Int J Biometeorol (2013) 57:355–366
DOI 10.1007/s00484-012-0558-2

ORIGINAL PAPER

Impact of future warming on winter chilling in Australia

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Received: 1 February 2012 / Revised: 19 May 2012 / Accepted: 19 May 2012 / Published online: 7 June 2012

Abstract Increases in temperature as a result of anthropogenically generated greenhouse gas (GHG) emissions are likely to impact key aspects of horticultural production. The potential effect of higher temperatures on fruit and nut trees' ability to break winter dormancy, which requires exposure to winter chilling temperatures, was considered. Three chill models (the 0–7.2°C, Modified Utah, and Dynamic models) were used to investigate changes in chill accumulation at 13 sites across Australia according to localised temperature change related to 1, 2 and 3°C increases in global average temperatures. This methodology avoids reliance on outcomes of future GHG emission pathways, which vary and are likely to change. Regional impacts and rates of decline in chilling differ among the chill models, with the 0–7.2°C model indicating the greatest reduction and the Dynamic model the slowest rate of decline. Elevated and high latitude eastern Australian sites were the least affected while the three more maritime, less elevated Western Australian locations were shown to bear the greatest impact from future warming.

Keywords Climate change · Vernalisation · Fruit · Nut

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Introduction

Climate plays a fundamental role in the successful production of commercial scale fruit and nut products. Winter dormancy is one key aspect of the annual cycle of deciduous fruit and nut trees along with the subsequent breaking of the dormant state. This state is maintained through the winter period each year to protect against damaging cold temperatures (Saure 1985). To be released from dormancy trees require exposure to a predetermined quantity of cold temperatures in a process known as winter chilling or vernalisation. Insufficient chilling can lead to sporadic and light bud-break, poor fruit development, small fruit size and uneven ripening times (Oukabli et al. 2003; Petri and Leite 2004; Saure 1985; Voller 1986). Expected future increases to temperature as a result of anthropogenically induced climate change may impact the vernalisation process leading to these adverse effects on production.

While the chilling process is not fully understood (Dennis 1994), the physiological response is often estimated by temperature based models (e.g. Cesaraccio et al. 2004; Fishman et al. 1987; Linsley-Noakes et al. 1994; Linvill 1990; Richardson et al. 1974; Shaltout and Unrath 1983; Weinberger 1950). Of the available models, the following are used commonly by researchers and growers; the 0–7.2°C (Bennett 1949; Weinberger 1950), Utah (Richardson et al. 1974) and Modified Utah (Linvill 1990), and the Dynamic (Erez et al. 1990; Fishman et al. 1987) models. All these models, although they contain differing levels of complexity, accumulate chill according to hourly temperature exposure and, once a threshold amount of chill has been amassed, define chilling as satisfied. Different species, and varieties within species, require different amounts of chill to break dormancy. Varietal chill requirements, or thresholds, have been defined according to different chill models resulting in chill thresholds reported in different units (e.g. Table 1).

Table 1 Examples of some reported chill requirements according to different models for various fruit and nut varieties

Variety	Dynamic model (chill portions)	Utah model (chill units)	0-7.2°C model (chill hours)
Sirora pistachio	59[a]		
Pistachio			800 – 1,000[b]
Granny Smith apple		1,040[c]	
Golden Delicious apple		1,277[c]	
Starking Delicious apple		1,234[d]; 1,208[e]	
Bartlett pear		1,210[d]	
European pear			600 – 1,500[b]
Rachele almond		376[f]	
Scharsch Franquette walnut	70[g]		700[7]
Orange Red apricot	69.1[h]	1,266[h]	739.3[h]
Desmayo Largueta almond	28[i]	220[i]; 428[f]	
Brooks sweet cherry		556[j]	36.7[j]

[a] Zhang and Taylor (2011)

[b] Baldocchi and Wong (2008)

[c] Ghariani and Stebbins (1994)

[d] Ashcroft et al. (1977)

[e] Mankotia et al. (2004)

[f] Alonso et al. (2005)

[g] Luedeling et al. (2009b)

[h] Ruiz et al. (2007)

[i] Ramírez et al. (2010)

[j] Alburquerque et al. (2008)

Few studies have quantitatively investigated projected impacts of increased temperatures on chill accumulation, although many discuss potential negative outcomes (Darbyshire et al. 2011; Harrington et al. 2010; Legave et al. 2008; Wand et al. 2008). Hennessy and Clayton-Greene (1995) conducted one of the first investigations into chill accumulation under climate warming conditions. Their study was for Australia and used the Modified Utah model. They implemented two methods to investigate future chill conditions, a sensitivity approach as well as a range of scenarios for the year 2030. The sensitivity study involved adding 1, 2 and 3°C to historical temperature records, meaning a constant temperature increase was applied across all locations. Comparison between sites using this method was not possible, as the rate of warming is likely to differ between regions. Additionally, uniform minimum and maximum temperatures increases were applied, this is also unlikely to eventuate. To allow investigation into site differences they also considered scenarios for 2030 using five climate models and two emission scenarios; however, these projection data was produced in 1992 and are now dated.

Recently, Luedeling et al. (2011a) conducted a global analysis of projected changes to chill accumulation according to the Dynamic model only. This model has been shown to equal or out-perform other chill models (Alburquerque et al. 2008; Campoy et al. 2011a; Erez et al. 1990; Luedeling et al. 2009b; Perez et al. 2008; Ruiz et al. 2007; Viti et al. 2010); however, the results may have limited application as few varietal chill thresholds have been measured in chill portions.

Luedeling and Brown (2010) compared the output of the 0–7.2°C, Utah and Dynamic models globally and verified that conversion factors between the chill models are regionally dependent and therefore inconsistent. Consequently, thresholds determined for varieties using one chill model cannot be interpreted using output from a different chill model. Some authors have investigated chill concurrently using two or more chill models (Alburquerque et al. 2008; Luedeling et al. 2009b, d, 2011b; Ruiz et al. 2007; Sunley et al. 2006; Viti et al. 2010) but conversion factors between the models were conflicting. Here, three common chill models are assessed for Australian conditions, allowing investigation into chill model sensitivity to warming, consideration of projected chill accumulation measured in different units (e.g. Table 1) and comparison to other studies. Growing support for the Dynamic model and previous research highlighting the higher sensitivities of alternate chill models to warming (Luedeling et al. 2009a) indicate that results from the Dynamic model will be most applicable.

Methodology regarding interpretation of climate projection data is a major consideration in this study. Appropriate representation of Atmosphere-Ocean General Circulation Model (AOGCM) uncertainty is important for projection analyses as models can differ greatly in output (Jun et al. 2008; Watterson 2011). Emission scenarios (Nakicenovic and Swart 2000) are intentionally excluded from the analysis. This is because the IPCC's Special Report on Emission Scenarios (SRES) greenhouse gas (GHG) emission scenario storylines may not eventuate, especially if GHG production continues unabated or if mitigation policies are implemented (e.g. Meinshausen et al. 2009). To improve the applicability of the results, SRES pathways are used for interpretation of results rather than being embedded in the methodology.

In this study, chill projections for 13 sites across Australia using three chilling models were calculated. Six AOGCMs were selected, cross-validated against existing model skill assessments (Suppiah et al. 2007; Watterson 2011), to ensure the maximum range of likely outcomes were included in the results. Temperature projections were created using localised monthly minimum and maximum temperature perturbations relating to 1, 2 and 3°C global average temperature increases. Thus, results are comparable across locations and are independent of GHG emission projection uncertainty.

Methods

Future chill conditions were evaluated at 13 perennial horticultural production locations in Australia (Fig. 1 and Table 2) as used by Darbyshire et al. (2011) for historical chilling analysis.

Climate data

Historical daily minimum and maximum data from 1911 to 2009 were sourced from 0.05° by 0.05° grids (Jones et al. 2009). This dataset was used by Darbyshire et al. (2011) to investigate historical chilling conditions in Australia as quality historical in situ meteorological data are not available for the major production areas. Climate projection output from 21 AOGCMs were provided by the Queensland Climate Change Centre of Excellence (QCCCE). The projection data were provided as localised monthly minimum and maximum temperature perturbations per 1°C global temperature increase from the 1975–2004 baseline. The pattern scaling methodology used to produce future climates, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), is described in Page and Jones (2001) and Ricketts and Page (2007). Where climate variables for some AOGCMs were not available from CSIRO, they were in-filled by QCCCE using regression methods.

Chill models

The 0–7.2°C model (Bennett 1949; Weinberger 1950) is a simple step-function which records one chill hour for every hour that temperature is within the 0–7.2°C interval and nil chill hours otherwise. The Modified Utah model (Linvill 1990) builds on the simplicity of the 0–7.2°C model. It incorporates an optimum chilling temperature, which is assigned one chill unit, with temperatures either side of the optimum declining in ability to contribute to the chilling process. This model additionally accounts for the negation effect of high temperatures on chilling, with temperatures over 14°C reversing previously accumulated chill, an aspect lacking in the 0–7.2°C model. These two models are time independent, meaning the effectiveness of chilling temperatures are constant across the chill period. Independence from time using the Modified Utah model means chill accumulated early in winter can be negated by late season warming.

The Dynamic model (Erez et al. 1990; Fishman et al. 1987) accumulates chill using a non-static approach. Cold temperatures initially contribute to the creation of an intermediate product. This product can then be destroyed by subsequent high temperatures. However, once a threshold amount of the intermediate product is amassed it is irreversibly banked as a chill portion. This model incorporates the aspects of the Modified Utah model, optimum chill temperatures and negation influences of high temperatures, although this aspect is time dependent. It further accounts for the enhancing effects of moderate temperatures on chilling. Mathematical descriptions of all three chill models are contained in Darbyshire et al. (2011).

Luedeling et al. (2009c) developed a simple yet effective chill statistic in their assessment of future chill conditions in California. They found the 10th percentile of accumulated

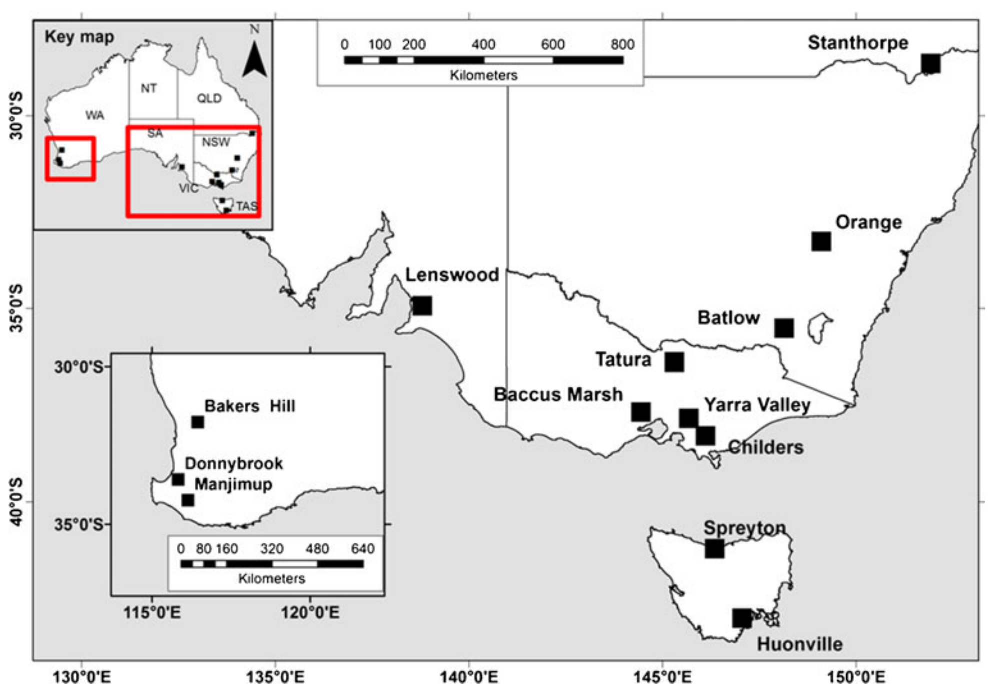

Fig. 1 The 13 sites used for chill analysis for the Australian states Western Australia (WA), South Australia (SA), Queensland (QLD), New South Wales (NSW), Victoria (VIC) and Tasmania (TAS) (from Darbyshire et al. 2011)

Table 2 Geographical and climate aspects of the study sites. Elevation is measured in metres above sea level. Mean winter temperature range is the absolute mean (June, July, August) temperature range for the years 1911–2009

Location	State	Latitude	Longitude	Elevation (m)	Mean winter temperature range (°C)
Batlow	NSW	−35.52	148.14	787	3.8–6.2
Orange	NSW	−33.27	149.10	865	4.7–7.9
Stanthorpe	QLD	−28.66	151.93	801	7.6–10.3
Lenswood	SA	−34.94	138.79	430	7.6–9.9
Huonville	TAS	−43.03	147.05	7	6.7–8.8
Spreyton	TAS	−41.22	146.35	16	7.6–9.8
Tatura	VIC	−36.39	145.31	112	7.8–9.9
Yarra Valley	VIC	−37.84	145.68	182	7.4–9.2
Childers	VIC	−38.30	146.11	364	7.2–8.9
Bacchus Marsh	VIC	−37.68	144.44	104	8.5–10.3
Manjimup	WA	−34.24	116.14	287	9.6–12.4
Donnybrook	WA	−33.58	115.83	67	10.1–12.9
Bakers Hill	WA	−31.77	116.45	301	10.0–12.8

chill from typical weather distributions, calculated from calibrated synthetically generated data, and classified this value as 'safe winter chill'. It represents a minimum threshold amount of chill that can be reliably expected in most years (90%). As stated by the authors, this variable is likely to be more useful than mean chill as it indicates the minimum likely amount of chill expected rather than that expected in an average year. Luedeling et al. (2011a) also used this approach to analyse future global chilling conditions. Similarly to Luedeling et al. (2009c) and Luedeling et al. (2011b), results will be calculated using safe winter chill.

Atmosphere-ocean general circulation model selection

A selection of atmosphere-ocean general circulation models (AOGCMs) was made from the 21 available, whereby appropriate representation of the range of model responses was the main criteria for selection, with the benefit of reducing possible confusion resulting from presenting too much redundant information (Smith and Chandler 2010). This method, described in Clarke et al. (2011), seeks to categorise and then rank AOGCM output for climate variables of interest over defined regions in Australia. Three AOGCMs (GISS-AOM, GISS-ER and GISS-EH) were not included in the model appraisal as they have been found to perform poorly in the Australian region (Smith and Chandler 2010; Suppiah et al. 2007; van Oldenborgh et al. 2005). The remaining 18 AOGCMs were assessed. Selection was performed through initially categorising the models into 'slightly warmer' (<0.5°C), 'warmer' (0.5–1.0°C) and 'hotter' (>1.0°C) groupings, for each AOGCM region, following Clarke et al. (2011). Through this approach the relative likelihood of the category can be evaluated through calculating the percentage of all models that fall into each category. Then for each AOGCM area, the absolute hottest and coolest models were identified and included for further analysis, regardless of likelihood.

For all areas, the hottest model was CSIRO-Mk3.5. The coolest model differed between areas, as identified in Table 3. By automatically including the hottest model and the four coolest models, the full range of likely temperature change was included for each area. Finally, for the most populated category in each AOGCM area, the model closest to the group median was identified. For four of the areas (WA, SA, NSW and QLD) this was the MRI-CGCM2.3.2 model. This model was also included for analysis. For the TAS and VIC areas many models were equally representative of the group median with no model clearly selectable.

Through this process, six models were selected for analysis; CSIRO-Mk3.5, BCCR-BCM2.0, MIROC3.2_medres, FGOALS-g1.0, ECHO-G, MRI-CGCM2.3.2 (Table 3). Suppiah et al. (2007) tested the reliability of 23 AOGCMs in the Australian region and found 15 AOGCMs performed adequately. The six AOGCMs selected here are included in their set of reliable models.

These selected models were also compared to a recent study that partitions 23 AOGCMs based on historical large-scale pattern change of temperature and precipitation (Watterson 2011). Watterson (2011) defined four 'representative future climates' each with particular temperature and precipitation conditions over Australia. The 23 models fell fairly evenly between the four categories resulting in the author concluding each future is equally likely (Watterson 2011). At least one of the six models selected here fell into each of the four categories. Therefore, each of the representative future climates defined by Watterson (2011) have representation in the selection of six AOGCMs, increasing confidence that appropriate uncertainty due to AOGCM variability was included in the results.

Projected hourly temperatures

Expected future warming of the globe will not be uniform, meaning that for a global average warming of 1°C, some regions will warm less and some will warm more than the global average. Seasonal changes are also likely to also vary from the average, with for example summer warming more than winter. Further, minimum and maximum temperatures are also expected to respond differentially to a prescribed degree of warming. These regional and temporal variations, as interpreted by AOGCMs, are incorporated into the modelling in this study. As a result, the projections relative to 1, 2 and 3°C increases in global average temperature are comparable across sites, improving on Hennessy and Clayton-

Table 3 Representative area (sites), overall coolest, overall hottest and most likely AOGCMs. The most likely category represents the model closest to group median of most populated category (slightly warmer, warmer or hotter)

Representative area (sites)	Coolest model	Most likely	Hottest model
NSW (Batlow, Orange)	ECHO-G	MRI-CGCM2.3.2	CSIRO Mk 3.5
QLD (Stanthorpe)	ECHO-G	MRI-CGCM2.3.2	CSIRO Mk 3.5
SA (Lenswood)	MIROC3.2_medres	MRI-CGCM2.3.2	CSIRO Mk 3.5
TAS (Huonville, Spreyton)	FGOALS-g1.0		CSIRO Mk 3.5
VIC (Tatura, Yarra Valley, Childers)	MIROC3.2_medres		CSIRO Mk 3.5
WA (Manjimup, Donnybrook, Bakers Hill)	BCCR-BCM2.0	MRI-CGCM2.3.2	CSIRO Mk 3.5

Greene's (1995) initial sensitivity analysis. Methodology also differed from the former sensitivity analysis in that minimum and maximum temperature perturbations were used rather than an average temperature change.

Monthly minimum and maximum temperature perturbations per 1°C global temperature increase for each of the six AOGCMs were added to the respective historical daily temperature time-series at each location. For example, the localised August minimum temperature perturbation at Batlow was added to the respective historical August minimum daily temperature time series at Batlow. The temperature perturbations per degree warming were scaled up to represent 2 and 3°C global perturbations by simple multiplication of the localised change per degree warming at each site by the respective global temperature increase (2 or 3). Similarly to 1°C perturbations these 2 and 3°C changes were added to the historical daily minimum/maximum dataset to produce projected temperature series.

The projected daily temperature time-series were then converted into hourly temperatures, the temporal scale required by the chill models, following the methods in Linvill (1990) and Darbyshire et al. (2011). The hourly temperature projection data were run through each of the three chill models for all six AOGCMs at each location. Chill was defined to accumulate from 1 May–31 August inclusively for all chill models. Safe winter chill defined by Luedeling et al. (2009c) was calculated and used to investigate changes in chill conditions.

The future chill conditions were presented using cumulative probability curves. The 99 years in the historical dataset were used to represent natural variability for 'present' conditions. The perturbed data similarly contained 99 points within each AOGCM to capture likely natural variation. Results using cumulative distribution functions indicate the portion, or percentage, of the distribution that achieves a minimum chill amount. Using safe winter chill, this is the 10th percentile of the data. The intersection of the 10th percentile line with the curves then determined the safe winter chill value.

Results

Future chill profiles differed between chill models as demonstrated at Batlow (Fig. 2). According to the Dynamic model, a 1°C increase in global average temperature caused a small decline in accumulated chill portions, with further warming causing greater decreases. The Modified Utah model results for a 1°C increase showed little impact on chill accumulation, and for some AOGCMs total chill accumulation increased (Fig. 2). Again, with further warming, accumulated chill declined. The 0–7.2°C model showed a progressive decline in chill accumulation with increases to global average temperatures.

The shape of the distribution of chill received also tended to change according to chill model. At Batlow, for the Dynamic model the distribution broadened with warming, meaning the variability of chill received increased. This was particularly evident under the warmest AOGCM for a 3°C increase (Fig. 2). Limited change was observed in the shape of future chill distribution for the Modified Utah and 0–7.2°C model, indicating similar variance to today will continue into the future.

Not all locations demonstrated divergence between the chill models. For example, results from Donnybrook indicated a decline across all chill models (Fig. 3). Variability did not change greatly with increasing temperature at Donnybrook, except for the 0–7.2°C model, which showed less variability with warming.

Site differences in response to warming were evident (Tables 4, 5, 6). Percentage change in safe winter chill from present values was included in the results to indicate likely changes from current conditions. The range of results represents the range of the six AOGCMs.

Changes to safe winter chill differed between the chill models. For instance, 3°C warming at Lenswood using the Dynamic model indicated a 19–37% decline in safe winter chill compared to current conditions while the Modified Utah model suggested a 30–53% drop and the 0–7.2°C model was more severe with a 57–78% reduction. The three Western Australia sites (Manjimup, Donnybrook and Bakers Hill) recorded the greatest decline in safe winter chill across all chill models. Other sites showed a much lower impact, particularly Batlow, Orange and Huonville. In general, the Dynamic model showed the least decline in safe winter chill, followed by the Modified Utah model, while the 0–7.2°C model tended to predict slightly larger reductions.

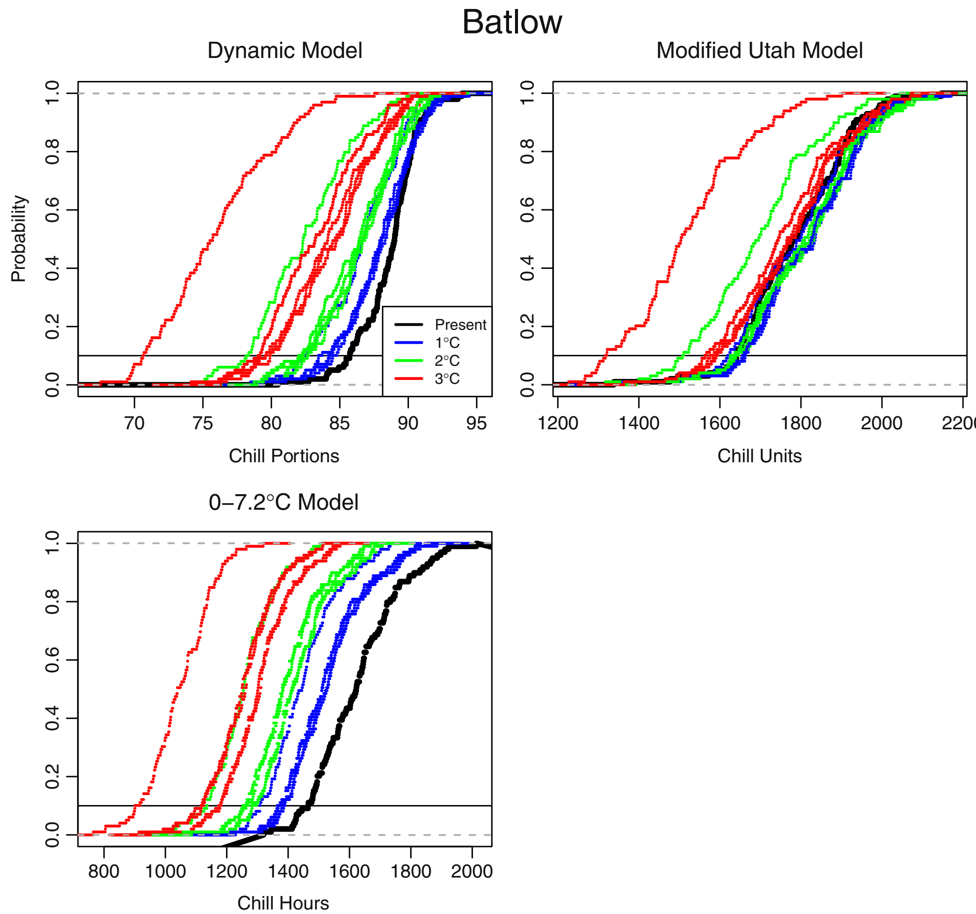

Fig. 2 Cumulative distribution functions for projected chill conditions at Batlow (NSW) according to the Dynamic, Modified Utah and 0–7.2°C models. Plots indicate current and localised change for a 1, 2 and 3°C global average temperature increase for six atmosphere-ocean general circulation models (AOGCMs). The *solid horizontal line* is the 10th percentile representing 'safe winter chill'

Discussion

The results from this study update and expand the only other chilling projection assessment for Australia (Hennessy and Clayton-Greene 1995) and contribute to the small number of studies that have calculated chill projections across the globe (Baldocchi and Wong 2008; Luedeling et al. 2011b; Luedeling et al. 2009a). Findings broadly support Luedeling et al.'s (2011a) global analysis of chill using the Dynamic model, indicating a decline in chill with increasing temperature over Australia. Site sensitivity to warming showed locations that are currently cooler (e.g. Batlow, Huonville and Orange) will experience a minor impact while warmer sites (e.g. Bakers Hill, Manjimup and Donnybrook) will be more adversely affected.

Comparison of these results to Hennessy and Clayton-Greene's (1995) assessment of future chilling conditions in Australia showed general agreement. Six locations were common to both studies, with the values in Hennessy and Clayton-Greene (1995) mostly falling within the ranges reported here. A notable exception was Orange; 1,908 chill units were computed for Orange under 3°C warming according to Hennessy and Clayton-Greene (1995), which is more than current conditions according to this assessment (1,481 chill units). This discrepancy has several potential causes. Firstly, different baseline climate datasets were used. Hennessy and Clayton-Greene (1995) used historical observations from stations with 2 or more years of continuous daily data while historical temperature surfaces spanning 99 years (Jones et al. 2009) were used here. Different projection data were also used. Here, localised monthly maximum and minimum warming according to mean global temperature increases was used whilst Hennessy and Clayton-Greene (1995) used simple 1°C, 2°C and 3°C additions for their sensitivity study. Secondly, different chill periods were applied. The chill period was bounded in this study while Hennessy and Clayton-Greene (1995) used the inbuilt model definition (the positive part of the curve). Finally, safe winter chill was used for analysis here while Hennessy and Clayton-Greene (1995) used mean accumulation, which will produce higher values.

The projected results can be used to evaluate appropriate growing regions into the future, assisting with forward planning and adaptation strategies. For instance, Zhang and Taylor (2011) determined a chill threshold of 59 chill portions for Sirora pistachio (Table 1). An industry report discussed expansion of pistachios in Australia (Robinson 1998) and identified locations near Tatura, Orange and Batlow, among other sites, as potential areas for development.

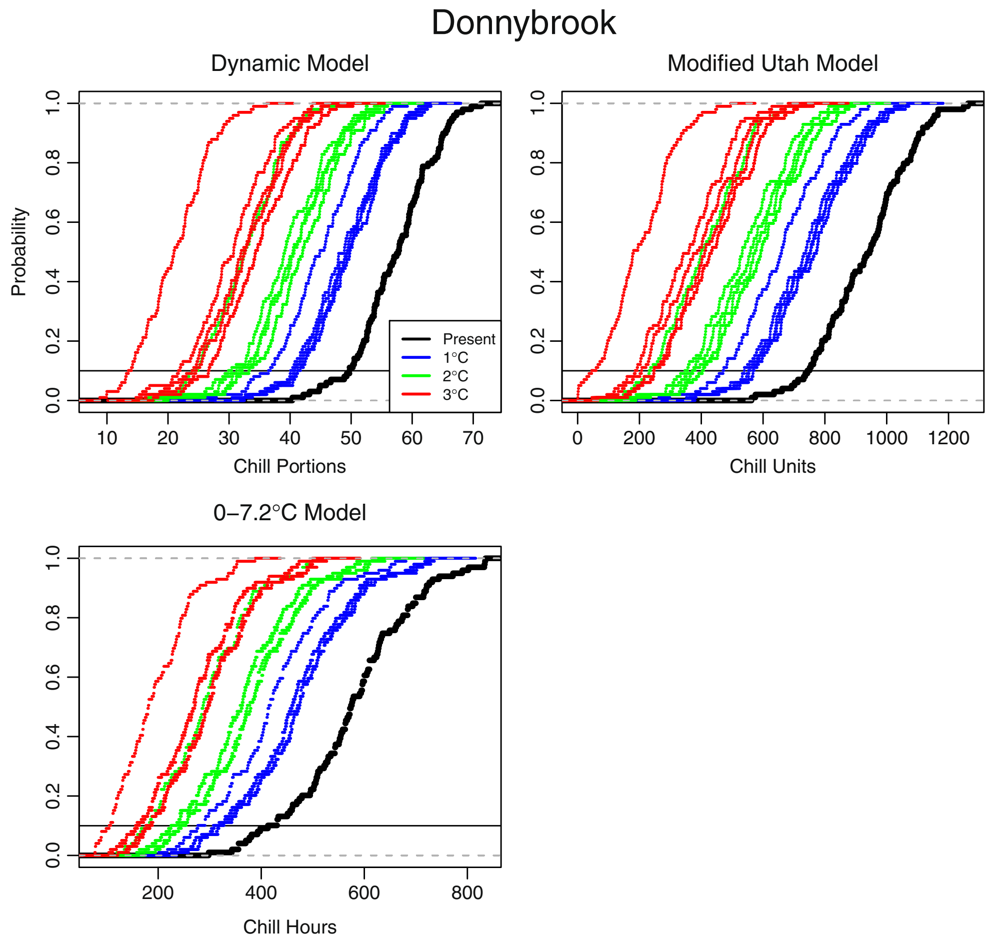

Fig. 3 Cumulative distribution functions for projected chill conditions at Donnybrook (WA) according to the Dynamic, Modified Utah and 0–7.2°C models. Plots indicate current and localised change for a 1, 2 and 3°C global average temperature increase for six AOGCMs. The *solid horizontal line* is the 10th percentile representing 'safe winter chill'

According to the results found here, sufficient chill will be accumulated at Batlow under all warming scenarios for this variety. Orange is also likely to be suitable in regard to chill conditions; however, one AOGCM indicates insufficient chill with 3°C warming. Tatura is likely to become unsuitable for Sirora pistachio, with 2°C or more increases to global average temperatures. It should be appreciated that chill is only one climate aspect that needs consideration for industry expansion, with other conditions, such as rainfall, also important to incorporate.

Given these results, adaptation of current planting can be considered in the context of likely exposure to adequate chill. Locations at risk of receiving insufficient chill have several management options available. For instance, rest breaking agents can be applied to existing crops in areas where insufficient chill is expected (e.g. Petri et al. 2008; Sheard et al. 2009). When replanting, growers may consider planting lower chill varieties (e.g. Topp and Sherman 2000). For some locations, larger transformational change may be necessary, such as converting to different horticultural crops or production systems. These decisions will be dependent on many factors, including trends in other climate variables as well as market and social drivers. Given the various adaptation options (Webb and Whetton 2010), regional effects and different grower capacity (Marshall et al. 2010), sweeping change is unlikely to occur and adaptation will differ from farm to farm.

In order for the fruit and nut industry to use the results found here, further on-site research on varietal chill thresholds is required. Many cultivars have not been the subject of chill analysis (e.g. Pink Lady apple) and certainly not within Australia. This is particularly important as recent research has indicated that geographical location can affect required chilling substantially (Campoy et al. 2012). Although different chill models have been used in chill analyses, there is growing support and evidence to suggest that they are not equally accurate in capturing the chilling process. It is recommended that new analyses or field observations be carried out using the Dynamic model due to positive findings in the literature (Alburquerque et al. 2008; Campoy et al. 2011a; Erez et al. 1990; Luedeling et al. 2009b; Perez et al. 2008; Ruiz et al. 2007; Viti et al. 2010), and its appealing structure—leading it to be described as the current milestone dormancy model (Campoy et al. 2011b). Use of other chill models for planning purposes may cause mismanagement as these models do not capture the chilling process as well as the Dynamic model.

Table 4 Safe winter chill portions (Dynamic model). The second row contains percentage change in safe winter chill from the historical dataset, that is the 'Present' column. The range in results represents the variation in response resulting from the six AOGCMs selected to represent the range of future temperature projections (Table 3)

Location	Present	1°C	2°C	3°C
Batlow	85.7	82.6–84.7	78.3–82.7	70.7–79.9
	–	−4 to −1%	−9 to −4%	−18 to −7%
Orange	80.4	74.6–78.8	65.9–74.4	56.2–71.2
	–	−7 to −2%	−18 to −7%	−30 to −11%
Stanthorpe	66.7	52.1–60.7	36.6–53	22.7–46.1
	–	−22 to −9%	−45 to −21%	−66 to −31%
Lenswood	80.7	73.9–76.6	63.6–72.5	51.2–65.7
	–	−8 to −5%	−21 to −10%	−37 to −19%
Huonville	84.5	81.6–83	75.8–8	68.8–77.2
	–	−3 to −2%	−10 to −4%	−19 to −9%
Spreyton	83.3	76.4–78.9	68.3–74	57.7–67.8
	–	−8 to −5%	−18 to −11%	−31 to −19%
Tatura	74.9	64.9–68.6	54.6–64.2	41–58.3
	–	−13 to −8%	−27 to −14%	−45 to −22%
Yarra Valley	82	75.2–78.2	65.2–74.1	53.7–68
	–	−8 to −5%	−20 to −10%	−35 to −17%
Childers	86.5	80.1–82.8	71.6–78.6	59.1–72.8
	–	−7 to −4%	−17 to −9%	−32 to −16%
Bacchus Marsh	73.6	65.6–68.9	52.7–63.1	39–56
	–	−11 to −6%	−28 to −14%	−47 to −24%
Manjimup	58.8	45.4–51.7	32.8–44.6	21.1–35
	–	−23 to −12%	−44 to −24%	−64 to −40%
Donnybrook	49.7	36.7–41.6	24.7–33.3	13.9–26.7
	–	−26 to −16%	−50 to −33%	−72 to −46%
Bakers Hill	49.8	35–40.5	21.8–32.1	11.4–24
	–	−30 to −19%	−56 to −36%	−77 to −52%

Variability in chill received, which is also important for management, differed between the chill models. Changes in variability are reflected by changes in the slope of the cumulative probability curves. A steeper curve indicates less variability while a flatter curve relates to greater variability. The 0–7.2°C model indicated similar or a decrease in variability with increased global average temperature. The observed decrease in variability was more prevalent in warmer locations (e.g. Donnybrook, Fig. 3). This is likely to be a result of the chill model structure, which has sharp step-change boundaries. For example, at Donnybrook, a larger proportion of temperatures were higher than the 7.2°C boundary, lowering the overall accumulated chill and shrinking the right tail of the distribution, lowering the overall variability.

The Modified Utah model was the only model to record an increase in chill with warming (Batlow). The model structure is the underlying cause. Batlow is a cold location by Australian standards with a mean winter temperature of approximately 3.8–6.2°C (Table 2). An increase of 1°C to global average temperature moved temperatures at Batlow into the optimum temperature range of the Modified Utah model, which peaks at 7°C. Therefore, total chill accumulation increased slightly for some of the AOGCMs; however, further warming pushed temperatures passed this optimum, causing a decline in chill accumulation.

Generally, the Dynamic model recorded lower percentage loss of safe winter chill across all locations. The dampening effect observed is likely a result of complexity of the relationship between temperature and chill in the model. The negation of high temperatures in the Dynamic model is quite intricate, dependent on the temperature value, duration and interaction with low temperatures. Additionally, the Dynamic model has provision for enhancing chill accumulation when chilling temperatures are cycled with moderate temperatures (13–15°C). The sophistication of the Dynamic model makes diagnosis of causation of observed changes more difficult.

Fixed chill periods were used in this assessment to calculate future chilling conditions. It is possible that timing of both the initiation and breaking of dormancy could shift with climate change. Depending on how the chill period is modified, artificial addition of warmer temperatures may have been included in this assessment, slightly overestimating declines. However, as Luedeling et al. (2011a)

Table 5 As for Table 4 but modelled using the Modified Utah model

Location	Present	1°C	2°C	3°C
Batlow	1,641	1,623–1,664	1,510–1,645	1,321–1,594
	–	−1– to 1%	−8 to 0%	−20 to −3%
Orange	1,481	1,378–1,455	1,198–1,404	938–1,326
	–	−7 to −2%	−19 to −5%	−37 to −10%
Stanthorpe	1,059	795–956	492–838	268–680
	–	−25 to −10%	−54 to −21%	−75 to −36%
Lenswood	1,785	1,520–1,631	1,189–1,463	842–1,256
	–	−15 to −9%	−33 to −18%	−53 to −30%
Huonville	1,737	1,638–1,693	1,487–1,615	1,293–1,521
	–	−6 to −3%	−14 to −7%	−26 to −12%
Spreyton	1,734	1,507–1,607	1,244–1,426	953–1,262
	–	−13 to −7%	−28 to −18%	−45 to −27%
Tatura	1,433	1,184–1,306	911–1,175	625–1,023
	–	−17 to −9%	−36 to −18%	−56 to −29%
Yarra Valley	1,727	1,508–1,614	1,219–1,462	871–1,294
	–	−13 to −7%	−29 to −15%	−50 to −25%
Childers	1,922	1,696–1,804	1,395–1,640	1,041–1,451
	–	−12 to −6%	−27 to −15%	−46 to −25%
Bacchus Marsh	1,405	1,141–1,262	855–1,106	550–935
	–	−19 to −10%	−39 to −21%	−61 to −33%
Manjimup	1,001	701–809	389–632	161–440
	–	−30 to −19%	−61 to −37%	−84 to −56%
Donnybrook	749	472–570	235–406	57–248
	–	−37 to −24%	−69 to −46%	−92 to −67%
Bakers Hill	801	466–613	193–399	7–246
	–	−42 to −23%	−76 to −50%	−99 to −69%

comment, the Dynamic model has an inbuilt process that restricts chill accumulation to periods of appropriate chilling temperatures. Therefore any bias would be mostly characterised in results from the Modified Utah model, due to the time-independent negation of higher temperatures.

The timing of future impacts due to enhanced greenhouse conditions are dependent on how GHG emission pathways evolve. This study specifically avoided framing the analysis using GHG emission scenarios (Nakicenovic and Swart 2000) to ensure results remain relevant if SRES pathways become redundant. However, an indication of likely timing of the impacts can be provided assuming a SRES framework does eventuate. For instance, a 1°C increase to global average temperatures is expected to occur around 2030 according to high emission scenarios (IPCC 2007), while this may be delayed if a lower emissions pathway is followed. Similarly, a 2°C increase is expected to occur at about 2050 for a fossil fuel intensive pathway (IPCC 2007) though may not occur until the next century if aggressive global mitigation efforts are enacted. Increases to global average temperature of 3°C are expected to occur around 2070 at the earliest, again timing is dependent on emission scenario, or more specifically, on global emissions and mitigation efforts. The advantage of using emission scenarios to inform likely timeframes of impacts rather than have them define the impacts themselves is that, if emission storylines are modified, reassessment of the time that threshold global temperatures are reached is required rather than reanalysis of the entire impact study.

AOGCMs are continually developed alongside GHG emission scenarios. Reanalysis of impact assessments may be necessary if results from updated AOGCMs differ significantly from the models used in this study. Nonetheless, AOGCM selection is very important in climate change impact analyses as results can vary greatly between models (Jun et al. 2008; Watterson 2011). Inclusion of a justification of AOGCM selection is a point of difference in this analysis compared to other impact studies (Baldocchi and Wong 2008; Eccel et al. 2009; Kaukoranta et al. 2010; Luedeling et al. 2011a; Luedeling et al. 2009c). The approach to subselect AOGCMs used was relatively simple but the full range of results from the available models are likely to have been captured and the selection was cross-checked with studies of climate model skill to avoid accidental bias. While

Table 6 As for Table 4 but modelled using the 0–7.2°C model

Location	Present	1°C	2°C	3°C
Batlow	1,466	1,309–1,388	1,136–1,294	914–1,180
	–	−11 to −5%	−23 to −12%	−38 to −20%
Orange	1,263	1,079–1,185	865–1,059	667–934
	–	−15 to −6%	−32 to −16%	−47 to −26%
Stanthorpe	781	615–692	447–606	302–524
	–	−21 to −11%	−43 to −22%	−61 to −33%
Lenswood	681	438–523	267–407	153–292
	–	−36 to −23%	−61 to −40%	−78 to −57%
Huonville	1,224	1,048–1,106	861–961	634–840
	–	−14 to −10%	−30 to −21%	−48 to −31%
Spreyton	873	669–723	499–590	360–466
	–	−23 to −17%	−43 to −32%	−59 to −47%
Tatura	941	735–815	542–693	375–562
	–	−22 to −13%	−42 to −26%	−60 to −40%
Yarra Valley	1,020	777–863	539–716	342–572
	–	−24 to −15%	−47 to −30%	−66 to −44%
Childers	995	698–809	469–636	288–495
	–	−30 to −19%	−53 to −36%	−71 to −50%
Bacchus Marsh	865	647–726	452–602	302–485
	–	−25 to −16%	−48 to −30%	−65 to −44%
Manjimup	325	192–232	108–165	52–114
	–	−41 to −29%	−67 to −49%	−84 to −65%
Donnybrook	427	288–326	182–251	107–186
	–	−33 to −24%	−57 to −41%	−75 to −56%
Bakers Hill	364	221–281	119–203	59–142
	–	−39 to −23%	−67 to −44%	−84 to −61%

more scrutiny of the reliability of individual AOGCMs could have been carried out, the aim of this study was to assess changes in chill rather than complete a model skill analysis. Through using previous climate model performance studies, a justification of the inclusion of AOGCMs was described. Such defences for model selection are recommended in all climate change impact studies.

Conclusions

This analysis represents a significant update to the previous climate impact analysis of chill in Australia and highlights that sensitivity studies are a useful method for impact assessments. Regional differences of impacts on chill are likely in Australia, with the Western Australia sites most adversely affected, potentially impacting future production success. The severity and rate of decline in chill accumulation was dependent on which chill model was used with the Dynamic model, indicating a slower rate of decline followed by the Modified Utah and 0–7.2°C models.

Many varietal thresholds have been reported in different, non-convertible, units. However, use of the results found here in combination with thresholds determined using the 0–7.2°C or Modified Utah models is not recommended. As the Dynamic model has been shown to be the most plausible descriptor of chill it should be used for future chill threshold assessments and management decisions. Indeed, reassessment of chill requirements using the Dynamic model is also required. Use of alternate chill models may lead to mismanagement as they do not characterise chill as well as the Dynamic model.

Projections using a sensitivity approach of localised temperature change per global average temperature increase have simplified communication of future climate projection uncertainty, and the results will remain viable into the future, regardless of GHG emission pathways. AOGCM selection was highlighted as an important methodological factor for consideration, with a justification of included AOGCMs necessary in all impact assessments. Future farm management decisions can be made with consideration of the likely changes in chill accumulation reported here, with adaptation, at least to some degree, being necessary for most production areas in Australia within the next 50 years.

Acknowledgements The authors thank the Australian Bureau of Meteorology for providing the historical data, and QCCCE and CSIRO for the projection data used in the analysis. Ian Smith (BOM), Kevin Hennessy (CSIRO) and Jim Ricketts (QCCCE) also provided valuable advice on data and methodology.

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