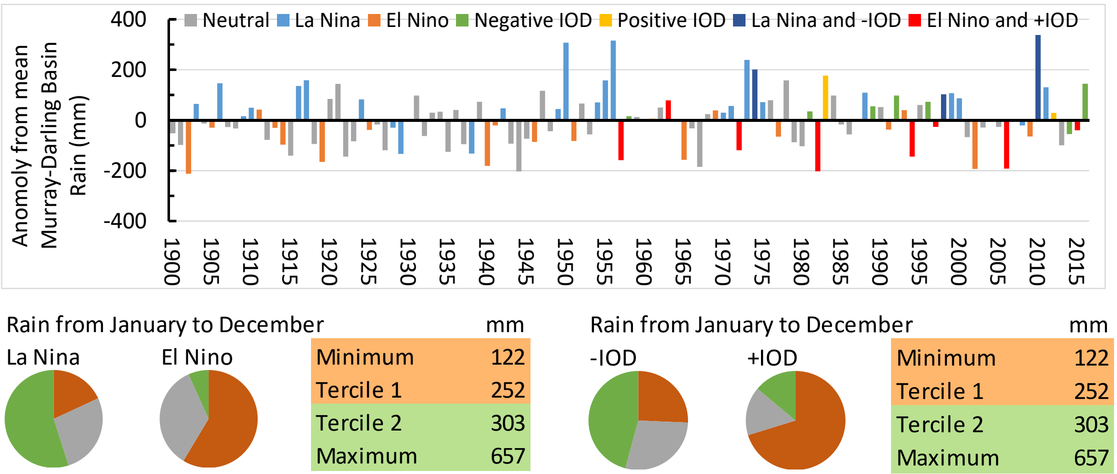


Figure 40. The anomaly from average rainfall in the Murray-Darling Basin (data from Bureau of Meteorology http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries sourced 19 March 2019) categorized by ENSO and DMI event years. ENSO categories of La Niña years and El Niño years are shown from 1900, while positive IOD years and negative IOD are shown from 1960. Years may be categorized as La Niña and negative IOD or as El Niño and negative IOD.

The pie charts show the chance that the annual January to December rain in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in brown), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in green).

The evapotranspiration response to ENSO and DMI categories showed that differences occur 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 was assessed as the difference or irrigation deficit (ETo – Rain). This can be seen in figure 41. There was an increased chance that greater irrigation deficit (tercile 3 , brown) occurs in El Niño years or positive IOD years, and that this is most likely to occur in the period between September and December rather than from January to March of the following year. In the example shown in figure 41 for Mildura, there was an increased chance that irrigation deficit during September to December was in the highest tercile to about 6 or 7 in 10 years. The reverse occurs in La Niña years or negative IOD yeasr when irrigation deficit was more likely to be in the lowest third of years (tercile 1, green). 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. Table 6 shows that the ENSO and the DMI indices measured by both the ERSSTv5 and HadISST 1.1 models, and SOI were significant with irrigation deficit, particularly during September to December. Only SOI was significnatly correlated with irrigation deficit during January to march of the following year.

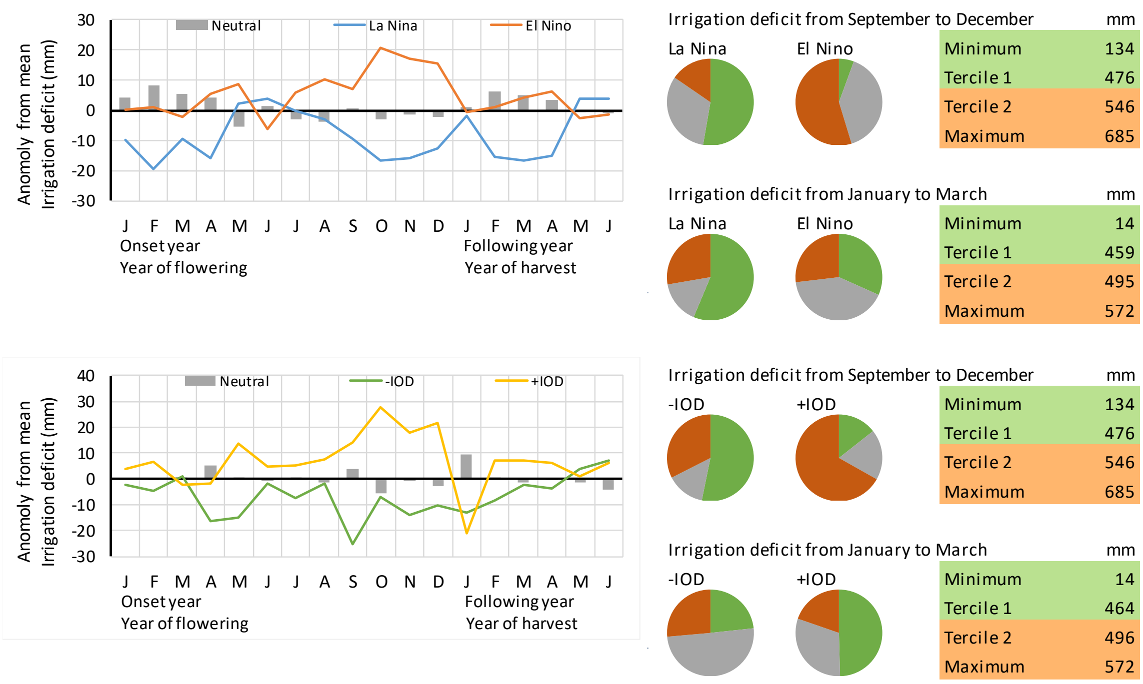


Figure 41. The anomoly of monthly irrigation deficit at Mildura, NSW in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017, and negative IOD yeasr and positive IOD years and neutral IOD years compared to all years from 1960 to 2017.

The pie charts show the chance that the irrigation deficit during the growing season (September of the event year to April of the following year), between September to December and between the following January and March in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in green), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in brown).

The number of days considered moisture balance positive (MB+ve) was affected more by DMI than by ENSO (figure 42). As with many indices the impact of ENSO or IOD was stronger during the event year than the following year. This meant that ENSO or IOD was likely to have a greater influence on the risk of excessively rainy and humid conditions leading to increased risk of diseases during the event year, but was likely to have minimal influence on the risk of rainy conditions during harvest. In the example shown in figure 42, for Mildura, an El Niño years or positive IOD year increases 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 or 5 in 10, while also correspondingly 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 have essentially the reverse effect. However during the following January to March La Niña increases while negative IOD decreases the likelihood that the number of MB+ve days was in the highest third of all years (tercile 3); while neither El Niño nor positive IOD effects MB+ve days during this period. Table 6 shows that the ENSO and the DMI indices measured by both the ERSSTv5 and HadISST 1.1 models, and SOI were significant with the number of MB+ve days during September to December but not during January to March.

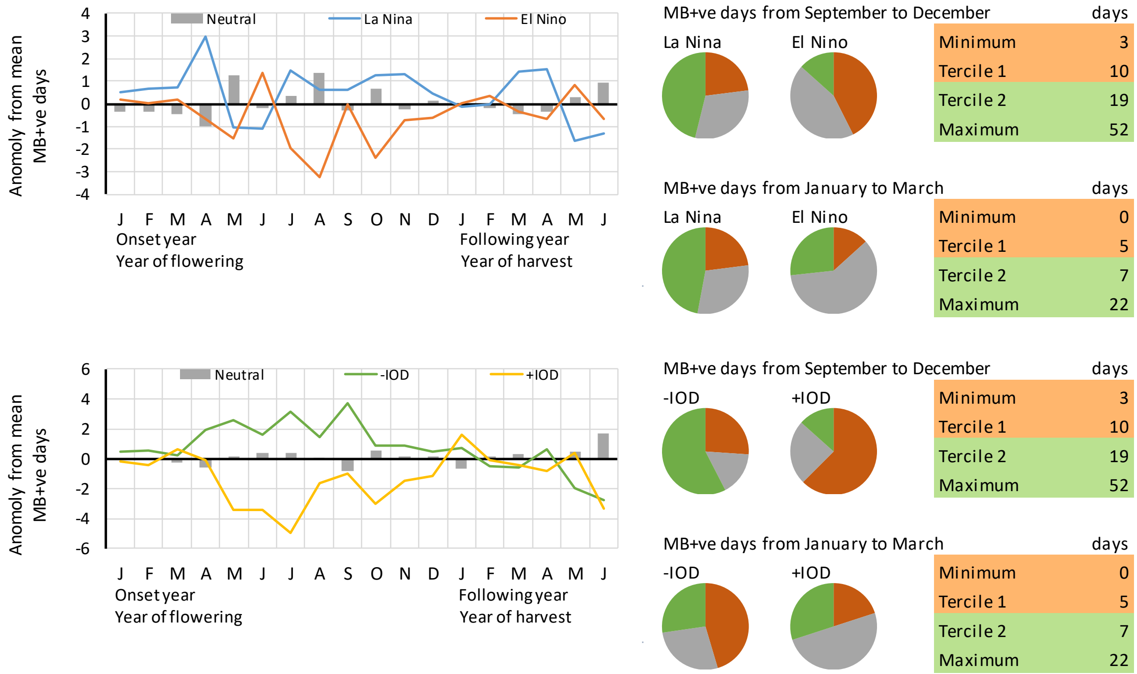


Figure 42. The anomoly in the number of days considered moisture balance positive (MB+ve) at Mildura, NSW in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017, and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017.

The pie charts show the chance that the number of days considered moisture balance positive (MB+ve) beween September and December and between January and March of the following year in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in brown), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in green).

Risks related to temperature

Mean Temperature was influenced by ENSO and DMI (which measures IOD) mainly in the spring to early summer period with mean temperature during January to March following the event year, that is in the year of harvest, being largely unaffected by ENSO and DMI (figure 43). The pie charts show there was typically an increased chance that mean temperature during El Niño years or positive IOD years was 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). In figure 43, showing mean temperature at Mildura, mean temperature during September to December was in the tercile 3 in about 6 or 7 years in 10 compared to the long term average of 3 in 10 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 yeasr had minimal impact on mean temperature. Mean temperature during the following January to March, that is in the year of harvest was largely unaffected by ENSO and DMI. Table 6 shows that in this instance the ENSO indice measured by HadISST 1.1, and the DMI indices measured by both the ERSSTv5 and HadISST 1.1 models were significant with mean temperature during September to December but not during January to March.

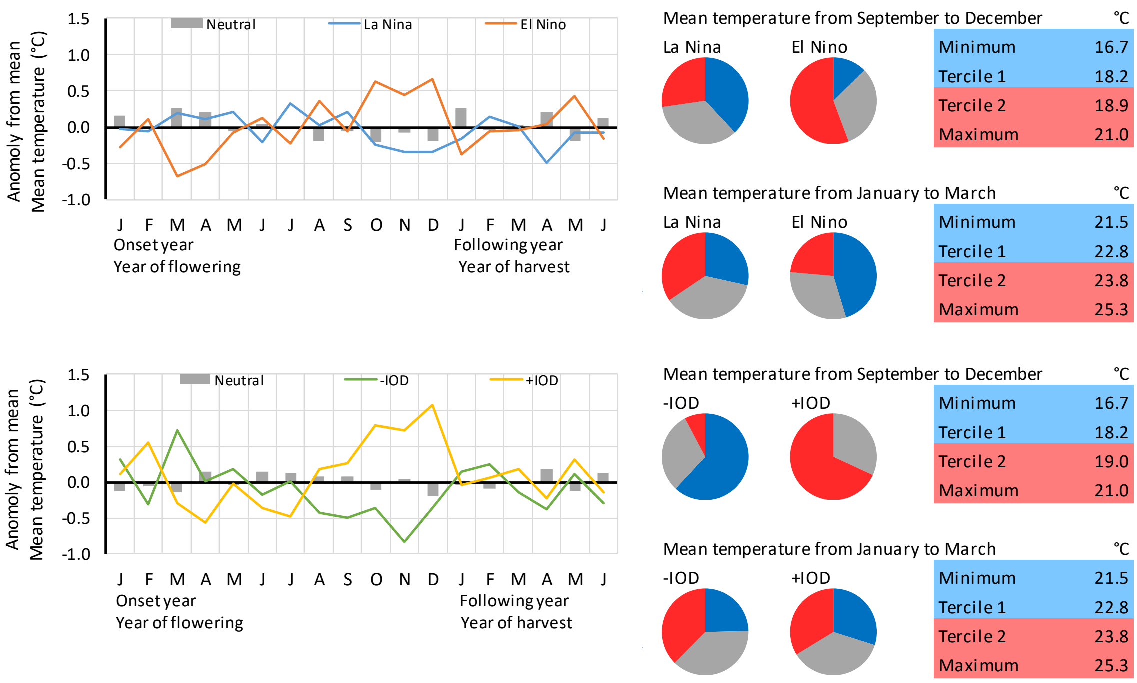


Figure 43. The anomoly of monthly mean temperature at Mildura, NSW in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017, and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017.

The pie charts show the chance that the mean temperature between September to December and between the following January and March in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in blue), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in red).

These differences in mean temperature affect the risk of generally warmer conditions advancing growth. This can be seen in figure 44, showing the dates that thresholds of heat accumulation are reached. 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 almonds). These heat accumulations are GDD base 4.5°C. The thresholds for Nonpareil almond 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 were reached sooner, while La Niña yeasr or negative IOD years retard the rate of development and the heat accumulation thresholds were reached later.

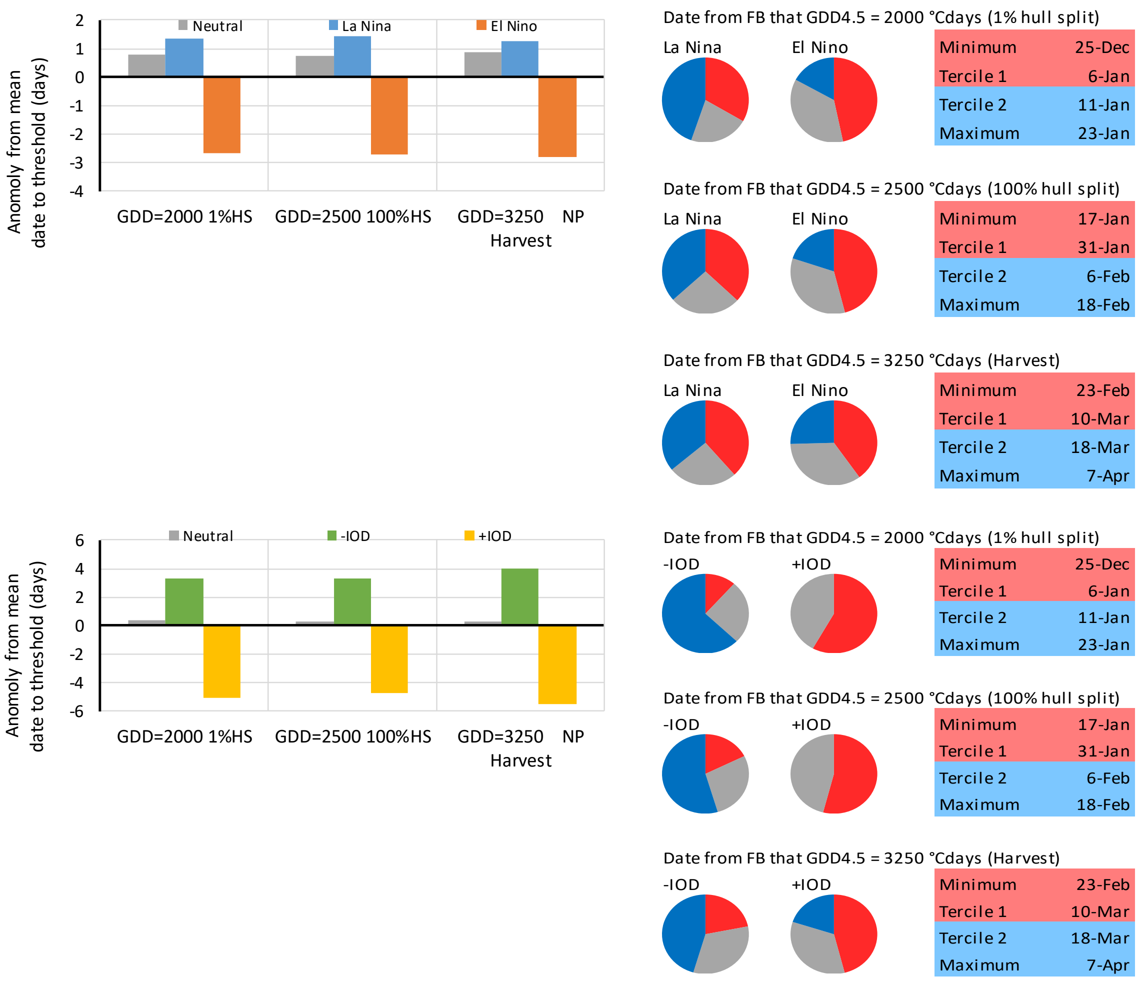


Figure 44. The anomoly at Mildura, NSW in the number of days when heat accumulation theresholds from 15th August to 2000 °Cdays (taken to represent date of 1% hull split of Nonpareil almond), 2500 °Cdays (taken to represent date of 100% hull split of Nonpareil almond), and 3250 °Cdays (taken to represent date of harvest of Nonpareil almond) in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017, and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017. These heat accumulations are GDD base 4.5°C.

The pie charts show the chance that the date that 2000, 2500 and 3250 °Cdays are reached is in in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in red), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in blue).

The influence of ENSO and DMI on maximum and minimum temperature were similar to the effect on mean temeprature (data not shown), however there were differences in the occurrence of extreme hot and extreme cold days. The number of days warmer than 35°C are shown in figure 45. An El Niño years or positive IOD year has more days warmer than 35°C during late spring to early summer and La Niña years or negative IOD years. The chance that an El Niño year or positive IOD year had as few days warmer than 35°C as the lower third of all years (tercile 1) during September to December was essentially nil at Mildura and half the years will has as many days warmer than 35°C as occurs 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. Table 6 shows that the correlation of the climate drivers and SOI on the indices was significant. The influence of event years and climate drivers does 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 is also shown (figure 45). This indice was chosen to represent hours that were not conducive to photosynthesis.

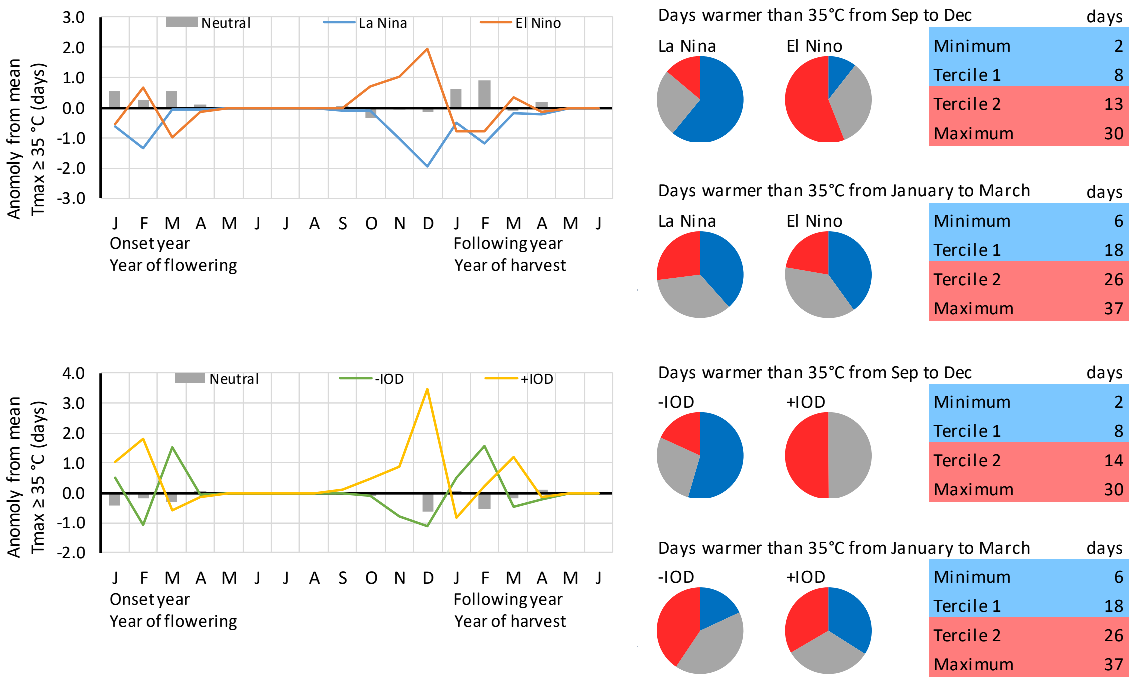


Figure 45. The anomoly at Mildura, NSW in the number of days warmer than 35°C in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017, and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017.

The pie charts show the chance that the number of days warmer than 35°C during September to December and during the following January to March; and the number of daylight hours warmer than 35°C during these same periods in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in blue), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in red).

Cold temperatures and frosts (nights colder than 2 °C) were also related to ENSO and DMI (figure 46). At Mildura, La Niña years had many fewer frosts and positive IOD yeasr many more frosts than the average year, while the corresponding changes in El Niño years and negative IOD years were not as dramatic (figure 46). The date of the last frost was more likely to be later in La Niña years or negative IOD years and earlier in El Niño years or positive IOD years. Table 6 shows that the climate drivers of Niño 3.4 and DMI were not significantly related to frost events or date of last frost.

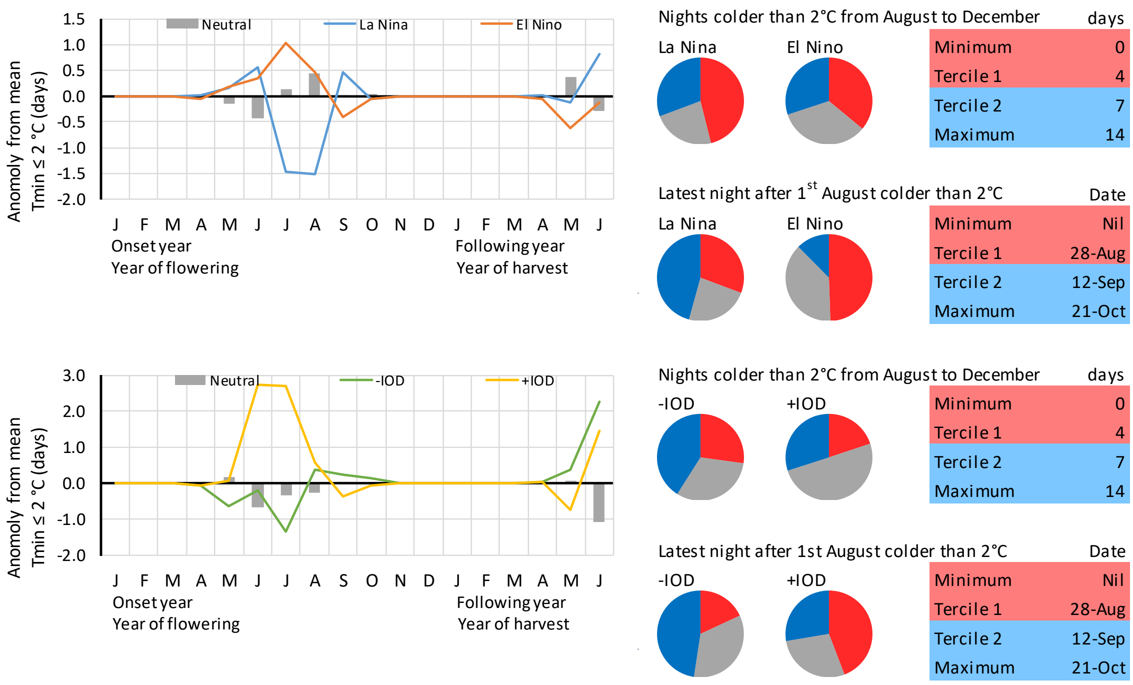


Figure 46. The anomoly at Mildura, NSW in the number of nights after 1st August colder than 2°C in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017, and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017.

The pie charts show the chance that the number of nights after 1st August colder than 2°C, and of the last date after 1st August colder than 2°C in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in blue), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in red).

ENSO and DMI had minimal influence on the accumulation of chill hours after August, and almost none before August (Figure 47). Therefore 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). Figure 47 shows chill accumulation at Mildura. Table 2 shows that DMI had a greater influence on chill accumulation than ENSO but absolute and relative differences were small, and the drivers had no or minimal correlation with chill accumulation.

Figure 47. The anomoly at Mildura, NSW in chill accumulation measured by the Dynamic model until 31st July in La Niña years and El Niño years and ENSO neutral years compared to all years from 1957 to 2017 and negative IOD years and positive IOD years and neutral IOD years compared to all years from 1960 to 2017.

The pie charts show the chance that chill accumulation by the dynamic model and by the Utah model in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in red), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in blue).

Pollination is a major concern to almond growers. Pollination conditions are thought to be unfavourable if temperatures are below about 15°C and if rain occurs. The risk of undesirable pollination condition was calculated as daylight hours warmer than 15°C and no rainfall. This indice was calculated to August (figure 48). Table 6 shows that the indice was not well correlated with climate drivers but was correlated with SOI. However there was an indication that El Nino 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.

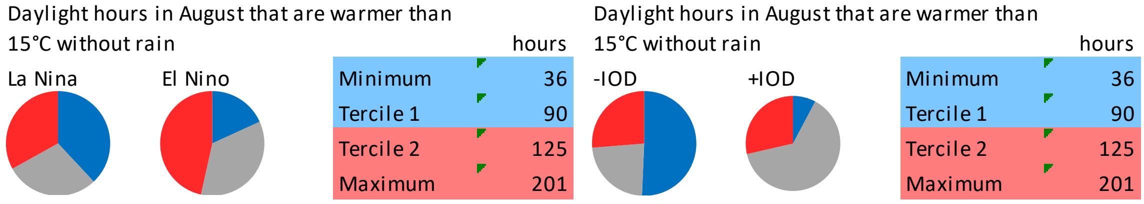


Figure. 48 The pie charts show the chance that the number of daylight hours warmer than 15°C in August which also have no rainfall in La Niña years and El Niño years or negative IOD years and positive IOD years were in the lowest third of all years (tercile 1- shown in blue), in the middle third of all years (tercile 2 - shown in grey), or highest third of all years (tercile 3 – shown in red).

Table 6. The correlation coefficients (r) of the agroclimatic indices 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. Table 26 Edinburgh.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.23	-0.26	0.51	-0.46	-0.49
Rain from September to December	-0.32	-0.31	0.26	-0.31	-0.31
Rain from January to March	0.02	-0.06	0.01	0.09	0.07
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	0.20	0.17	-0.16	0.32	0.32
Irrigation deficit from September to December	0.35	0.31	-0.25	0.53	0.46
Irrigation deficit from January to March	-0.11	-0.12	0.03	-0.07	0.14
Rainy and humid conditions					
MB+ve days from September to December	-0.33	-0.29	0.19	-0.56	-0.44
MB+ve days from January to March	0.03	0.03	0.12	0.23	0.00
Heat accumulation					
Mean temperature from September to December	0.23	0.15	-0.11	0.55	0.38
Mean temperature from January to March	-0.31	-0.37	0.27	0.30	0.26
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.23	-0.14	0.22	-0.54	-0.41
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.15	-0.07	0.12	-0.43	-0.34
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.04	0.04	-0.07	-0.39	-0.22
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.03	0.07	-0.03	-0.14	-0.10
Utah chill units accumulated to 31st July	0.02	0.06	0.00	-0.21	-0.15
Heatwaves					
Days warmer than 35°C from September to December	0.33	0.26	-0.22	0.41	0.32
Days warmer than 35°C from January to March	-0.28	-0.34	0.19	0.10	0.17
Daylight hours warmer than 35°C from September to December	0.35	0.29	-0.21	0.35	0.25
Daylight hours warmer than 35°C from January to March	-0.24	-0.31	0.16	0.08	0.17
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	0.05	-0.03	-0.38	0.12	0.11

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).

Table 6. The correlation coefficients (r) of the agroclimatic indices 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. Table 6B Murray Bridge.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.11	-0.19	0.29	-0.29	-0.36
Rain from September to December	-0.21	-0.21	0.21	-0.20	-0.22
Rain from January to March	-0.01	-0.08	0.05	0.00	0.03
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	0.18	0.12	-0.12	0.32	0.29
Irrigation deficit from September to December	0.30	0.26	-0.21	0.48	0.42
Irrigation deficit from January to March	-0.06	-0.11	0.00	0.04	0.13
Rainy and humid conditions					
MB+ve days from September to December	-0.21	-0.17	0.10	-0.46	-0.41
MB+ve days from January to March	0.08	0.10	0.00	0.12	-0.11
Heat accumulation					
Mean temperature from September to December	0.16	0.07	-0.06	0.45	0.26
Mean temperature from January to March	-0.24	-0.33	0.19	0.31	0.20
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.15	-0.04	0.14	-0.45	-0.28
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.11	0.00	0.09	-0.37	-0.23
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.01	0.09	-0.10	-0.31	-0.11
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.17	0.24	-0.08	-0.27	-0.18
Utah chill units accumulated to 31st July	0.09	0.18	-0.01	-0.31	-0.21
Heatwaves					
Days warmer than 35°C from September to December	0.32	0.24	-0.21	0.41	0.29
Days warmer than 35°C from January to March	-0.11	-0.22	0.05	0.17	0.10
Daylight hours warmer than 35°C from September to December	0.29	0.20	-0.15	0.31	0.18
Daylight hours warmer than 35°C from January to March	-0.12	-0.22	0.06	0.14	0.09
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	0.00	-0.38	0.14	0.11

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).

Table 6. The correlation coefficients (r) of the agroclimatic indices 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. Table 6C Loxton.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.13	-0.14	0.30	-0.48	-0.44
Rain from September to December	-0.32	-0.31	0.40	-0.24	-0.30
Rain from January to March	-0.16	-0.21	0.19	0.08	0.07
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	0.30	0.24	-0.30	0.17	0.19
Irrigation deficit from September to December	0.43	0.40	-0.39	0.47	0.42
Irrigation deficit from January to March	0.04	-0.03	-0.13	-0.20	-0.09
Rainy and humid conditions					
MB+ve days from September to December	-0.23	-0.22	0.23	-0.38	-0.35
MB+ve days from January to March	-0.04	-0.02	0.16	0.28	0.13
Heat accumulation					
Mean temperature from September to December	0.22	0.18	-0.10	0.41	0.32
Mean temperature from January to March	-0.16	-0.20	0.17	0.27	0.22
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.19	-0.13	0.13	-0.38	-0.33
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.13	-0.07	0.08	-0.31	-0.28
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.06	-0.02	-0.05	-0.23	-0.16
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.05	0.05	-0.14	-0.17	-0.17
Utah chill units accumulated to 31st July	0.02	0.09	-0.04	-0.30	-0.23
Heatwaves					
Days warmer than 35°C from September to December	0.40	0.34	-0.29	0.38	0.26
Days warmer than 35°C from January to March	-0.01	-0.12	-0.07	0.06	-0.02
Daylight hours warmer than 35°C from September to December	0.41	0.35	-0.28	0.29	0.21
Daylight hours warmer than 35°C from January to March	-0.01	-0.11	-0.05	0.05	0.00
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	0.13	0.02	-0.38	0.20	0.11

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).

Table 6. The correlation coefficients (r) of the agroclimatic indices 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. Table 6D Renmark.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.11	-0.10	0.26	-0.43	-0.38
Rain from September to December	-0.34	-0.32	0.37	-0.25	-0.30
Rain from January to March	-0.18	-0.22	0.25	0.08	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	0.36	0.31	-0.36	0.18	0.19
Irrigation deficit from September to December	0.46	0.43	-0.40	0.48	0.43
Irrigation deficit from January to March	0.08	0.01	-0.18	-0.20	-0.11
Rainy and humid conditions					
MB+ve days from September to December	-0.30	-0.30	0.28	-0.40	-0.38
MB+ve days from January to March	-0.14	-0.11	0.23	0.23	0.16
Heat accumulation					
Mean temperature from September to December	0.27	0.22	-0.16	0.48	0.35
Mean temperature from January to March	-0.18	-0.25	0.15	0.27	0.22
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.26	-0.20	0.23	-0.46	-0.38
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.21	-0.14	0.17	-0.39	-0.34
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.12	-0.06	0.01	-0.29	-0.19
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.02	0.07	-0.10	-0.13	-0.03
Utah chill units accumulated to 31st July	0.01	0.13	-0.05	-0.25	-0.09
Heatwaves					
Days warmer than 35°C from September to December	0.41	0.32	-0.29	0.44	0.26
Days warmer than 35°C from January to March	-0.03	-0.16	-0.04	0.06	0.00
Daylight hours warmer than 35°C from September to December	0.43	0.34	-0.29	0.39	0.24
Daylight hours warmer than 35°C from January to March	-0.01	-0.14	-0.06	0.04	-0.02
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	0.17	0.06	-0.38	0.16	0.10

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).

Table 6. The correlation coefficients (r) of the agroclimatic indices 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. Table 6E Mildura.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	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 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).

Table 6. The correlation coefficients (r) of the agroclimatic indices 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. Table 6F Griffith.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.16	-0.27	0.37	-0.38	-0.40
Rain from September to December	-0.42	-0.42	0.45	-0.28	-0.34
Rain from January to March	-0.26	-0.25	0.20	0.08	0.06
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	0.49	0.43	-0.48	0.24	0.23
Irrigation deficit from September to December	0.53	0.50	-0.45	0.49	0.45
Irrigation deficit from January to March	0.20	0.14	-0.20	-0.11	-0.16
Rainy and humid conditions					
MB+ve days from September to December	-0.45	-0.43	0.36	-0.50	-0.47
MB+ve days from January to March	-0.16	-0.13	0.20	0.16	0.15
Heat accumulation					
Mean temperature from September to December	0.33	0.24	-0.21	0.58	0.37
Mean temperature from January to March	-0.01	-0.14	0.01	0.18	-0.03
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.33	-0.22	0.30	-0.59	-0.42
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.32	-0.21	0.28	-0.55	-0.37
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.26	-0.15	0.13	-0.41	-0.18
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.06	0.12	0.00	-0.29	-0.19
Utah chill units accumulated to 31st July	-0.03	0.05	0.11	-0.40	-0.21
Heatwaves					
Days warmer than 35°C from September to December	0.39	0.31	-0.31	0.39	0.19
Days warmer than 35°C from January to March	0.19	0.05	-0.22	-0.13	-0.30
Daylight hours warmer than 35°C from September to December	0.44	0.36	-0.34	0.40	0.20
Daylight hours warmer than 35°C from January to March	0.18	0.04	-0.20	-0.09	-0.27
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	0.15	0.08	-0.41	0.17	0.13

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).

Impact of projected future climate

A future climate is likely to be warmer and possibly drier although there is greater uncertainty in the rainfall projections and changes in the seasonality of rainfall may affect the risks of almond production. A warming climate will increase mean temperature during the growing season and increase heat units and a decrease in chill units. There will be a change in the average hours per day that are considered photosynthetically desirable. There will be an increase in heatwaves and a decrease in frosts. There are also likely to be an increase in desirable pollination conditions. There are no clearly defined trends in rainfall but an increase in evapotranspiration is expected, and this will affect irrigation requirements and also the risk of rain at harvest.

An example of how the indices are projected to change from the 20 year period from 1986 to 2005 (used as it is the base period from which climate projections are based) in two future climates are shown in the figures below. Detailed information for one representative location in each of the four almond growing regions are provided in the appendix and in booklets detailing climate strengths and challenges of each region.

The following bar charts portray indices used to assess the climate risks to almonds in future climates of either 1°C warmer (e.g. 2050 under RCP4.5 or RCP2.6 scenarios), 2°C warmer (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios), 20% drier, 10% wetter or 20% wetter. The evapotranspiration was increased by 4% per 1 °C warming. 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.

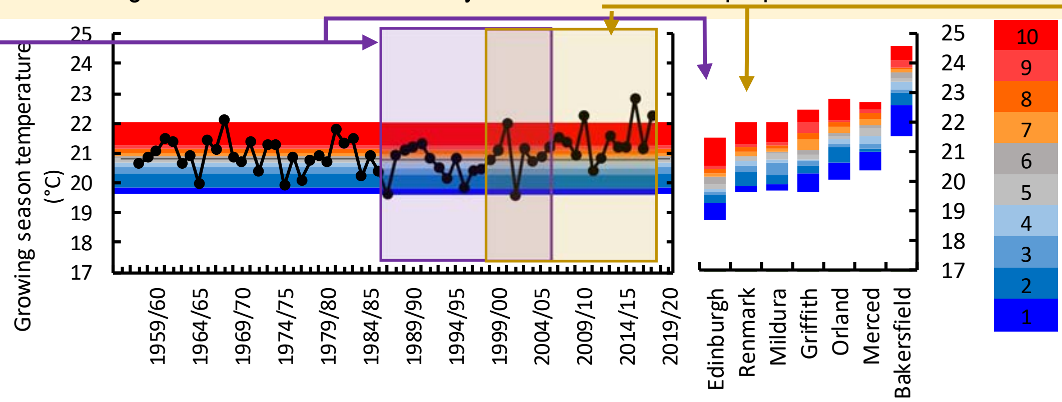
The table next to each graph shows the minimum, median (half the values are lower than this, and half higher) and maximum values in each of the 20 year periods.

Illustrated guide of 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.

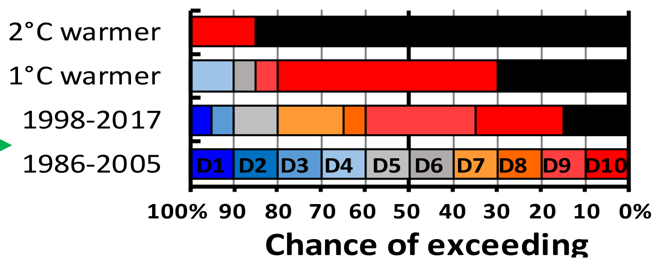
Next the historic values in the 20 year period from 1998 to 2017 are examined. These values are grouped according to the deciles calculated earlier. Unlike the period from 1986 to 2005, there may be more or less than two values in each of those deciles. There may also be values that are higher or lower 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 3 values during 1998 to 2017 above the maximum during 1986 to 2005 would be counted as 3 out of 20 values, or 15% 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.

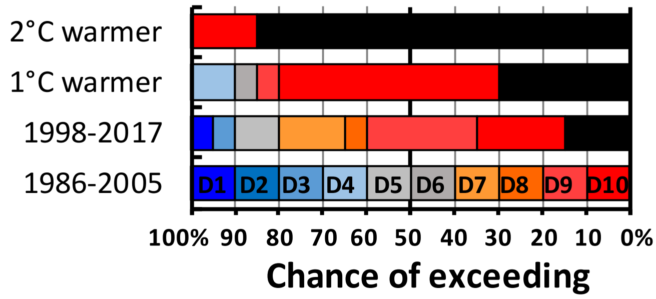


	Minimum	Median	Maximum
2°C warmer	21.6	22.8	24.0
1°C warmer	20.6	21.8	23.0
1998-2017	19.6	21.2	22.8
1986-2005	19.6	20.8	22.0

Risks related to temperature

In general across all the almond growing locations examined the growing season mean temperature and heat units have increased in the 20 years from 1998 to 2017 with about three quarters of all years being warmer than the median, and several years receiving more than the historic maximum during 1986 to 2005 (figure 49). Further warming will increase the amount of heat units received and not surprisingly the projections indicate there will be very few years with 'below median' heat units in a warmer world. In general 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 more years in 10 years, while a 2 °C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) would mean almost every year was as warm or warmer than what was a 1 in 10 hot year with over half the years being warmer than any experienced during the historic period from 1986 to 2005. This new climate would be similar or hotter than the historic climate at Bakersfield, California which is among that states hottest growing regions.

Growing season temperature



	Minimum	Median	Maximum
2°C warmer	21.6	22.8	24.0
1°C warmer	20.6	21.8	23.0
1998-2017	19.6	21.2	22.8
1986-2005	19.6	20.8	22.0

Figure 49. The current and altered chance of growing season temperature at Renmark, SA being as warm or warmer as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of being warmer than any year on record during this 20 year period.

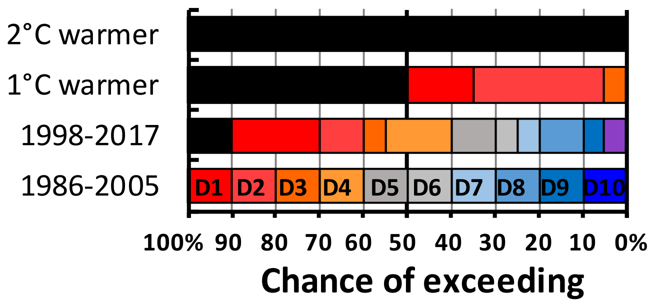
An example from this graph is that a 1 °C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) there is a 90% chance of a year being decile 6 or warmer, and a 30% chance of a year being warmer than any during the 1986 to 2005 year period.

In a 2 °C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) every year would be as warm as what was formerly a 1 in 10 hot year, with at least 8 in 10 of these years being warmer than any experienced during the 20 year base period from 1986 to 2005.

There is an assumption that warmer climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

Chill accumulation for most of the almond growing locations examined was similar or slightly lower during the 20 years from 1998 to 2017 to those received during the 20 year period from 1986 to 2005. However chill accumulation declines in response to 1 °C warming (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) and all locations have less chill than the former median amount of chill (figure 50). In other words, the 50% of years that had high chilling are projected not to occur in a 1°C warmer climate. A 2 °C warmer world (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) would mean that for almost all locations the chill accumulation in every year is likely to be lower than that experienced during the base period or the last 20 years, while in a few locations there may be some years where the chill accumulation is as low as that which would be received in a formerly very warm and low chill accumulation year. Of concern is that the reportedly minimum chill to satisfy Nonpareil's dormancy requirements of 23 chill portions is projected to occur in only some locations with a 2 °C warmer climate. However chill accumulation can continue in August meaning that accumulation of sufficient chill may continue to be achieved but it is unknown how flowering may be affected although it is likely to be at a later time of year.

Chill (Dynamic model chill portions) accumulated by 31st July



	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

Figure 50. The current and altered chance of chill accumulation until 31st July at Mildura, Vic. being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of chill accumulation being lower than any year on record during this 20 year period, and the purple represents chill accumulation being higher than any on record during this 20 year period.

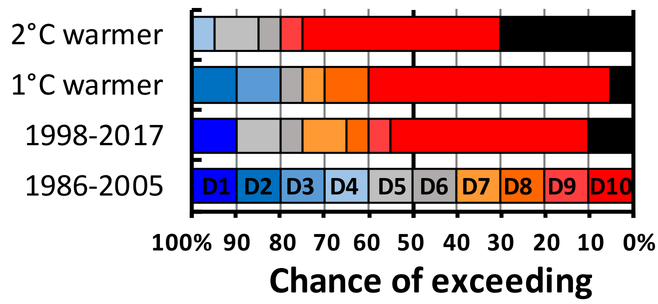
An example from this graph is that a 1 °C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) there is a 65% chance of chill accumulation being as high or higher as a decile 2 year and a 50% chance of it being lower than any on record during the 1986 to 2005 period, which from the table to the right was 43 chill portions.

In a 2 °C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) every year would have less chill accumulation as the minimum during the period from 1986 to 2005.

There is an assumption that warmer climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

The warmer climate is projected to alter the number of days with extreme temperature leading to an increase in heatwaves and a decrease in frosts (figure 51, 52). The number of days warmer than 35 °C in the 20 years from 1998 to 2017 for most locations was 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 (figure 51). Warming by 2 °C further increases the projected median number of warm days to about the same amount that occurs in the hottest 8 in 10 years. The projected new minimum number of days warmer than 35 °C days in a 2 °C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) is about the same as the median number of warm days experienced during the 20 year period from 1986 to 2005. In this 2 °C warmer climate 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 are likely to remain 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.

The number of days warmer than 35 °C



	Minimum	Median	Maximum
2°C warmer	32	56	72
1°C warmer	24	45	63
1998-2017	21	44	69
1986-2005	20	36	58

Figure 51. The current and altered chance of the number of days warmer than 35 °C in a year at Renmark, SA being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of being warmer than any year on record during this 20 year period.

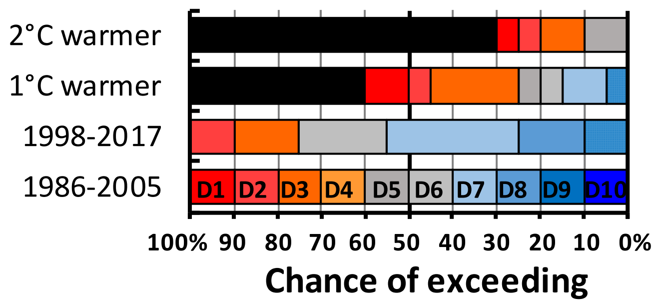
An example from this graph is that a 1 °C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) there is a 80% chance of a year having at least as many hot days as a decile 6 warm year during the 1986 to 2005 year period and a 60% chance of a year having at least as many hot days as a 1 in 10 (decile 10) warm year during the 1986 to 2005 year period.

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 56 per year which is similar to what occurred in about the hottest 8 in 10 years. The modelled new minimum number of 32 days warmer than 35°C days in a 2°C warmer climate is only slightly less than the median number of 36 warm days experienced during the 20 year period from 1986 to 2005. Furthermore there will be 3 in 10 years that have more hot days than any experienced during the 20 years from 1986 to 2005.

There is an assumption that warmer climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

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 comparted to the 20 years from 1986 to 2005 (figure 52). 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 condition during spring are likely to have more clear nights, drier soils and lower humidity.

The number of nights colder 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

Figure 52. The current and altered chance of the number of nights colder than 2 °C after 1st July at Mildura, Vic. being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of fewer cold nights than any year on record during this 20 year period.

An example from this graph is that a 1 °C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) the chance of having at least as many cold nights as occurred during a typical or median year (decile 6 or higher) has reduced from 50% to 20%; and there is a 40% chance of a year having fewer cold nights than what was the fewest cold nights in a year during the period 1986 to 2006 (which from the table to the right can be seen as there having been 5 nights).

In a 2 °C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) 7 in 10 years would have fewer frost potential nights as the minimum during the period from 1986 to 2005.

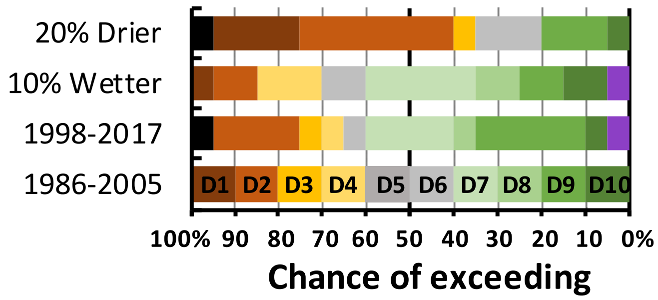
There is an assumption that warmer climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the graph shows the minimum, median (half the values are lower than this, and half higher) and maximum values in each of the 20 year periods.

Risks related to rain and humidity

There is no clear trend in rainfall but there has been an increase in evapotranspiration and irrigation deficit which the climate model projected to continue.

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 (figure 53). 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 about 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 3 in 10 dry growing season becoming the new median and some growing seasons being drier than any during the 20 years from 1985 to 2006.

Growing season rainfall



	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

Figure 53. The current and altered chance of growing season rain at Mildura, Vic. being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of growing season rainfall being lower than any year on record during this 20 year period, and the purple represents growing season rain being higher than any on record during this 20 year period.

An example from this graph is that during the 20 years from 1998 to 2017 there have been both drier years and wetter years than any during the period from 1986 to 2005.

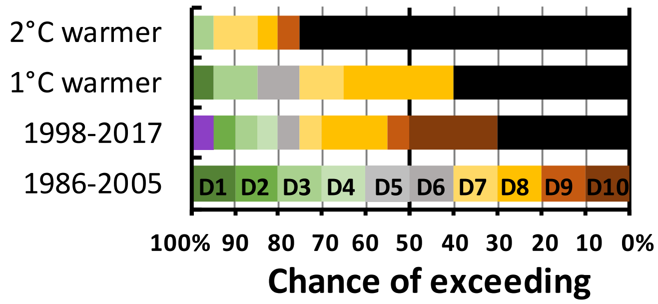
A climate that is 10% wetter is projected to have similar chance of growing season rainfall as the 20 years from 1998 to 2017 apart from the very dry years.

The chance of rainfall being as high or higher as what was a decile 3 year during the 20 years from 1986 to 2005 in a climate that is 20% drier is expected to decline from 80% to 40%. However in this same 20% drier climate there is projected to be a 5% chance of a wet decile 10 year.

There is an assumption that drier climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

Evapotranspiration during the growing season in a future climate that is 1 °C warmer 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 (figure 54). However while a 1 °C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) is projected to increase evapotranspiration by 4%, the 8% increase in response to a 2 °C warmer climate (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) may result in about 8 in 10 growing seasons have as great or greater evaporative demand to that which occurred in the highest 2 in 10 year growing seasons.

Growing season evapotranspiration



	Minimum	Median	Maximum
2°C warmer	1109	1229	1296
1°C warmer	1068	1184	1248
1998-2017	1001	1188	1267
1986-2005	1027	1138	1200

100mm is equivalent to 1ML / ha

Figure 54. The current and altered chance of growing season evapotranspiration at Mildura, Vic. being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of growing season evapotranspiration being higher than any year on record during this 20 year period, and the purple represents growing season evapotranspiration being lower than any on record during this 20 year period.

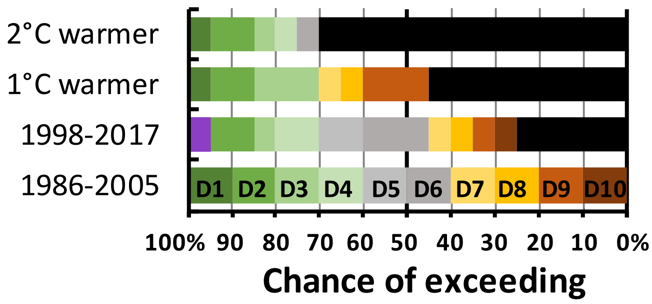
An example from this graph is that a 1 °C warmer climate (e.g. 2050 under RCP4.5 or RCP2.6 scenarios) when evapotranspiration is projected to increase by 4% there is a 75% chance of growing season evapotranspiration being as high or higher as a decile 5 year and an 65% chance of it being higher than a 1 in 10 (decile 10) maximum evapotranspiration year during the 1986 to 2005 year period, and 40% chance of evapotranspiration being more than this maximum.

Warming by 2 °C (e.g. 2050 under RCP8.5 or 2090 under RCP4.5 scenarios) with increased evapotranspiration by 8% is projected to have a 75% chance of growing season evapotranspiration to be higher than any on record during the period 1986 to 2005, and only a 5% chance (1 in 20 years) that evapotranspiration is less than the median (Decile 5 or less) during the base period from 1986 to 2005.

There is an assumption that warmer climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

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 (figure 55).

Growing season Irrigation deficit (ETo - R)



	Minimum	Median	Maximum
2°C warmer	719	1131	1188
1°C warmer	678	1086	1140
1998-2017	211	1049	1200
1986-2005	637	1040	1093

100mm is equivalent to 1ML / ha

Figure 55. The current and altered chance of growing season irrigation deficit (Eto - R) at Mildura, Vic. being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of growing season irrigation deficit being higher than any year on record during this 20 year period, and the purple represents growing season irrigation deficit being lower than any on record during this 20 year period.

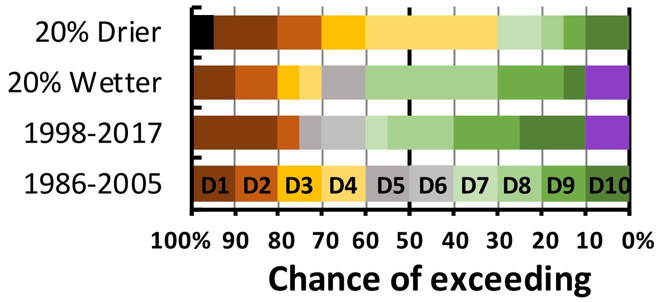
An example from this graph is that the irrigation deficit in a 1°C warmer climate would be more extreme than the base period (1986 to 2005) and the recent 20 year period (1998 to 2017) with 7 in 10 years being higher than the former median.

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.

There is an assumption that warmer climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

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 as indicated by both the amount of rainfall (figure 56) and the number of days that could be classed as moisture balance positive (figure 57). A climate that is 20% drier during the harvest season would mean about 3 in 10 years are as problematic as the current median year but wet harvest seasons are likely to continue to occur.

Harvest season rainfall. Harvest season taken to be from 1st February to 30th April.



Minimum	Median	Maximum
1	27	106
1	41	158
1	45	327
1	34	132

Figure 56. The current and altered chance of harvest season rain (February to April) at Mildura, Vic. being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of harvest season rainfall being lower than any year on record during this 20 year period, and the purple represents harvest season rain being higher than any on record during this 20 year period.

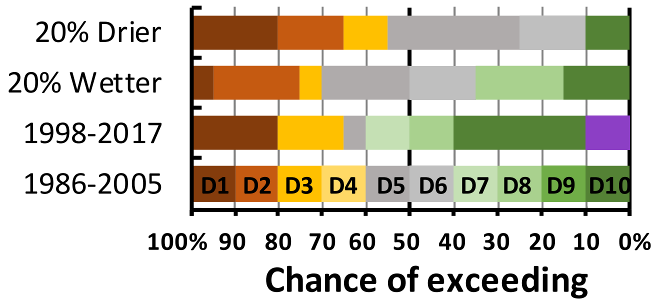
An example from this graph is that during the 20 years from 1998 to 2017 there have been wetter years than any during the period from 1986 to 2005. Just how wet can be seen from the table to the right that shows the maximum during the 20 years from 1986 to 2005 of 132 mm and the maximum during the 20 years from 1997 to 2017 of 327mm.

A climate that is 20% wetter is projected to have similar harvest season rainfall as the 20 years from 1998 to 2017 and even a few more drier years.

In a 20% drier climate there are projected to be fewer wetter years with the chance of having as least as much as the median (decile 5) rainfall reducing from 50% to 30%.

There is an assumption that drier climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

Number of Moisture balance positive (MB+ve) days during the harvest season. Harvest season taken to be from 1st February to 30th April.



Minimum	Median	Maximum
0	5	14
0	7	14
0	9	18
0	6	14

Figure 57. The current and altered chance of the number of moisture balance positive days (MB+ve) during the harvest season rain (February to April) at Mildura, Vic. being as high or higher as the historic decile calculated from 1986 to 2005. These deciles are colour coded and named in the lower bar for the period 1986 to 2005. The black symbol in the bars represents the chance of harvest season rainfall being lower than any year on record during this 20 year period, and the purple represents harvest season rain being higher than any on record during this 20 year period.

An example from this graph is that during the 20 years from 1998 to 2017 there have been 10% of years with more MB+ve days than any during the period from 1986 to 2005.

The number of MB+ve days in a climate that is 20% wetter is projected to be similar as that during the historic period from 1986 to 2005.

In a 20% drier climate there are projected to be fewer years with the chance of having above the median number of MB+ve days with the chance of achieving decile 6 and above reducing from 50% to 25%.

There is an assumption that drier climates have the same year-to-year variability as that during the historic period from 1986 to 2005. The table next to the 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.

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Appendix 1. Griffith

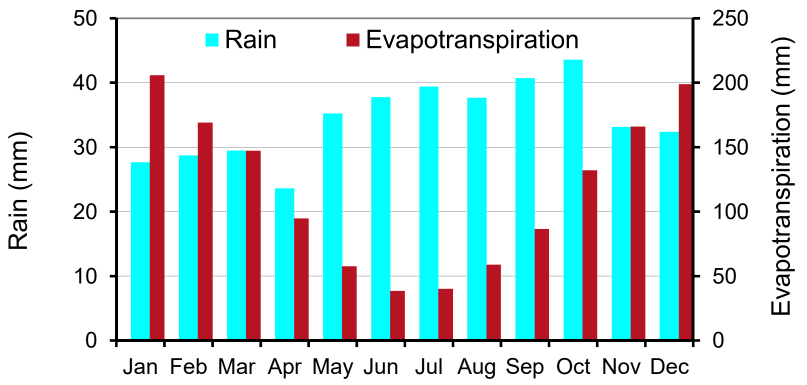
The yearly climate at a glance

Griffith is used here to describe the climate of New South Wales' Riverina region. Griffith 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 Griffith Airport AWS meteorological station (station 75041). The source was patched point data (https://silo.longpaddock.qld.gov.au/).

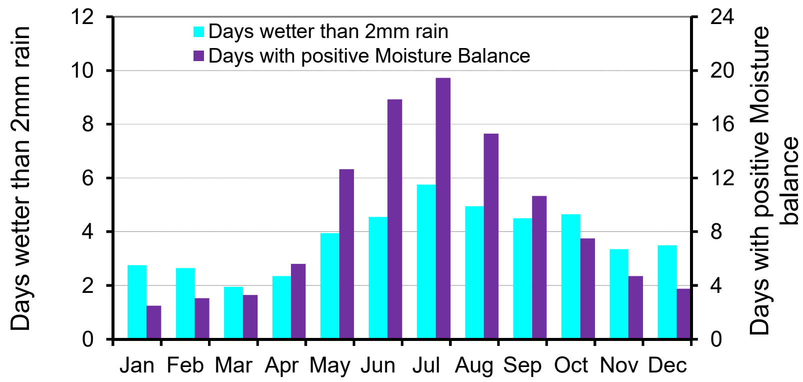
Low rainfall and high evapotranspiration

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

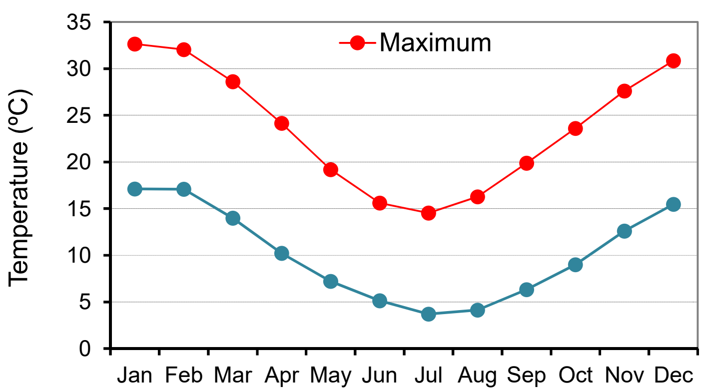
Evaporative demand is seasonal and much higher in summer than in winter.



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.



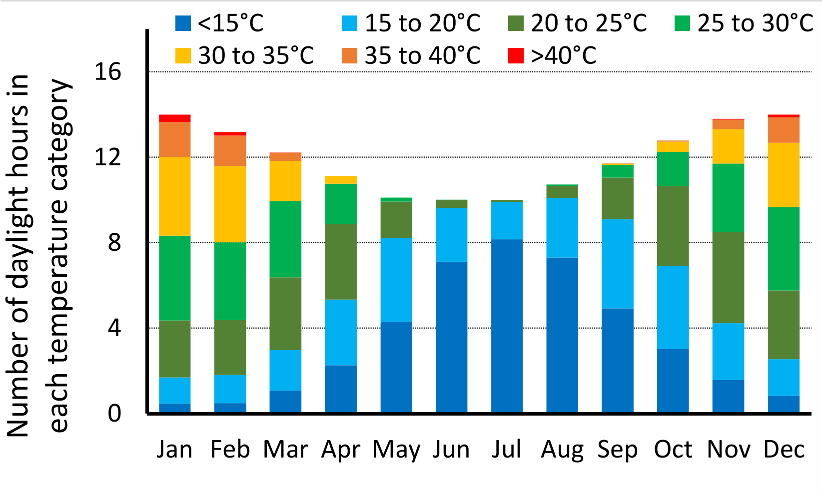
Season pattern of hot summers and cold winters



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

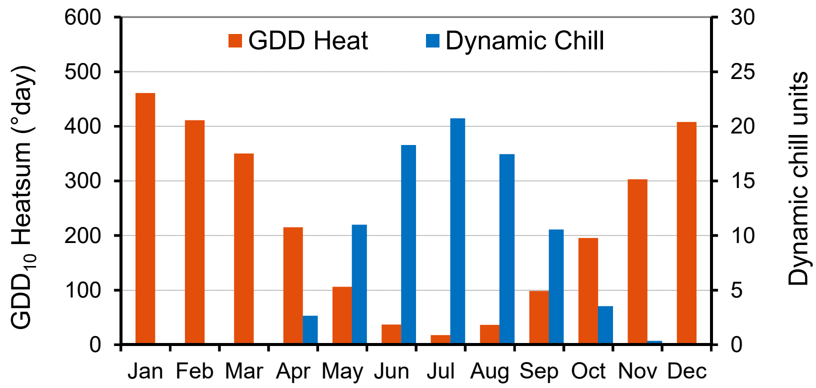
Plenty of daylight hours with temperatures desirable for photosynthesis



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.

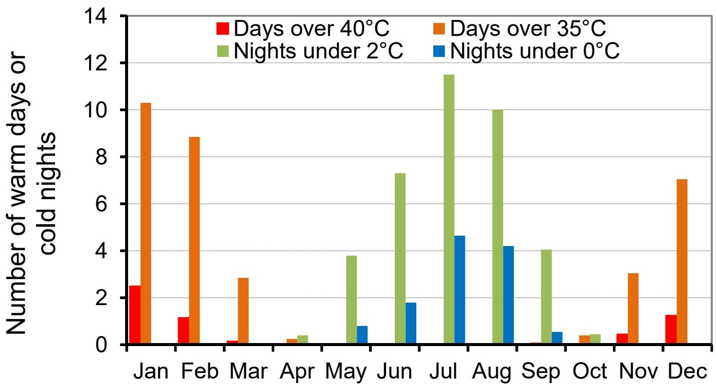
An abundance of heat units and moderate chill units



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

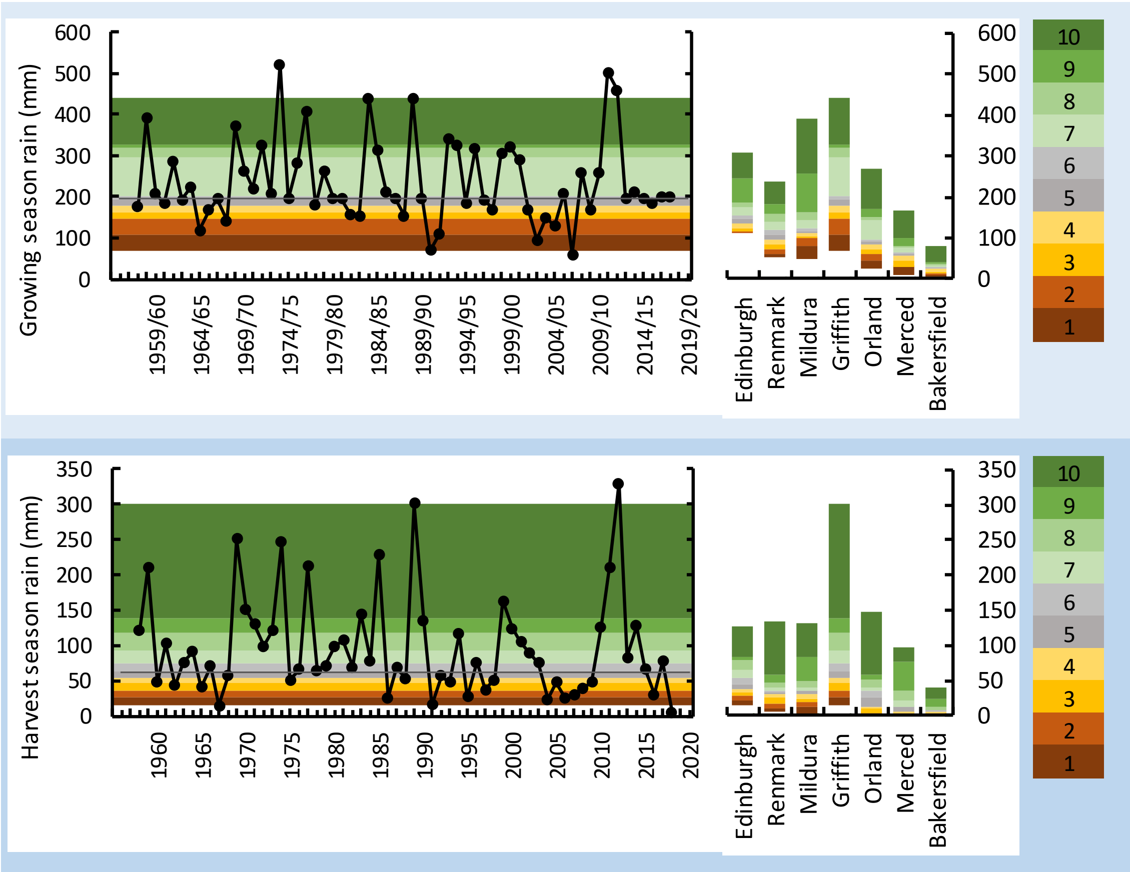


Days warmer than 35°C are common in summer (almost 1 in 3 days). Days hotter than 40°C are much less frequent but not uncommon.

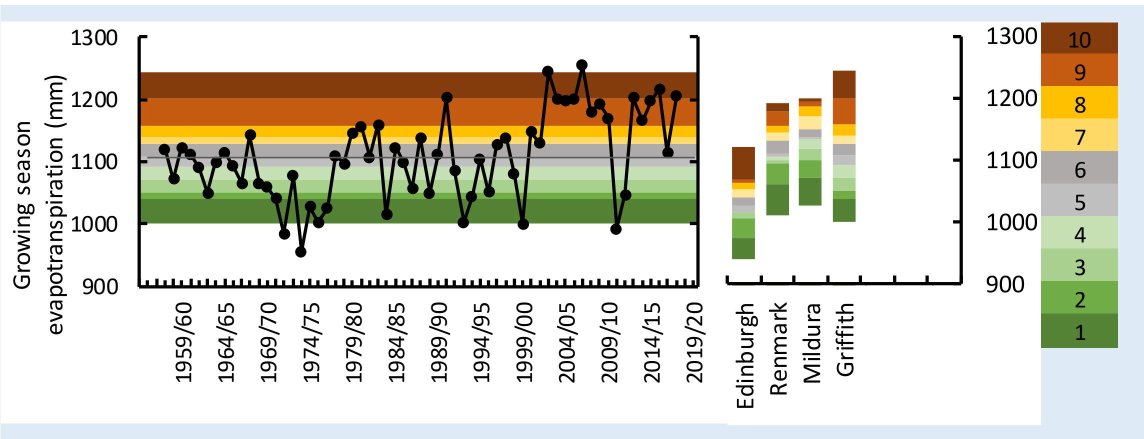
Cold nights can occur from late autumn to early spring, with nights colder than 0°C typically confined to a few occasions per month in May and the winter months. Frost is possible when the screen temperature is colder than 2°C.

Historic trends in climate

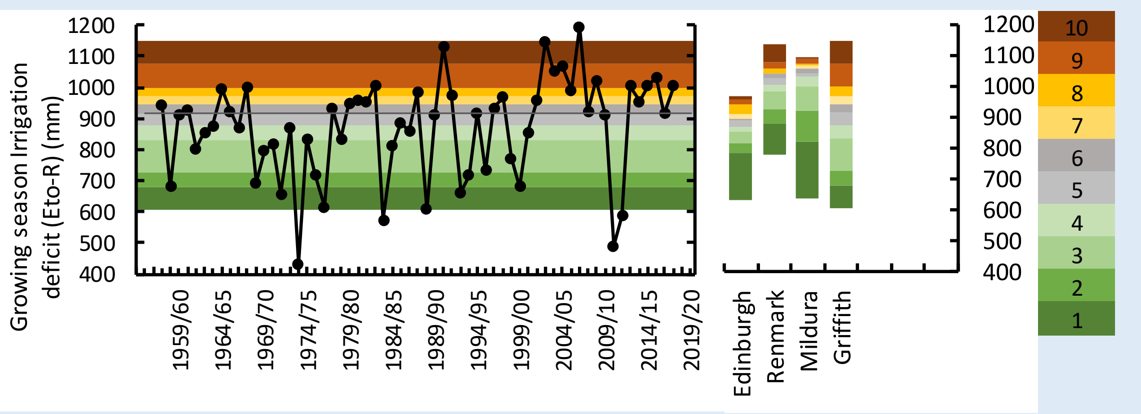
Trends and variation in rainfall, evapotranspiration and irrigation deficit



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.*

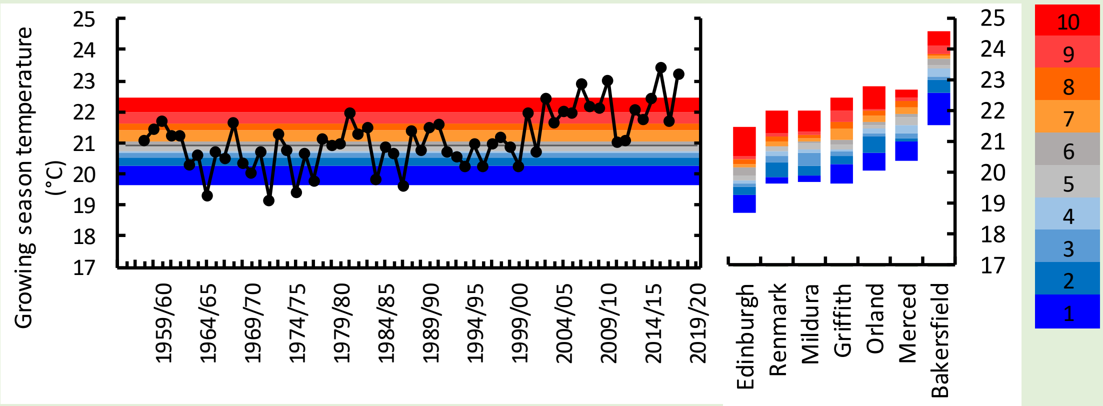


Evapotranspiration (ETo) like rainfall shows year-to-year variation, but unlike rainfall there is a trend of increasing evapotranspiration in recent decades. 100mm is equivalent to 1ML / ha.

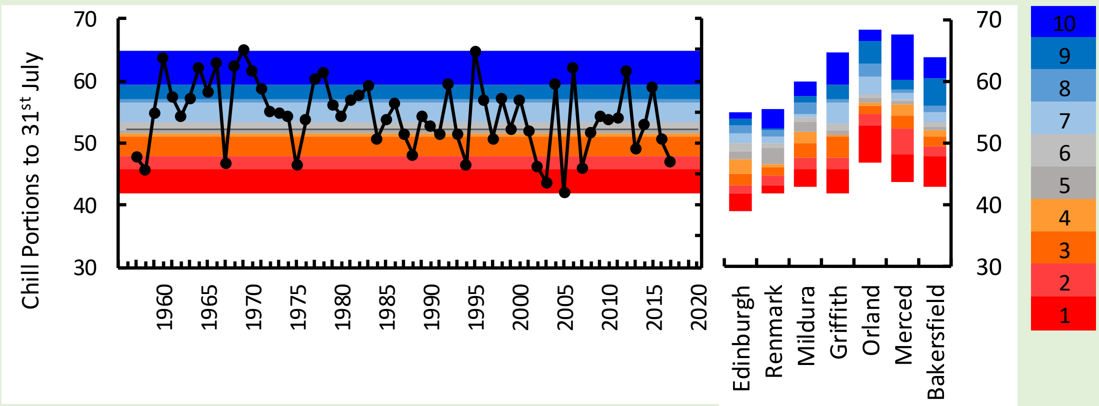


Irrigation demand, measured as the difference between evapotranspiration and rainfall (ETo - R), shows year-to-year variation and an increasing trend in recent decades. 100mm is equivalent to 1ML / ha.

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

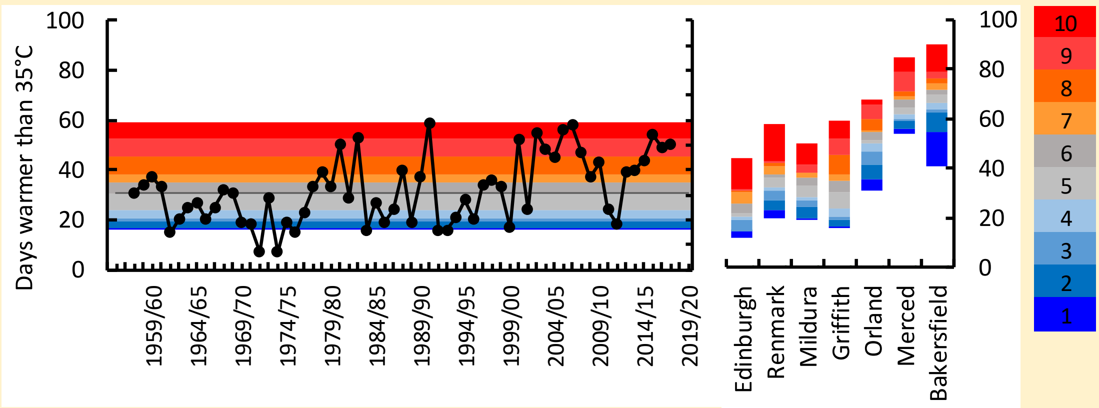


Mean temperature and therefore heat accumulation during the growing season varies from year-to-year. There is a trend of increasingly warmer conditions with many seasons being warmer than median (decile 6 or above) in the past 20 years. Temperatures in Australian almond growing locations are generally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

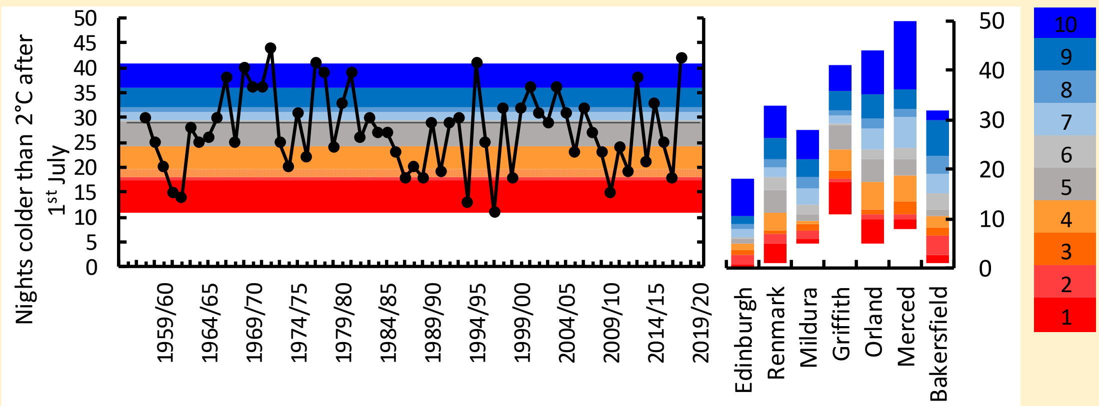


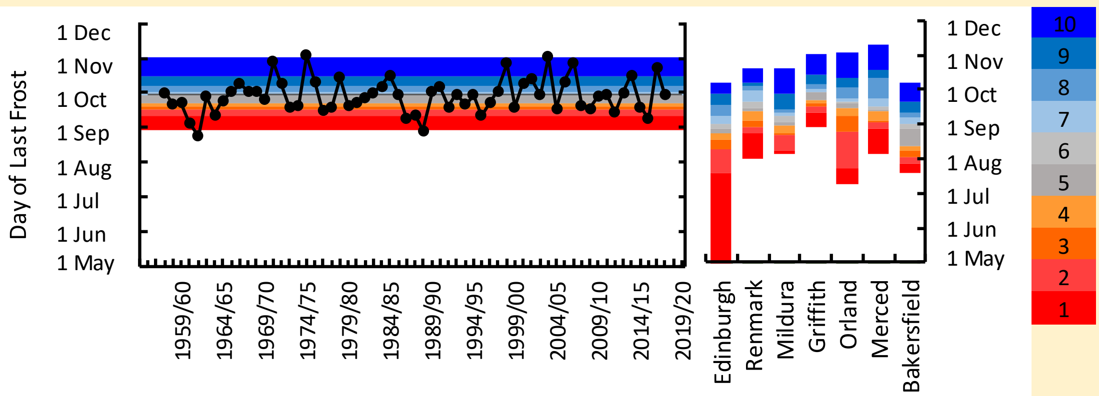
Chill accumulation at Griffith varies from year-to-year. There have been many more below median (decile 5 and lower) chill years in the past 20 years. Chill accumulation is typically less in more coastal Australian locations. Most Australian almond growing locations generally have less chill than Californian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

Trends and variation in heatwaves and frost potential nights



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



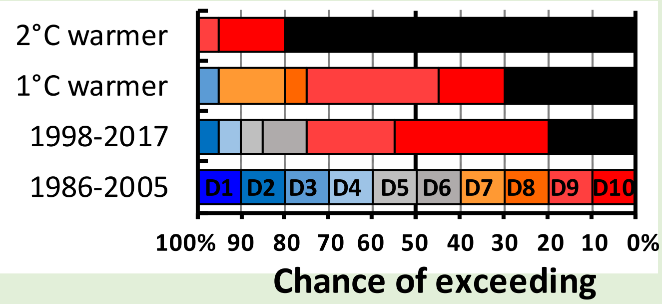


The number of nights sufficiently cold for frosts to potentially occur can be large in some years. Overall the number of cold nights are about as common in the inland Australian almond growing locations as in the Californian locations. The date of the last cold night has considerable year-to-year variation.

Recent and Future climate

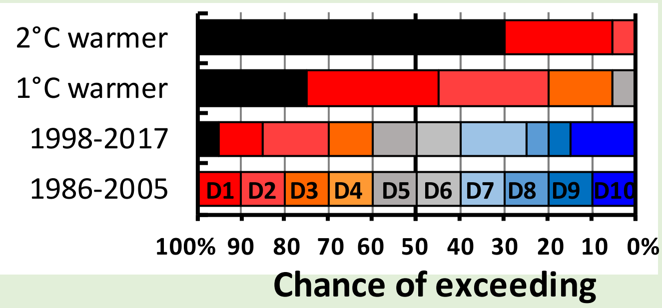
An increase in growing season temperature and heat units, and a decrease in chill units.

Growing season temperature (°C)



	Minimum	Median	Maximum
2°C warmer	21.6	22.9	24.4
1°C warmer	20.6	21.9	23.4
1998-2017	20.3	22.0	23.4
1986-2005	19.6	20.9	22.4

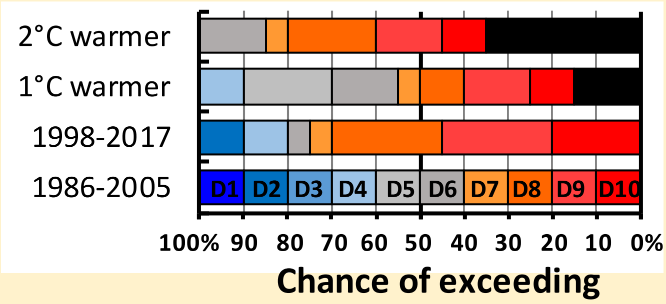
Chill accumulation until 31st July (Dynamic model chill portions)



	Minimum	Median	Maximum
2°C warmer	30	39	48
1°C warmer	37	45	51
1998-2017	42	53	62
1986-2005	44	52	65

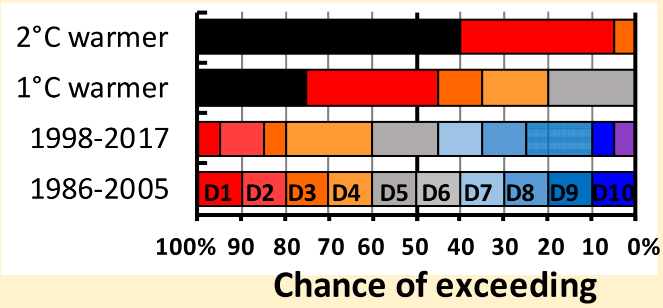
An increase in heatwaves and a decrease in frosts

Days warmer than 35°C



Minimum	Median	Maximum
32	49	83
22	38	68
17	44	58
16	31	59

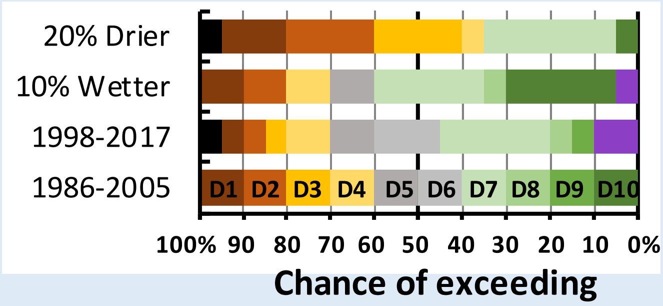
Nights cooler than 2°C after 1st July



Minimum	Median	Maximum
2	10	19
4	17	29
15	28	38
11	29	41

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

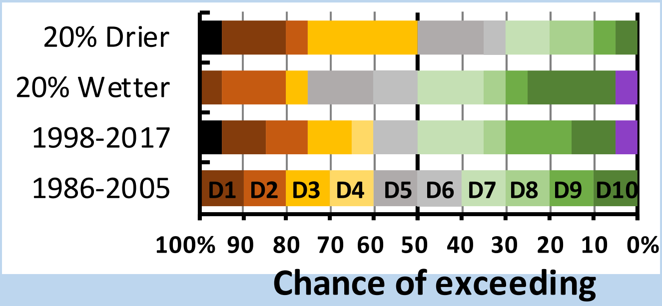
Growing season rain (mm)



Minimum	Median	Maximum
56	156	352
77	215	484
60	198	501
70	195	440

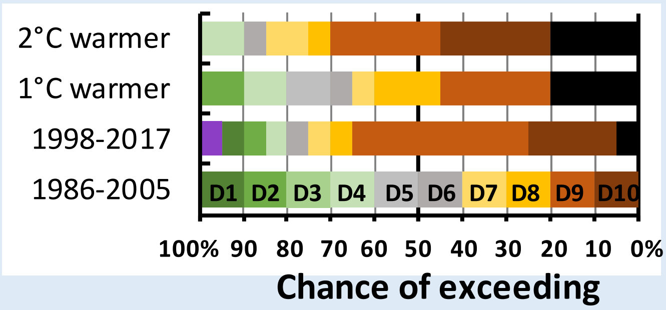
100mm is equivalent to 1ML / ha

February to April rain (mm)



Minimum	Median	Maximum
12	50	241
18	74	361
24	76	329
15	62	301

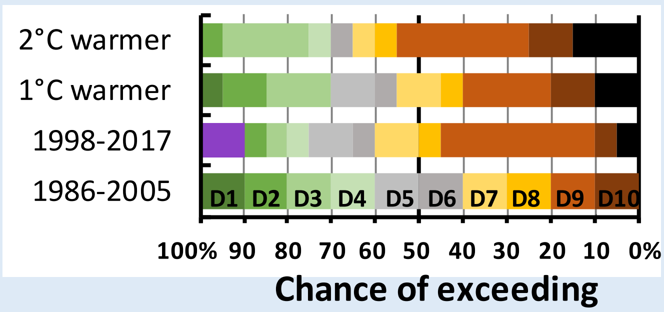
Growing season evapotranspiration (mm)



Minimum	Median	Maximum
1060	1173	1319
1020	1129	1269
992	1174	1255
1000	1107	1244

100mm is equivalent to 1ML / ha

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

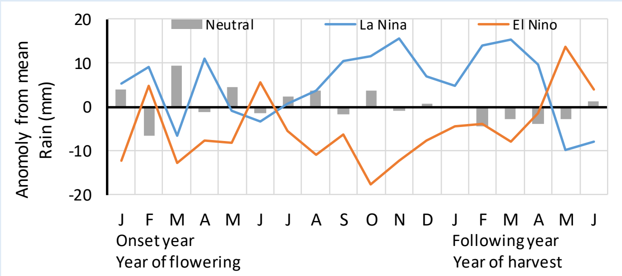


Minimum	Median	Maximum
693	1004	1248
651	960	1198
490	965	1195
609	916	1149

100mm is equivalent to 1ML / ha

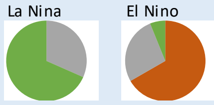
Influence of climate drivers

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



Rain from September to December

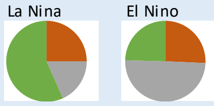
La Nina El Nino



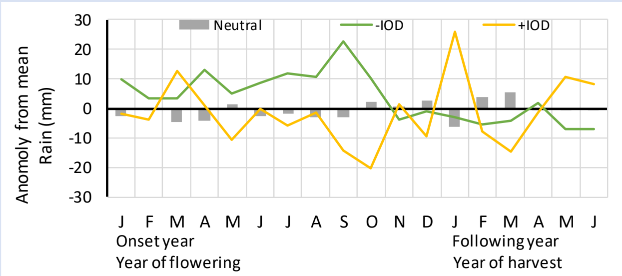
	mm
Minimum	30
Tercile 1	100
Tercile 2	172
Maximum	327

Rain from January to March

La Nina El Nino

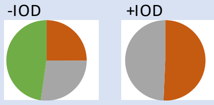


	mm
Minimum	4
Tercile 1	65
Tercile 2	112
Maximum	335



Rain from September to December

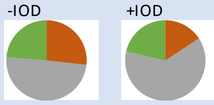
-IOD +IOD



	mm
Minimum	30
Tercile 1	100
Tercile 2	172
Maximum	327

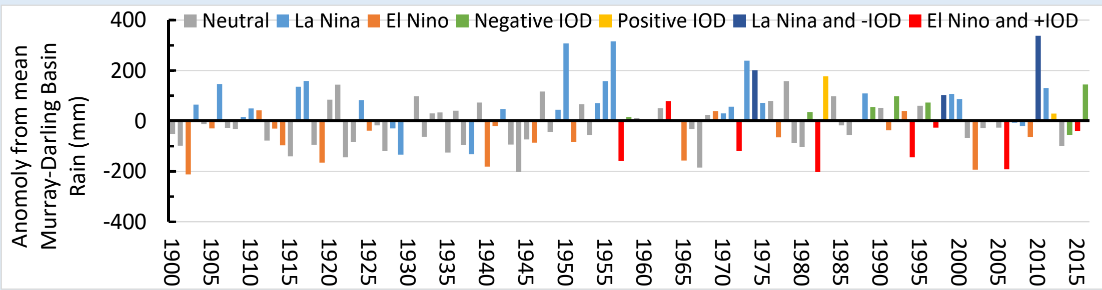
Rain from January to March

-IOD +IOD



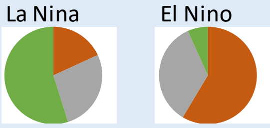
	mm
Minimum	4
Tercile 1	58
Tercile 2	112
Maximum	335

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.



Rain from January to December

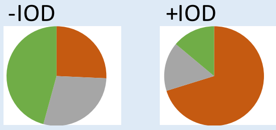
La Nina El Nino



	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

Rain from January to December

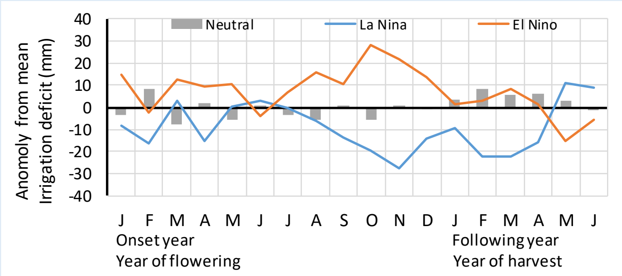
-IOD +IOD



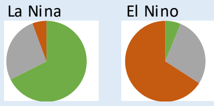
	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

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

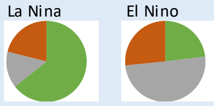
More evapotranspiration and increased irrigation deficit with El Niño and positive IOD

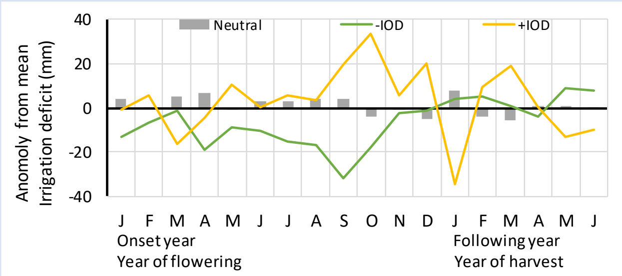


Irrigation deficit from September to December	mm
Minimum	152
Tercile 1	407
Tercile 2	494
Maximum	668



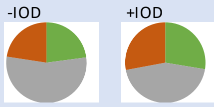
Irrigation deficit from January to March	mm
Minimum	127
Tercile 1	396
Tercile 2	456
Maximum	559





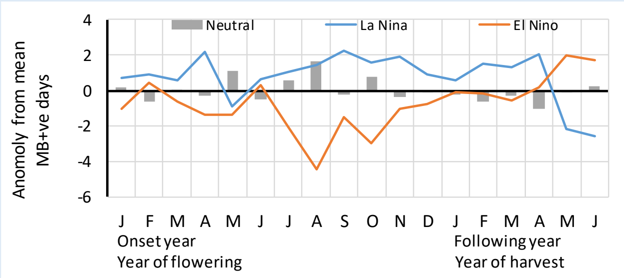
Irrigation deficit from September to December	mm
Minimum	152
Tercile 1	407
Tercile 2	494
Maximum	668

Irrigation deficit from January to March	mm
Minimum	127
Tercile 1	396
Tercile 2	462
Maximum	559

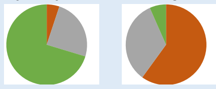


Irrigation deficit was influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year). 100mm is equivalent to 1ML / ha.

Rainy and humid conditions with La Niña and negative IOD

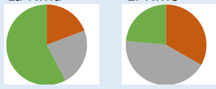


MB+ve days from September to December

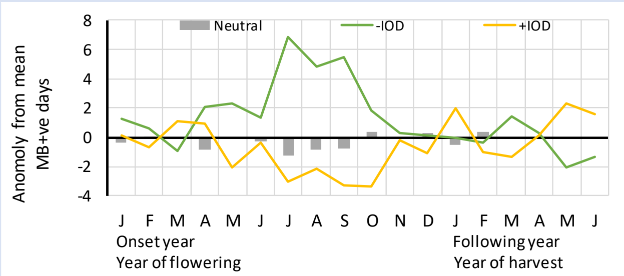


	days
Minimum	4
Tercile 1	18
Tercile 2	27
Maximum	56

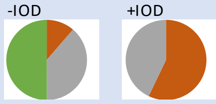
MB+ve days from January to March



	days
Minimum	0
Tercile 1	8
Tercile 2	13
Maximum	30

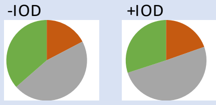


MB+ve days from September to December



	days
Minimum	5
Tercile 1	18
Tercile 2	28
Maximum	56

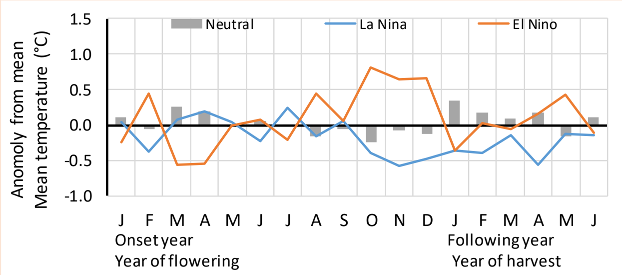
MB+ve days from January to March



	days
Minimum	0
Tercile 1	8
Tercile 2	13
Maximum	30

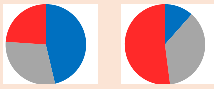
Rainy and humid conditions measured by the number of Moisture Balance positive (MB+ve) days were influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year).

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



Mean temperature from September to December

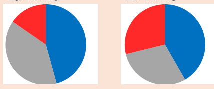
La Nina El Nino



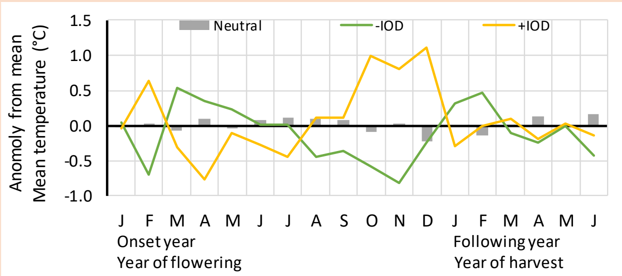
	°C
Minimum	15.8
Tercile 1	17.8
Tercile 2	18.8
Maximum	20.5

Mean temperature from January to March

La Nina El Nino

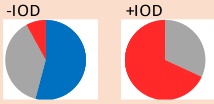


	°C
Minimum	21.2
Tercile 1	23.1
Tercile 2	24.4
Maximum	26.1



Mean temperature from September to December

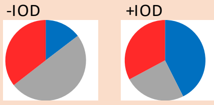
-IOD +IOD



	°C
Minimum	15.8
Tercile 1	17.8
Tercile 2	18.8
Maximum	20.5

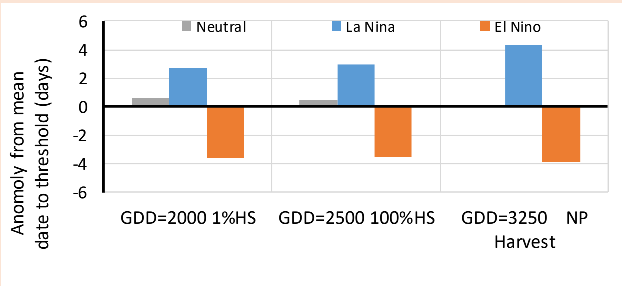
Mean temperature from January to March

-IOD +IOD



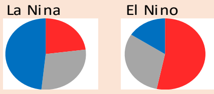
	°C
Minimum	21.2
Tercile 1	23.1
Tercile 2	24.4
Maximum	26.1

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).



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

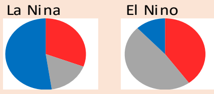
La Nina El Nino



Minimum	27-Dec
Tercile 1	8-Jan
Tercile 2	14-Jan
Maximum	30-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

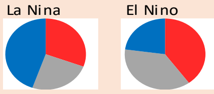
La Nina El Nino



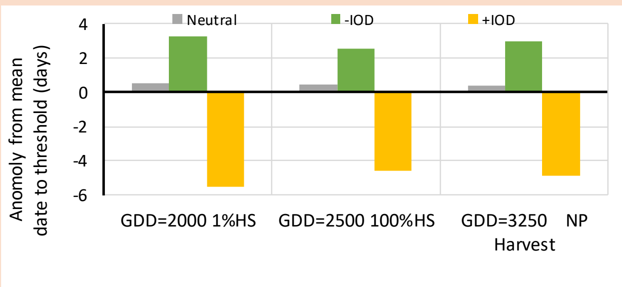
Minimum	19-Jan
Tercile 1	31-Jan
Tercile 2	8-Feb
Maximum	23-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

La Nina El Nino

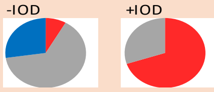


Minimum	21-Feb
Tercile 1	11-Mar
Tercile 2	19-Mar
Maximum	14-Apr



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

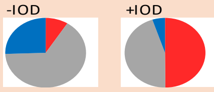
-IOD +IOD



Minimum	27-Dec
Tercile 1	8-Jan
Tercile 2	15-Jan
Maximum	30-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

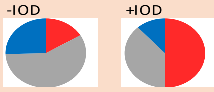
-IOD +IOD



Minimum	19-Jan
Tercile 1	31-Jan
Tercile 2	9-Feb
Maximum	23-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

-IOD +IOD



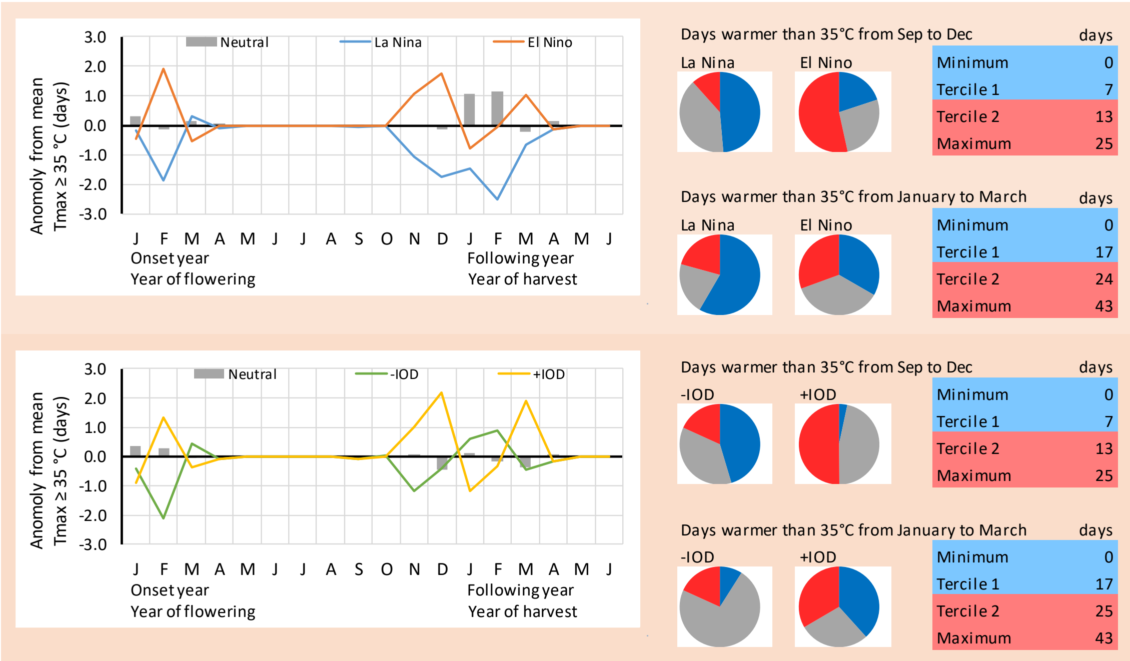
Minimum	21-Feb
Tercile 1	11-Mar
Tercile 2	21-Mar
Maximum	14-Apr

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

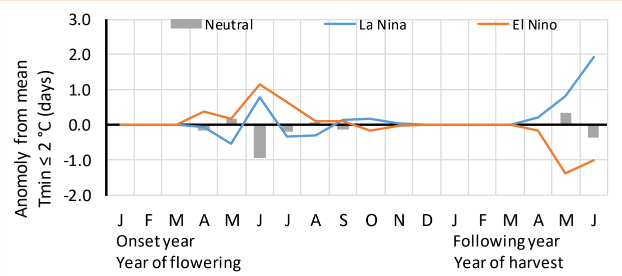
ENSO and IOD had minimal influence on the accumulation of chill hours after August, and almost none before August.

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



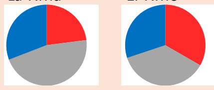
Heatwaves, measured as days warmer than 35 °C were influenced by the time of year and by ENSO and IOD. El Niño years or positive IOD years were likely to have more spring and early summer heatwaves than La Niña years or negative IOD years. Heatwaves in later summer were largely independent of ENSO and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

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



Nights colder than 2°C from August to December

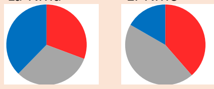
La Nina El Nino



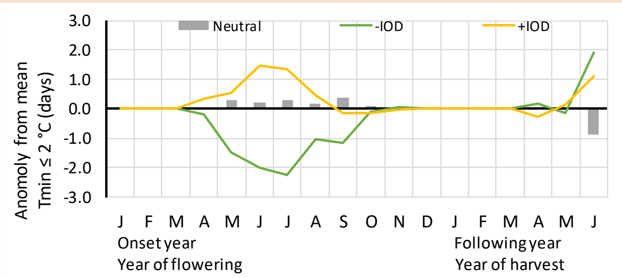
	days
Minimum	0
Tercile 1	10
Tercile 2	17
Maximum	27

Latest night after 1st August colder than 2°C

La Nina El Nino

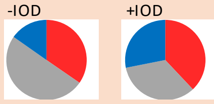


	Date
Minimum	25-Aug
Tercile 1	20-Sep
Tercile 2	1-Oct
Maximum	4-Nov



Nights colder than 2°C from August to December

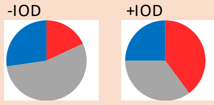
-IOD +IOD



	days
Minimum	0
Tercile 1	11
Tercile 2	17
Maximum	27

Latest night after 1st August colder than 2°C

-IOD +IOD



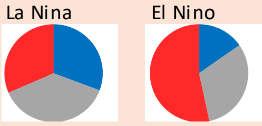
	Date
Minimum	25-Aug
Tercile 1	20-Sep
Tercile 2	1-Oct
Maximum	4-Nov

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

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

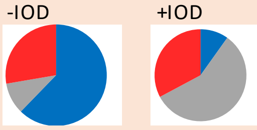
La Nina El Nino



	hours
Minimum	23
Tercile 1	73
Tercile 2	97
Maximum	193

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

-IOD +IOD



	hours
Minimum	23
Tercile 1	73
Tercile 2	96
Maximum	193

Favourable Pollination conditions were influenced by ENSO or IOD.

The correlation coefficients (r) of the agroclimatic indices 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.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.16	-0.27	0.37	-0.38	-0.40
Rain from September to December	-0.42	-0.42	0.45	-0.28	-0.34
Rain from January to March	-0.26	-0.25	0.20	0.08	0.06
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	0.49	0.43	-0.48	0.24	0.23
Irrigation deficit from September to December	0.53	0.50	-0.45	0.49	0.45
Irrigation deficit from January to March	0.20	0.14	-0.20	-0.11	-0.16
Rainy and humid conditions					
MB+ve days from September to December	-0.45	-0.43	0.36	-0.50	-0.47
MB+ve days from January to March	-0.16	-0.13	0.20	0.16	0.15
Heat accumulation					
Mean temperature from September to December	0.33	0.24	-0.21	0.58	0.37
Mean temperature from January to March	-0.01	-0.14	0.01	0.18	-0.03
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.33	-0.22	0.30	-0.59	-0.42
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.32	-0.21	0.28	-0.55	-0.37
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.26	-0.15	0.13	-0.41	-0.18
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.06	0.12	0.00	-0.29	-0.19
Utah chill units accumulated to 31st July	-0.03	0.05	0.11	-0.40	-0.21
Heatwaves					
Days warmer than 35°C from September to December	0.39	0.31	-0.31	0.39	0.19
Days warmer than 35°C from January to March	0.19	0.05	-0.22	-0.13	-0.30
Daylight hours warmer than 35°C from September to December	0.44	0.36	-0.34	0.40	0.20
Daylight hours warmer than 35°C from January to March	0.18	0.04	-0.20	-0.09	-0.27
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	0.15	0.08	-0.41	0.17	0.13

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).

Appendix 2. Mildura

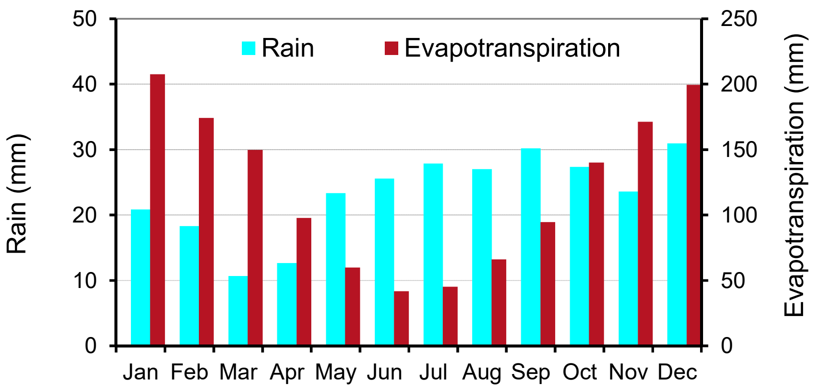
The yearly climate at a glance

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/).

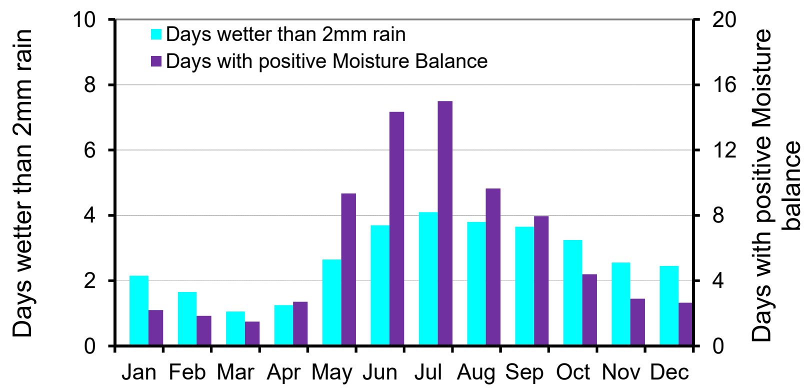
Low rainfall and high evapotranspiration

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

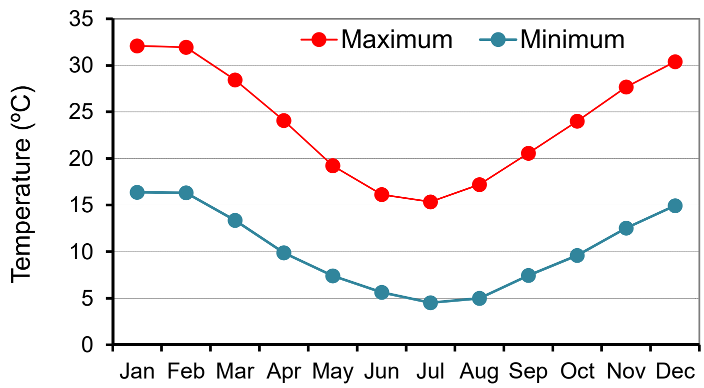
Evaporative demand is seasonal and much higher in summer than in winter.



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.



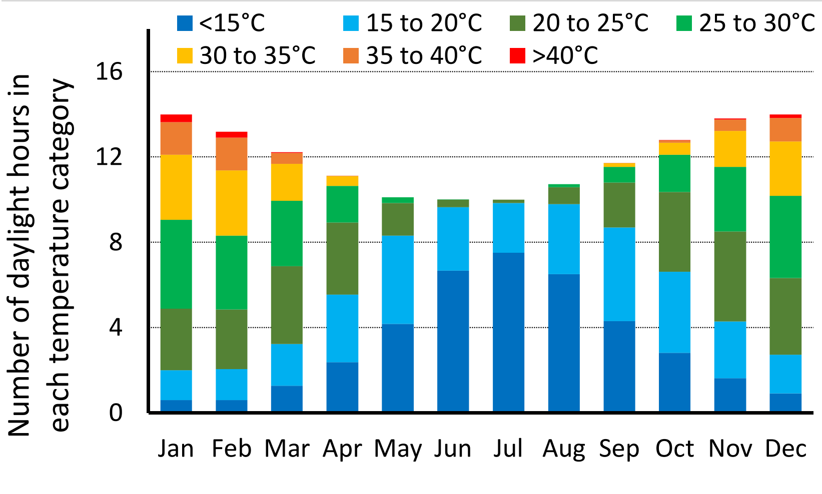
Season pattern of hot summers and cold winters



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.

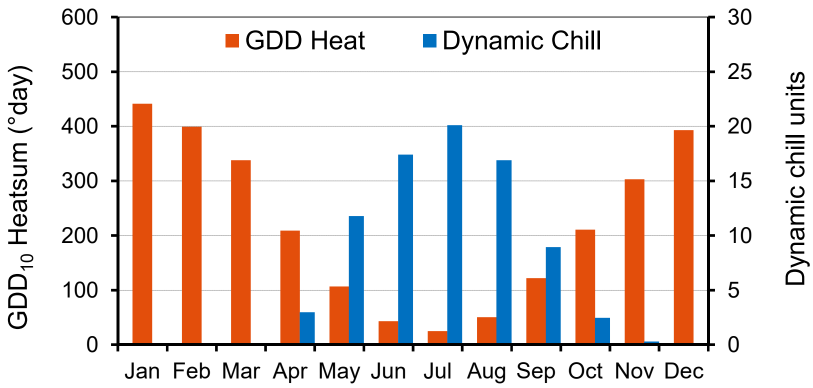
Plenty of daylight hours with temperatures desirable for photosynthesis



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.

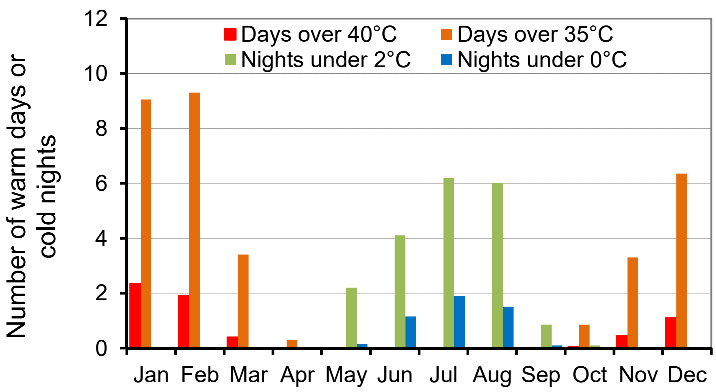
An abundance of heat units and moderate chill units



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

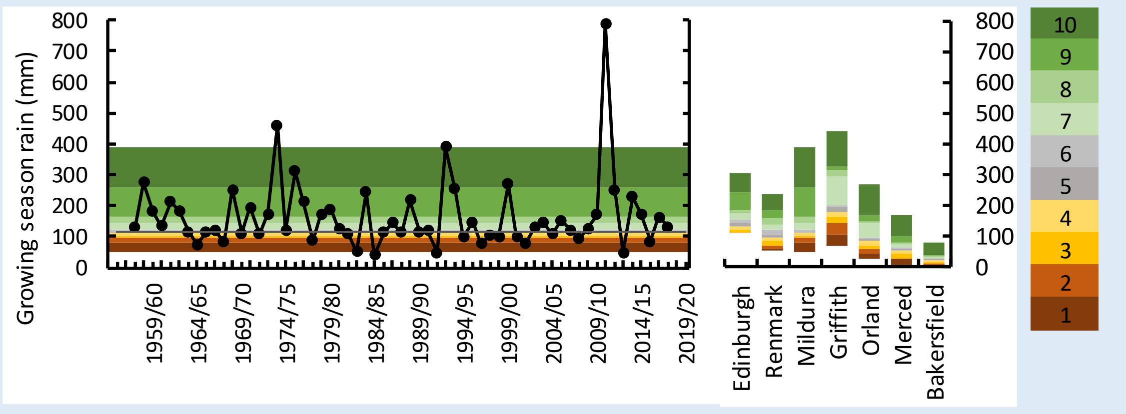


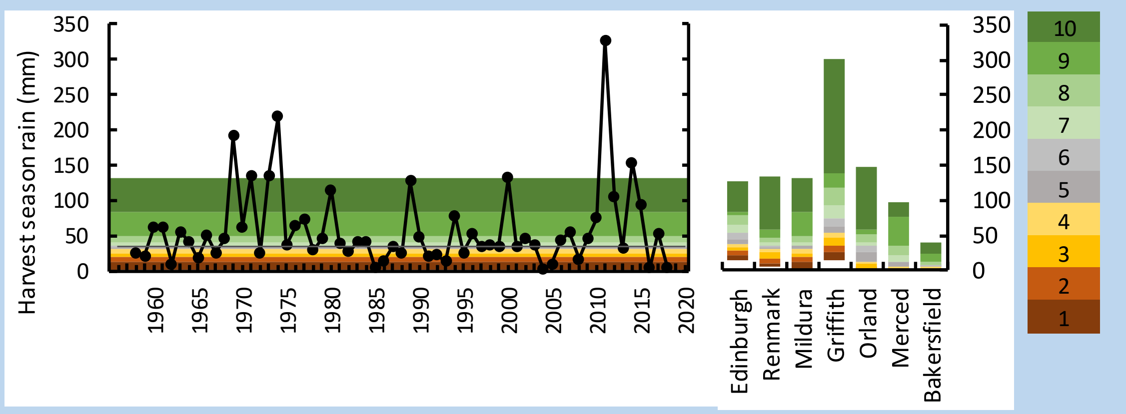
Days warmer than 35°C are common in summer (almost 1 in 3 days). Days hotter than 40°C are much less frequent but not uncommon.

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.

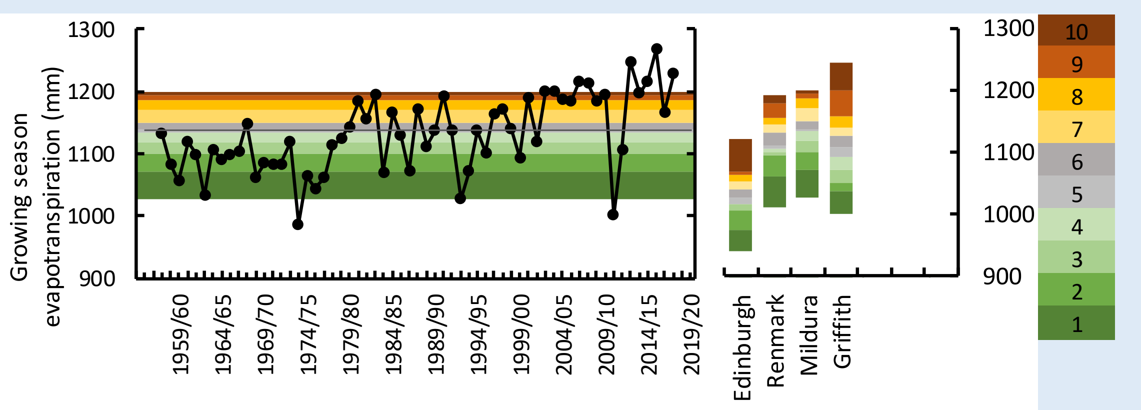
Historic trends in climate

Trends and variation in rainfall, evapotranspiration and irrigation deficit

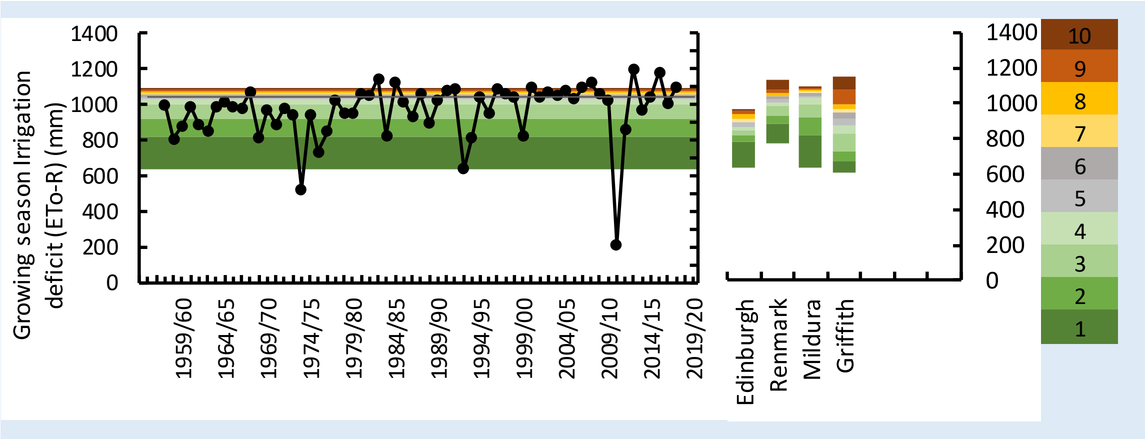




There is considerable year-to-year variation in rainfall. Almonds are grown in both wetter locations in Australia and drier locations in central and southern California. Growing season and Harvest season in Australia were calculated from October to April and February to April; and April to October and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

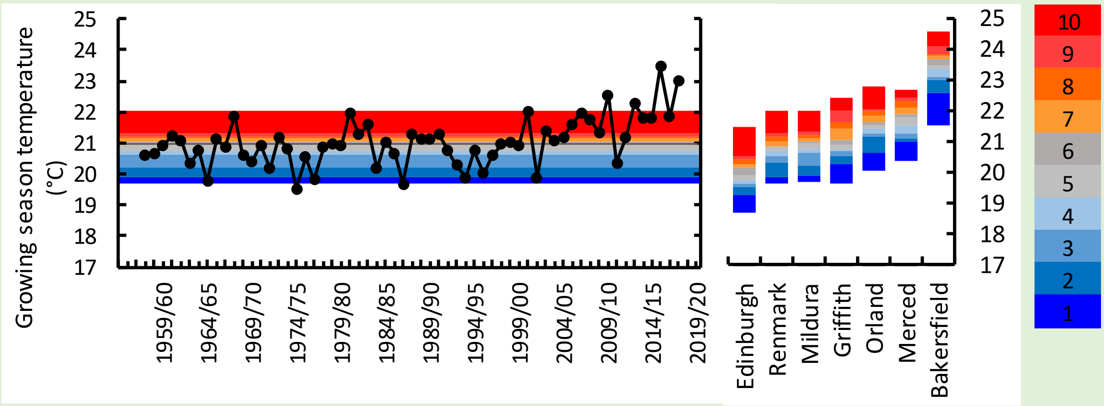


Evapotranspiration (ETo) like rainfall shows year-to-year variation, but unlike rainfall there is a trend of increasing evapotranspiration in recent decades. 100mm is equivalent to 1ML / ha.

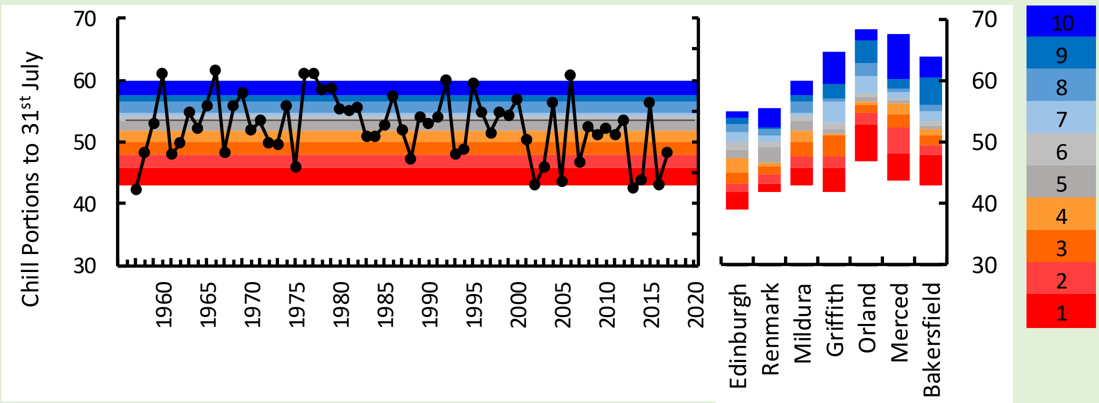


Irrigation demand, measured as the difference between evapotranspiration and rainfall (ETo - R), shows year-to-year variation and an increasing trend in recent decades. 100mm is equivalent to 1ML / ha.

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

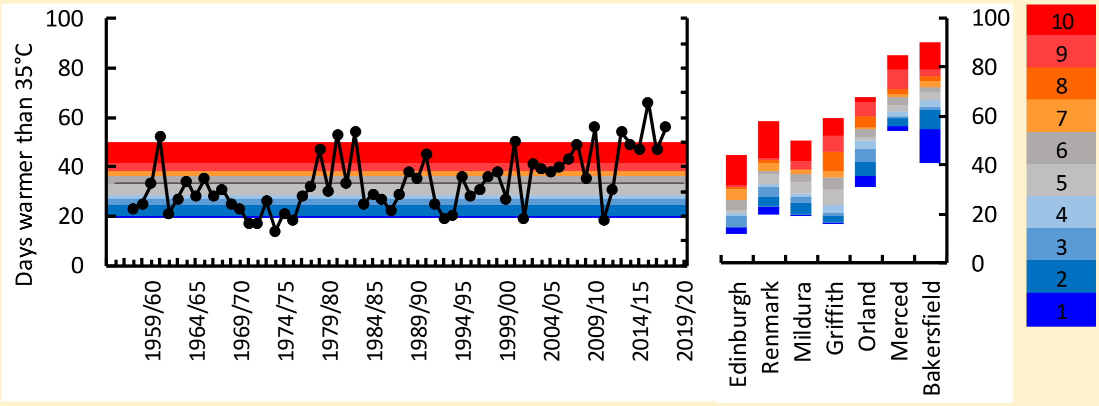


Mean temperature and therefore heat accumulation during the growing season varies from year-to-year. There is a trend of increasingly warmer conditions with many seasons being warmer than median (decile 6 or above) in the past 20 years. Temperatures in Australian almond growing locations are generally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

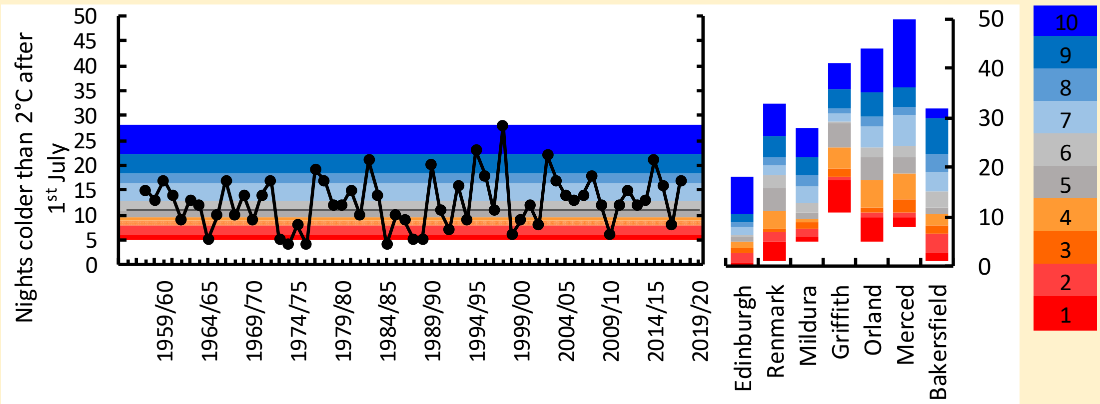


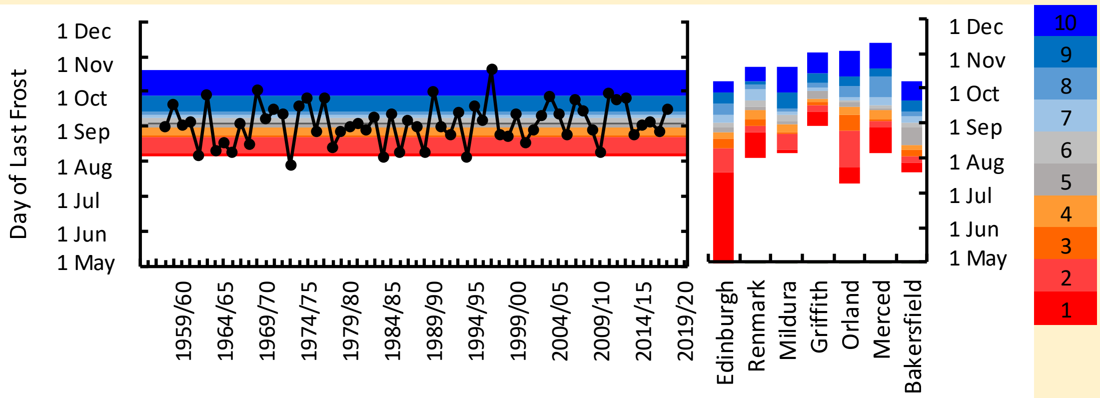
Chill accumulation at Mildura varies from year-to-year. There have been many more below median (decile 5 and lower) chill years in the past 20 years. Chill accumulation is typically less in more coastal Australian locations. Most Australian almond growing locations generally have less chill than Californian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

Trends and variation in heatwaves and frost potential nights



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



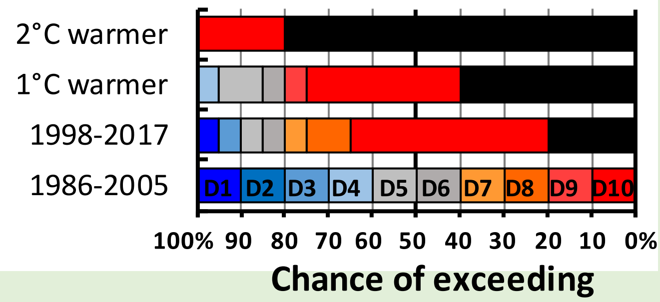


The number of nights sufficiently cold for frosts to potentially occur can be large in some years. Overall the number of cold nights are about as common in the inland Australian almond growing locations as in the Californian locations. The date of the last cold night has considerable year-to-year variation.

Recent and Future climate

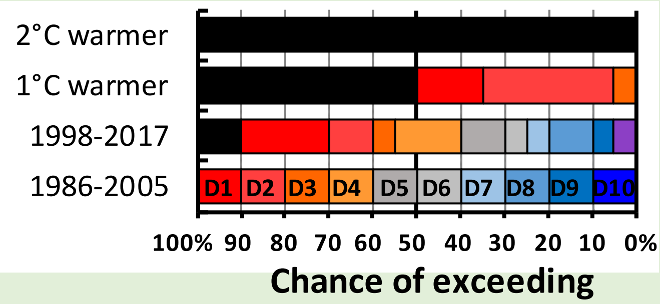
An increase in growing season temperature and heat units, and a decrease in chill units

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

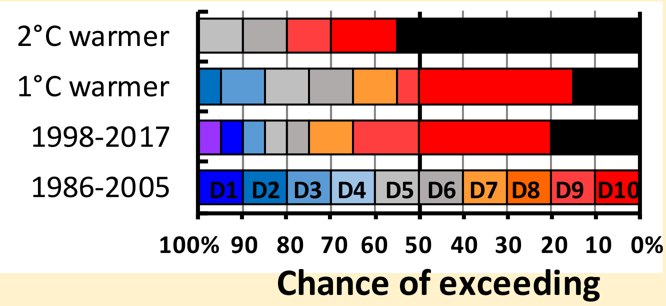
Chill accumulation until 31st July (Dynamic model chill portions)



	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

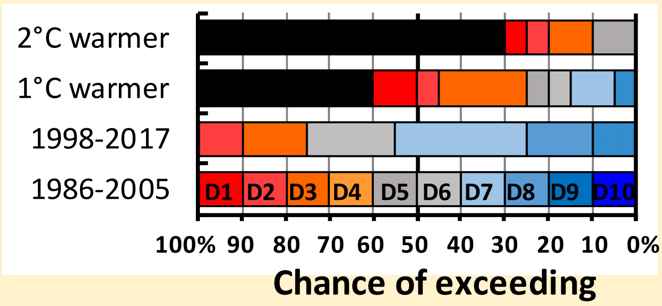
An increase in heatwaves and a decrease in frosts

Days warmer than 35°C



Minimum	Median	Maximum
31	51	72
23	42	60
18	41	66
19	33	50

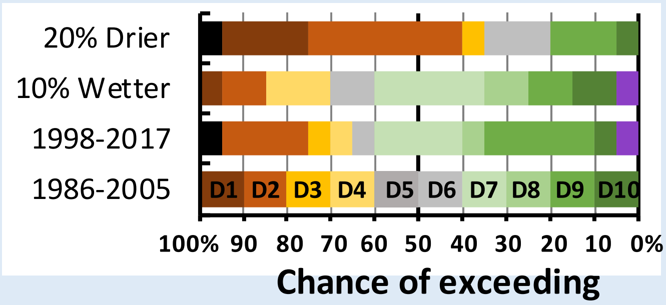
Nights cooler than 2°C after 1st July



Minimum	Median	Maximum
0	3	11
2	6	19
6	13	28
5	11	28

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

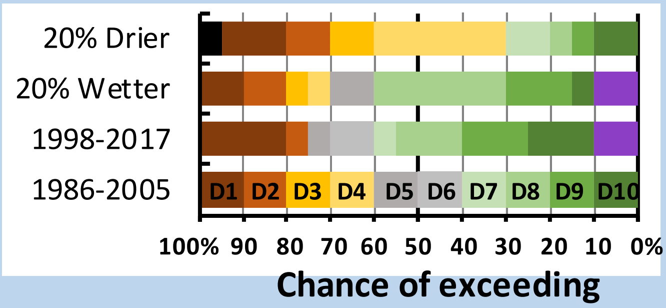
Growing season rain (mm)



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

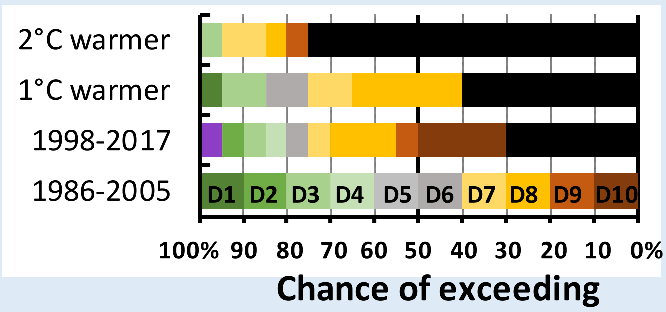
100mm is equivalent to 1ML / ha

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

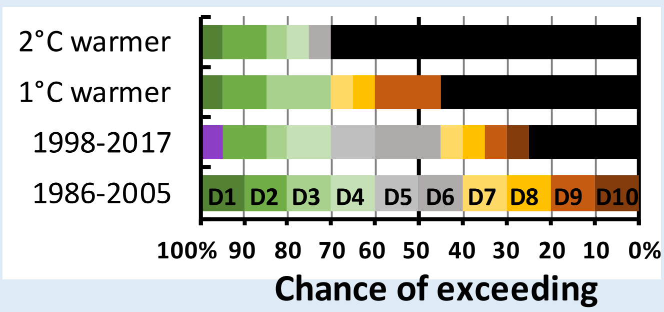
Growing season evapotranspiration (mm)



	Minimum	Median	Maximum
2°C warmer	1109	1229	1296
1°C warmer	1068	1184	1248
1998-2017	1001	1188	1267
1986-2005	1027	1138	1200

100mm is equivalent to 1ML / ha

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

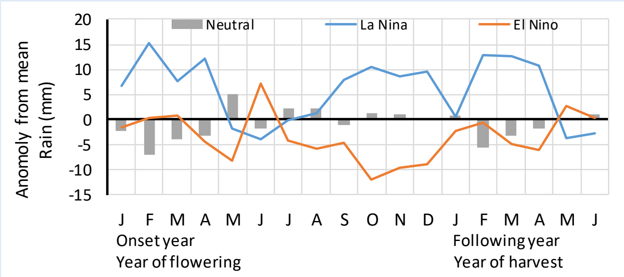


	Minimum	Median	Maximum
2°C warmer	719	1131	1188
1°C warmer	678	1086	1140
1998-2017	211	1049	1200
1986-2005	637	1040	1093

100mm is equivalent to 1ML / ha

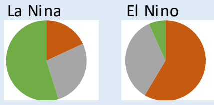
Influence of climate drivers

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



Rain from September to December mm

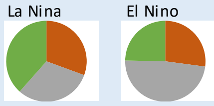
La Nina El Nino



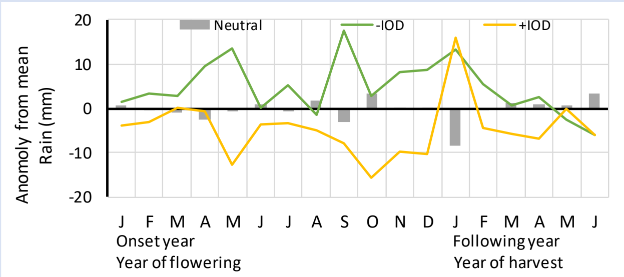
Minimum	20
Tercile 1	69
Tercile 2	120
Maximum	388

Rain from January to March mm

La Nina El Nino

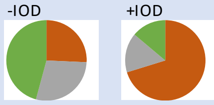


Minimum	2
Tercile 1	37
Tercile 2	67
Maximum	444



Rain from September to December mm

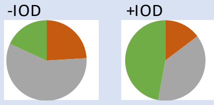
-IOD +IOD



Minimum	20
Tercile 1	69
Tercile 2	120
Maximum	388

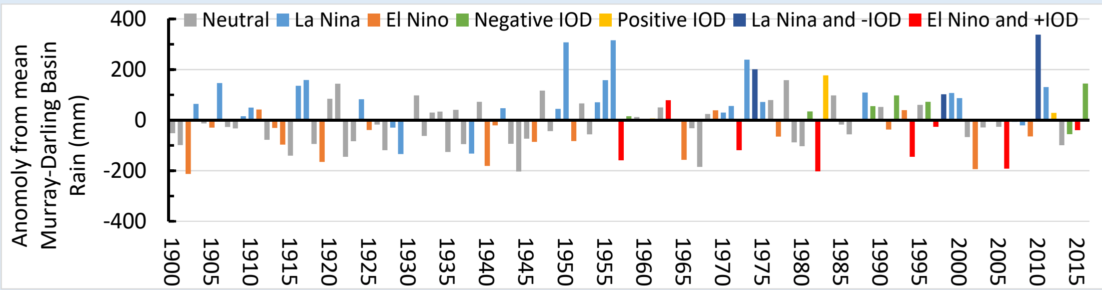
Rain from January to March mm

-IOD +IOD



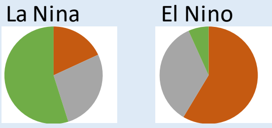
Minimum	2
Tercile 1	37
Tercile 2	67
Maximum	444

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.



Rain from January to December mm

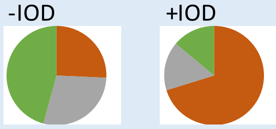
La Nina El Nino



Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

Rain from January to December mm

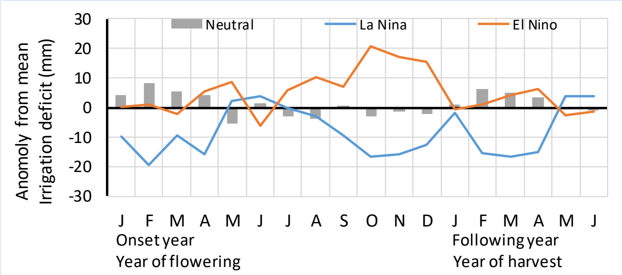
-IOD +IOD



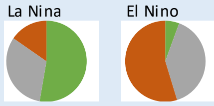
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

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

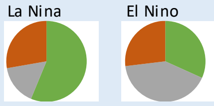


Irrigation deficit from September to December

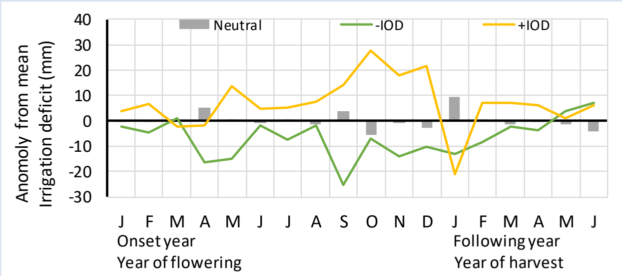


	mm
Minimum	134
Tercile 1	476
Tercile 2	546
Maximum	685

Irrigation deficit from January to March



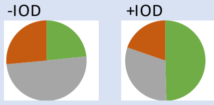
	mm
Minimum	14
Tercile 1	459
Tercile 2	495
Maximum	572



Irrigation deficit from September to December

	mm
Minimum	134
Tercile 1	476
Tercile 2	546
Maximum	685

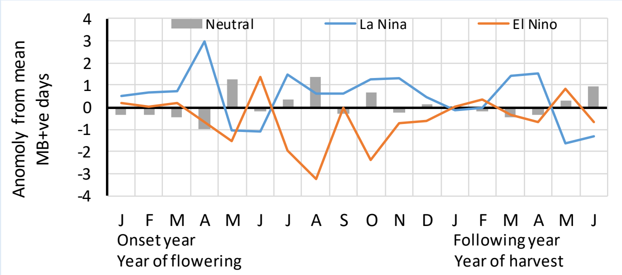
Irrigation deficit from January to March



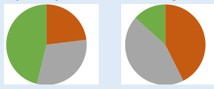
	mm
Minimum	14
Tercile 1	464
Tercile 2	496
Maximum	572

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

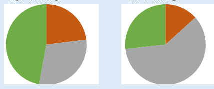


MB+ve days from September to December

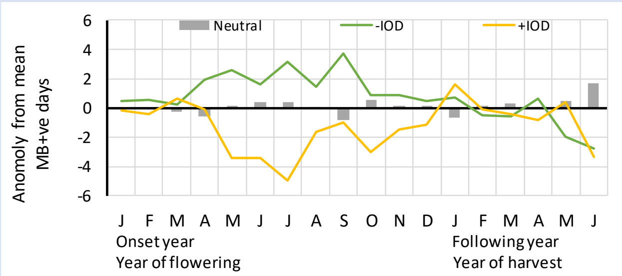


	days
Minimum	3
Tercile 1	10
Tercile 2	19
Maximum	52

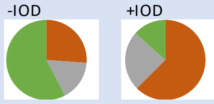
MB+ve days from January to March



	days
Minimum	0
Tercile 1	5
Tercile 2	7
Maximum	22

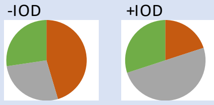


MB+ve days from September to December



	days
Minimum	3
Tercile 1	10
Tercile 2	19
Maximum	52

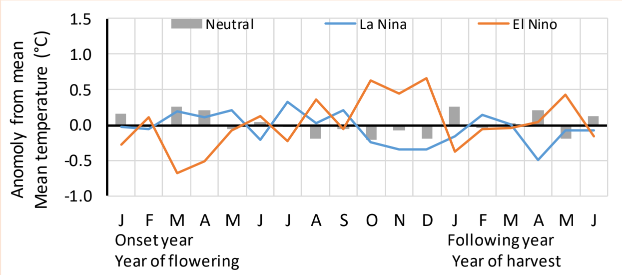
MB+ve days from January to March



	days
Minimum	0
Tercile 1	5
Tercile 2	7
Maximum	22

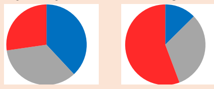
Rainy and humid conditions measured by the number of Moisture Balance positive (MB+ve) days were influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year).

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



Mean temperature from September to December

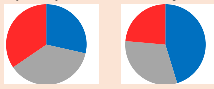
La Nina El Nino



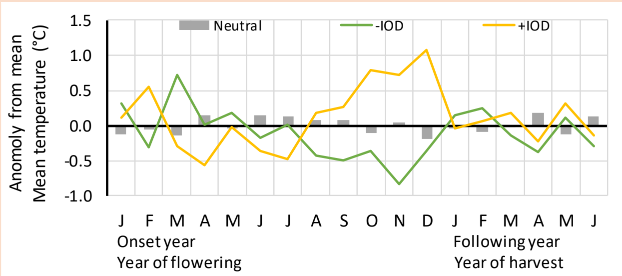
°C	
Minimum	16.7
Tercile 1	18.2
Tercile 2	18.9
Maximum	21.0

Mean temperature from January to March

La Nina El Nino

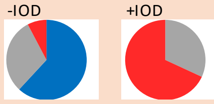


°C	
Minimum	21.5
Tercile 1	22.8
Tercile 2	23.8
Maximum	25.3



Mean temperature from September to December

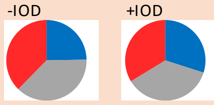
-IOD +IOD



°C	
Minimum	16.7
Tercile 1	18.2
Tercile 2	19.0
Maximum	21.0

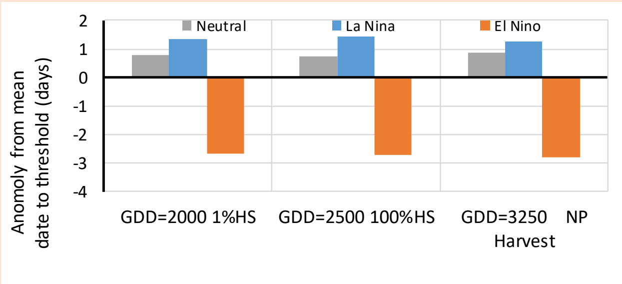
Mean temperature from January to March

-IOD +IOD



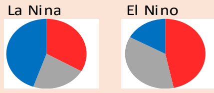
°C	
Minimum	21.5
Tercile 1	22.8
Tercile 2	23.8
Maximum	25.3

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).



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

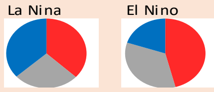
La Nina El Nino



Minimum	25-Dec
Tercile 1	6-Jan
Tercile 2	11-Jan
Maximum	23-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

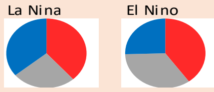
La Nina El Nino



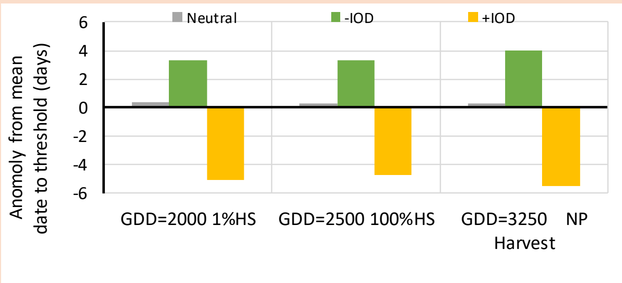
Minimum	17-Jan
Tercile 1	31-Jan
Tercile 2	6-Feb
Maximum	18-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

La Nina El Nino

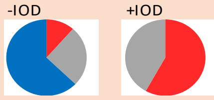


Minimum	23-Feb
Tercile 1	10-Mar
Tercile 2	18-Mar
Maximum	7-Apr



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

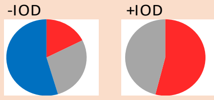
-IOD +IOD



Minimum	25-Dec
Tercile 1	6-Jan
Tercile 2	11-Jan
Maximum	23-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

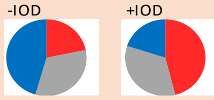
-IOD +IOD



Minimum	17-Jan
Tercile 1	31-Jan
Tercile 2	6-Feb
Maximum	18-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

-IOD +IOD



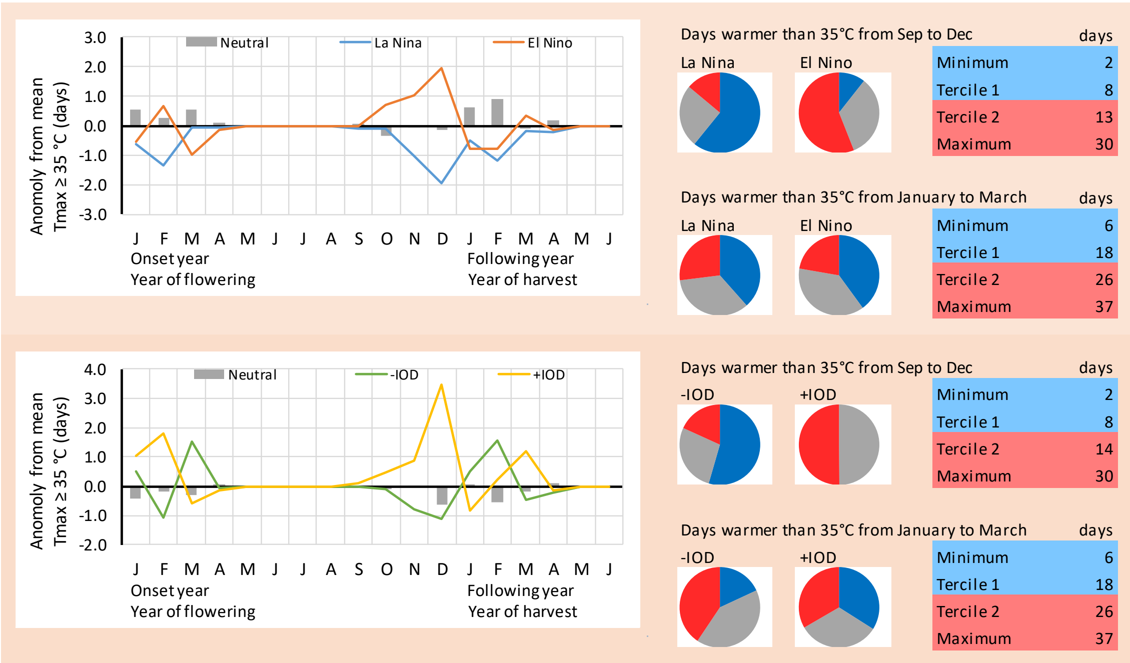
Minimum	23-Feb
Tercile 1	10-Mar
Tercile 2	18-Mar
Maximum	7-Apr

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

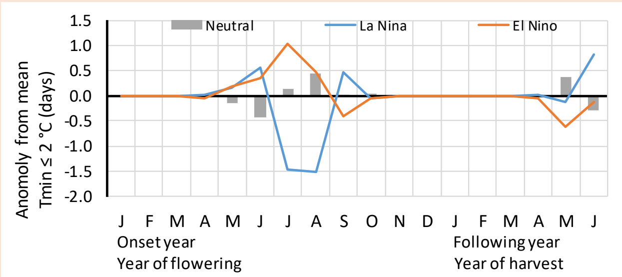
ENSO and IOD had minimal influence on the accumulation of chill hours after August, and almost none before August.

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



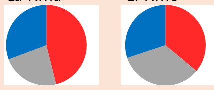
Heatwaves, measured as days warmer than 35 °C were influenced by the time of year and by ENSO and IOD. El Niño years or positive IOD years were likely to have more spring and early summer heatwaves than La Niña years or negative IOD years. Heatwaves in later summer were largely independent of ENSO and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

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



Nights colder than 2°C from August to December

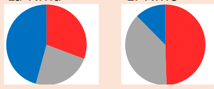
La Nina El Nino



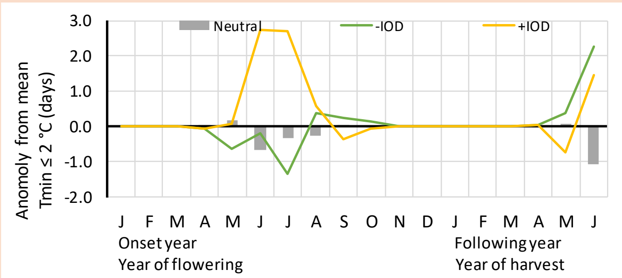
	days
Minimum	0
Tercile 1	4
Tercile 2	7
Maximum	14

Latest night after 1st August colder than 2°C

La Nina El Nino

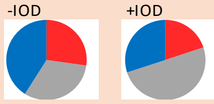


	Date
Minimum	Nil
Tercile 1	28-Aug
Tercile 2	12-Sep
Maximum	21-Oct



Nights colder than 2°C from August to December

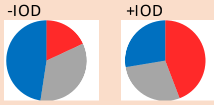
-IOD +IOD



	days
Minimum	0
Tercile 1	4
Tercile 2	7
Maximum	14

Latest night after 1st August colder than 2°C

-IOD +IOD



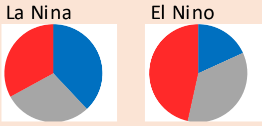
	Date
Minimum	Nil
Tercile 1	28-Aug
Tercile 2	12-Sep
Maximum	21-Oct

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

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

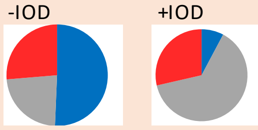
La Nina El Nino



	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.

The correlation coefficients (r) of the agroclimatic indices 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.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	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 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).

Appendix 3. Renmark

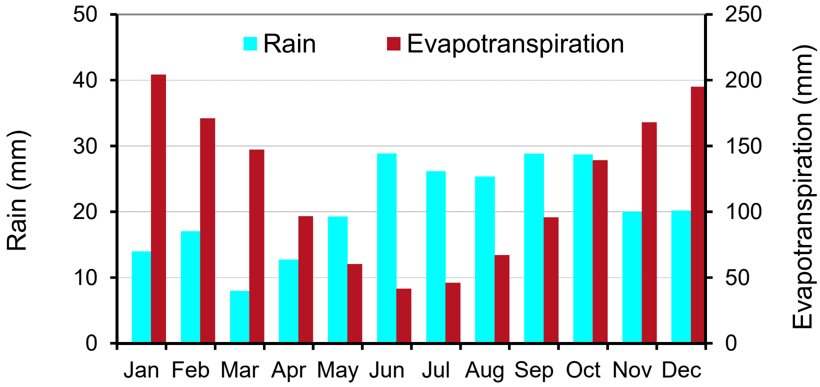
The yearly climate at a glance

Renmark is used here to describe the climate of South Australia's Riverland region. Renmark 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 Renmark Aero meteorological station (station 24048). The source was patched point data (https://silo.longpaddock.qld.gov.au/).

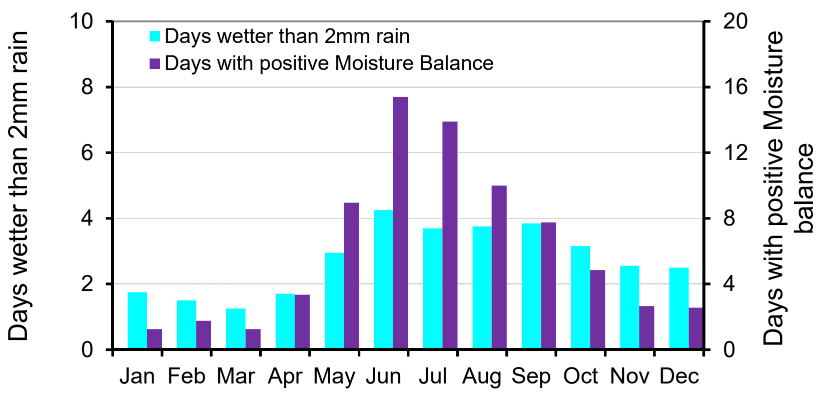
Low rainfall and high evapotranspiration

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

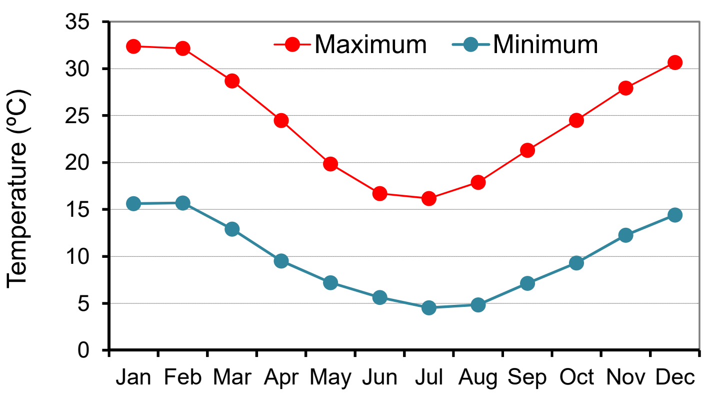
Evaporative demand is seasonal and much higher in summer than in winter.



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.



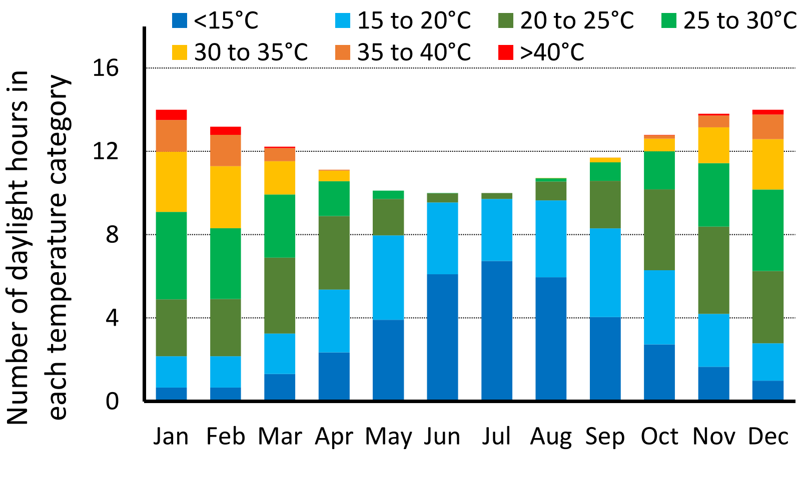
Season pattern of hot summers and cold winters



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

Winter months have mean maximum temperatures between 15° and 20°C, while mean minimum temperatures are about 5°C.

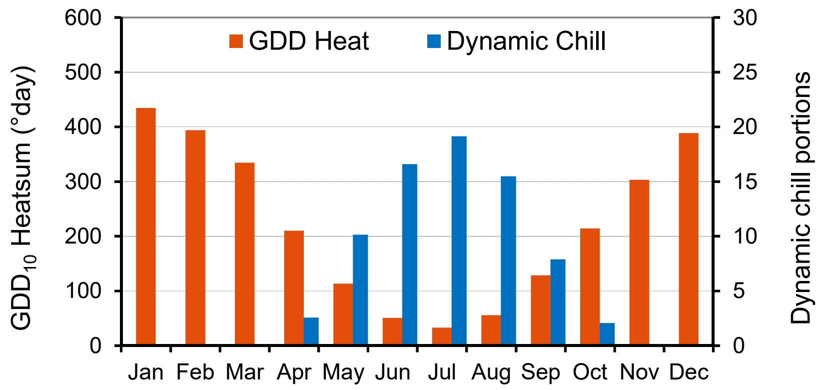
Plenty of daylight hours with temperatures desirable for photosynthesis



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.

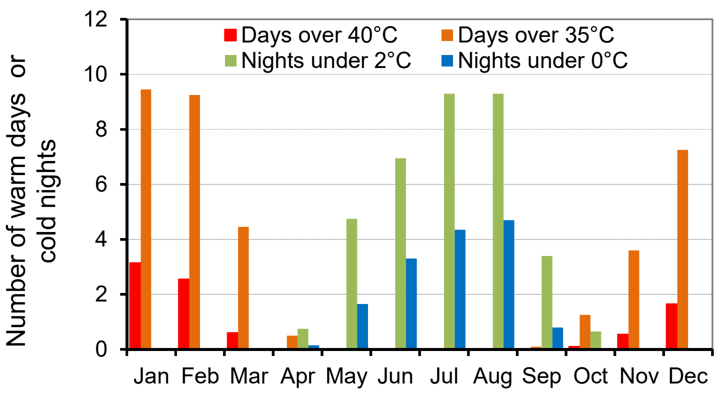
An abundance of heat units and moderate chill units



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



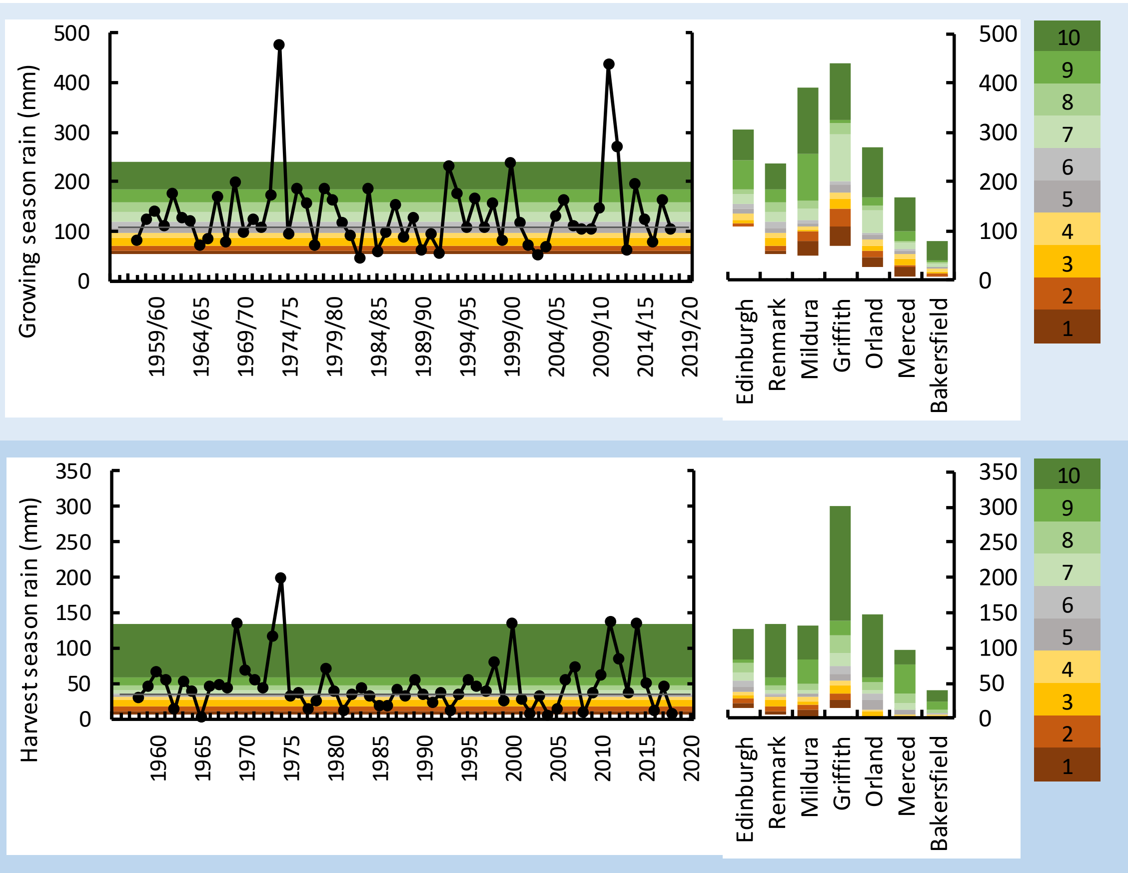
Days warmer than 35°C are common in summer (almost 1 in 3 days). Days hotter than 40°C are less frequent but not uncommon.

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.

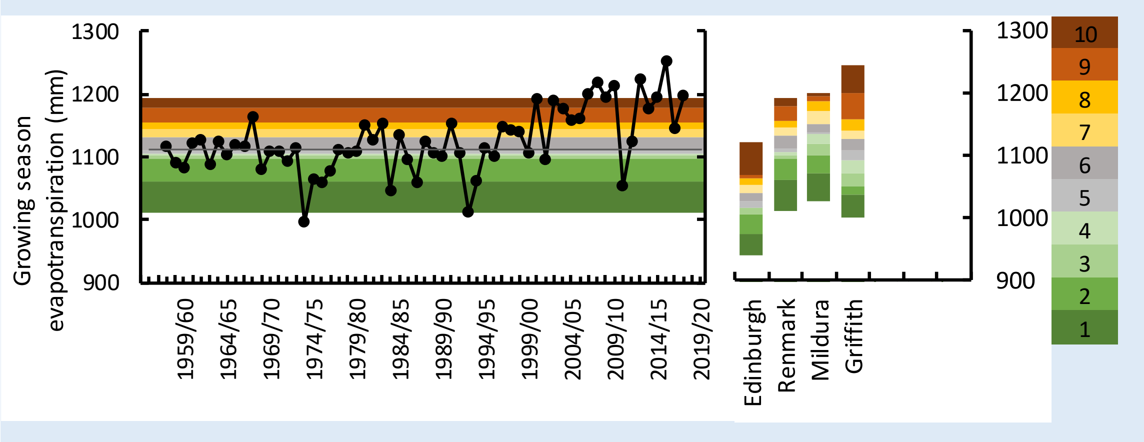
Information from the meteorological station at the Loxton Research Centre (station 24024) was used to determine the number of nights colder than 0°C and 2°C as the information prior to the mid 1990's from Renmark is unusually low and possibly an error associated with relocating the Renmark meteorological station.

Historic trends in climate

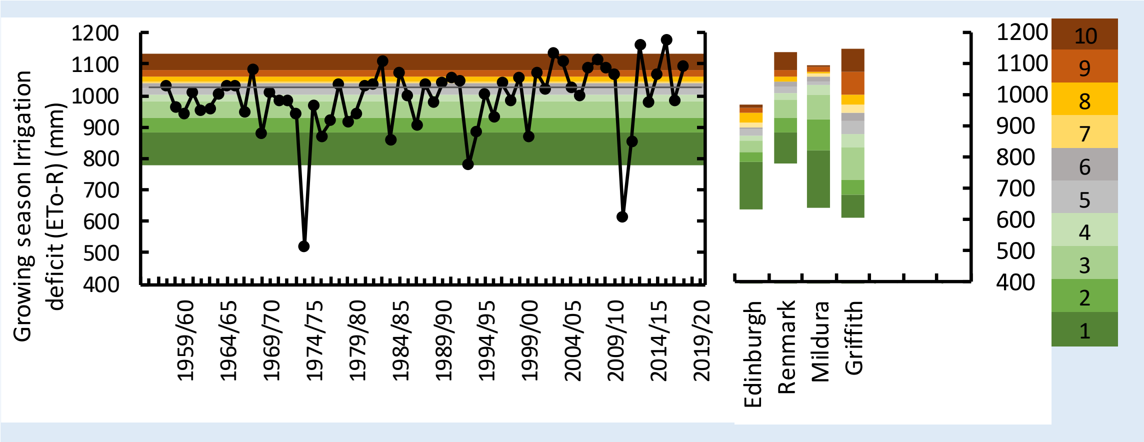
Trends and variation in rainfall, evapotranspiration and irrigation deficit



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.*

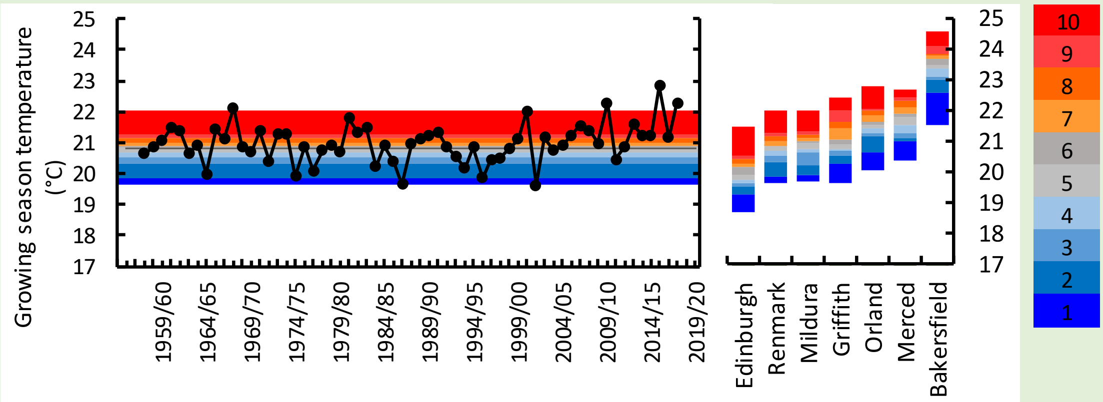


Evapotranspiration (ETo) like rainfall shows year-to-year variation, but unlike rainfall there is a trend of increasing evapotranspiration in recent decades. 100mm is equivalent to 1ML / ha.

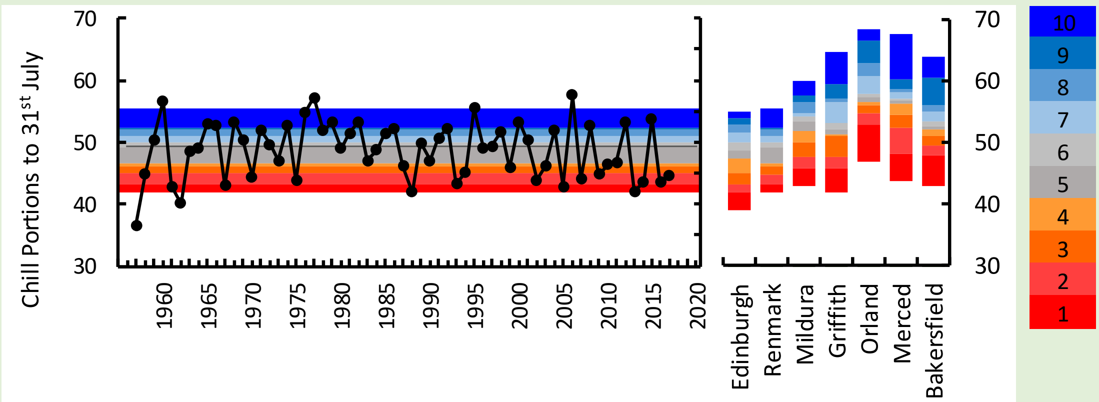


Irrigation demand, measured as the difference between evapotranspiration and rainfall (ETo - R), shows year-to-year variation and an increasing trend in recent decades. 100mm is equivalent to 1ML / ha.

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

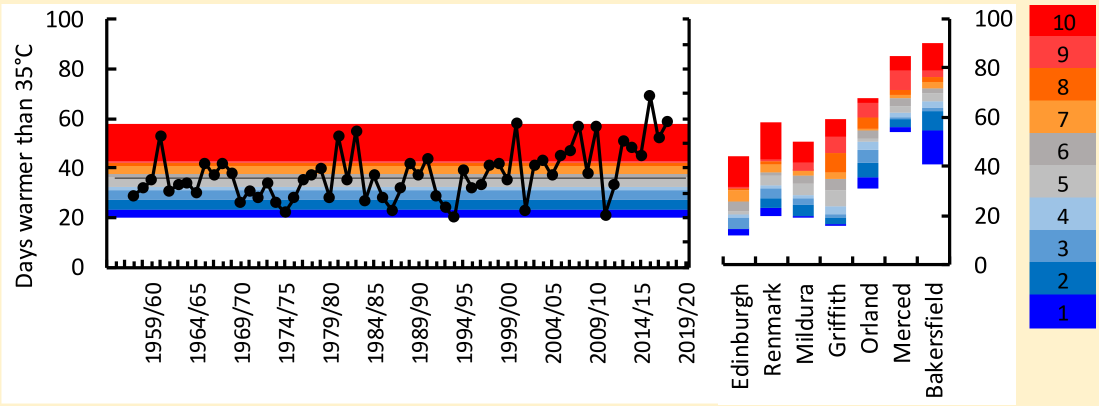


Mean temperature and therefore heat accumulation during the growing season varies from year-to-year. There is a trend of increasingly warmer conditions with many seasons being warmer than median (decile 6 or above) in the past 20 years. Temperatures in Australian almond growing locations are generally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

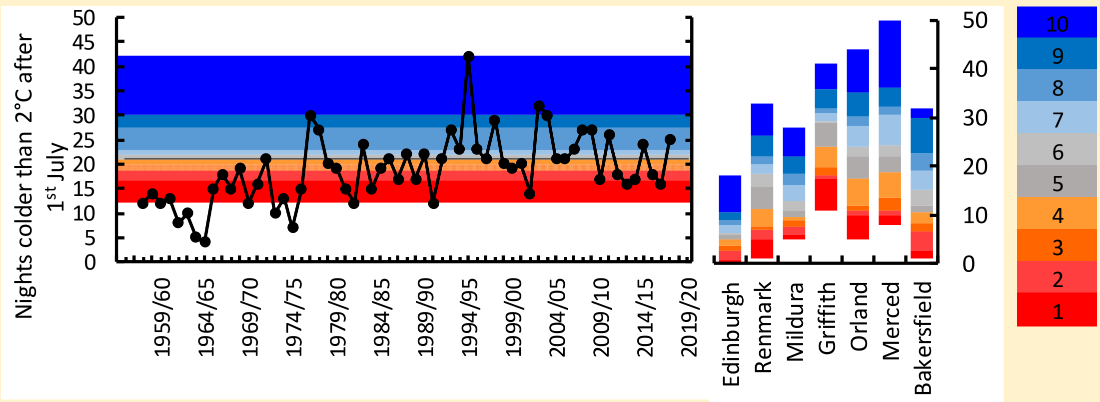


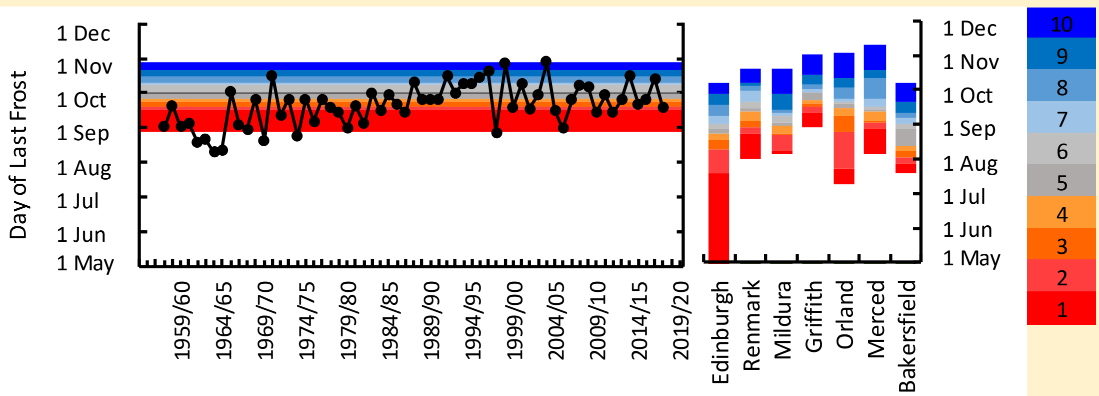
Chill accumulation at Renmark varies from year-to-year. There have been many more below median (decile 5 and lower) chill years in the past 20 years. Chill accumulation is typically less in more coastal Australian locations. Most Australian almond growing locations generally have less chill than Californian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

Trends and variation in heatwaves and frost potential nights



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



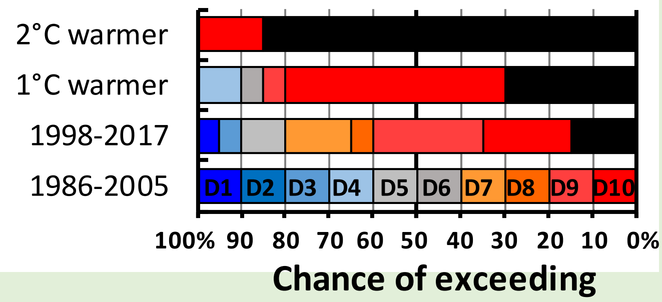


The number of nights sufficiently cold for frosts to potentially occur can be large in some years. Overall the number of cold nights are about as common in the inland Australian almond growing locations as in the Californian locations. The date of the last cold night has considerable year-to-year variation.

Recent and Future climate

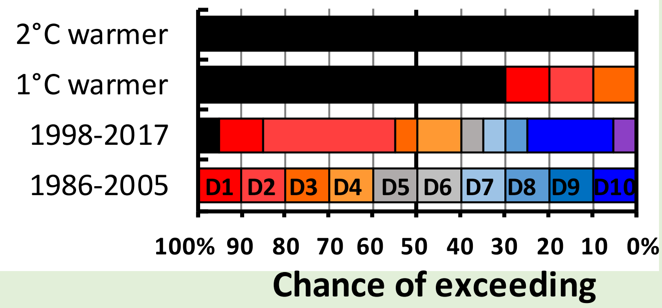
An increase in growing season temperature and heat units, and a decrease in chill units

Growing season temperature (°C)



	Minimum	Median	Maximum
2°C warmer	21.6	22.8	24.0
1°C warmer	20.6	21.8	23.0
1998-2017	19.6	21.2	22.8
1986-2005	19.6	20.8	22.0

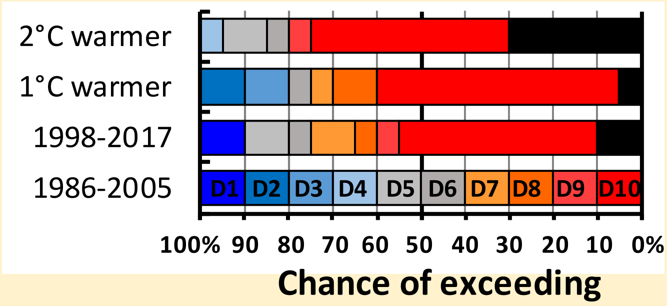
Chill accumulation until 31st July (Dynamic model chill portions)



	Minimum	Median	Maximum
2°C warmer	23	32	38
1°C warmer	33	40	46
1998-2017	42	47	58
1986-2005	42	50	55

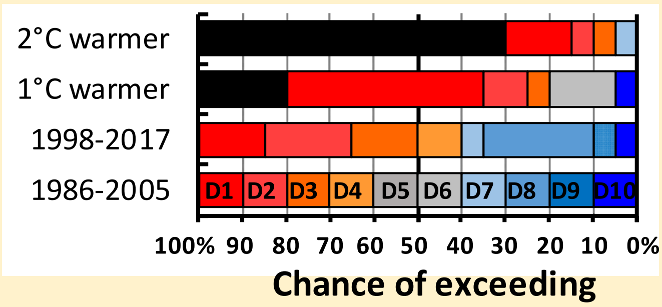
An increase in heatwaves and a decrease in frosts

Days warmer than 35°C



	Minimum	Median	Maximum
2°C warmer	32	56	72
1°C warmer	24	45	63
1998-2017	21	44	69
1986-2005	20	36	58

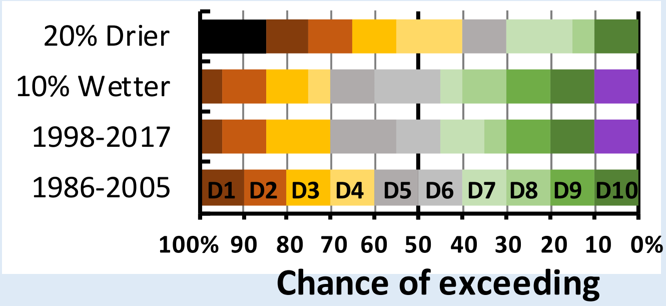
Nights cooler than 2°C after 1st July



	Minimum	Median	Maximum
2°C warmer	4	9	23
1°C warmer	8	15	34
1998-2017	14	21	32
1986-2005	12	21	42

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

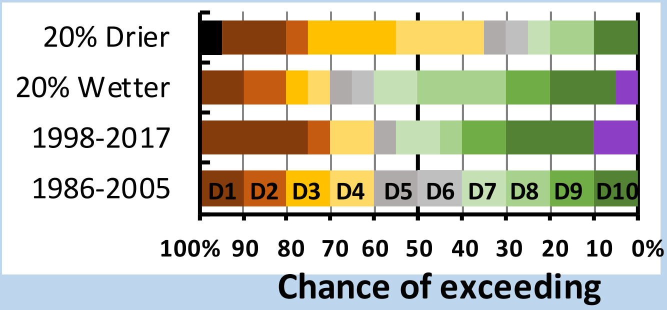
Growing season rain (mm)



	Minimum	Median	Maximum
20% Drier	42	86	191
10% Wetter	58	118	263
1998-2017	53	121	436
1986-2005	53	107	239

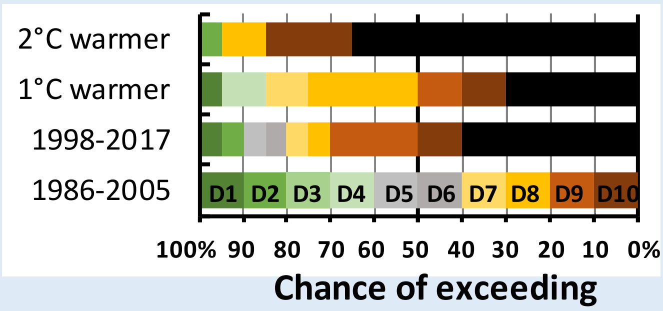
100mm is equivalent to 1ML / ha

February to April rain (mm)



	Minimum	Median	Maximum
20% Drier	4	26	108
20% Wetter	6	40	162
1998-2017	5	41	137
1986-2005	5	33	135

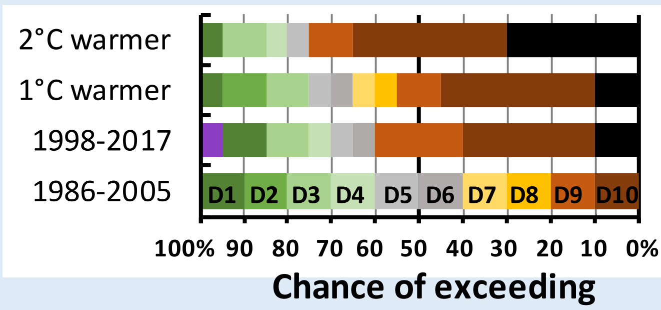
Growing season evapotranspiration (mm)



	Minimum	Median	Maximum
2°C warmer	1093	1200	1288
1°C warmer	1052	1155	1241
1998-2017	1053	1177	1254
1986-2005	1012	1111	1193

100mm is equivalent to 1ML / ha

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

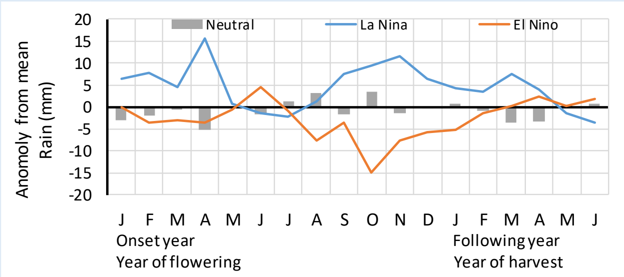


	Minimum	Median	Maximum
2°C warmer	860	1116	1231
1°C warmer	819	1071	1184
1998-2017	617	1063	1176
1986-2005	779	1026	1136

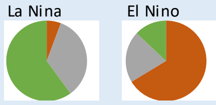
100mm is equivalent to 1ML / ha

Influence of climate drivers

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

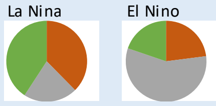


Rain from September to December

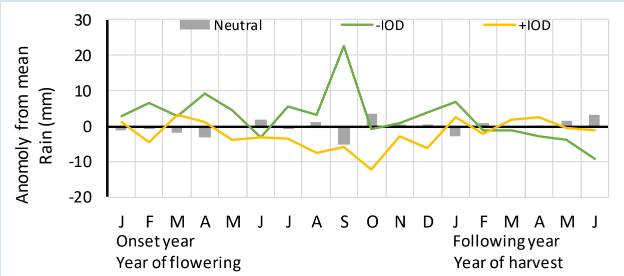


	mm
Minimum	6
Tercile 1	65
Tercile 2	111
Maximum	247

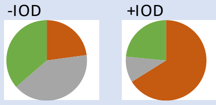
Rain from January to March



	mm
Minimum	0
Tercile 1	24
Tercile 2	50
Maximum	231

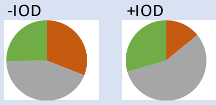


Rain from September to December



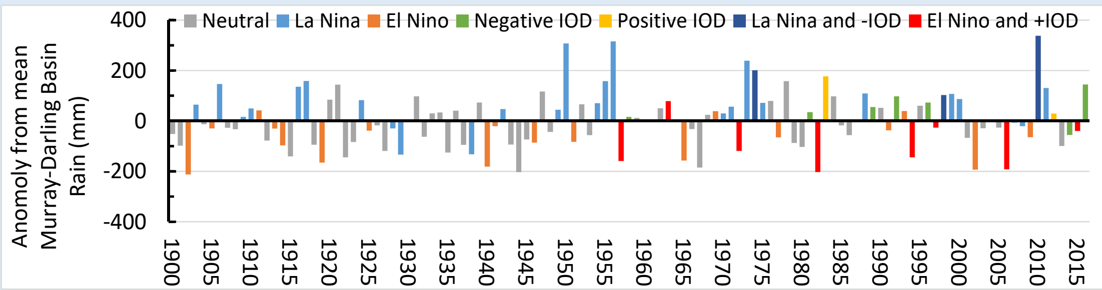
	mm
Minimum	6
Tercile 1	65
Tercile 2	113
Maximum	247

Rain from January to March

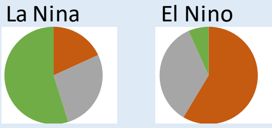


	mm
Minimum	0
Tercile 1	23
Tercile 2	50
Maximum	231

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.

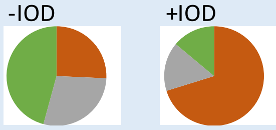


Rain from January to December



	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

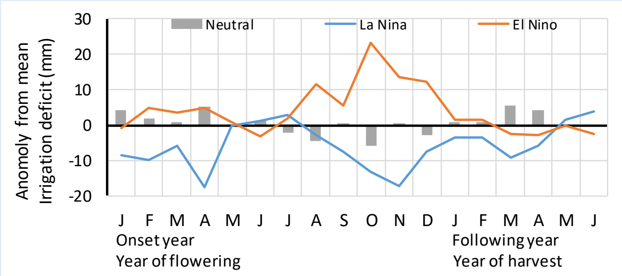
Rain from January to December



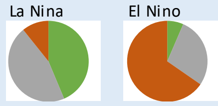
	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

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

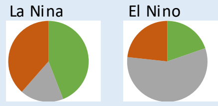


Irrigation deficit from September to December

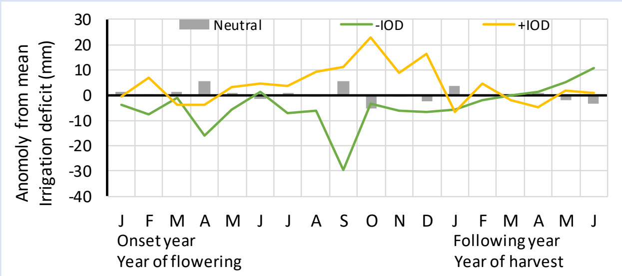


	mm
Minimum	240
Tercile 1	469
Tercile 2	548
Maximum	685

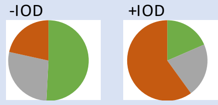
Irrigation deficit from January to March



	mm
Minimum	242
Tercile 1	468
Tercile 2	500
Maximum	579

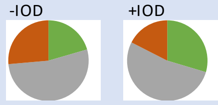


Irrigation deficit from September to December



	mm
Minimum	240
Tercile 1	469
Tercile 2	551
Maximum	685

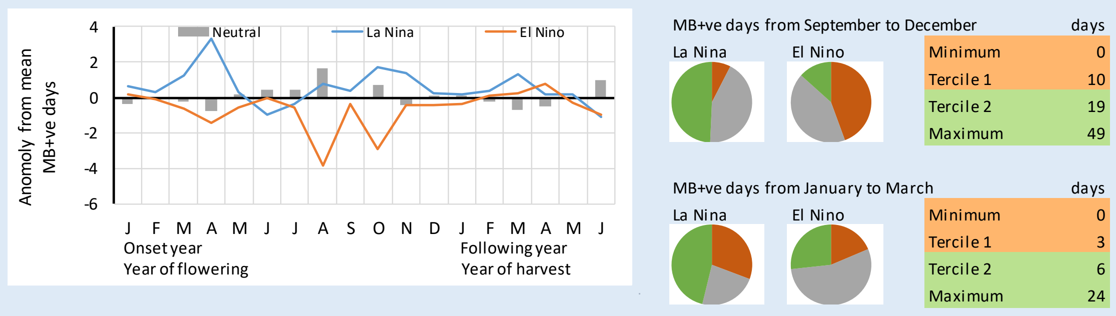
Irrigation deficit from January to March

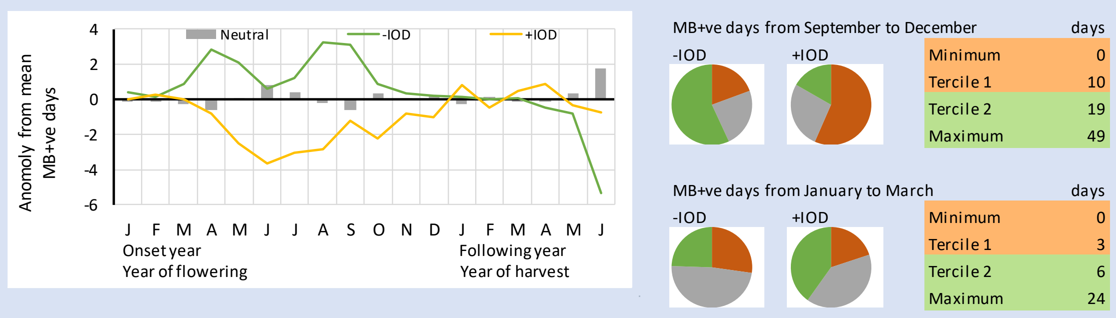


	mm
Minimum	242
Tercile 1	468
Tercile 2	500
Maximum	579

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.

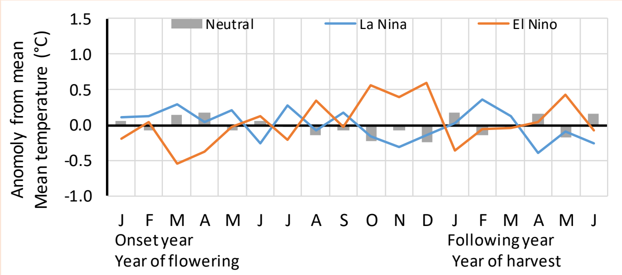
Rainy and humid conditions with La Niña and negative IOD





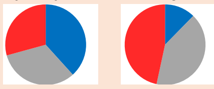
Rainy and humid conditions measured by the number of Moisture Balance positive (MB+ve) days were influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year).

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



Mean temperature from September to December

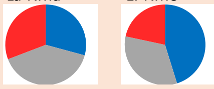
La Nina El Nino



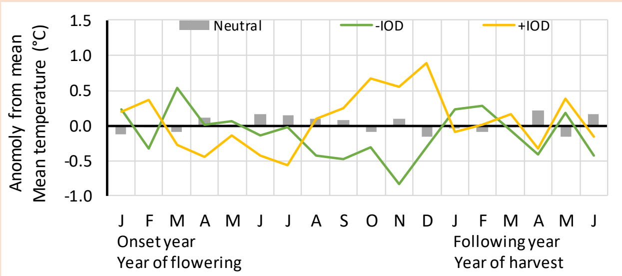
	°C
Minimum	17.2
Tercile 1	18.4
Tercile 2	19.0
Maximum	20.5

Mean temperature from January to March

La Nina El Nino

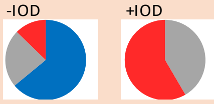


	°C
Minimum	21.3
Tercile 1	22.8
Tercile 2	23.8
Maximum	24.9



Mean temperature from September to December

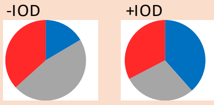
-IOD +IOD



	°C
Minimum	17.2
Tercile 1	18.4
Tercile 2	19.0
Maximum	20.5

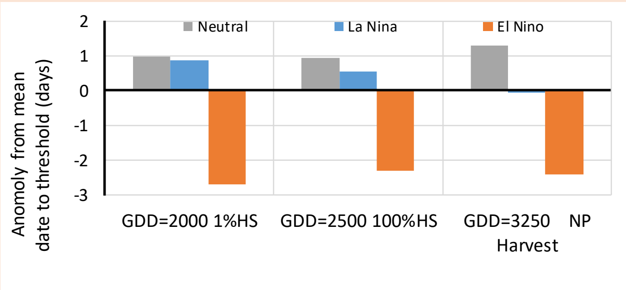
Mean temperature from January to March

-IOD +IOD



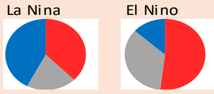
	°C
Minimum	21.3
Tercile 1	22.8
Tercile 2	23.8
Maximum	24.9

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).



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

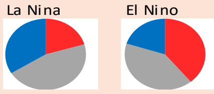
La Nina El Nino



Minimum	28-Dec
Tercile 1	7-Jan
Tercile 2	11-Jan
Maximum	19-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

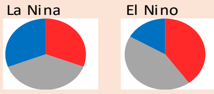
La Nina El Nino



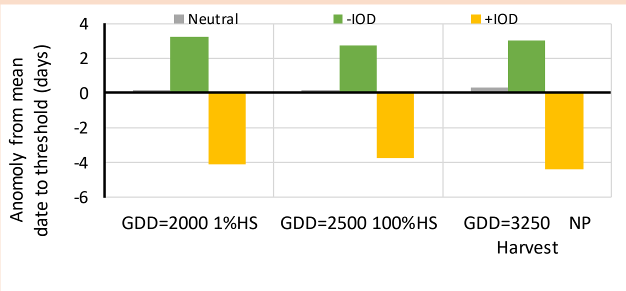
Minimum	20-Jan
Tercile 1	30-Jan
Tercile 2	6-Feb
Maximum	15-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

La Nina El Nino

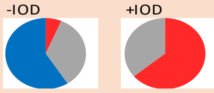


Minimum	26-Feb
Tercile 1	10-Mar
Tercile 2	19-Mar
Maximum	3-Apr



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

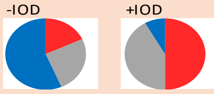
-IOD +IOD



Minimum	28-Dec
Tercile 1	6-Jan
Tercile 2	11-Jan
Maximum	19-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

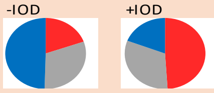
-IOD +IOD



Minimum	20-Jan
Tercile 1	30-Jan
Tercile 2	5-Feb
Maximum	15-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

-IOD +IOD



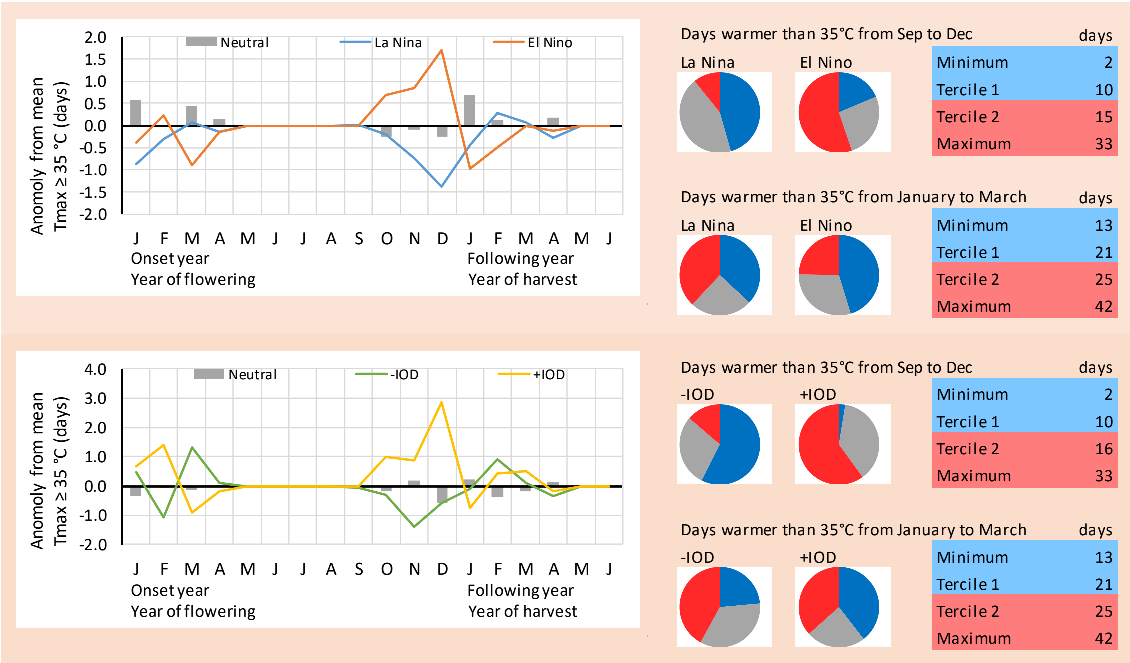
Minimum	26-Feb
Tercile 1	10-Mar
Tercile 2	18-Mar
Maximum	3-Apr

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

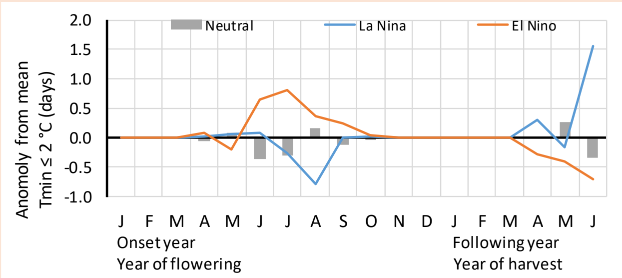
ENSO and IOD had minimal influence on the accumulation of chill hours after August, and almost none before August.

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



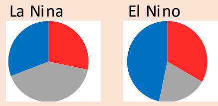
Heatwaves, measured as days warmer than 35 °C were influenced by the time of year and by ENSO and IOD. El Niño years or positive IOD years were likely to have more spring and early summer heatwaves than La Niña years or negative IOD years. Heatwaves in later summer were largely independent of ENSO and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

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



Nights colder than 2°C from August to December

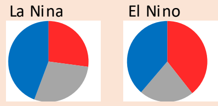
La Nina, El Nino



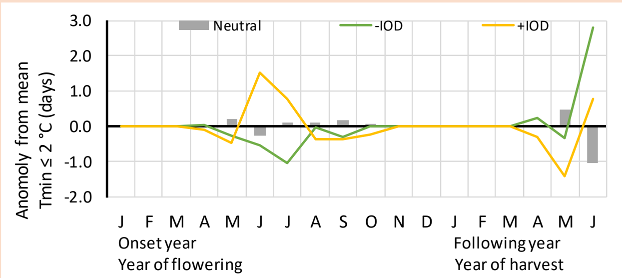
	days
Minimum	0
Tercile 1	7
Tercile 2	11
Maximum	21

Latest night after 1st August colder than 2°C

La Nina, El Nino

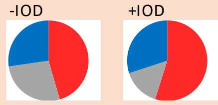


	Date
Minimum	Nil
Tercile 1	14-Sep
Tercile 2	27-Sep
Maximum	30-Oct



Nights colder than 2°C from August to December

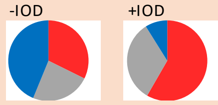
-IOD, +IOD



	days
Minimum	0
Tercile 1	8
Tercile 2	11
Maximum	21

Latest night after 1st August colder than 2°C

-IOD, +IOD



	Date
Minimum	Nil
Tercile 1	15-Sep
Tercile 2	28-Sep
Maximum	30-Oct

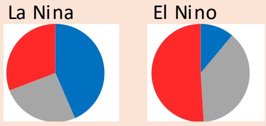
The number of frost from August to December, and the date of last frost (frost measured as nights colder than 2 °C) was not strongly influenced to ENSO or IOD.

Information from the meteorological station at the Loxton Research Centre (station 24024) was used to determine the number of nights colder than 0°C and 2°C as the information prior to the mid 1990's from Renmark was unusually low and possibly an error associated with relocating the Renmark meteorological station.

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

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

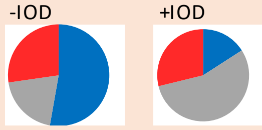
La Nina, El Nino



	hours
Minimum	36
Tercile 1	90
Tercile 2	125
Maximum	201

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

-IOD, +IOD



	hours
Minimum	36
Tercile 1	90
Tercile 2	125
Maximum	201

Favourable Pollination conditions were influenced by ENSO or IOD.

The correlation coefficients (r) of the agroclimatic indices 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.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.11	-0.10	0.26	-0.43	-0.38
Rain from September to December	-0.34	-0.32	0.37	-0.25	-0.30
Rain from January to March	-0.18	-0.22	0.25	0.08	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	0.36	0.31	-0.36	0.18	0.19
Irrigation deficit from September to December	0.46	0.43	-0.40	0.48	0.43
Irrigation deficit from January to March	0.08	0.01	-0.18	-0.20	-0.11
Rainy and humid conditions					
MB+ve days from September to December	-0.30	-0.30	0.28	-0.40	-0.38
MB+ve days from January to March	-0.14	-0.11	0.23	0.23	0.16
Heat accumulation					
Mean temperature from September to December	0.27	0.22	-0.16	0.48	0.35
Mean temperature from January to March	-0.18	-0.25	0.15	0.27	0.22
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.26	-0.20	0.23	-0.46	-0.38
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.21	-0.14	0.17	-0.39	-0.34
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.12	-0.06	0.01	-0.29	-0.19
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.02	0.07	-0.10	-0.13	-0.03
Utah chill units accumulated to 31st July	0.01	0.13	-0.05	-0.25	-0.09
Heatwaves					
Days warmer than 35°C from September to December	0.41	0.32	-0.29	0.44	0.26
Days warmer than 35°C from January to March	-0.03	-0.16	-0.04	0.06	0.00
Daylight hours warmer than 35°C from September to December	0.43	0.34	-0.29	0.39	0.24
Daylight hours warmer than 35°C from January to March	-0.01	-0.14	-0.06	0.04	-0.02
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	0.17	0.06	-0.38	0.16	0.10

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).

Appendix 4. Loxton

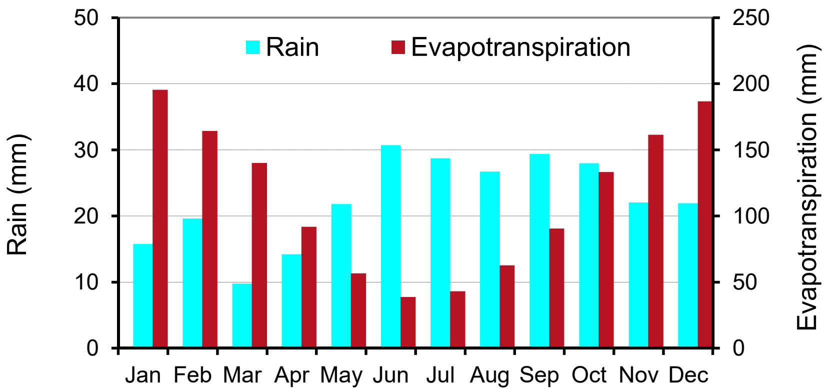
The yearly climate at a glance

Loxton 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 Loxton Research Centre meteorological station (station 24024). The source was patched point data (https://silo.longpaddock.qld.gov.au/).

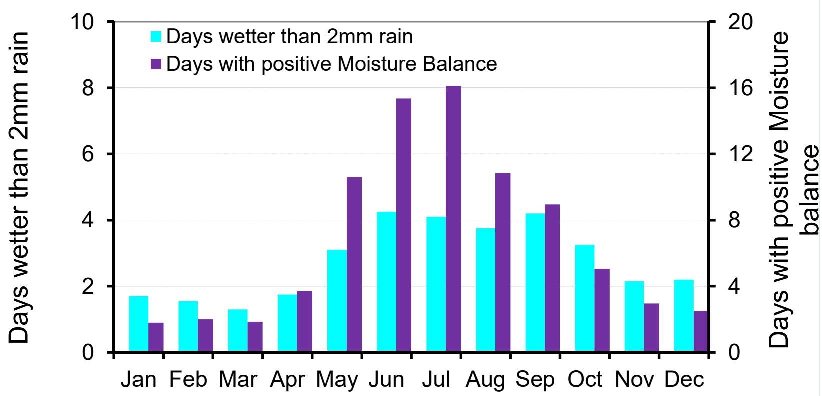
Low rainfall and high evapotranspiration

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

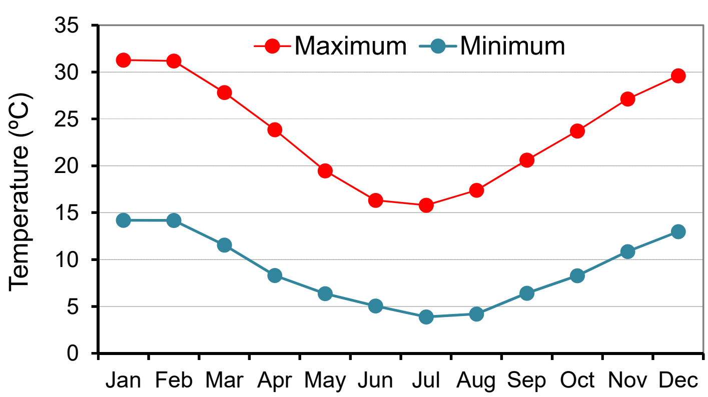
Evaporative demand is seasonal and much higher in summer than in winter.



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.



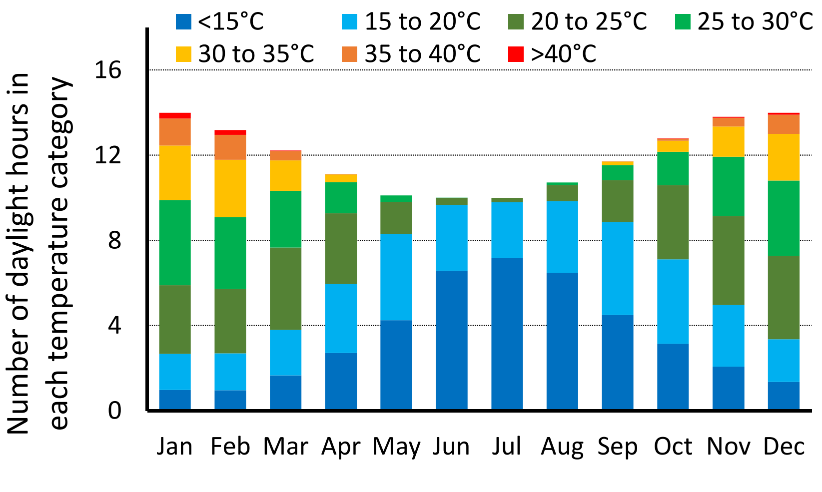
Season pattern of hot summers and cold winters



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

Winter months have mean maximum temperatures between 15° and 20°C, while mean minimum temperatures are about 5°C.

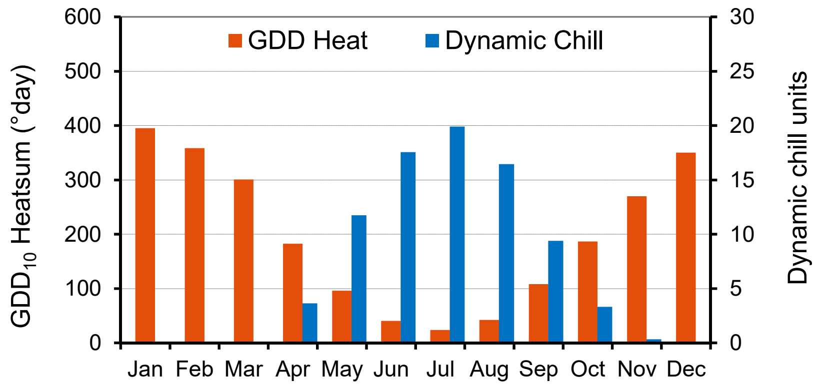
Plenty of daylight hours with temperatures desirable for photosynthesis



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.

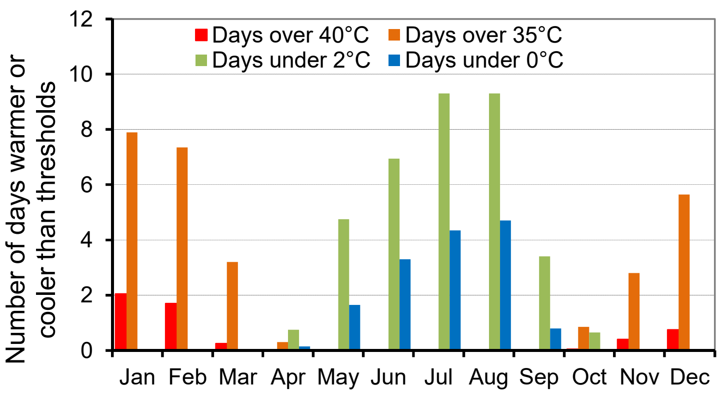
An abundance of heat units and moderate chill units



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

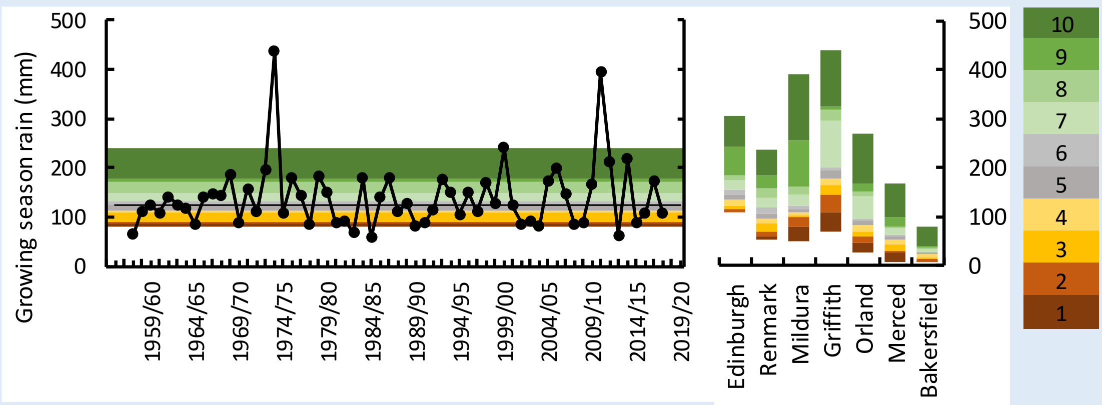


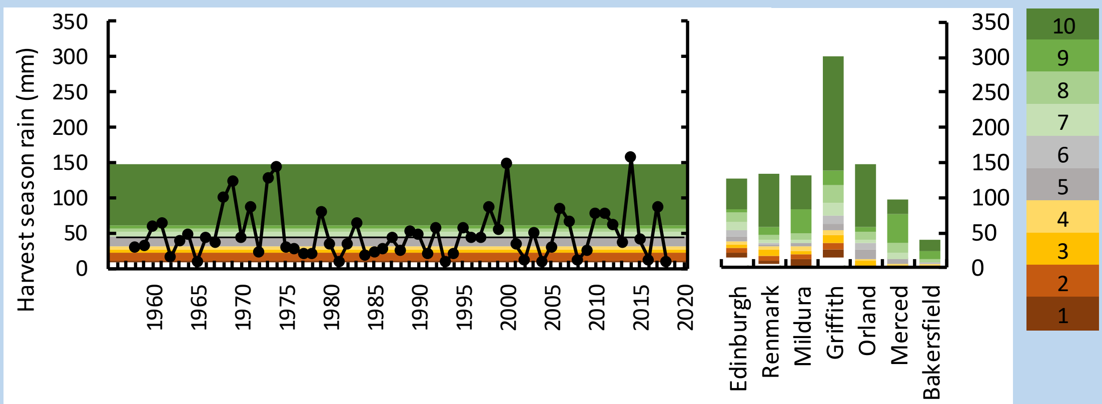
Days warmer than 35°C are common in summer (almost 1 in 4 days). Days hotter than 40°C are less frequent but not uncommon.

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.

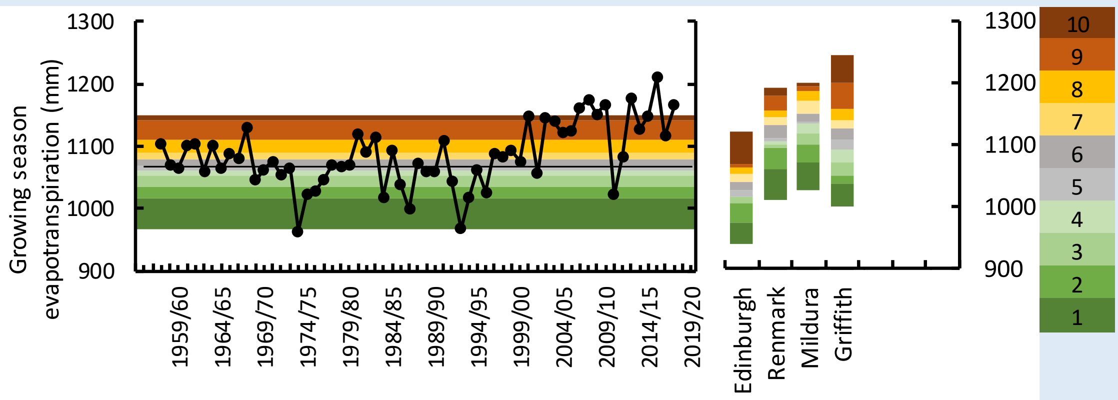
Historic trends in climate

Trends and variation in rainfall, evapotranspiration and irrigation deficit

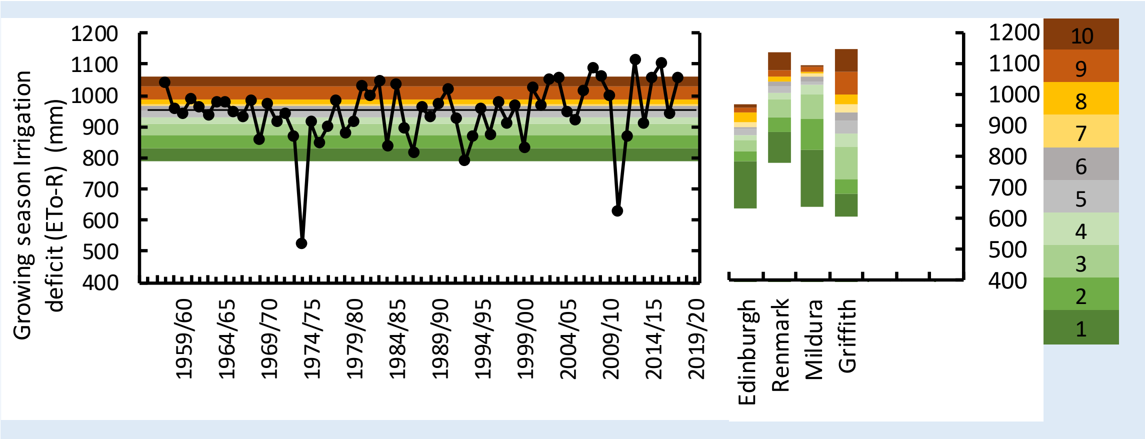




There is considerable year-to-year variation in rainfall. Almonds are grown in both wetter locations in Australia and drier locations in central and southern California. Growing season and Harvest season in Australia were calculated from October to April and February to April; and April to October and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

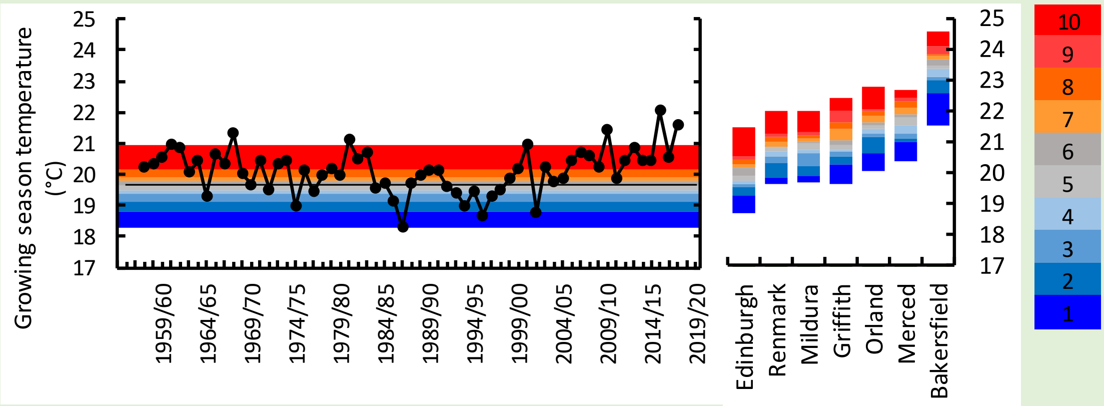


Evapotranspiration (ETo) like rainfall shows year-to-year variation, but unlike rainfall there is a trend of increasing evapotranspiration in recent decades. 100mm is equivalent to 1ML / ha.

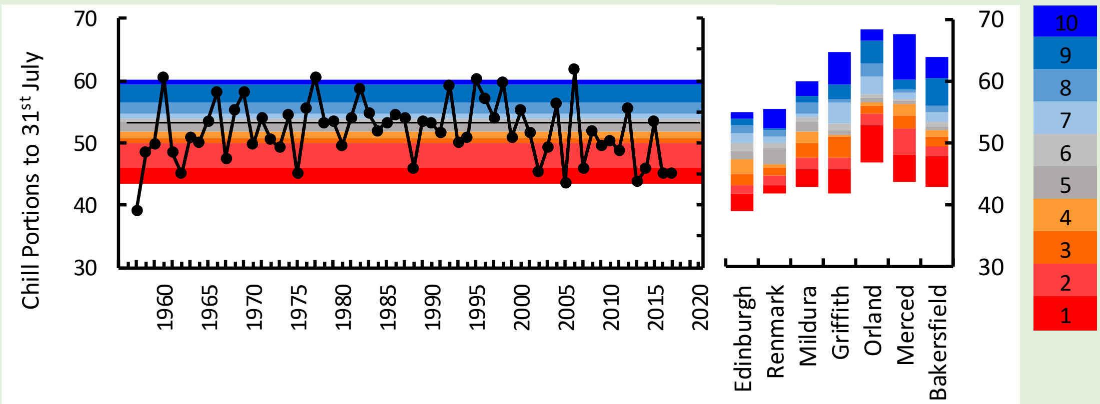


Irrigation demand, measured as the difference between evapotranspiration and rainfall (ETo - R), shows year-to-year variation and an increasing trend in recent decades. 100mm is equivalent to 1ML / ha.

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

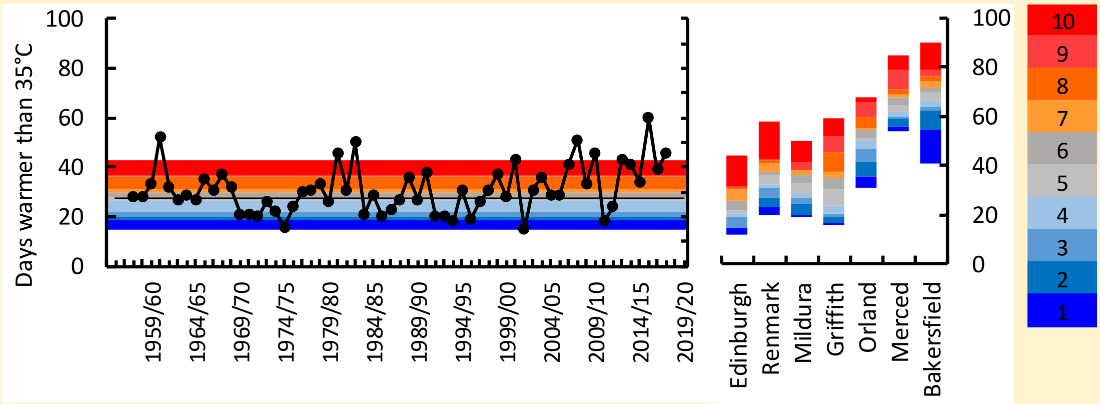


Mean temperature and therefore heat accumulation during the growing season varies from year-to-year. There is a trend of increasingly warmer conditions with many seasons being warmer than median (decile 6 or above) in the past 20 years. Temperatures in Australian almond growing locations are generally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

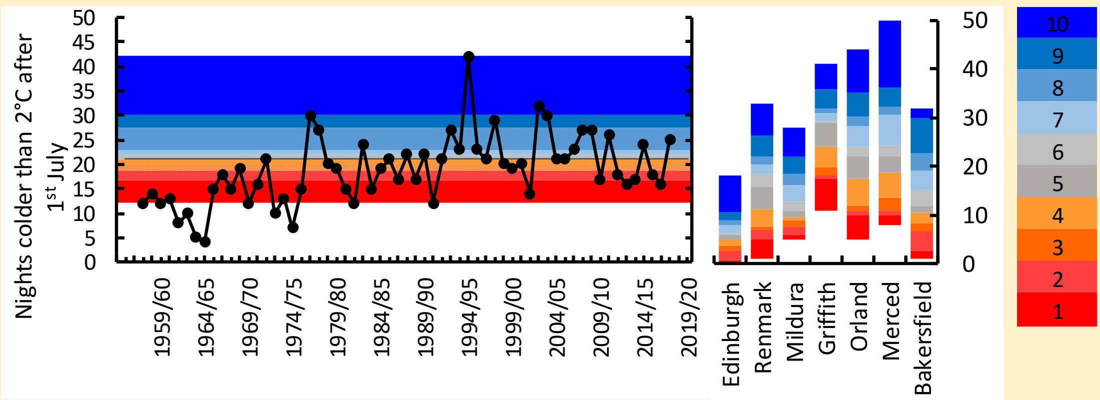


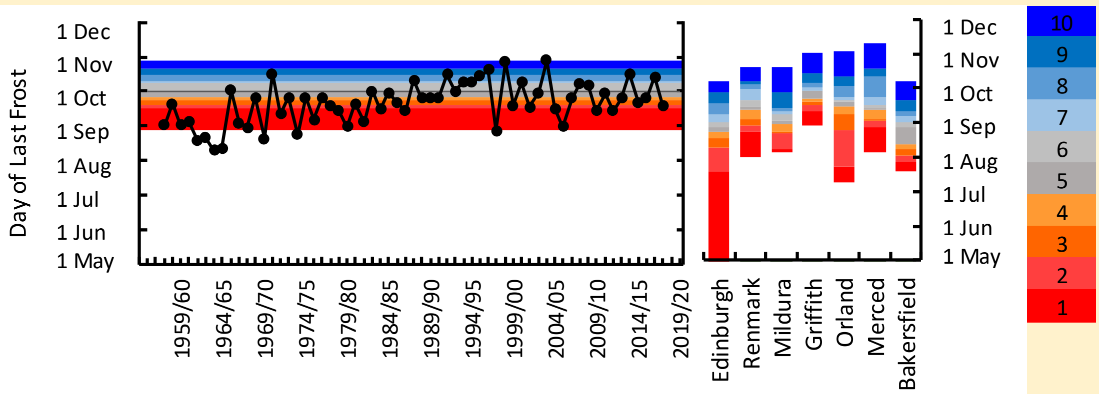
Chill accumulation at Loxton varies from year-to-year. There have been many more below median (decile 5 and lower) chill years in the past 20 years. Chill accumulation is typically less in more coastal Australian locations. Most Australian almond growing locations generally have less chill than Californian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

Trends and variation in heatwaves and frost potential nights



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



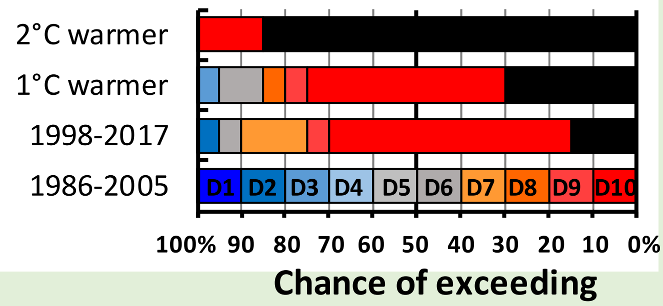


The number of nights sufficiently cold for frosts to potentially occur can be large in some years. Overall the number of cold nights are about as common in the inland Australian almond growing locations as in the Californian almond growing locations. The date of the last cold night has considerable year-to-year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

Recent and Future climate

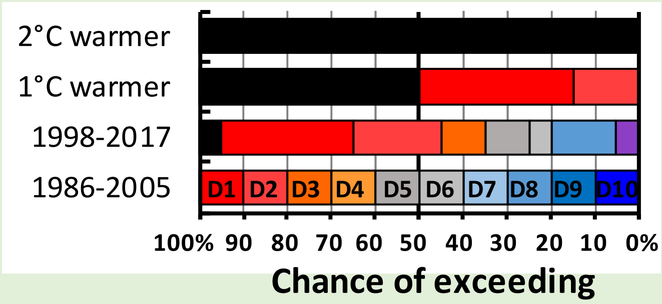
An increase in growing season temperature and heat units, and a decrease in chill units

Growing season temperature (°C)



	Minimum	Median	Maximum
2°C warmer	20.3	21.7	23.0
1°C warmer	19.3	20.7	22.0
1998-2017	18.8	20.4	22.0
1986-2005	18.3	19.7	21.0

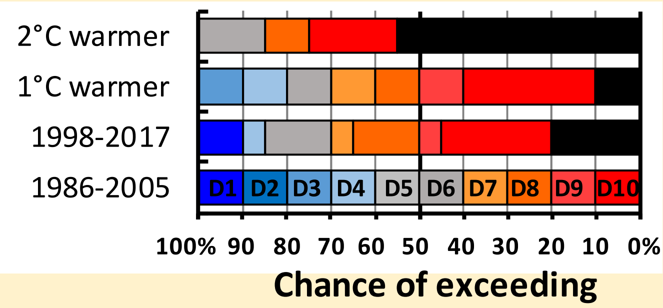
Chill accumulation until 31st July (Dynamic model chill portions)



	Minimum	Median	Maximum
2°C warmer	28	36	43
1°C warmer	36	43	48
1998-2017	44	51	62
1986-2005	45	53	60

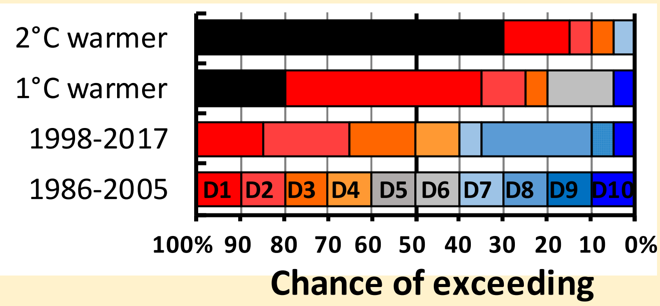
An increase in heatwaves and a decrease in frosts

Days warmer than 35°C



	Minimum	Median	Maximum
2°C warmer	28	45	60
1°C warmer	21	36	53
1998-2017	15	35	60
1986-2005	15	28	43

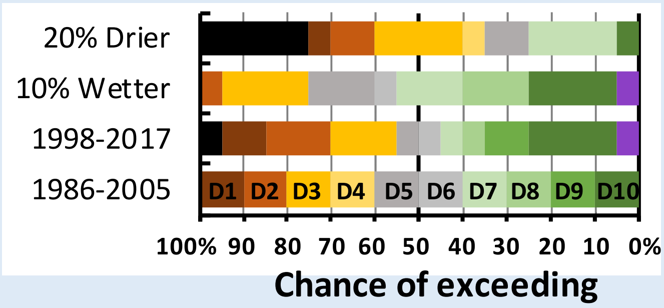
Nights cooler than 2°C after 1st July



	Minimum	Median	Maximum
2°C warmer	4	9	23
1°C warmer	8	15	34
1998-2017	14	21	32
1986-2005	12	21	42

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

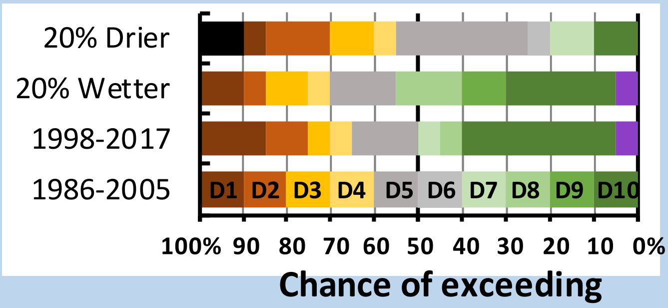
Growing season rain (mm)



	Minimum	Median	Maximum
20% Drier	65	100	193
10% Wetter	89	138	265
1998-2017	63	136	394
1986-2005	81	125	241

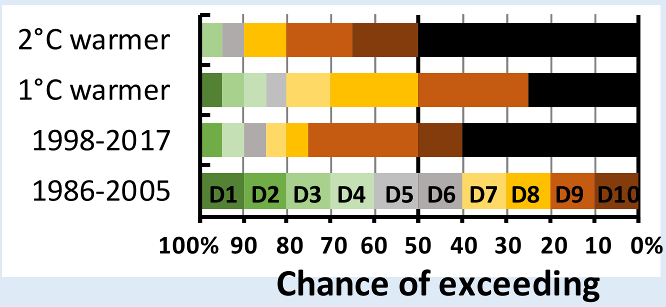
100mm is equivalent to 1ML / ha

February to April rain (mm)



	Minimum	Median	Maximum
20% Drier	6	35	118
20% Wetter	10	53	178
1998-2017	9	53	157
1986-2005	8	44	148

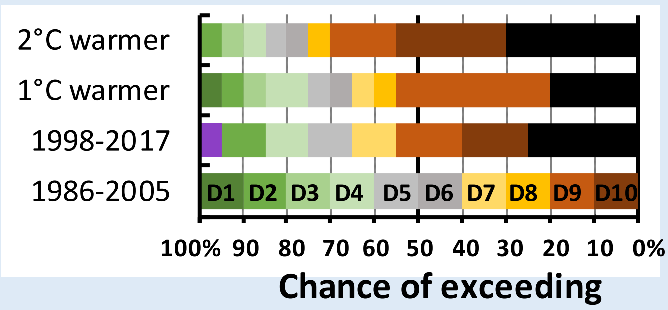
Growing season evapotranspiration (mm)



	Minimum	Median	Maximum
2°C warmer	1044	1153	1240
1°C warmer	1006	1111	1194
1998-2017	1023	1134	1210
1986-2005	967	1068	1148

100mm is equivalent to 1ML / ha

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

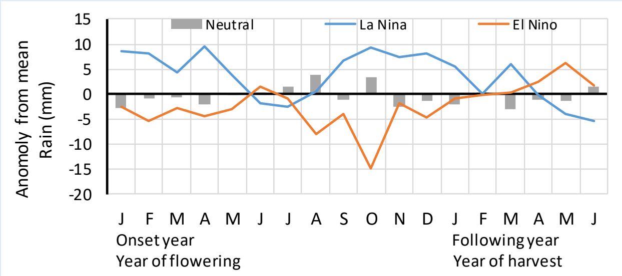


	Minimum	Median	Maximum
2°C warmer	867	1040	1150
1°C warmer	828	996	1104
1998-2017	629	985	1114
1986-2005	790	953	1059

100mm is equivalent to 1ML / ha

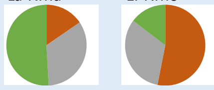
Influence of climate drivers

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



Rain from September to December

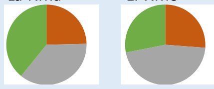
La Nina El Nino



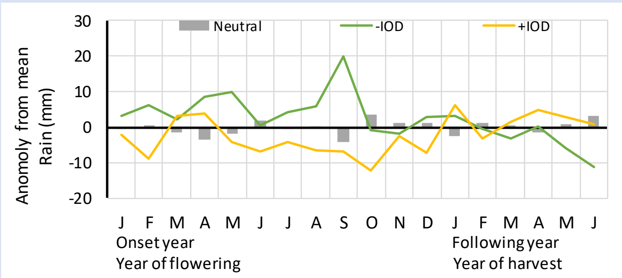
	mm
Minimum	8
Tercile 1	70
Tercile 2	115
Maximum	274

Rain from January to March

La Nina El Nino

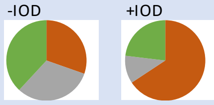


	mm
Minimum	1
Tercile 1	27
Tercile 2	54
Maximum	198



Rain from September to December

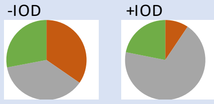
-IOD +IOD



	mm
Minimum	8
Tercile 1	70
Tercile 2	119
Maximum	274

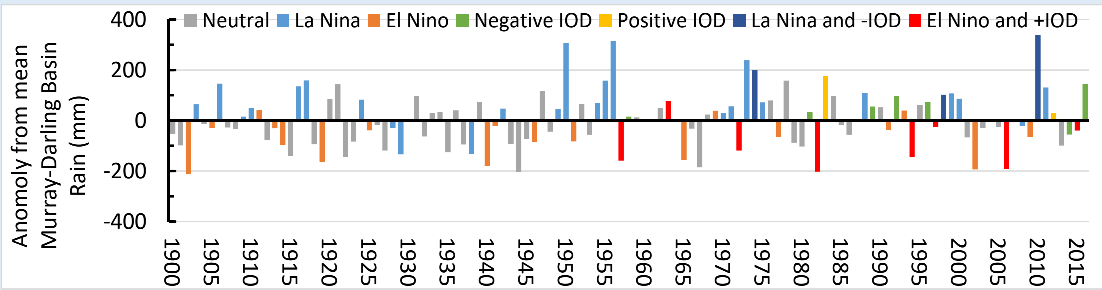
Rain from January to March

-IOD +IOD



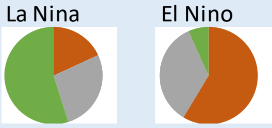
	mm
Minimum	1
Tercile 1	27
Tercile 2	54
Maximum	198

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.



Rain from January to December

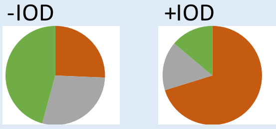
La Nina El Nino



	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

Rain from January to December

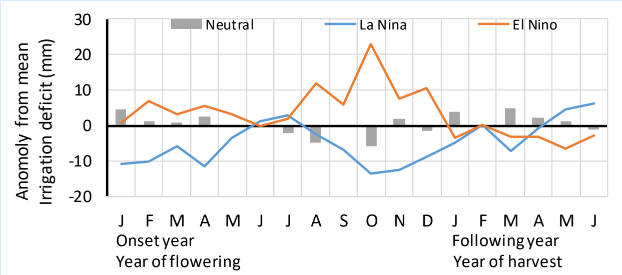
-IOD +IOD



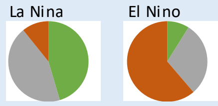
	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

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

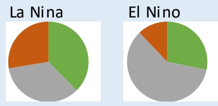


Irrigation deficit from September to December

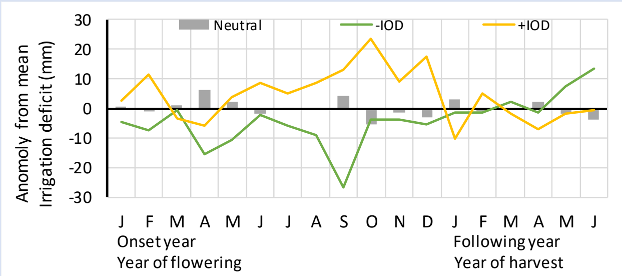


	mm
Minimum	267
Tercile 1	456
Tercile 2	523
Maximum	637

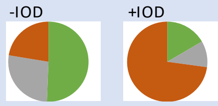
Irrigation deficit from January to March



	mm
Minimum	259
Tercile 1	447
Tercile 2	479
Maximum	561

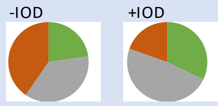


Irrigation deficit from September to December



	mm
Minimum	267
Tercile 1	456
Tercile 2	523
Maximum	637

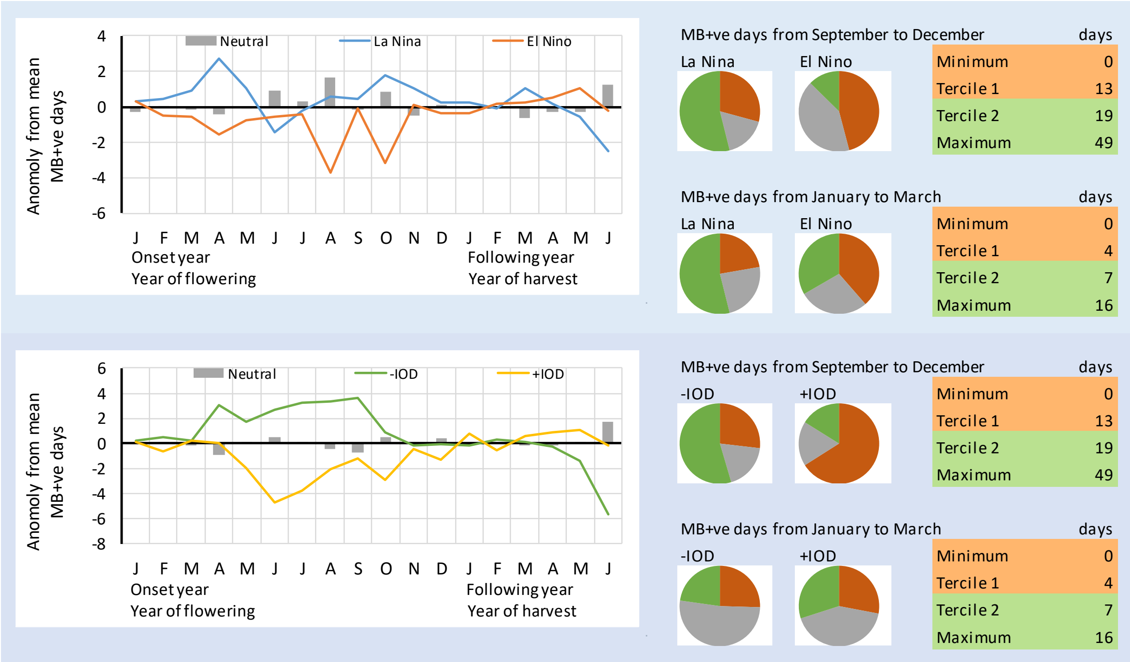
Irrigation deficit from January to March



	mm
Minimum	259
Tercile 1	441
Tercile 2	479
Maximum	561

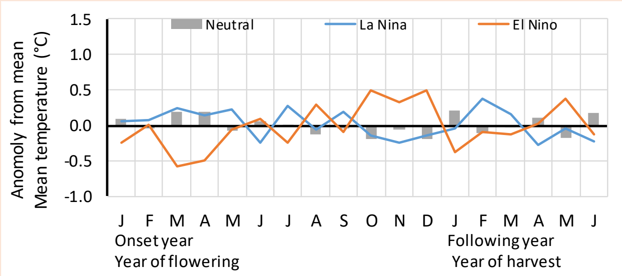
Irrigation deficit was influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year). 100mm is equivalent to 1ML / ha.

Rainy and humid conditions with La Niña and negative IOD



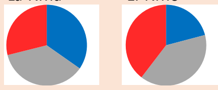
Rainy and humid conditions measured by the number of Moisture Balance positive (MB+ve) days were influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year).

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



Mean temperature from September to December °C

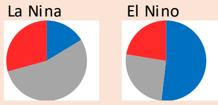
La Nina El Nino



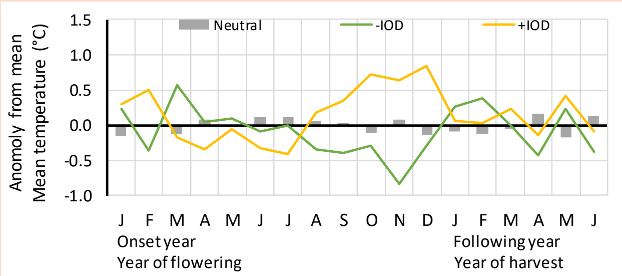
Minimum	16.2
Tercile 1	17.5
Tercile 2	18.2
Maximum	19.8

Mean temperature from January to March °C

La Nina El Nino

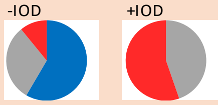


Minimum	20.0
Tercile 1	21.9
Tercile 2	23.0
Maximum	24.2



Mean temperature from September to December °C

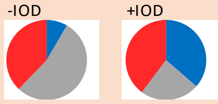
-IOD +IOD



Minimum	16.2
Tercile 1	17.5
Tercile 2	18.3
Maximum	19.8

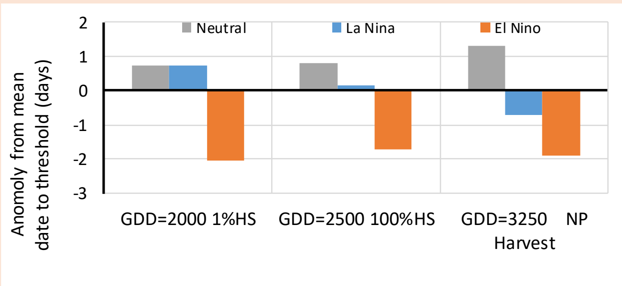
Mean temperature from January to March °C

-IOD +IOD



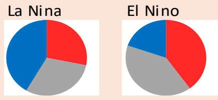
Minimum	20.0
Tercile 1	21.9
Tercile 2	22.9
Maximum	24.2

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).



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

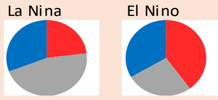
La Nina El Nino



Minimum	1-Jan
Tercile 1	11-Jan
Tercile 2	16-Jan
Maximum	30-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

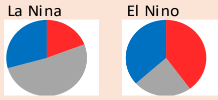
La Nina El Nino



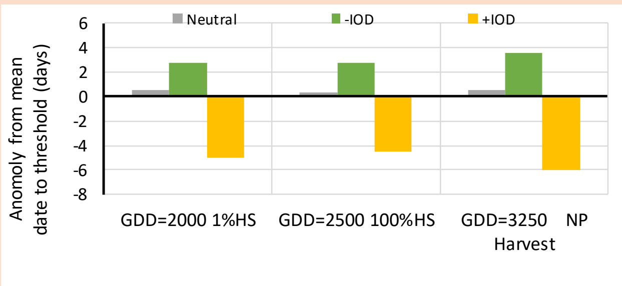
Minimum	25-Jan
Tercile 1	5-Feb
Tercile 2	13-Feb
Maximum	27-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

La Nina El Nino

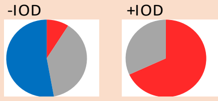


Minimum	5-Mar
Tercile 1	19-Mar
Tercile 2	28-Mar
Maximum	27-Apr



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

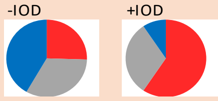
-IOD +IOD



Minimum	1-Jan
Tercile 1	11-Jan
Tercile 2	16-Jan
Maximum	30-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

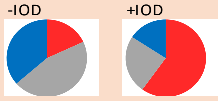
-IOD +IOD



Minimum	25-Jan
Tercile 1	5-Feb
Tercile 2	13-Feb
Maximum	27-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

-IOD +IOD



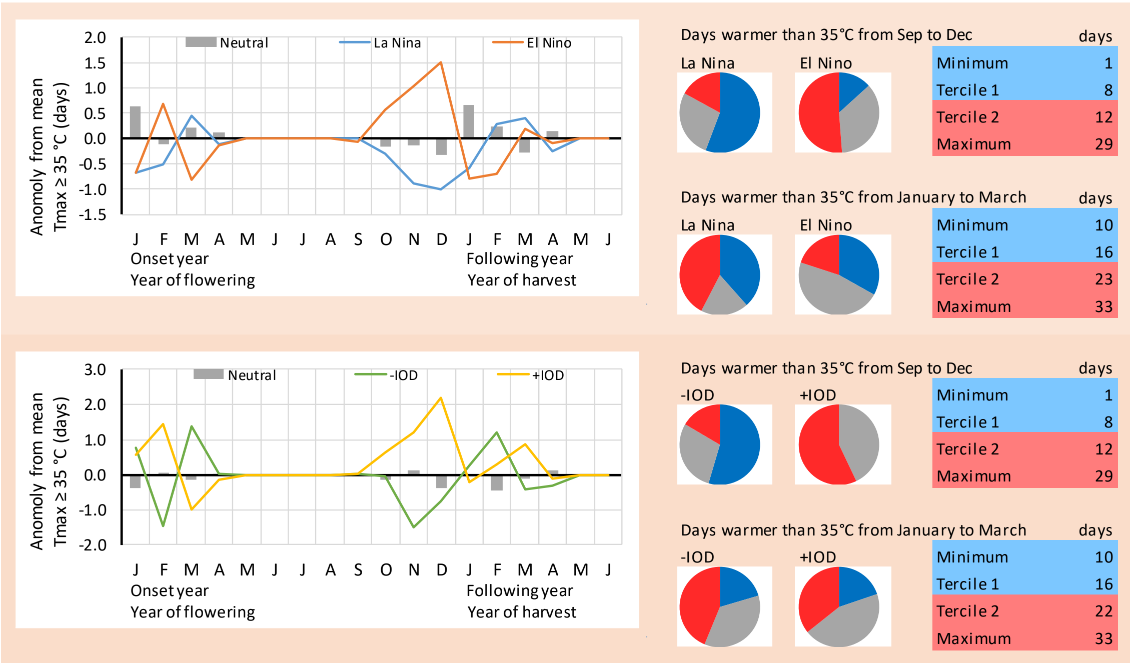
Minimum	5-Mar
Tercile 1	19-Mar
Tercile 2	29-Mar
Maximum	27-Apr

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

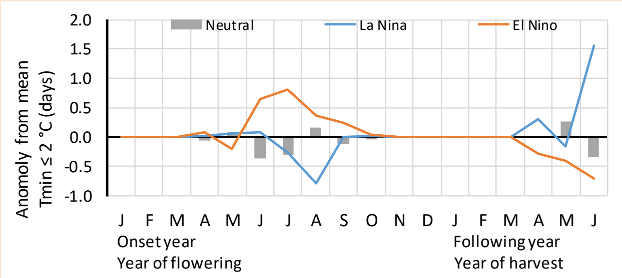
ENSO and IOD had minimal influence on the accumulation of chill hours after August, and almost none before August.

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



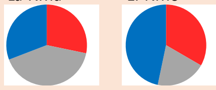
Heatwaves, measured as days warmer than 35 °C were influenced by the time of year and by ENSO and IOD. El Niño years or positive IOD years were likely to have more spring and early summer heatwaves than La Niña years or negative IOD years. Heatwaves in later summer were largely independent of ENSO and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

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



Nights colder than 2°C from August to December

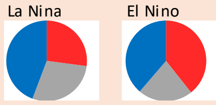
La Nina El Nino



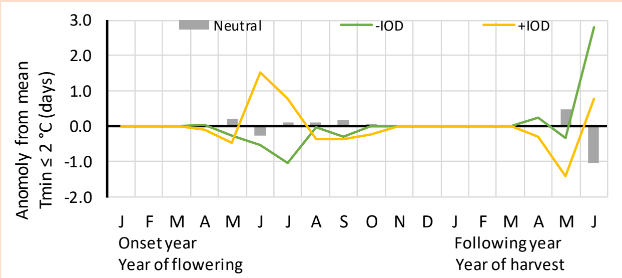
	days
Minimum	0
Tercile 1	7
Tercile 2	11
Maximum	21

Latest night after 1st August colder than 2°C

La Nina El Nino

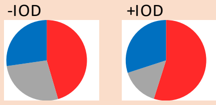


	Date
Minimum	Nil
Tercile 1	14-Sep
Tercile 2	27-Sep
Maximum	30-Oct



Nights colder than 2°C from August to December

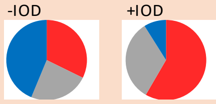
-IOD +IOD



	days
Minimum	0
Tercile 1	8
Tercile 2	11
Maximum	21

Latest night after 1st August colder than 2°C

-IOD +IOD



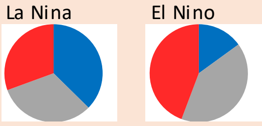
	Date
Minimum	Nil
Tercile 1	15-Sep
Tercile 2	28-Sep
Maximum	30-Oct

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

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

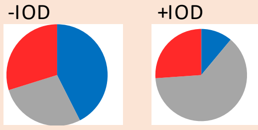
La Nina El Nino



	hours
Minimum	37
Tercile 1	83
Tercile 2	115
Maximum	184

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

-IOD +IOD



	hours
Minimum	37
Tercile 1	82
Tercile 2	115
Maximum	184

Favourable Pollination conditions were influenced by ENSO or IOD.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.13	-0.14	0.30	-0.48	-0.44
Rain from September to December	-0.32	-0.31	0.40	-0.24	-0.30
Rain from January to March	-0.16	-0.21	0.19	0.08	0.07
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	0.30	0.24	-0.30	0.17	0.19
Irrigation deficit from September to December	0.43	0.40	-0.39	0.47	0.42
Irrigation deficit from January to March	0.04	-0.03	-0.13	-0.20	-0.09
Rainy and humid conditions					
MB+ve days from September to December	-0.23	-0.22	0.23	-0.38	-0.35
MB+ve days from January to March	-0.04	-0.02	0.16	0.28	0.13
Heat accumulation					
Mean temperature from September to December	0.22	0.18	-0.10	0.41	0.32
Mean temperature from January to March	-0.16	-0.20	0.17	0.27	0.22
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.19	-0.13	0.13	-0.38	-0.33
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.13	-0.07	0.08	-0.31	-0.28
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.06	-0.02	-0.05	-0.23	-0.16
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.05	0.05	-0.14	-0.17	-0.17
Utah chill units accumulated to 31st July	0.02	0.09	-0.04	-0.30	-0.23
Heatwaves					
Days warmer than 35°C from September to December	0.40	0.34	-0.29	0.38	0.26
Days warmer than 35°C from January to March	-0.01	-0.12	-0.07	0.06	-0.02
Daylight hours warmer than 35°C from September to December	0.41	0.35	-0.28	0.29	0.21
Daylight hours warmer than 35°C from January to March	-0.01	-0.11	-0.05	0.05	0.00
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	0.13	0.02	-0.38	0.20	0.11

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).

Appendix 5. Murray Bridge

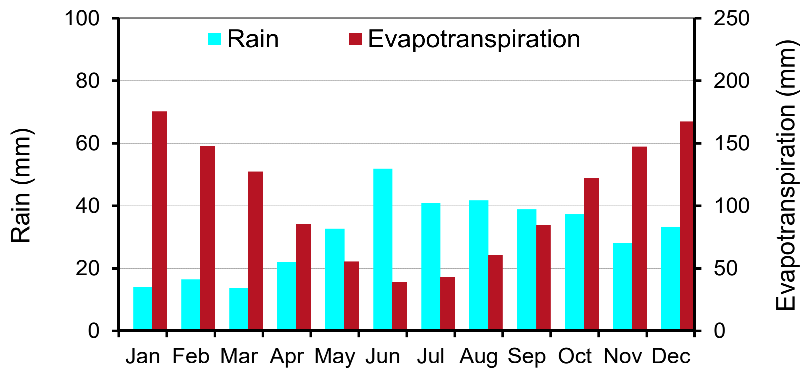
The yearly climate at a glance

Murray Bridge is used here to describe the climate of South Australia's Murraylands region. Murray Bridge has a warm dry climate with distinct seasonality in temperature and evapotranspiration (ETo) with a seasonally wetter winter and drier summer. 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 Murray Bridge Comparison meteorological station (station 24521). The source was patched point data (https://silo.longpaddock.qld.gov.au/).

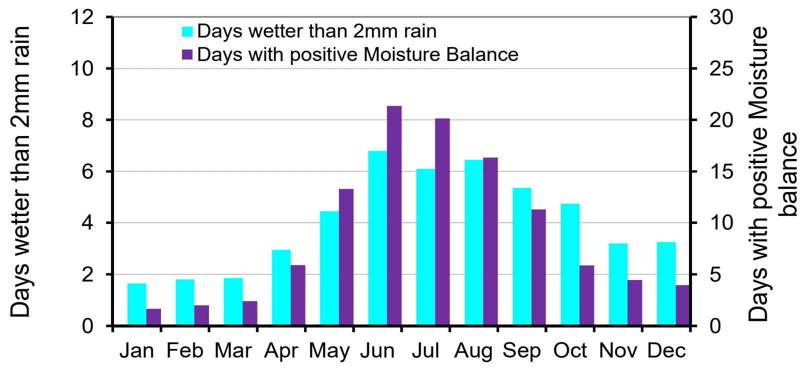
Low rainfall and high evapotranspiration

Rainfall is low in most months although winter and spring months are wetter than summer and autumn months.

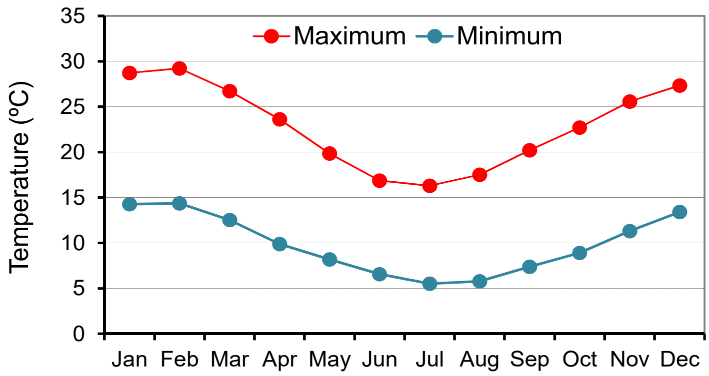
Evaporative demand is seasonal and much higher in summer than in winter.



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.



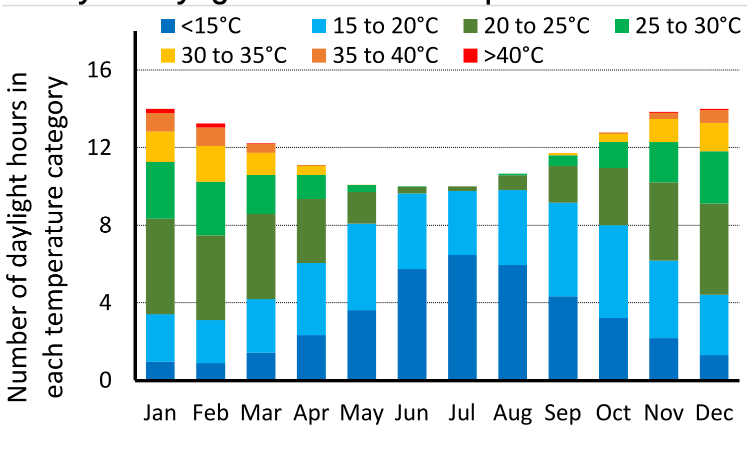
Season pattern of hot summers and cold winters



Summers are characterised by mean monthly maximum temperatures close to 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.

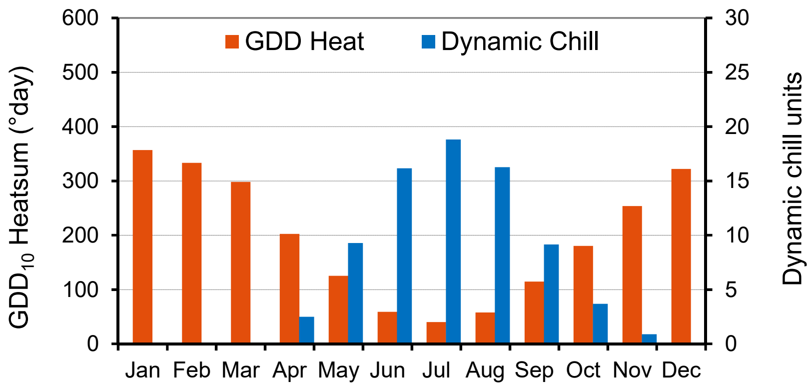
Plenty of daylight hours with temperatures desirable for photosynthesis



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.

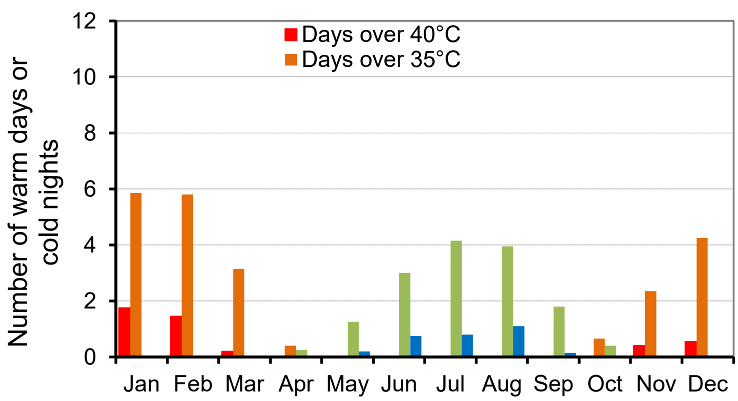
An abundance of heat units and moderate chill units



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

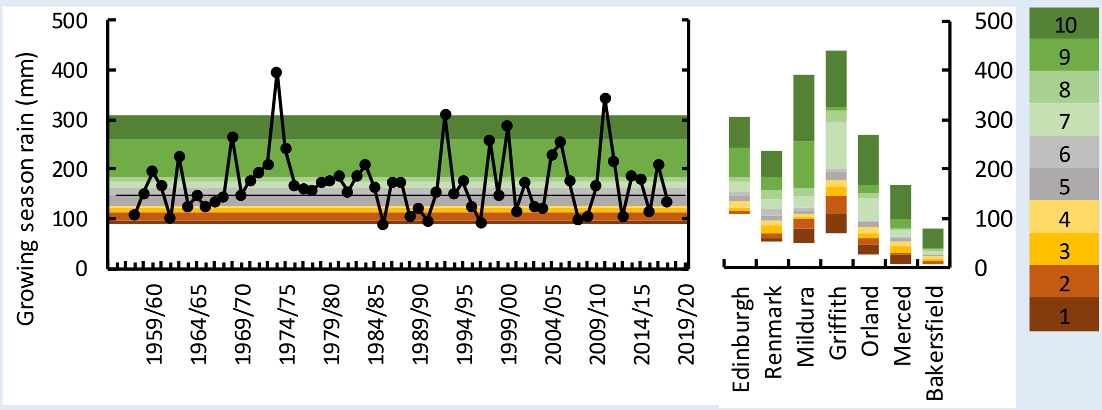


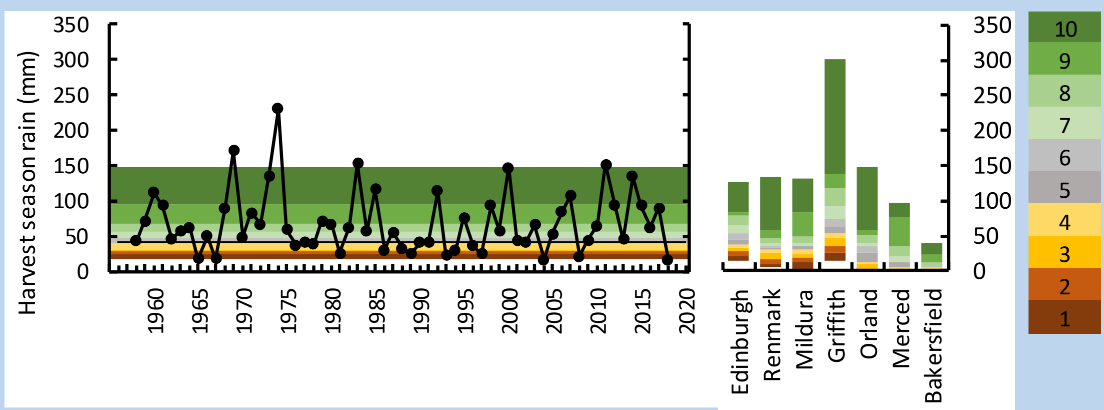
Days warmer than 35°C are common in summer (almost 1 in 5 days). Days hotter than 40°C are less frequent but not uncommon.

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.

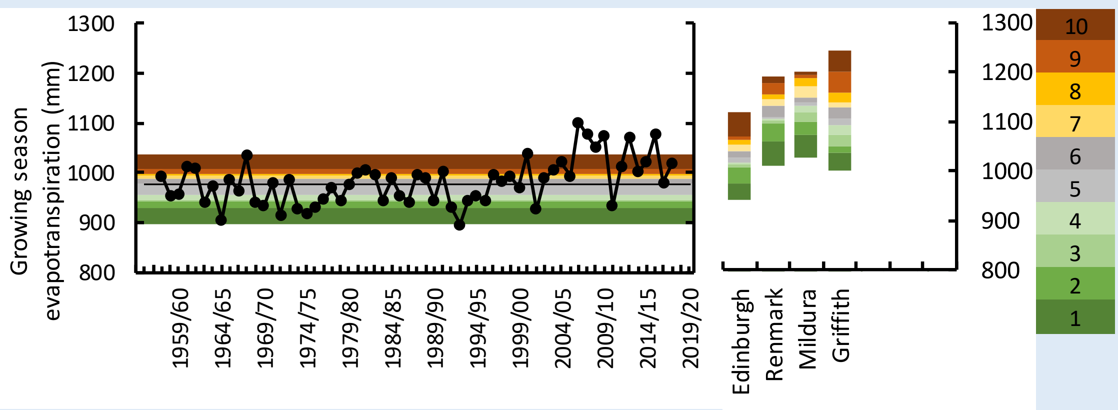
Historic trends in climate

Trends and variation in rainfall, evapotranspiration and irrigation deficit

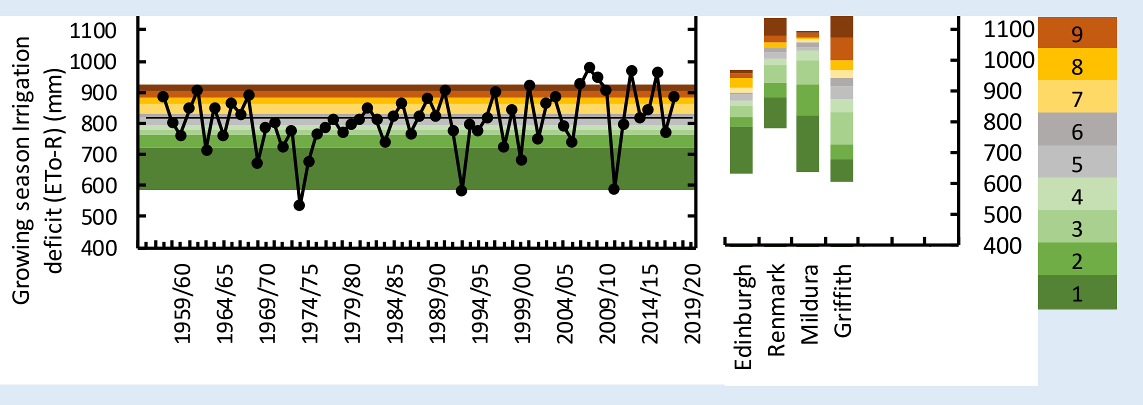




There is considerable year-to-year variation in rainfall. Almonds are grown in both wetter locations in Australia and drier locations in central and southern California. Growing season and Harvest season in Australia were calculated from October to April and February to April; and April to October and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

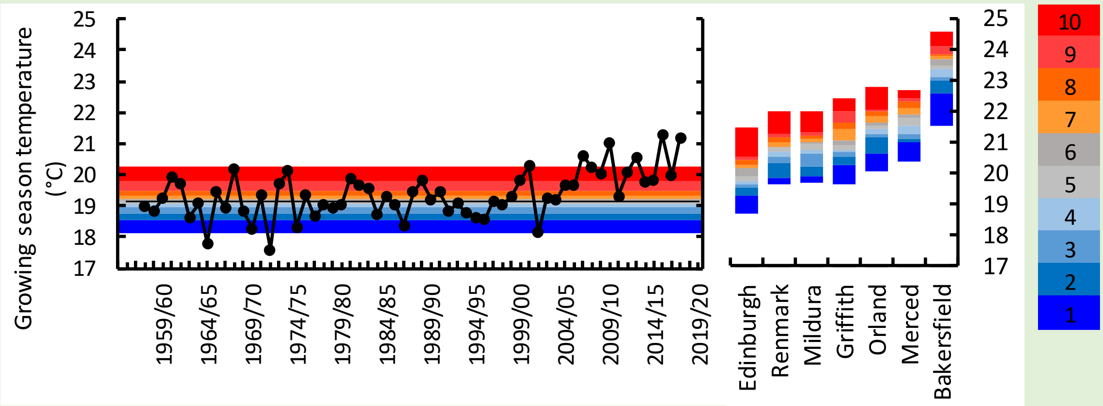


Evapotranspiration (ETo) like rainfall shows year-to-year variation, but unlike rainfall there is a trend of increasing evapotranspiration in recent decades. 100mm is equivalent to 1ML / ha.

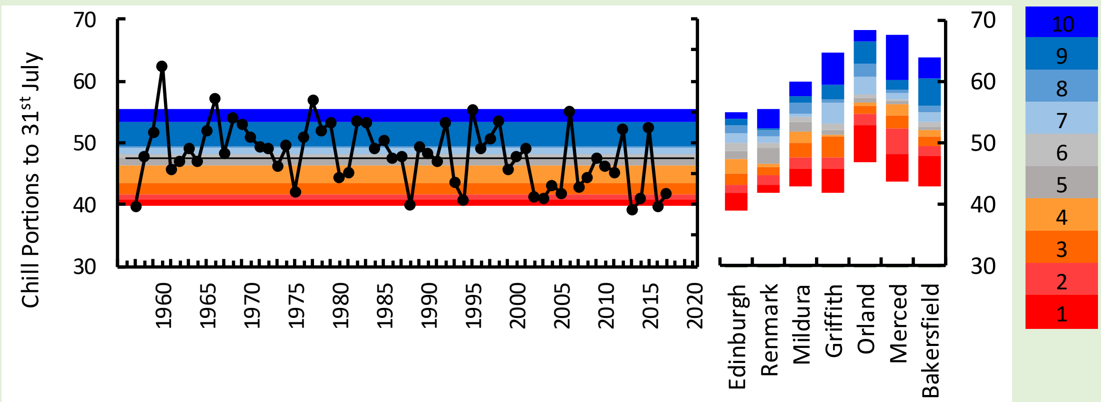


Irrigation demand, measured as the difference between evapotranspiration and rainfall (ETo - R), shows year-to-year variation and an increasing trend in recent decades. 100mm is equivalent to 1ML / ha.

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

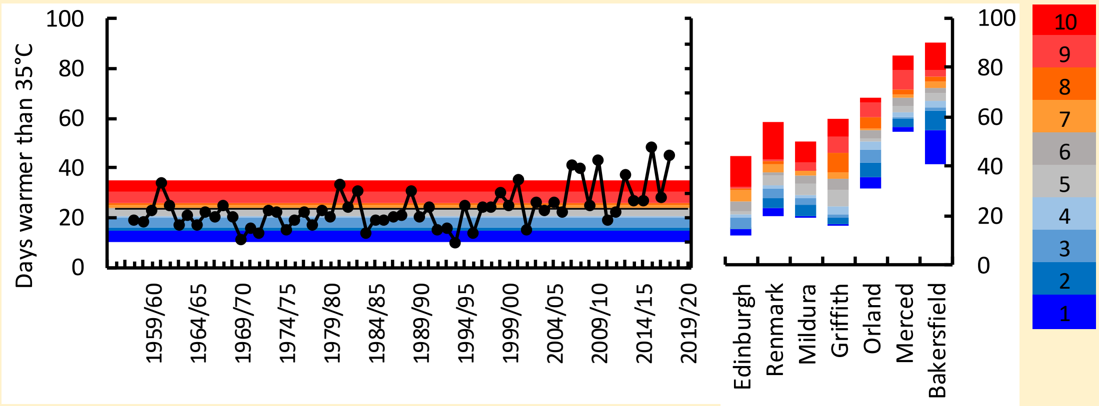


Mean temperature and therefore heat accumulation during the growing season varies from year-to-year. There is a trend of increasingly warmer conditions with many seasons being warmer than median (decile 6 or above) in the past 20 years. Temperatures in Australian almond growing locations are generally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

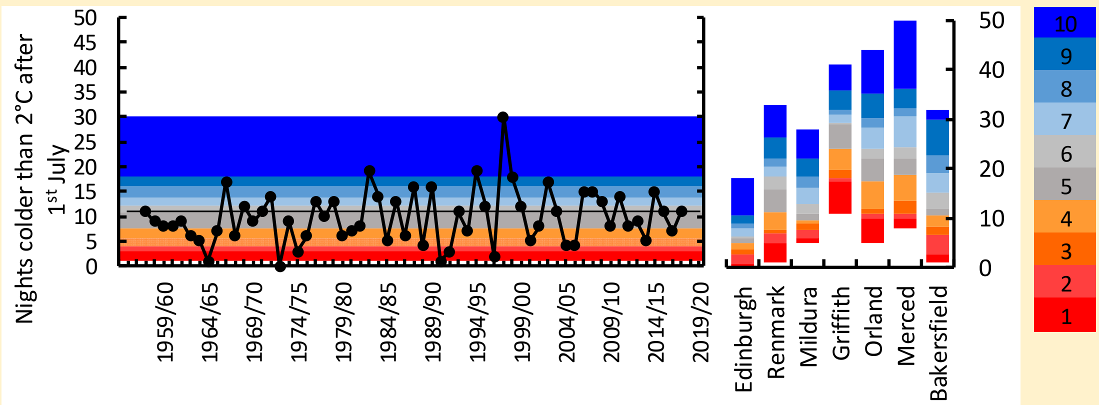


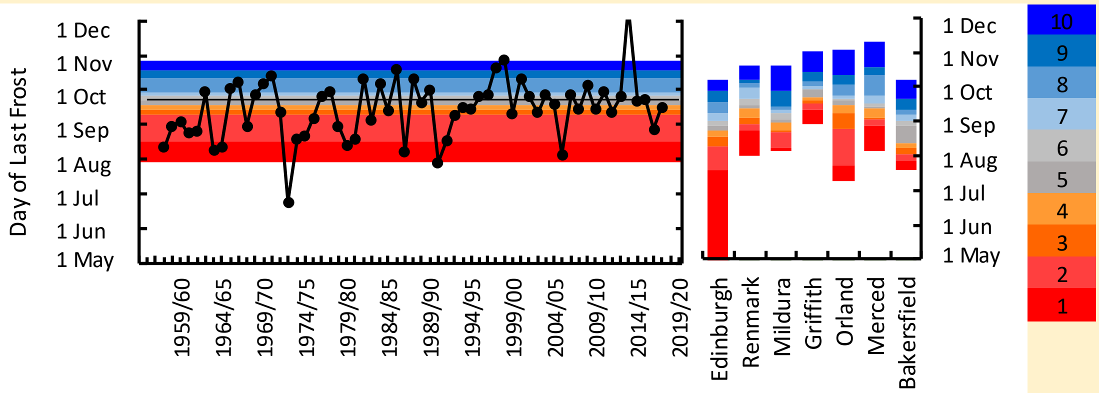
Chill accumulation at Murray Bridge varies from year-to-year. There have been many more below median (decile 5 and lower) chill years in the past 20 years. Chill accumulation is typically less in more coastal Australian locations. Most Australian almond growing locations generally have less chill than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

Trends and variation in heatwaves and frost potential nights



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



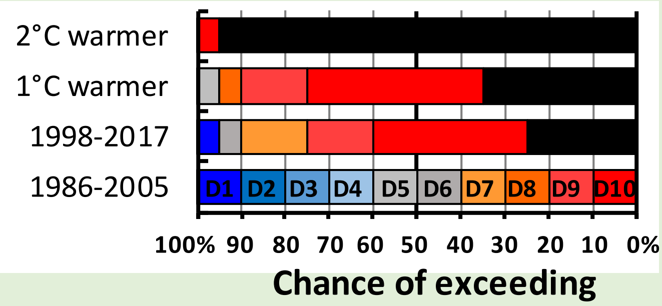


The number of nights sufficiently cold for frosts to potentially occur can be large in some years. Overall the number of cold nights are about as common in the inland Australian almond growing locations as in the Californian locations. The date of the last cold night has considerable year-to-year variation.

Recent and Future climate

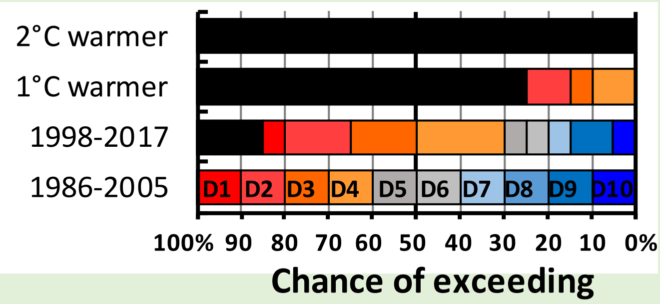
An increase in growing season temperature and heat units, and a decrease in chill units

Growing season temperature (°C)



	Minimum	Median	Maximum
2°C warmer	20.1	21.2	22.3
1°C warmer	19.1	20.2	21.3
1998-2017	18.1	19.8	21.3
1986-2005	18.1	19.2	20.3

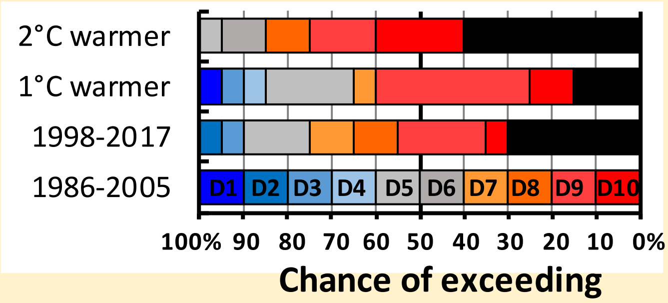
Chill accumulation until 31st July (Dynamic model chill portions)



	Minimum	Median	Maximum
2°C warmer	19	25	36
1°C warmer	28	35	45
1998-2017	39	45	55
1986-2005	40	48	55

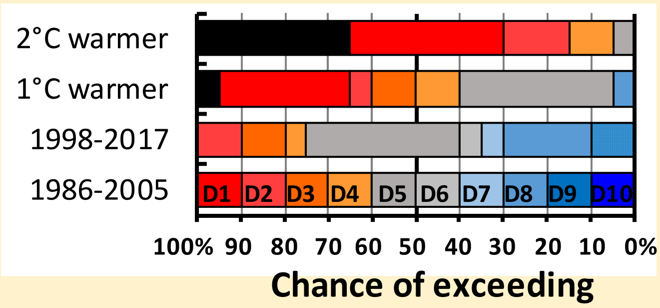
An increase in heatwaves and a decrease in frosts

Days warmer than 35°C



	Minimum	Median	Maximum
2°C warmer	21	33	45
1°C warmer	13	29	42
1998-2017	15	27	48
1986-2005	10	24	35

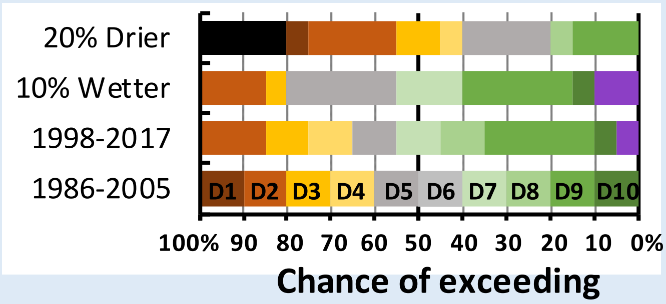
Nights cooler than 2°C after 1st July



	Minimum	Median	Maximum
2°C warmer	0	2	10
1°C warmer	0	6	16
1998-2017	4	11	30
1986-2005	1	11	30

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

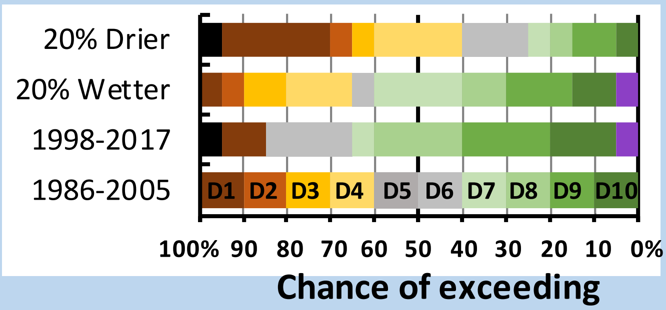
Growing season rain (mm)



	Minimum	Median	Maximum
20% Drier	71	118	248
10% Wetter	98	163	341
1998-2017	98	175	344
1986-2005	89	148	310

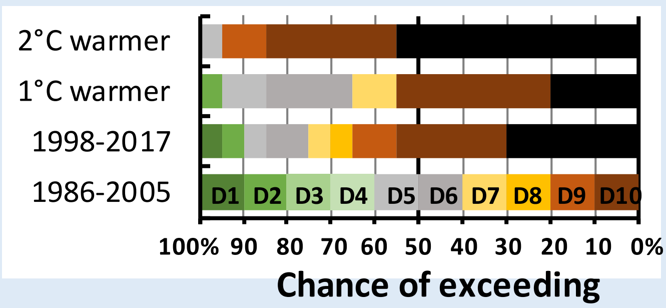
100mm is equivalent to 1ML / ha

February to April rain (mm)



	Minimum	Median	Maximum
20% Drier	14	33	118
20% Wetter	20	49	176
1998-2017	17	66	151
1986-2005	17	41	147

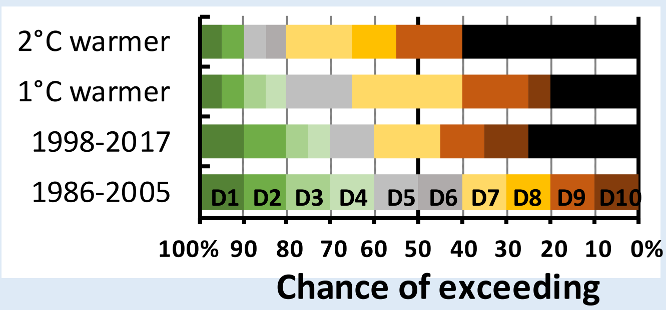
Growing season evapotranspiration (mm)



	Minimum	Median	Maximum
2°C warmer	967	1054	1120
1°C warmer	931	1015	1078
1998-2017	927	1008	1101
1986-2005	895	976	1037

100mm is equivalent to 1ML / ha

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

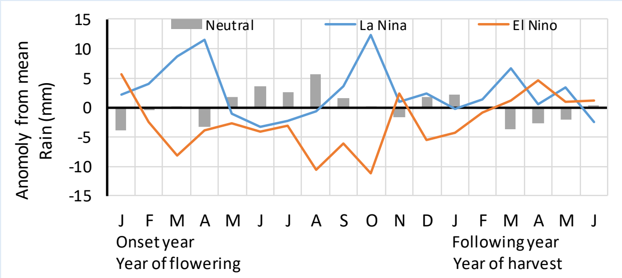


	Minimum	Median	Maximum
2°C warmer	657	897	1005
1°C warmer	621	859	964
1998-2017	590	843	979
1986-2005	586	820	922

100mm is equivalent to 1ML / ha

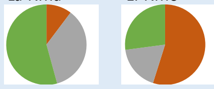
Influence of climate drivers

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



Rain from September to December — mm

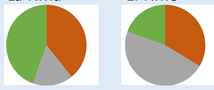
La Nina | El Nino



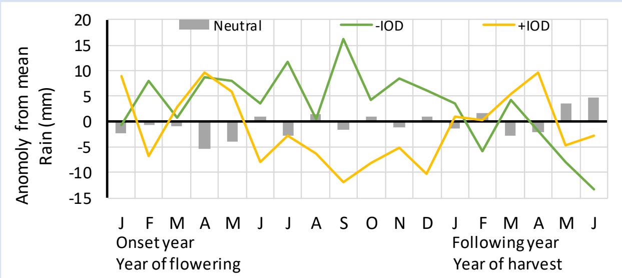
Minimum	44
Tercile 1	94
Tercile 2	141
Maximum	343

Rain from January to March — mm

La Nina | El Nino

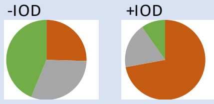


Minimum	4
Tercile 1	35
Tercile 2	69
Maximum	187



Rain from September to December — mm

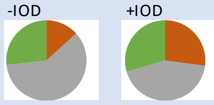
-IOD | +IOD



Minimum	44
Tercile 1	94
Tercile 2	143
Maximum	343

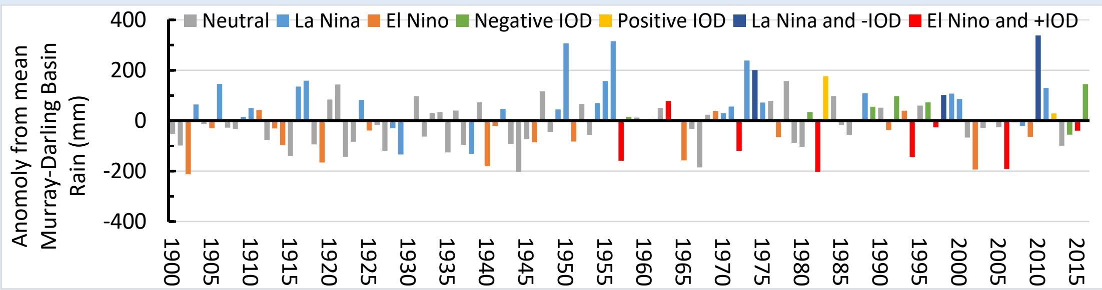
Rain from January to March — mm

-IOD | +IOD



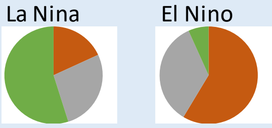
Minimum	4
Tercile 1	34
Tercile 2	69
Maximum	187

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.



Rain from January to December — mm

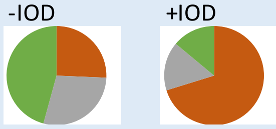
La Nina | El Nino



Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

Rain from January to December — mm

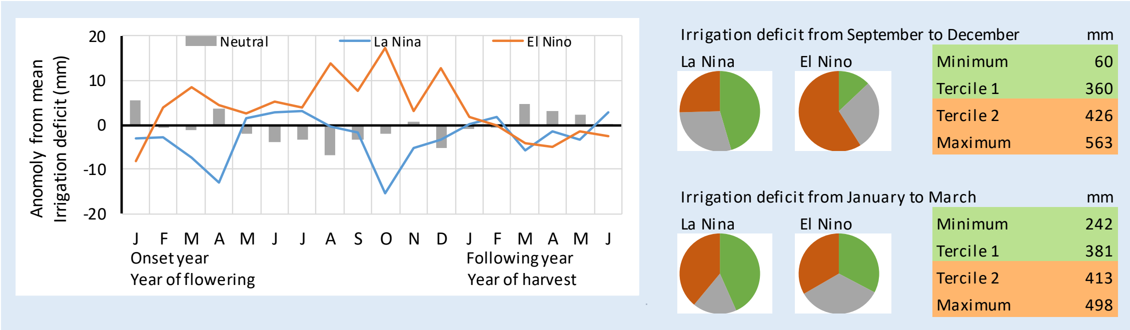
-IOD | +IOD

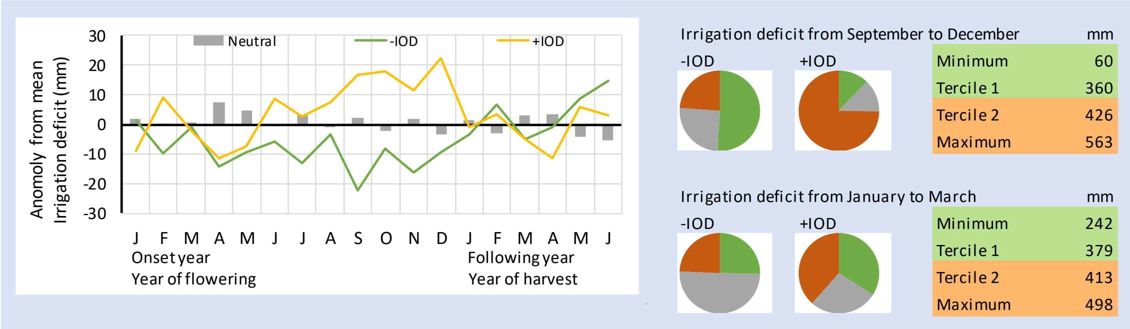


Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

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

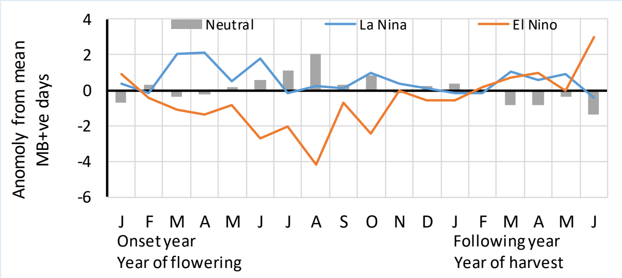
More evapotranspiration and increased irrigation deficit with El Niño and positive IOD





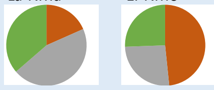
Irrigation deficit was influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year). 100mm is equivalent to 1ML / ha.

Rainy and humid conditions with La Niña and negative IOD



MB+ve days from September to December — days

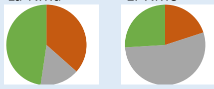
La Nina — El Nino



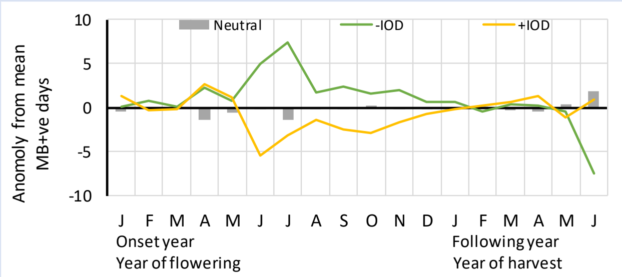
Minimum	8
Tercile 1	18
Tercile 2	28
Maximum	75

MB+ve days from January to March — days

La Nina — El Nino

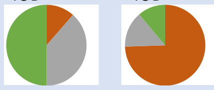


Minimum	0
Tercile 1	5
Tercile 2	9
Maximum	18



MB+ve days from September to December — days

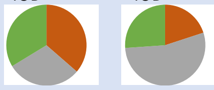
-IOD — +IOD



Minimum	8
Tercile 1	18
Tercile 2	28
Maximum	75

MB+ve days from January to March — days

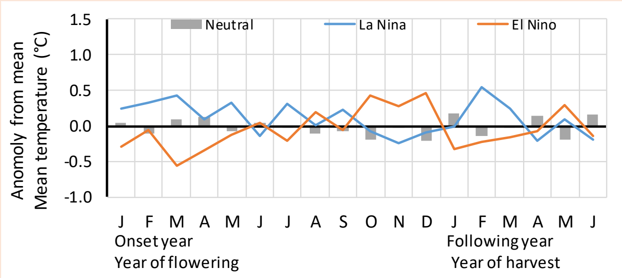
-IOD — +IOD



Minimum	0
Tercile 1	5
Tercile 2	9
Maximum	18

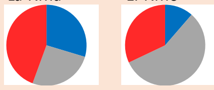
Rainy and humid conditions measured by the number of Moisture Balance positive (MB+ve) days were influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year).

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



Mean temperature from September to December °C

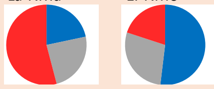
La Nina El Nino



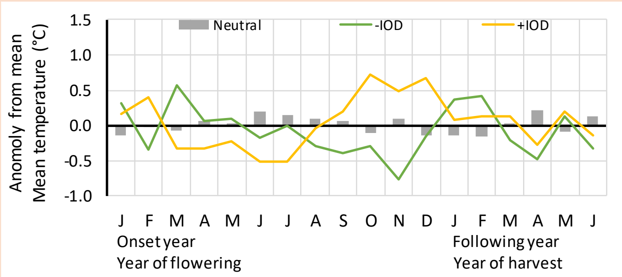
Minimum	14.8
Tercile 1	16.8
Tercile 2	17.6
Maximum	19.4

Mean temperature from January to March °C

La Nina El Nino

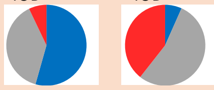


Minimum	19.6
Tercile 1	20.8
Tercile 2	21.7
Maximum	22.8



Mean temperature from September to December °C

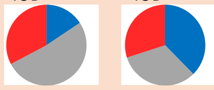
-IOD +IOD



Minimum	14.8
Tercile 1	16.9
Tercile 2	17.6
Maximum	19.4

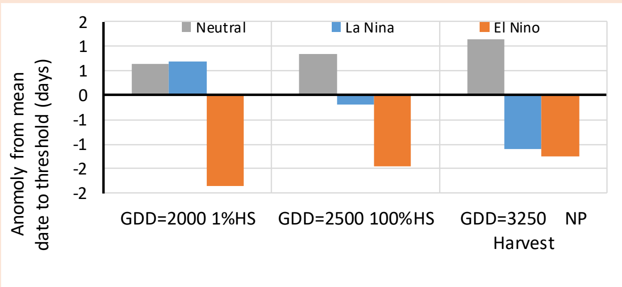
Mean temperature from January to March °C

-IOD +IOD



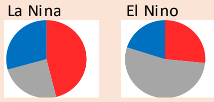
Minimum	19.6
Tercile 1	20.8
Tercile 2	21.7
Maximum	22.8

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).



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

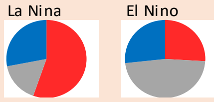
La Nina El Nino



Minimum	4-Jan
Tercile 1	16-Jan
Tercile 2	23-Jan
Maximum	11-Feb

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

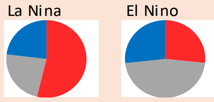
La Nina El Nino



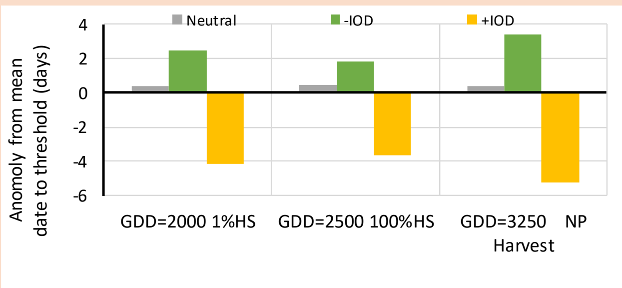
Minimum	30-Jan
Tercile 1	13-Feb
Tercile 2	21-Feb
Maximum	14-Mar

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

La Nina El Nino

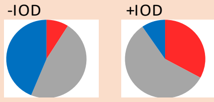


Minimum	12-Mar
Tercile 1	31-Mar
Tercile 2	13-Apr
Maximum	11-May



Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)

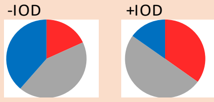
-IOD +IOD



Minimum	4-Jan
Tercile 1	16-Jan
Tercile 2	22-Jan
Maximum	11-Feb

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

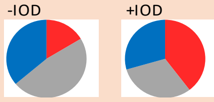
-IOD +IOD



Minimum	30-Jan
Tercile 1	12-Feb
Tercile 2	21-Feb
Maximum	14-Mar

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)

-IOD +IOD



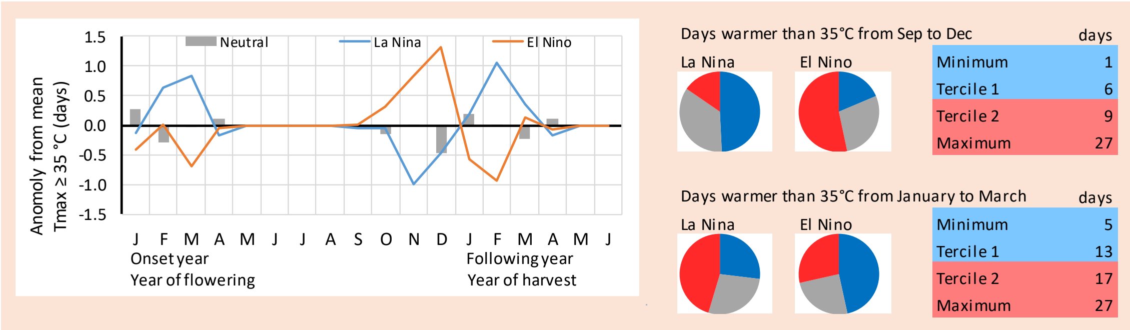
Minimum	12-Mar
Tercile 1	31-Mar
Tercile 2	12-Apr
Maximum	11-May

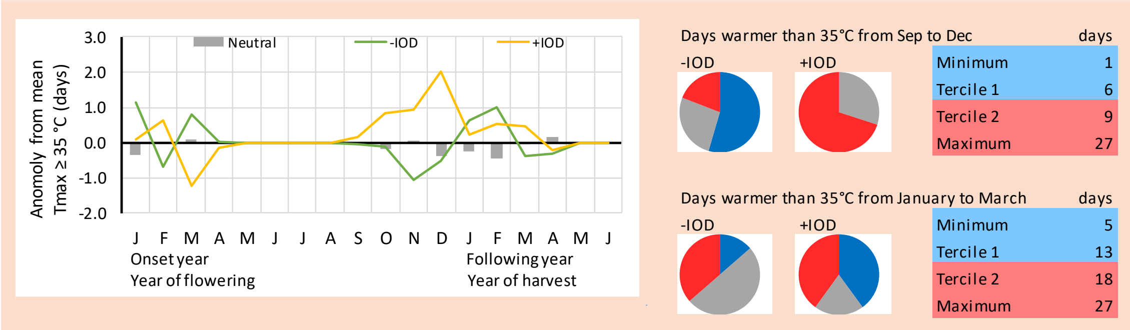
Heat accumulation from date of full bloom (taken to be 15th August) was faster in El Nino years and positive IOD years.

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.

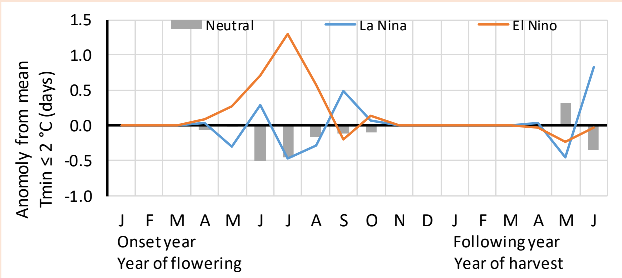
Heatwaves are more likely in El Niño years and positive IOD years





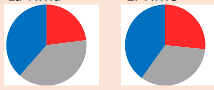
Heatwaves, measured as days warmer than 35 °C were influenced by the time of year and by ENSO and IOD. El Niño years or positive IOD years were likely to have more spring and early summer heatwaves than La Niña years or negative IOD years. Heatwaves in later summer were largely independent of ENSO and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

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



Nights colder than 2°C from August to December

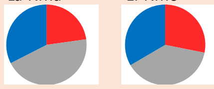
La Nina El Nino



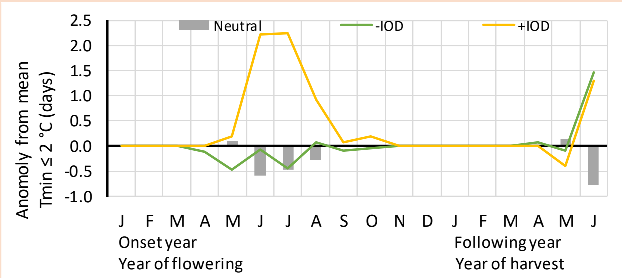
	days
Minimum	0
Tercile 1	3
Tercile 2	6
Maximum	15

Latest night after 1st August colder than 2°C

La Nina El Nino

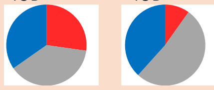


	Date
Minimum	Nil
Tercile 1	7-Sep
Tercile 2	28-Sep
Maximum	28-Oct



Nights colder than 2°C from August to December

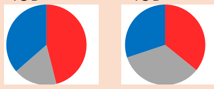
-IOD +IOD



	days
Minimum	0
Tercile 1	3
Tercile 2	6
Maximum	15

Latest night after 1st August colder than 2°C

-IOD +IOD



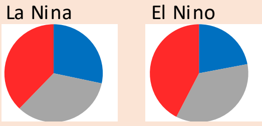
	Date
Minimum	Nil
Tercile 1	11-Sep
Tercile 2	28-Sep
Maximum	28-Oct

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

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

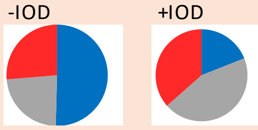
La Nina El Nino



	hours
Minimum	31
Tercile 1	72
Tercile 2	101
Maximum	172

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

-IOD +IOD



	hours
Minimum	31
Tercile 1	72
Tercile 2	101
Maximum	172

Favourable Pollination conditions were influenced by ENSO or IOD.

The correlation coefficients (r) of the agroclimatic indices 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.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.11	-0.19	0.29	-0.29	-0.36
Rain from September to December	-0.21	-0.21	0.21	-0.20	-0.22
Rain from January to March	-0.01	-0.08	0.05	0.00	0.03
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	0.18	0.12	-0.12	0.32	0.29
Irrigation deficit from September to December	0.30	0.26	-0.21	0.48	0.42
Irrigation deficit from January to March	-0.06	-0.11	0.00	0.04	0.13
Rainy and humid conditions					
MB+ve days from September to December	-0.21	-0.17	0.10	-0.46	-0.41
MB+ve days from January to March	0.08	0.10	0.00	0.12	-0.11
Heat accumulation					
Mean temperature from September to December	0.16	0.07	-0.06	0.45	0.26
Mean temperature from January to March	-0.24	-0.33	0.19	0.31	0.20
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.15	-0.04	0.14	-0.45	-0.28
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.11	0.00	0.09	-0.37	-0.23
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.01	0.09	-0.10	-0.31	-0.11
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.17	0.24	-0.08	-0.27	-0.18
Utah chill units accumulated to 31st July	0.09	0.18	-0.01	-0.31	-0.21
Heatwaves					
Days warmer than 35°C from September to December	0.32	0.24	-0.21	0.41	0.29
Days warmer than 35°C from January to March	-0.11	-0.22	0.05	0.17	0.10
Daylight hours warmer than 35°C from September to December	0.29	0.20	-0.15	0.31	0.18
Daylight hours warmer than 35°C from January to March	-0.12	-0.22	0.06	0.14	0.09
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	0.00	-0.38	0.14	0.11

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).

Appendix 6. Edinburgh

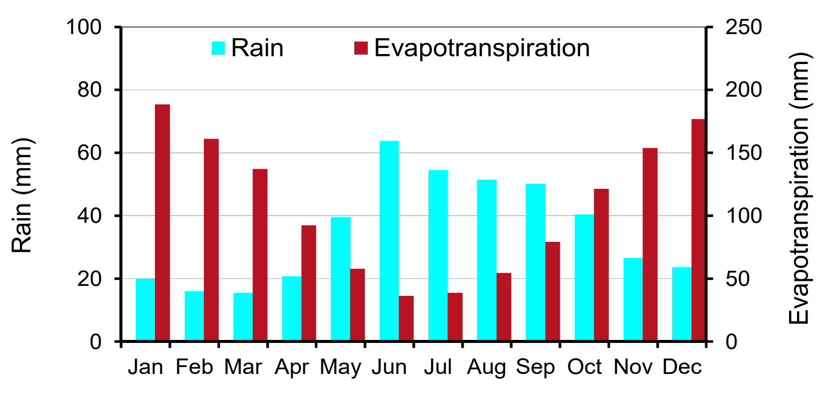
The yearly climate at a glance

Edinburgh RAAF is used here to describe the climate of South Australia's North Adelaide Plains. Edinburgh has a warm dry climate with distinct seasonality in temperature and evapotranspiration (ETo) and a seasonally wetter winter and drier summer. 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 Edinburgh RAAF meteorological station (station 23083). The source was patched point data (https://silo.longpaddock.qld.gov.au/).

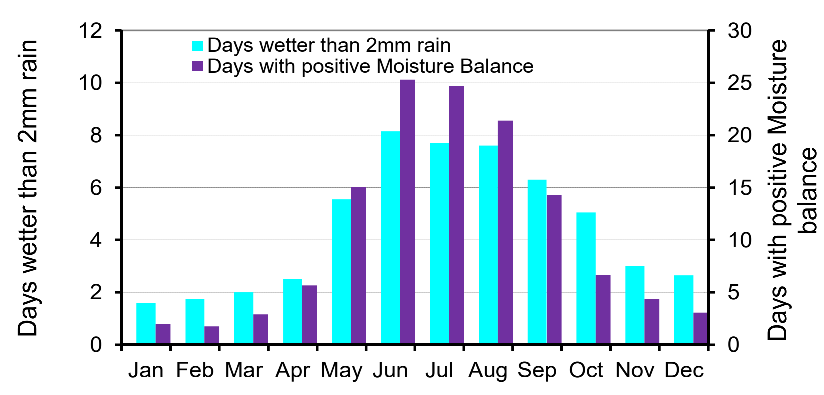
Low rainfall and high evapotranspiration

Rainfall is low in most months although winter and spring months are wetter than summer and autumn months.

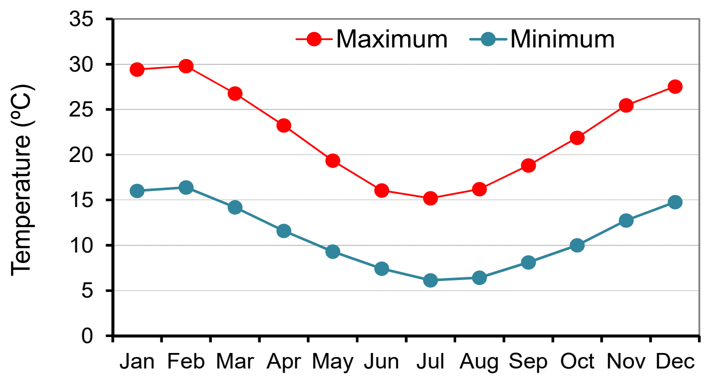
Evaporative demand is seasonal and much higher in summer than in winter.



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.



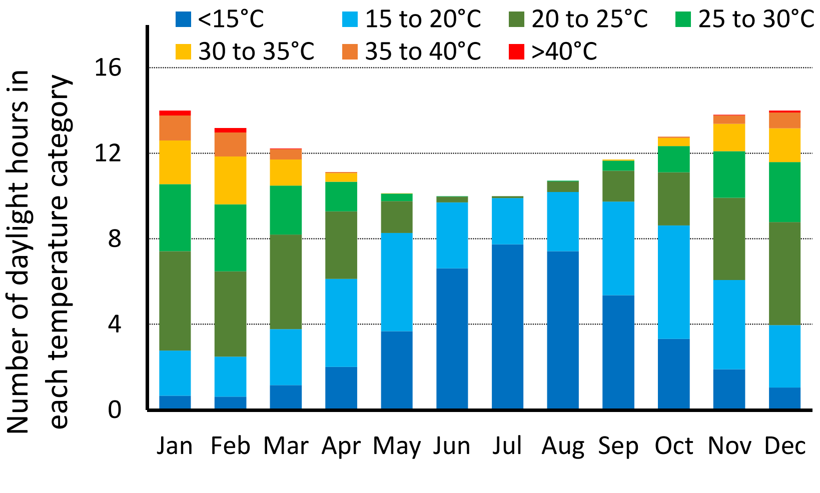
Season pattern of hot summers and cold winters



Summer months are characterised by mean maximum temperatures of about 30°C and mean minimum temperatures of about 15°C.

Winter months have mean maximum temperatures between 15° and 20°C, while mean minimum temperatures are about 5°C.

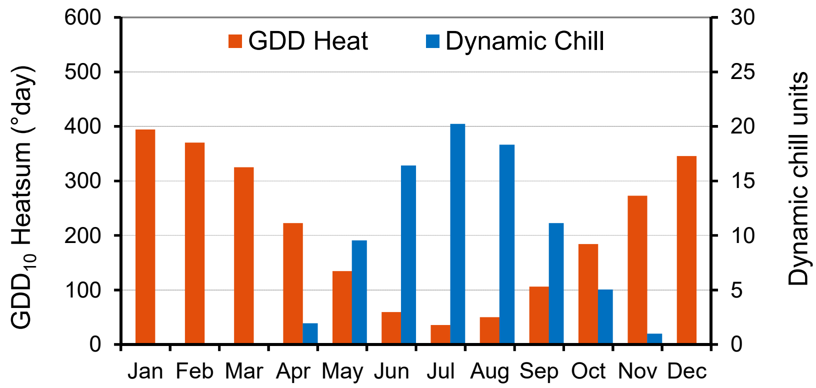
Plenty of daylight hours with temperatures desirable for photosynthesis



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.

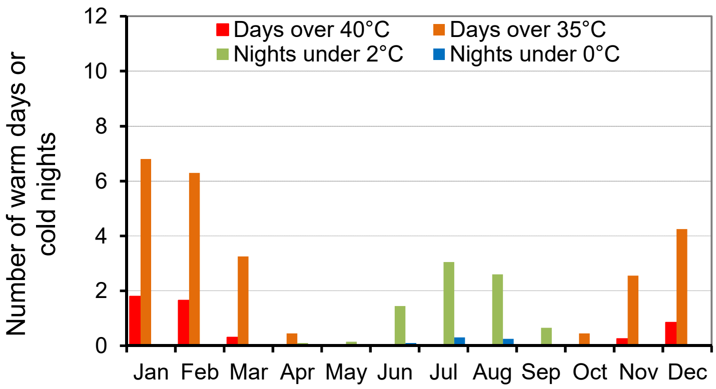
An abundance of heat units and moderate chill units



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

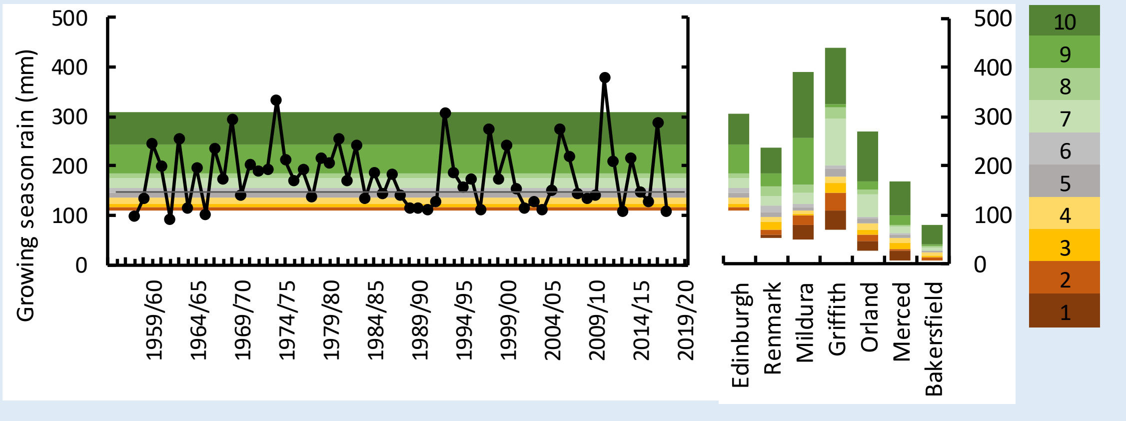


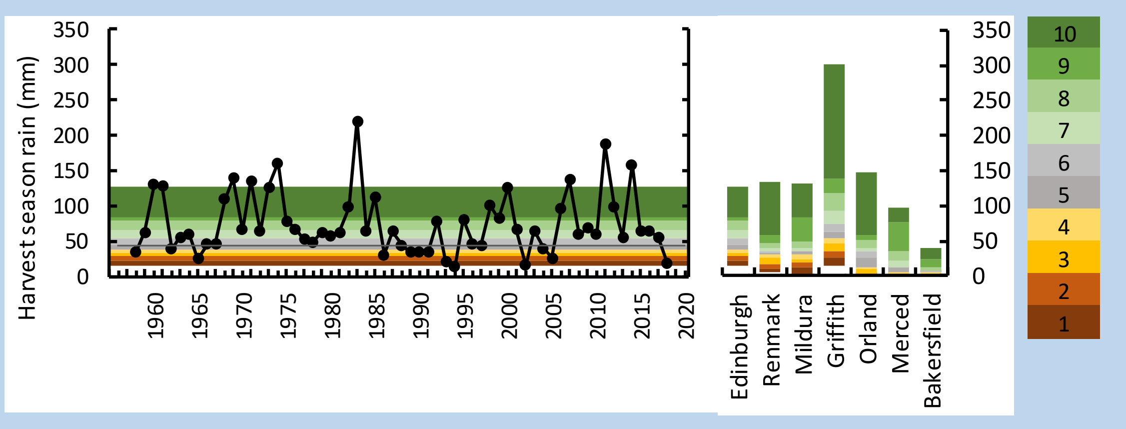
Days warmer than 35°C are common in summer (about 1 in 5 days). Days hotter than 40°C are much less frequent but not uncommon.

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 the winter months. Frost is possible when the screen temperature is colder than 2°C.

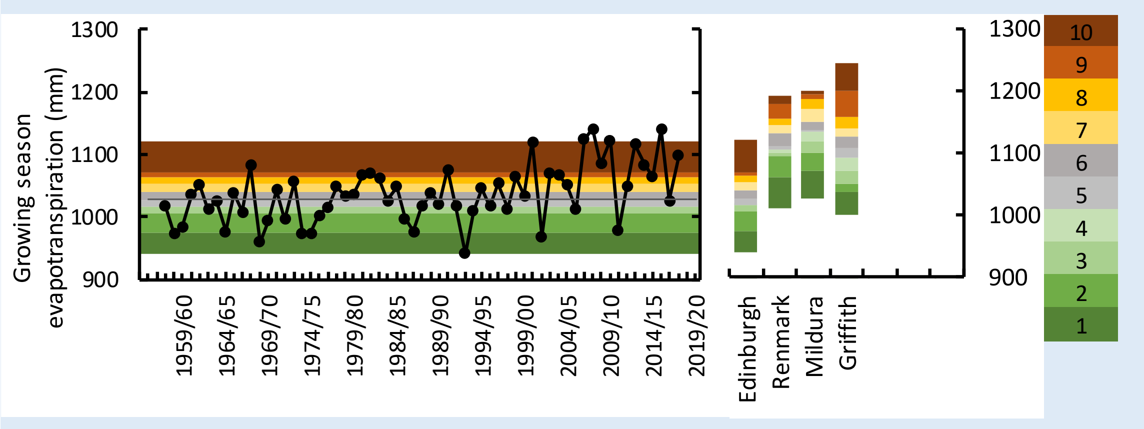
Historic trends in climate

Trends and variation in rainfall, evapotranspiration and irrigation deficit

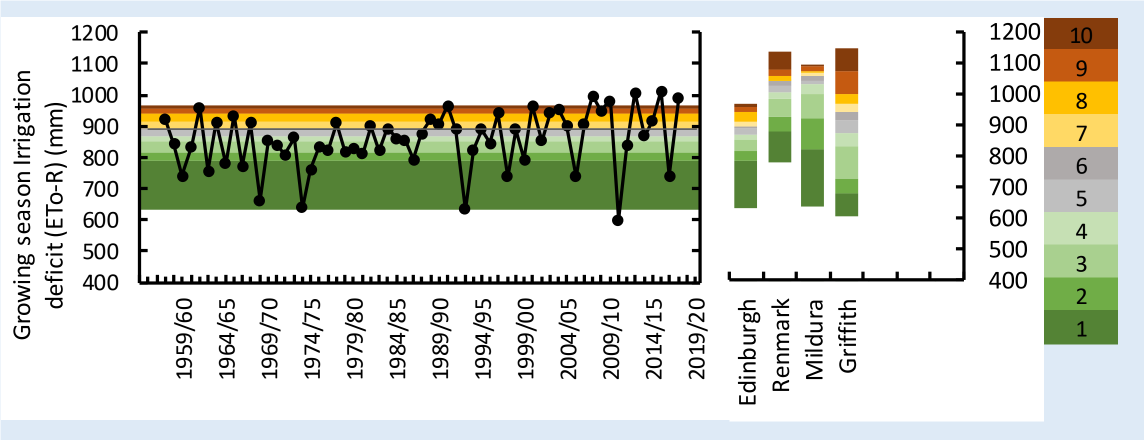




There is considerable year-to-year variation in rainfall. Almonds are grown in both wetter locations in Australia and drier locations in central and southern California. Growing season and Harvest season in Australia were calculated from October to April and February to April; and April to October and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

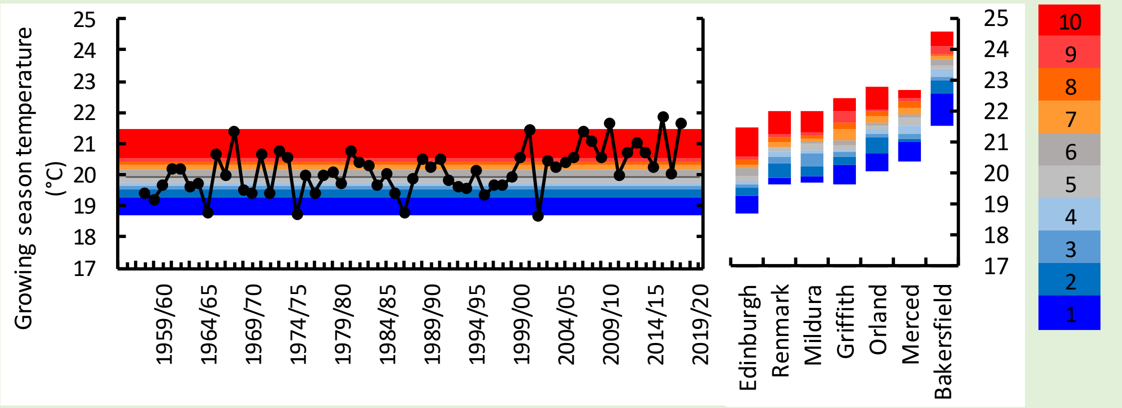


Evapotranspiration (ETo) like rainfall shows year-to-year variation, but unlike rainfall there is a trend of increasing evapotranspiration in recent decades. 100mm is equivalent to 1ML / ha.

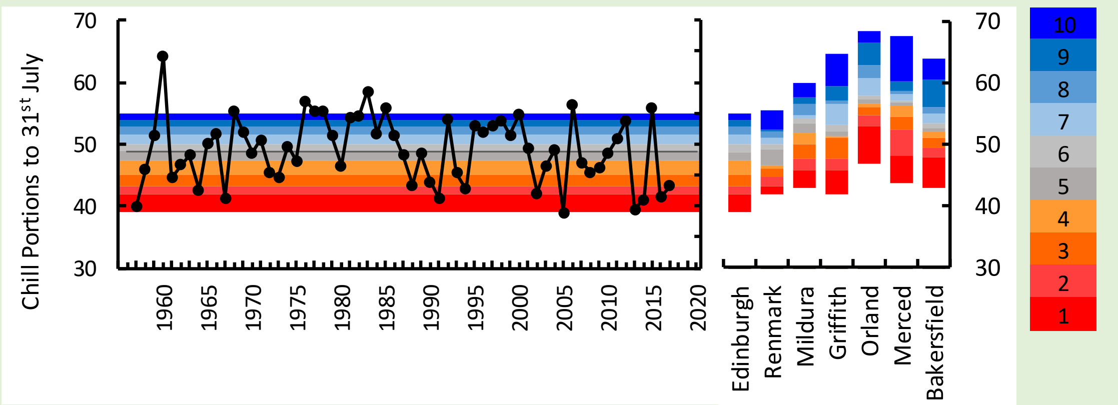


Irrigation demand, measured as the difference between evapotranspiration and rainfall (ETo - R), shows year-to-year variation and an increasing trend in recent decades. 100mm is equivalent to 1ML / ha.

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

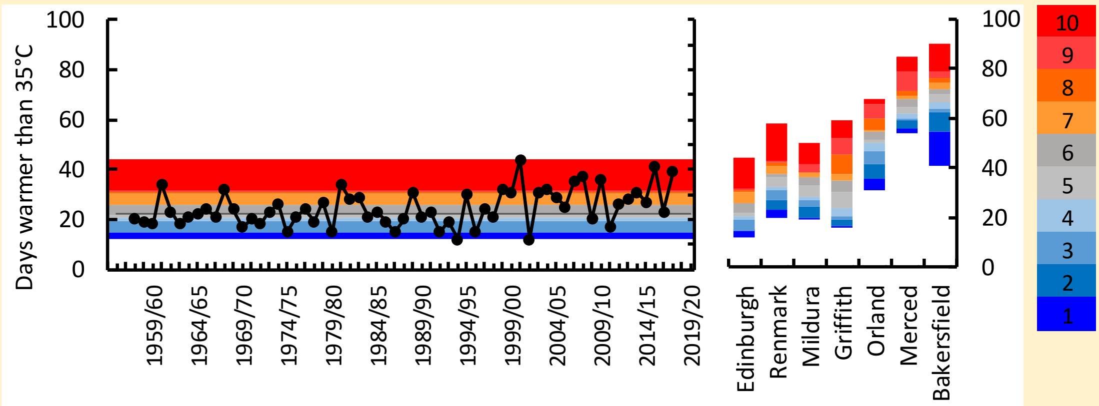


Mean temperature and therefore heat accumulation during the growing season varies from year-to-year. There is a trend of increasingly warmer conditions with many seasons being warmer than median (decile 6 or above) in the past 20 years. Temperatures in Australian almond growing locations are generally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

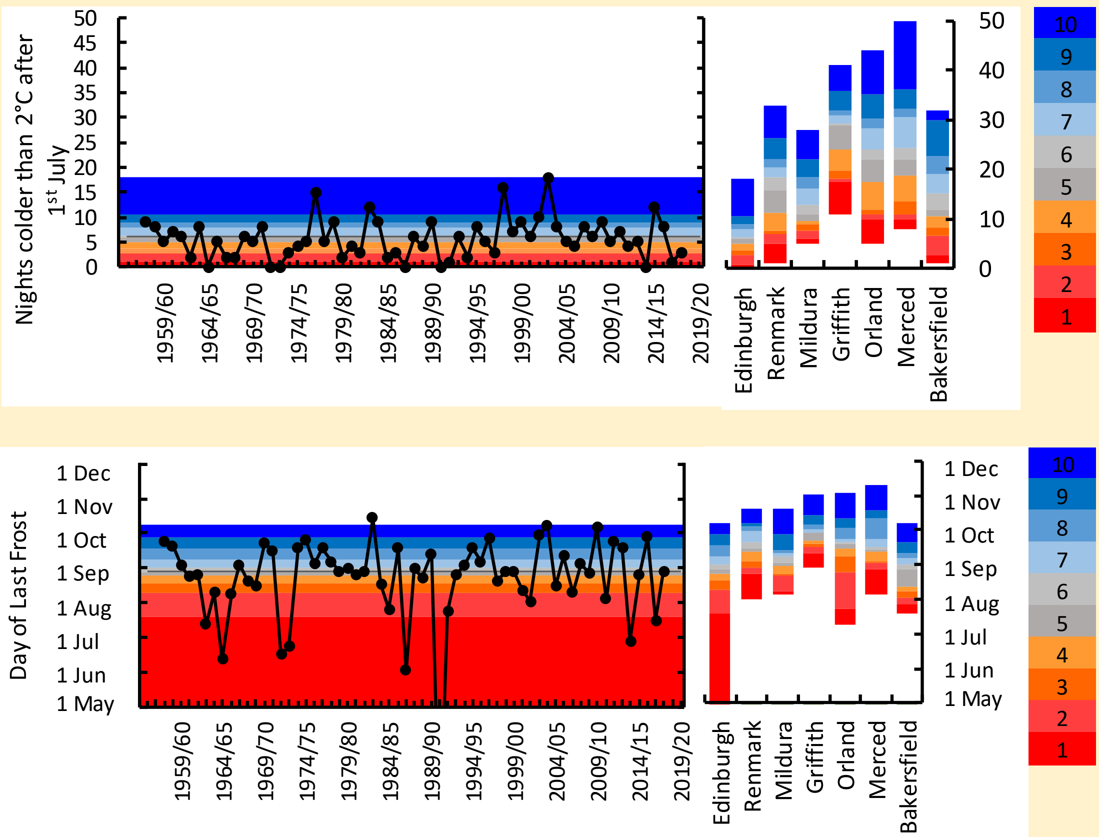


Chill accumulation at Edinburgh varies from year-to-year. There have been many more below median (decile 5 and lower) chill years in the past 20 years. Chill accumulation is typically less in more coastal Australian locations. Most Australian almond growing locations generally have less chill than Californian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

Trends and variation in heatwaves and frost potential nights



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

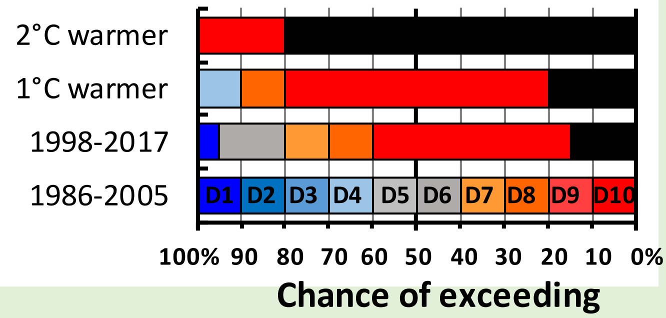


The number of nights sufficiently cold for frosts to potentially occur can be large in some years. Overall the number of cold nights are about as common in the inland Australian almond growing locations as in the Californian locations. The date of the last cold night has considerable year-to-year variation.

Recent and Future climate

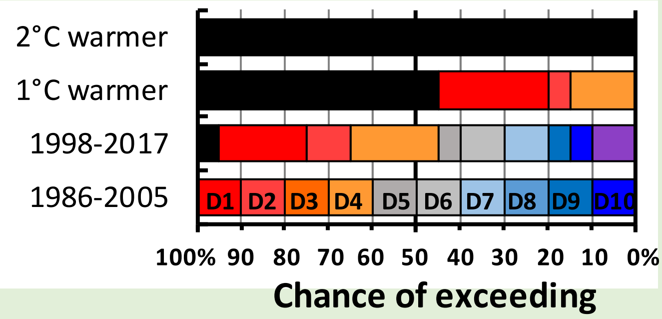
An increase in growing season temperature and heat units, and a decrease in chill units

Growing season temperature (°C)



	Minimum	Median	Maximum
2°C warmer	20.7	21.9	23.5
1°C warmer	19.7	20.9	22.5
1998-2017	18.7	20.5	21.8
1986-2005	18.7	19.9	21.5

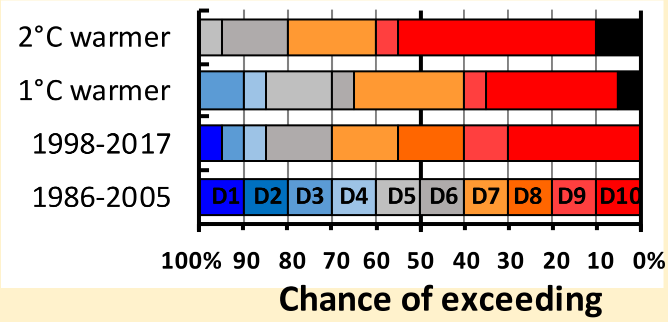
Chill accumulation until 31st July (Dynamic model chill portions)



	Minimum	Median	Maximum
2°C warmer	18	29	39
1°C warmer	33	38	46
1998-2017	39	49	56
1986-2005	41	49	56

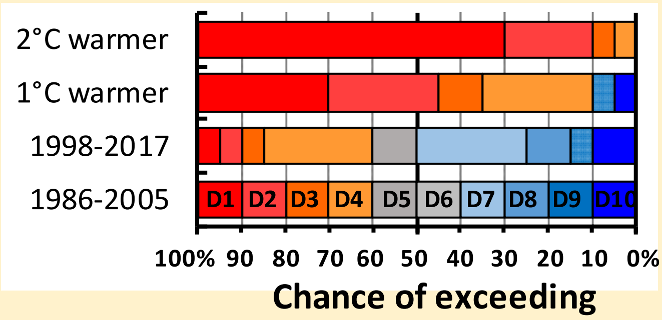
An increase in heatwaves and a decrease in frosts

Days warmer than 35°C



	Minimum	Median	Maximum
2°C warmer	22	36	61
1°C warmer	16	29	53
1998-2017	12	30	44
1986-2005	12	22	44

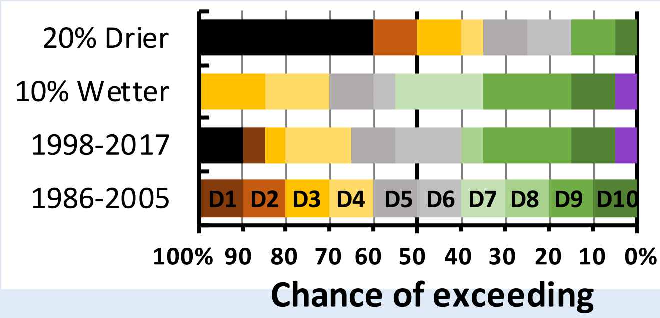
Nights cooler than 2°C after 1st July



	Minimum	Median	Maximum
2°C warmer	0	0	4
1°C warmer	0	2	12
1998-2017	0	7	18
1986-2005	0	6	18

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

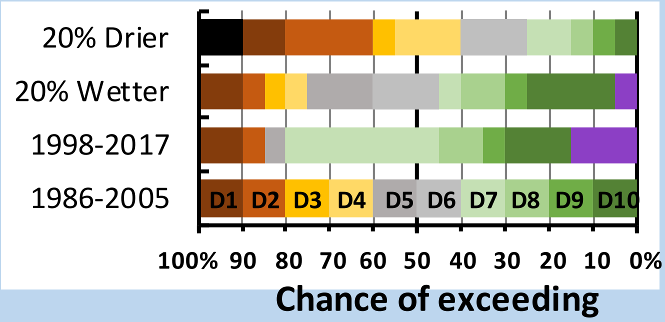
Growing season rain (mm)



	Minimum	Median	Maximum
20% Drier	89	117	246
10% Wetter	122	161	338
1998-2017	108	151	378
1986-2005	111	146	307

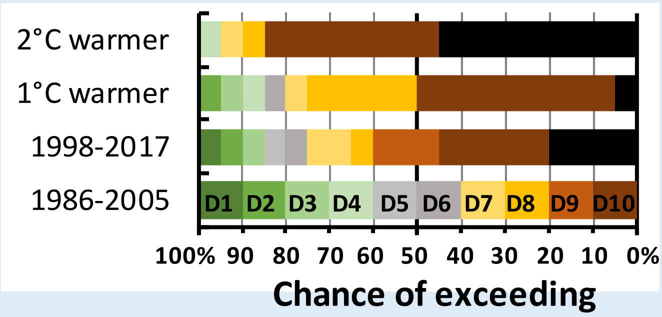
100mm is equivalent to 1ML / ha

February to April rain (mm)



	Minimum	Median	Maximum
20% Drier	11	35	101
20% Wetter	17	53	151
1998-2017	16	66	187
1986-2005	14	44	126

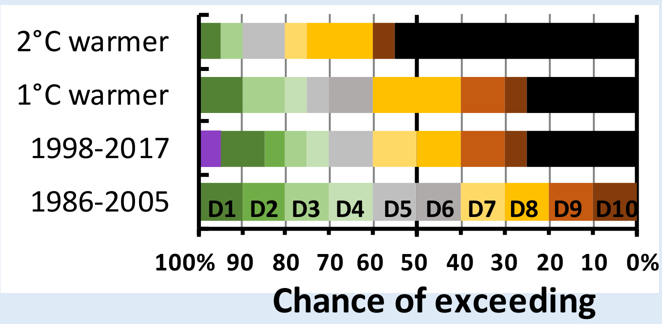
Growing season evapotranspiration (mm)



	Minimum	Median	Maximum
2°C warmer	1017	1110	1210
1°C warmer	980	1069	1165
1998-2017	969	1065	1142
1986-2005	942	1028	1120

100mm is equivalent to 1ML / ha

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

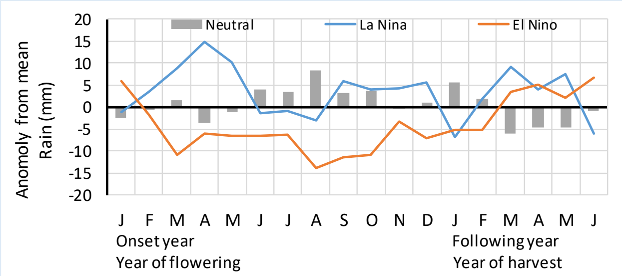


	Minimum	Median	Maximum
2°C warmer	710	972	1056
1°C warmer	672	931	1011
1998-2017	599	904	1012
1986-2005	635	889	966

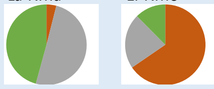
100mm is equivalent to 1ML / ha

Influence of climate drivers

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

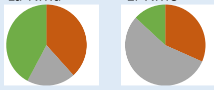


Rain from September to December

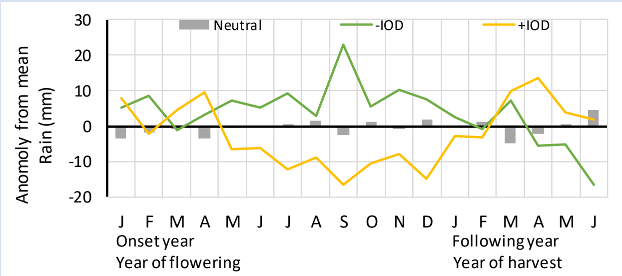


	mm
Minimum	44
Tercile 1	98
Tercile 2	146
Maximum	363

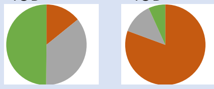
Rain from January to March



	mm
Minimum	6
Tercile 1	42
Tercile 2	72
Maximum	193

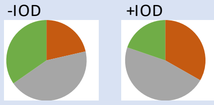


Rain from September to December



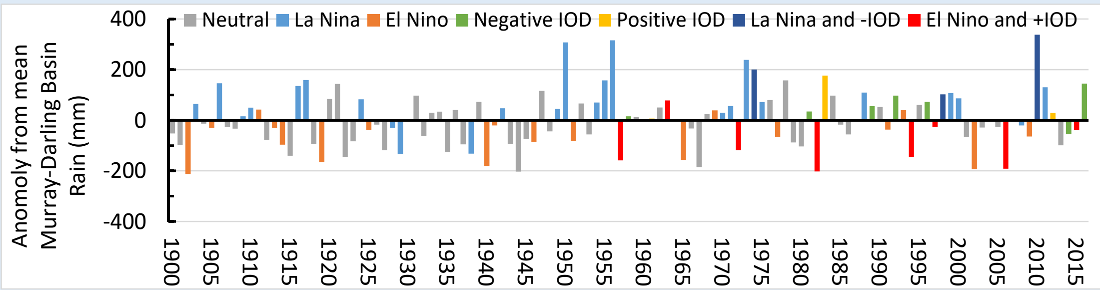
	mm
Minimum	44
Tercile 1	98
Tercile 2	152
Maximum	363

Rain from January to March

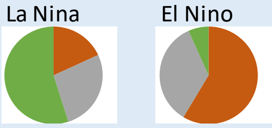


	mm
Minimum	6
Tercile 1	42
Tercile 2	72
Maximum	193

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.

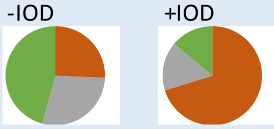


Rain from January to December



	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

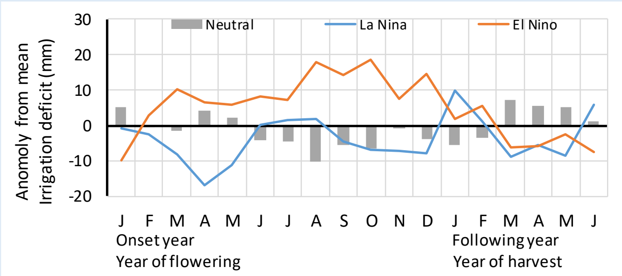
Rain from January to December



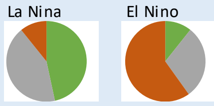
	mm
Minimum	122
Tercile 1	252
Tercile 2	303
Maximum	657

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

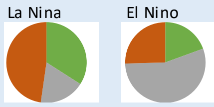


Irrigation deficit from September to December

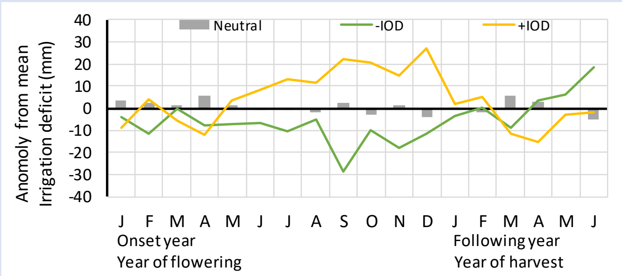


	mm
Minimum	72
Tercile 1	372
Tercile 2	452
Maximum	574

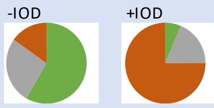
Irrigation deficit from January to March



	mm
Minimum	262
Tercile 1	413
Tercile 2	446
Maximum	525

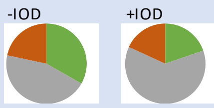


Irrigation deficit from September to December



	mm
Minimum	72
Tercile 1	372
Tercile 2	455
Maximum	574

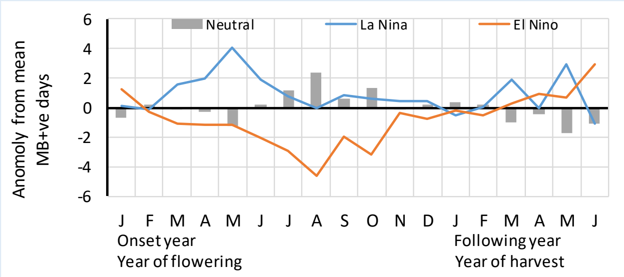
Irrigation deficit from January to March



	mm
Minimum	262
Tercile 1	413
Tercile 2	446
Maximum	525

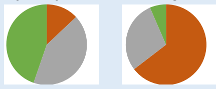
Irrigation deficit was influenced by ENSO and IOD to a larger extent during the year of flowering (year of onset) than during the harvest period (following year). 100mm is equivalent to 1ML / ha.

Rainy and humid conditions with La Niña and negative IOD



MB+ve days from September to December

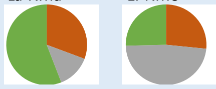
La Nina El Nino



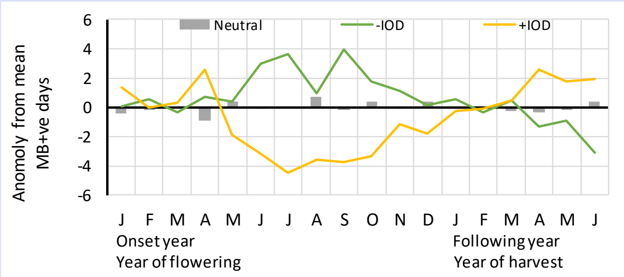
	days
Minimum	6
Tercile 1	22
Tercile 2	32
Maximum	71

MB+ve days from January to March

La Nina El Nino

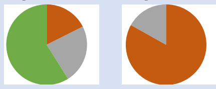


	days
Minimum	0
Tercile 1	5
Tercile 2	9
Maximum	18



MB+ve days from September to December

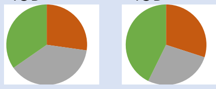
-IOD +IOD



	days
Minimum	6
Tercile 1	22
Tercile 2	32
Maximum	71

MB+ve days from January to March

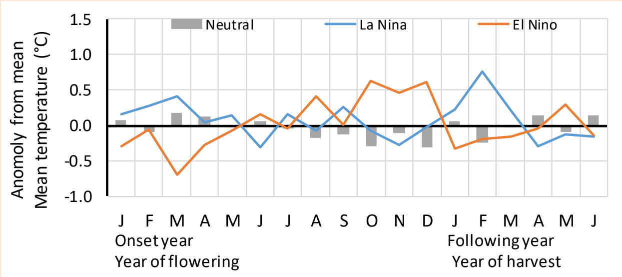
-IOD +IOD



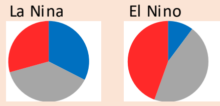
	days
Minimum	0
Tercile 1	5
Tercile 2	9
Maximum	18

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

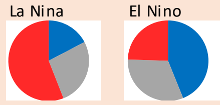


Mean temperature from September to December

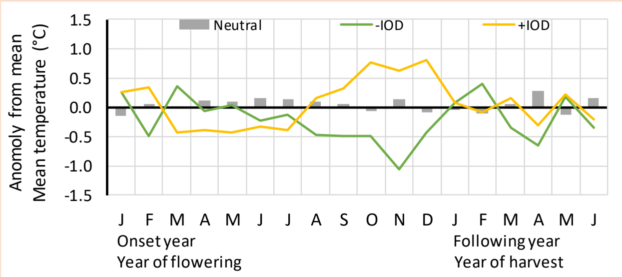


	°C
Minimum	15.6
Tercile 1	17.1
Tercile 2	17.9
Maximum	19.6

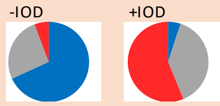
Mean temperature from January to March



	°C
Minimum	20.4
Tercile 1	21.9
Tercile 2	22.8
Maximum	24.3

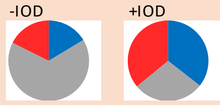


Mean temperature from September to December



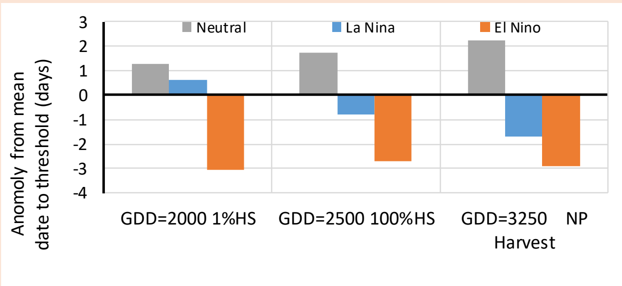
	°C
Minimum	16.0
Tercile 1	17.2
Tercile 2	17.9
Maximum	19.6

Mean temperature from January to March

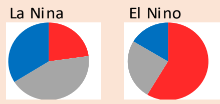


	°C
Minimum	20.4
Tercile 1	21.9
Tercile 2	22.9
Maximum	24.3

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).

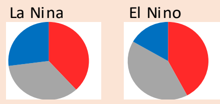


Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)



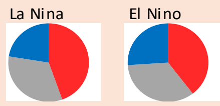
Minimum	3-Jan
Tercile 1	14-Jan
Tercile 2	19-Jan
Maximum	31-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)

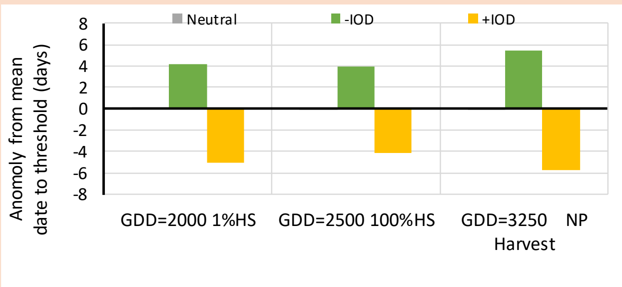


Minimum	27-Jan
Tercile 1	8-Feb
Tercile 2	16-Feb
Maximum	27-Feb

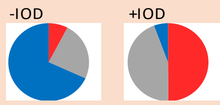
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)



Minimum	6-Mar
Tercile 1	22-Mar
Tercile 2	1-Apr
Maximum	20-Apr

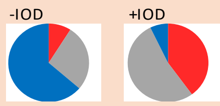


Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)



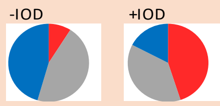
Minimum	3-Jan
Tercile 1	13-Jan
Tercile 2	19-Jan
Maximum	31-Jan

Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)



Minimum	27-Jan
Tercile 1	8-Feb
Tercile 2	16-Feb
Maximum	27-Feb

Date from FB that GDD4.5 = 3250 °Cdays (Harvest)



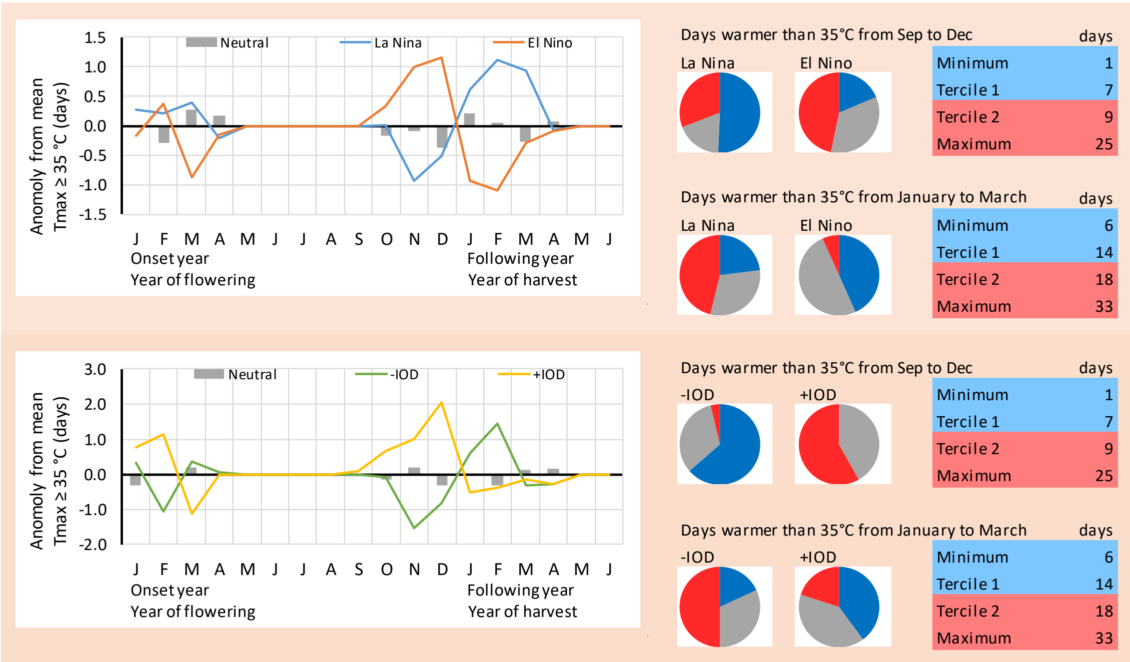
Minimum	6-Mar
Tercile 1	21-Mar
Tercile 2	1-Apr
Maximum	20-Apr

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

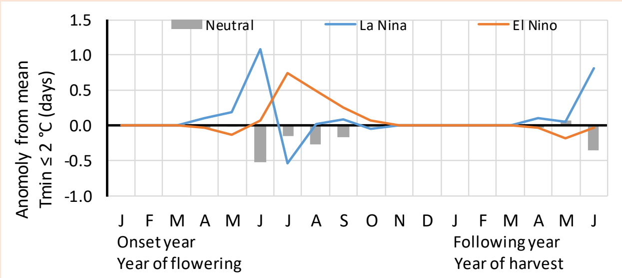
ENSO and IOD had minimal influence on the accumulation of chill hours after August, and almost none before August.

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



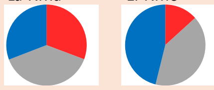
Heatwaves, measured as days warmer than 35 °C were influenced by the time of year and by ENSO and IOD. El Niño years or positive IOD years were likely to have more spring and early summer heatwaves than La Niña years or negative IOD years. Heatwaves in later summer were largely independent of ENSO and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

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



Nights colder than 2°C from August to December

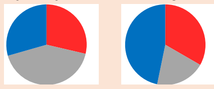
La Nina El Nino



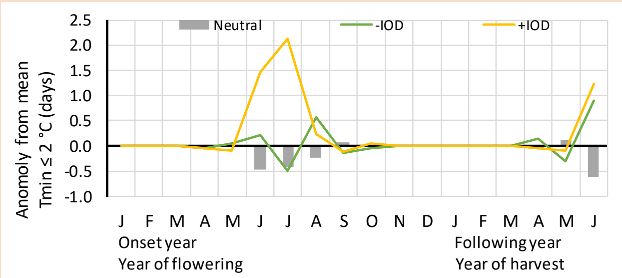
	days
Minimum	0
Tercile 1	1
Tercile 2	3
Maximum	12

Latest night after 1st August colder than 2°C

La Nina El Nino

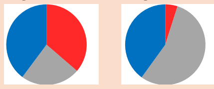


	Date
Minimum	Nil
Tercile 1	21-Aug
Tercile 2	7-Sep
Maximum	16-Oct



Nights colder than 2°C from August to December

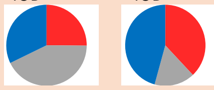
-IOD +IOD



	days
Minimum	0
Tercile 1	1
Tercile 2	3
Maximum	12

Latest night after 1st August colder than 2°C

-IOD +IOD



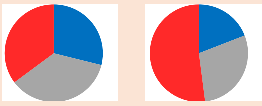
	Date
Minimum	Nil
Tercile 1	20-Aug
Tercile 2	5-Sep
Maximum	16-Oct

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

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

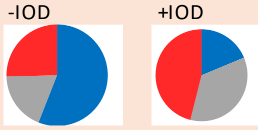
La Nina El Nino



	hours
Minimum	22
Tercile 1	47
Tercile 2	76
Maximum	164

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

-IOD +IOD



	hours
Minimum	22
Tercile 1	47
Tercile 2	73
Maximum	164

Favourable Pollination conditions were influenced by ENSO or IOD.

The correlation coefficients (r) of the agroclimatic indices 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.

	Niño 3.4		SOI	DMI	
	HadISST 1.1	ERSSTv5		HadISST 1.1	ERSSTv5
Rainfall on orchard and in MDB					
Rain from May to August	-0.23	-0.26	0.51	-0.46	-0.49
Rain from September to December	-0.32	-0.31	0.26	-0.31	-0.31
Rain from January to March	0.02	-0.06	0.01	0.09	0.07
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	0.20	0.17	-0.16	0.32	0.32
Irrigation deficit from September to December	0.35	0.31	-0.25	0.53	0.46
Irrigation deficit from January to March	-0.11	-0.12	0.03	-0.07	0.14
Rainy and humid conditions					
MB+ve days from September to December	-0.33	-0.29	0.19	-0.56	-0.44
MB+ve days from January to March	0.03	0.03	0.12	0.23	0.00
Heat accumulation					
Mean temperature from September to December	0.23	0.15	-0.11	0.55	0.38
Mean temperature from January to March	-0.31	-0.37	0.27	0.30	0.26
Date from FB that GDD4.5 = 2000 °Cdays (1% hull split)	-0.23	-0.14	0.22	-0.54	-0.41
Date from FB that GDD4.5 = 2500 °Cdays (100% hull split)	-0.15	-0.07	0.12	-0.43	-0.34
Date from FB that GDD4.5 = 3250 °Cdays (Harvest)	-0.04	0.04	-0.07	-0.39	-0.22
Chill accumulation					
Dynamic chill portions accumulated to 31st July	0.03	0.07	-0.03	-0.14	-0.10
Utah chill units accumulated to 31st July	0.02	0.06	0.00	-0.21	-0.15
Heatwaves					
Days warmer than 35°C from September to December	0.33	0.26	-0.22	0.41	0.32
Days warmer than 35°C from January to March	-0.28	-0.34	0.19	0.10	0.17
Daylight hours warmer than 35°C from September to December	0.35	0.29	-0.21	0.35	0.25
Daylight hours warmer than 35°C from January to March	-0.24	-0.31	0.16	0.08	0.17
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	0.05	-0.03	-0.38	0.12	0.11

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).

Appendix 2. Methods and Outputs from

Theme 2: Field trials to examine the impact of climate and weather on Almond tree physiology

Project Al14006 Managing almond production in a variable and changing climate

Contents

Methods

Activity 1. Monitoring in Commercial orchards

Field sites were installed in four orchards from March 2015, with evaluation of yields in 2015 marking the commencement of plant based assessments. The orchards being monitored are located at Walker Flat, New Residence (Loxton region), Lindsay Point (NE of Renmark) and Lake Powell (East of Mildura). Meso-sites located at different elevations were located in each orchard in an otherwise similar orchard management unit. Three meso-sites were installed at the Walker flat orchard, and four meso-sites on the other orchards. At each meso-site three replicate plots, each containing four trees and two buffer trees were marked.

The Walker Flat orchard (Lat. -34°44’15S, Long. 139° 31’19E) was the most southerly orchard assessed. The 107 ha were planted on previous cropping land in 2004 on 7.0m rows running E-W along contour lines. The spacing between trees of 5.5 m gives 260 trees per hectare. The soils are sands of varying depths (0.3 m to more than 2.0 m) over clay. The three meso-sites on this orchard are located on a southerly slope at elevations of 74 m, 81 m and 88 m. The variety nonpareil was planted in every second row and accounts for 50% of the trees, with every other row planted to either carmel (in on average two of the three occasions) or price (in on average one of the three occasions). This gives a 50:33:17 ratio of nonpareil: carmel:price. All trees have been grafted onto nemaguard rootstock.

Annual yields on nonpareil kernel were 0.5 t/ha in 2011, increasing to average 0.8 t/ha in 2012 and 2013, and further increasing to average 1.1 t/ha in 2014 and 2015.

Annual water use was 7 ML/ha for the crop leading to the 2011 harvest, increasing to average 9 ML/ha for the crop leading to the 2012 and 2013 harvests, and further increasing to 10.5 ML/ha for the crop leading to the 2014 and 2015 harvests. Fertiliser application typically comprises annual amounts of 250 kg /ha nitrogen, 45 kg/ha phosphorus and 300 kg/ha potassium and about 2 kg/ha iron applied through the irrigation system. Smaller amounts of zinc, boron and other trace elements are applied.

The New Residence property (Company name Larila almonds) (Lat. -34°23’50S, Long. 140° 25’34E) is the smallest orchard at 18.6 ha. The soils are loamy sands to vary depths (0.7 m to at least 1.7 m). The orchard was planted in 1998 on a former citrus orchard making it the oldest orchard to be examined. The rows at 6.7 m spacings run down the contours (heading of 62°), and the distance between trees within a row are 6.1 m giving 244 trees per hectare. The four meso-sites are located on the upper and lower parts of two transects; one in a localized valley and the other on a localized ridge. Each plot consists of four trees in a row of nonpareil with other plots at the same meso-site located on adjacent rows of nonpareil. The elevations of the meso-sites are 23 m and 35 m for the lower and upper valley sites, and 31 m and 46 m for the lower and upper ridge sites. These elevations were measured for the middle two experimental trees (there was less than 1.0 m difference between the elevations of the twelve experimental trees within the three plots at each meso-site).

The variety nonpareil is planted in every second row and accounts for 50% of the trees, with every other row planted to either carmel or price giving a 50:25:25 ratio of nonpareil: carmel:price. All trees have been grafted onto nemaguard rootstock.

Yields from the orchard average about 3.5 t/ha, and could be considered slightly above average for the region. Water use for irrigation at approximately 12-14 ML per hectare was in line with that for the region. Fertiliser application typically comprised annual amounts of 320 kg /ha nitrogen, 70 kg/ha phosphorus and 350 kg/ha potassium and about 2 kg/ha iron applied as foliar sprays or through the irrigation system. Smaller amounts of manganese and zinc were applied as foliar applications.

The Lindsay Point property (company name CMV group) (Lat. -34°04’42S, Long. 141° 00’01E) has some of the highest stocking rates. The row spacings are 6.0 m and the distance between trees was 3.0 m giving 556 trees per hectare. The 330 ha orchard was previously a vineyard with small area of almonds (planted in 1981). The vines were removed and replanted to almonds from the late 2000’s with the latest planting occurring in 2013. The block containing the research plots was planted in 2009. This soil within the experimental block is a sandy clay loam over clay. It has an easterly aspect with N-S rows allowing for experimental plots to be located along individual rows. The elevations of the rows containing experimental plots are 39 m, 45 m, 46 m and 56 m.

The two middle experimental rows were moved to be in the current positions and closer proximity and similar elevations in June 2015 as although all experimental rows are located within one block of almonds with the same management schedule, the size of the block meant that upper two rows are irrigated on a different valve to the lower two rows and are effectively two sub-blocks. To reduce the chance that the different management of the two sub-blocks affecting findings the two middle rows (upper part of one sub-block and lower row in the second sub-block) have similar elevations.

The variety nonpareil is planted in every second row and accounts for 50% of the trees, with every other row planted to either carmel (in on average two of the three occasions) or monterey (in on average one of the three occasions). This gives a 50:33:17 ratio of nonpareil: carmel:monterey. All trees have been grafted onto nemaguard rootstock.

Yields in 2012 were 1.53 t/ha but averaged 3.3 t/ha from 2103. The lower yield in 2012 is likely due to plant age (planted in 2009). Water use averages 6-8ML/ha of non-bearing trees (first 3 years) and 14.5 ML/ha in bearing trees. Fertiliser application typically comprises annual amounts of 290 kg /ha nitrogen, 40 kg/ha phosphorus and 250 kg/ha potassium and about 2 kg/ha iron applied through the irrigation system. Smaller amounts of zinc, boron and other trace elements are applied as foliar applications.

The Lake Powell property (company name Select Harvest) (Lat. -34°43'46S, Long. 142° 54'44E) is the largest of the four orchards at 812 ha of almonds, and located at a similar latitude to the walker Flat orchard in SA's Riverland. The property was formerly used for cropping and potatoes on pivot irrigation. The blocks containing the research plots were planted in 2006 at row spacings of 7.25m and the distance between trees within a row are 4.65 m giving 303 trees per hectare.

The four meso-sites are located on the upper and lower parts of two transects located on two adjacent blocks with slopes having northerly aspects but also with a very gentle slope towards the west. As the rows run N-S, that is, down the steeper contours, each plot consists of four trees in a row of nonpareil with other plots at the same meso-site located on adjacent rows of nonpareil. The elevations of the meso-sites are 65 m and 78 m in one block and 66 m and 70 m in the other block. The elevations of these sites are for the second (middle) of the three plots at a meso-site, and are recorded between the second and third experimental tree. There is less than 1.0 m difference between the elevations of the twelve experimental trees within the three plots at each meso-site.

The variety nonpareil is planted in every second row and accounts for 50% of the trees, with every other row planted to either carmel (in on average two of the three occasions) or price (in on average one of the three occasions). This gives a 50:33:17 ratio of nonpareil: carmel:price. All trees have been grafted onto nemaguard rootstock.

Annual yield of nonpareil kernel remained steady at about 1.3 t/ha from 2009 to 2012, then increasing to average 2.4 t/ha from 2013 to 2015. Annual water use was 6.5 ML/ha for the crop leading to the 2010 and 2011 harvests, increasing to 10.4 ML/ha for the crop leading to the 2012 harvest, then averaging 12.5 ML/ha for the crops leading to subsequent harvests (2013, 2014, 2015). Fertiliser application varies within the orchard and between years. The annual range for most situations is from low 200's to 300 kg/ha nitrogen, 51 to 40 kg/ha phosphorus and high 200's to high 300's kg/ha potassium and about 2 kg/ha iron all typically applied through the irrigation system. Smaller amounts of zinc, boron and other trace elements are applied as foliar applications.

Temperature and %RH measurements of each plot and exterior to the orchard canopy were measured using Tinytag Plus 2 TPG 4500 located at 1.2 m height (standard for Australian weather recording) and housed in a sunlight (radiation) shield consisting of eight circular plastic rings of which two are solid enclosures and the remaining six form an internal cavity of 8 cm height and 11.5 cm diameter (831 cm^3). Additionally loggers were placed outside the canopy in larger screens (*Dimensions Base 400mm x 400mm; Height 500mm; Roof 630 x 630mm*). Temperature and %RH were logged hourly. The data loggers within the orchard were used to measure meso-climate, and those outside the canopy were used to account for the influence of shading by the almond trees on the temperature and %RH measurements. The loggers outside the canopy at Walker Flat was located within 2 m of the orchards own weather station, which will also allow comparison to these data. At the Lindsay Point and Lake Powell orchards the unshaded data loggers are located within 10 m of weather stations managed by Lower Murray Water. Logger positions were re-randomised annually.

A range of Climate indices at each meso-site were calculated including growing season mean temperature, number of days warmer than 35°C and 40°C; the number of days (nights) cooler than 2°C before June, after August, and after October; chill accumulation using the Dynamic chill model and the Utah model prior to 31st July, effective day temperature in December (see earlier section for details of calculation methods).

In July 2016 additional equipment was installed at the Walker Flat orchard to monitor the vertical profile of temperature and wind both within the canopy and in matched external locations outside the orchard as a function of elevation. This was done using a series of towers capable of attaining a height of 5.5m.

Each group of towers (a separate tower is used for temperature and for wind measurements) comprises temperature and relative humidity measurements at 0.1m (ground), 1.2m (lower canopy and also standard bureau of meteorology height), 1.8m (mid canopy), 3.6m (upper canopy) and 5.5m (above canopy), and wind speed at 2.4m (in canopy) and 5.5m (above canopy). Soil temperature was monitored at 0.2m soil depth. Wind direction was monitored at 5.5m only.

Two plots were monitored at each of the three elevations at the Walker flat orchard. One representative location corresponding to each elevation was monitored in the adjacent native bush area outside the orchard area. These were used to examine the influence of the almond canopy on the meso-climate independently of the influence of elevation.

Soil moisture was monitored using gypsum blocks at four depths at each meso-site in one plot.

Soil mapping of the experimental areas was done by an EM38 soil survey. These data are a composite value for a soil that may be related to soil physical and chemical properties. It is not possible to separate the various physical and chemical properties of a soil by the EM38 value. Overall differences in EM38 readings between research sites within an orchard were small at all orchards and largely unrelated to elevation besides at the Lindsay point orchard (Table 1).

Table 1. Elevation and EM38 at each research plot.

Orchard	Meso-site	Elevation (m)	EM38 at 1m depth ds/m	EM38 at 0.5m depth ds/m
Walker Flat	High	88	29.6	24.8
	Mid	81	41.6	31.5
	Low	74	36.6	30.7
New Residence	Valley Low	23	9.6	14.0
	Valley High	35	12.4	14.7
	Ridge Low	32	10.5	13.97
	Ridge High	46	12.7	15.07
Lindsay Point	Low	39	20.6	22.5
	Mid-Low	45	43.6	37.57
	Mid-High	46	51.0	46.67
	High	56	62.3	48.67
Lake Powell	West High	70	6.6	9.8
	West Low	66	6.4	9.8
	East High	78	8.1	9.9
	East Low	65	17.1	14.69

Phenology was assessed on the experimental trees. The progression of flowering and hull split was monitored on all experimental trees using the method outlined by Connell (Pers. Comm. and subsequently codified in Thomas and Connell, 2018). The procedure for assessing flowering involved counting the proportion of floral buds that have attained BBCH 60 ('open flowers' of stage F) or later on small sections of the tree, then estimating the proportion of open flowers or later stages of the entire tree. Measurements were collected every three to four days. Linear regression of these proportions with date of measurement were used to calculate when 10%, 50% 80% or 100% of floral buds (or flowers) had reached the 'open flower' stage.

Development of other floral stages such as 'green tip' (BBCH 55 or stage C), 'pink tip' (BBCH 57 or stage D), 'petal fall' (stage G) were followed in some years and orchards.

A similar procedure was used to calculate dates of 1% and 100% hull split. Hull split can be segregated into several stages (University of California, 2002). A fruit was considered to have a split hull when it had attained

Stage 2C Deep V over the suture line which is not visibly separated but can be squeezed open by pressing both ends of the hull (University of California, 2002).

Yields of each tree were assessed. Trees were 'shaken' by the orchard managers at the time of commercial harvest. All fallen material (leaves, fruit) was collected, weighed and a subsample of approximately 1.5kg stored in a sealed plastic bag. This subsample was weighed and fruit separated before fresh weight of fruit measured and then dried in a fan forced oven at 35°C for 2 weeks / constant moisture.

The dry weight of fruit was recorded and the fruit was de-hulled and shelled using Jessee mini almond huller and sheller (Jessee equipment manufacturing, Chico, California, USA). The dry weight of kernel was recorded. Yield of kernel per tree and per hectare was calculated. The weight of a randomly selected sample of 100 kernel samples was recorded. The number of deformed kernels (miss-shapen, 'doubles', shriveled appearance, 'split') in this 100 kernel sample was recorded.

Data of tree physiology measures (yield and its components), phenology measures (dates of flowering, hull split, harvest) and meso-climate (various climate indices) was analysed using ANOVA with meso-sites at each orchard as the treatments. Pearsons correlation coefficient was used to examine relationships between variables within each orchard and also by examining all orchards.

Activity 2. Monitoring of almonds growing on pots enclosed in passively solar heated chambers

Bare-rooted plants of nonpareil, carmel and price varieties were received from a commercial nursery in July 2015 and potted into 100l pots containing a soil:cocopeat mixture. Three plots each of six plants of nonpareil and six of carmel were arranged as 4 rows of 3 plants. Varieties were alternated between the two varieties. Both rows and within row spacings were 2.5m. A buffer of price, nonpareil and carmel trees surrounded all sides of these experimental plots to aid pollination and to reduce edge effects.

In March 2017, half the trees of each variety in each pot were randomly selected as treatment trees to receive passive solar heating. An enclosure 1.5 m*1.5 m * 1.8m high and side walls covered with clear polycarbonate sheeting from 0.2 m height was built around these plants.

Temperature was monitored using Tinytag TPG 4505 dataloggers at 1.3 m height in all plants, and in each of four randomly selected control (unheated ambient air) and treatment (passively solar heated air) additionally at 0.7 m, 1.6 m and 2.0 m.

Flowering, hull split and yield were determined on each experimental plant (method as for field grown plants).

Plants were grown with adequate water (field capacity daily) with irrigation up to four times daily when plants had high leaf area and weather conditions were extreme. Nutrition was supplied with a complete slow release fertilizer with added trace elements. Plants did not show visible signs of water or nutrition stress.

Data of tree physiology measures (yield and its components), phenology measures (dates of flowering, hull split, harvest) and meso-climate (various climate indices) was analysed using ANOVA with passively heat chambr and control (ambient air) as the treatments.

Output / Results

Activity 1. Monitoring in Commercial orchards

Meso-climate at the Orchards

The meso-sites had distinct meso-climates which when examined on a daily basis are best observed as differences from the site average (figure 1). These figures show the daily traces of temperature and the anomalies of the meso-sites daily maximum, daily minimum and daily mean temperature from the site average. The anomalies in temperature were small or non-existent during the dormant period but became more apparent during the growing season, seen clearly in the observations at the Lindsay Point and New Residence orchards. Table 2 shows several climate indices calculated for the meso-sites in each year and the average for the period from 2016 to 2019. What figure 1 and table 2 show is that the lower elevation meso-sites generally had cooler temperature which occurred from both cooler daily minimum temperature and cooler daily maximum temperatures. The impact of elevation on meso-climate can be seen most clearly at the Lindsay Point and Walker Flat orchards. The situation at New Residence differs. The topography of the New Residence orchard with a localised protected valley draining to the Murray River would account for the over cool temperatures, greater chill accumulation, larger number of nights colder than 2°C and fewer days warmer than 35°C than the more exposed Ridge meso-sites on the orchard. The Lake Powell orchard had few differences between meso-sites but did show generally warmer temperatures at higher elevation and cooler at lower elevation. The reasons for the relatively minor difference in meso-climate at Lake Powell are unclear. The elevation difference between meso-sites at Lake Powell was small at 13m, but comparable to that at Walker Flat (14m). However it is conceivable that air was more able to flow freely down elevation gradients at Lake Powell owing to rows running up-down elevations, slightly wider tree rows, and younger and smaller trees at Lake Powell compared to Walker Flat (rows running with elevation, slightly narrower tree rows, and older and larger trees).

Year-to-year differences existed in climate and meso-climate. For example the growing season of 2016/2017 was cooler across all orchards with fewer days warmer than 35°C, and also lower chill accumulation in the winter of 2016. However chill accumulation is high is all instances and above the minimum requirement for completion of dormancy in Nonpareil. Minor meso-site differences in chill accumulation did exist in some orchards in some years (e.g. New Residence in most years, and Walker Flat in some years).

Similarly the number of nights colder than 2°C, and therefore prone to frost varied more between years and orchards than between meso-sites. For example more nights colder than 2°C in 2017 than many other years. However some meso-sites were more likely to experience cold night temperatures; the lowest elevation meso-site at Walker Flat and the Valley meso-sites at New Residence.

The occurrence of extreme warm days was as previously noted related to years, but also to orchards and meso-sites. The Lake Powell orchard had an average of 4 days warmer than 40°C, the Walker Flat orchard had an average of 2 days warmer than 40°C, and the exposed Ridge meso-sites at New Residence had an average of 6 days warmer than 40°C but the protected Valley meso-sites had no days warmer than 40°C (data not shown). The low number of days warmer than 35°C at the Walker flat orchard was probably related to its more coastal and southerly location compared to the other orchards. The Lindsay Point orchard had a very low number of days warmer than 35°C and no day warmer than 40°C, despite its northerly location. The reduction in the number of extremely warm days is probably related to the high tree density of approximately double other orchards leading to a more protected meso-climate. This protected meso-climate as a consequence of the orchards leaf canopy can be beneficial as shown above, but may also increase some risks to almond production; namely delayed and reduced drying of fruit near or after harvest.

The importance of the leaf canopy on modifying the orchard can be examined from the information from the temperature and wind sensor-array within and above canopies at Walker Flat (figure 2, 3, 4). These array of sensors indicated temperature and wind within the canopies varied considerably on a day-to-day basis. Temperature within the canopy are generally cooler and less windy than outside the orchard. These differences are greatest when the orchard has a fuller canopy and largely disappear as the canopy becomes leafless.

Figure 2 shows the average monthly daily maximum temperature at 1.2m height above ground at exterior to the orchard at the High elevation, and the corresponding temperature at noon. This location was used to compare the temperatures of other locations with anomalies in temperature reported from this location. Figure 2 also shows average monthly soil temperature at 0.15 m depth exterior to the orchard and within the orchard at the High, Mid and Low elevation meso-sites. As can be seen soil temperatures become progressively cooler within the orchard as the season progressed, irrigation was applied leading to a cooler environment and canopies became leafier. As the season progressed further the cooler soil temperatures within the orchard compared to outside the orchard become less and eventually cease. This is most likely due to reduced shading and irrigation, with the small amounts of rainfall contributing to cooling the soil on the exterior of the orchard.

Figure 3 shows the difference in noon average monthly temperature within the canopy at height above ground of 0.1m, 1.2m, 1.8m. 3.6m, and 5.4m, that is, cusp of top of canopy and above canopy and similar heights above ground on sensors outside the orchard at each of the Low, Mid and High elevation meso-sites. The temperature differences (differentials) were in relation to a common point of 1.2m height above ground on the sensors located exterior to the orchards that aligned with the High meso-site; negative temperature differentials mean that that point is cooler, and positive differentials mean the point is warmer. The temperature differential at 1.2m height above ground at the exterior to orchard of the High meso-site (red line) is always 0.0.

At dawn there are minor difference in air temperature between the exterior and interior of the orchard throughout the year (data not shown). There was also little difference as a consequence of canopy height. The situation differs during daylight hours when a leafy canopy exists. During daylight hours temperature gradients existed within the canopy (either when leafed or leafless) when the canopy had leaves. Overall there was a positive gradient as the height in the canopy increased. That is, the lower part of the canopy was colder compared to the upper part of the canopy and the common measuring point of exterior to the orchard at 1.2m height. This was probably related to the greater reduction in sunlight with increasing canopy depth. The reverse gradient occurred exterior to the orchard where a negative thermal gradient existed, that is, the heights closer to the ground were warmer than heights further from the ground. This would also be related to sunlight and radiation absorption by the ground surface.

Figure 4 shows the average daily wind run, and average of maximum daily wind gust at 2.4m and 5.4m height above ground exterior to the orchard and within the orchard height. Wind gusts (maximum speed) and wind run (km per day) are greater at 5.4 m height above ground than 2.4m height above ground for both the exterior and interior of the orchard. Not surprisingly the presence of the orchard and its canopy reduces wind at all speeds leading to both reduced wind gusts and wind runs. The greater wind speeds and higher temperatures in the upper canopy compared to the lower canopy would stimulate evapotranspiration which may explain why hull split occurs earlier in the upper canopy. The lower wind speeds in the lower canopy would reduce transpiration, which while beneficial to increasing water use efficiency of the growing canopy are likely to be detrimental to drying of the hulls and kernels near the time of harvest. This reduced evaporative potential when canopies become greater is likely to be exacerbated in higher density orchards (i.e. H2 or H3 orchards); a condition that may be detrimental to both hull drying and harvest operations and also to general pest and disease control throughout the growing season.

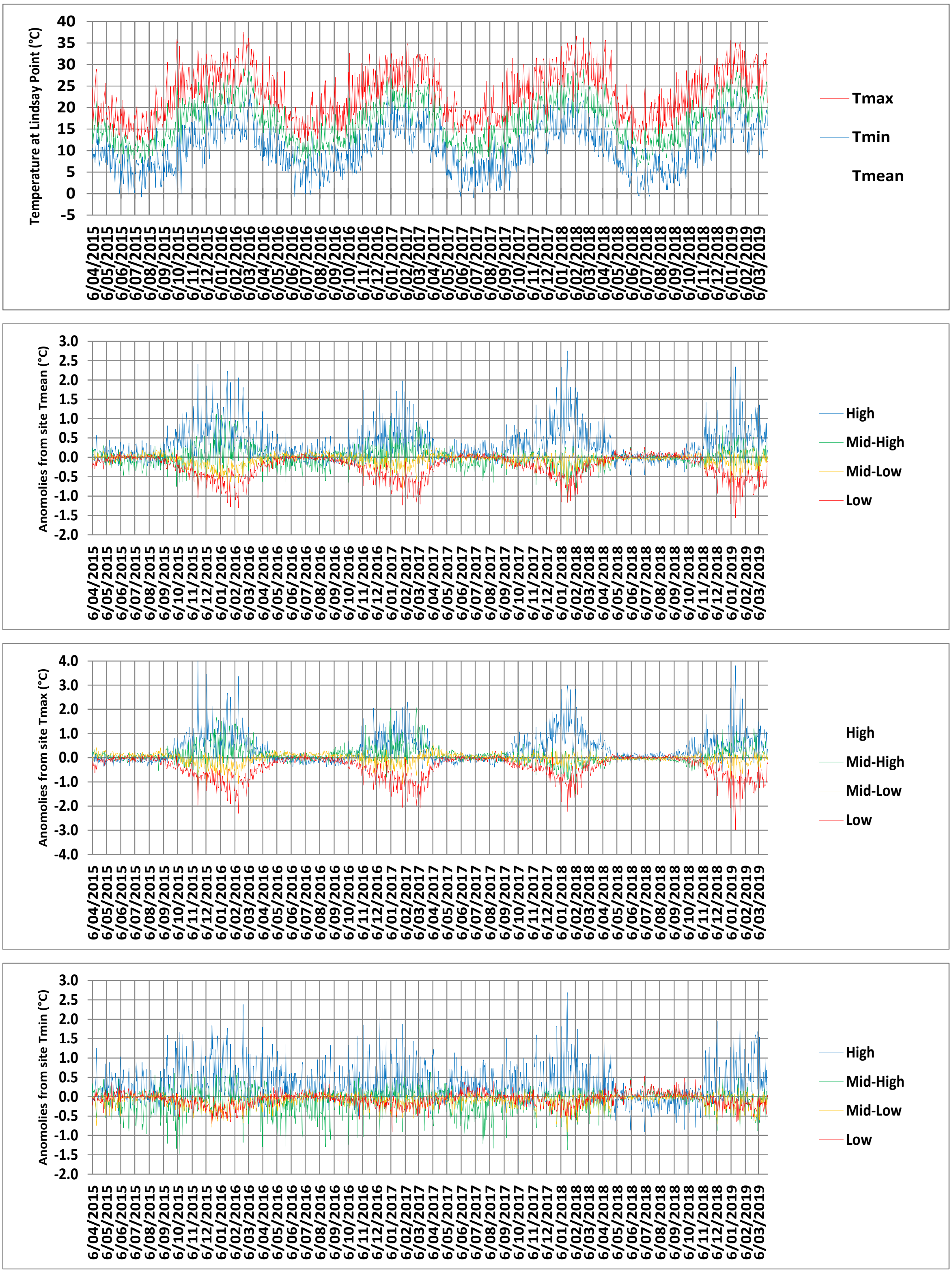


Figure 1A. Daily mean, maximum and minimum temperatures for the orchard at Lindsay Point, Vic. (calculated as the average of all meso-sites, and the anomalies in daily mean, maximum and minimum temperatures temperature from this orchard average at each meso-site.

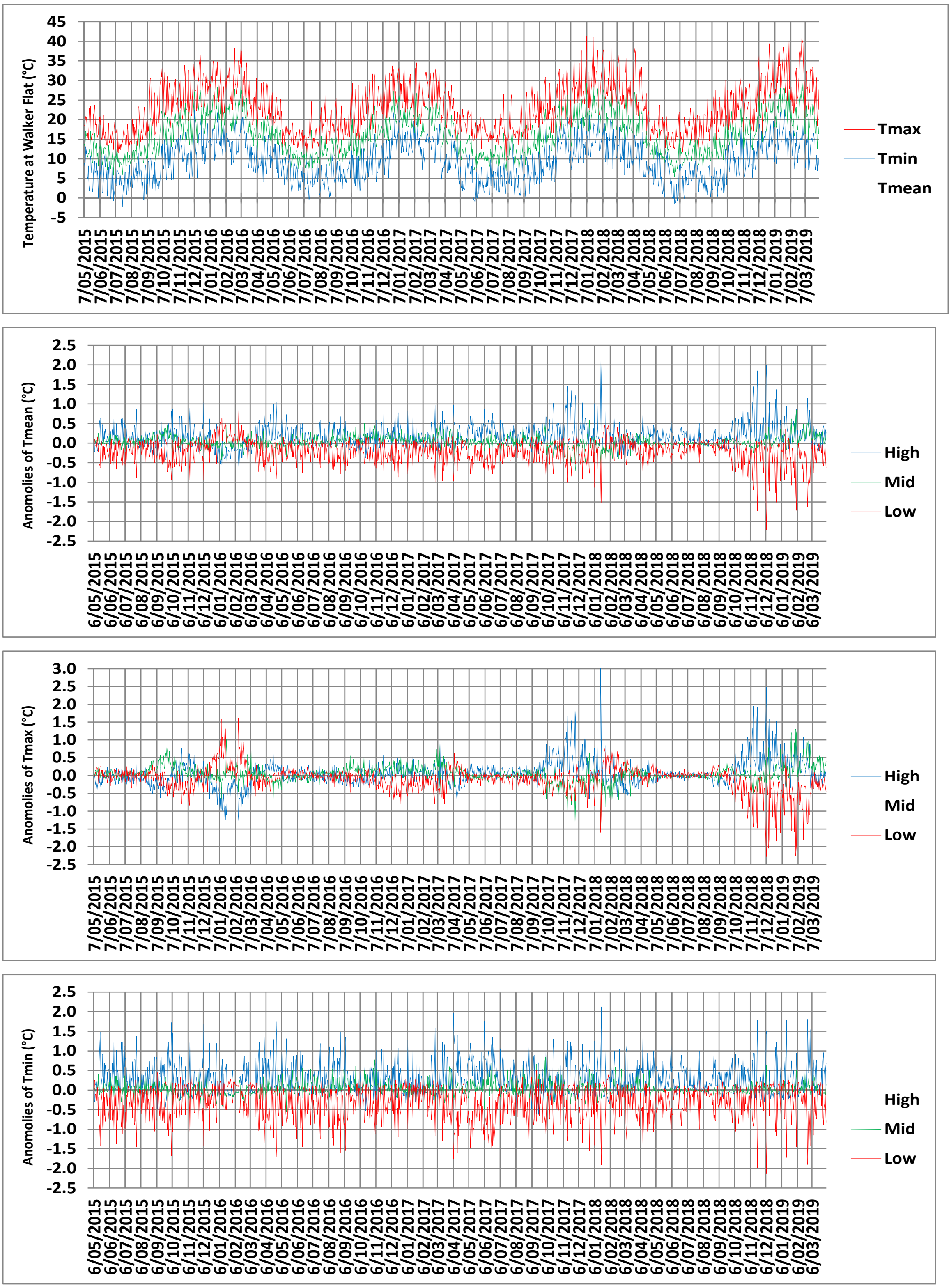


Figure 1B. Daily mean, maximum and minimum temperatures for the orchard at Walker Flat, SA (calculated as the average of all meso-sites, and the anomalies in daily mean, maximum and minimum temperatures temperature from this orchard average at each meso-site.

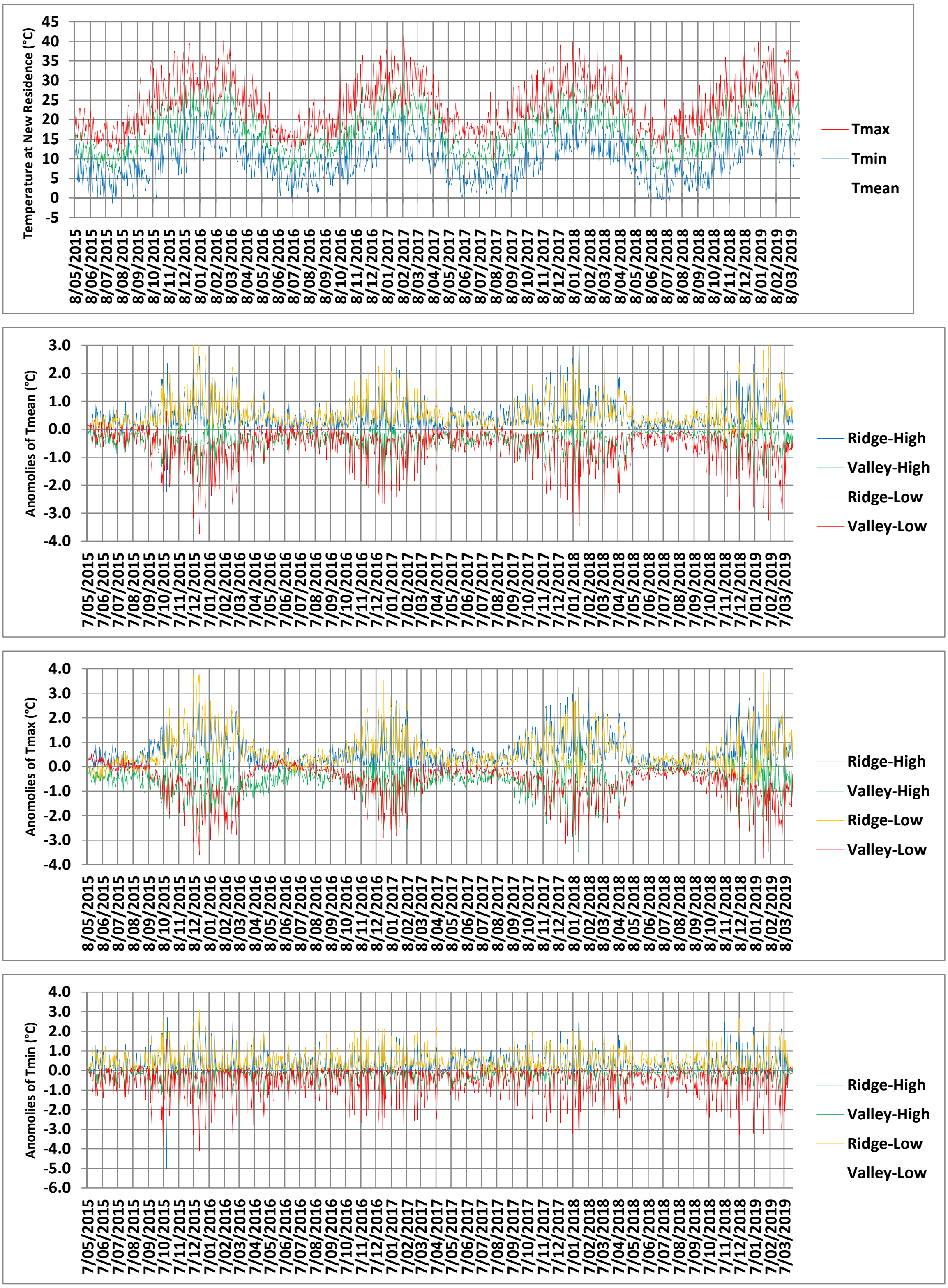


Figure 1C. Daily mean, maximum and minimum temperatures for the orchard at New Residence, SA (calculated as the average of all meso-sites, and the anomalies in daily mean, maximum and minimum temperatures temperature from this orchard average at each meso-site.

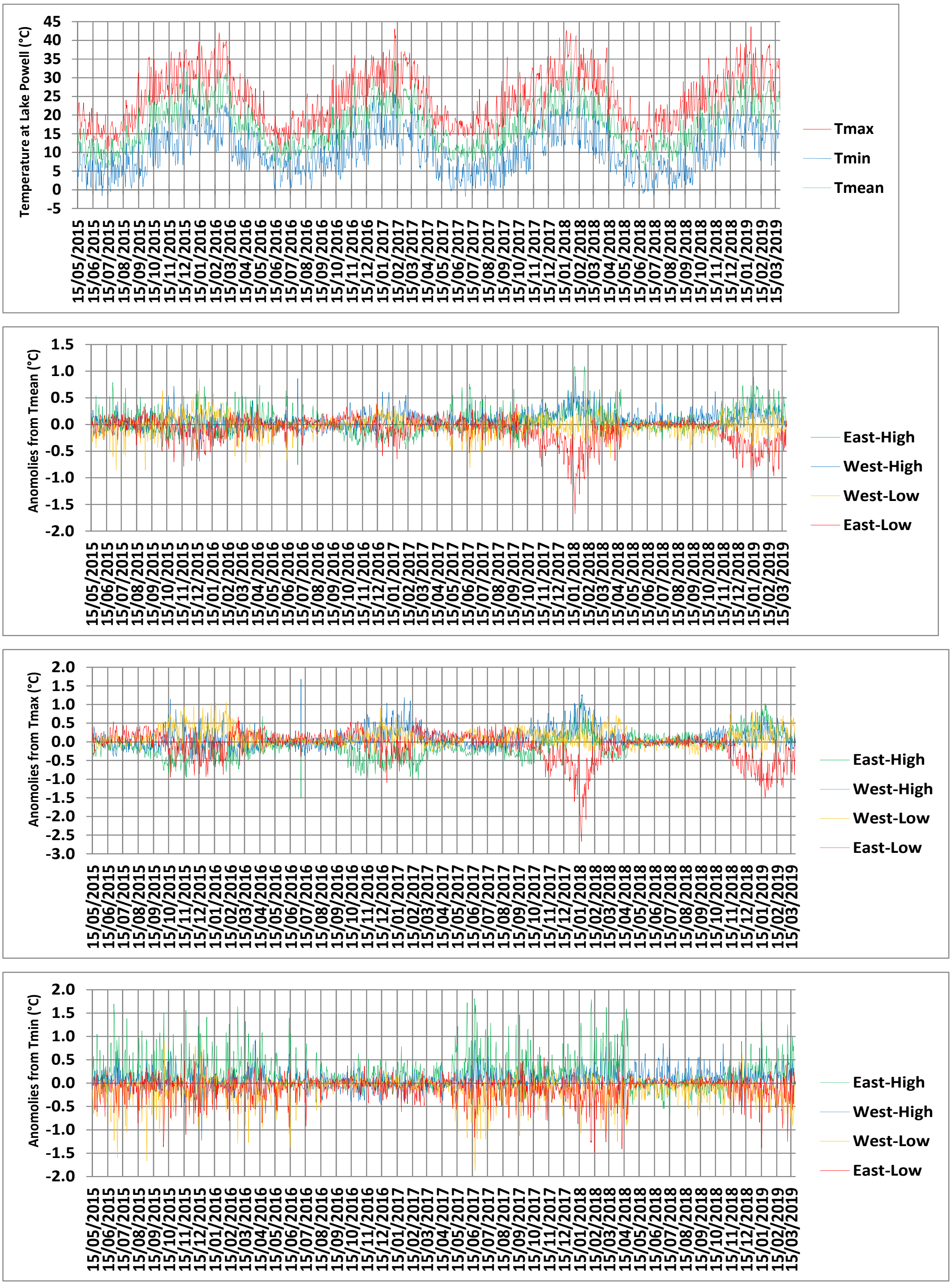


Figure 1D. Daily mean, maximum and minimum temperatures for the orchard at Lake Powell, Vic. (calculated as the average of all meso-sites, and the anomalies in daily mean, maximum and minimum temperatures temperature from this orchard average at each meso-site.

Table 2. Climate indices at the meso-sites in each measurement year (classified as budburst year – year of harvest) and the average of all years. Indices include growing season mean temperature (GST) where growing season was deemed to be from August to April, daily maximum temperature (Max) and daily minimum temperature (Min) during the growing season, number of days cooler than 2°C after August, number of days warmer than 35°C and 40°C, number of pollination hours measured as hours warmer than 15C during August, and Dynamic chill portions measured until 31st July.

Orchard	Meso-site	GST (°C)	Max (°C)	Min (°C)	Days <2°C (after August)	Days >35°C	Days >40°C	Hours >15°C (in August)	Dynamic Chill Portions
Lindsay	Low	18.5	36.3	0.7	4	3	0	147	53
Point	Mid-Low	18.7	37.4	0.6	4	6	0	151	52
2015-2016	Mid-High	18.9	37.7	0.5	5	8	0	150	51
	High	19.3	38.8	1.6	2	14	0	144	53
Lindsay	Low	17.6	33.4	1.3	3	0	0	171	39
Point	Mid-Low	17.9	34.3	1.3	3	0	0	176	38
2016-2017	Mid-High	18.1	35.7	0.6	4	2	0	170	40
	High	18.3	37.1	1.4	3	3	0	169	40
Lindsay	Low	18.6	36.0	0.6	6	5	0	161	46
Point	Mid-Low	18.8	36.8	0.5	6	7	0	163	46
2017-2018	Mid-High	18.7	36.5	0.4	7	6	0	161	46
	High	19.3	38.8	0.6	7	16	0	161	47
Lindsay	Low	18.2	33.9	0.8	3	0	0	170	42
Point	Mid-Low	18.5	35.3	0.6	3	3	0	168	43
2018-2019	Mid-High	18.6	36.2	0.8	3	4	0	169	43
	High	18.9	38.8	0.5	3	7	0	173	42
Lindsay	Low	18.2	34.9	0.7	4	2	0	162	45
Point	Mid-Low	18.5	36.0	0.6	4	4	0	164	45
2016-2019	Mid-High	18.6	36.5	0.5	5	5	0	162	45
	High	19.0	38.4	0.6	4	10	0	162	45

Table 2 (continued)

Orchard	Meso-site	GST (°C)	Max (°C)	Min (°C)	Days <2°C (after August)	Days >35°C	Days >40°C	Hours >15°C (in August)	Dynamic Chill Portions
Walker	Low	18.0	38.8	-1.2	9	11	0	118	46
Flat	Mid	18.2	38.9	-0.7	5	9	0	122	47
2015-2016	High	18.2	38.4	-0.6	4	5	0	117	48
Walker	Low	16.6	34.2	-0.5	13	0	0	156	44
Flat	Mid	16.9	34.9	0.1	7	0	0	160	42
2016-2017	High	17.0	34.5	0.8	6	0	0	159	41
Walker	Low	17.9	40.5	-0.9	12	19	1	137	51
Flat	Mid	18.1	41.4	-0.4	9	18	2	143	46
2017-2018	High	18.3	42.5	-0.4	9	21	2	144	46
Walker	Low	17.6	40.1	-0.1	13	15	1	147	44
Flat	Mid	18.0	42.0	0.3	10	20	4	146	45
2018-2019	High	18.2	41.5	0.7	6	20	4	146	45
Walker	Low	17.6	38.4	-0.7	11.7	11.4	0.6	140	46
Flat	Mid	17.8	39.3	-0.2	7.9	11.8	1.6	143	45
2016-2019	High	17.9	39.2	0.1	6.3	11.5	1.6	141	45

Orchard	Meso-site	GST (°C)	Max (°C)	Min (°C)	Days <2°C (after August)	Days >35°C	Days >40°C	Hours >15°C (in August)	Dynamic Chill Portions
New	Valley-Low	18.4	38.2	-0.4	6	7	0	146	44
Residence	Ridge-Low	19.8	42.9	0.9	2	43	8	152	43
2015-2016	Valley-High	18.7	39.0	-0.5	6	11	0	131	46
	Ridge-High	19.6	42.3	0.3	3	38	4	152	43
New	Valley-Low	17.7	39.7	0.6	6	6	0	160	43
Residence	Ridge-Low	18.8	44.5	1.8	1	28	5	174	40
2016-2017	Valley-High	17.8	39.4	0.9	5	5	0	154	42
	Ridge-High	18.5	44.3	1.4	1	26	5	169	40
New	Valley-Low	18.1	37.2	0.0	7	5	0	138	47
Residence	Ridge-Low	19.3	42.6	0.3	2	25	3	154	44
2017-2018	Valley-High	18.3	37.1	-0.1	8	7	0	132	48
	Ridge-High	19.4	42.9	0.5	2	28	3	161	43
New	Valley-Low	18.0	37.4	0.5	6	7	0	154	46
Residence	Ridge-Low	19.2	42.6	1.9	1	24	6	168	43
2018-2019	Valley-High	18.5	37.4	1.3	4	14	0	153	44
	Ridge-High	19.2	42.3	1.6	2	30	5	161	43
New	Valley-Low	18.0	38.1	0.2	6	6	0	149	45
Residence	Ridge-Low	19.3	43.2	1.2	2	30	6	162	43
2016-2019	Valley-High	18.3	38.3	0.4	6	9	0	143	45
	Ridge-High	19.2	42.9	0.9	2	31	4	161	42

Table 2 (continued)

Orchard	Meso-site	GST (°C)	Max (°C)	Min (°C)	Days <2°C (after August)	Days >35°C	Days >40°C	Hours >15°C (in August)	Dynamic Chill Portions
Lake Powell 2015-2016	East-Low	19.9	42.1	0.0	6	39	5	145	42
	West-Low	20.0	42.0	-0.4	7	46	4	141	43
	West-High	20.0	42.2	0.5	6	42	3	138	43
	East-High	20.0	42.1	0.9	5	35	2	137	43
Lake Powell 2016-2017	East-Low	18.8	43.1	-0.2	4	21	2	168	43
	West-Low	18.9	43.2	0.1	3	20	2	164	44
	West-High	18.9	43.4	0.1	4	22	3	163	43
	East-High	18.7	42.6	0.5	3	18	2	165	43
Lake Powell 2017-2018	East-Low	19.2	41.1	-0.2	11	25	4	147	46
	West-Low	19.5	43.0	-0.2	9	31	7	146	45
	West-High	19.6	43.9	-0.1	9	33	9	144	46
	East-High	19.6	43.5	-0.1	6	30	8	138	47
Lake Powell 2018-2019	East-Low	19.1	42.8	-0.2	11	22	1	165	46
	West-Low	19.3	43.5	-0.3	14	30	2	166	46
	West-High	19.5	44.1	0.1	10	29	1	164	46
	East-High	19.5	44.2	-0.2	13	31	2	166	46
Lake Powell 2016-2019	East-Low	19.3	42.3	-0.2	8	27	3	156	44
	West-Low	19.4	42.9	-0.2	8	32	4	154	44
	West-High	19.5	43.4	0.2	7	32	4	152	45
	East-High	19.5	43.1	0.3	7	29	4	152	45

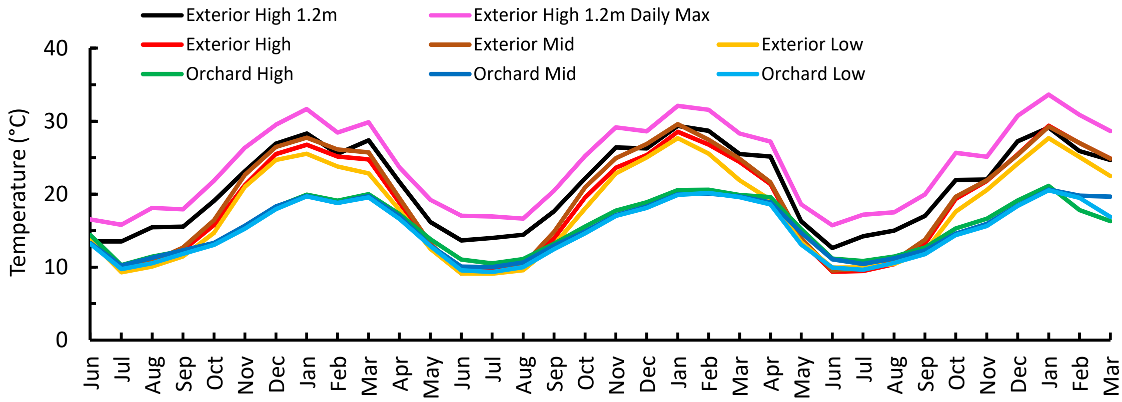


Figure 2. Average monthly daily maximum temperature at 1.2m height above ground at exterior to the orchard at the High elevation, and the corresponding temperature at noon, and average monthly soil temperature at 0.15 m depth exterior to the orchard and within the orchard at the High, Mid and Low elevation meso-sites.

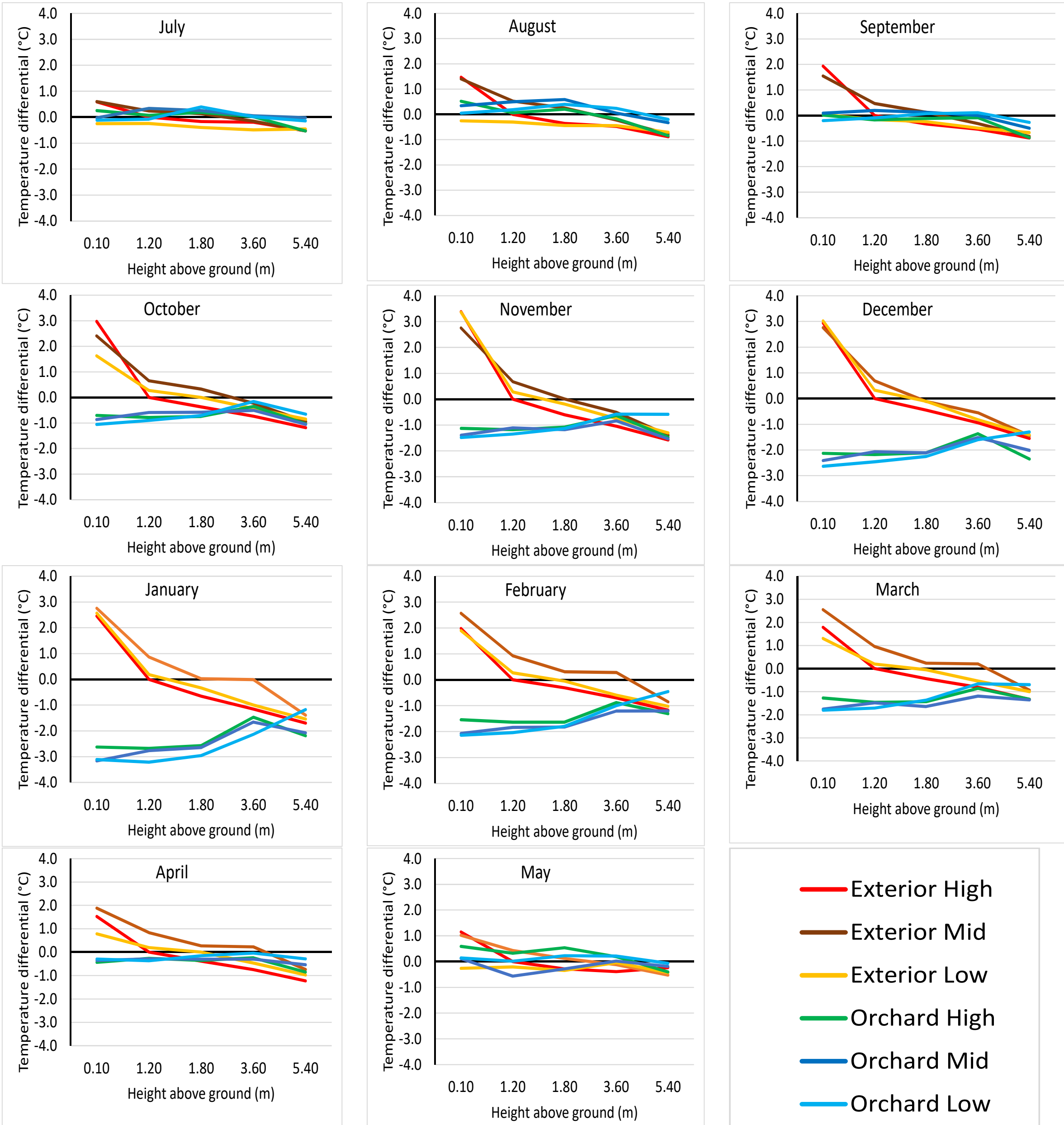


Figure 3. Average monthly noon temperature differentials exterior to the orchard and within the canopy at 0.1m, 1.2m, 1.8m. 3.6m, and 5.4m height above ground at the Low, Mid and High elevation meso-sites.

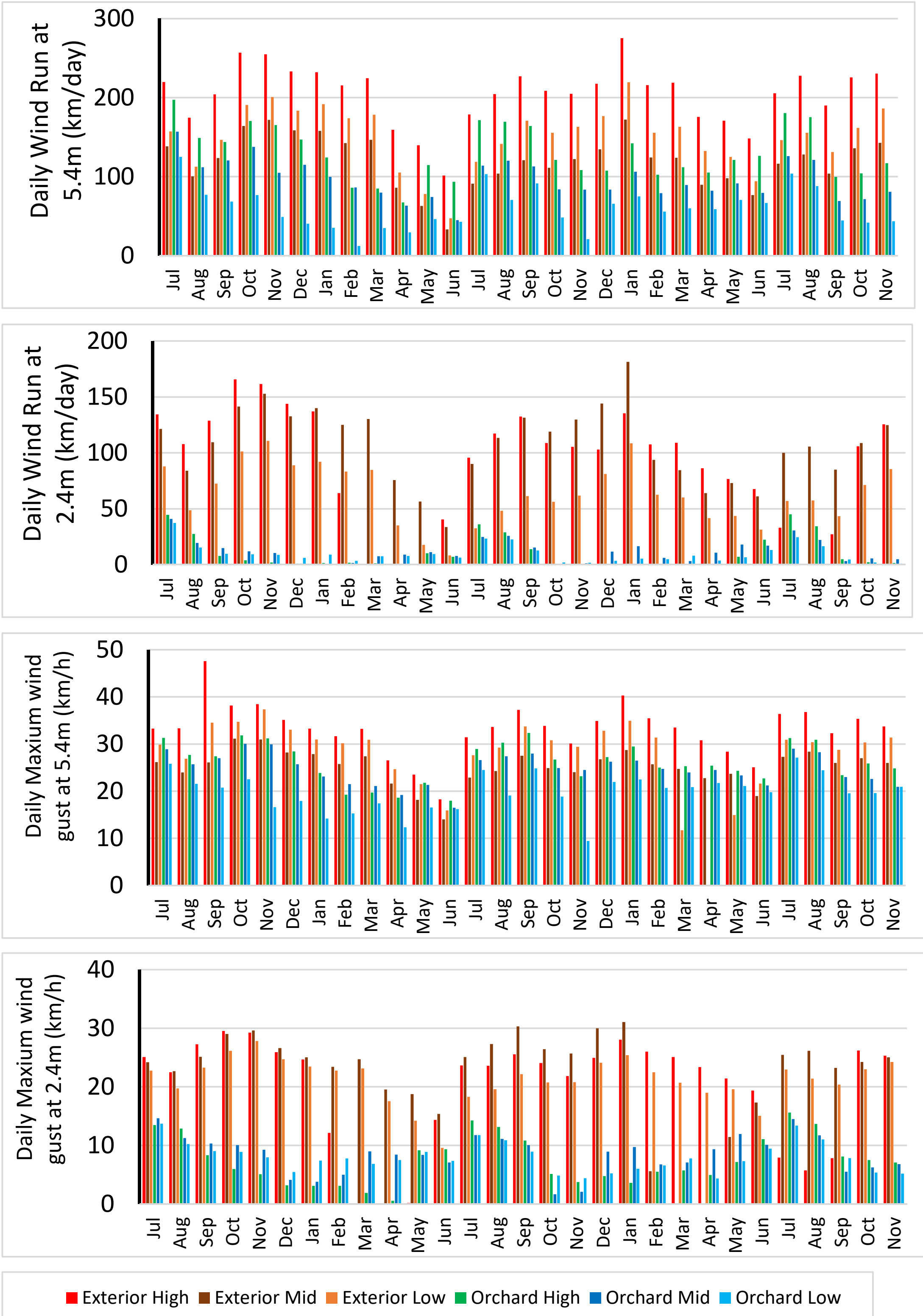


Figure 4. Monthly average of daily wind run and daily maximum wind gust measured at 5.4m and 2.4m height above ground exterior to the orchard and within the orchard at the High, Mid and Low meso-sites. Data from July 2016 to May 2018.

Phenology: flowering, hull split and maturity

Phenology observations are shown in table 3. This table shows that larger differences existed in the date of hull split (1% or 100%) and date of harvest than dates of flowering. Overall date of flowering was relatively stable across years, orchards and meso-sites with a range of about 7 days for the dates of 10%, 50% or 80% flowering. The one exception was the walker flat orchard in one year when differences in the dates of all stages of flowering occurred. In that instance flowering was about 7 days earlier in the High meso-site.

Dates of the commencement of hull split (1% hull split) and completion of hull split (100% hull split) were more affected by meso-site, orchard and year than date of flowering. The dates of commencement of hull split could be up to 22 days and completion of hullsplit could be up to 25 days, but could also be 1 day for both phenostages. The average difference between meso-sites was 9 days for both phenstages. Hull split had a tendency of occurring earlier on the higher meso-sites; seen more clearly at the High meso-sites at the Lindsay Point and Walker Flat orchards, and smaller differences at New Residence when comparing the High to Low meso-sites within the Ridges and Valley meso-sites. At New Residence, hull split at the ridge meso-sites was typically earlier than at the Valley meso-sites.

Date of Harvest was determined by orchard managers. On occasions fruit were harvested at an earlier than commercially acceptable date. This is apparent by examining the %moisture content of the fruit.

The phenological dates were correlated with climate indices. Date of 10% flowering was negatively related to chill accumulation in all but the Walker Flat orchard (Figure 104). Generally weaker but significant relationships existed between dates of 80% flowering and chill accumulation. These relationships show that flowering occurred earlier when chill accumulation until 31st July was larger.

Dates of 1% and 100% hull split were negatively correlated with growing season mean temperature (Figure 5).These relationships were strongest at Walker Flat and Lake Powell. Although no relationship existed at Lindsay point with date of 1% hull split, a weak relationship existed between GST and date of 100% hull split. Hull split can be modified by other environmental factors. For example it was noticed that reduced soil moisture leads to earlier hull split. The soil moisture at the meso-sites are shown in figure 6. Generally, soil tension was maintained at a low (close to zero), and therefore non limiting level throughout the growing period, but at a more negative soil tension in the non-growing season. There were exceptions caused by equipment failure where soil tension increased for short periods.

The phenology and corresponding temperature observations have been used when developing and testing the phenology model for almonds (next section).

Table 3. Phenology at the meso-sites at each orchard. Phenology observations consist of the day in August in the budburst and flowering year when 10%, 50% and 80% flowering occurred, the day after 1st January when 1% and 100%% hull split occurred, and the day after 1st January in the year of harvest when the trees were harvested. The average of each meso-site and the range are shown. The % fruit moisture at harvest is shown along with the average for each meso-site. Values in bold are significant.

Orchard	Meso-site	Day in August 10% FL	50% FL	80% FL	Day after 1st January 1% HS	100% HS	Harvest	Moisture (%)
Lindsay Point 2015-2016	Low	6	14	19	22	51	60	25
	Mid-Low	6	12	18	22	43	60	21
	Mid-High	6	13	20	25	53	60	24
	High	6	13	20	17	39	60	8
	range ; mean	0	2	2	**8**	**14**		**20**
Lindsay Point 2016-2017	Low	10	16	20	26	57	67	22
	Mid-Low	10	15	19	24	53	67	23
	Mid-High	10	15	18	28	59	67	22
	High	10	15	18	21	59	67	6
	range ; mean	1	1	2	7	6		**18**
Lindsay Point 2017-2018	Low	9	16	21	30	53	58	88
	Mid-Low	8	13	19	33	53	58	89
	Mid-High	8	14	20	33	55	58	88
	High	8	14	20	30	53	58	47
	range ; mean	0	3	2	3	2		**78**
Lindsay Point 2018-2019	Low	9	13	15	18	47	63	26
	Mid-Low	9	12	14	18	46	63	26
	Mid-High	9	12	14	18	52	63	29
	High	9	12	14	18	46	63	13
	range ; mean	0	1	1	1	6		**23**
Walker Flat 2015-2016	Low	8	14	20	16	42	57	20
	Mid	4	11	17	16	38	63	22
	High	0	8	13	19	36	63	24
	range ; mean	**8**	**6**	**7**	3	**6**		20
Walker Flat 2016-2017	Low	9	12	14	33	59	69	64
	Mid	9	14	17	23	53	69	41
	High	9	13	15	22	55	67	35
	range ; mean	1	2	2	11	6		**47**
Walker Flat 2017-2018	Low	11	13	15	18	39	52	63
	Mid	10	13	15	11	31	52	36
	High	10	13	14	6	29	43	14
	range ; mean	0	0	1	**11**	**10**		**38**
Walker Flat 2018-2019	Low	7	10	12	18	43	58	142
	Mid	7	10	13	12	43	49	55
	High	7	9	12	4	18	44	11
	range ; mean	0	1	1	**14**	**25**		**70**

Table 3 (continued)

Orchard	Meso-site	Day in August 10% FL	 50% FL	 80% FL	Day after 1st January 1% HS	 100% HS	 Harvest	Moisture (%)
	Valley-Low	7	15	21	31	60	69	5
New Residence	Ridge-Low	7	14	18	12	35	64	13
2015-2016	Valley-High	7	13	19	27	54	69	6
	Ridge-High	7	14	18	9	35	64	11
	range ; mean	0	2	3	**22**	**25**		**9**
	Valley-Low	12	17	21	24	43	75	6
New Residence	Ridge-Low	11	15	20	21	38	68	12
2016-2017	Valley-High	12	16	20	20	43	75	1
	Ridge-High	11	15	20	22	38	68	8
	range ; mean	1	1	1	5	**5**		**7**
	Valley-Low	6	11	14	32	45	74	10
New Residence	Ridge-Low	5	10	15	11	31	71	13
2017-2018	Valley-High	5	10	14	32	46	74	11
	Ridge-High	5	10	14	23	38	71	10
	range ; mean	1	1	1	**21**	**15**		11
	Valley-Low	10	14	16	12	55	68	9
New Residence	Ridge-Low	10	14	16	13	46	68	26
2018-2019	Valley-High	10	15	16	17	55	68	9
	Ridge-High	10	14	16	16	48	68	11
	range ; mean	0	1	1	5	**9**		**14**
Lake Powell	East-Low	7	15	18	8	27	42	18
2015-2016	West-Low	9	15	18	1	27	42	10
	West-High	9	15	18	2	27	42	9
	East-High	7	14	18	4	27	42	17
	range ; mean	2	0	0	6	0		**14**
Lake Powell	East-Low	10	16	19	21	37	58	14
2016-2017	West-Low	10	16	19	22	37	58	3
	West-High	10	16	19	14	37	58	1
	East-High	10	17	20	20	37	58	6
	range ; mean	0	1	1	**8**	0		**6**
Lake Powell	East-Low	5	13	18	5	27	56	10
2017-2018	West-Low	5	14	18	4	23	56	8
	West-High	5	14	18	7	31	56	6
	East-High	5	15	19	12	32	56	8
	range ; mean	0	2	2	**8**	**9**		8
Lake Powell	East-Low	5	13	15	14	34	55	24
2018-2019	West-Low	6	14	15	17	32	55	13
	West-High	6	14	15	5	29	55	11
	East-High	7	11	14	13	31	55	21
	range ; mean	2	3	1	**12**	5		**17**

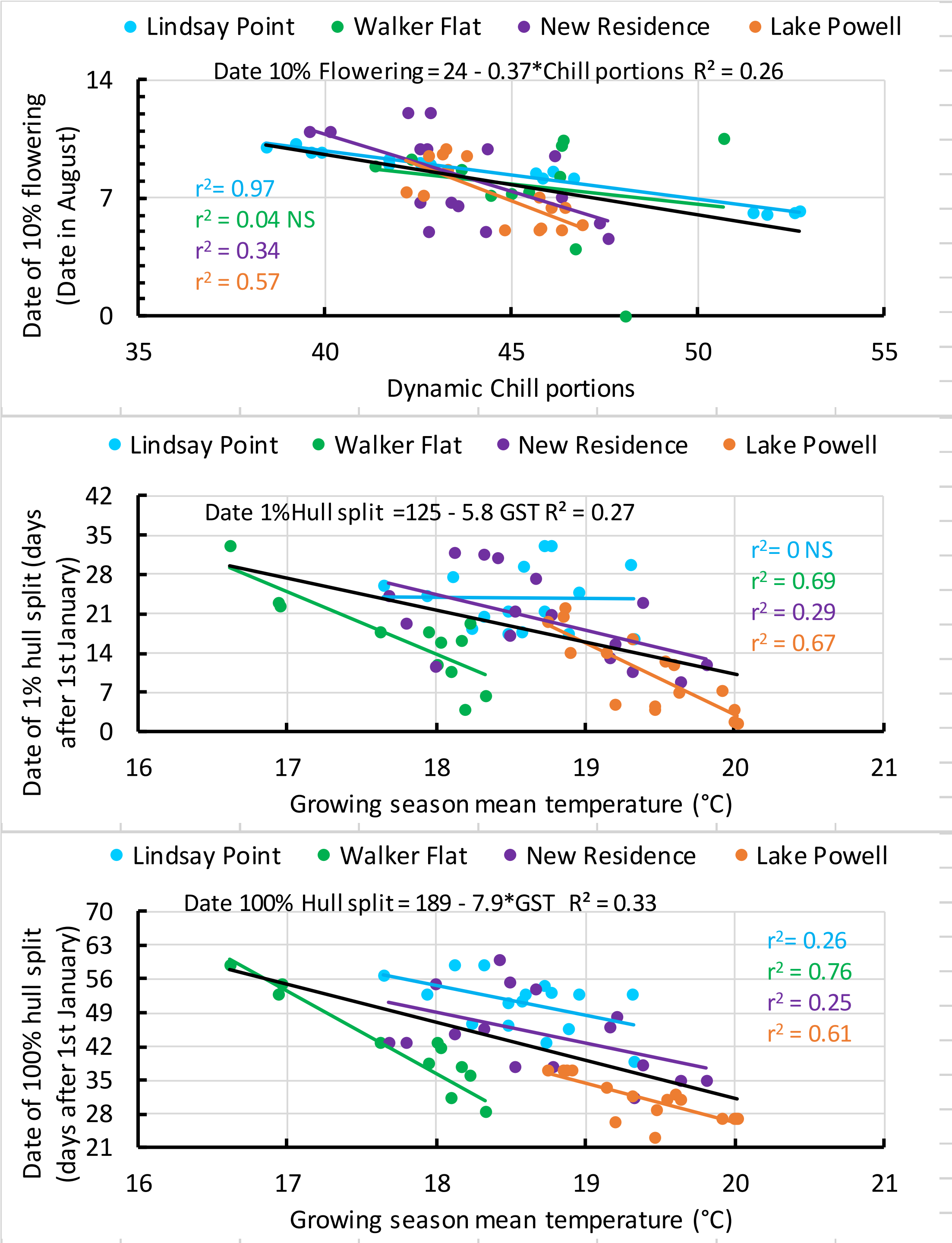


Figure 5. Correlations of some key phenology dates with climate indices. Regression equation for all orchards with line in black. Correlation and lines shown for individual orchards with orchards designated by colours. n = 12 for the Walker Flat orchard, 16 for other orchards and 60 for the relationship with all orchards.

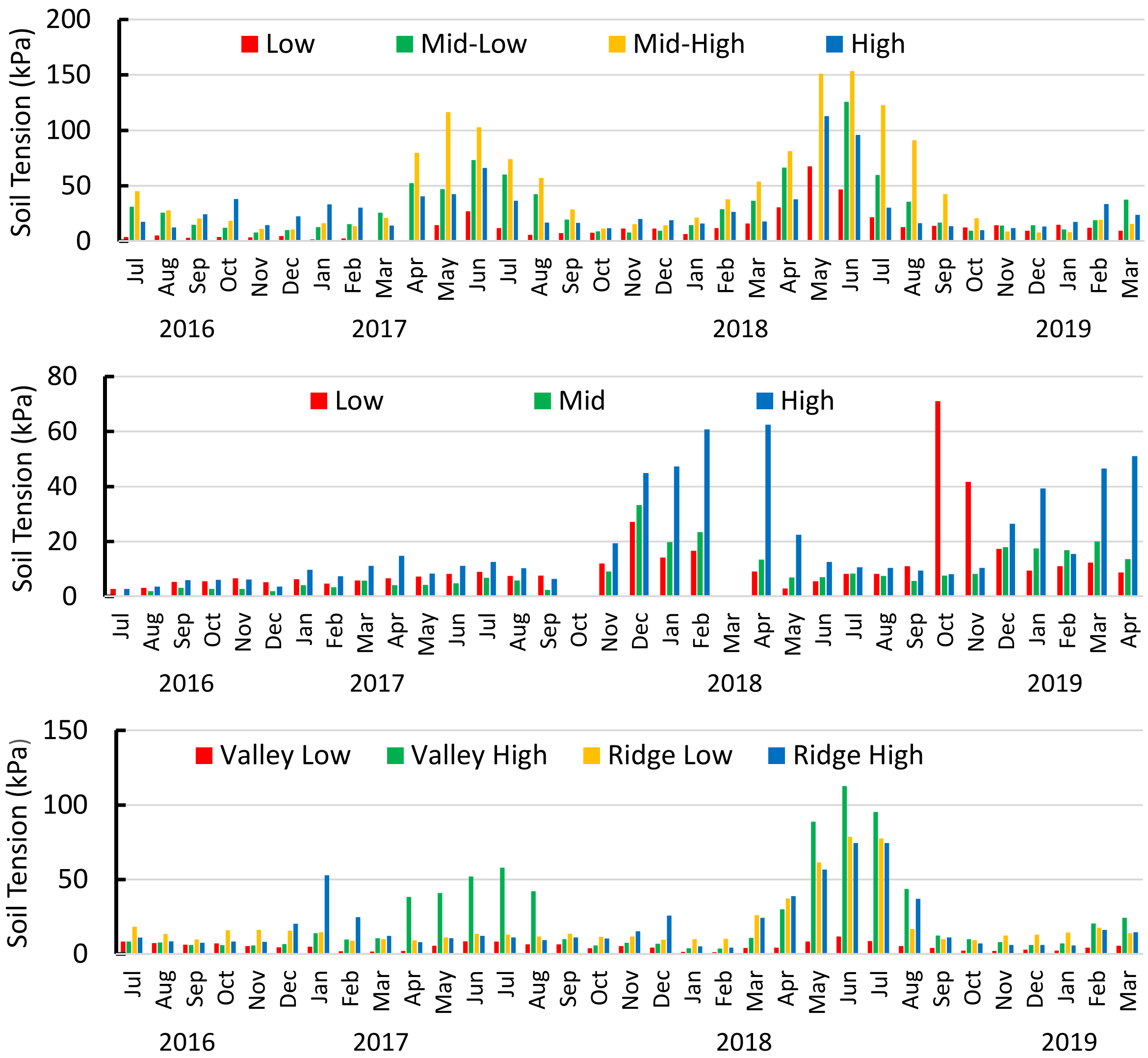


Figure 6. Average monthly soil tension (kPa) at Lindsay point (Top), Walker Flat (middle) and New residence (lower).

Harvest yield and quality

Yield and associated measures such as crackout, kernel weight and kernel deformities are shown in table 4 and figure 7. Differences existed between meso-sites, but there was no consistency in findings. For example, at Lindsay Point yield increased with elevation in 2016, decreased in 2017, increased in 2018 and decreased in 2019, with the 4 year average being no different between meso-sites. A similar finding was observed at Walker Flat where higher yielding meso-sites in one year were compensated by lower yield the following year. Yield showed less variation and compensation at the Lake Powell and New Residence orchards. Crackout and average kernel weight showed some inconsistent differences between meso-sites. There was no relationship between kernel weight and yield (apart from Lake Powell where higher yields were associated with small kernels) but there was an overall positive relationship between crackout and yield at all orchards (Figure 8). This relationship between higher yields had higher crackout implies either kernels were larger and contributed more to the fruit dry weight and/or the %shell and hull were reduced. Average kernel dry weights showed a non-significant and slightly negative relationship with yield meaning that higher yields did not have smaller kernels.

Yield was positively related growing seasons that were warmer (Figure 8). However yield was also negatively related ($r = -0.42$, $n=16$) to more warm days at the Lake Powell orchard which had more warm days than other orchards, suggesting excessive heat can reduce yield. Additionally it was found that higher effective day temperature in December when buds were forming reduced yield in the following flowering year when these buds would be contributing. That is, effective temperature in December 2017 was negatively related to yield in 2019. Effective day temperature during summer, calculated as $T_{max} – (T_{max}-T_{min})/4$ has been related to non-infectious bud failure in Californian orchards. Although the incidence on non-infectious bud failure symptoms were not noted during this project it is not known if bud failure symptoms increased after excessively warm periods and contributed to a reduction in the following years yield.

Yield was also positively related to a greater accumulation of chill (Figure 9), implying colder winters with greater chill accumulation are beneficial to yield. The number of pollination hours , that is hours warmer than 15°C in August ranged between 140 and 160 hours with little difference between meso-sites.

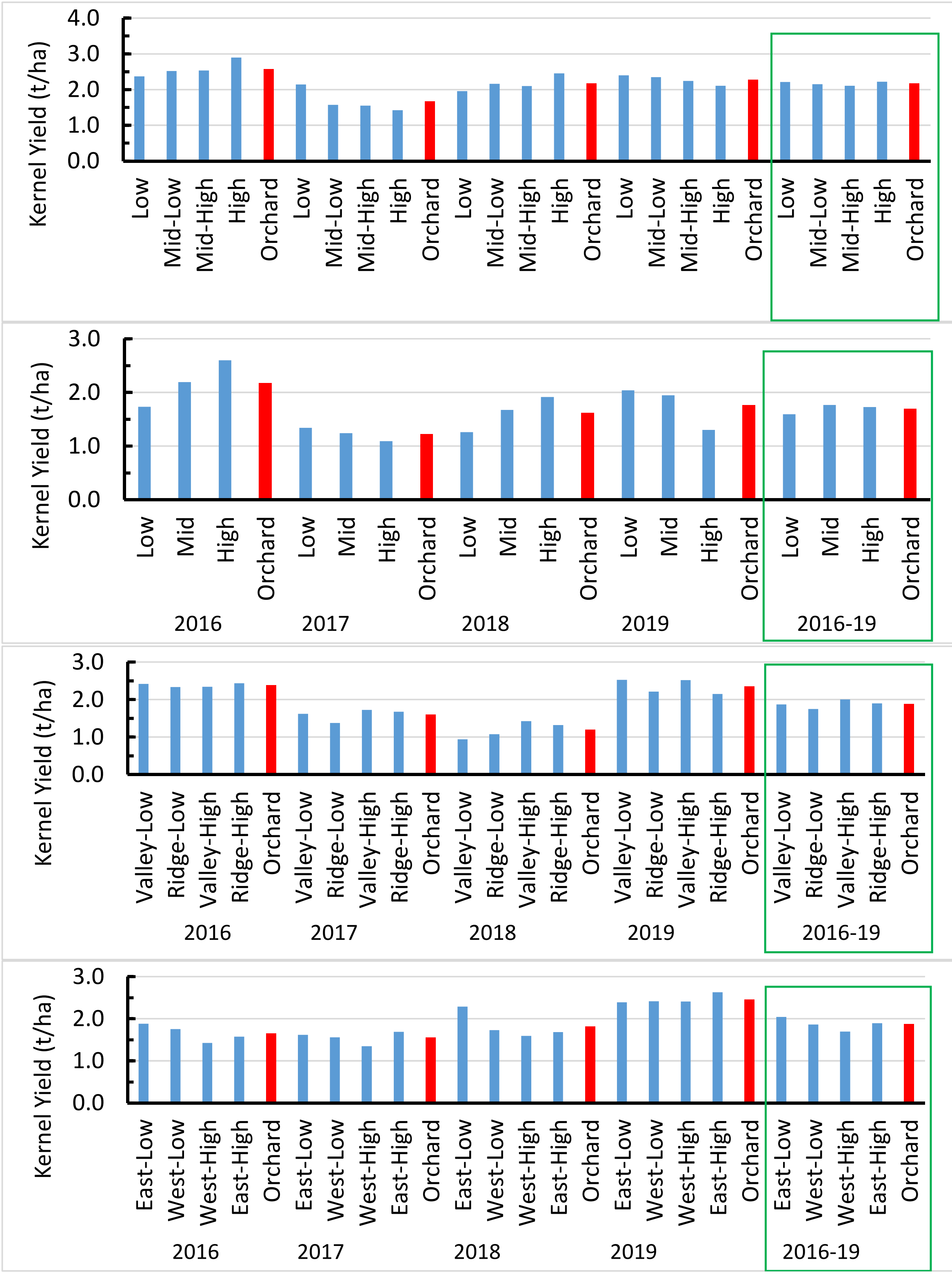


Figure 7. Yield of Nonpareil at each meso-site and the average of the sites (orchard) in each year, and the average over the 4 years from 2016 to 2019 (highlighted by the green box). Lindsay Point (upper), Walker Flat (mid upper), New Residence (mid lower) and Lake Powell (lower).

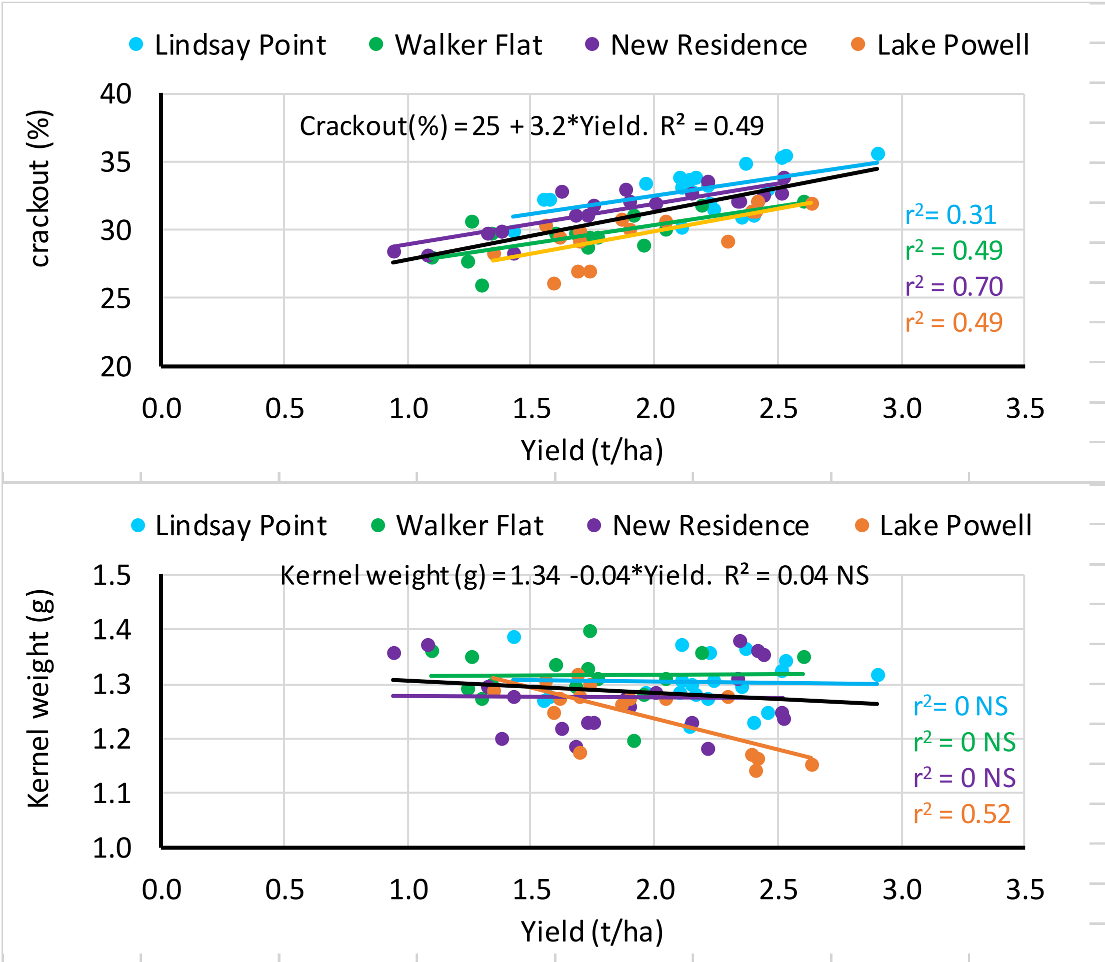


Figure 8. Relationship of crackout and average kernel weight with yield. Regression equation for all orchards with line in black. Correlation and lines shown for individual orchards with orchards designated by colours. n = 12 for the Walker Flat orchard, 16 for other orchards and 60 for the relationship with all orchards.

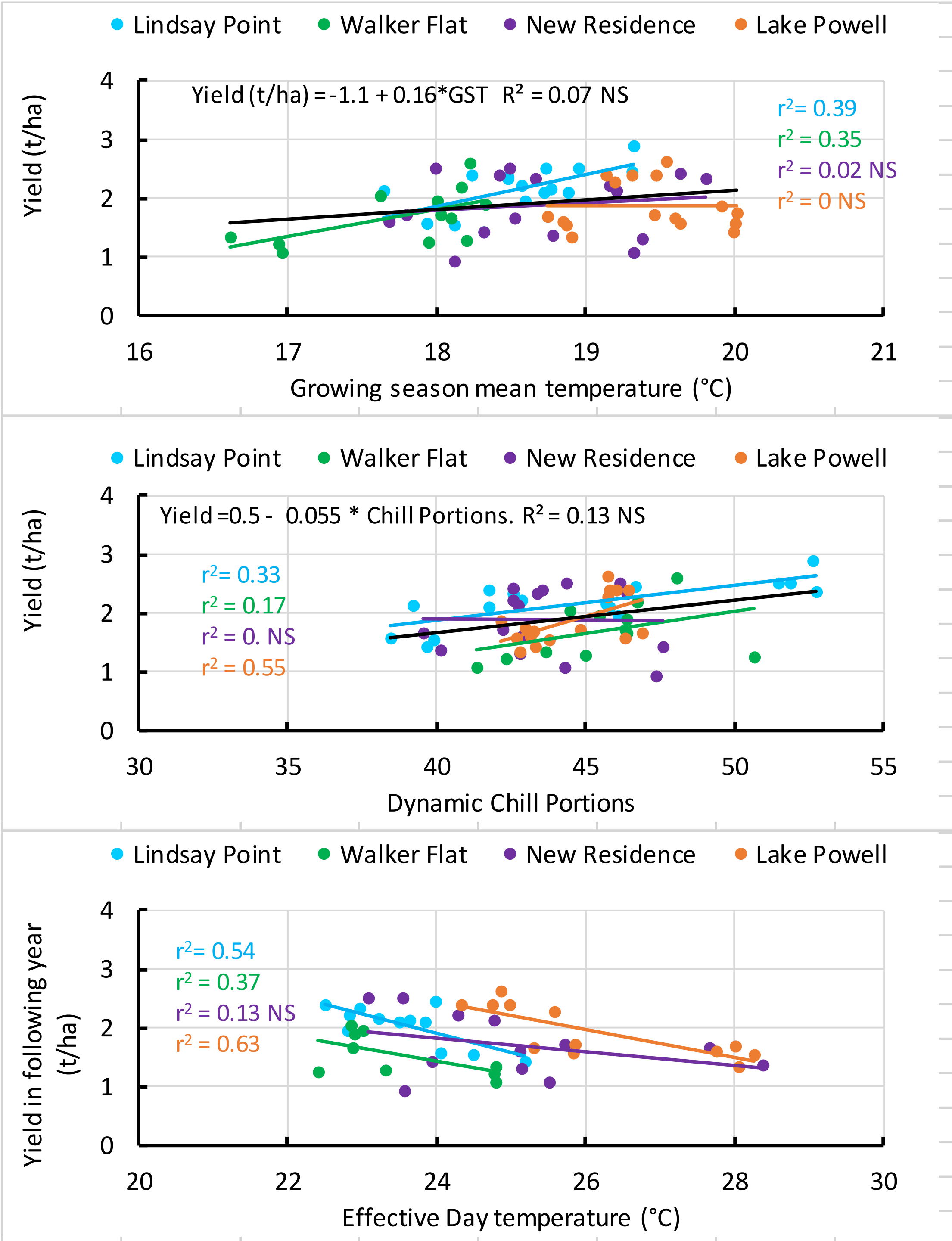


Figure 9. Relationship of yield of Nonpareil with growing season mean temperature and with chill accumulation; and of yield in following year as a function of effective day temperature in December of the preceeding flowering year (that is December 2017 related to yield in 2019). Regression equation for all orchards with line in black. Correlation and lines shown for individual orchards with orchards designated by colours. n = 12 for the Walker Flat orchard, 16 for other orchards and 60 for the relationship with all orchards; apart from the correlations of yield in following year where n = 9 for Walker Flat and 12 for other orchards.

Table 4. Yield and its' components at each orchards meso-sites and mean of all meso-sites for each year and the average from the 2016 to 2019 harvests. Meso-sites are significantly different when the mean of all meso-sites is bold.

Orchard	**Meso-site**	**Yield (t/ha)**	**Crackout (%)**	**Average Kernel Dwt (g)**	**Deformities (%)**
Lindsay Point 2016	Low	2.4	35.0	1.4	7.0
	Mid-Low	2.5	35.4	1.3	4.3
	Mid-High	2.5	35.6	1.3	3.8
	High	2.9	35.7	1.3	4.7
	Mean	**2.6**	35.4	1.3	**5.0**
Lindsay Point 2017	Low	2.1	33.8	1.2	8.8
	Mid-Low	1.6	32.3	1.3	5.8
	Mid-High	1.6	32.3	1.3	6.7
	High	1.4	30.0	1.4	5.8
	Mean	**1.7**	**32.1**	**1.3**	6.8
Lindsay Point 2018	Low	2.0	33.5	1.3	4.7
	Mid-Low	2.2	33.9	1.3	3.4
	Mid-High	2.1	33.9	1.3	3.3
	High	2.5	33.0	1.3	4.0
	Mean	**2.2**	33.6	1.3	3.8
Lindsay Point 2019	Low	2.4	31.2	1.2	5.0
	Mid-Low	2.4	30.9	1.3	5.5
	Mid-High	2.2	31.6	1.3	4.2
	High	2.1	30.3	1.4	3.7
	Mean	**2.3**	31.0	**1.3**	4.6
Lindsay Point 2016-2019	Low	2.2	33.3	1.3	6.9
	Mid-Low	2.2	32.9	1.3	5.2
	Mid-High	2.1	33.2	1.3	4.9
	High	2.2	32.0	1.4	4.7
	Mean	2.2	32.8	1.3	5.4

Table 4. Continued

Orchard	Meso-site	Yield (t/ha)	Crackout (%)	Average Kernel Dwt (g)	Deformities (%)
	Low	1.7	29.5	1.4	12.7
Walker Flat	Mid	2.2	31.8	1.4	14.7
2016	High	2.6	32.2	1.4	16.2
	Mean	**2.2**	**31.2**	1.4	14.5
Walker Flat	Low	1.3	29.8	1.3	17.8
	Mid	1.2	27.8	1.3	17.5
2017	High	1.1	28.0	1.4	22.3
	Mean	**1.2**	28.5	**1.3**	19.2
Walker Flat	Low	1.3	30.7	1.4	9.3
	Mid	1.7	29.8	1.3	12.3
2018	High	1.9	31.1	1.2	6.2
	Mean	**1.6**	**30.6**	**1.3**	**9.3**
Walker Flat	Low	2.0	30.1	1.3	4.7
	Mid	2.0	29.0	1.3	6.3
2019	High	1.3	26.0	1.3	4.7
	Mean	**1.8**	**28.4**	1.3	5.2
Walker Flat	Low	1.6	29.8	1.3	11.7
	Mid	1.8	29.5	1.3	12.8
2016-2019	High	1.7	28.8	1.3	14.4
	Mean	1.7	29.4	1.3	13.0

Table 4. Continued

Orchard	Meso-site	Yield (t/ha)	Crackout (%)	Average Kernel Dwt (g)	Deformities (%)
New Residence 2016	Valley-Low	2.4	32.1	1.4	1.8
	Ridge-Low	2.3	32.1	1.3	4.2
	Valley-High	2.3	32.2	1.4	2.7
	Ridge-High	2.4	32.6	1.4	3.8
	Mean	2.4	32.2	1.4	3.1
New Residence 2017	Valley-Low	1.6	32.9	1.2	7.3
	Ridge-Low	1.4	30.0	1.2	14.8
	Valley-High	1.7	31.2	1.2	6.2
	Ridge-High	1.7	31.1	1.2	14.3
	Mean	**1.6**	31.3	1.2	**10.7**
New Residence 2018	Valley-Low	0.9	28.6	1.4	3.3
	Ridge-Low	1.1	28.2	1.4	5.8
	Valley-High	1.4	28.4	1.3	4.2
	Ridge-High	1.3	29.9	1.3	4.8
	Mean	**1.2**	28.8	**1.3**	4.5
New Residence 2019	Valley-Low	2.5	34.0	1.2	2.5
	Ridge-Low	2.2	33.6	1.2	5.2
	Valley-High	2.5	32.7	1.2	4.5
	Ridge-High	2.2	32.7	1.2	7.0
	Mean	**2.4**	33.3	1.2	4.8
New Residence 2016-2019	Valley-Low	1.9	33.0	1.3	3.9
	Ridge-Low	1.8	31.9	1.2	8.1
	Valley-High	2.0	32.0	1.3	4.4
	Ridge-High	1.9	32.1	1.3	8.4
	Mean	1.9	32.3	1.3	6.2

Table 4. Continued

Orchard	Meso-site	Yield (t/ha)	Crackout (%)	Average Kernel Dwt (g)	Deformities (%)
Lake Powell 2016	East-Low	1.9	31.1	1.4	2.8
	West-Low	1.8	30.1	1.3	2.3
	West-High	1.4	30.2	1.4	4.5
	East-High	1.6	29.2	1.5	2.3
	Mean	**1.7**	30.1	**1.4**	3.0
Lake Powell 2017	East-Low	1.6	29.5	1.3	8.8
	West-Low	1.6	30.4	1.3	11.7
	West-High	1.4	28.3	1.3	8.3
	East-High	1.7	29.2	1.2	10.2
	Mean	**1.6**	29.3	1.3	9.8
Lake Powell 2018	East-Low	2.3	29.2	1.3	10.0
	West-Low	1.7	27.1	1.3	7.5
	West-High	1.6	26.1	1.2	9.7
	East-High	1.7	27.0	1.3	9.7
	Mean	1.8	27.4	1.3	9.2
Lake Powell 2019	East-Low	2.4	31.4	1.2	1.5
	West-Low	2.4	32.2	1.2	1.2
	West-High	2.4	31.5	1.1	1.5
	East-High	2.6	32.0	1.2	2.8
	Mean	2.5	31.8	1.2	1.8
Lake Powell 2016-2019	East-Low	2.0	30.7	1.3	4.4
	West-Low	1.9	30.9	1.3	5.1
	West-High	1.7	30.0	1.3	4.8
	East-High	1.9	30.1	1.3	5.1
	Mean	1.9	30.4	1.3	4.8

Activity 2. Monitoring of almonds growing on pots enclosed in passively solar heated chambers

The micro-climate within the passively solar heated chambers was warmer by about 1.5°C in the enclosed portion of the chambers while differences in temperature above the chamber height (1.8m) were minimal. These warmer conditions within the chamber were greater during daylight hours than night with only small (roughly 0.2°C) differences in minimum temperatures. There was a corresponding increase in growing season mean temperature from X to Y in 2017-18 and from A to Y in 2018/19. The warmer conditions within the chambers reduced chill accumulation to 31st July from 34 to 26 chill portions in 2017 and from 38 to 35 in 2018.

Nonpareil plants grown in the chambers commenced flowering 3 days earlier in 2017 and 5 days earlier in 2018. Crop development and progression through the flowering stage was more rapid in the heated plants and the date that 80% flowering occurred was the same in 2017 and 4 days later than unheated plants in 2018. Flowering in Carmel was about 5 to 10 days later than Nonpareil and not affected by heating chambers.
Hull split was only measured in 2018/19 due to crop loss in 2017/18. Heating chambers did not significantly affect the time of commencing or completing hull split.
Yield but not average kernel weight was reduced by roughly 50% in the plants grown in the heating chambers. However the difference in yield were not significant owing to the large variation between plants.

Conclusions

Meso-climates do exist within an orchard (that is between meso-sites). The lower elevation meso-sites generally had cooler daily minimum and daily maximum temperature but local topography and perhaps row orientation affected this general relationship. The canopy itself can modify the climate with leafier canopies (due to growth and development or tree density) tending to be cooler but also less windy.

Crop development (phenology) was relatively stable between meso-sites in any year and location. This is beneficial as it allows similar management within orchards. The relationship between phenology and climate is explored further in another theme of the project. However two general relationships are apparent when examining data collected over four complete crop cycles in the four orchards. Flowering was earlier when chill accumulation was higher (that is in colder winters); and hull split occurred earlier when growing season temperature was higher (that is, when spring and summer was hotter).

Yield and its components differed between the meso-sites, but not in a consistent manner, with no meso-site having consistently higher or lower yields. That is, while different meso-sites may have higher yields in one year, the yields in the following year may be the same or lower than another meso-site. The four year average yield was not different between any meso-site within an individual orchard. However while average kernel weight did not compensate for yield size, there was an overall positive relationship between crackout and yield at all orchards implying the %shell and hull were reduced when trees retained more fruit and therefore had higher yields.

The relationship between yield and temperature is not conclusive. Warmer growing seasons benefited yield. However in some orchards a larger number of hot days reduced yield, and warmer conditions during the period of bud formation reduced yield from these buds. Yield was also positively related to a greater accumulation of chill implying colder winters with greater chill accumulation are beneficial to yield.

Appendix 3. Methods and Outputs from

Theme 3: Examination, collation and evaluation of an Almond phenology model

Project Al14006 Managing almond production in a variable and changing climate

Contents

Methods

A literature review of phenology and development models of almonds and several related species was undertaken. This review is included as a seperate attachment (Appendix 4).

A number of phenology models were developed using available models from the literature that described separate phenostages. There were several flowering models that were evaluated. These are detailed in table 1.

Table 1. Almond flowering models

Reference	Stage predicted	Location	Form	Chill type and threshold	Heat type and threshold
Rattigan and Hill, 1986	50%	South Australia	Sequential	300 Utah	6800 GDH
Rattigan and Hill, 1987	50%	Victoria	Sequential	340 Utah	7300 GDH
				Average of 320 Utah	Average of 7050 GDH
Alonso et al., 2005	50%	Aragon, Spain	Sequential	403 Utah	7758 Asymcur
Diez et al., 2017	50%	Catalonia, Spain	Sequential	20.8 Dynamic	7100 Asymcur
Pope et al., 2014	10%	California	Overlap	≥23 Dynamic	Variable Asymcur

Most flowering models predict 50% flowering while that of Pope et al. (2014) predicts date of 10% flowering. Similarly most flowering models are sequential, in that chill is first satisfied and then heat is satisfied; whereas the overlap model by Pope et al., (2014) requires a minimum amount of chilling and once this is satisfied heat is accumulated but the amount of heat is determined by chilling above the minimum required. Chill is accumulated using different models, as is heat. The Utah chill model is used in the earlier flowering models while the later use Dynamic chill model. Heat is accumulated as growing degree hours (GDH) with models by Rattigan and Hill (1986 and 1987) using the method of Richardson *et al.* (1975) which uses a base temperature of 4.5°C and assumes each degree above this until 25°C equates to 1 GDH°, and all temperatures greater than 25°C also equate to 21.5 GDH°. The remaining models use a variant of the formula of Richardson *et al.* (1975) is that described by Anderson *et al.* (1986), and named ASYMCUR. This formula of Anderson *et al.* (1986) assumes that heat accumulates between the base temperature (Tb, set to 4°C) and the critical temperature (Tc set to 36°C) with optimum accumulation at the optimum temperature (To set to 25°C).

The equation for GDH between the base and the optimum temperature is:

$GDH = FA/2 \times (1 + \cos(\pi + \pi (T-Tb)/(To-Tb)))$.

The equation for GDH between the optimum and the maximum temperature is:

$GDH = FA \times (1 + \cos(\pi/2 + \pi/2 (T-To)/(Tc-To)))$,

where A = To-Tb, and F is a factor of stress (assumed to be 1 unless the plant is under stress).

These hourly temperatures were interpolated from daily minimum and maximum values as described in an earlier section.

The fruit growth model of Tombesi et al., (2010) was initially selected to progress phenology to hull split. Tombesi et al. (2010) examined the relationship between heat accumulation and fruit maturity of almonds in California. They correlated 8 years of phenological data from three genetics trials in California with temperature and other environmental indices. They found that heat degree-days in the first 90 days after full bloom (DAFB) were a better predictor of the time of 1% hull split than either degree-days in the first 30 or 50

DAFB or the total degree-days from full bloom to 1% hull split. Heat degrees days were calculated using the single sine method described by Zalom et al. (1983) with thresholds of 5 °C and 35 °C.

Nut maturation was initially determined by Connell et al. (2010) by the progression from 1% hull split to 100% hull split in a genetic trial at Chico, California. They found Nonpareil had a maturation period of between 23 and 25 days, while the period between 100% hull split and commercial harvest averaged 14 days. This delay would in part be associated with the requirement for further desiccation of the fruit (hull, shell and kernel) to occur before fruit can be harvested by shaking operations, and also because of logistics relating to impending or recently received weather (*e.g.* rain can delay harvest owing to increased risk of pathogens damaging the kernel).

Models for fruit growth and for nut maturation and harvest using heat accumulation measured as single sine with 5 °C and 35 °C thresholds from 80% flowering to 1% hull split that signified the end of fruit growth, and to 100% hull split that signified the end of nut maturation, and to harvest date were developed from phenology observations collected during this research project.

These resulting combined phenology models were incomplete for the development from the end of the predicted flowering, that is, either 10% or 50% flowering to the commencement of fruit growth, that is, 80% flowering. A relationship was required for he progression from 50% or 10% flowering to 80% flowering. During the initial evaluation of the combined almond phenology model this progression of flowering was calculated as a linear relationship with heat accumulation using observations from The University of Californian Almond regional variety trials (http://fruitsandnuts.ucdavis.edu/dsadditions/Regional_Almond_Variety_Trials/) at the Chico and San Joan trial sites from 1997-2006 and corresponding meteorological observations. GHD and Asymcur heat accumulation thresholds were calculated from these data and the resulting thresholds denoted as CAL.

Thresholds for progression from 10% or 50% flowering to 80% flowering were also calculated from the observations collected during this research project (details of field sites, temperature observations and phenology data are described in Theme 2. Field trials to examine the impact of climate and weather on Almond tree physiology – see earlier; and also briefly described below). These thresholds were denoted AUS.

Additionally the linear relationship between GDD in the 90 days (and 50 days and 30days) after 80% flowering and date of 1% hull split were calculated in order to develop a similar relationships in Australia as those described by Tombesi et al (2010) in California. Additionally the GDD for the entire period from 80% flowering to 1%hull split, 100% hull split and to harvest were calculated from the Australian data. These relationships and thresholds were denoted AUS.

The observed data used to evaluate the models included observations of nonpareil almond phenology collected in the four field monitoring sites in commercially managed orchards (aged from 6 to 14 years) across the major Australian almond producing regions from budburst years 2015 to 2018. Trials were located at Walker Flat, SA (Lat. -34°44'15S, Long. 139° 31'19E); New Residence, SA (Lat. -34°23'50S, Long. 140° 25'34E); Lindsay Point, Vic. (Lat. -34°04'42S, Long. 141° 00'01E); Lake Powell, Vic. (Lat. -34°43'46S, Long. 142° 54'44E). In each orchard between three and four sites located along elevation gradients designed to create temperature meso-climates were accessed in each orchard with each site consisting of 12 trees (3 plots of four trees with buffers between plots). Temperature was monitored at each meso-site at 1.2 m height in sheltered screens. Available data consists of flowering from August 2015 to August 2018, with corresponding hull split and harvest for these flowering years (harvest in 2016 to 2019).

Flowering and hull split were assessed using similar methods to those used in the University of Californian Almond regional variety trials (Pers comm. 2015, Joseph Connell, Farm Advisor Emeritus, UC Cooperative Extension, Butte County, California). Flowering was assessed on each tree by first counting roughly 100 floral buds/ flowers on a few branches to get an idea what 100 floral buds/ flowers looks like. Next, an estimate of how many out of the roughly 100 floral buds/ flowers were open (Felipe stage F) on several groups of branches scattered throughout the tree, before making a few counts of 10 or 20 floral buds/ flowers to check the initial estimate. Hull split was similarly assessed using the criteria of that hulls were split when they had assumed at least Stage 2C - Deep V over the suture line which is not visibly separated but can be squeezed open by pressing both ends of the hull (University of California, 2002). Dates of 10%, 50% and 80% flowering and 1% and 100% hull split were determined by linear interpolation of the percent flowering and hull split on the measurement days.

The ability of the discrete models and the combined model to predict the date that phenological stages occurred was examined. The predicted phenology dates were calculated using both the CAL and the AUS thresholds.

Model robustness and error was examined as correlation, mean bias and RMSE between the observed and predicted day of each phenological stage were examined.

The thresholds and analysis of model robustness and error were established using the entire 4 year dataset from budburst year 2015 to 2018. The AUS thresholds calculated using the 4 years of data collected during this research project were used in the excel version of the phenology model that is available to almond growers.

Additionally the observed phenology in the final year (budburst year 2018) were compared to predicted phenology when the model was developed using the initial three years of data (from budburst 2015 to 2018).

Output / Results

Figure 1 shows the observed and predicted dates of flowering, hull split and harvest while table 2 and table 3 details the model robustness and errors. Using the AUS constants, that is, the thresholds to progress phenological development derived from Australian data) improved the models compared to CAL thresholds (thresholds derived from Californian data). Table 2 shows the robustness and errors when using unconstrained models according to Californian models and Australian thresholds were used. The Californian models used CAL thresholds to progress flowering to 80% flowering (Full Bloom) then the linear relationship between GDD in the 90days after full bloom was used to predict date of 1% hull split (after Tombesi et al. 2010) and the calendar relationship of 24 days to progress development to 100% hull split and 14 days to progress to harvest (after Connell et al. 2010). Mean bias and RMSE were typically reduced and correlation was increased, that is, the accuracy and precision of the model was improved when using the AUS thresholds were used to progress flowering and fruit development used heat accumulation over the entire period. Using the AUS thresholds, RMSE of full bloom varied between 4 and 7 days depending on the flower model used with the model of Rattigan and Hill (1986, 1987) performing best with a RMSE of 3 days and mean bias of 2 days, and that of Alonso et al., (2005) performing worst with a RMSE of 8 days and mean bias of -7 days. The model of Pope et al., (2014) essentially performed similarly to that of Rattigan and Hill although with both mean bias and RMSE of 1 day greater, but this model has the advantage that the date of 10% flowering (that is near the commencement of flowering) can be predicted. The CAL thresholds gave similar but slightly worse predictions with RMSE and mean bias typically increasing by 2-3 days.

The models of Rattigan and Hill (1986) and Alonso et al. (2005) use chill determined by Utah chill units (or a method similar to Utah chill units in the case of Rattigan and Hill), and subsequent heat accumulation to determine the date of 50% flowering, whereas the flowering models of Diez et al., (2017) and Pope et al (2014) use the Dynamic model to determine chill requirements. As one of the intended uses of the model is to evaluate how phenology shifts in future warmer climates, it is important that the underlying drivers of the model are robust in warmer climates. The Dynamic model is considered the most robust chill model in warmer climates and most suitable to evaluate chilling in future warmer climates (Leudeling, 2012), suggesting that the flowering models of Pope et al., (2014) or Diez et al., (2017) should be used preferentially.

The differences became more extreme when incorporating fruit growth and maturation. Predictions of date of 1% hull split, 100% hull split and harvest based on Californian linear relationship of GDD in the 90days after full bloom and calendar relationship had RMSE between 17 and 28 days and mean bias between 14 and 27 days. Gradziel (2010) noted poor correlation between accumulated degree days and key almond phenological stages such as hull split, and suggested that even within California regional differences in cultural practices, particularly fruit set, and level of fertilization and irrigation could be influencing the date of hull split. As it is likely these factors have changed over the last decades since the observed data used to develop the model was collected, it is not surprising that the prediction of date of 1% hull split was not robust. Tombesi et al. (2010) unsuccessfully attempted to account for some of the year-to-year and locational variability of the models by additional relationships of cumulative potential evapotranspiration or temperatures above 30°C in the last half of fruit development, suggesting further improvements may be difficult. However developing a linear relationship for Australian conditions between heat accumulation GDD in the 90days after full bloom and date of 1% hull split, and heat accumulation for this entire phenoperiod were successful. Prediction of date of 1% hull split, 100% hull split and harvest each had RMSE of about 10 days and mean bias of 1-2 days when predictions used heat accumulation over the respective entire period. These were considerably smaller than predictions based on Californian linear relationship of GDD in the 90days after full bloom and calendar relationships (Table 3).

The benefit of a robust relationship between heat accumulation during the initial fruit growth period and later development and critical phenostages is that it provides more time for planning of management decisions. For this reason the Australian data was used to develop a linear relationship for Australian conditions between heat accumulation GDD in the 90days after full bloom and date of 1% hull split and subsequent development. The robustness of this relationship is compared in table 3 which also separately examines the fruit growth and maturation models of Tombesi et al. (2010) and Connell et al. (2010). Table 3 shows that the fruit growth model of Tombesi et al. (2010) performs badly under Australian conditions having a mean bias of 17 days and RMSE of 19 days for 1% hull split while a similar model developed using Australian data using heat accumulation in the 90days after full bloom predicted 1%hull split with a mean bias of 1 day and RMSE of 7 days. These were similar to using a heat accumulation threshold from the date of full bloom to predict date of

1%hull split. The errors in dates of prediction of 1% hull split were continued to dates of 100% hull split and harvest. However the actual relationship noted by Connell et al. (2010) of 24 days to progress from 1% to 100% hull split and a further 14 days to harvest were as accurate as a relationship using heat accumulation (Table 3).

Validation of Australian models was undertaken by examining the predictions during the 2018 budburst year when the thresholds were calculated using only the three budburst years from 2015 to 2018. The RMSE and mean bias of these predictions from the budburst year 2018 were similar to those calculated for prediction models using the calibration dataset (budburst year 2015 – 2017) (Table 4) and those for the complete dataset (budburst years 2015-2018) (Table 2 and 3).

Table 2. Mean bias, r^2 and RMSE of predicted dates of phenostages when thresholds derived from Californian data were to progress flowering to 80% flowering (Full Bloom) then Tombesi et al GDD 90 days to 1%HS then Connell et al. (2010) calendar relationship for fruit maturation to 100% hull split and harvest (CAL); and when Australian thresholds were used to progress flowering to 80% flowering (Full Bloom) then GDD to progress to hull split and harvest (AUS). Four flowering models are compared.

	CAL			AUS		
	Mean bias	r^2	RMSE	Mean bias	r^2	RMSE
Rattigan and Hill (1986, 1987)						
Date of 50% flowering	2	0.20	4	2	0.16	4
Date of 80% flowering (Full bloom)	4	0.40	5	2	0.44	3
Date of 1% hull split	19	0.13	21	1	0.26	8
Date of 100% hull split	19	0.13	22	1	0.30	10
Date of Harvest	24	0.18	25	1	0.21	10
Alonso et al. 2005						
Date of 50% flowering	-6	0.17	7	-6	0.16	7
Date of 80% flowering (Full bloom)	-4	0.33	6	-7	0.32	8
Date of 1% hull split	14	0.14	17	-3	0.24	9
Date of 100% hull split	14	0.13	18	-3	0.29	11
Date of Harvest	19	0.16	21	-2	0.19	11
Diez et al. 2017						
Date of 50% flowering	6	0.41	7	5	0.38	7
Date of 80% flowering (Full bloom)	7	0.13	9	4	0.17	6
Date of 1% hull split	21	0.06	23	2	0.22	9
Date of 100% hull split	21	0.07	24	2	0.28	11
Date of Harvest	26	0.12	27	2	0.19	11
Pope et al. 2014						
Date of 10% flowering	5	0.51	7	4	0.44	6
Date of 50% flowering	7	0.32	8	3	0.27	5
Date of 80% flowering (Full bloom)	8	0.12	10	3	0.18	4
Date of 1% hull split	22	0.07	24	1	0.25	9
Date of 100% hull split	22	0.09	24	1	0.30	10
Date of Harvest	27	0.16	28	1	0.20	11

Table 3. Errors of predicted date of 1% and 100% hull split and harvest when models commence at observed date of 80% flowering (full bloom). Mean bias, r^2 and RMSE of predicted dates of phenostages when A. Tombesi et al. (2010) relationship of GDD in the 90 days after full bloom was used to predict date of 1%Hull split, then Connell et al. (2010) calendar relationship for fruit maturation to 100%hull split and harvest (CAL); when the Australian dataset was used to develop a relationship of GDD in the 90 days after full bloom was used to predict date of 1%Hull split, then Connell et al. (2010) relationship for fruit maturation to 100%HS and Harvest (AUS). B. when predictions used heat accumulation over the respective entire period (AUS only). C. If observed date of 1% hull split is used and Connell et al. (2010)calendar relationship for fruit maturation to 100%hull split and harvest is used (CAL), or when GDD over these periods was used (AUS).

	CAL			AUS		
	Mean bias	r^2	RMSE	Mean bias	r^2	RMSE
A.						
Date of 1% hull split	17	0.22	19	-1	0.27	7
Date of 100% hull split	17	0.18	19	-1	0.21	10
Date of Harvest	22	0.17	23	4	0.19	9
B.						
Date of 1% hull split				-0.2	0.30	8
Date of 100% hull split				0.0	0.32	10
Date of Harvest				0.2	0.22	10
C.						
Date of 100% hull split	0.0	0.64	6.5	-0.5	0.19	10
Date of Harvest	4.8	0.40	9.8	-0.5	0.18	8

Table 4. Mean bias, r^2 and RMSE of predicted dates of phenostages for the Calibration dataset (budburst year 2015 to 2017) and validation dataset (budburst year 2018) when A. Australian thresholds were used to progress flowering to 80% flowering (Full Bloom) then GDD to progress to hull split and harvest using four flowering models; B1. when the observed date of Full bloom was used to develop a relationship of GDD in the 90 days after full bloom to predict date of 1%hull split, then Connell et al. (2010) relationship for fruit maturation to 100%hull split and Harvest. B2. when predictions used heat accumulation over the respective entire period; and C. when the observed date of 1% hull split was used date of 100% hull split and date of harvest are predicted using GDD over these periods.

	Calibration			Validation		
	Mean bias	r^2	RMSE	Mean bias	r^2	RMSE
A						
Rattigan and Hill (1986, 1987)						
Date of 50% flowering	2	0.16	4	3	0.01	4
Date of 80% flowering (Full bloom)	1	0.37	3	0	0.01	1
Date of 1% hull split	-1	0.26	8	-4	0.02	7
Date of 100% hull split	1	0.30	10	2	0.03	11
Date of Harvest	0	0.17	11	-3	0.01	12
Alonso et al. 2005						
Date of 50% flowering	-6	0.16	7	-4	0.23	5
Date of 80% flowering (Full bloom)	-8	0.27	9	-8	0.29	8
Date of 1% hull split	-4	0.24	10	-6	0.00	9
Date of 100% hull split	-3	0.28	11	-1	0.02	12
Date of Harvest	-4	0.16	12	-5	0.03	14
Diez et al. 2017						
Date of 50% flowering	5	0.38	7	3	0.13	4
Date of 80% flowering (Full bloom)	3	0.14	5	0	0.25	2
Date of 1% hull split	0	0.22	9	-4	0.00	7
Date of 100% hull split	2	0.28	11	2	0.02	12
Date of Harvest	1	0.15	12	-3	0.03	12
Pope et al. 2014						
Date of 10% flowering	4	0.44	6	3	0.01	4
Date of 50% flowering	3	0.27	5	2	0.02	3
Date of 80% flowering (Full bloom)	2	0.20	4	-1	0.06	2
Date of 1% hull split	0	0.25	9	-5	0.01	7
Date of 100% hull split	1	0.30	10	1	0.03	11
Date of Harvest	0	0.16	11	-3	0.02	12
B1.						
Date of 1% hull split	-1	0.26	8	-4	0.03	6
Date of 100% hull split	-1	0.20	10	0	0.00	10
Date of Harvest	3	0.17	9	1	0.04	10
B2.						
Date of 1% hull split	-1.4	0.28	8	-4.7	0.01	7
Date of 100% hull split	0.4	0.33	9	1.1	0.05	11
Date of Harvest	-0.6	0.18	11	-3.0	0.01	12
D.						
Date of 100% hull split	-0.2	0.18	10	0.8	0.01	11
Date of Harvest	-1.0	0.17	9	-2.5	0.04	10

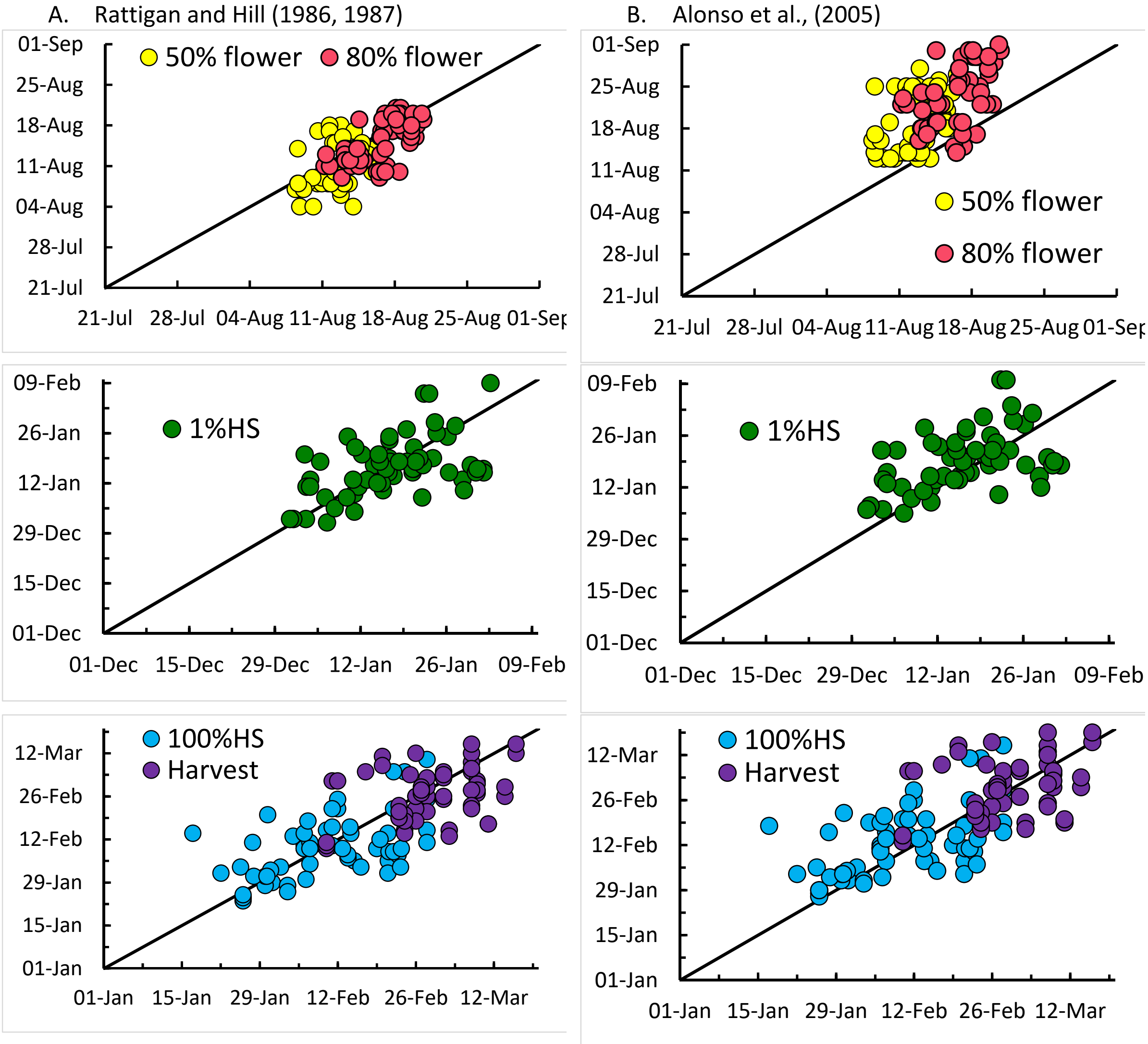


Figure 1. Predicted and observed day of flowering (upper), 1% hull split (middle) and 100% hull split and harvest (lower) using the flowering models of A. Rattigan and Hill (1986, 1987), B. (Alonso et al., 2005), C. Diez et al. (2017); and D. Pope et al. (2014). The flowering models predict date of 50% flowering apart from that of Pope et al. (2014) which predicts date of 10% flowering. Predictions of subsequent phenostages use the unconstrained model and the heat accumulation thresholds derived from Australian data (this research project). The diagonal line shows the 1:1 relationship.

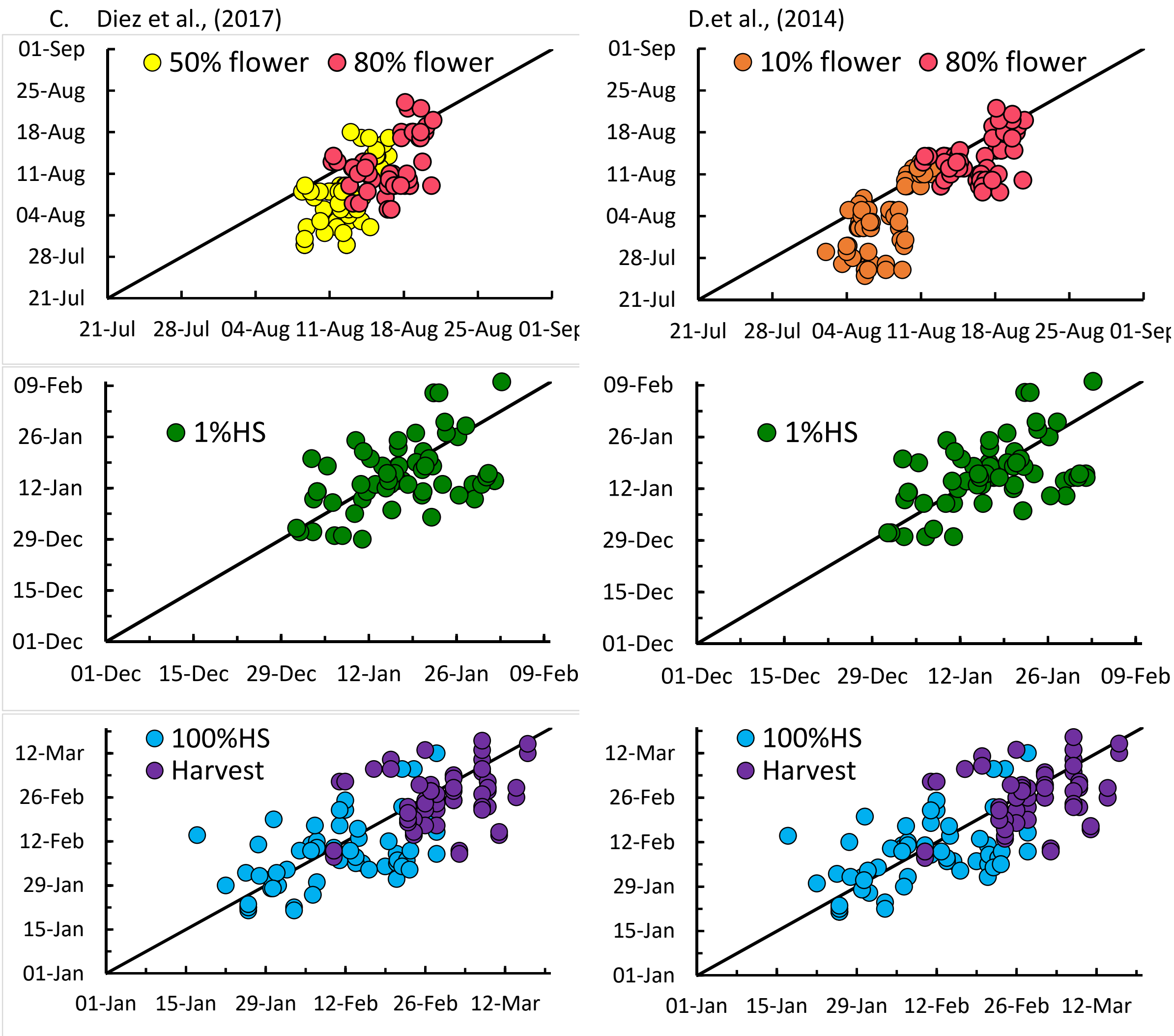


Figure 1. Continued. Predicted and observed day of flowering (upper), 1% hull split (middle) and 100% hull split and harvest (lower) using the flowering models of A. Rattigan and Hill (1986, 1987), B. (Alonso et al., 2005), C. Diez et al. (2017); and D. Pope et al. (2014). The flowering models predict date of 50% flowering apart from that of Pope et al. (2014) which predicts date of 10% flowering. Predictions of subsequent phenostages use the unconstrained model and the heat accumulation thresholds derived from Australian data (this research project). The diagonal line shows the 1:1 relationship.

Conclusions

Phenology models of discrete phenological stages of almond development were combined to create a continuous model. The models were developed using observed data from California, largely during the period 1996 to 2006, and tested under Australian conditions during 2015-2018. The discrete models, and in particular the flowering, flower progression and nut maturation models were able to predict phenological development with remarkable accuracy and precision, although the ability of the continuous model to accurately predict phenology declined as the development stages progressed as errors became exacerbated. This difference in the models ability to predict phenology in a new location (Australia) compared to California where the discrete models were developed highlights that both the discrete and the continuous models could be used by managers to assist orchard operations and by researchers. Appropriate use of any model entails an understanding of the uncertainty and the process of error propagation. In the case of almond phenology it is important to appreciate that bud burst and flowering are predominantly determined by climate but the timing of maturity and harvest is a more complex interaction between climate, crop load and management. This interaction is a challenge for modellers but good news for the orchardist as it points to options to manipulate maturity in current and future climates.

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Appendix 4. Literature review detailing combined chill, heat summation model(s) of phenology with focus on Almond specific models, and also related crops such as peach and other *Prunus* species.

Project Al14006 Managing almond production in a variable and changing climate

Summary

Crop management decisions are influenced by phenology, but not determined by phenology as there are other considerations for example logistics of labour supply, transport, or delays in operations caused by weather events. Nevertheless phenology models can provide greater certainty of the timing of key development stages (for example in almonds, the key stages are budswell, flowering, hull split and harvest ready fruit). Not only are phenology models useful for orchard management such as pest control and the logistics of harvest, but they can be used as a research tool. Robust phenology models can be used to explore how key stages such as flowering date may change in a future warmer climate. This shift in phenology may change the risk of undesirable weather events.

There is no unified phenology model for almonds that explains the influence of environment on the development of all the major phenological stages. However, phenology models, largely based on temperature, exist for several stages of Almond production. These include several combined chill and heat requirement for budbreak and floral development (Rattigan and Hill, 1986, 1987; Degrandi-Hoffmann *et al.*, 1996; Ramirex *et al.,* 2010, Pope *et al.*, 2014); and prediction of 1% hull split based on temperature in the 90 days after 1% bloom (Tombesi *et al.,* 2010). Other research provides information on the differences between varieties in reaching 1% hull split, and the time taken from 1% to 100% hull split (Connell *et al.,* 2010). Most aspects of these models remain untested under Australian conditions, and several models do not include current commercial varieties used in Australia. One stage of almond production that has no model is that for the time between 100% hull split and date that fruit are harvested.

Developing a robust model that encompasses the entire years' cycle from budburst /flowering to harvest will require the need to include current varieties and use chill accumulation models that are appropriate for warmer conditions in the current and future climates (Luedeling and Brown, 2011).

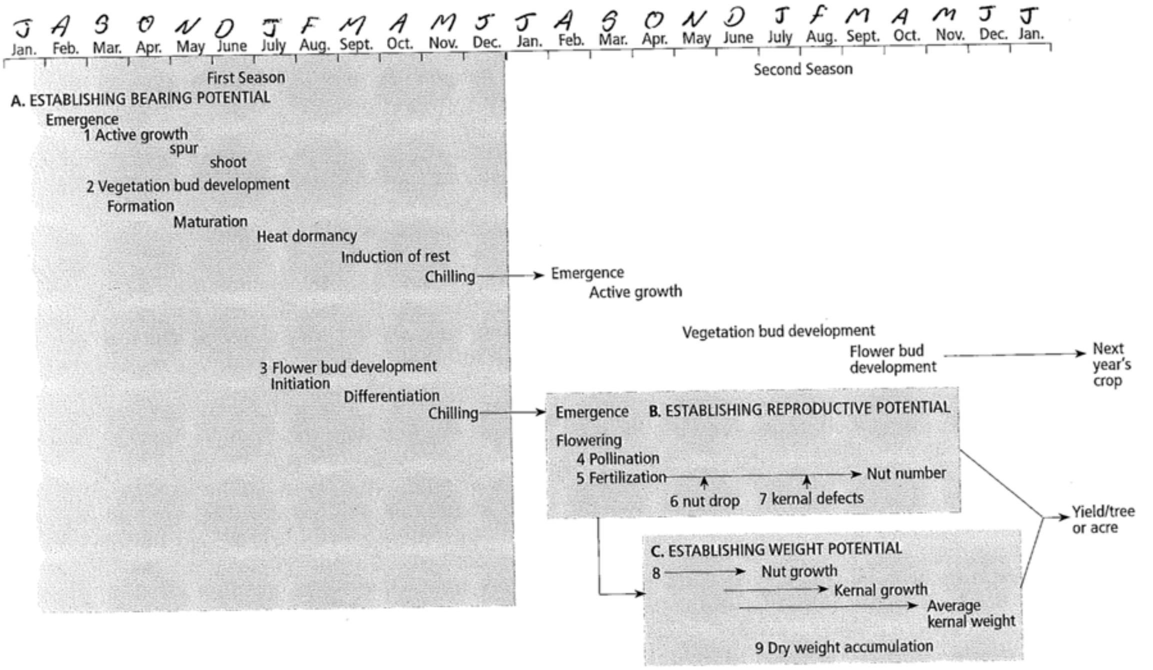
Initial steps in this process include testing the suitability and robustness of the discrete sub-models under Australian conditions; combining the individual sub-models of discrete stages into a single amalgamated model that describes and explains a longer series of phenological development; testing the suitability and robustness of the amalgamated model under Australian conditions.

Introduction

Plant phenology models seek to explain the relationship between environmental factors and plant development. The influences of temperature and photoperiod are most commonly examined. While robust phenology models exist for some crops, notably annual cropping plants, there is less understanding of perennial species, including deciduous fruit trees.

The growth cycle of almonds and other deciduous fruit tree species is multi-yeared. Vegetative and floral buds are developed during the active growth period in year-one and then undergo a dormancy period before emergence and active growth to produce leaves, flowers and fruit in the subsequent year (see figure 1). While it would be desirable that a phenology model explains development over such an extended period, this may not be possible. There are a range of phenology models that describe discrete stages of development. For example, understanding the mechanisms and explaining the influence of environment on flowering, or of fruit growth. It may be possible to combine these discrete stages into a single unified model that describes and explains a longer series of phenological development within a single year of growth and development.

An initial focus of many phenology models of deciduous trees was on the timing of bud burst and flowering as this elucidated the relative risk and management of low temperature / frost damage to these more delicate plant organs, and also indicated when vegetative and fruit growth would commence and it's management would be required. Bud burst and flowering occur after the plant has undergone a period of dormancy, thus an understanding of the dormancy process was required.



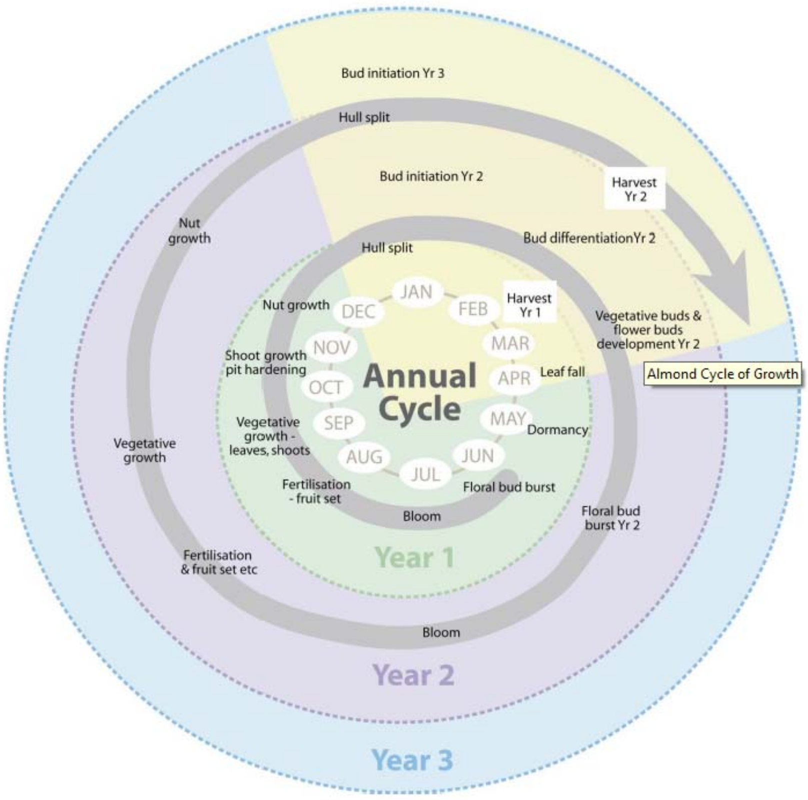


Figure 1. Diagrams showing phenology and development of almonds. Upper figure from Kester *et al*., 1996 showing months in southern hemisphere (using single letter) and in northern hemisphere; lower from McMichael (2009) showing months in southern hemisphere.

Dormancy

Despite the importance of dormancy to deciduous plants there remains some uncertainty about the processes involved. There are several reviews of dormancy (Saure, 1985; Lang *et al*., 1987; Faust *et al*., 1997; Erez 2000) that show the progression of understanding.

Lang *et al.* (1987) established a common nomenclature to progress the understanding of dormancy. Dormancy was described as 'a temporary suspension of visible growth of any plant structure containing a meristem' (Lang *et al.*, 1987). Three stages of dormancy were developed; paradormancy, ecodormancy and endodormancy. These three phases can overlap (Saure, 1985) and under conditions of adequate chilling buds would progress through these stages. Paradormancy involves inhibition of lateral buds by the terminal bud, or correlative inhibition of lateral buds by apical buds. It occurs in late summer or early autumn. It may involve growth cessation due to alternative resource needs (Kester and Gradziel, 1996), or high-temperature or drought stress (Denisov, 1988).

The two phases of endodormancy and ecodormancy could be considered to occur as part of the 'winter' dormancy period. Endodormancy occurs in response to shortened days and/or reduced temperatures, not the loss of leaves. In many deciduous fruit trees endodormancy occurs in autumn and prevents buds from emerging until spring. During endodormancy the plant will not grow even under good, warm, growing conditions. Endodormancy is controlled by physiological factors inside the primordial meristem that change in response to temperature and photoperiod (Erez, 2000; Lang, *et al.*, 1987). The exact processes are not well understood. Endodormancy ends after the accumulation of a certain amount of hours of cool temperatures above freezing or the requirement of chill accumulation has been met. The ecodormancy then commences where the plants are dormant but ready to grow when the environmental conditions are not right usually as it is too cold. That is, they are no longer regulated by internal plant growth regulators and can sense external factors, such as ambient warmth, lack of water or cold temperatures (Anderson *et al.*, 1986). Polito (2009) proposed that meristematic buds must accumulate a certain amount of warm temperatures before entering the next stage. In effect the accumulation of heat during this period will stimulate growth, bud swell and flowering.

The theory proposed above describing the breaking of dormancy by the sequential chill accumulation to satisfy endodormancy requirements followed by heat accumulation to satisfy ecodormancy requirements is known as the sequential theory and has become the most widely accepted. The simplified framework additionally proposes that heat accumulation prior to endodormancy being achieved is ineffective, and that chill accumulation after endodormancy is achieved is ineffective. Instead budburst or flowering will occur after the necessary forcing or heat requirements for these stages have been fulfilled (see figure 2).

It should be noted that the sequential theory is not universally accepted as it is considered too simplistic and requires modification (see Chuine, 2000; Leudeling *et al.*, 2009, Pope *et al.*, 2014 for further details and for alternate approaches).

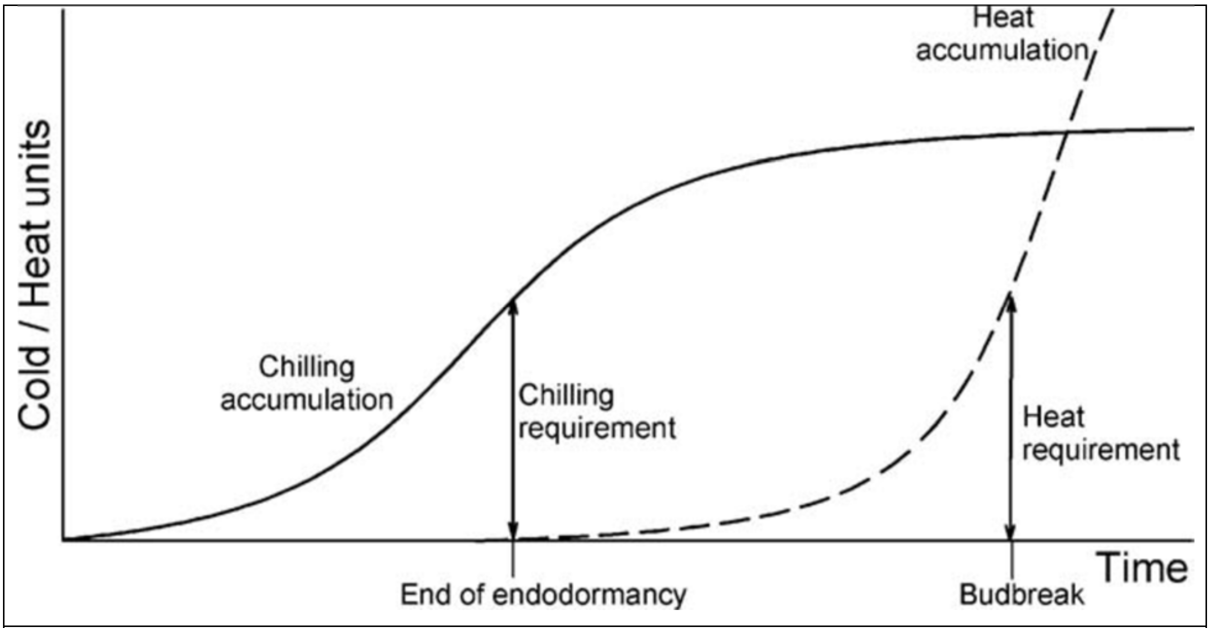


Figure 2. Schematic illustration of chilling and heat accumulation during the dormancy period as a function of time, under the assumption that chilling and heat are accumulated sequentially. From Luedeling *et al.,* 2009.

Combined Chill and Heat models to explain flowering

Many phenology models to predict date of flowering are based on the sequential theory of dormancy (see above), but there are alternative theories which are discussed below. The sequential theory assumes that determining the amount of chill accumulation to complete endodormancy and subsequent heat accumulation to satisfy ecodormancy requires information about three date: the date dormancy commences, the date endodormancy is complete (date where chill satisfied and heat accumulation commences), and the date ecodormancy is achieved.

The date dormancy commences is implied as the date chill accumulation commences. There are a number of ways to select the date that chill accumulation commences. The simplest approach is to use a fixed date, for example 1 October in Northern Hemisphere, which would correspond to 1 April in the southern hemisphere. An alternative is to calculate the first day in each year with a positive chill accumulation (*e.g.* Rattigan and Hill, 1986; Ghrab *et al.*, 2014 and several others as this is one of the more typical variants), or the first date after 1 October when chill accumulates in 10 or more consecutive days – *e.g.* Auburn method described in Schwartz *et al.* (1997). Several researchers (*e.g.* Luedeling *et al.*, 2009; Ramirez *et al.*, 2009; Luedeling and Brown, 2011; Miranda *et al.*, 2013; Ghrab *et al.*, 2014; Pope *et al.*, 2014) have used the dynamic model to determine chill accumulation as it does not accumulate chill under warmer conditions. In effect, the start date is defined by the chill portions model rather than by the researcher. It should be noted that many of these studies have evaluated several of the more 'classical' chill accumulation models including the dynamic model and usually concluded that it describes the required chill more consistently than other models of chill accumulation which is a more important point that the lack of a requirement to define a start date for chill accumulation.

The end of endormancy in deciduous fruit tree (or vine or herbaceous) crops including almonds and other *Prunus* species is determined experimentally by forcing growth of dormant buds under controlled temperature conditions (see Ashcroft *et al.,* 1977; Linsley-Noakes and Allen, 1994; Egea *et al.,* 2003; Okie and Blackburn, 2011). This stage can also be determined by statistical methods (see below) where accumulated chill and heat are correlated with observed flowering dates (for example Ashcroft *et al.*, 1977; Rattigan and Hill, 1986; Alonso *et al.,* 2005; Leudeling *et al.*, 2009; Raminez *et al.*, 2009; Miranda *et al.*, 2013; Maulion *et al.*, 2014).

The forcing studies involve cutting and placing dormant shoots in growth cabinets to either compliment the already provided chill accumulation and/or to provide heat accumulation in order to determine the minimum amount of chill accumulation required (and hence completion of endodormancy) before heat accumulation will allow buds to grow and bud burst or flowering to commence. These studies can determine both the chill and heat requirements.

The date ecodormancy is complete is the observed date of budburst or flowering, typically measured as the date where 50% flowering is observed.

Statistical methods to determine chill and heat requirements (end of endodormancy) for flowering

There are many statistical approaches to determining chill and heat requirements. Some of the more common approaches are explained below. All require many years of observations of date of flowering and corresponding temperature measurements. As mentioned earlier, it should be noted that the sequential theory is not universally accepted as it is considered too simplistic (see Chuine, 2000; Leudeling *et al.*, 2009, Pope *et al.*, 2014), and some of the methods described below summarise development and evaluation of alternate theories and provide comparison to models using the sequential theory.

Ashcroft *et al.* (1977) assumed a sequential model of chill accumulation prior to an end date and heat accumulation from this date until date of flowering. They determined the required chill accumulation from a start date as that where the heat accumulation from this end date to the date of flowering had the lowest standard deviation for a sample of seven years. The analysis consisted of creating matrices for each year of chill accumulation to a date and subsequent heat accumulation to flowering; then determining which combination of chill accumulation provided the lowest standard deviation in subsequent heat accumulation.

Alonso *et al.* (2005) used correlations between temperature indices for a day (either daily maximum, daily minimum or daily mean temperature) averaged for periods of 5 to 30 days (in 5 day increments) to create 18 vectors for each date (combinations of temperature [3 methods] averaged over various durations [6 durations – 5, 10...30 days]) and the date of flowering of almonds in Spain for a sample of seven years. The temperature indices were designed to address the importance of subsequent days on flowering with the date of transition from endodormancy to ecodormancy determined by the earliest date when the negative correlation between the temperature vector and date of flowering became statistically significant. The eventual temperature vector of choice was daily mean temperature averaged over 15 days. Chill accumulation to this date of transition was considered to be the chill requirement for breaking dormancy, and heat accumulation from this date of transition to date of 50% flowering was considered to be the heat requirements for flowering.

Leudeling *et al.* (2009) consider the sequential theory overly simplistic but evaluated it using a method similar to Ashcroft *et al.* (1977) to model budburst and flowering in Walnut. In effect as only chill accumulation is required to satisfy endodormancy and only subsequent heat accumulation is required to satisfy ecodormancy, then the normalised relationship between chill and heat accumulation of any year should pass through a common point. The chosen combination of chill requirement and subsequent heat requirement was where the chill requirement had the lowest standard deviation for the examined years.

Miranda *et al.* (2013) used observations from 6 years and 14 locations in Spain to model peach flowering. They used iterative processes to evaluate either heat accumulation only models or chill and heat accumulation models where dates to commence heat accumulation, the base temperatures used for heat accumulation and the required amount of heat accumulation were modelled. They found models that incorporated a chill accumulation performed better, and that the dynamic model provided the best index of chill accumulation.

Chuine (2000) developed the concept of a unified model where the periods of chill accumulation and heat accumulation can be sequential or may overlap, and that the mathematical functions describing chill accumulation and heat accumulation are defined by iterative means. This approach encompasses many options.

Pope *et al.* (2014) explored the use of a critical chill requirement and a critical heat requirement for flowering in almond assuming a partially compensatory relationship between additional chill received and heat required, and that required chill accumulation may continue after heat accumulation commences (*i.e.* chill overlap models compared to sequential models). This is similar to some aspects of Chuine's (2000) unified model. However Pope *et al.* (2014) used more standard indices of chill and heat accumulation. Pope *et al.* (2014) found models where the chill accumulation overlapped to a larger extent performed better than when the overlap was less or nil (*i.e*. use of the sequential theory).

Modelling date of flowering in almonds

Rattigan and Hill (1986) developed criteria of chill accumulation and heat accumulation using some of the older and currently thought to be less robust models to calculate both chill and heat accumulation to determine the date of almond flowering in Australia (Virginia in the North Adelaide Plains). They based their approach on the statistical methods proposed by Ashcroft *et al.* (1977). Their model was parameterised to predict date of 50% flowering to within a few days when evaluated against the observed date used to develop the model, but the error in predicted date of flowering was not provided for validation datasets of independent data. Rattigan and Hill (1987) subsequently evaluated their chill and heat requirements developed for Virginia for almond flowering in Nangiloc (in Victoria) and for a location in France. While flowering could be predicted with reasonable accuracy, the errors in prediction are understandably larger when the model is used at a different location. Nevertheless the errors are relatively small (less than 5 days in 90% of cases). This suggests it may be possible to develop a phenology model to describe date of flowering that is applicable across many locations.

Date of flowering in almonds in Spain was also modelled by Alonso et al. (2005). See earlier section.

Recently almonds in Spain were also modelled by Diez et al., (2017). They used the Dynamic model to calculate chill accumulation finding that a minimum of about 20 chill portions were required to satisfy dormancy. This is similar to the 23 chill portions noted by Ramirez et al. (2010) and used by Pope et al. (2014) (see below).

A more recent model of flowering was described for three almond varieties growing in California by Pope *et al.* (2014). This analysis included observations that budburst and flowering in almonds, as in many crops, is influenced both by the accumulation of chill and the accumulation of heat such that less heat accumulation is required to 'force' flowering if more chill accumulation has occurred (*e.g.* Neiddu *et al.*, 1990 in almond; Linsley-Noakes and Allen, 1994 in nectarine; Okie and Blackburn 2011 in peach; Chaar and Astorga, 2012 in peach). The model by Pope *et al.* (2014) predicted the date of 10% flowering to within a few days but does not model date of full bloom (which is typically defined as 50% flowering although values of 80% flowering or 100% flowering have been used). It may be possible to model the relationship between 10% flowering and full bloom. This is because the progression of flowering in almond like many other crops is influenced by subsequent temperature with trees blooming for fewer days when temperatures are high, compared with when they are low (Rattigan and Hill, 1986; Bernard and Socias i Company 1995; Degrandi-Hoffman *et al.*, 1996). The relationship between spread of flowering and temperature is complex as some studies show the chill accumulation received prior to flowering can affect this relationship (NeSmith and Bridges, 1992; Ghrab *et al.*, 2014). A simple heat accumulation model was developed by Degrandi-Hoffman *et al.* (1996) to describe the progression of flowering in several almond cultivars growing in California as a function of accumulated GDH° with unique base temperatures for each cultivar. Perez-Pastor *et al.* (2004) and Mounzer *et al.* (2008) describe similar relationships for apricot and peach respectively. The relationship to describe progression of almond flowering by Degrandi-Hoffman *et al.* (1996) could be combined with the model to predict date of 10% flowering developed by Pope *et al.* (2014). While these models were developed for California, they are good candidates for testing in Australia.

These flowering models (Rattigan and Hill, 1986; Pope *et al.,* 2014 combined with Degrandi-Hoffman *et al.* 1996) are of interest to this Research Project as it indicates the date of flowering in almonds for Australia's many production regions may be able to be predicted from temperature data. Both approaches using three independent relationships will provide two independent estimates of the date of flowering. Furthermore it may be possible to re-examine the data of Rattigan and Hill (1986, 1987) to develop a model using what are now considered the more robust methods of calculating both chill and heat accumulation (see section of calculation of chill and heat indices) using the same or a different statistical method (see section on statistical methods).

Fruit growth and development, and the role of temperature

Fruit growth typically follows a double sigmoidal pattern (growth, lag, growth) that is typically explained by weight and dimensional changes, and changes in cell division and enlargement or various organs. Generally the first growth period corresponds to rapid cell division, the lag to a slowing or cessation of cell division, and the second growth period to cell enlargement and/or maturation.

The development of the almond fruit can be divided into several stages (Figure 3). During stage 1 the fruit grow in dimension such that the seed and hull reach their full size. It is during this stage that cell division and cell expansion occur. The majority of cell division and cell expansion normally occurs from 0 to 6 weeks and 6 to 12 weeks after flowering, respectively (Hawker & Buttrose, 1980). The transition from stage 1 to stage 2 is where pit hardening occurs. Pit hardening is the lignification and hardening of the endocarp (shell), the inside layer which surrounds the seed (kernel). Pit hardening begins on the inner surface of the shell cavity and at the end opposite to the stem attachment (Kester *et al.*, 1996). Stage 2 is associated with growth of the embryo (which eventually forms the kernel) to its full dimensional size. Stage 3 is associated with the increase in dry weight of the embryo. Hull split then marks the transition to fruit maturity where the fruit components (hull, shell, kernel) dehydrate and an abscission zone forms which allow fruit to fall when shaken.

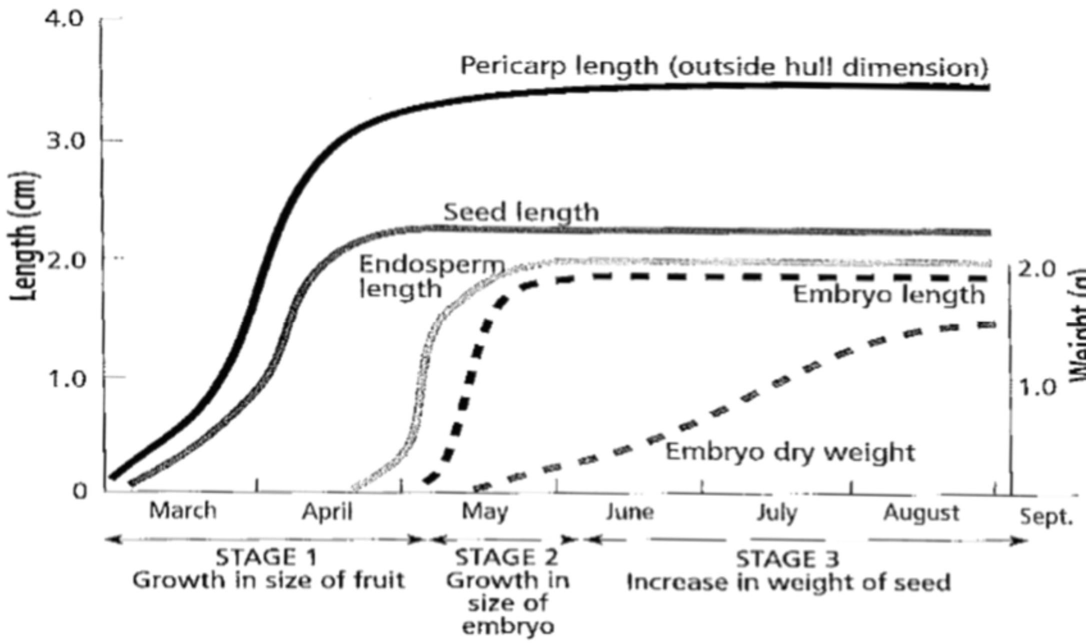


Figure 3. Kernel development showing development stages. From Kester *et al.*, 1996.

In almond fruits, the relationships between temperature during initial fruit growth and fruit and kernel dimensions are not as well understood. There may be an influence of prevailing temperatures as growth during stage 1 controls seed length which controls embryo length determined during stage 2 (which can only grow to dimensions previously determined by the seed length). Some analysis by Gradziel (2010) indicates accumulated heat provided a poor predictor of kernel development as measured by dry weight.

The understanding and relationship of temperature to fruit growth and carbon accumulation is more developed in other *Prunus*, notably peach. Dejong and Goudriaan (1989) describe peach fruit growth in terms of sink demand, where during phase 1 cells are dividing and differentiating and the relative growth rate is declining. During phase 2 the cells are expanding and maturing but the relative growth rate is stable. The separation between these phases corresponds to the lag typically observed in the double sigmoidal growth relationship. Temperature may alter the timing of the shift in phases and hence maturity. Temperature may also affect the fruit size. Lopez and Dejong (2007) found that peach fruit development rates were higher in warmer spring conditions but that peach fruit growth rates may be limited by insufficient resources from the tree. This meant that fruit grew faster but for a shorter period such that fruit size was reduced. In stonefruit final fruit size may be modified by management practices such as thinning to reduce resource competition. The L-peach model (see Lopez *et al.*, 2010) is not a phenology model, but rather uses the relationships between carbon allocation and tree architecture to model management practices such as tree pruning and fruit thinning. A similar model for almonds (L-almond) is in progress (See Dejong 2010 - 10-PREC1-DeJong, Assessing the Carbon Budget of Almond Trees and Developing a 3-D Computer Model of Tree Architectural Growth and Dry- Matter Partitioning in Almond).

Modelling Hull split in almonds

Tombesi *et al.* (2010) examined the relationship between heat accumulation and fruit maturity of almonds in California. They correlated 8 years of phenological data from three genetics trials in California with temperature and other environmental indices. They found that GDH° in the first 90 days after full bloom (DAFB) were a better predictor of the time of 1% hull split than either GDH° in the first 30 or 50 DAFB or the total GDH° from full bloom to 1% hull split. In comparison Gradziel (2010) noted "the poor correlation between accumulated degree days and key almond phenological stages such as hull-split appeared to be the consequence of sizable regional differences in cultural practices, particularly fruit set, and level of fertilization and irrigation."

The finding by Tombesi *et al.* (2010) that heat accumulation in the 90 DAFB were related to maturity (measured by time to hull split) contrasted to findings in other stonefruit (specifically peach, nectarine, plum, and prune) where the GDH° in the first 30 days after full bloom could be related to either the reference date (date when 80% of fruit have hardened pits near their distal end which along with the fruit size at this time may be used to determine the level of fruit thinning) or to date of harvest (Ben Mimoun and DeJong, 1999; Marra *et al.*, 2002; Lopez and DeJong 2007, Day *et al.*, 2008). However, the relationships with almond and the other *Prunus* species examined (peach, nectarine, plum prune) do indicate growth conditions during early fruit growth are influential to the overall fruit growing period.

Tombesi *et al.*, (2010) further attempted to account for some of the year-to-year and locational variability between the relationship of time from full bloom to 1% hull split and the associated accumulated GHD in the 90 DAFB by additional relationships of cumulative potential evapotranspiration (ETo), or cumulative high temperatures above 30°C in the last half of fruit development or crop load. These were not successful.

Modelling hull split and date of harvest

The progression from 1% hull split to 100% hull split was examined over a 10 year period at one genetic trial (Chico) in California (Connell *et al.*, 2010). Once a cultivar reaches the maturity stage of 100% hull split an early commercial mechanical harvest operation can begin as nuts can be effectively shaken from the trees. However the time of commercial harvest may be later due to undesirable weather conditions or harvest logistics. Another reason for the delay between 100% hull split and date of harvest is that the definition of hull split typically refers to the initial separation of the hull (*i.e.* figure b3 in University of California, 2002 where splitting has occurred along the entire suture but the hull may not yet be separated although the hull can be opened by squeezing both ends of the hull) which is prior to full exposure of the shell and dehydration of the hull, shell and kernel. The difference between 100% hull split and commercial harvest can be considerable. For example in the trial examined by Connell *et al.* (2010) the 10-year average hull split initiation date or 1% hull split for 'Nonpareil' nuts was July 17, the average date of 100% hull split on 'Nonpareil' was on August 11 and its commercial harvest date defined as the average date nuts were mechanically shaken from the trees was August 25. This delay would in part be associated with the requirement for further desiccation of the fruit (hull, shell and kernel) to occur before fruit can be harvested by shaking operations, and also because of logistics relating to impending or recently received weather (*e.g.* rain can delay harvest owing to increased risk of pathogens damaging the kernel).

Connell *et al.* (2010) provide the average time (days) from 1 to 100% hull split of Nonpareil and several other varieties, but do not provide relationships with temperature or other environmental variables such as evapotranspiration or rainfall. It is likely management practices such as irrigation supply may also influence the rate of progression from 1% to 100% hull split. The year-to-year variation in the time for hull split to be complete was also not supplied. It may be possible to obtain these data from this and other Californian studies or similar data from Australia to explore these relationships.

Methods of measuring chill accumulation

Both chill accumulation and heat accumulation can be measured by many indices. Unfortunately there is no globally accepted method of measuring chill with several standard models developed for calculating chill accumulation. Five widely used chill models are the 0 to 7.2°C model (Weinberger, 1950), Utah model (Richardson *et al.*, 1974), modified Utah (Linvill, 1990), Positive Utah model (Lindsay-Noakes *et al.,* 1994) and the Dynamic model (Fishman *et al.,* 1987a, 1987b), although many other models do exist (*e.g.* see Chuine 2000).

One of the earliest models sums hours between 0 and 7.2°C over winter (Weinberger, 1950). Each hour between 0 and 7.2°C is counted as a chill hour. The Utah model (Richardson *et al.*, 1974) assigns values for Richardson units (similar to chill hours) between 1 and -1 according to temperature. Cooler temperatures are assigned positive values, while moderate temperatures that are not responsible for chill accumulation are assigned values of zero. Warmer temperatures that negate the chilling that has already occurred are assigned negative values. A variant of the Utah model, the modified Utah model (Linvill, 1990), smooths the step function of the Utah model to assign continuous values between 1 and -1. It was found to be superior to the original Utah function. A further variant of the Utah model is the positive Utah model (Linsley-Noakes *et al.*, 1994). The Positive Utah model does not include the negation aspects of high temperatures. It has been found to perform better than the Utah model in mild locations in South Africa (Linsley-Noakes *et al.,* 1994) so could be useful in Australian conditions.

The dynamic model (Fishman *et al.* 1987a, 1987b) is considered the most biologically accurate model. It assumes that chill results from a two-step process where cold temperatures initially form an intermediate product in the buds and warm temperatures can destroy this intermediate product. When a certain quantity of the intermediate product has accumulated, it is transformed irreversibly into a chill portion, which can no longer be destroyed.

Unfortunately there is limited conversion between chill models as shown by Luedeling and Brown's (2011) study into the comparability of chill models on a global scale. Darbyshire *et al.* (2011) support this global assessment in an Australian setting.

Methods of measuring heat accumulation

Temperatures that contribute to heat accumulation required for growth and development are typically measured as growing degree days (GDD°) or growing degree hours (GDH°). The simplest heat accumulation indice is growing degree days (GDD°). Growing degree days use only daily minimum and maximum temperatures to describe heat accumulation. It is common for temperatures cooler than a base temperature to be ignored (typically 10°C although others can be used - *e.g.* 4°C).

Growing degree hours are similar to growing degree days except hourly temperature is used. These hourly temperatures may be measured or interpolated from daily minimum and maximum values. As with growing degree days, growing degree hours can also be measured using a variety of mathematical functions designed to account for the different effectiveness of temperature on growth and development. There are a number of common formula used to calculate heat accumulation in deciduous fruit trees from hourly temperature. One method used is that of Richardson *et al.* (1975) which uses a base temperature of 4.5°C and assumes each degree above this until 25°C equates to 1 GDH°, and all temperatures greater than 25°C also equate to 21.5 GDH°.

A variant of the formula of Richardson *et al.* (1975) is that described by Anderson *et al.* (1986), and was used in the ASYMCUR growth model. This formula of Anderson *et al.* (1986) assumes that heat accumulates between the base temperature (Tb, set to 4°C) and the critical temperature (Tc set to 36°C) with optimum accumulation at the optimum temperature (To set to 25°C).

The equation for GDH between the base and the optimum temperature is:

$GDH = FA/2 \times (1 + \cos(\pi + \pi (T-Tb)/(To-Tb)))$.

The equation for GDH between the optimum and the maximum temperature is:

$GDH = FA \times (1 + \cos(\pi/2 + \pi/2 (T-To)/(Tc-To)))$,

where A = To-Tb, and F is a factor of stress (assumed to be 1 unless the plant is under stress).

Further variants of heat accumulation include use of:

Different base temperatures (*e.g.* 10°C used by Linsley-Noakes and Allen, 1994).

Different methods to calculate GDD: *e.g.* Ruml *et al.* (2010) evaluate the influence of how GDD° is calculated and specifically how to estimate the base temperature on the effectiveness in predicting full bloom and harvest of apricots. These may be estimated as part of model parameterisation (*e.g.* Miranda *et al.*, 2013).

Inclusion of higher temperatures may also be ignored or allocated a lower efficiency of heat accumulation.

Zalom *et al.* (1983) review and provide mathematical equations to calculate GDD° using several methods. This list is not exclusive as various equation forms (linear, quadratic, sigmoidal) have been used to calculate heat accumulation (*e.g.* see Chuine, 2000).

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