Research Team – **David Carey,** Senior Horticulturist, Horticulture and Forestry Science, DAF Qld & **Peter Deuter**, Horticultural Consultant, PLD Horticulture.

Drought and Climate Adaptation Program

Cauliflower – Critical Temperature Thresholds

Critical Temperature Thresholds (CTT).

Local weather conditions influence all stages of plant establishment, development and growth, ultimately determining crop productivity and marketability. Every crop has a unique range of optimum, and tolerable environmental conditions that favour its growth. Identifying and understanding the relationships between crop growth stages and 'expected' weather is very important in maximizing crop productivity. For a crop to be successfully grown and marketed in a region, the sequences of its growth phases must align with the climate, in order to maximise the potential of good growth, quality and marketable (harvestable) yield.

Grotjahn, R. (2021) demonstrates the effect of short durations of temperatures, above or below the optimum, which can have devastating consequences on horticultural crops and their produce. For high temperatures it may be measured in hours to days. Two days in a row, above the optimum, are more severe than one day. This makes the task of identifying Critical Temperature Thresholds difficult, and exacerbated by the fact that, "the thresholds have ranges due to the variation among cultivars and the conditions each plant experiences over time" (Grotjahn, R., 2021, p.40).

Introduction

Cauliflower (*Brassica oleracea* var. *botrytis*) is one of several cultivated vegetables in the species *Brassica oleracea*. Growth and development of cauliflower is strongly influenced by environmental conditions such as temperature and radiation (Salter, 1960; Wurr et al., 1990). The immature flower, often called the "curd" is eaten, often cooked but also used fresh in salads or processed and frozen. Cauliflower has wide adaptability, from temperate regions to the tropics. Cabbage and Broccoli are closely related members of the Brassica species. Worldwide there are two major cauliflower types (Singh et al., 2018), the European (first cultivated and selected in Italy, France, England, Germany and the Netherlands) and the more tropical Indian types, which are more tolerant to high temperature and humidity. These more heat tolerant Indian types can be classified as extra early (>30 ^{0}C), early (25-30$^{0.}$ C), mid (20-25^0 C), mid-late (15-20^0 C) and late (<15^{0}C). Singh et al. (2018), go on to state that certain favourable genes for tolerance to high temperature and rainfall, unknown in European types, are being used to develop improved varieties. Research in Malaysia by Norfadzilah et al., (2019), evaluating a number of tropical genotypes, identified Hybrid C2 (1360) from Green Eagle seed company as a good candidate to be grown in locations that experience high tropical temperatures ranging from 25°C-35°C.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Cauliflower is much more demanding in its environmental requirements than any of the other Brassicas. The formation of the curd and its quality is greatly influenced by the prevailing weather conditions (Aleem et al., 2021, Dept Env & Primary Industries Victoria, AG 0421). Cauliflower is a plant which naturally prefers a cool climate and is grown mostly in mild, cool to cold areas. The quality of the curd (colour, shape, size and structure) can be severely impacted by hot weather during the head maturation phase (Aleem et al., 2021).

A wide range of growing locations, varieties and maturity times means that production can occur almost year-round, particularly in more mild and cooler areas of Australia, where cauliflowers are grown for the fresh, processing and export markets.

The main cauliflower production regions in Australia are the Lockyer Valley, Granite Belt and Eastern Darling Downs (SE Qld), Central West (NSW), Lindenow, Werribee, Lang Lang, Gippsland, and Shepparton (Vic), South-West and the Swan Coastal Plain (WA), Virginia (SA) and Cambridge, Richmond and Devonport (Tas).

Summary

Changes in temperature affect many crops and these effects can be complex in species such as cauliflower, where distinct phases of growth are affected by temperature in different ways. Cauliflower has three distinct growth phases - viz. juvenile (vegetative), curd initiation and curd growth (Wurr & Fellows, 2004). A number of researchers around the world have investigated the role and impact of temperature on cauliflower quality, during these distinct growth phases.

Cauliflower curd quality is ultimately judged by consumers who “buy with their eyes”, looking for fresh, blemish free curds of uniform shape and colour. Curd riceyness, leafiness (leaflets protruding through the curd) and fuzziness are obvious quality flaws (Singh, et.al., 2018). Unsuitable temperatures can cause malformed, misshapen curds, riceyness (see image below), premature heading, and bolting or early seed stalk development, depending on the plant growth stage (Lin et al., (2019).

Poor quality cauliflower heads like this heat affected example are unmarketable.

Curd quality is also influenced by below optimal temperatures (frosts) close to harvest (Wurr, et al., (2004).

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Trimmed cauliflower curd (head).

Non-optimal temperatures cause riceyness and, bumbled off-white heads.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Critical Temperatures and Development Phases.

International research literature (Kahn et al., 2007) indicates that cauliflower grows best in locations with average temperature ranging from 5 – 8°C to 25 – 28°C. Oleson et al., (2000) reviewed previous research and determined the base temperature for their cauliflower model should be 5.1^{0} C. Cauliflower may tolerate temperatures from -10°C to 40°C for a few days during the vegetative growth phase (Singh et al., 2018). Warland et al., (2006) documented a 10% marketable yield decline in cabbage, cauliflower, potato and rutabaga crops grown in southern Ontario for every 10-day period that the temperature reached 30^{o}C or above during the growing period. These results shed new insight into the mechanisms by which weather affects yield.

Cauliflower growth phases.

Cauliflower plant and curd development is a complex multi-stage process, with temperature being a key component (driver) Chen-Yu et.al., (2019), Aleem et al., (2021).

A range of commercial cauliflower varieties are available to Australian producers. These varieties are grouped and sown according to their classification as spring, summer, autumn or winter varieties. The determination of an individual commercial varieties' suitability to a "season" varies according to the historic (known) temperature data for the particular growing location. For example, a winter variety used in Southeast Queensland is very unlikely to produce a marketable curd in the much colder Victorian winter season.

1. Juvenile phase.

Once seed has germinated, the young cauliflower plant enters the vegetative (juvenile) growth phase (Kato.1964). The duration of this juvenile phase depends on environmental conditions, including light intensity that drive leaf development, as outlined by Wellensiek and Higazy, (1961) and Pierik, (1967). Booij and Struik, (1990) and Hand and Atherton (1987), determined that leaf number is a useful measure for the duration of this growth phase. The presence of leaf number ranging from 8 to 19 marks the end of juvenility in different cultivars and the beginning of the curd initiation and development phase. The cauliflower plants vegetative development phase is slowed by colder temperatures and accelerated by optimum growing temperatures.

2. Curd induction or initiation phase

The term "vernalization" is sometimes used to describe the transition of cauliflower into the reproductive, curd development phase. Vernalization implies that cool temperatures hasten curd initiation, but several researchers including Wurr *et al*., (1990), showed this may not always be the case.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Bhatia et al., (2016) state that Indian cauliflower types have been selected over the last 200 years and are typically adapted the high temperature and humidity during curd initiation and development. Indian cauliflower genotypes are used in different parts of the world for the development of cauliflower hybrids due to their inherent characteristics to tolerate both, high temperatures and relative humidity, according to Dey et al., (2011)

3. Curd growth phase

This phase follows on from curd initiation. The diameter of the curd increases with temperature up to a maximum size as determined by genetic potential (Wiebe, 1975; Wurr *et al*., 1990). Lower temperatures increase the duration of the curd growth phase. The relationship between radiation, temperature and curd growth are highly dependent on the date of transplanting or direct seeding (Norfadzilah et al., 2019; Ray& Mishra 2017; Wiebe, 1974).

The immature flower (curd) is harvested for consumption at the end of the curd growth phase. If left to continue to develop through subsequent growth phases the immature curd (inflorescence), will mature, flower, and set seed. These additional growth phases will not be considered in this review of critical temperature thresholds as they are only necessary for seed production, so not relevant to fresh market production.

Juvenile phase – critical temperatures.

a) **Seed Germination**. Brassica seed germination time varies with temperature, species & variety (Russo et al., 2010). Commercially acceptable germination can be achieved for most brassica species with mean daily air temperatures between 10°C and 27°C. Temperatures (24hr mean) below 4°C or above 32° C are severely detrimental. Research indicates that a mean daily air temperature range of 16°C – 27°C is optimal for seed germination (Russo, et al., 2010). The International Seed Testing Association prescribes germination testing regimes of continuous 20°C or alternating 20/30° C with the germination percentage counted after 10 days (Vegetable brassicas and related crucifers, G.R. Dixon, 2006, p82). Swarup and Chatterjee (1972), in their review of the origin and improvement of Indian cauliflowers, conclude that cauliflower grows in average temperatures ranging from 5°C to 28°C.

   The vast majority of cauliflower crops grown in Australia are grown from transplants, though some are direct seeded. Australian farmers use transplants (2 – 3 true-leaf seedlings) to maximise cropping and ground use. Improved efficiency is achieved by moving the seed germination and early development phase off-farm, saving 6 – 8 weeks of direct seeding ground space for each planting. Seed is germinated in a nursery under controlled conditions, so although extremely high temperatures could impact Brassica seed germination, it is rarely an issue in commercial seedling production.

The optimal Temperature for seed germination is > 16°C & < 28°C

The Critical Temperature Threshold for seed germination is > 5°C & < 30°C

b) V**egetative growth.** This phase of the cauliflower plant is relatively unaffected by temperature extremes. Temperature range during the vegetative growth phase does however influence the length of time before the plant is of sufficient size and leaf number to enter the curd initiation growth phase. Hand and Atherton (1987) determined that the juvenile vegetative stage in cauliflower persisted until a critical number of leaves are present on the plant. This critical leaf number varied with variety but ranged from 13 to 19 leaves. According to Booij and Struik (1990) the rate of leaf development increased with warmer temperatures.
This is backed up by Lin et al., (2019) who determined that a temperature of 30°C accelerated the ending of the juvenile stage. Lin, et al, (2019) state that the optimum mean temperature range for growing cauliflower is 18 – 25°C but note that heat tolerance varies between cultivars. Swarup and Chaterjee (1999) in their paper "Origin and genetic improvement of Indian cauliflower", determined that during the vegetative growth period, cauliflower plants may endure temperatures as low as 0°C and as high as 40°C for a few days.

The optimal Temperature for vegetative growth is > 17°C & < 26°C

The Critical Temperature Threshold for vegetative growth is > 5°C & < 30°C

Curd induction or initiation phase – critical temperatures.

Aleem, et al., (2020), concluded that cauliflower is a cool season crop and temperature plays a critical role in curd induction. Along with a number of other authors, Lin et al., (2019), and Warland et al., (2006) conclude that cauliflower curd initiation is closely linked to temperature. Singh, et al., (2018) determined that most genotypes require an optimum temperature of 20 – 25°C for curd initiation. However, Aleem, et al., (2020), state that cauliflower genotypes have been identified that can develop curd at high temperatures, but the mechanism of this heat tolerance in these varieties is not clear. They go on to state that a variety known as CF – Early, identified as being a heat tolerant genotype, was capable of curd induction at an average maximum temperature of 34°C. In the same study, another genotype (variety), TSX – C40, was shown to initiate curd development when maximum temperature was between 21.5 – 26.0°C. This demonstrates the differences between varieties and their suitability to specific geographic locations and seasons.

Fellows, et al., (1999), determined during a field experiment in the United Kingdom, that for the early summer cauliflower cultivars Perfection and Gypsy, temperatures representing the lower, optimum and upper limit of curd induction were 2.2, 9.4 and 24°C.

They reported that under optimum conditions, curd induction only takes about six days, and that the underlying difference in this timing between crops or cultivars is actually the duration of the juvenile growth phase.

Optimum temperatures for curd induction in European summer/autumn cauliflower crops was estimated as 9.0-9.5°C (Wurr et al., 1993), 12.8°C (Grevsen and Olesen, 1994) and 14°C (Pearson et al., 1994), while those for Roscoff, an heirloom variety of winter cauliflower seem likely to be around 12-14°C (Wurr and Fellows, 1998). Research on Indian (tropical types) by Bhatia et al., (2016) identified four different cauliflower maturity groups used in the North Indian plain, all having different tolerance to high temperatures and humidity, with the most temperature tolerant variety having an optimum temperature for induction of 20-27°C. Weibe (1975) determined that the temperature range inducive for curd initiation ends at 23–25ºC for the variety "Aristokrat", while tropical types reach this limit at 28-30ºC.

Singh et al., (2018) state that most cauliflower genotypes require an optimum temperature of 20 – 25ºC for curd induction. This Indian Council of Agricultural Research work is more informative than the European research data, as it aligns better with Queenslands & Australia's climate and summer growing conditions.

The optimal Temperature for curd initiation is > 20ºC & < 25ºC

The Critical Temperature Threshold for curd initiation is > 20ºC & < 27ºC

Buttoning.

This disorder is characterized by the production of small exposed unmarketable curds called buttons, also called pre-mature heading.

According to Khan et al., (2019) in young broccoli and cauliflower plants, there is a fine balance between vegetative and reproductive growth. If the balance tips toward reproduction while the plant is small and young, root and leaf growth are restricted, and the developing head becomes exposed on a small plant. The exposed head never reaches marketable size and soon breaks up as the flower stalks elongate. This "premature" head development is called buttoning. Buttoning is most likely to occur when young (post-vegetative) plants experience stress, or shock during this critical curd development phase. A review by Masarirambi et al., (2011) determined the cause of this disorder is often limited nitrogen (N) supply, the delay of transplanting, inadequate water or other plant growth stresses. According to Norman (1992) and Fritz et al. (2009), any check in growth due to dry soil or delay in transplanting may cause small curds to be formed. Too little or too much hardening, cold weather for 10 days or more at 4 to 10°C, diseases, insects and micronutrient deficiencies have been reported to also cause broccoli and cauliflower buttoning (Fritz et al., 2009). Research indicates that buttoning is a plant stress response and temperature is only a minor factor.

Curd growth phase – critical temperatures.

Warland et al., (2006) concluded that a maximum temperature above 30^{0}C for 10 days caused a 10% reduction in cauliflower yield. In their future climate modelling work in 2004, Wurr et al., (2003) predicted a drastic impact on crop yield due to increasing temperatures, stating that the phases of juvenility and curd growth were shortened by increased temperature". Khan, et al., (1990) in their Oklahoma State University Cole Crop Production guide state that, broccoli, cabbage and cauliflower all lose quality when maximum temperatures exceed 26.7^{o}C, and the upper limit of growth is about 29.5^o C. They also reported that high temperatures cause cauliflower heads to become loose and branchy and may favour bract development (leaflets protruding though the curd), while cauliflower curds can also develop a fuzzy, "ricey" appearance.

The optimal Temperature for curd growth is > 20^{o}C & < 25^{o}C

The Critical Temperature Threshold for curd growth is > 20^{o}C & < 30^{o}C

Future climate implications – crop performance and yield.

A diverse range of commercial cauliflower varieties is available to Australian growers. These varieties are grouped and grown according to their seasonal suitability, spring, summer, autumn, and winter. Australian commercial seed supplier catalogues indicate suggested variety, timing and location, production slots, e.g., Terranova Product Guide – 2022[1] , South Pacific Seeds Product Guide[2] 2023, & Seminis Product Guide 2022-2024[3].

Varietal suitability changes according to geographic production location. For example, a variety suited to winter in the Lockyer Valley, Queensland, is unlikely to produce a marketable curd if grown in the much colder Victorian winter conditions. A warming climate will mean that in currently colder winter areas growers may move to an existing variety that performs better (faster growth, better quality) at their location. These winter growers will have existing varietal choice options that are suited to milder (warmer) conditions, however current "hot" summer production areas may not have that option.

---

[1] https://terranovaseeds.com.au/wp-content/uploads/2022/03/Terranova-Product-Guide-2022.pdf

[2] https://spssales.com.au/product/iceberg/

[3] - https://www.vegetables.bayer.com/au/en-au/resources.html

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

These summer production locations, which are currently on the verge of being too hot in certain months will experience more days that are above their best summer varieties CTT. This will cause a shortening of the current summer season, so as to avoid quality and crop loss in a hotter summer.

Australia and Queensland's climate is warming (reference, links below), meaning that some current summer cauliflower production locations and varieties are likely to become commercially non-viable in the future. Producers will need to continue to adapt to these changes, revising their production location and timing. Plant breeders will need to develop and introduce new heat resistant varieties. Consumers may need to be convinced to accept the more yellow, open curded tropical varieties, similar to those being used in India. Curd quality will determine consumers buying patterns, and locations that produce lower quality product will inevitably see cauliflower production decline and the growing season change.

Locations or months previously deemed non-viable due to minimum temperature constraints may become commercially viable. For example, the cauliflower production season in the Granite Belt region (currently late spring, summer and autumn), could extend further into winter and begin earlier in the spring, extending the production window, as temperatures rise. Cauliflower variety choices and production windows will need to be adjusted accordingly.

Queensland is already experiencing the impacts of climate change:

The Climate Change in Australia website {CSIRO and Bureau of Meteorology, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/), cited [January 2023]}[4] contains the following statements.

All of Queensland has warmed since 1910.

Average annual temperature has increased by 1.5°C since 1910. Under a high emissions scenario (RCP8.5), by mid-century, Queensland can expect an average annual temperature increase of around 1.3-2.5 °C (central **estimate of 1.9 °C**).

These statements about Queensland's changing climate refer to annual average temperature increases (1.3 – 2.5°C), so they smooth out the usual fluctuations in daily, weekly and monthly temperature at any location. The State of the Climate 2022 Report[5], Future Climate section states, "new research in Australia and around the world, together with the IPCC's Sixth Assessment Report, enhance our understanding of the state of

---

[4] https://www.climatechangeinaustralia.gov.au/en/changing-climate/state-climate-statements/queensland/

[5] https://www.csiro.au/en/research/environmental-impacts/climate-change/State-of-the-Climate

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Australia's future climate. In coming decades, Australia is projected to experience, continued warming, with more extremely hot days and fewer extremely cool days."

This has serious implications for horticultural production in Queensland, where higher temperatures will impact existing crops, production timing product quality and production

locations. While some production may be able/forced to move to a new location, land suitability, water availability, workforce and supporting infrastructure (e.g., road networks & power availability) pose significant constraints.

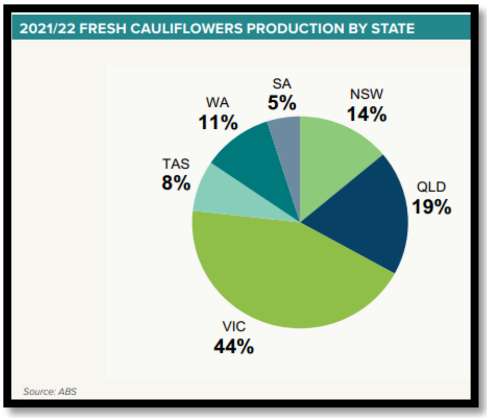
Cauliflower - Critical Temperature Thresholds (from published research).

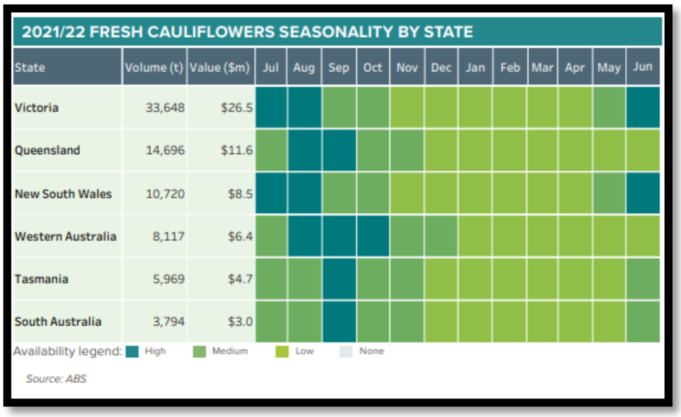
	Critical Temperature ^{0}C	
Growth Stage	**Lower**	**Upper**
Germination	< 5	>30
Vegetative	<5	>30
Curd Induction	<20	>27
Curd growth	<20	>30

It is important to realise that to achieve a mean monthly maximum of 30°C (for example), there will be a spread of cooler and hotter days. In a biological system, plant stress caused by several days in a row above a critical temperature tends to tip the system into decline. To simulate the effects of high temperatures on consecutive days, we have used the critical temperature + 2°C for 3 days and applied this to each crops' threshold. So, for cauliflower at the curd growth stage, the literature indicates the Critical Temperature Threshold is 30°C mean monthly maximum temperature. To simulate the effects of high temperatures, we have chosen **32°C for 3 consecutive days as the Critical Temperature Threshold** for the **curd growth** stage.

Commodity production data.

Australia produced around $60.7 million worth of cauliflower in 2021--22, down from around $63.1 million in 2020-21. In Australia, Victoria and Queensland account for more than half of Australia's total cauliflower production by volume (Australian Horticulture Statistics Handbook 2021-22)[6].





2021/22 FRESH CAULIFLOWERS SEASONALITY BY STATE

State	Volume (t)	Value ($m)	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Victoria	33,648	$26.5	High	High	Medium	Medium	Low	Low	Low	Low	Low	Low	Medium	High
Queensland	14,696	$11.6	Medium	High	High	Medium	Medium	Low	Low	Low	Low	Low	Low	Low
New South Wales	10,720	$8.5	High	High	Medium	Medium	Low	Low	Low	Low	Low	Low	Medium	High
Western Australia	8,117	$6.4	Medium	High	High	High	Medium	Medium	Low	Low	Low	Low	Low	Low
Tasmania	5,969	$4.7	Medium	Medium	High	Medium	Medium	Low	Low	Low	Low	Low	Low	Medium
South Australia	3,794	$3.0	Medium	Medium	High	Medium	Medium	Low	Low	Low	Low	Low	Low	Medium

Availability legend: High Medium Low None

Source: ABS

Figure 1.Fresh cauliflower production in each state and corresponding seasonal availability (Source: web reference above)

6 https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/grower-resources/mt21006-assets/australian-horticulture-statistics-handbook/

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Production regions, seasons and critical temperature thresholds

Critical Temperature Thresholds - Climate Monitor analysis/verification of annual historical temperatures at selected production areas.**

I. Queensland

a) Lockyer Valley, Southeast Queensland (autumn, winter, spring production).

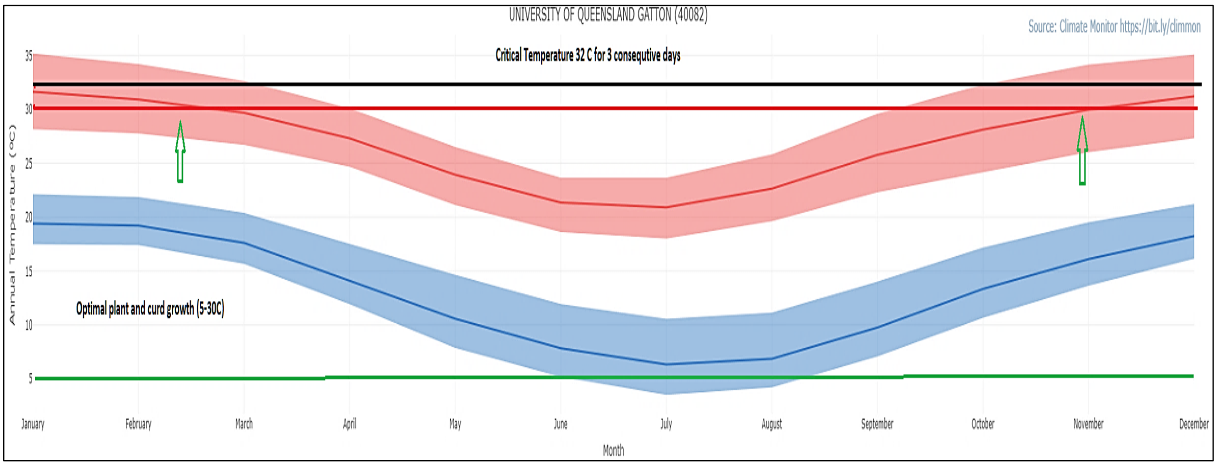


Figure 2. Monthly historical maximum (red) and minimum (blue) temperatures and mean temperatures at Gatton (solid lines within each coloured band), with cauliflower critical temperatures – overlaid. Note: The graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

The cauliflower production season is completed in the Lockyer Valley by the end of October each year. The majority of the harvest is completed by the end of September, because rising temperatures in late spring and early summer negatively impact marketable quality. The 'curd development and growth phase' in cauliflower is the most sensitive to high temperatures.

** Climate Monitor is a Web based Tool which allows the user to analyse and graph minimum and maximum temperature and rainfall for all available years, calculate thermal time (chill and heat units) and be able to retrieve, analyse and graph temperature thresholds (for a chosen location).

High maximum temperatures (>30^{o} C) during curd growth and development reduce curd size, yield and most importantly quality (colour and shape). In warmer years, when spring temperatures rise quickly above the historic mean, quality drops, sales decline quickly and prices for local product plummet as wholesalers and chain stores source better quality produce from alternate (cooler) locations.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Using the unique weather data analysis of the Climate Monitor Web-tool, producers can easily review historical spring temperatures at any location in Australia. It is important to realise that to achieve a mean monthly maximum above 30°C there will be a spread of cooler and hotter days. In a biological system, plant stress caused by several days in a row above a critical temperature tends to tip the system into decline. An analysis of the number of times a maximum temperature of 33°C has occurred for 3 consecutive days in spring (Sept to November) in Gatton is displayed below. The years (2009, 2017, 2019) with hotter springs would have caused a decline in cauliflower quality, crop downgrades and losses.

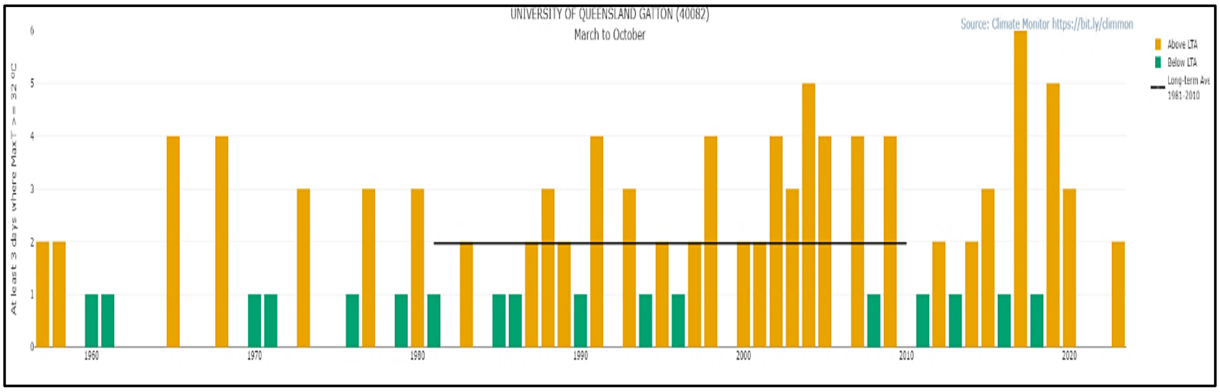


Figure 3. Climate Monitor analysis showing the number of times each year and season (March – Oct) that Gatton has experienced at least 3 consecutive days that were 32°C or above.

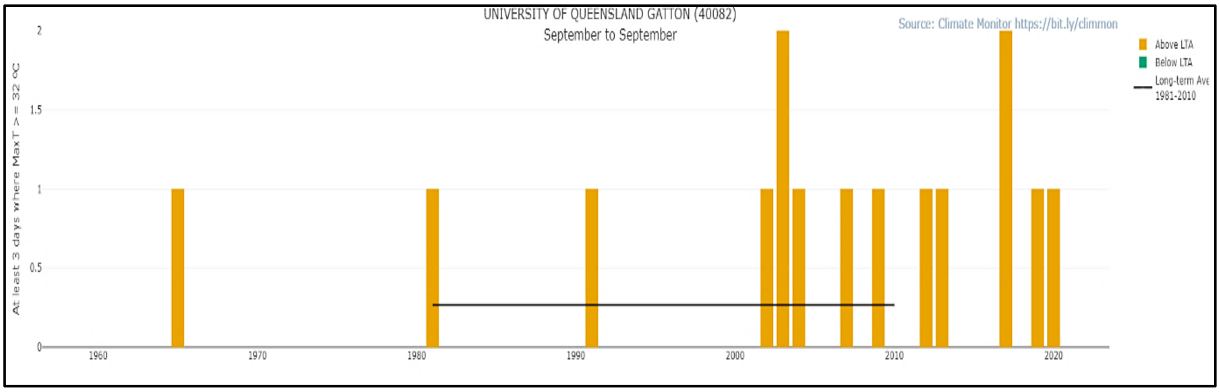


Figure 4. Climate Monitor analysis showing the number of times in each year that Gatton has experienced at least 3 consecutive days that were 32°C or above in September. The cauliflower season ends in the Lockyer Valley as spring temperatures exceed the CTT.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

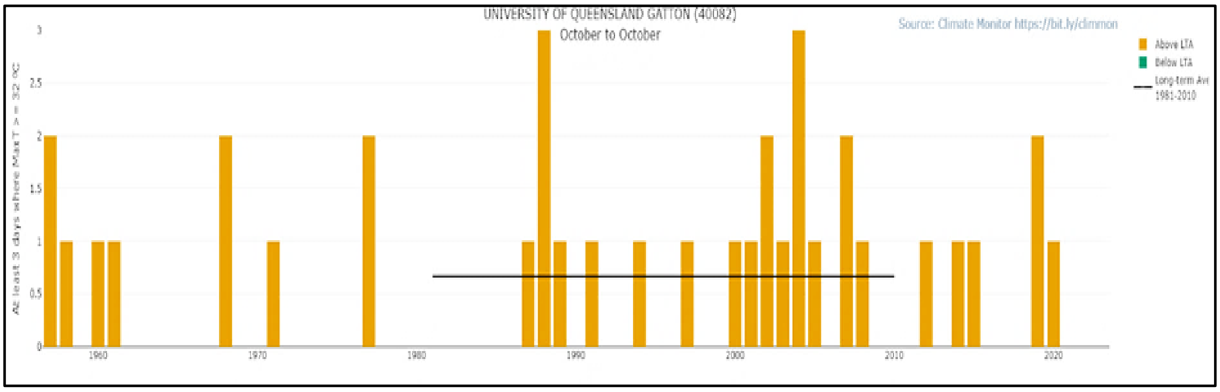


Figure 5. Climate Monitor analysis showing the <u>number of times</u> in each year that Gatton has experienced at least 3 consecutive days that were 32ºC or above in <u>October. Excessive high temperatures reduce both yield and quality.</u>

The winter-based production season in the Lockyer Valley commences with the first plantings in mid-February, followed by consecutive weekly plantings until the end of June. First harvest occurs in late May, while final harvests occur in late September or early October, with production peaking from June to August. Lower yields and reduced curd quality are often experienced in late September, especially in warmer years.

<u>b)</u> <u>Granite Belt</u>, Southern Queensland (Late spring, summer and early autumn production).

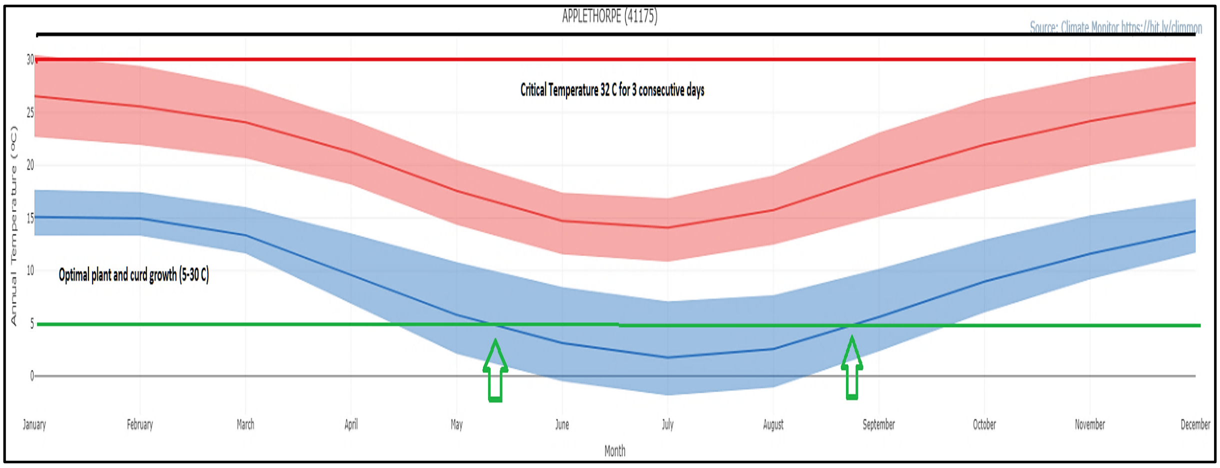


Figure 6. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperature (solid lines within each coloured band), with cauliflower critical temperatures – overlaid, at Applethorpe on the Granite Belt.

Note: The graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

Using 20–30^0 C as the mean maximum temperature threshold for marketable cauliflower production in the "curd induction and development phase", and the annual temperature data from Applethorpe, Qld, it would be expected that cauliflower harvesting in the Granite

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from <u>Climate Monitor</u>, a free, publicly available DCAP web-tool.

Belt would be possible all summer. Frosts and cold temperatures during winter, autumn and early spring, restrict plantings during those seasons. This closely describes the production system in this district, where first plantings occur in late August (and harvests commence in mid-December), and final plantings occur in March, which are then harvested in May (on the higher altitude, less frost prone farms).

The Granite Belt is a warm season cauliflower production area, and using the analysis power of Climate Monitor, growers can easily review historical temperatures at their production location. Maximum Critical Temperature Thresholds are not exceeded at present, though January is on the cusp of exceeding the maximum temperature thresholds. Current minimum temperatures prevent economically viable production through late autumn and winter. This is when the warmer temperatures in the Lockyer Valley allows growers to produce high quality cauliflowers.

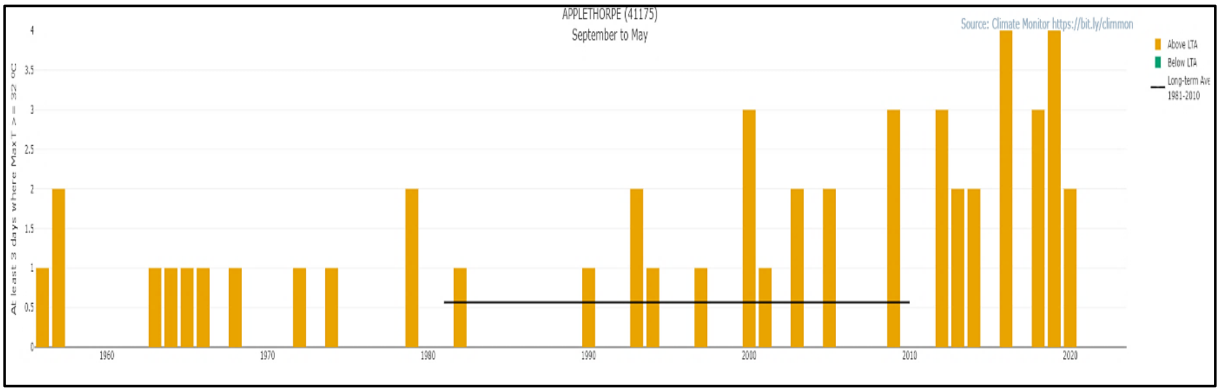


Figure 7. The number of times in all years to-date (Sept – May) at Applethorpe when 3 consecutive days or more have reached or exceeded 32ºC.

Future temperature insight.

As underlying temperatures continue to rise, and extreme heat days become more frequent[7], it is likely that the Granite Belt production window will lengthen with rising minimum temperatures, while the Lockyer Valley's season will shorten as late spring maximums continue to rise and early autumn temperatures remain high for longer.

The Representative Concentration Pathways scenario RCP8.5 (Schwalm, et al., 2020), has been chosen in this study to represent a future climate (2016-45), in an effort to understand the impacts on each of the current lettuce production locations.

[7] http://www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

a) Lockyer Valley (Gatton)

Projected future (2016-45) and current climate data for Gatton.

Annual average Tmax	Annual average Tmin	Annual heat risk	Annual frost risk
Annual °C	Annual °C	Annual days Tmax ≥ 35°C Edit	Annual days Tmin ≤ 2°C Edit
1961 - 1990 Past average **26.5**	1961 - 1990 Past average **12.9**	1961 - 1990 Past average **11.4**	1961 - 1990 Past average **8.5**
1991 - 2020 Recent average **27.3**	1991 - 2020 Recent average **13.2**	1991 - 2020 Recent average **20.2**	1991 - 2020 Recent average **7.7**
High emissions 2016 - 2045 Future average **28.2** 27.8 - 28.4	High emissions 2016 - 2045 Future average **14.2** 14.0 - 14.6	High emissions 2016 - 2045 Future average **26.9** 23.9 - 30.2	High emissions 2016 - 2045 Future average **3.9** 2.4 - 5.1
View charts →	View charts →	View charts →	View charts →

Figure 8. Projected future temperature outlook for Gatton under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020). The graphic uses 1991 – 2020 for comparison of the 2016 to 2045 average temperature shift.

The high emissions pathway model indicates a temperature shift, showing a 1.7°C increase in maximum temperatures and a 1.3°C increase in minimum temperatures by 2045. Importantly the annual heat risk, when the maximum temperature at Gatton exceeds 35°C, increases from 11 to 27 days (Figure 8).

Projected annual crop specific upper CTT heat risk shift (1961 – 90 baseline period).

Year Range	Number of years with annual heat risk below 37 (days Tmax ≥ 32°C)	Number of years with annual heat risk above 87 (days Tmax ≥ 32°C)
1961-1990	2.3 in 10 years	0 in 10 years
1991-2020	1 in 10 years	1 in 10 years
2016-2045	0 in 10 years	4.3 in 10 years

** This chart shows the average number of years out of 10 and the number of days in those years that **the crop specific upper CTT** has or is projected to occur. The default annual heat risk days (below and above columns) shown for this location and crop, are the 10th percentile (left column) and 90th percentile (right column) of the observed 1991-2020 and projected 2016-2045 values.*

Figure 9. Cauliflower specific, upper CTT heat risk shift comparison table for Gatton.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

 Note graphs are best viewed at >140 magnification

Figure 9 above shows that by 2045, 43% of years (4.3 in 10) will have at least 87 days when the maximum temperature equals or exceeds cauliflowers upper CTT. This only occurred in 10% of years (1 in 10) during the 1991-2020 period, a significant shift.

Future temperatures at Gatton and the impact on the timing and occurrence of cauliflower critical temperature thresholds (CCT).

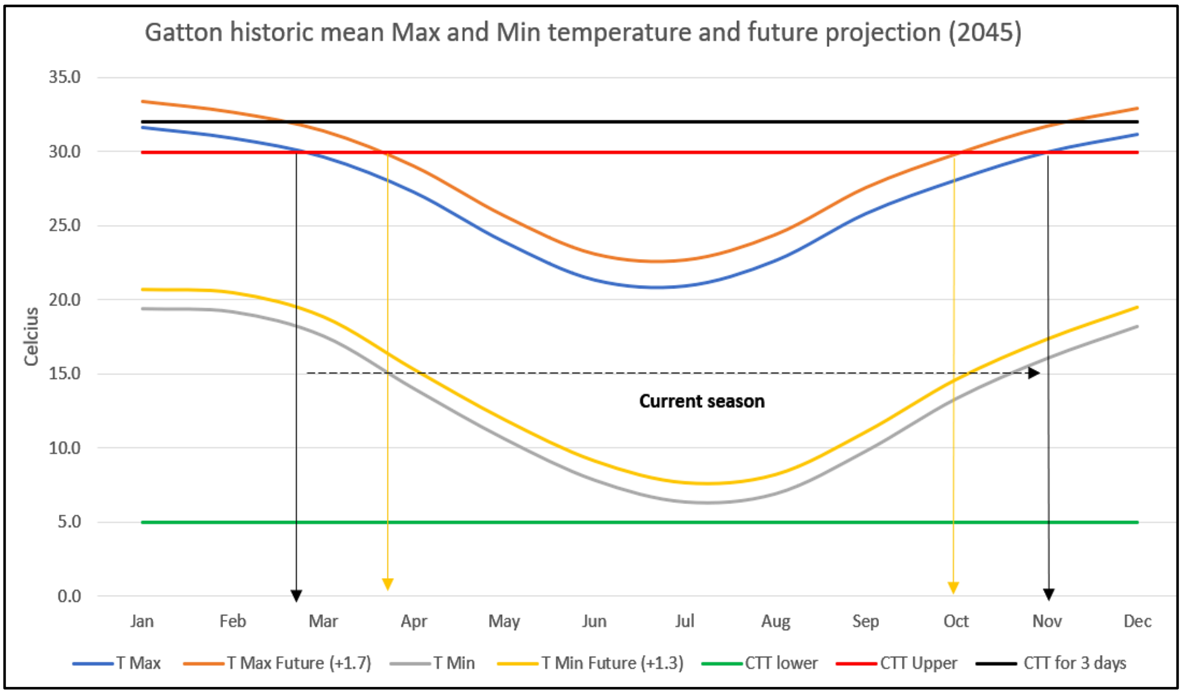


Figure 10. Current mean monthly temperatures at Gatton, cauliflowers upper CTT (32º C) & the impact of the projected future annual temperature shifts on the optimum growing season.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

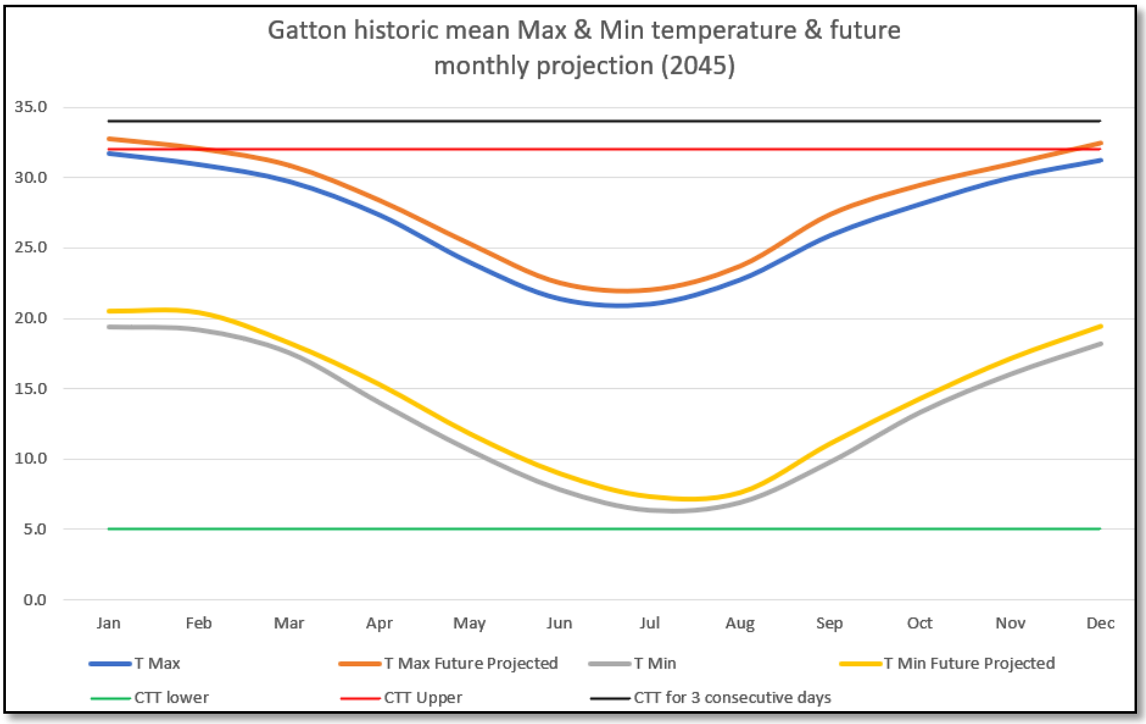


Figure 11. above displays the mean monthly temperatures at Gatton, & the projected future mean monthly temperature shifts (2016-2045) at Gatton. The monthly future climate data displayed here is not publicly available but displays the individual monthly changes that underpin the projected annual changes in both maximum and minimum temperatures. The monthly projected change data has been included here, so the reader can appreciate and better understand the actual monthly changes that underpin the publicly available projected annual changes (2016-45).

Maximum temperatures currently prevent cauliflower production in the Lockyer Valley during the late spring, summer and early autumn period. Higher daily maximum temperatures in the Lockyer Valley will result in a further shortening of the cauliflower production window. Currently average monthly maximum temperatures allow transplanting to begin in late February or early March, with final harvest occurring in early November.

Figure 10 above shows how and why this shift will shorten the Lockyer Valley growing season. Cauliflower plants will experience maximum temperatures that exceed their CCT, both earlier and later in the calendar year. Transplanting of the first crops could be delayed by around 3 weeks (mid-March) with last harvests brought forward by almost a month, from the beginning of November back to the beginning of October. This would be a 7-week reduction in the Lockyer Valley's (historical) cauliflower growing season.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

 Note graphs are best viewed at >140 magnification

Figure 8 & Figure 10 above, show that minimum temperatures currently have no negative impact on cauliflower production timing or curd quality in the Lockyer Valley production season. The projected warmer minimums would increase plant growth rates and shorten the time between planting and harvest.

Maximum temperature is the critical weather factor that dictates the cauliflower production window in the Lockyer Valley. Increases in maximum temperatures in early autumn will delay the start of the growing season and their quicker ramping up in early spring will quickly curtail the end of the season (Figure 10).

The monthly projected change data (Figure 11) has been included here, so the reader can appreciate and better understand the actual monthly changes that underpin the publicly available projected annual changes (2016-45).

b) Granite Belt, Stanthorpe (Applethorpe)

Projected future (2016-45) and current climate data for Applethorpe

Data source: Climate Services for agriculture site: https://myclimateview.com.au/

Annual average Tmax	Annual average Tmin	Annual heat risk	Annual frost risk
Annual	Annual	Annual	Annual
°C	°C	days Tmax ≥ 35°C	days Tmin ≤ 2°C
		Edit	Edit
1961 - 1990 Past average **20.3**	1961 - 1990 Past average **8.8**	1961 - 1990 Past average **0.5**	1961 - 1990 Past average **57.2**
1991 - 2020 Recent average **21.2**	1991 - 2020 Recent average **9.1**	1991 - 2020 Recent average **1.2**	1991 - 2020 Recent average **53.3**
High emissions 2016 - 2045 Future average **22.1** 21.7 - 22.4	High emissions 2016 - 2045 Future average **10.1** 9.9 - 10.5	High emissions 2016 - 2045 Future average **1.8** 1.4 - 2.4	High emissions 2016 - 2045 Future average **39.7** 34.9 - 43.9
View charts →	View charts →	View charts →	View charts →

Figure 12. Projected future temperature outlook for Applethorpe under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020). The graphic uses 1991 – 2020 for comparison of the 2016 to 2045 average temperature shift.

The high emissions pathway model indicates a temperature shift, showing a 1.8°C increase in average monthly maximum temperatures and a 1.3°C increase in average monthly minimum temperatures by 2045. The annual heat risk at Applethorpe increases from 0.5 days to 1.8 days ≥ 35° C. A decrease in annual frost risk from 57 to 40 days is expected (Figure 12).

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Projected annual crop specific upper CTT heat risk shift (1961 – 90 baseline period).

Year Range	Number of years with annual heat risk below 1 (days Tmax ≥ 32°C)	Number of years with annual heat risk above 18 (days Tmax ≥ 32°C)
1961-1990	2.7 in 10 years	0 in 10 years
1991-2020	1 in 10 years	1 in 10 years
2016-2045	0.2 in 10 years	1.8 in 10 years

***** *This chart shows the average number of years out of 10 and the number of days in those years that the crop specific upper CTT has or is projected to occur. The default annual heat risk days (below and above columns) shown for this location and crop, are the 10th percentile (left column) and 90th percentile (right column) of the observed 1991-2020 and projected 2016-2045 values*

Figure 13. Cauliflower specific, upper CTT heat risk shift comparison table for Applethorpe.

Data source: Climate Services for agriculture site:https://myclimateview.com.au/

Figure 9 & Figure 13 above shows that by 2045, 18% of years (1.8 in 10) will have at least 18 days when the maximum temperature equals or exceeds cauliflowers upper CTT. This only occurred in 10% of years (1 in 10) during the 1991-2020 period.

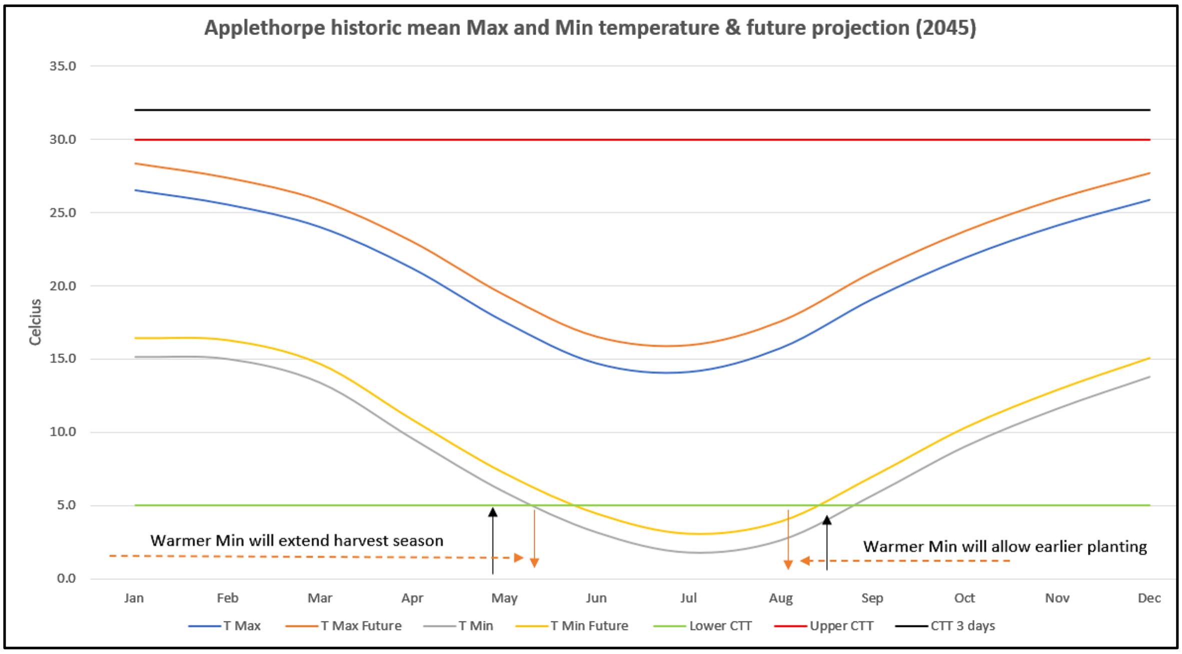


Figure 14. Current mean monthly temperatures at Applethorpe, cauliflowers lower CTT (5 C) & the impact of future projected annual temperatures on the optimum growing seasons.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

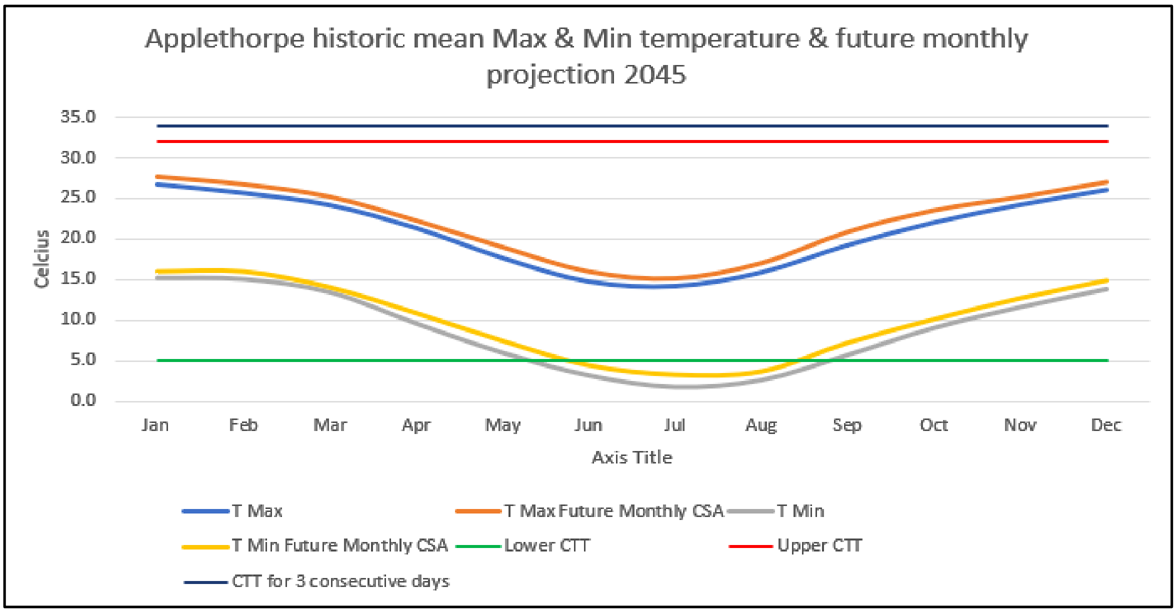


Figure 15. above displays the mean monthly temperatures at Applethorpe, & the projected future mean monthly temperature shifts (2016-2045) at Applethorpe. The monthly future climate data displayed here is not publicly available but displays the individual monthly changes that underpin the projected annual changes in both maximum and minimum temperatures. The monthly projected change data has been included here, so the reader can appreciate and better understand the actual monthly changes that underpin the publicly available projected annual changes (2016-45).

Minimum temperatures currently prevent cauliflower production in the Granite Belt during the late autumn and colder winter period. The forecast increase in average monthly minimum temperatures in the Granite Belt as detailed above (2016-45) will allow an extension of the existing cauliflower production window. Currently average monthly minimum temperatures fall below cauliflowers lower CTT in May and stay below the CTT until September.

Figure 14 above shows how this minimum temperature shift will lengthen the Granite Belt growing season. Cauliflower plants will not experience minimum temperatures that are below their lower CCT until later in the autumn. This minimum CTT period that currently prevents quality cauliflower production will also be shortened further by a warmer spring. Transplanting of the first crops could be brought forward by several weeks, with last harvests also extended later into the autumn.

Maximum temperatures will also increase as shown in Figure 12, 13 &14 above, however, annual maximum monthly temperatures will remain well below 32^{o}C, cauliflowers upper CTT. Changes in annual monthly maximum temperature will not limit curd quality or alter the production window in the Granite Belt.

Minimum temperature is the critical weather factor that will continue to dictate the cauliflower production window in the Granite Belt.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Forecast increases in minimum temperatures will allow growers to transplant earlier in the spring and also harvest later in the autumn. This should result in a 3-to-4-week extension of the Granite Belts' (historical) cauliflower growing season, enhancing product availability and quality.

The monthly projected temperature change data (Figure 15) has been included here, so the reader can appreciate and better understand the actual monthly changes that underpin the publicly available projected annual changes (2016-45).

Interstate production – future insights.

Future climate data analysis for all locations (2016-2045) is based on current projections sourced from Australias, **Climate Services for Agriculture** site: now called My Climate View

ii) New South Wales (Bathurst)

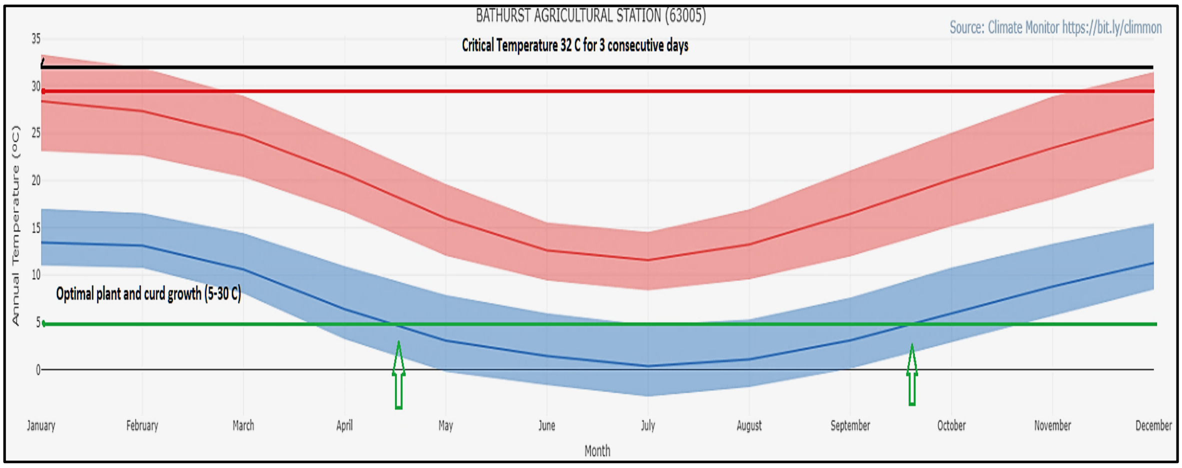


Figure 16. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with cauliflower critical temperatures – overlaid, at Bathurst. Note: The graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

Commercial Australian seed catalogues (e.g., Terranova Seeds)[8], indicate that by using modern varieties in the Bathurst district, cauliflower crops are transplanted from October onward with last harvest occurring in May. The Critical Temperature Threshold analysis above indicates that from October until May optimal plant and curd growth temperature criteria are met, though in some years January maximum temperatures exceed the upper CTT. Minimum temperatures from early April until mid-September are below cauliflower CTT causing production to cease as both curd quality and plant growth rapidly decline.

---

[8] https://terranovaseeds.com.au/wp-content/uploads/2021/05/Cauliflower_Planting_Guide_April_2021.pdf

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Projected future (2016-45) and current climate data for Bathurst.

Table 1. Projected future temperature comparison for Bathurst under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020).

Time Period	Annual Average T Max ^{0}C	Annual Average T Min^{0}C	Annual Heat Risk Days T Max ≥ 35^{0}C	Annual Frost Risk Days ≤ 2^{0}C
1961-1990 Past Average	20.3	6.7	4	89.8
1991 -2020 Recent Average	21.2	6.9	8.7	87.7
2016-45 High Emissions Future Average	22.0	7.9	11.5	67

The high emissions pathway model indicates a temperature shift, showing a 1.7^{o}C increase in maximum temperatures and a 1.2^{o}C increase in minimum temperatures by 2045. Importantly the number of days when the maximum temperature in Bathurst exceeds 35^{o}C increases from 4 to 11 (Table 1).

Projected annual crop specific upper CTT heat risk shift (1961 – 90 baseline period).

Year Range	Number of years with annual heat risk below 12 (days Tmax ≥ 32°C)	Number of years with annual heat risk above 40 (days Tmax ≥ 32°C)
1961-1990	3.7 in 10 years	0.3 in 10 years
1991-2020	1 in 10 years	1 in 10 years
2016-2045	0.7 in 10 years	2.8 in 10 years

** This chart shows the average number of years out of 10 and the number of days in those years that the crop specific upper CTT has or is projected to occur. The default annual heat risk days (below and above columns) shown for this location and crop, are the 10th percentile (left column) and 90th percentile (right column) of the observed 1991-2020 and projected 2016-2045 values*

Figure 17. Cauliflower specific, upper CTT heat risk shift comparison table for Bathurst.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Figure 17 above shows that by 2045, 28% of years (2.8 in 10) will have at least 40 days when the maximum temperature equals or exceeds cauliflowers upper CTT. This only occurred in 10% of years (1 in 10) during the 1991-2020 period.

iii) Victoria (Bairnsdale)

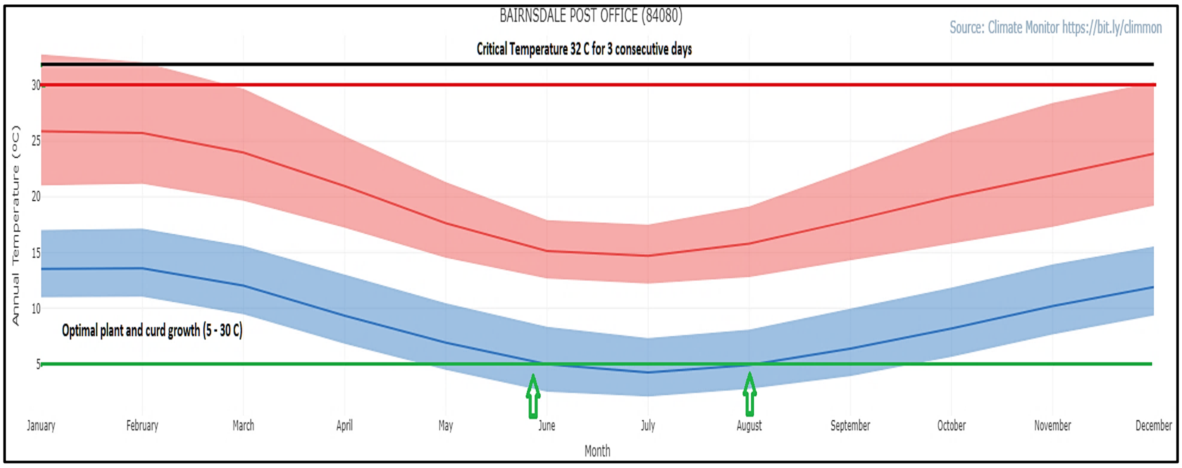


Figure 18. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with cauliflower critical temperatures – overlaid, at Bairnsdale. Note: The graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

Minimum temperatures limit cauliflower production at this location. Minimum temperatures from June until mid-September limit crop growth and development. While year-round production is possible, winter varieties transplanted in early July will not harvest until early November.

While cauliflower harvesting can occur in all months in **East Gippsland**, growth rate and quality drops off significantly in the middle of winter, due to low temperature effects on quality.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Projected future (2016-45) and current climate data for ***Bairnsdale***

Table 2. Projected future temperature comparison for Bairnsdale under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020)

Time Period	Annual Average T Max ^{0}C	Annual Average T Min^{0}C	Annual Heat Risk Days T Max ≥ 35^{0}C	Annual Frost Risk Days ≤ 2^{0}C
1961-1990 Past Average	20.3	8.8	5.1	20.3
1991 -2020 Recent Average	20.7	9.5	7.3	6.6
2016-45 High Emissions Future Average	21.4	10.2	8.5	5.7

The high emissions pathway model indicates a temperature shift, showing a 1.1°C increase in maximum temperatures and a 1.4°C increase in minimum temperatures by 2045. Importantly the number of days when the maximum temperature in Bathurst exceeds 35°C increases from 5 to 8 (Table 2).

Projected annual crop specific upper CTT heat risk shift (1961 – 90 baseline period).

Year Range	Number of years with annual heat risk below 9 (days Tmax ≥ 32°C)	Number of years with annual heat risk above 21 (days Tmax ≥ 32°C)
1961-1990	2.3 in 10 years	0 in 10 years
1991-2020	1 in 10 years	1 in 10 years
2016-2045	0.8 in 10 years	2 in 10 years

** This chart shows the average number of years out of 10 and the number of days in those years that the crop specific upper CTT has or is projected to occur. The default annual heat risk days (below and above columns) shown for this location and crop, are the 10th percentile (left column) and 90th percentile (right column) of the observed 1991-2020 and projected 2016-2045 values*

Figure 19 Cauliflower specific, upper CTT heat risk shift comparison table for Bairnsdale.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Figure 19 above shows that by 2045, 20% of years (2 in 10) will have at least 21 days when the maximum temperature equals or exceeds cauliflowers upper CTT. This only occurred in 10% of years (1 in 10) during the 1991-2020 period.

iv) Tasmania (Devonport)

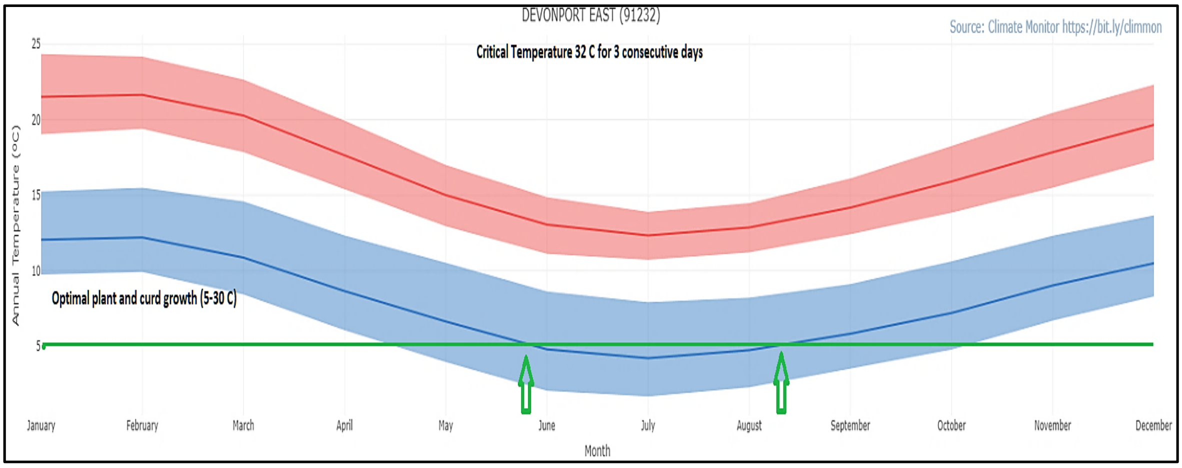


Figure 20. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with cauliflower critical temperatures – overlaid, at Devonport. Note: The graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

Maximum and minimum temperatures from early September until late March are adequate for Cauliflower production with growth rates slowing as winter approaches. Tasmania growers use robust cool weather varieties with the main harvest season being January to June. Minimum temperatures from June until mid-September limit crop growth and development. Cauliflowers upper CTT (32°C) rarely occurs in Tasmanian summers.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Projected future (2016-45) and current climate data for Devonport.

Table 3. Projected future temperature comparison for Devonport under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020)

Time Period	Annual Average T Max ^{0}C	Annual Average T Min^{0}C	Annual Heat Risk Days T Max ≥ 35^{0}C	Annual Frost Risk Days ≤ 2^{0}C
1961-1990 Past Average	17	7.8	0	29.5
1991 -2020 Recent Average	17.4	8.3	0	20.7
2016-45 High Emissions Future Average	18.1	9.0	0	13

The high emissions pathway model indicates a temperature shift, showing a 1.1°C increase in maximum temperatures and a 1.2°C increase in minimum temperatures by 2045. Importantly the number of frost days at Devonport will decrease from 29 to 13, a significant decrease (Table 3).

Projected annual crop specific upper CTT heat risk shift (1961 – 90 baseline period).

Year Range	Number of years with annual heat risk below 0 (days Tmax ≥ 32°C)	Number of years with annual heat risk above 2 (days Tmax ≥ 32°C)
1961-1990	0 in 10 years	0 in 10 years
1991-2020	0 in 10 years	0 in 10 years
2016-2045	0 in 10 years	0.1 in 10 years

** This chart shows the average number of years out of 10 and the number of days in those years that the crop specific upper CTT has or is projected to occur. The default annual heat risk days (below and above columns) shown for this location and crop, are the 10th percentile (left column) and 90th percentile (right column) of the observed 1991-2020 and projected 2016-2045 values*

Figure 21. Cauliflower specific, upper CTT heat risk shift comparison table for Devonport.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Figure 21 above shows that by 2045, only 1% of years (0.1 in 10) will have at least 2 days when the maximum temperature equals or exceeds cauliflowers upper CTT. Minimum temperatures determine and limit the cauliflower season in Devonport.

v) South Australia (Virginia)

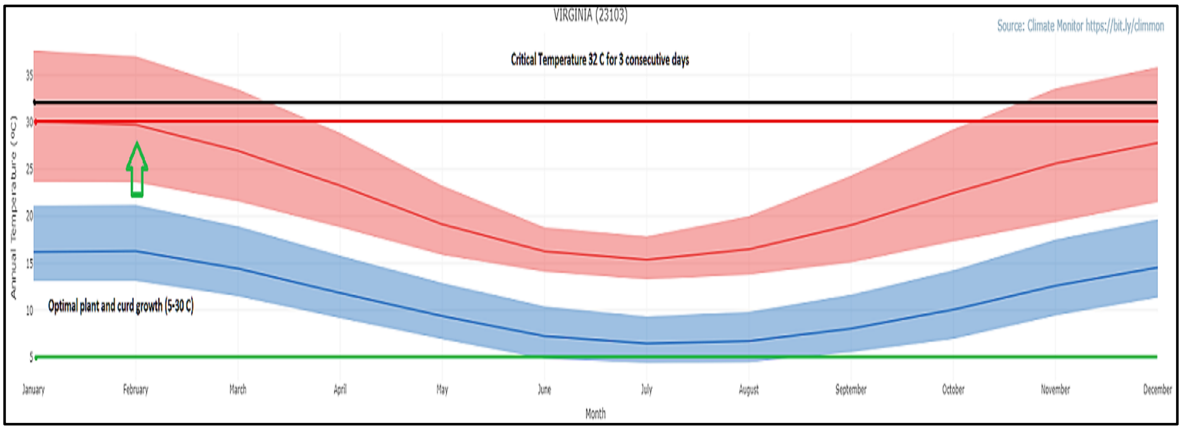


Figure 22. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with cauliflower critical temperatures – overlaid, at Virginia. Note: The graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

The Critical Temperature Threshold analysis for the Virginia production area indicates that currently mean maximum temperatures in January exceeds 30°C, 50% of the time Figure 22. The quality of maturing cauliflowers during January, as well as November and December will be compromised in many years. Maximum temperatures of over 35°C are common in January and it is not until March that the maximum temperature in the majority of years drops below the upper CTT and closer to the optimal plant and curd growth temperature range. To maximise quality, transplanting begins in February with last harvest in mid-November. Minimum temperatures from May until mid-September limit crop growth and development.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Projected future (2016-45) and current climate data for Virginia.

Table 4. Projected future temperature comparison for Virginia under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020).

Time Period	Annual Average T Max °C	Annual Average T Min°C	Annual Heat Risk Days T Max ≥ 35°C	Annual Frost Risk Days ≤ 2°C
1961-1990 Past Average	22.4	11.2	21.1	2.3
1991 -2020 Recent Average	23	11.5	25.4	1.9
2016-45 High Emissions Future Average	23.8	12.3	29.9	0.8

The high emissions pathway model indicates a temperature shift, showing a 1.4°C increase in maximum temperatures and a 1.1°C increase in minimum temperatures by 2045. Importantly the number of days when the maximum temperature in Virginia exceeds 35°C increases from 21 to 30 (Table 4).

Projected annual crop specific upper CTT heat risk shift (1961 – 90 baseline period).

Year Range	Number of years with annual heat risk below 37 (days Tmax ≥ 32°C)	Number of years with annual heat risk above 59 (days Tmax ≥ 32°C)
1961-1990	3.7 in 10 years	0 in 10 years
1991-2020	1 in 10 years	0.7 in 10 years
2016-2045	0.3 in 10 years	1.8 in 10 years

** This chart shows the average number of years out of 10 and the number of days in those years that the crop specific upper CTT has or is projected to occur. The default annual heat risk days (below and above columns) shown for this location and crop, are the 10th percentile (left column) and 90th percentile (right column) of the observed 1991-2020 and projected 2016-2045 values*

Figure 23. Cauliflower specific, upper CTT heat risk shift comparison table for Virginia.

Figure 23 shows that by 2045, only 18% of years (1.8 in 10) will have at least 59 days when the maximum temperature equals or exceeds cauliflowers upper CTT. This only occurred in 7% of years in the 1990-2021 period.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

vi) Western Australia (Gingin)

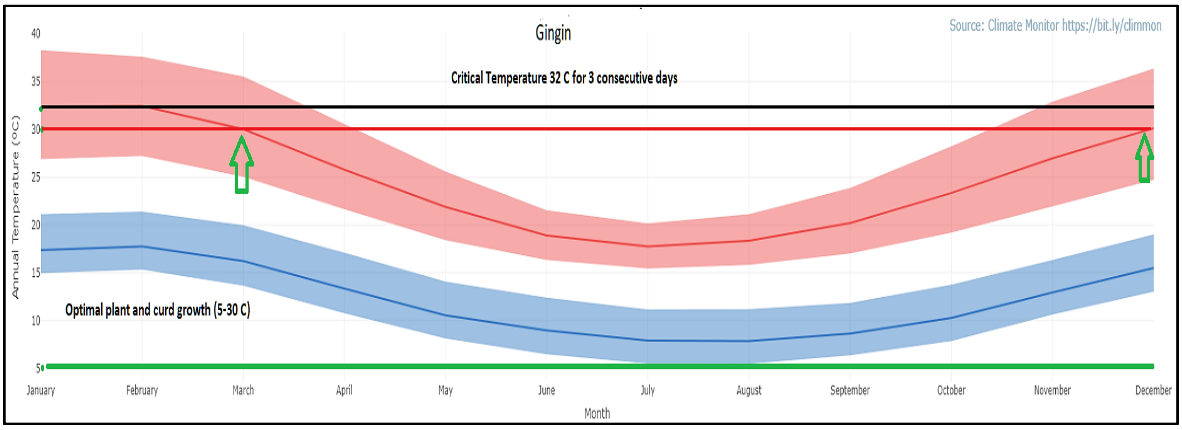


Figure 24. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with cauliflower critical temperatures – overlaid, at Gingin. Note: The graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

The Critical Temperature Threshold analysis for the Gingin production area indicates that currently mean maximum temperatures in January and February greatly exceeds 32°C in most years, and it is not until early March that daily maximum temperatures drop below the maximum CTT of cauliflower in 50% of past years. The minimum threshold (5°C) for cauliflower production is not limiting at this location.

Future maximum temperature increases will further reduce the growing window for cauliflower at Gingin. Increased summer maximum temperatures will further shorten the local production season.

Projected future (2016-45) and current climate data for Gingin.

Table 5. Projected future temperature outlook for Gingin under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020).

Time Period	Annual Average T Max °C	Annual Average T Min°C	Annual Heat Risk Days T Max ≥ 35°C	Annual Frost Risk Days ≤ 2°C
1961-1990 Past Average	24.5	12.5	26.5	0.7
1991-2020 Recent Average	25.2	12.7	30.1	1.4
2016-45 High Emissions Future Average	25.8	13.4	35.7	0.7

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from [Climate Monitor](), a free, publicly available DCAP web-tool.

The high emissions pathway model indicates a temperature shift, showing a 1.3ºC increase in maximum temperatures and a 0.9ºC increase in minimum temperatures by 2045. Importantly the number of days when the maximum temperature in Virginia exceeds 35ºC increases from 26 to 35 (Table 5).

Projected annual crop specific upper CTT heat risk shift (1961 – 90 baseline period).

Year Range	Number of years with annual heat risk below 47 (days Tmax ≥ 32°C)	Number of years with annual heat risk above 76 (days Tmax ≥ 32°C)
1961-1990	3.3 in 10 years	0 in 10 years
1991-2020	0.7 in 10 years	0.7 in 10 years
2016-2045	0.2 in 10 years	2.4 in 10 years

** This chart shows the average number of years out of 10 and the number of days in those years that <u>the crop specific upper CTT</u> has or is projected to occur. The default annual heat risk days (<u>below</u> and <u>above</u> columns) shown for this location and crop, are the 10th percentile (left column) and 90th percentile (right column) of the observed 1991-2020 and projected 2016-2045 values*

Figure 25. Cauliflower specific, upper CTT heat risk shift comparison table for Gingin.

Figure 25 above shows that by 2045, only 24% of years (2.4 in 10) will have at least 76 days when the maximum temperature <u>equals or exceeds cauliflowers upper CTT</u>. This only occurred in 7% of years (0.7 in 10) in the 1990-2021 period.

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Annual Heat and Frost Risk, by the year 2045, for cauliflower production at reviewed locations in Australia.

Growing Location	Current Max Temp °C	Projected Max temp change °C by 2045	Current Min Temp °C	Projected Min temp change °C by 2045	Current number of days ≥ 32° C	Projected number of days ≥32 ° C by 2045	Current number of frost days	Projected number of frost days by 2045
Gatton (Qld)	27.3	+0.9	13.2	+1.0	64	84	7	4
Applethorpe (Qld	21.2	+0.9	9.1	+1.0	9.5	11.5	53	40
Bathurst (NSW)	21.2	+0.8	6.9	+1.0	25.8	31.5	87.7	67
Bairnsdale (Vic)	20.7	+0.7	9.5	+0.7	15.5	18	6.6	5.7
Virginia (SA)	23.0	+0.8	11.5	+0.8	45.8	52.3	1.9	0.8
Gingin (WA)	25.2	+0.6	12.7	+0.7	62	68.3	1.4	0.7

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Do your own analysis.

If you are interested in other production locations within Australia, you can evaluate a location yourself.

1. Use Climate Monitor to easily analyse and graph the location of interest.

   Access Climate Monitor at

   https://www.longpaddock.qld.gov.au/dcap/horticulture-industry/

   Click on the **Go Climate Monitor** button under the picture.

2. Use the Climate Services for Agriculture site to explore the projected temperature, rainfall and evaporation changes**.**

   Access Climate Services for Agriculture at

   https://climateservicesforag.indraweb.io/

The projected future climate data used in this CTT document was sourced from the original (July - Nov 2022) Climate Services for Agriculture website (now My Climate View). The site has undergone several format and projected data period changes in the last 18 months. The data format available and used at the time of writing this CTT document are for the 2045 period.

The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Appendix I

https://www.climatechangeinaustralia.gov.au/en/changing-climate/future-climate-scenarios/greenhouse-gas-scenarios/

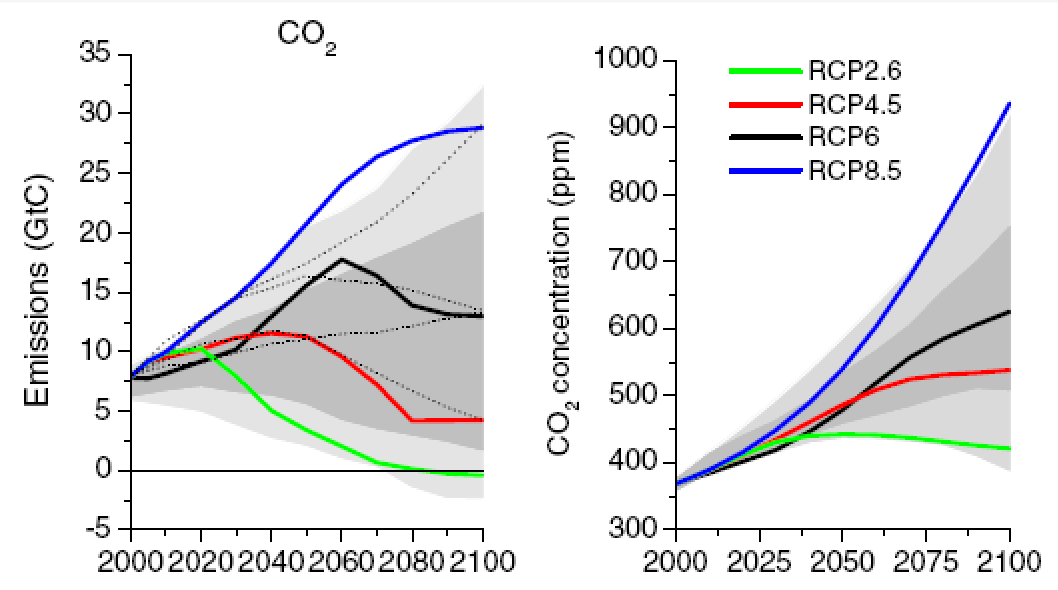
GREENHOUSE GAS SCENARIOS

(REPRESENTATIVE CONCENTRATION PATHWAYS - RCPS)

The future of anthropogenic greenhouse gas and aerosol emissions (and hence their resultant radiative forcing) is highly uncertain, encompassing substantial unknowns in population and economic growth, technological developments and transfer, and political and social changes.

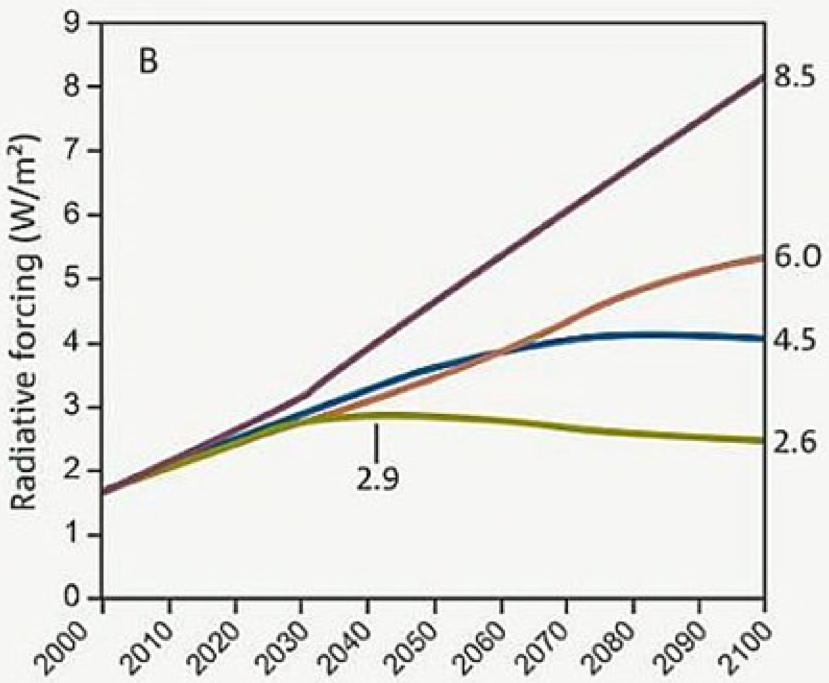
The climate modelling community has developed Representative Concentration Pathways (RCPs) to explore credible future options. The Australian climate change projections found on this site are derived from climate models forced by the RCPs.

These scenarios span the range of plausible global warming scenarios. They provide a range of options for the world's governments and other institutions for decision making.



Emissions of CO_2 across the RCPs (left), and trends in concentrations of carbon dioxide (right). Grey area indicates the 98th and 90th percentiles (light/dark grey) of the values from the literature). The dotted lines indicate four of the SRES marker scenarios.

SOURCE: van Vuuren et. al. (2011)



Radiative forcing for the different RCPs. The numbers on the right show the final radiative forcing at 2100 and give each scenario its name (8.5, 6.0, 4.5 and 2.6 W/m²)

SOURCE: Climate Change in Australia Technical Report

RCPs are prescribed pathways for greenhouse gas and aerosol concentrations, together with land use change, which are consistent with a set of broad climate outcomes used by the climate modelling community. The pathways are characterised by the radiative forcing produced by the end of the 21st century. Radiative forcing is the extra heat the lower atmosphere will retain as a result of additional greenhouse gases, measured in Watts per square metre (W/m²).

The RCPs represent a wider set of futures that the previous emissions scenarios used by climate modelling community (SRES), and now explicitly include the effect of mitigation strategies. As with SRES, no particular scenario is deemed more likely than the others, however, some require major and rapid change to emissions to be achieved.

THERE ARE FOUR RCPS

RCP8.5- a future with little curbing of emissions, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by 2100.

RCP6.0– lower emissions, achieved by application of some mitigation strategies and technologies. CO_2 concentration rising less rapidly (than RCP8.5), but still reaching 660 ppm by 2100 and total radiative forcing stabilising shortly after 2100.

RCP4.5- CO_2 concentrations are slightly above those of RCP6.0 until after mid-century, but emissions peak earlier (around 2040), and the CO_2 concentration reaches 540 ppm by 2100.

RCP2.6 - the most ambitious mitigation scenario, with emissions peaking early in the century (around 2020), then rapidly declining. Such a pathway would require early participation from all emitters, including developing countries, as well as the application of technologies for actively removing carbon dioxide from the atmosphere. The CO_2 concentration reaches 440 ppm by 2040 then slowly declines to 420 ppm by 2100).

References

Aleem, S., Sharif, I., Tahir, M., Najeebullah, M., Nawaz, A., Khan, M. I., & Arshad, W. (2021). Impact of heat stress on cauliflower (Brassica Oleracea var. Botrytis): A physiological assessment. Pakistan Journal of Agricultural Research, 34(3), 479-486.

Bhatia, R., Dey, S. S., Sood, S., Sharma, K., Sharma, V. K., Parkash, C., & Kumar, R. (2016). Optimizing protocol for efficient microspore embryogenesis and doubled haploid development in different maturity groups of cauliflower (B. oleracea var. botrytis L.) in India. *Euphytica*, *212*(3), 439-454.

Booij, R., & Struik, P. C. (1990). Effects of temperature on leaf and curd initiation in relation to juvenility of cauliflower. *Scientia Horticulturae*, *44*(3-4), 201-214.

Dey, S. S., Sharma, S. R., Parkash, C., Barwal, R. N., & Bhatia, R. (2011). Genetic Divergence in Snowball Cauliflower (Brassica oleracea var. botrytis L.). *Indian journal of plant genetic resources*.

Dept Env & Primary Industries Victoria, AG 0421 (Rev 2013) Web link: http://www.depi.vic.gov.au/agriculture-and-food/horticulture/vegetables/vegetables-a-z/cauliflowers

Dixon, G. R, (2006) Vegetable Brassicas and related crucifers (Vegetable brassicas and related crucifers | Crop Production Science in Horticulture (cabidigitallibrary.org)).

Fellows, J. R., Wurr, D. C. E., Phelps, K., & Reader, R. J. (1999). Initiation of early summer cauliflowers in response to temperature. *Journal of Horticultural Science and Biotechnology (United Kingdom)*.

Fritz, V. A., Rosen, C. J., Grabowski, M. A., Hutchison, W. D., Becker, R. L., Tong, C. B., ... & Nennich, T. T. (2009). Growing broccoli, cabbage and cauliflower in Minnesota. *University of Minnesota Extension Bulletin*, 1-15.

Grevsen, K., & Olesen, J. E. (1994). Modelling cauliflower development from transplanting to curd initiation. Journal of Horticultural Science (United Kingdom).

Grotjahn, R. (2021). Weather Extremes That Affect Various Agricultural Commodities. In: Extreme Events and Climate Change: A Multidisciplinary Approach, First Edition. Edited by Federico Castillo, Michael Wehner, and Dáithí A. Stone. John Wiley & Sons, Inc. Published 2021 by John Wiley & Sons, Inc.

Hand, D., & Atherton, J. (1987). Curd initiation in the cauliflower. I: Juvenility. Journal of experimental botany, 38(197), 2050-2058.

Hasanuzzaman M., Nahar K., and Fujita M. (2013). Extreme temperature responses, oxidative stress and antioxidant defense in plants. In: Vahdati K, Leslie C. (eds). Abiotic stress – plant responses and applications in agriculture. In Tech, Rijeka, pp 169–205. https://www.intechopen.com/chapters/43317

Kahn, B. A., Edelson, J., & Damicone, J. P. (2007). Cole crop production (Broccoli, Cabbage, and Cauliflower). Oklahoma Cooperative Extension Service.

Kahn, B. A., Cartwright, B. O., Motes, J. E., & Patterson, C. L. (1990). Cole crop production (broccoli, cabbage, and cauliflower). OSU extension facts-Cooperative Extension Service, Oklahoma State University (USA).

Kato, T., 1964. On the flower head formation and development of cauliflower plants. I. Ecological studies on the flower head formation and development. J. Jpn. Soc. Hortic. Sci., 33: 52-62.

Lin, C. Y., Chen, K. S., Chen, H. P., Lee, H. I., & Hsieh, C. H. (2019). Curd Initiation and Transformation in Tropical Cauliflower Cultivars under Different Temperature Treatments. HortScience.

Masarirambi, M. T., Oseni, T. O., Shongwe, V. D., & Mhazo, N. (2011). Physiological disorders of Brassicas/Cole crops found in Swaziland: A review. *AFRICAN JOURNAL OF PLANT SCIENCE*, (RESEARCH).

Norfadzilah, A. F., Suhana, O., Farahzety, A. M., Nur Adliza, B., Nur Syafini, G., & Rozlaily, Z. (2019). Growth and Inflorescence Development of Several Cauliflower (Brassica oleracea var. botrytis L.) Hybrids in Malaysian Environment. *TRANSACTIONS OF THE MALAYSIAN SOCIETY OF PLANT PHYSIOLOGY*, 109.

Olesen, J. E., & Grevsen, K. (2000). A simulation model of climate effects on plant productivity and variability in cauliflower (Brassica oleracea L. botrytis). Scientia Horticulturae, 83(2), 83-107.

Pearson, S., Hadley, P., & Wheldon, A. (1994). A model of the effects of temperature on the growth and development of cauliflower (Brassica oleracea L. botrytis). Scientia horticulturae, 59(2), 91-106.

Pierik, R. L. M. (1967). Regeneration, vernalization and flowering in Lunaria annua L. in vivo and in vitro. Wageningen University and Research.

Russo, V. M., Bruton, B. D., & Sams, C. E. (2010). Classification of temperature response in germination of Brassicas. *Industrial Crops and Products*, *31*(1), 48-51.

Salter, P.J., 1960. The growth and development of early summer cauliflower in relation to environmental factors. J. Hortic. Sci. 35, 21±33.

Schwalm, C. R., Glendon, S., & Duffy, P. B. (2020). RCP8. 5 tracks cumulative CO2 emissions. Proceedings of the National Academy of Sciences, 117(33), 19656-19657.

Singh, B. K., Bijendra, S., & Singh, P. M. (2018). Breeding cauliflower: a review. International Journal of Vegetable Science, 24(1), 58-84.

Swarup, V., & Chatterjee, S. S. (1999). Origin and genetic improvement of Indian cauliflower. *Asian Agri-History (India)*.

Warland, J., McKeown, A. W., & McDonald, M. R. (2006). Impact of high air temperatures on Brassicacae crops in southern Ontario.

Weibe, H. J. (1975). The morphological development of cauliflower and broccoli cultivars depend on temperature. *Sci. Hort*, *3*(95), 101.

Wellensiek, S. J. (2019). Lunaria Annua: En. Dollar Plant, Honesty, Money plant; Fr. Lunaire, Médaille de Judas; Monnaie du pape; Ge. Mondviole, Stumpfes Silberblatt. In CRC Handbook of Flowering (pp. 324-329). CRC Press.

Wellensiek, S.J. and Higazy, M.K., 1961. The juvenile phase for flowering in *Lunaria biennis.*

Proc. K. Ned. Akad. Wet. Ser. C, 64: 458-463.

Wurr, D.C.E., Fellows, J.R., Hiron, R.W.P., 1990. The effect of field environmental conditions on the growth and development of four cauliflower cultivars. J. Horticulture. Sci. 65, 565±572.

Wurr, D., Fellows, J., Phelps, K., & Reader, R. (1993). Vernalization in Summer/Autumn Cauliflower (Brassica oleracea var. botrytis L.). *Journal of Experimental Botany*, 1507-1514.

Wurr, D. C. E., Fellows, J. R., & Fuller, M. P. (2004). Simulated effects of climate change on the production pattern of winter cauliflower in the UK. *Scientia horticulturae*, *101*(4), 359-372.