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

Drought and Climate Adaptation Program

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

Chinese cabbage **(***Brassica campestris ssp. pekinensis***)** is a popular vegetable native to East Asia (Li, 1981). Chinese cabbage originated in China, with the earliest records occurring in the fifth century Chinese literature (Larkcom,1991). It is not a true cabbage and is actually part of the mustard group within the family Brassicaceae. Mature heads have more than 50 leaves, are oblong in shape and less tightly packed than cabbages. The broad outer leaves are pale green, with wide broad white midribs, while the overlapping inner leaves are a whitish green. The youngest innermost leaves are often a very pale-yellow green (Figure 3). Chinese cabbage is a very popular vegetable in China, and a primary vegetable crop in Japan and in Korea where it is a major ingredient of Kimchi, one of the nation's most popular foods (Lee et al., 2020).

Over the last 15 - 20 years Chinese cabbage has become more popular in Europe, America and Australia. In Australia, large-scale commercial production began in the late 80's and occurs mainly in Western Australia, New South Wales, Queensland and Victoria with a few isolated crops grown Tasmania, South Australia and the Northern Territory. A biennial or annual, cool season brassica, it is grown as an annual for the fresh market in Australia (Daly & Tompkins,1997).

Head size, shape and colour vary depending on the cultivar, from the short 'barrel' or wong bok types preferred by the domestic market, to the long slender 'rocket' or michihili types, mainly grown for the export market. External leaf colours range from dark to pale green,

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with inner leaves being paler, often with a yellowish tinge. Outer leaves of mature Chinese cabbages are closely wrapped, over the top of the dense inner heart of paler leaves (Daly & Tompkins,1997). Often called Wombok in Australia the Wong bok types are usually ready for harvest at around eight weeks after transplanting, in ideal growing conditions.

In Australia, Chinese cabbage is mostly eaten fresh, though can be steamed, or stir-fried. Pickled Chinese cabbage (Kimchi) is very common overseas, especially in South Korea and is gaining popularity in Australia.

The quality and size of mature Chinese cabbages is strongly influenced by temperature and climatic conditions as explained and documented by Soonja et al., 2014, Moon et al., 2015, and Sim et al.,2021, and many other researchers. Research experiments by Han et al.,2018, measured and documented the head size and yield reduction, caused by high temperatures (37 °C & 30 °C day/night temperatures) for 3, 6 and 9 days respectively compared to plants grown at 25 °C / 18 °C. Daly & Tomkins (1997) state that Chinese cabbage cultivars vary in temperature requirements. Many cultivars require temperatures in the range 13- 20 °C, with cultivars that are prone to bolting, requiring warmer growing conditions according to Larkcom (1991).

These Australian researchers go on to state that crops grown in colder periods should be protected from low temperatures and cold winds, which increase the likelihood of bolting. Like other Brassicas, exposure to low temperatures, especially when plants are young induces flower stalk development or bolting (Heide, 1970; Guttormsen & Moe,1985). Lowering growing temperature from 20 to 10°C has been shown to promote flower stalk development in young plants of Chinese cabbage (Lorenz, 1946; Mero, 1984).

In 2021/22 Chinese cabbage was the most important and largest portion of Australia's Asian vegetable production category sold on the fresh market. Chinese cabbage accounted for 38% of leafy Asian vegetable sales (11, 228 Tonnes), with the brassica, leafy greens, Pak Choy and Bok Choy being the next most popular at 28% and 15% respectively.

The majority of Australia's fresh market Asian greens production, of which a large percentage is Chinese Cabbage, occurs in New South Wales (43%), with the States of Queensland (28%), and Victoria (24%) being the next largest producers. Western Australia, the Northern Territory, South Australia, and Tasmania grow 3%, 2%, <1% and <1% of the national crop respectively.

In Queensland, the Lockyer Valley, Darling Downs and Stanthorpe districts are the major production regions. In New South Wales, the Sydney Basin, Richmond and Windsor regions are major production locations, while in Victoria, the Werribee and Gippsland regions are central to production. The Adelaide plains production region is important in S.A, while in

W.A., Manjimup and Gingin are important. This geographic spread of production locations allows fresh Chinese cabbage to be available year-round within Australia[1].

Summary

Chinese cabbage has grown in popularity in Australia over the last 10 years and this has driven increased production. Chinese cabbage is mainly used in, stir fry's, can be boiled, eaten raw in salads or as part of a coleslaw or salted and fermented as the main ingredient in Kimchi.

Chinese cabbage cultivars vary in temperature requirements. Many cultivars require temperatures in the range 13-20^{0}C, with cultivars prone to bolting requiring warmer conditions (Larkcom, 1991). Chinese cabbage is very sensitive to bolting which is caused by low temperatures during early growth. Bolting occurs when the flower stalk elongates within the head and is most advanced when the flower stalk breaks through the top of the head (Figure 4) .

Chinese cabbage is an annual crop, usually transplanted in the field in most Australian production regions, though some direct seeding does occur. To ensure continual supply throughout the local growing season, producers' plant regularly, usually every week or ten days with individual plantings ready for harvest around 9 weeks later.

Most vegetable crops including Chinese cabbage are adapted to a modest range of temperatures, with the optimum varying considerably for warm and cool season varieties. Many researchers including Fordham, (1989) have outlined how plant breeders have identified natural variation in Chinese cabbage cultivars grown under different temperatures. Opena & Ho (1979) and Guttormsen & Moe (1985) conducted extensive research and demonstrated the effect of temperature on the yield potential of a diverse range of Chinese cabbage cultivars. These authors also highlighted the importance of on-going breeding in order to improve crop yield and marketability in warmer seasons and climates.

Wong bok has an oblong head with wide flat leaves, similar in head shape to a Cos lettuce. Chinese cabbages have more thin, delicate and textured leaves than the waxy leaves of round-headed cabbage, so this important brassica vegetable is more delicate in both look and taste.

Chinese cabbage head quality is ultimately judged by consumers who "buy with their eyes", looking for firm, cabbage heads of uniform colour and shape with no leaf yellowing or blemishes.

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[1] https://www.horticulture.com.au/globalassets/hort-innovation/australian-horticulture-statistics-handbook/ahsh-2021-22-vegetables-r.pdf

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Chinese Cabbage Critical Temperature Thresholds.

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

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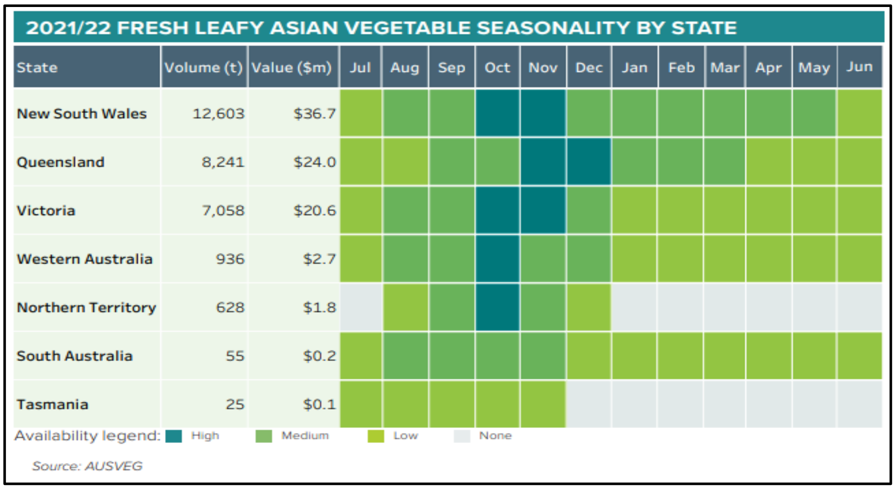


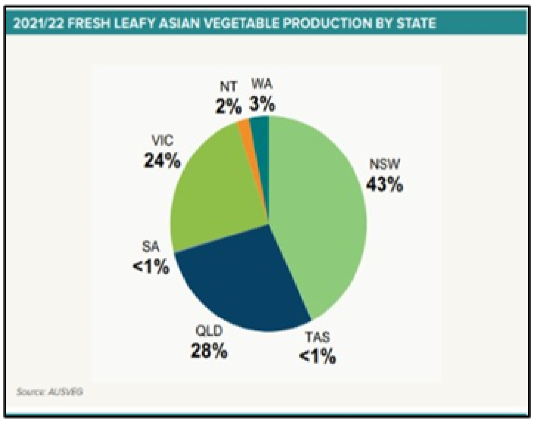
2021/22 FRESH LEAFY ASIAN VEGETABLE SEASONALITY BY STATE

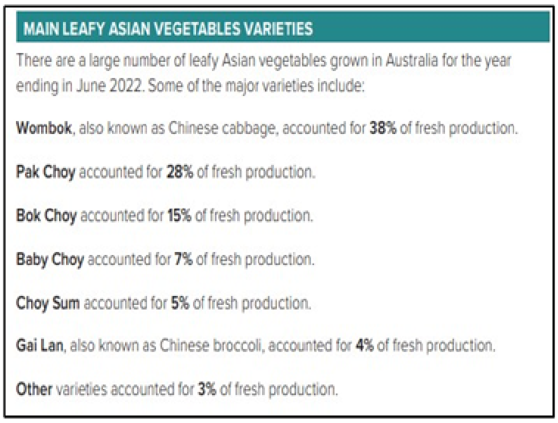
State	Volume (t)	Value ($m)	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
New South Wales	12,603	$36.7												
Queensland	8,241	$24.0												
Victoria	7,058	$20.6												
Western Australia	936	$2.7												
Northern Territory	628	$1.8												
South Australia	55	$0.2												
Tasmania	25	$0.1												

Availability legend: High Medium Low None

Source: AUSVEG

Figure 1. Australian Chinese cabbage availability by month and production volume in each state (2021-22)





MAIN LEAFY ASIAN VEGETABLES VARIETIES

There are a large number of leafy Asian vegetables grown in Australia for the year ending in June 2022. Some of the major varieties include:

Wombok, also known as Chinese cabbage, accounted for **38%** of fresh production.

Pak Choy accounted for **28%** of fresh production.

Bok Choy accounted for **15%** of fresh production.

Baby Choy accounted for **7%** of fresh production.

Choy Sum accounted for **5%** of fresh production.

Gai Lan, also known as Chinese broccoli, accounted for **4%** of fresh production.

Other varieties accounted for **3%** of fresh production.

Figure 2. Asian leafy vegetable production by state, and % of individual crop contribution including Chinese cabbage (38%). Image of, a Wong Bok (Napa) Chinese cabbage (left) and the taller Michihli type (right), grown for export.

Chinese cabbages which form a head can be classified as the short, wong bok or tall, michihili types, the latter specifically grown for the specialist Asian export market. Queensland and Western Australia supply 98% of the export volume. Australian exports have declined by around 80% since 203/4 due to overseas competition (Lee 2008).

Apart from physical differences, these two types generally differ in their growth rates, disease susceptibility and ease with which they can be grown in colder temperatures.

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 Note graphs are best viewed at >140 magnification

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

Critical Temperatures and Development Phases.

The development of the Chinese cabbage plant from transplanting to harvest can be divided into three phases: the seedling ,rosette and heading phase (head growth & filling), Yu et al., (2013). In the young seedling stage, plant leaves are round and flat with long petioles, but once the rosette stage is reached, new inner leaves are formed and expand rapidly on short petioles, growing more upright on the compressed plant stem (Opena et al., 1998; Sun et al., 2019).

In the head formation and filling stage, the inner rosette leaves begin to elongate and curve inward and upward. New leaves form and expand rapidly from the short internal stem and these elongated multi-leaf layers form dense leafy heads, that are firm to the touch when ready for harvest. A mature Chinese cabbage is relatively firm with wrinkled outer leaves and broad fleshy petioles (Sun et al., 2019).

Figure 3. External view of Chinese cabbage at left with broad fleshy mid-rib and wrinkly leaf tissue visible, while internal cross-section at right displays typical leaf tall folded dense leaf structure that forms the mature head.

Chinese cabbage is classified as a cool season plant and according to Opena and Ho (1979) requires optimum mean temperature of 15-16^{o}C to produce firm heads. Many researchers including, Kuo & Tsay (1981), Mero & Honma (1984) and Wie et al., (2020) identified significant differences in temperature tolerance amongst Chinese cabbage cultivars. Opena and Ho (1979) stated that even heat tolerant cultivars suffer poor yields when growing at mean temperatures above 25^{o}C. High temperatures also promote soft rot (*Erwinia cartovora* var *atroseptica,* Holland) which can decimate yield, especially when accompanied by periods of high humidity, Son (2015) & Lee (2016).

Oh et al.,(2015) state that the rate of photosynthesis in Chinese cabbage leaves decreases in air temperatures above 25^{o}C. Cool sunny days with day temperatures between 20^{o}C and 22^{o}C and night temperatures between 16^{o}C and 18^{o}C are considered optimal Chinese cabbage growing conditions, Opena(1979), Kato (1981),Oh (2015) and Lee(2015).

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Huang et al., (2020) determined that Chinese cabbage is particularly sensitive to weather stress, noting that essential plant hormones and minerals can be reduced by small amounts of low, temperature stress. High temperatures impact yield, as demonstrated by Lee et al., (2015) and Cho (2013) who found that, high-temperature stress decreases both plant growth, physiological activity and yield. Sim et al.,(2021) in their research paper, quote work by Huang et al., (2003), stating when Chinese cabbage is exposed to high temperatures, core breakdown, tip burn, and decreased yields can occur (Hwang et al., 2003).

Australian cultivar evaluation trials, of Chinese cabbage have involved selection for slow-bolting, late maturing cultivars in order to extend the growing season into cooler months and selection for tolerance to a range of disorders, such as gomasho, tipburn and bacterial soft rot according to an extensive Australian review by Daly & Tomkins (1997).

This review of Chinese cabbage production in Australia by Daly & Tomkins (1979) highlights that bolting (developing a seed head) will make cabbage heads unmarketable. Temperature is the dominant factor that promotes bolting. Consistent average growing temperatures greater than 15-18^{0}C are necessary to prevent bolting in the most cold tolerant cultivars, while even higher average temperatures are needed for cold sensitive lines. The colder the temperature, the less the exposure time required for the plant to start developing a flower stalk. Bolting is of practical importance when growing Chinese cabbage into or out of the colder months of the year. Day length also plays a minor role in triggering Chinese cabbage to bolt, though the relationship between plant size, and growing temperature is the major factor in Australia, where shorter days occur during the colder months. Daly & Tomkins (1997).

Cabbage growth phases.

Yu et al., in their 2013 research publication describe the growth phases of the Chinese cabbage plant from planting / transplanting to harvest in great detail. These authors carried out extensive plant physiology studies, investigating and mapping leaf genome coding, as well as leaf / plant hormone and nutrient levels. They determined that the development of the Chinese cabbage plant from transplanting to harvest can be divided into three growth phases: the seedling, the rosette, and the heading phase (head growth & filling). The time it takes to develop from one stage to another depends on a number of factors including, variety, weather (temperature, day length, rainfall etc), and crop management.

Most Australian producers use commercially grown transplants, and the seedlings are often grown in polyhouses or glasshouses for three to four weeks before transplanting in the field (McKay and Phillips, 1990).

Transplanting is initially more expensive than direct seeding, but cuts out 4 weeks of, "in-field time", results in more even plant spacing, and allows better control of plant growth and environmental factors, such as temperature, during early seedling growth. Direct seeding requires more seed, uses extra land, labour and irrigation, so, modern commercial growers usually transplant, often weekly.

Germination phase.

Once planted, Chinese cabbage seed germination is rapid, when soil temperatures (influenced by air temperature) are in the optimal range, it usually takes four to seven days from sowing to seedling emergence. Maynard, & Hochmuth, (2006) recommend germination tests for Chinese cabbage seed should be conducted at temperatures of 20 to 30°C. Hegarty (1975) determined that diurnally alternating temperatures increased the germination of cabbage seeds. Wagenvoort & Bierhuilzen (1977) investigated vegetable seed germination and determined that soil temperatures from 5 to 25°C resulted in acceptable germination of cabbage seed. This 5°C soil temperature minimum is also stated in the Ontario Ministry of Agriculture Food and Rural Affairs publication which outlines how to grow Chinese cabbage.
Online reference :https://www.omafra.gov.on.ca/CropOp/en/spec_veg/brassicas/chinc.html#)

Research work by Rodreguez et.al., (2015) concluded that the high temperature tolerant (more tropical) Chinese cabbage varieties exhibited poor seed germination at air temperatures below 12°C. Opena (1988), states that Chinese cabbage grows best under cool conditions and requires average temperatures of 22 °C for seedling emergence, while detailed research into Chinese cabbage plant health at a range of growing temperatures by Shim et al., (2018) concluded that the optimal air temperature to maximize glucosinolate content in the leaves of Chinese cabbage plants was around 28°C
Fang et al., (2004), state that the optimal temperature for cabbage seed is 18 to 25°C, at which, germination will occur in 2 – 3 days
The paper by Rodreguez et.al., (2015) states that at temperatures above 32 °C both seed germination and leaf expansion was dramatically compromised.

The optimal temperature for seed germination is > 18°C & < 28°C
The Critical Temperature Threshold for seed germination is > 12°C & < 31°C

Juvenile phase – critical temperatures.

Once germinated young Chinese cabbage seedlings enter the vegetative (juvenile) phase. Vegetative development is considered to begin at seed germination and continues through seedling growth (25-30 days, depending on the planting date), and into the rosette stage.

The rosette stage, is marked by the young plant beginning to form basal leaves that surround the plant stems, fully covering the ground, with newly formed leaf stems (petioles) and leaves beginning to turn upwards. This stage lasts around 10 days, and the end of the rosette stage, head formation begins. The head formation stage is marked by the leaves beginning to become more erect and starting to cup (Kato 1964a).
A recent Western Australian publication by Burt et al., (2006) states that Chinese cabbage prefers average temperatures of 18 to 22°C during early growth.

Temperature sensitivity can vary according to a plants stage of growth as detailed by Oh et al., (2014), who state that Chinese cabbages grow well at relatively high temperatures in the early growth stages until head formation. However, when head formation begins, the plants become susceptible to high temperatures, and soft rot

In their Specialty Crops publication, The Ontario Ministry of Agriculture Food and Rural Affairs states the optimum temperature range for Chinese cabbage production is 15-24°C.[2] Moe and Guttormsen (1985) determined that the critical temperature for beginning vernalisation and inducing bolting was below 12 °C. It should be noted however, that there is a complex relationship between the length of time the plant is exposed to an inducing temperature, plant age, variety and to a lesser daylength. Research by Elers (1982) and Guttormsen and Moe (1985a &b) have shown that low temperature is the main factor causing flower formation and premature bolting in Chinese cabbage.

Optimal temperature for vegetative growth is > 15°C & < 24°C
The Critical Temperature Threshold for vegetative growth is > 12°C & < 32°C

Head growth – critical temperatures.

Chinese cabbage (Wong Bok) grown for the Australian domestic market, form compact, broad to oblong heads, on average 20-35 cm long and 20-30 cm wide.

Head formation in Chinese cabbage usually begins when the plant has reached the eight to tenth leaf stage (Kato, 1981), with final head size related to, and dependant on, the size and leaf area of the wrapper leaves (Kato 1967). Opena et al.,(1988) were of the opinion, that in quick maturing Chinese cabbage varieties, heading began at the 12th to 13th leaf stage, while in late maturing varieties heading did not occur until the plant had developed the 24th or 25th leaf. This variation reflects the innate genetic differences that exist, and that have been utilized to breed and select improved cultivars.

Much of the varietal improvement has been influenced by, consumer preference, yield, growing techniques, cropping seasons, and pest incidence. Wantabe (1981) stated that over 300 commercial cultivars were available in Japan, alone.

To illustrate and quantify, just some of the benefits of these worldwide breeding efforts, Matsumura (1981) states that the yield of Chinese cabbage in Japan has doubled since 1960, because of breeding efforts and subsequent commercial sale of high yielding, uniform F1 hybrid cultivars.

Many researchers acknowledge the variation in the temperature tolerance of different Chinese cabbage cultivars, referring to these types being more heat tolerant, e.g., Opena

[2] https://www.omafra.gov.on.ca/CropOp/en/spec_veg/brassicas/chinc.html

and Lo (1979) & Park et al., (2013). Heat-tolerant Chinese cabbage varieties have been shown to have larger root systems than heat sensitive varieties (Kuo and Tsay 1981) and this may allow greater water uptake, enhancing leaf growth, so that head development can occur at high temperatures.

Chinese cabbage is very sensitive to bolting or flower stalk initiation, and this is primarily caused by cold temperatures during early plant growth and is the main limiting factor in growing Chinese cabbage into, or out of, winter in Australia. The use of bolting tolerant cultivars is essential to reduce significant yield loss in these plantings (Daly and Tomkins 1997). Generally, two weeks exposure to temperatures of 13 °C or lower induce bolting (Nakamura, 1976). The optimum mean temperature range for head formation in Chinese cabbage is 15° to 20 °C according to research by Opena and Lo (1979) While Guttormsen and Moe (1985 b), in their Norwegian protected cropping research determined that mean growing temperatures of 18°C - 21°C produced heads of good quality. These researchers also concluded that, for the one heat tolerant variety they included in their work, the optimal head development temperature was above 24°C.

"Bolting" the start of flower stalk development – an overview.
The physiological process (vernalisation) that occurs when Chinese cabbage switch from vegetative growth to reproductive growth, that is, internal seed stalk development and growth begin, is quite complex. After vernalisation plants have acquired the ability to flower but may require additional environmental cues, or weeks of growth to do so. Information and research presented by Phillips and Goldy (2020) identified that Chinese cabbage and a number of other Brassicas have a wide variation in juvenile periods and temperature thresholds that will cause them to bolt. Consistent temperatures in their vernalisation range for two to eight weeks causes faster flower head elongation. According to Phillips and Goldy (2020) early maturing Chinese cabbage can take as little as one week to become vernalised, though Elers and Weibe (1984) in their Chinese cabbage research determined that vernalization duration was lowest at 5 - 8 °C and that for slight vernalization one week was sufficient; but for complete vernalization about 3 weeks were needed. Importantly as detailed in the review by Phillips and Goldy (2020) temperatures above 16°C immediately after vernalisation will reverse or slow internal flower stalk elongation.

Phillips and Goldy (2020) state that Brassica bolting generally occurs later in the season after the plant is vernalized and is driven by stress. It is usually characterized by the plant racing through its head formation to immediately create flowers in response to hot temperatures.

Wiebe (1989) in his review of vernalisation of vegetable crops determined that the upper temperature margin for vernalization is found between 10° C and 14° C for most Brassica species. Feike et al., (2010) in their research, state they identified lower and upper optimum growth temperatures of 14 °C and 24°C respectively.

In their Western Australian Chinese cabbage growing guide, Burt et al., (2006) state that at temperatures above 25 to 30˚C, heads are softer and may have some bitterness, with more risk of diseases such as bacterial soft rot.

The optimal temperatures for head growth are > 14ºC & <24ºC.
The Critical Temperature Threshold for head growth is > 10ºC & < 30ºC

Figure 4. Poor quality Chinese cabbage head with internal seed stalk (bolting) at left, and non – heading, due to high temperature on right .

Future climate implications – crop performance and yield.

A range of commercial Chinese cabbage varieties are available to Australian growers. These varieties are grouped according to their suitability to a geographic production location and season.
The Australian climate is warming (reference below), meaning that some current Chinese cabbage varieties, production locations and production timeslots will change or may even become commercially non-viable due to a decline in marketable yield and / or a shortened production season. In cooler growing areas, warming minimum temperatures could allow earlier planting in spring and an extension of the current growing season later into autumn. In Queensland and Australia, the fresh, and food service industry is supplied year-round.

Growers in different areas produce in their "traditional" vegetable production season and locations. These geographically diverse production locations allow vegetable farmers to maximise crop quality and yield, throughout the year, by aligning the crops critical temperature thresholds with suitable local production time slots (windows). Producers choose the correct variety, or varieties for their production location, season, and local climate.
Increasing production costs (seed, fertilizer, fuel, packaging, labour, transport and electricity) mean that today's horticultural farming businesses, marketable yield must be maximised from every planting, if a farm is to remain viable.

The warming trend could see the Lockyer Valley's current spring, autumn and winter Chinese cabbage production window, shorten, as hotter maximum temperatures in late spring and early autumn further impact Chinese cabbage head quality, increase water requirements, increase growing difficulty and reduce marketable yield.
Producers will need to continue to adapt to these changes, revising their production location, varieties, management practices and timing in response to their knowledge and their own on-going seasonal experiences.

Plant breeders may be able to develop and introduce new more heat resistant varieties, although this option appears limited given Australia's reliance on overseas breeding and the fact that, currently, in some hotter growing locations, even with the best varieties, both head quality and yield suffer.

Consumer demand drives product supply and modern consumers have no tolerance for blemished product. Chinese cabbage supply and product quality determine consumer demand, and locations that run the risk of producing lower quality product will inevitably be avoided as the chain stores source and buy vegetables from more favourable (consistent quality) production locations, to ensure year-round supply. Locations or months previously deemed non-viable due to maximum or minimum temperature constraints may become commercially viable. For example, the Chinese cabbage production season in the Granite Belt, could extend further into the autumn and begin earlier in the spring, extending the edges of the current production window, as minimum temperatures rise. Conversely as both minimum and maximum temperatures rise in the Lockyer Valley, the current, "traditional" production season is likely to shorten. Increasing maximum temperatures, warmer minimums, heatwaves and increased storm frequency will impact production viability, yield, product quality and production timing of Chinese cabbage throughout Queensland and Australia.

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] contains the following statements[3].

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 Queenslands 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.

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[3] https://www.climatechangeinaustralia.gov.au/en/changing-climate/state-climate-statements/queensland/
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The State of the Climate 2022 Report [4], Future Climate section states, "new research in Australia and around the world, together with the IPCC's Sixth Assessment Report, enhance understanding of the state of 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, higher temperatures will impact, existing crops, production timing, and locations. While some production may be able, or forced, to move to a new location, land suitability, water availability, workforce and supporting infrastructure (e.g., road networks & power availability) pose significant constraints.

Chinese cabbage-Critical Temperatures Thresholds (from published research).

	Critical Temperature ^{0}C	
Growth Stage	**Lower ^{o}C**	**Upper ^{o}C**
Germination	> 12	< 31
Juvenile (vegetative)	> 12	< 32
Head growth	>10	< 30

It is important to realise that to achieve a mean monthly maximum of 30^{o}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^{o}C for 3 days and applied this to each crops' threshold.
So, for Chinese cabbage in the head growth stage, the literature indicates the Critical Temperature Threshold is 30^{o}C mean maximum temperature. To simulate the effects of high temperatures, we have chosen **32^{o}C for 3 consecutive days as the Critical Temperature Threshold** for the **head growth** stage.

Commodity production data.
Australia produced around $86.1 million dollars' worth of Asian vegetables for the fresh market in 2021-22 and according to Ausveg data [5]. Chinese cabbage was the largest contributor to this fresh produce category, being 38% of the total production value or $32.7 million dollars. This production was sold as fresh produce, within which the small Kimchi (fermenting/ pickling) market, is a secondary use, with fresh produce sourced from local wholesalers or resellers. The majority of fresh market Chinese cabbage is grown in New South Wales (43%), while the Queensland (28%) and Victoria (24%), production combine to contribute the bulk of the national crop. Western Australia grows 3% of the total, while South Australia and Tasmania produce <1% each, and the Northern Territory grows just 2% of the national crop.

[4] https://www.csiro.au/en/research/environmental-impacts/climate-change/State-of-the-Climate
The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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 Note graphs are best viewed at >140 magnification

Chinese Cabbage Critical Temperature Thresholds.

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

Drought and Climate Adaptation Program

Chinese cabbage production occurs in all states, with product transported inter-state to fill any supply shortages. Chinese cabbage export opportunities do arise from time to time, but this market is ad-hoc, price sensitive and very price competitive. The taller "long cabbage", or "rocket" types, known as Michihili, are preferred by the export market and not favoured by the Australian fresh market.

The modern Australian supply chain relies largely on state based, grower businesses contracted to fulfill pre-arranged supply orders to the Supermarkets on a daily or weekly basis. A small number of medium sized Queensland businesses grow high quality Chinese cabbage at carefully chosen locations, both, throughout the state and inter-state, so as to maximise their supply period. Some of these Queensland based businesses move production throughout the year, so maximising crop quality and yield. Production sites are selected based on climatic suitability, to maximise product quality and supply continuity [5].

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, and spring crops).

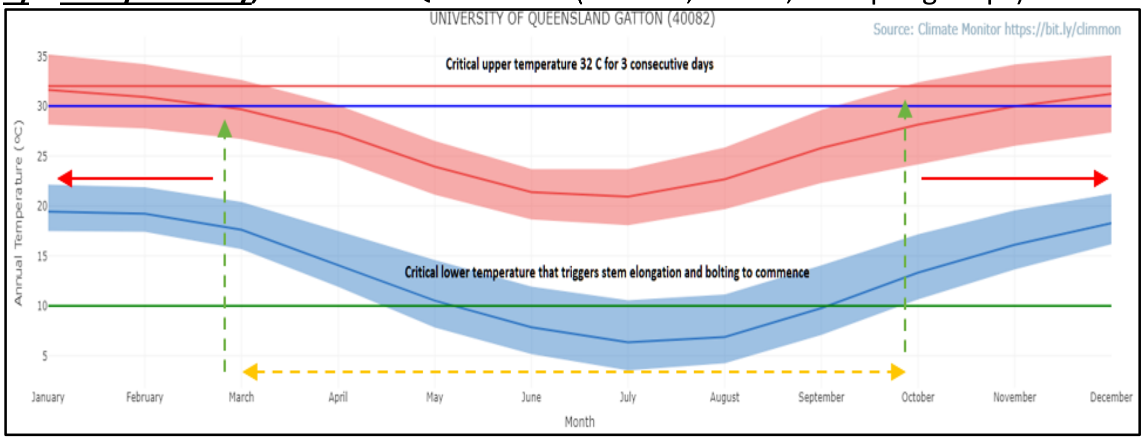

Figure 5. Monthly historical maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), at Gatton, with Chinese cabbage critical temperatures – overlaid. Green arrows and yellow dotted line define the current production window, while red arrows indicate non-viable months. Note: The monthly temperature graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

** Climate Monitor[6] 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

[5] https://www.horticulture.com.au/globalassets/hort-innovation/australian-horticulture-statistics-handbook/ahsh-2021-22-vegetables-r.pdf

[6] https://grf-smartfarm.daf.qld.gov.au/shiny/apps/climatemon/

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time (chill and heat units) and be able to retrieve, analyse and graph temperature thresholds (for a chosen location).

Chinese cabbage is traditionally gown through autumn, winter, and early spring in the Lockyer Valley, production region. Transplanting often starts from March, with regular (weekly) plantings occurring throughout the growing season, with late September final harvest being the norm. October maximum temperatures begin to exceed Chinese cabbages upper temperature threshold, and this signals the plant to develop soft (loose) heads at the same time as internal seed stalk, that has developed slowly through the mild night temperatures of the Lockyer Valley winter begins to elongate as daytime temperatures warm and growth rates increase. Soft rot caused by a combination of increased humidity and high late spring temperatures can greatly reduce yield, and often leads to almost total crop loss.

As detailed in the references above when minimum temperatures fall below the lower critical temperature threshold (10^{o}C) this triggers the Chinese cabbage plant to begin developing an internal flower stalk (bolting).

The internal growing point slowly begins to elongate within the plant (Figure 4). This is a complex temperature driven, physiological response and the extent and speed of, "bolting" is determined by the balance of the number of hours spent below the lower CTT and offset or partly negated by the number of hours spent above the plants lower CTT each day (Guttormsen and Moe 1985). Semi-mature plants that have already developed a lot of leaf and partially filled a head are less dramatically impacted than younger plants.

In locations such as Gatton where warm daily maximum temperatures prevail through winter, vegetative leaf growth rates continue, because as detailed above, the optimum head growth temperature range for Chinese cabbage is 18^{o}C to 24^{o}C and in most years these daytime temperatures are the norm from May to mid-August (Figure 6). Plants continue to actively grow leaf and fill out, developing heads through this period. Plantings that grow through July and August cool minimums, will have a developing internal seed stalk low in the head, and this will begin to elongate and develop more quickly as warmer September minimums and maximums prevail. These temperatures combined with the plants, "primed" by low minimums to "run to seed" meaning, growers must keep a very close eye on internal seed stalk development as the developing internal stem causes the plant to form loose heads. Internal stem development (bolting) can make the plant unsaleable.

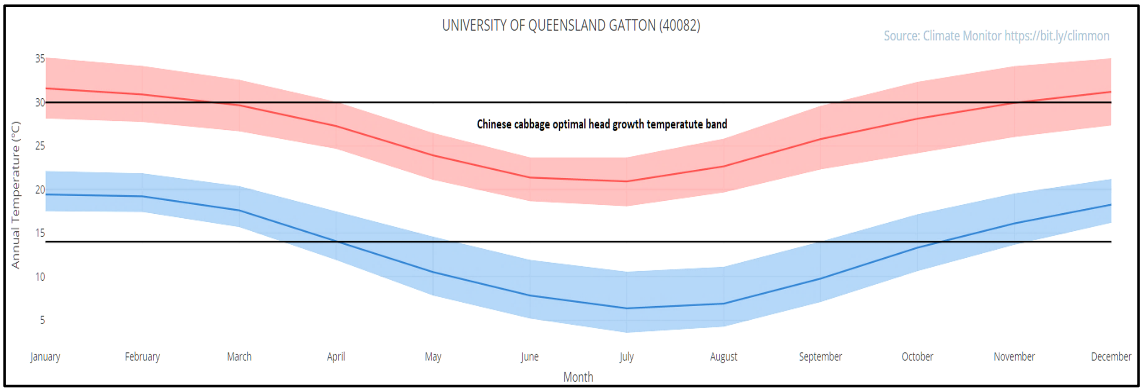

Figure 6. Monthly historical maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), at Gatton, with Chinese cabbage optimal head growth temperatures – overlaid. Warm daily maximum temperatures promote plant leaf growth , even though the slow development of the internal seed stalk has been initiated by overnight minimums below the plants lower CTT. Note: The annual temperature graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years.

In some years and seasons a hot spring (e.g., El Nino influence), will cause head quality issues, such as head softness, bolting & increased head soft rots, especially after rain. In hot humid conditions yield and crop loss can be almost 100%. Figure 5 above, illustrates temperatures that determine the traditional Lockyer Valley growing season Note that in many years the Chinese cabbage plants upper CTT of 32°C is reached from late September through until February.

The traditional Chinese cabbage production season in the Lockyer Valley aligns well with the 30°C upper limit for optimal Chinese cabbage head growth, but as late spring maximum temperatures begin to increase, quality can decline very quickly.

Although the Chinese cabbage plants lower CTT (10°C) is exceeded in the winter months, the warm daily maximum temperatures (≥ 16°C) and short daily duration, offsets and slows

vernalisation and internal stem elongation, allowing the variety used by local growers to fill out firm, marketable heads, until such time as maximum temperatures stress the plants further, causing soft heads, with obvious and excessive internal seed stalk. The cooler months from April to early September produce large, firm, high-quality Chinese cabbages, ideal for the Australian fresh market. Both production volume and head quality peak during this traditional growing period in the Lockyer Valley, when a small number of specialist growers supply consumer demand.

To satisfy fresh market, demand throughout the hot summer months, high quality Chinese cabbage is grown in cooler locations ,mostly in southern states, with some also grown on the Granite Belt and inner Darling Downs.

Using the unique weather data analysis capability of Climate Monitor, producers can easily review historical 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 ≥32°C has occurred for 3 consecutive days in October to February at Gatton is displayed below. The October to February summer period is unsuitable for Chinese cabbage production as the upper CTT is regularly exceeded. On average since 1956 during October to February there have been 7 occasions when maximums of ≥ 32 C have occurred for at least 3 days in a row. In 2020 this occurred 10 times, meaning at least 30 days when maximums of 32°C or higher occurred for at least 3 days (Figure 7).

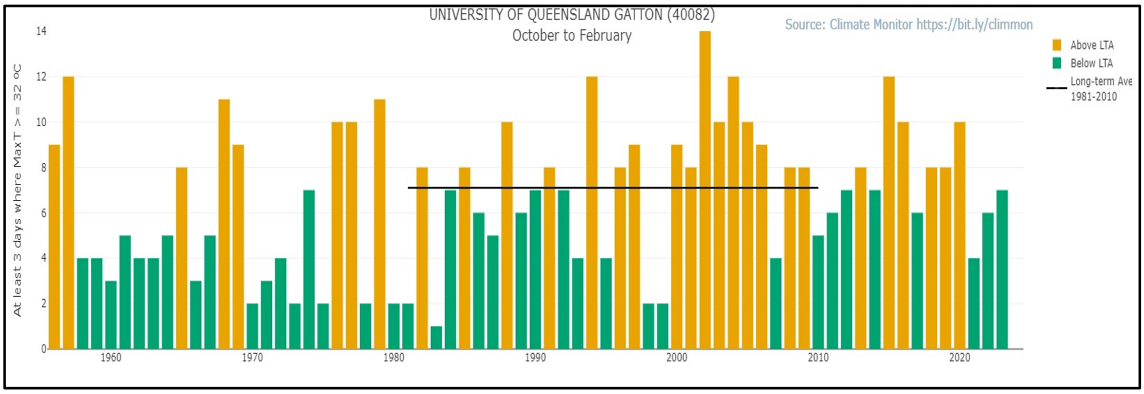

Figure 7. Climate Monitor analysis showing the number of times each year and season (October – February) that Gatton has experienced at least, 3 consecutive days that achieved maximums of 32°C or above.

An analysis of the same threshold temperatures (at least 3 consecutive days ≥ 32°C) at Gatton during the month of September for all years to-date, shows why the Lockyer Valley Chinese cabbage season comes to an end during September, before hotter temperatures in late spring reduce both crop yield and quality.

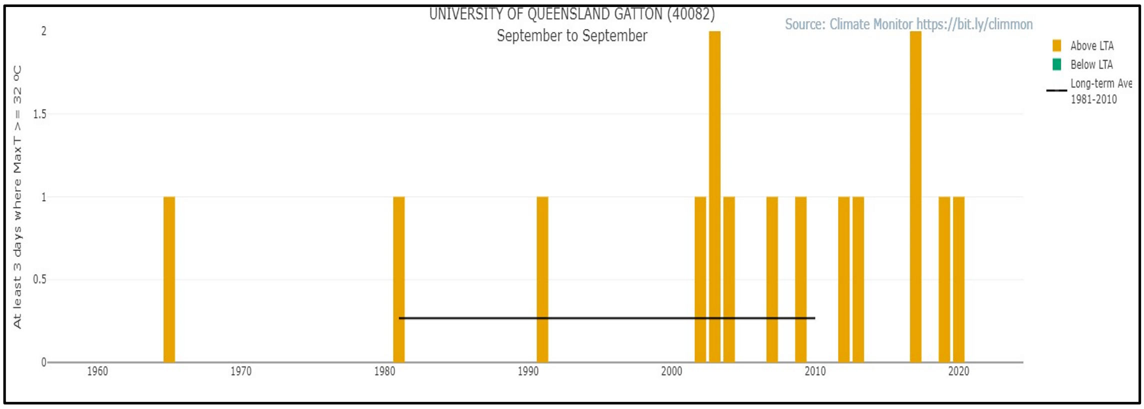

Figure 8. Climate Monitor analysis showing the number of times in each year that Gatton has experienced days that were 32°C or above for 3 consecutive days during September. These temperatures are above the upper CTT for growing marketable cabbage heads.

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The critical temperature range for Chinese cabbage head growth, is nights with minimums above 10°C and maximum daily temperatures equal to or less than 30°C, as detailed in the literature review above. The Climate Monitor analysis below based on these temperature parameters over the Lockyer Valley's traditional peak Chinese cabbage production season March – September shows these optimum temperatures, occur regularly, on average for 90 days each year during the "production season".

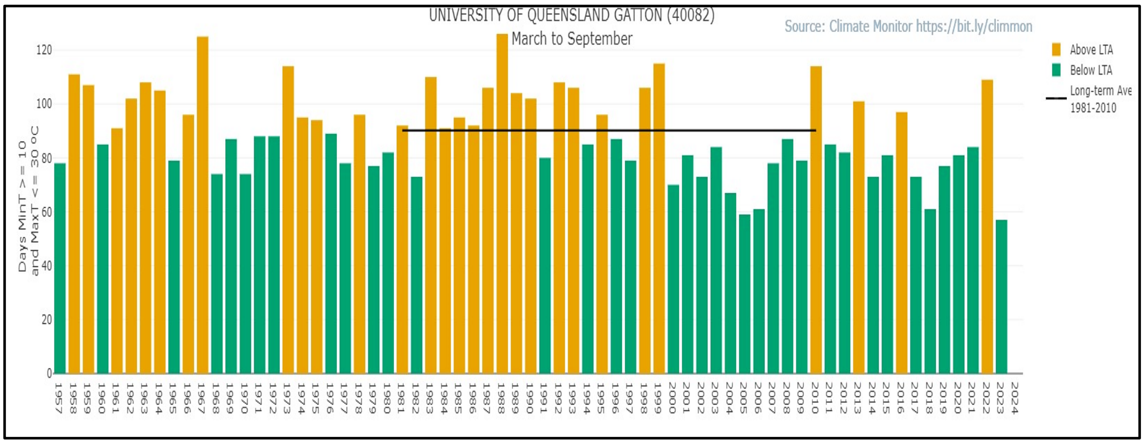

Figure 9. Climate Monitor analysis showing the number of days in each year that Gatton has experienced days with minimums ≥10 and maximum temperatures ≤30°C between March and September, the Chinese cabbage plants optimum temperature range for quality head production.

b) Granite Belt, Southern Queensland (Early spring, summer and early autumn production).

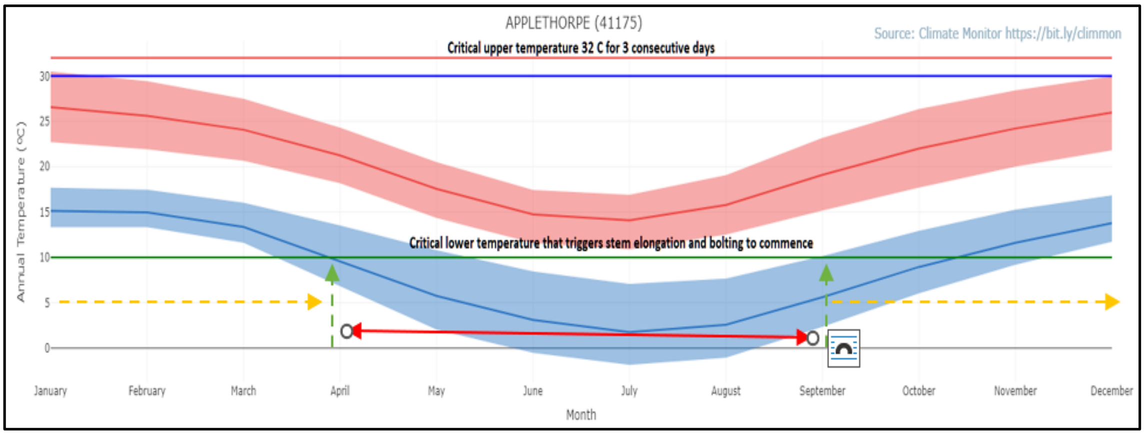

Figure 10. Climate Monitor monthly historical maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), at Applethorpe, with Chinese cabbage critical temperatures – overlaid. Green arrows and yellow dotted lines define the current production window, while red arrows indicate non-viable months. Note: The monthly temperature 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 10 – 32°C as the mean minimum and maximum temperature threshold for marketable Chinese cabbage production in the "head growth phase", and the annual temperature data from Applethorpe, Qld, it would be expected that cabbage harvesting in the Granite Belt would be possible all summer. Frosts and cold temperatures during winter, late autumn and early spring, restrict plantings during those seasons. This closely describes the actual production system in this district, where first plantings occur in September (harvests commence in November), and final plantings occur in February, which are then harvested into early April, on the higher altitude, less frost prone farms.

The Granite Belt is a warm season Chinese cabbage 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, even in the peak of summer, underlining both the potential and increasing importance of this high-altitude Queensland production location. Current minimum temperatures prevent economically viable production through late autumn, winter and early spring. This is when the warmer minimum and maximum temperatures in the Lockyer Valley allow growers to produce high quality Chinese cabbage in their milder winter climate.

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, due to rising minimum spring temperatures, and autumn temperatures that remain high for longer. In the Lockyer Valley the season will shorten as late spring and early summer maximums continue to rise further, impacting yield and quality.
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 production locations.

[7] http://www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml),
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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 (2050's) and current climate data for Gatton.

Data source: Climate Services for Agriculture output, My Climate View

Past and projected future average maximum temperature

Select time period: Past and future 1964 to 2085 | Past only 1964 to 2023

Global emissions scenario What's this? Medium emissions scenario RCP4.5 | High emissions scenario RCP8.5

Past		Future	
1964–1993 average	1994–2023 average	2030s average	2050s average
26.6 °C	27.3 °C	28.2 °C	29.0 °C

This chart shows the past and future range in average annual maximum temperature at your location. Annual is defined as between 1 January and 31 December.

Past and projected future average minimum temperature

Select time period: Past and future 1964 to 2085 | Past only 1964 to 2023

Global emissions scenario What's this? Medium emissions scenario RCP4.5 | High emissions scenario RCP8.5

Past		Future	
1964–1993 average	1994–2023 average	2030s average	2050s average
12.9 °C	13.2 °C	14.2 °C	15.0 °C

This chart shows the past and future range in average annual minimum temperature at your location. Annual is defined as between 1 January and 31 December

Past and projected future annual hot days

Select time period: Past and future 1964 to 2085 | Past only 1964 to 2023

Global emissions scenario What's this? Medium emissions scenario RCP4.5 | High emissions scenario RCP8.5

Past		Future	
1964–1993 average	1994–2023 average	2030s average	2050s average
12 days	20 days	27 days	40 days

This chart shows the past and future range in total annual hot days at your location. Hot days are defined as days with a maximum temperature greater than or equal to 35 °C between 1 January and 31 December.

Past and projected future annual cold days

Select time period: Past and future 1964 to 2085 | Past only 1964 to 2023

Global emissions scenario What's this? Medium emissions scenario RCP4.5 | High emissions scenario RCP8.5

Past		Future	
1964–1993 average	1994–2023 average	2030s average	2050s average
8 days	7 days	4 days	2 days

This chart shows the past and future range in total annual cold days at your location. Cold days are defined as days with a minimum temperature less than or equal to 2 °C between 1 January and 31 December.

Figure 11. Projected future temperature, annual hot and frost days for Gatton under the high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020). The graphic uses 1964 – 1993 for comparison of the 2030's & 2050 average temperature shift.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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Projected annual crop specific upper CTT hot days risk shift (1964 – 93 baseline period).
Data source: Climate Services for Agriculture output, My Climate View
** This chart shows the average number of days in past and projected future years and year periods that **the crop specific upper CTT** has or is projected to occur using the high emissions greenhouse gas scenario RCP 8.5.*

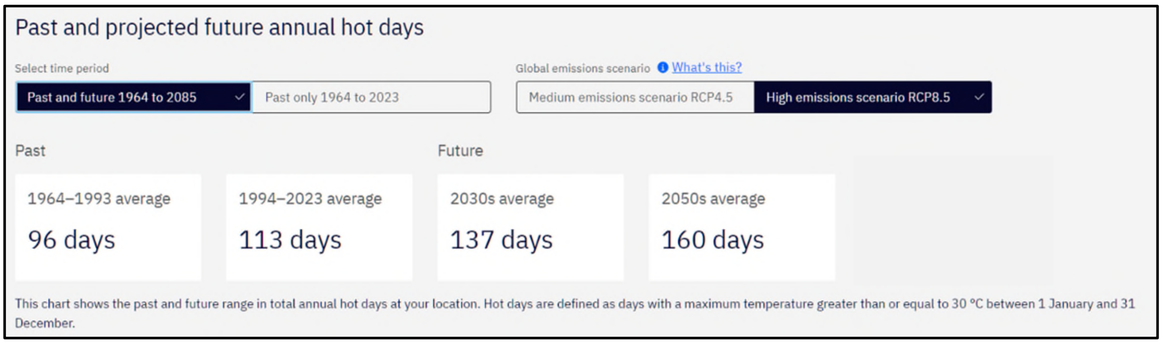

Figure 12. Chinese cabbage specific, upper CTT heat risk shift comparison table for Gatton.

The high emissions pathway model indicates a temperature shift, showing a 2.4°C annual increase in maximum temperatures and a 2.1°C annual increase in minimum temperatures by the 2050's. Importantly the number of days when the maximum temperature in Gatton equals or exceeds 30°C increases from 113 to 160 when compared to the recent past (Figure 12).

The future annual crop specific hot days shift as displayed above (Figure 12) indicates that by 2050, on average Gatton in the Lockyer Valley will experience at least 160 days where the maximum temperature is ≥ 30°C. This is an increase of 47 days per year during the 2050's, compared to what actually occurred in the 1994-2023 period.
When compared to the 1964-1993 period, the projected number of days of 30°C or above at this location increases by 64 days, a significant shift.

Projected future and current climate data for Gatton.

Table 1 Projected future temperature comparison for Gatton under high emissions scenario RCP 8.5, where cumulative global emissions are currently tracking[8].

Time Period	Annual Average T Max ^{0}C	Annual Average T Min^{0}C	Annual Heat Risk Days. Based on the crop specific upper CTT T Max ≥ 30^{0}C	Annual Cold Risk Days. Based on the crop specific lower CTT T Min ≤ 10C
1964-1993 Past Average	**26.6**	**12.9**	**96**	**114**
1994 -2023 Recent Average	27.3	13.2	113	114
2030's High Emissions - Future Average	28.2	14.2	137	94
2050's High Emissions - Future Average	**29.0**	**15.0**	**160**	**82**
Difference from Past Average	**+2.4**	**+2.1**	**+64**	**-32**

The high emissions pathway model indicates a temperature shift, showing a 2.4°C increase in maximum temperatures and a 2.1°C increase in minimum temperatures by the 2050's. Importantly the number of days when the maximum temperature in **Gatton** exceeds 30°C increases from 96 to 160 (64 days), and the cold risk decreases by 32 days.

[8] https://myclimateview.com.au/

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Future temperatures at Gatton and the impact on the timing and occurrence of Chinese cabbage critical temperature thresholds (CTT).

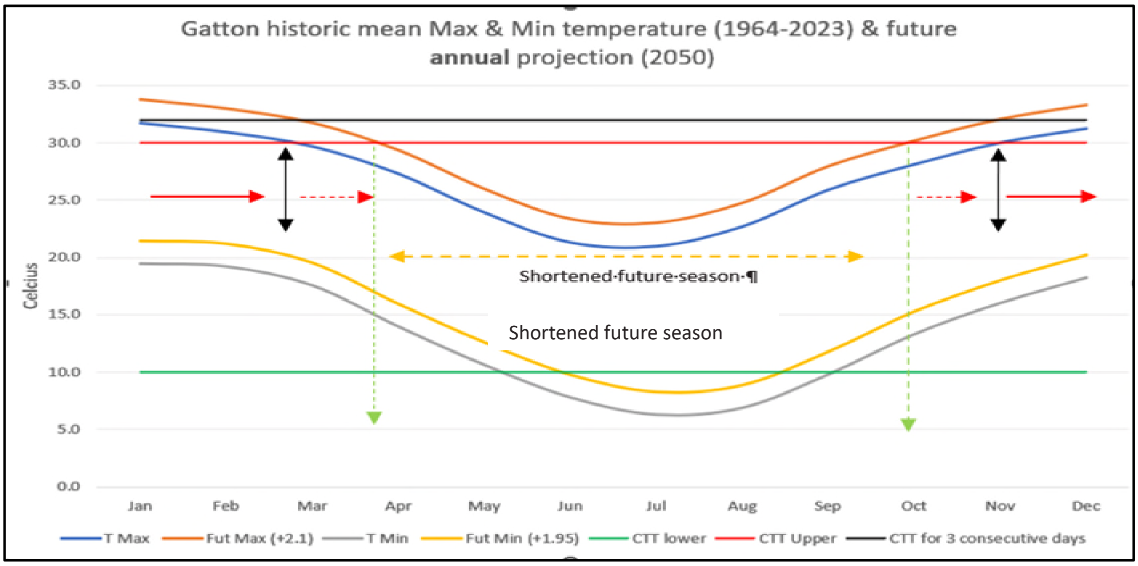

Figure 13. Current mean monthly temperatures at Gatton, Chinese cabbages upper CTT (30° C) and lower CTT (10°C) & the impact of projected future mean annual temperature shifts (2050's) on the optimum growing season. Green arrows and the yellow dotted line define the future production window, double ended black arrows, the historic production months & season. Red arrows indicate the historic non-viable and future non-viable projected temperature shift.

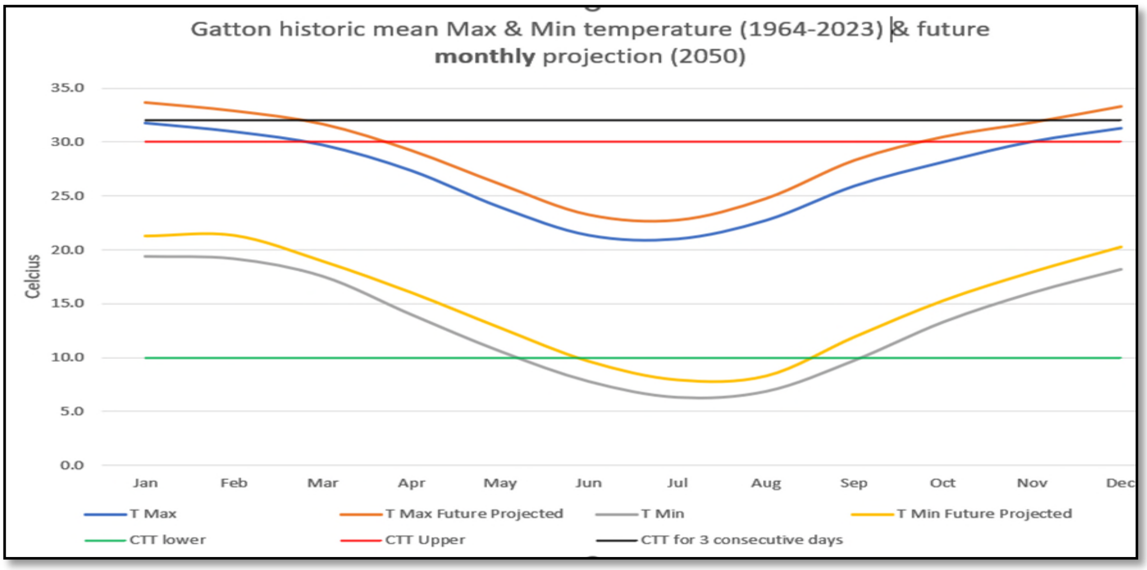

Figure 14. Current mean monthly temperatures at Gatton, Chinese cabbages' upper CTT (30° C) & the impact of projected future mean monthly temperature shifts (2050) on the optimum growing season. (Note, the monthly future climate data displayed here is not publicly available but reflects the individual monthly changes that underpin the projected annual changes in maximum and minimum temperatures).

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

Maximum temperatures currently prevent high quality fresh market Chinese cabbage production in the Lockyer Valley during the late spring and summer period. The projected increase in future daily maximum temperatures in the Lockyer Valley will result in a further & significant shortening of the Chinese cabbage production window. Currently average monthly maximum temperatures allow transplanting to begin in early February, with final harvest occurring in early November.
Figure 13 & Figure 14 above show how and why this shift will shorten the Lockyer Valley growing season. Chinese cabbage plants will experience maximum temperatures that exceed their upper CCT, both earlier and later in the calendar year. Transplanting of the first crops could be delayed by around 3 weeks until April, with last harvests brought forward by almost a month (to avoid internal seeding issues), from the beginning of November back to the beginning of early October. There could be a significant reduction in the Lockyer Valley's (historical) Chinese cabbage growing season. Higher daily maximum temperatures would also require extra irrigation and associated labour and electricity costs. Higher nightly minimum temperatures would reduce and slow "bolting" pressure in late winter and early spring. Remember the graphics above, depict mean monthly temperatures and do not convey daily and weekly temperature variations and extremes.

Minimum temperatures will increase as shown in Figure 11, Figure 13 & Figure 14, above. Mean minimum temperatures currently below the plants lower CTT in the late autumn and winter, signal the plant to try and begin to develop a seed stalk and enter the reproductive stage. The projected increases in minimum temperatures will delay the beginning of the "bolting" period and reduce its length, and impact on head firmness. The projected warmer minimums would increase plant growth rates and quality in early spring and shorten the time between planting and harvest.

Maximum temperature is the most important critical weather factor that dictates the current and future Chinese cabbage production window in the Lockyer Valley. Increased minimum temperatures will however slightly increase over-winter growth rates and reduce "bolting", improving the quality and reliability of the spring crop. Projected increases in future maximum temperatures in late autumn and early spring in the Lockyer Valley shorten the current cabbage production window (Figure 14).

When considering projected maximum and minimum temperature shifts at any location, the reader should keep in mind the daily duration (number of hours each day) the plant is likely to experience these conditions.

a) Granite Belt, Stanthorpe (Applethorpe)

Projected future (2050's) and current climate data for Applethorpe.

Table 2 Projected future temperature comparison for Applethorpe under high emissions scenario RCP 8.5, where cumulative global emissions are currently tracking[9].

Time Period	Annual Average T Max ^{0}C	Annual Average T Min^{0}C	Annual Heat Risk Days. Based on the crop specific upper CTT T Max ≥ 30^{0}C	Annual Cold Risk Days. Based on the crop specific lower CTT T Min ≤ 10C
1964-1993 Past Average	**20.5**	**8.8**	**13**	**188**
1994 -2023 Recent Average	21.2	9.1	22	186
2030's High Emissions - Future Average	22.1	10.1	28	162
2050's High Emissions - Future Average	**23.0**	**10.9**	**40**	**146**
Difference from Past Average	**+1.5**	**+2.1**	**+27**	**-42**

The high emissions pathway model indicates a temperature shift, showing a 1.5°C increase in maximum temperatures and a 2.1°C increase in minimum temperatures by the 2050's. Importantly the number of days when the maximum temperature in Applethorpe exceeds 30°C is projected to increase from 13 to 40 days, and the cold risk decreases by 42 days.

Data source: Climate Services for Agriculture output, My Climate View

9 https://myclimateview.com.au/

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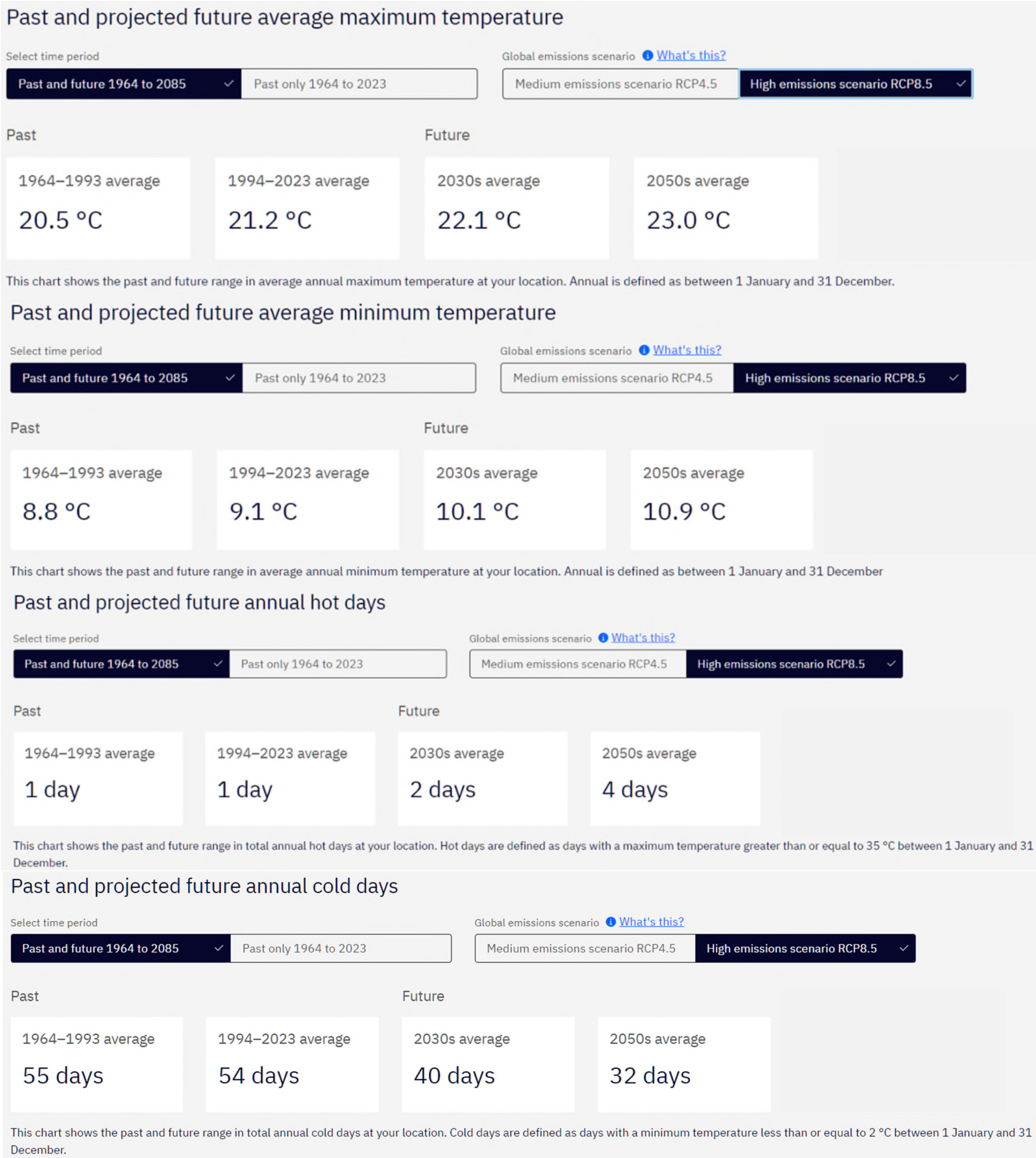

Figure 15. Projected future temperature outlook for Applethorpe under high emissions scenario RPC 8.5, where cumulative global emissions are currently tracking (Schwalm, et al., 2020). The graphic uses 1964 – 1993 for comparison of the 2030 to 2050 average temperature shift.

The high emissions pathway model indicates a temperature shift, showing a 2.5°C increase in average annual maximum temperatures and a 2.1°C increase in average annual minimum temperatures by the 2050's, when compared to the 1964-93 base period.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Projected 2050's maximums and minimum temperatures increase by 1.8° C compared to the 1994-2023 recent past averages.

The annual number of hot days at Applethorpe increases from 1 day to an average of 4 days ≥ 35° C each year and this is accompanied by a projected decrease in annual frost risk from 54 to 32 days (Figure 15) when compared the recent past.

Projected annual crop specific upper CTT hot days shift (1964 – 93 baseline period).

** **This chart shows the average number of days in past and projected years that the crop specific upper CTT has or is projected to occur** using the high emissions greenhouse gas scenario RCP 8.5.*

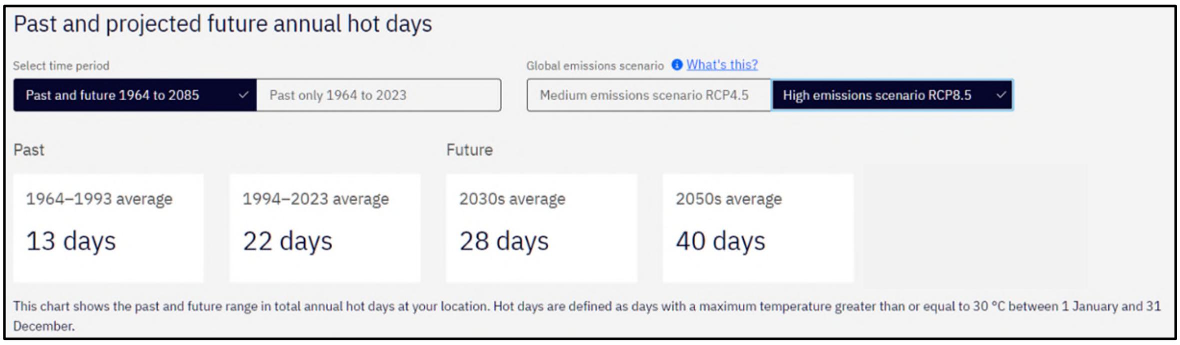

Figure 16. The Chinese cabbage plants specific, upper CTT hot days shift comparison table for Applethorpe.

Data source: Climate Services for Agriculture output, My Climate View

Figure 16 above, shows that by the 2050's, Applethorpe will have on average at least an extra 18 days each year when the maximum temperature equals or exceeds the Chinese cabbage plants upper CTT, compared to the recent past 1994 - 2023. It is worth noting that this 2050's projection represents a significant increase when compared to the recent past 1994-2023 base period.

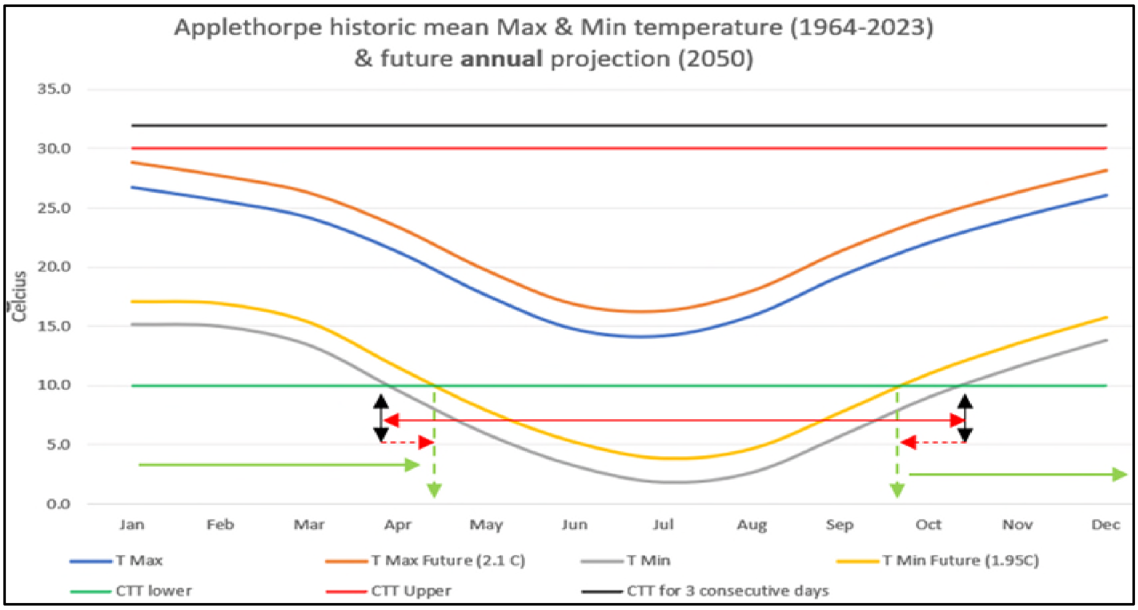

Figure 17. Current mean monthly temperatures at Applethorpe, cabbages upper CTT (30° C), lower CTT (10° C) & the impact of projected future mean annual temperature shifts (2050's) on the optimum growing season. Green solid arrows and the green dotted arrows define the longer future spring to autumn production window, due to warmer minimums. The double ended black arrows, mark the current and historic, season start and end months. Solid red arrows indicate the historic non-viable period through the winter, while the red dashed arrows show how warmer autumn and spring minimums will lengthen the season.

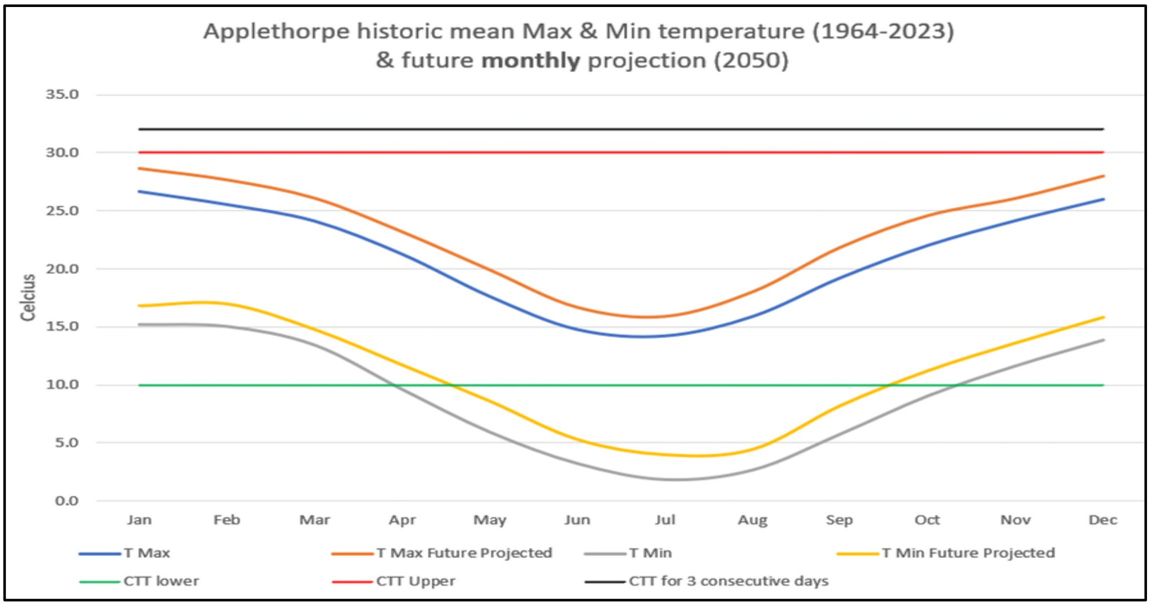

Figure 18. Current mean monthly temperatures at Applethorpe, cabbages' upper CTT (30° C) & the impact of projected future mean monthly temperature shifts (2050's) on the optimum growing season. (Note, the monthly future climate data displayed here is not publicly available but reflects the individual monthly changes that underpin the projected annual changes in maximum and minimum temperatures). Site specific mean temperature data source, DCAP Climate Monitor

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

Minimum temperatures currently prevent Chinese cabbage production in the Granite Belt during the late autumn, cold winter and early spring period. The projected increase in average monthly minimum temperatures in the Granite Belt as detailed above for the 2050's will allow an extension of the existing Chinese cabbage production window. Currently average monthly minimum temperatures fall below cabbages' lower CTT in April and stay below the lower CTT until mid-September.
Figure 17 & Figure 18 above show how the projected mean minimum monthly temperature shift, will lengthen the Granite Belt growing season. Chinese cabbage plants will not experience minimum temperatures that are below their lower CCT until later in the autumn. The Chinese cabbage production season will also start earlier due to warmer spring minimums. Transplanting of the first crops could be brought forward by several weeks, with last harvests also extended later into the autumn.
Maximum temperatures will increase as shown in, Figure 17 & **Error! Reference source not found.**Figure 18 above, however, annual maximum monthly temperatures will remain well below 30ºC, the Chinese cabbage plants upper CTT. Changes in mean monthly maximum temperature alone will not alter Chinese cabbage quality or alter the production window in the Granite Belt in the 2050's. When considering projected maximum and minimum temperature shifts at any location, the reader should keep in mind the daily duration (number of hours each day) the plant is likely to experience these conditions.

Minimum temperature is the critical weather factor that will continue to dictate the Chinese cabbage production window in the Granite Belt. Forecast increases in minimum temperatures will allow growers to transplant earlier in the spring, and also harvest later into the autumn. This should result in a significant extension of the Granite Belts' (historical) Chinese cabbage growing season, enhancing product availability and quality.

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

Interstate production – future insights.

Future climate data analysis for all locations (2050's) is based on current projections sourced from Australias, Climate Services for Agriculture website, My Climate View.

ii) New South Wales (Richmond)

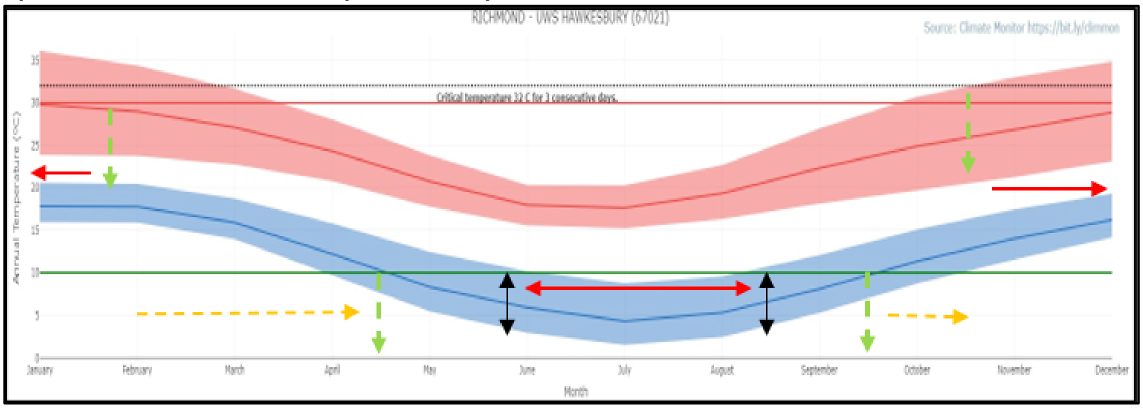

Figure 19. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with Chinese cabbage critical temperatures – overlaid, at Richmond. Note: The temperature graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years. Green arrows indicate the start and end months of a split growing season, yellow the potential production window, black double ended arrows mark the start and end of lower CTT period and the red arrows the non-growing months.

Commercial Australian seed catalogues (e.g., Lefroy Valley Australian product guide)[10] indicate that by using modern varieties, Chinese cabbage can be transplanted in the Richmond district from September onward with last harvest occurring in March or April. The Critical Temperature Threshold analysis above, indicates that the peak of summer heat in December and January, would impact head quality in most years as daily maximum temperatures are too high. The cold winter months, May, June, July, August and early September are too cold. The Chinese cabbage plants lower CTT is exceeded throughout winter, when very low growth rates, vernalisation and seed stalk development prevent commercial production. A split season from Mid-September to November, then from mid-February through until mid-April sit within the upper and lower CTT for quality Chinese cabbage production in most years at Richmond.
Even with a split season, in the hotter drier years (El Nino), viability, and yield will be impacted in late spring and early autumn in some years - due to higher maximum temperatures.

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[10] https://lefroyvalley.com/products

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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 Note graphs are best viewed at >140 magnification

Projected future (2050's) and current climate data for **Richmond.**

Table 3 Projected future temperature comparison for Richmond under high emissions scenario RCP 8.5, where cumulative global emissions are currently tracking[11].

Time Period	Annual Average T Max ^{0}C	Annual Average T Min^{0}C	Annual Heat Risk Days. Based on the crop specific upper CTT T Max ≥ 30^{0}C	Annual Cold Risk Days. Based on the crop specific lower CTT T Min ≤ 10C
1964-1993 Past Average	**23.9**	**11.1**	**54**	**156**
1994 -2023 Recent Average	24.6	11.5	66	151
2030's High Emissions - Future Average	25.4	12.4	77	133
2050's High Emissions - Future Average	**26.3**	**13.3**	**94**	**118**
Difference from Past Average	**+2.1**	**+2.2**	**+40**	**-38**

The high emissions pathway model indicates a temperature shift, showing a 2.1°C increase in maximum temperatures and a 2.2°C increase in minimum temperatures by the 2050's. Importantly the number of days when the maximum temperature in Richmond equals or exceeds 30°C increases from 54 to 94 and this change is accompanied by 38 less crop specific cold days (Table 3). The projected temperature shift will alter the existing Chinese cabbage production pattern, with hotter summer maximums lengthening the current production gap in the peak of summer. This change will be somewhat offset by warmer minimum temperatures in early spring and also in mid-autumn, allowing earlier planting and later autumn harvests.

When considering projected maximum and minimum temperature shifts at any location, the reader should keep in mind the daily duration (number of hours each day) the plant is likely to experience these conditions.

11 https://myclimateview.com.au/

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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 hot days shift (1964 – 2023 baseline period).

**** This chart shows the average number of days in past and projected years that the crop specific upper CTT has or is projected to occur*** *using the high emissions greenhouse gas scenario RCP 8.5.*

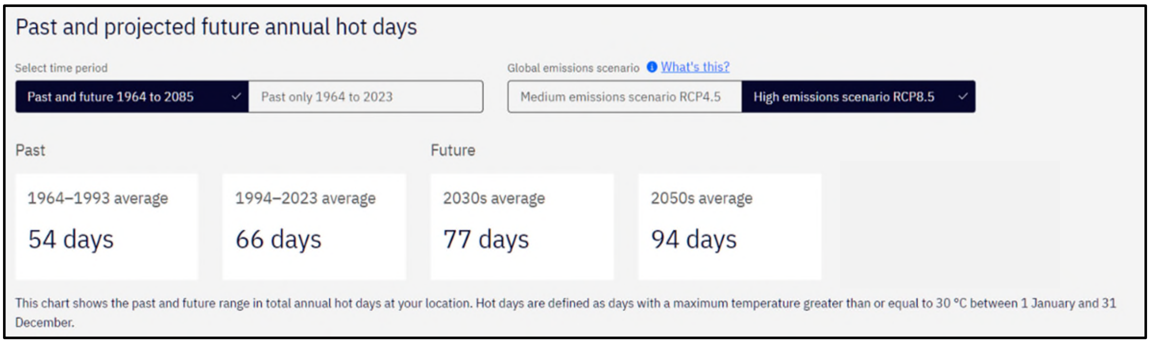

Figure 20. Chinese cabbage specific, upper CTT heat risk shift comparison table for Richmond (NSW).

Figure 20 above shows that by the 2050's, Richmond will have at least 94 days when the maximum temperature equals or exceeds Chinese cabbages upper CTT. This is 28 more days (4 weeks) more than was experienced in the recent past (1994-2023).

iii) Victoria (Bairnsdale)

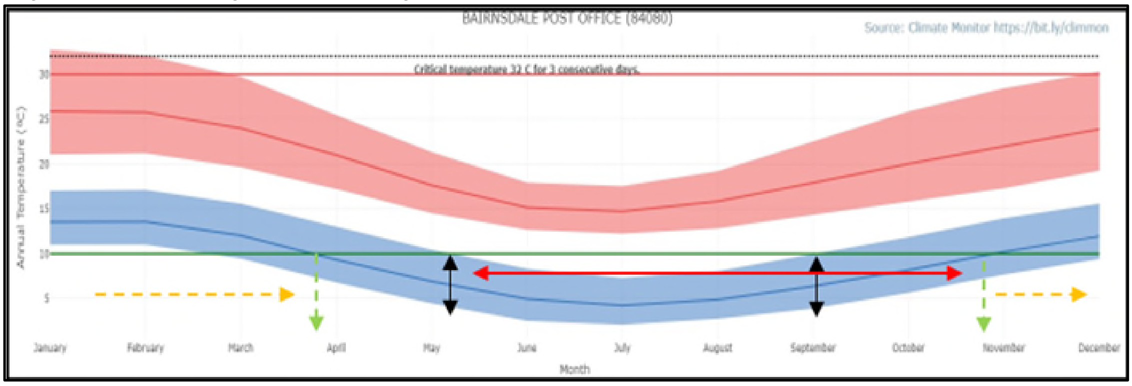

Figure 21. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum temperatures (blue) and mean temperatures (solid lines within each coloured band), with the Chinese cabbage plants critical temperatures – overlaid, at Bairnsdale. Note: The temperature graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years. Green arrows indicate the start and end months the growing season, yellow the potential production window, black double ended arrows mark the start and end of lower CTT period and the red arrows the non-growing months.

Minimum temperatures limit Chinese cabbage production at this location from May until late October in most years. Low temperatures at Bairnsdale, in late autumn, throughout winter and into early spring slow growth rates, limiting plant leaf (vegetative) growth and trigger internal seed stalk development. Currently maximum temperatures in the hottest years in January and early February exceed the upper CTT and so, in warmer years, a number of these consecutive hot days could impact Chinese cabbage quality, cause tip-burn and reduce yield if soil moisture was low, due to inadequate irrigation.

Looking at the occurrence of 32°C days in January, temperature data reveals this is an unusual occurrence and the likelihood of 3 consecutive days in Bairnsdale on average in January is low.

Projected future (2050's) and current climate data for ***Bairnsdale***

Table 4 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 °C	Annual Average T Min°C	Annual Heat Risk Days. Based on the crop specific upper CTT T Max ≥ 30°C	Annual Cold Risk Days. Based on the crop specific lower CTT T Min ≤ 10C
1964-1993 Past Average	**20.2**	**8.8**	**21**	**224**
1994 -2023 Recent Average	20.7	9.6	25	202
2030's High Emissions - Future Average	21.4	10.2	28	186
2050's High Emissions - Future Average	**22.2**	**10.9**	**34**	**165**
Difference from Past Average	**+2.0**	**+2.1**	**+14**	**-59**

The high emissions pathway model indicates a temperature shift, showing a 2.0°C increase in maximum temperatures and a 2.1°C increase in minimum temperatures by the 2050's. Importantly the number of days when the maximum temperature in Bairnsdale exceeds 30°C increases from 21 to 34 and the number of cold days decreases by 59 (Table 4).

The projected temperature shift will alter the existing production pattern, with the projected hotter summers likely to further reduce January harvest quality in some years. Warmer minimum temperatures will allow earlier spring plantings and slightly extend the harvest, later into the autumn. When considering projected maximum and minimum temperature shifts at any location, the reader should keep in mind the daily duration (number of hours each day) the plant is likely to experience these conditions.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

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

Projected annual crop specific upper CTT hot days shift (1964 – 2023 baseline period).

**** This chart shows the average number of days in past and projected years that the crop specific upper CTT has or is projected to occur*** *using the high emissions greenhouse gas scenario RCP 8.5.*

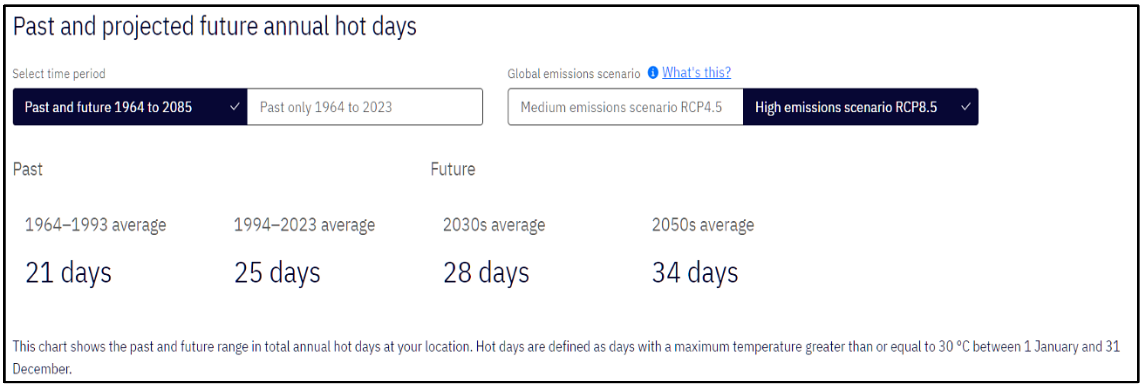

Figure 22 Chinese cabbage specific, upper CTT hot days shift comparison table for Bairnsdale.

Figure 22 above shows that by the 2050's, Bairnsdale will have at least 34 days each year when the maximum temperature equals or exceeds the Chinese cabbages plants upper CTT. This is a significant change compared to the recent past 1994-2023 .

iv) Tasmania (Devonport)

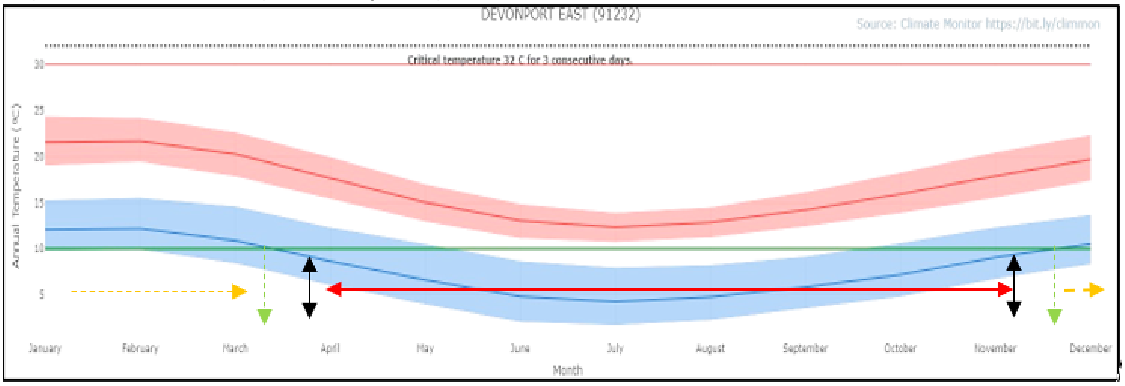

Figure 23. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with cabbage critical temperatures – overlaid, at Devonport. Note: The temperature graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years. Green arrows indicate the start and end months the very limited growing season, yellow the potential production window, black double ended arrows mark the start and end of lower CTT period and the red arrows the non-growing months.

There is very limited commercial production of Chinese cabbage in Tasmania. Mean monthly minimum temperatures from March until mid-November are below the Chinese cabbage plants lower CTT. These low temperatures result ion extremely slow growth rates, plant vernalisation and subsequent seeding (bolting).

Maximum and minimum temperatures from early December until early March are adequate however local market demand is very small and growers must compete with large mainland suppliers, who benefit from a warmer growing environment and economies of scale.

Projected future (2050's) and current climate data for **Devonport.**

Table 5 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. Based on the crop specific upper CTT T Max ≥ 30^{0}C	Annual Cold Risk Days. Based on the crop specific lower CTT T Min ≤ 10C
1964-1993 Past Average	**17.0**	**7.9**	**0**	**255**
1994 -2023 Recent Average	17.4	8.3	0	236
2030's High Emissions - Future Average	18.1	9.0	1	219
2050's High Emissions - Future Average	**18.7**	**9.6**	**1**	**199**
Difference from Past Average	**+1.7**	**+1.7**	**+1**	**-56**

The high emissions pathway model indicates a temperature shift, showing a 1.7°C increase in maximum temperatures and a 1.7°C increase in minimum temperatures by the 2050's. The number of cold days at Devonport will decrease from 236 to 199, a significant decrease (Table 5**Error! Reference source not found.**). Warmer minimum temperatures will allow earlier spring plantings and slightly extend the harvest, later into the autumn. The projected temperature shift may slightly alter the existing production season, however the minor production volume is unlikely to alter significantly at this cool, southerly location.

When considering projected maximum and minimum temperature shifts at any location, the reader should keep in mind the daily duration (number of hours each day) the plant is likely to experience these conditions.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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

Projected annual crop specific lower CTT cold days shift (1964 – 93 baseline period).

** This chart shows the average number of days in past and projected years that the crop specific upper CTT has or is projected to occur using the high emissions greenhouse gas scenario RCP 8.5.*

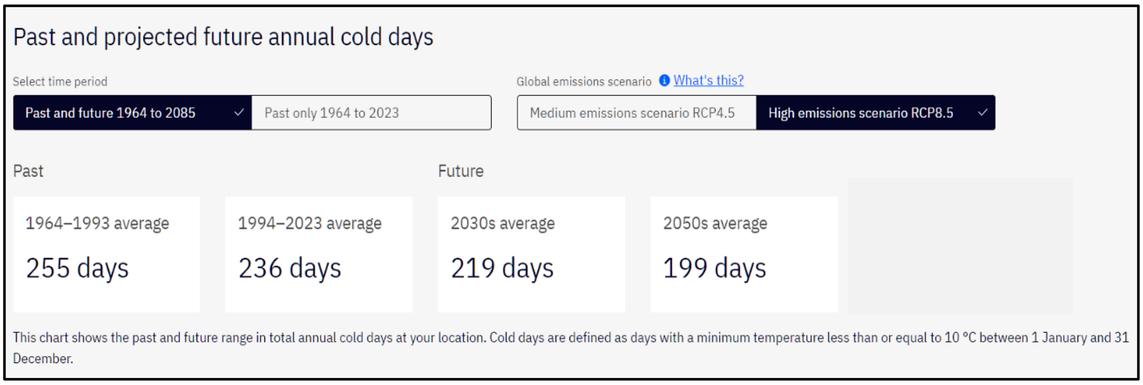

Figure 24. Chinese cabbage specific, lower CTT cold days risk shift comparison table for Devonport.

Figure 24 above confirms that cold days equalling or exceeding the Chinese cabbage plants lower CTT will continue to continue to determine and limit the very short Chinese cabbage season in Devonport.

v) South Australia (Virginia)

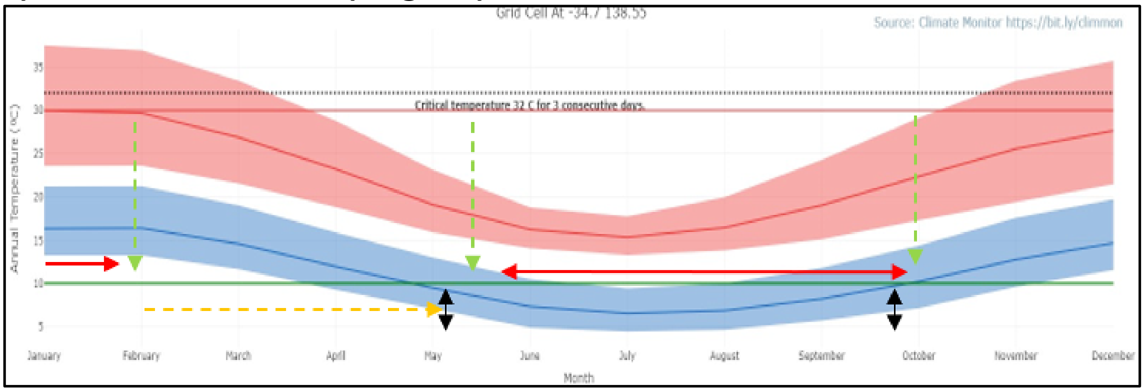

Figure 25. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with Chinese cabbages critical temperatures – overlaid, at Virginia. Note: The temperature graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years. . Green arrows indicate the start and end months of the growing season, yellow the potential production window, black double ended arrows mark the start and end of lower CTT period and the red arrows the non-growing months.

Mean maximum and minimum temperatures from early February until May are within the Chinese cabbage plants upper and lower CTT, with Chinese cabbage growth rates slowing in May as winter approaches. Minimum temperatures fall below the plants lower CTT throughout winter with the accompanying, relatively cool maximums greatly reducing vegetative growth.

Plants subjected to minimums below 10 °C in the cold months would begin to develop internal seed stalk and bolt in September and October as plants resume active growth.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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Transplanting again in October is an option with plants maturing in 8 – 9 weeks being harvested in December, before the more intense heat of January.

This very short late spring season would be problematic in hot years when plants maturing in late November and December would experience multiple days above their upper CTT. When considering projected maximum and minimum temperature shifts at any location, the reader should keep in mind the daily duration (number of hours each day) the plant is likely to experience these conditions.

Projected future (2050's) and current climate data for **Virginia.**

Table 6. 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 ^{0}C	Annual Average T Min^{0}C	Annual Heat Risk Days. Based on the crop specific upper CTT T Max ≥ 30^{0}C	Annual Cold Risk Days. Based on the crop specific lower CTT T Min ≤ 10C
1964-1993 Past Average	**22.4**	**11.2**	**56**	**161**
1994 -2023 Recent Average	23.1	11.5	64	154
2030's High Emissions - Future Average	23.8	12.3	71	133
2050's High Emissions - Future Average	**24.5**	**12.8**	**79**	**118**
Difference from Past Average	**+2.1**	**+1.6**	**+23**	**-43**

The high emissions pathway model indicates a temperature shift, showing a 2.1^{o}C increase in maximum temperatures and a 1.6^{o}C increase in minimum temperatures by the 2050's. Importantly the number of days when the maximum temperature in Virginia exceeds 30^{o}C increases from 64 to 79 (Table 6) when comparing to the recent average.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

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

Projected annual crop specific upper CTT heat risk shift (1964 – 93 baseline period).

** This chart shows the average number of days in past and projected years that the crop specific upper CTT has or is projected to occur using the high emissions greenhouse gas scenario RCP 8.5.*

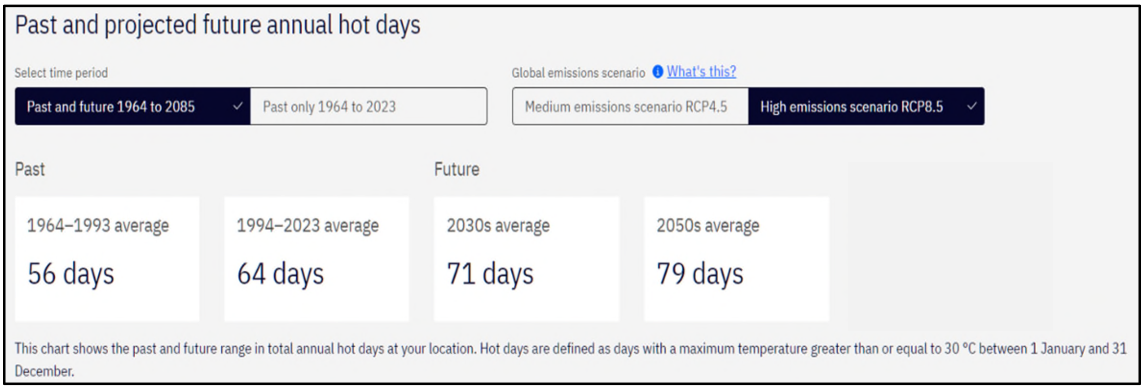


Figure 26.Chinese cabbage specific, upper CTT heat risk shift comparison table for Virginia.

Figure 26 shows that by the 2050's, Virginia will experience at least 79 days annually when the maximum temperature equals or exceeds the Chinese cabbage plants upper CTT. This is a significant change when compared to past temperature observations.

vi) Western Australia (Gingin)

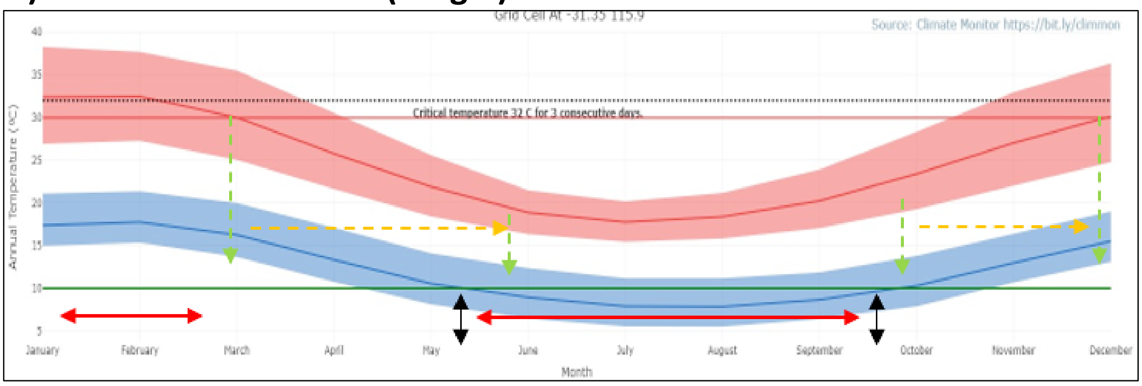


Figure 27. Climate Monitor analysis showing the annual historic monthly temperatures maximum (red) and minimum (blue) temperatures and mean temperatures (solid lines within each coloured band), with Chinese cabbages critical temperatures – overlaid, at Gingin. Note: The temperature graph shows the 10th to 90th percentile, i.e., you expect the temperature to be in this range for 8 out of 10 years. . Green arrows indicate the start and end months of the growing season, yellow the potential production window, black double ended arrows mark the start and end of lower CTT period and the red arrows the non-growing months.

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 mean maximum temperatures drop below

the maximum CTT of cabbage. Maximum temperatures in late November and throughout December in hotter years also exceed Chinese cabbages upper CTT.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
The historic location specific, high quality climate information use herein, is sourced from Climate Monitor, a free, publicly available DCAP web-tool.

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

The minimum CCT threshold (10⁰C) for Chinese cabbage production is exceeded from late May until late September in most years slowing vegetative growth and signalling Chinese cabbage to bolt. Optimum temperatures for quality Chinese cabbage growth occur from

March until the early June in most years currently. There is also a short production window from late spring into early summer in most years.

Projected minimum temperature increases at this location, will enhance plant growth rates during the cooler months, extend the harvest season later into June and allow an earlier transplanting in spring. Future maximum temperature increases will further reduce the growing window for Chinese cabbage at Gingin. Increased summer maximum temperatures will shorten the local production season. When considering projected maximum and minimum temperature shifts at any location, the reader should keep in mind the daily duration (number of hours each day) the plant is likely to experience these conditions.

Projected future (2050's) and current climate data for **Gingin.**

Table 7. 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 ⁰C	Annual Average T Min⁰C	Annual Heat Risk Days. Based on the crop specific upper CTT T Max ≥ 30⁰C	Annual Cold Risk Days. Based on the crop specific lower CTT T Min ≤ 10C
1964-1993 Past Average	**24.5**	**12.5**	**76**	**113**
1994 -2023 Recent Average	25.3	12.7	91	115
2030's High Emissions - Future Average	25.8	13.4	97	92
2050's High Emissions - Future Average	**26.7**	**14.0**	**111**	**79**
Difference from Past Average	**+2.2**	**+1.5**	**+35**	**-34**

The high emissions pathway model indicates a temperature shift, showing a 2.2ᵒC increase in maximum temperatures and a 1.5ᵒC increase in minimum temperatures by the 2050's. Importantly the number of days when the maximum temperature in Gingin exceeds 30ᵒC increases from 91 to 111 (Table 7) compared to the recent past.

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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

These projected maximum temperature changes will see a shortening of the summer growing period, while the increased minimums will enhance plant growth rates and slightly extend the growing period coming into and out of the colder months.

Projected annual crop specific upper CTT hot days (1964 – 93 baseline period).

** This chart shows the average number of days in past and projected years that the crop specific upper CTT has or is projected to occur using the high emissions greenhouse gas scenario RCP 8.5.*

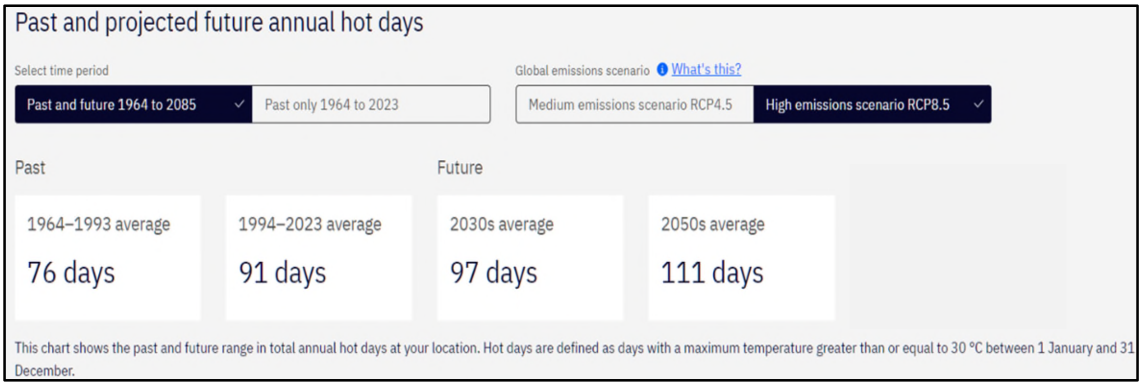


Figure 28. Chinese cabbage specific, upper CTT heat risk shift comparison table for Gingin.

Figure 28 above shows that by the 2050's, Gingin will have at least 111 days when the maximum temperature equals or exceeds the Chinese cabbage plants upper CTT. This represents an increase of 18 more hot days compared to the average in the 1964-1923 period.

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

Drought and Climate Adaptation Program

Annual Heat and Frost Risk, by the 2050's, for Chinese cabbage production at reviewed locations in Australia.

Growing Location	Current Max Temp °C	Projected Max temp change °C by 2050's	Current Min Temp °C	Projected Min temp change °C by 2050's	Current number of hot days ≥ 30° C	Projected number of hot days ≥ 30° C by 2050's	Current number of cold days ≤ 10° C	Projected number of cold days ≤ 10° C by 2050's
Gatton (Qld)	**27.3**	+1.7	**13.2**	+1.8	**113**	160	**114**	82
Applethorpe (Qld	**21.2**	+1.8	**9.1**	+1.8	**22**	40	**186**	146
Richmond (NSW)	**24.6**	+1.7	**11.5**	+1.8	**66**	94	**151**	118
Bairnsdale (Vic)	**20.7**	+1.5	**9.6**	+1.3	**25**	34	**202**	165
Devonport (Tas)	**17.4**	+1.7	**8.3**	+1.7	**0**	1	**236**	199
Virginia (SA)	**23.1**	+1.4	**11.5**	+1.3	**64**	79	**154**	118
Gingin (WA)	**25.3**	+1.4	**12.7**	+1.3	**91**	111	**115**	79

The projected future climate data used in this CTT document are sourced from the most recent (February 2024) My Climate View website (formerly CSA). The updated site underwent some changes, it now displays the 2030 and 2050 average projections. The data and graphics format used in each individual crop CTT document in this DCAP funded work, varies slightly to reflect changes made to the layout of the underlying Climate Services for Australia (My Climate View) publicly available data set.
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 My Climate View website to explore the projected temperature, rainfall and evaporation changes at your chosen location.
   Access Climate Services for Agriculture future climate projections at
   https://myclimateview.com.au/

Appendix I

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

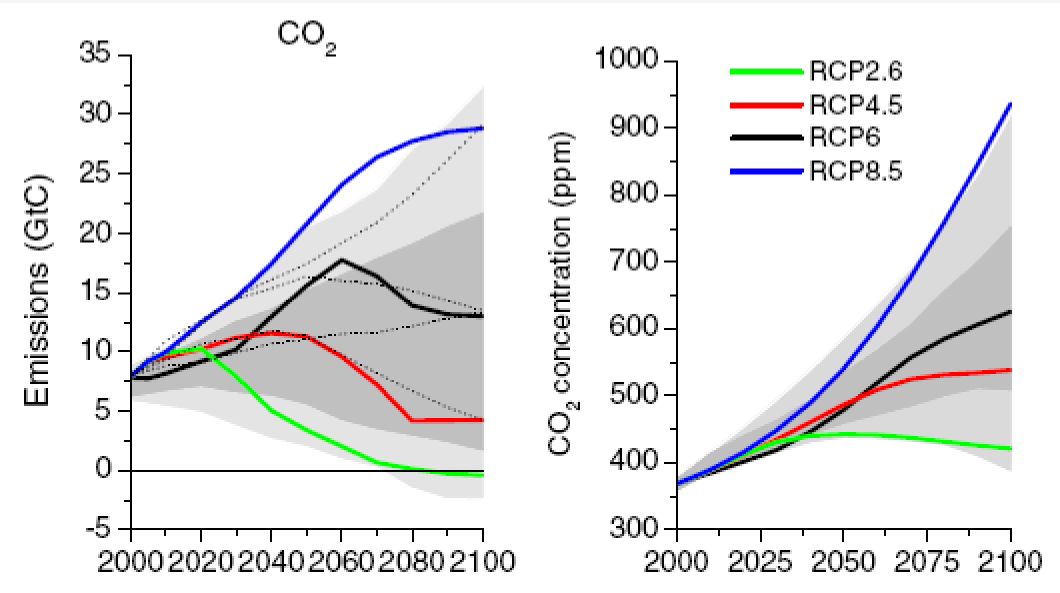
GREENHOUSE GAS SCENARIOS

(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.

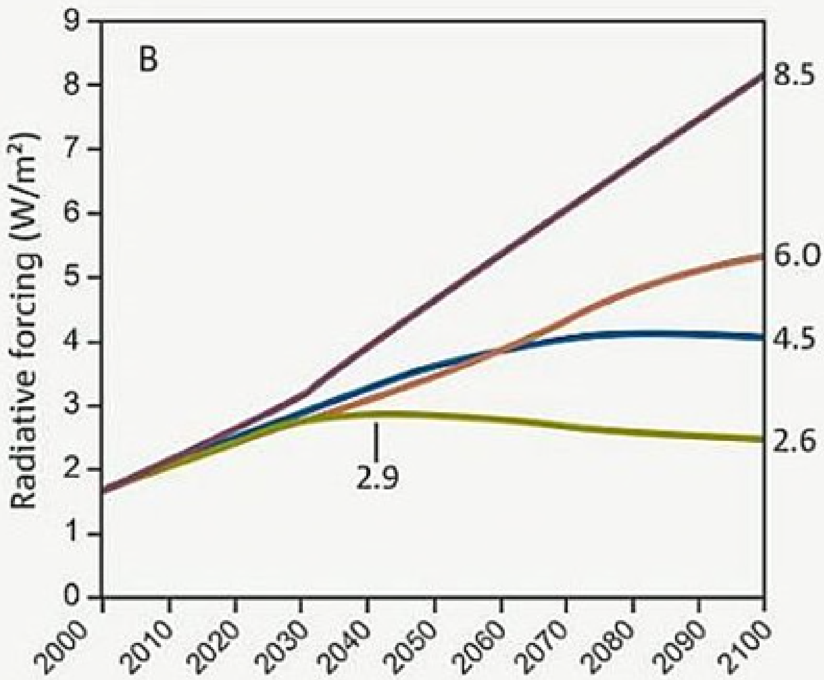
The climate modelling community has developed Representative Concentration Pathways (RCPs) to explore credible future options. The Australian climate change projections found on this site are derived from climate models forced by the RCPs.

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).

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