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Sensitivity of winter chill models for fruit and nut trees to climatic changes expected in California's Central Valley

Eike Luedeling[a,1,*], Minghua Zhang[a,2,*], Volker Luedeling[b], Evan H. Girvetz[c,3]

[a] Department of Land, Air and Water Resources, University of California Davis, One Shields Ave, Davis, CA 95616, United States
[b] Software Developer, D-30149 Hannover, Germany
[c] College of Forest Resources, University of Washington, Box 352100, Seattle, WA 98195, United States

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ABSTRACT

Many fruit and nut crops require cold temperatures in winter to break dormancy. Quantifying this chilling requirement and selecting appropriate cultivars for the climate of a growing region is crucial for successful cultivation of such crops. Several models exist to quantify winter chill, and each growing region uses a model that has been shown to perform well under local climatic conditions. We tested the sensitivity of four commonly used chilling models to projected climatic change likely to affect fruit and nut production in the near future.

For six sites in California's Central Valley, we generated 100 years of synthetic hourly weather records, representing climatic conditions in 1950, 2000 and projected temperatures in 2041–2060 derived from three IPCC-AR4 General Circulation Models (GCMs; CSIRO, HadCM3 and MIROC; A2 greenhouse gas emissions scenario). Mean winter chill for each site and year was calculated using the Chilling Hours, Utah, Positive Utah and Dynamic models.

All chilling models predicted substantial decreases in winter chill at all sites, but the extent of these decreases varied depending on the model used. Across all sites between 1950 and 2050, mean chilling was predicted to decrease by 33% (Chilling Hours), 26% (Utah Model), 16% (Dynamic Model) and 14% (Positive Utah Model).

Research efforts are needed to identify the most appropriate chilling model for preparing fruit and nut growers for the imminent effects of climate change.

1. Introduction

Many fruit and nut trees require cold temperatures during the winter to overcome their seasonal dormancy (Knight, 1801; Samish, 1954; Vegis, 1961; Saure, 1985; Erez, 2000). Most fruit and nut species that evolved in temperate or cool subtropical climates have such chilling requirements that need to be fulfilled each winter to achieve homogeneous and simultaneous flowering and regular crop yields. In order to select appropriate fruit and nut species and cultivars for the climate of a given site, researchers have developed chilling models, which convert temperature records into a metric of coldness (Bennett, 1949; Richardson et al., 1974; Erez et al., 1990). Using the same chilling model to quantify both a cultivar's chilling requirement and the amount of winter chill available at a given location enables growers to predict whether the cultivar will perform well under the specific temperature conditions of their sites. Chilling models also constitute tools to understand and manage the interannual variation in the time, at with tree crops complete their dormancy. Many growers use estimated winter chill to determine the time line for certain management measures, such as the spraying of rest-breaking chemicals, or to predict their yield potential for the season.

What remains unclear is how well different chilling models predict winter chill, when temperature conditions deviate from historic patterns. Since overwhelming scientific evidence suggests that the global climate is warming (IPCC, 2007), most growing regions might experience substantial temperature increases in the near future, with likely consequences for available winter chill. In California, the strongest warming trend has been identified for daily minimum temperatures during the winter months (LaDochy et al., 2007), indicating that winter chill might be strongly affected by climate change. Fruit and nut orchards might thus be among those agricultural systems in California, and probably in other parts of the world, that are most vulnerable to the environmental

* Corresponding authors. Tel.: +1 530 574 3794.
E-mail addresses: eluedeling@ucdavis.edu (E. Luedeling), mhzhang@ucdavis.edu (M. Zhang), girvetz@u.washington.edu (E.H. Girvetz).
[1] Tel.: +1 530 574 3794.
[2] Tel.: +1 530 754 9292.
[3] Tel.: +1 206 543 5772.

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Table 1
Pairs of CIMIS and NCDC weather stations, location of each station and duration of weather records used in this study.

CIMIS station	Coordinates	Duration	NCDC station	Coordinates	Duration
Davis	38.54°N, 121.78°W	1982–2008	Davis	38.55°N, 121.74°W	1951–2008
San Benito	36.85°N, 121.36°W	1982–2008	Hollister	36.85°N, 121.40°W	1951–2008
Gerber	40.05°N, 122.16°W	1982–2008	Red Bluff	40.15°N, 122.25°W	1951–2008
Shafter	35.53°N, 119.28°W	1982–2008	Bakersfield	35.42°N, 119.05°W	1951–2008
Tracy	37.73°N, 121.47°W	2001–2008	Tracy	37.70°N, 121.42°W	1951–2008
Winters	38.50°N, 121.98°W	1998–2008	Winters	38.53°N, 121.97°W	1951–2008

stresses invoked by climate change. While most annual crops are primarily affected by temperature changes during the spring and summer months, the sustainability of an orchard depends on the prevalence of a certain temperature regime throughout the entire year. Failure to meet the climatic requirements of tree crops can have devastating consequences for growers, since in order to be economically viable, orchards must remain productive over several decades to pay off the investments needed for orchard establishment. It is thus crucial for the sustainability of an orchard operation to accurately estimate the effect of changing climatic conditions on the biology of the cropping systems. This is especially important during the dormant season, since insufficient chilling can severely compromise fruit and nut yields.

The implications of climate change for winter chill have occasionally been investigated (Baldocchi and Wong, 2008; Luedeling et al., in press), but no studies have compared the effects of temperature increases on winter chill, when quantified with different chilling models. The objective of this study is thus to provide an estimate of how sensitively four major chilling models react to observed past, and predicted future climate change, helping tree crop growers refine the tools available to them for understanding and reacting to the consequences of climate change.

1.1. Chilling models in California

In California, one of the most productive fruit and nut growing regions in the world, growers currently cultivate over a million hectares of tree crops with chilling requirements, such as almonds (*Prunus dulcis* Mill. D.A.Webb), walnuts (*Juglans regia* L.), peaches (*Prunus persica* (L.) Batsch), apricots (*Prunus armeniaca* L.) and cherries (*Prunus avium* L.) (USDA, 2004). Depending on species cultivated and location of production, growers in California use one of three different models to quantify chilling. The two most commonly used models are the Chilling Hours Model, developed in the 1930s and 1940s (Bennett, 1949; Weinberger, 1950), and the Utah Model, a refined model added in the 1970s (Richardson et al., 1974). In recent years, growers of cherries, a species with a relatively high chilling requirement, have adopted a third model, the Dynamic Model, which was developed for the warmer conditions in Israel (Fishman et al., 1987a,b; Erez et al., 1990), where the traditional models did not work well. This recent adoption of a new model suggests that warmer winter temperatures require shifting towards a different method to quantify winter chill. It also implies that depending on the range of prevailing temperatures, chilling models can react differently to climate change. We therefore treat California as a test case for the effects of climate change on winter chill, comparing chilling estimates by four chilling models under past observed and future projected climatic conditions.

2. Materials and methods

2.1. Past observed climatic data

For estimating winter chill, we obtained hourly temperature and daily solar radiation records from six weather stations of the California Irrigation Management Information System (CIMIS; California Department of Water Resources, 2008). Stations used were Davis, San Benito (located in Hollister), Gerber, Shafter, Tracy and Winters (Table 1).

Since the CIMIS network was not established before 1982, its suitability for monitoring climatic changes is limited. Daily temperature records for California are available for a much longer time span, providing a better dataset for this purpose. We therefore paired each CIMIS station with a nearby weather station of the network administered by the National Climatic Data Center (NCDC, 2008). For four CIMIS stations, an NCDC station was found in the same town, whereas for Gerber and Shafter, the closest NCDC stations were Red Bluff and Bakersfield at 14 and 24 km distance from the CIMIS station (Fig. 1). From all NCDC stations, records were obtained for all available dates between 1/1/1951 and 4/1/2008 (Table 1).

2.2. Climate scenarios

2.2.1. Future climate scenarios

For the projection of future temperatures, we used projected changes in temperature and precipitation from three General Circulation Models: UKMO-HadCM3, CSIRO-MK3.0, and MIROC3.2 (medres)—each run under the A2 greenhouse gas emission scenario of the Intergovernmental Panel on Climate Change AR4 (IPCC, 2007). The future monthly projections from these models were downscaled by Neilson et al. (unpublished data) to a 5 arc-min (~8 km) resolution using the PRISM (http://www.prism.or-

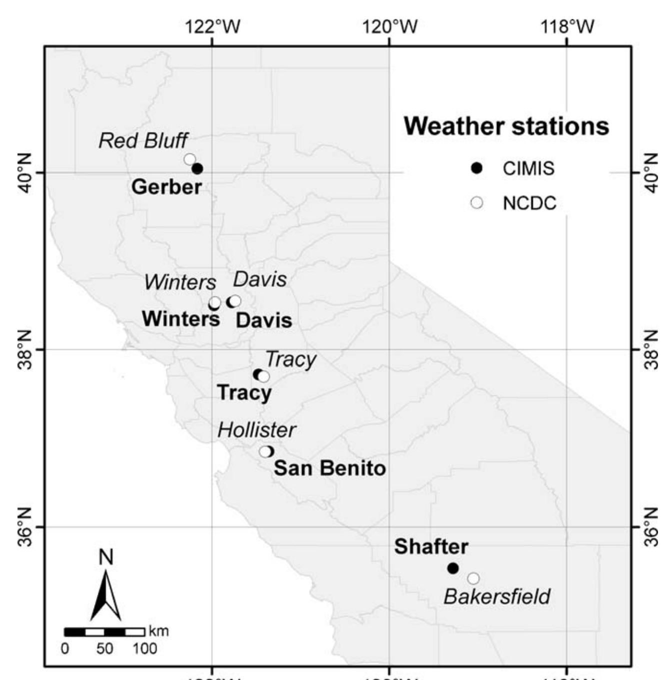

Fig. 1. Location of the CIMIS and NCDC weather stations used in this study within the State of California.

egonstate.edu) climate dataset to calibrate the downscaling. These data were then accessed and analyzed using the ClimateWizard climate change analysis toolbox (http://ClimateWizard.org, E. Girvetz, unpublished data). Using ClimateWizard, the average daily minimum and daily maximum temperatures and daily precipitation projected for each month during 2041–2060 were calculated at each of the six study locations. A 20-year period was averaged to give a robust estimation of monthly temperatures in 2050 that is not influenced by year-to-year modeled fluctuations in the projected climate.

Relative to the long-term average for each site (1951–2006), mean daily maximum temperature was projected to increase by 1.5 °C for the CSIRO model, by 2.3 °C for the HadCM3 model and by 2.2 °C for the MIROC model, on average over all sites (Table 2). Increases in mean daily minimum temperature were projected to be slightly greater at 1.7 °C for the CSIRO model, 2.6 °C for the HadCM3 model and 2.8 °C for the MIROC model (Table 2).

2.2.2. Past climate scenarios

For estimating mean daily minimum and maximum temperatures and precipitation in 1950 and 2000, we first performed separate linear regression analyses for each parameter and station for each month of the year, expressing each parameter as:

$X(m) = a{\cdot}t + b$, with $X(m)$ being the weather parameter analyzed for a particular month m, t the time in years and a and b the coefficients of the regression equations.

For the regressions, we used all available daily data between 1951 and 2006. This time period corresponds to the reference period used by the ClimateWizard. Based on the regression equations, representative estimates of mean monthly maximum temperature, mean monthly minimum temperature and mean monthly precipitation were obtained for both 1950 and 2000. We preferred deriving estimates by regression analysis over using actual observations for these 2 years, because such estimates are less prone to bias introduced by interannual climatic variation.

For the past climate scenarios, mean temperature increases between 1950 and 2000, averaged over all sites, were 0.5 °C for the daily minimum and 0.6 °C for the daily maximum temperature (Table 2). Temperature increases were highest at Winters (minimum: +1.2 °C; maximum: +1.6 °C), and lowest at Hollister (minimum: −0.7 °C; maximum: +1.5 °C).

2.3. Synthetic daily weather records

For each climate scenario, we generated 100 years of daily minimum and maximum temperatures, using the LARS-WG stochastic weather generator (Semenov, 2008). Rather than a time series, each of these data sets represents 100 replicate simulations of the year considered in the scenario, with a random seed introducing interannual variability that is typical of the time period used for calibration of the weather generator. In this calibration, LARS-WG analyzes daily records of minimum and maximum temperature, rainfall and solar radiation of a given site, and calculates statistics that mathematically represent the weather at the site, including the duration of wet and dry periods. Based on these statistics, the weather generator can then be used to produce synthetic weather records for the site, which have the same statistical properties as the observed records. It is also possible to impose climate change scenarios onto these records, such as elevated monthly temperatures or reduced rainfall. These input scenarios provide the assumed deviation of key weather parameters (minimum and maximum temperature, precipitation and solar radiation) from weather conditions prevailing during the calibration period. These deviations were obtained by calculating the difference between the monthly means of minimum and maximum temperature and precipitation assumed for the five scenarios and the mean of the same parameters during the time period used to calibrate the weather generator (1951–2006).

Table 2
Mean daily minimum and maximum temperatures for all climate scenarios at all sites.

Year/GCM	Davis	Hollister	Red Bluff	Shafter	Tracy	Winters
Mean daily minimum temperature (°C)						
1950	8.2	7.0	10.2	9.7	8.3	9.4
2000	7.8	7.4	10.0	9.1	8.1	8.7
2050/CSIRO	8.5	6.7	10.4	10.2	8.5	9.9
2050/HadCM3	9.9	8.4	12.0	11.4	9.9	11.1
2050/MIROC	10.6	9.6	12.8	12.4	11.0	11.8
Mean daily maximum temperature (°C)						
1950	23.4	22.1	24.1	25.8	23.8	24.7
2000	23.0	21.2	24.2	25.8	23.6	23.8
2050/CSIRO	23.7	22.8	24.0	25.7	23.8	25.4
2050/HadCM3	24.9	23.6	25.6	27.2	25.2	26.1
2050/MIROC	25.7	24.2	26.5	28.4	26.0	27.0

2.4. Downscaling of daily temperature records to hourly resolution

Calculating winter chill with the commonly used models requires hourly records of temperature. Since the weather generator's output only consisted of daily values, hourly temperatures had to be derived from these records. Rather than using idealized mathematical curves, we used a procedure based on Partial Least Squares regression (Luedeling et al., in press), relating observed hourly temperatures during the whole duration of the CIMIS data set to observed daily minimum and maximum temperatures of the NCDC data set and daylength modeled using Jarmo Lammi's sunrise/sunset/daylength calculator (downloaded on April 16th, 2008 from http://www.geocities.com/jjlammi/). The statistics package JMP 7 (SAS Institute, Cary, NC, USA) was used to combine available information on hourly and daily temperature and daylength into a data table, to screen all datasets for unreasonable outliers (often representing 'no data'), and to calculate separate regression analyses for each hour of the day. The regression equations obtained from this procedure were used to estimate hourly temperatures for each hour of the synthetic 100-year weather records, resulting in continuous estimates of temperature for 876,000 h per station.

2.5. Chilling models

2.5.1. Chilling Hours Model

The Chilling Hours Model (sometimes referred to as Weinberger Model; Bennett, 1949; Weinberger, 1950), as originally proposed, simply calculates the number of hours, when the temperature (T) is below 7.2 °C (45 F, sometimes converted to 7 or 7.22 °C). It soon became apparent that freezing temperatures did not contribute to winter chill accumulation, leading to the exclusion of such temperatures (Bennett, 1949). At a given time t during the dormancy period (in hours after a fixed starting time at the beginning of the dormancy season), the number of accumulated Chilling Hours (CH) is thus given as:

$$\mathrm{CH}_t = \sum_{i=1}^{t} T_{7.2}, \quad \text{with } T_{7.2} = \begin{cases} 0\,^\circ\mathrm{C} < T < 7.2\,^\circ\mathrm{C} & : 1 \\ \text{else} & : 0 \end{cases}$$

2.5.2. Utah Model

The second model tested was the Utah Model (Richardson et al., 1974), which is similar in concept to the Chilling Hours Model, but assigns different weights to different ranges of temperatures. This approach reflects research showing that chilling efficiency varied with temperature, including negative chilling accumulation by high temperatures (Erez and Lavee, 1971; Richardson et al., 1974). The exact definition of the temperature steps used in this model has been modified to suit the climate of different regions (Shaltout and Unrath, 1983; Richardson et al., 1986), but in California only the original version is currently used:

$$\text{Utah}_t = \sum_{i=1}^{t} T_U, \quad \text{with } T_U = \begin{cases} T \leq 1.4\,^\circ\text{C} & : 0 \\ 1.4\,^\circ\text{C} < T \leq 2.4\,^\circ\text{C} & : 0.5 \\ 2.4\,^\circ\text{C} < T \leq 9.1\,^\circ\text{C} & : 1 \\ 9.1\,^\circ\text{C} < T \leq 12.4\,^\circ\text{C} & : 0.5 \\ 12.4\,^\circ\text{C} < T \leq 15.9\,^\circ\text{C} & : 0 \\ 15.9\,^\circ\text{C} < T \leq 18.0\,^\circ\text{C} & : -0.5 \\ T \geq 18.0\,^\circ\text{C} & : -1 \end{cases}$$

2.5.3. Positive Utah Model

In addition to the models typically used in California, one modified version of the Utah Model is worth considering, because it has been shown to perform well in regions with a warmer climate than present-day California, such as South Africa (Linsley-Noakes and Allan, 1994). In this Positive Utah Model, the negative contributions of warm temperatures to accumulated chilling were removed from the original equation of the Utah Model:

$$\text{Utah+}_t = \sum_{i=1}^{t} T_{U+}, \quad \text{with } T_{U+} = \begin{cases} T \leq 1.4\,^\circ\text{C} & : 0 \\ 1.4\,^\circ\text{C} < T \leq 2.4\,^\circ\text{C} & : 0.5 \\ 2.4\,^\circ\text{C} < T \leq 9.1\,^\circ\text{C} & : 1 \\ 9.1\,^\circ\text{C} < T \leq 12.4\,^\circ\text{C} & : 0.5 \\ T \geq 12.4\,^\circ\text{C} & : 0 \end{cases}$$

2.5.4. Dynamic Model

The Dynamic Model (Fishman et al., 1987a,b; Erez et al., 1990) is currently used in Israel and South Africa. It has also been adopted by cherry growers in California, found to be superior to currently used models in Spain (Ruiz et al., 2007) and suggested for general use in Chile (Perez et al., 2008). The Dynamic Model is currently the only model that explains experimental evidence from controlled temperature studies in Israel. The main findings from these trials were that moderate temperatures enhanced previous chilling (Erez et al., 1979b), and that only recently accumulated chilling was subject to negation (Erez et al., 1979a).

The Dynamic Model postulates that winter chill accumulates in a two-step process. Initially, cold temperatures lead to the formation of an intermediate product. Once a certain quantity of this intermediate has accumulated, it can be transformed into a so-called Chill Portion by a process requiring relatively warm temperatures.

The equations used to calculate Chill Portions are more complex than the other models. While they are difficult to derive from the original publications, we extracted them from a spreadsheet used by plant physiologists to calculate Chill Portions (Kitren Glozer and Amnon Erez, personal communication):

$$x_i = \frac{e^{\text{slp}\cdot\text{tetmlt}\cdot((T_K - \text{tetmlt})/T_K)}}{1 + e^{\text{slp}\cdot\text{tetmlt}\cdot((T_K - \text{tetmlt})/T_K)}}$$

$$x_s = \frac{a_0}{a_1} \cdot e^{(e_1 - e_0)/T_K}$$

$$\text{ak}_1 = a_1 \cdot e^{-(e_1/T_K)}$$

$$\text{inter}_E = x_s - (x_s - \text{inter}_s) \cdot e^{-\text{ak}_1}$$

$$\text{inter}_S = \begin{cases} t = t_0 & : 0 \\ t > t_0 \wedge \text{inter}_{E_{t-1}} < 1 & : \text{inter}_{E_{t-1}} \\ t > t_0 \wedge \text{inter}_{E_{t-1}} \geq 1 & : \text{inter}_{E_{t-1}} \cdot (1 - x_i) \end{cases}$$

$$\text{delt} = \begin{cases} t = t_0 & : 0 \\ t > t_0 \wedge \text{inter}_E < 1 & : 0 \\ t > t_0 \wedge \text{inter}_E \geq 1 & : x_i \cdot \text{inter}_E \end{cases}$$

$$\text{chill portions}_t = \begin{cases} t = t_0 & : \text{delt} \\ t \geq t_0 & : \text{delt} + \text{chill portions}_{t-1} \end{cases}$$

The experimentally derived constants slp, tetmlt, a_0, a_1, e_0 and e_1 were set to 1.6, 277, 139,500, 2.567×10^{18}, 12,888.8 and 4153.5, respectively, according to standard practice in horticultural applications (Kitren Glozer and Amnon Erez, personal communication). T_K is the measured hourly temperature in Kelvin, while t denotes the time during the season (in hours), with t_0 being the starting point of chilling accumulation.

2.6. Summation of seasonal winter chill

For each chilling model, accumulated chilling was calculated for each hour of the temperature record, with the beginning of the chilling season set to November 1st, and the end of the season set to February 29th or March 1st (depending on whether or not the year was a leap year). To facilitate data processing, we developed a Java-based spreadsheet calculator to automatically calculate all chilling estimates from the hourly temperature records.

Since the different chilling models estimate winter chill on different scales, standardization was necessary for comparison. We chose 1950 as the base year for this comparison, and normalized all chilling estimates for the remaining four climate scenarios by the mean chilling observed over all years of the 100-year synthetic weather record for 1950. For each point in time and GCM model run, winter chill estimates were compared using Student's *t*-test.

3. Results

3.1. Winter chill estimates

Among the six stations, winter chill in 1950 ranged from 894 to 1277 Chilling Hours, from 1222 to 1780 Utah Chill Units, from 1509 to 1911 Positive Chill Units and from 68.0 to 81.3 Chill Portions (Table 3). Comparing predicted winter chill for 2000 with observed winter chill during the 10-year period centered on the year 2000 indicated that chilling estimates were representative of actual observations.

The order of the stations was not identical for all models, indicating that winter chill projections calculated with one model are not proportional to winter chill derived using the other models. While most stations did not shift their relative position much over the various model runs, Shafter ranked between 2nd and 6th in winter chill in 2000, depending on which model was used (Table 3). By 2000, winter chill among the study sites had declined to 833–1179 Chilling Hours, 1380–1698 Chill Units, 1588–1881 Positive Chill Units and 69.9–78.0 Chill Portions. Among the simulations representing 2050 conditions, winter chill ranged between 540 and 955 Chilling Hours, between 841 and 1488 Chill Units, between 1273 and 1744 Positive Chill Units, and between 53.3 and 71.2 Chill Portions.

For all sites, mean winter chill declined markedly over time, regardless of the General Circulation Model and chilling model used in the simulation. The only temporary increase in winter chill occurred between 1950 and 2000 at Hollister, when quantifying chilling with the Utah Model, Positive Utah Model or Dynamic Model.

The variation of chilling estimates around the mean predicted winter chill increased for all stations and all chilling models (Table 3), indicating that future winter chill will not only be lower but also less reliable than it is at present. This development most strongly affected the Utah model, for which the coefficient of variation increased by 68% between 1950 and the average of the three 2050 scenarios, on average over all stations. Chill Portions (coefficient of variation increase by 58%), Chilling Hours (+48%) and

Table 3
Means and coefficients of variation (CV%, in percent) of winter chill for six sites in California, quantified with four chilling models[a].

Year/GCM	Chilling Hours		Utah Chill Units		Positive Utah		Chill Portions	
	Mean	CV%	Mean	CV%	Mean	CV%	Mean	CV%
Davis								
1950	1112	13	1708	8	1853	5	79.3	5
2000	1007	13	1597	9	1773	6	76.6	5
2050/CSIRO	812	16	1378	12	1624	7	70.3	7
2050/HadCM3	707	18	1255	14	1533	8	67.3	8
2050/MIROC	619	20	1110	16	1442	8	62.5	9
Hollister								
1950	894	12	1222	11	1509	5	68.0	8
2000	833	15	1380	11	1588	6	72.5	7
2050/CSIRO	689	17	1091	15	1418	7	63.0	9
2050/HadCM3	650	18	975	17	1356	8	59.0	10
2050/MIROC	556	20	841	22	1273	9	53.7	13
Red Bluff								
1950	1221	11	1743	7	1911	5	79.1	5
2000	1179	11	1698	8	1881	5	78.0	5
2050/CSIRO	955	13	1488	10	1744	6	71.2	7
2050/HadCM3	865	15	1401	11	1687	6	68.8	8
2050/MIROC	750	17	1269	13	1603	7	64.8	9
Shafter								
1950	1127	10	1454	8	1726	4	70.3	7
2000	1096	11	1442	9	1721	5	69.9	7
2050/CSIRO	925	13	1221	11	1601	5	62.3	8
2050/HadCM3	836	15	1103	13	1534	6	58.2	10
2050/MIROC	742	17	985	15	1475	6	53.3	11
Tracy								
1950	1054	14	1661	11	1828	7	77.6	6
2000	903	16	1447	13	1687	7	72.1	8
2050/CSIRO	743	19	1237	16	1551	8	65.9	9
2050/HadCM3	635	21	1103	19	1456	9	62.1	11
2050/MIROC	540	24	918	23	1347	9	56.5	12
Winters								
1950	1277	10	1780	8	1910	6	81.3	5
2000	995	13	1563	11	1764	6	74.9	7
2050/CSIRO	884	15	1415	12	1670	7	70.1	8
2050/HadCM3	788	16	1315	13	1600	7	67.4	9
2050/MIROC	691	18	1176	15	1516	8	63.0	10

[a] Winter chill was calculated from synthetic 100-year weather records, representing observed mean temperatures around 1950 and 2000, as well as predicted temperatures in 2050, using the General Circulation Models CSIRO, HadCM3 and MIROC and the IPCC A2 emissions scenario. The Chilling Hours Model, the Utah Model, the Positive Utah Model and the Dynamic Model (Chill Portions) were used to quantify winter chill.

Positive Chill Units (+36%) were also predicted to become less reliable.

3.2. Model comparison

When expressing winter chill calculated with the four models as a proportion relative to mean chilling in 1950, differences between the chilling projections became apparent (Figs. 2 and 3). On average across all stations, the loss of annual chilling between 1950 and 2000 amounted to 10%, when quantified in Chilling Hours, compared to 4% (Utah Chill Units), 3% (Positive Chill Units) and 2% (Chill Portions) for the other models. Averaging over all three General Circulation Models, annual winter chill loss by 2050, compared to 1950, would amount to moderate 15 and 17%, when using Positive Chill Units and Chill Portions, respectively. When calculating winter chill with the models commonly used in California, however, chilling would decline by 26% (Utah Chill Units) and 33% (Chilling Hours). If the climate simulated by the MIROC GCM, which consistently caused the greatest decline in winter chill, turns out to be accurate, California growers could face chilling losses up to 42% of 1950 Chilling Hours, on average. In a quarter of all years, growers would have to expect less than 50% of 1950 Chilling Hours, compared to 58% of Utah Chill Units, 76% of Positive Chill Units and 72% of Chill Portions. For all three General Circulation Models, winter chill conditions as high as or higher than mean winter chill in 1950 occurred in less than 3% of years in the synthetic records for 2050. The only exception was the CSIRO GCM projection, which retained winter chill conditions equal to or above 1950 conditions in 5–6% of simulated years for 2050 for all chill models except Chilling Hours (2% of simulated years).

Simulated winter chill losses in 2050, as averaged over all chilling models and all GCM runs were highest in Tracy at −29% (−39% Chilling Hours; −35% Utah Chill Units; −21% Positive Chill Units; −21% Chill Portions), followed by Winters at −25% (−38%; −27%; −16%; −18%), Davis at −24% (−36%; −27%; −17%; −16%), Shafter at −20% (−26%; −24%; −11%; −18%), Red Bluff at −19% (−30%; −20%; −12%; −14%) and Hollister at −19% (−29%; −21%; −11%; −14%).

4. Discussion

4.1. Projections of winter chill

It was apparent that winter chill decreased throughout California's Central Valley between 1950 and 2000, and must be expected to decrease further, according to the temperatures predicted by General Circulation Model projections created for the Intergovernmental Panel on Climate Change (IPCC, 2007).

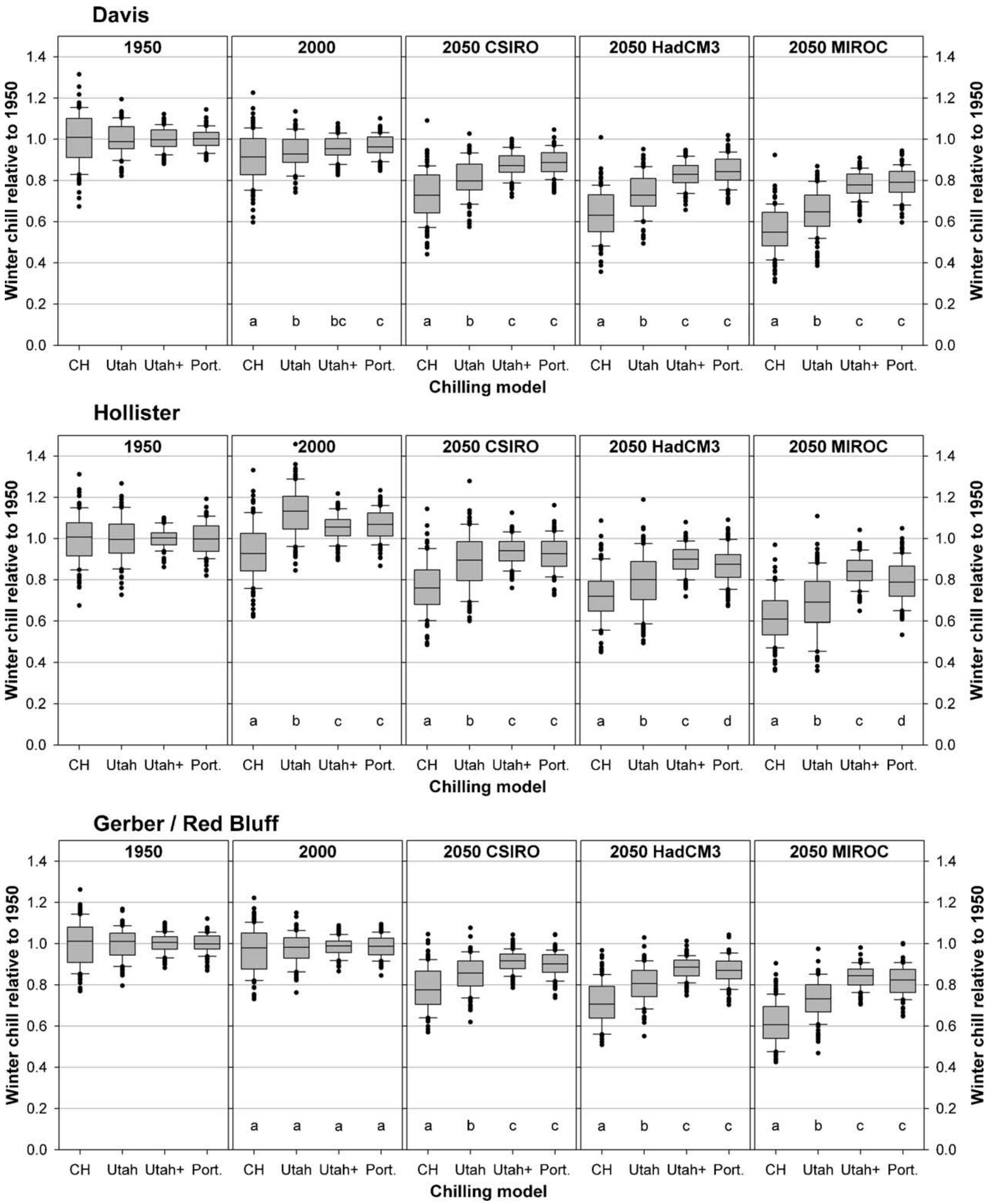

Fig. 2. Distribution of winter chill at Davis, Hollister and Gerber/Red Bluff, calculated from 100 years of synthetic weather records for 1950, 2000 and for temperatures predicted for 2050 by three General Circulation Models. Winter chill is quantified using the Chilling Hours Model (CH), the Utah Model (Utah), the Positive Utah Model (Utah+) and the Dynamic Model (Port.), and given relative to mean winter chill in 1950. In box plots, the central line indicates the median of the distribution, the edges of the boxes are the 25 and 75% quantiles, error bars are the 10 and 90% quantiles, and dots indicate outliers. Different letters below boxes within one set indicate significant differences at $p < 0.05$.

Averaged over all chilling models and GCMs, expected losses of winter chill between 1950 and 2050 ranged between 19 and 29%. Since most cultivars are selected for suitability to the range of winter chill currently observed in a certain region, these losses are likely to have severe adverse effects on cultivation in many parts of the state. Given the length of time needed to establish a productive orchard, growers might find themselves poorly prepared for the consequences of climate change in the near future. Our estimates of the number of Chilling Hours expected in 2050 correspond roughly with those given by Baldocchi and Wong (2008) for Red Bluff and Davis, assuming that the GCM used in their study generated projections in a similar range as the MIROC-GCM in our study.

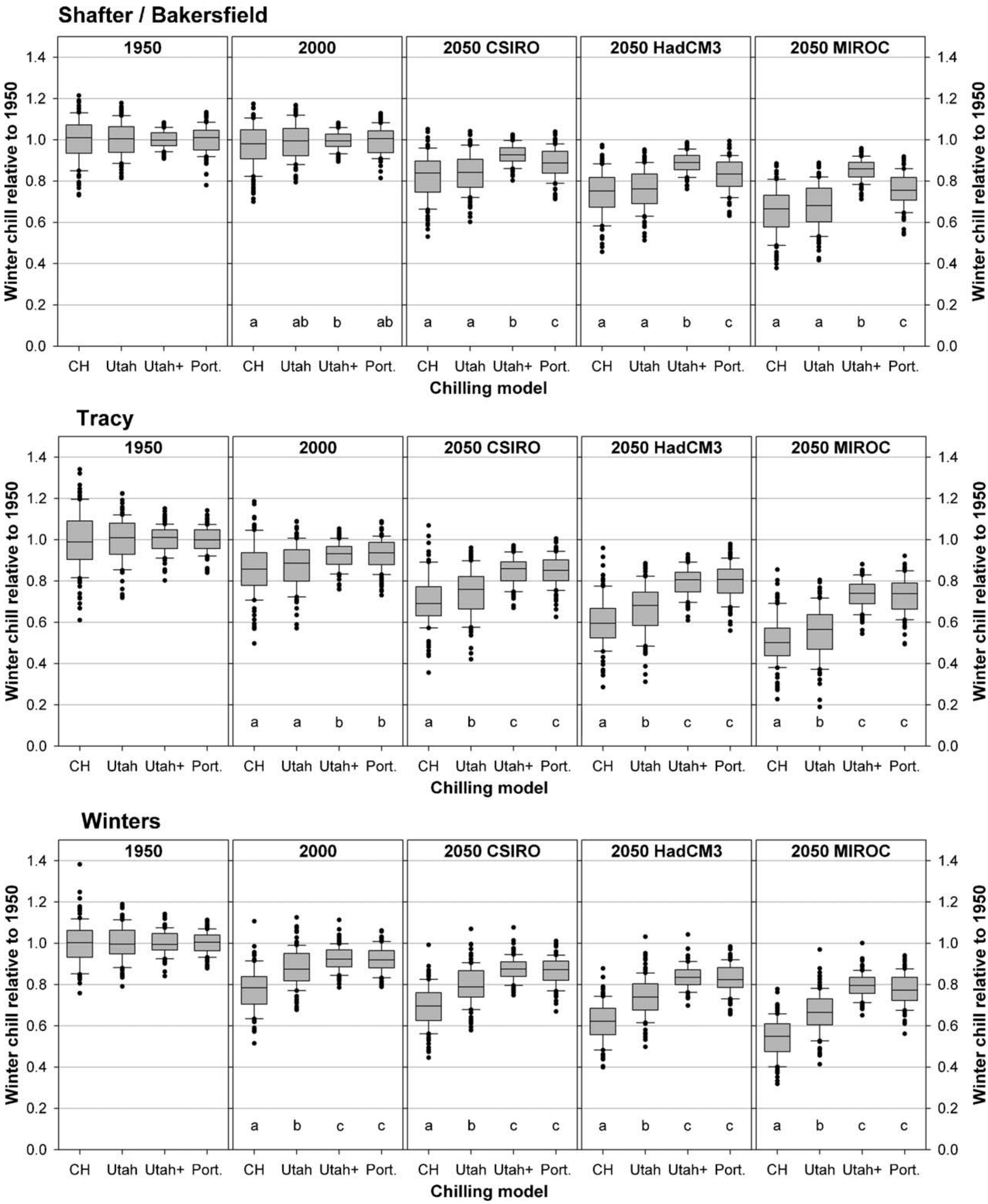

Fig. 3. Distribution of winter chill at Shafter/Bakersfield, Tracy and Winters, calculated from 100 years of synthetic weather records for 1950, 2000 and for temperatures predicted for 2050 by three General Circulation Models. Winter chill is quantified using the Chilling Hours Model (CH), the Utah Model (Utah), the Positive Utah Model (Utah+) and the Dynamic Model (Port.), and given relative to mean winter chill in 1950. In box plots, the central line indicates the median of the distribution, the edges of the boxes are the 25 and 75% quantiles, error bars are the 10 and 90% quantiles, and dots indicate outliers. Different letters below boxes within one set indicate significant differences at $p < 0.05$.

For all four chilling models, but especially for the Chilling Hours Model, consequences of climate change for fruit and nut growers may be severe. Growers throughout California select their cultivars according to the winter chill they have traditionally experienced at their production sites. Winter chill losses of up to 40% within four to five decades are thus likely to affect most growers in the Central Valley. While many will be able to adapt to climatic changes by transitioning to varieties and cultivars with lower chilling requirements, some growers may be forced to move to a different crop species. For some tree crops with relatively high chilling requirements, such as cherries, apples or prunes, most of the production could be forced north towards Oregon or Washington, where conditions are likely to remain suitable. The array of fruit and nut trees suited to winter temperatures in the Central Valley could thus become limited to species with lower chilling requirements, such as almonds or pomegranates. When these changes are required will depend on which chilling model turns out to be most accurate.

4.2. Chill model comparison

The extent to which winter chill has declined and must be expected to further decrease in the future, depended strongly on the model used to quantify chilling. While our data projected the number of Dynamic Model Chill Portions to decrease by between 14 and 21% between 1950 and 2050, predicted losses of Chilling Hours were about twice as high (29–39%). Quantified in Utah Chill Units, chill decreases were between these estimates (21–35%), while losses of Positive Utah Chill Units were relatively low (11–21%) and often statistically indistinguishable from decreases in Chill Portions (Figs. 2 and 3).

Since the biological processes underlying the breaking of dormancy and the influence of temperature on these processes are poorly understood, all of these chilling models are merely proxies of winter chill, relying entirely on empirical evidence. Deciding which model is most accurate is thus difficult without extensive experimental model comparisons or analyses of phenological records. The significant differences between the winter chill estimates of the different models, however, hint at a large variation among the models in their suitability for predicting the impact of rising temperatures on winter chill in California.

The convincing theoretical framework of the Dynamic Model, its use in warm subtropical countries and its recent adoption by the California cherry industry suggest that this model might be most appropriate for a warmer California. Assuming for a moment that this is true, growers and crop industries might be well advised to convert their chilling estimates to units of this model, rather than relying on Chilling Hours or Utah Chill Units. If such a switch is not undertaken, growers will soon feel forced to transition to lower chill varieties, reflecting the losses of up to 40% of mean annual Chilling Hours that can be expected until 2050. The potentially more appropriate Dynamic Model only predicts losses of about 20% of winter chill. While changes will ultimately be inevitable, using an inappropriate chilling model might thus lead to rushed conversions that will unnecessarily affect the competitiveness of fruit and nut growers.

4.3. Response of chilling models to rising temperatures

While the rate of chilling reduction varied with model used, the direction of the change was similar in almost all site/scenario combinations. The only exception was observed between 1950 and 2000 at Hollister, where the Chilling Hours Model predicted a 7% decrease in winter chill, while the Utah Model, the Positive Utah Model and the Dynamic Model showed increases by 13, 5 and 7%, respectively.

This observation illustrates the differential response of the chilling models to rising temperatures. Unlike the other sites analyzed, Hollister is located in California's Coastal Range, where higher cloud cover and frequent fogs generate a temperature regime that is quite different from that of the Central Valley. While minimum temperatures between 1950 and 2000 rose by 1.3 °C, the specific climate at Hollister led to a reduction in daily maximum temperatures by 1.6 °C. According to experimental evidence of the effects of different temperature regimes on winter chill, rising minimum temperatures in the range observed at Hollister should lead to a reduction in winter chill accumulation, whereas decreases in the maximum temperature should reduce the amount of chilling negation and enhance the positive effect of moderate temperatures. Only the Dynamic Model contains mechanisms to account for all of these effects. The Utah Model does not contain the chill-enhancing effect of moderate temperatures, the Positive Utah Model, in addition, does not have a chilling negation mechanism, and the Chilling Hours Model only reacts to a minimum temperature threshold. These different characteristics of the four models explain the varying responses to the climatic change observed at Hollister.

4.4. Implications for chilling quantification in a changing climate

Our study clearly showed that the Chilling Hours Model is most sensitive to rising temperatures, followed by the Utah Model, the Positive Utah Model and the Dynamic Model. From its conceptual layout, the Chilling Hours Model is also the least convincing, because it does not provide a mechanism for chilling negation by higher temperatures, which has been well documented in controlled chilling experiments (Erez et al., 1979a,b; Young, 1992). The same is true for the Positive Utah Model, in spite of its successful application in South Africa (Linsley-Noakes and Allan, 1994). The Utah Model has such a mechanism, but does not explain experimental results on the influence of moderate temperatures (Erez and Couvillon, 1987), or the effect of different temperature cycle lengths on chilling accumulation (Erez et al., 1979a). The only model that includes all these elements is the Dynamic Model (Erez et al., 1990), making it the most likely to be applicable throughout the climate changes that are expected to affect California agriculture. A recent evaluation of observations of walnut phenology at eight sites in California found that among the four models, the Dynamic Model delivered the best explanation of bloom and leafing dates (Luedeling et al., unpublished data).

Theoretical considerations alone cannot provide proof that the Dynamic Model should be favored in California in times of rising temperatures. Neither can the sensitivity analysis presented in this paper. Our results provide a clear indication, however, that the commonly used chilling models are not guaranteed to remain successful, as temperatures rise. Due to their conceptual weaknesses, they may even be unlikely to be the most useful tools available.

This study is thus a call for action to identify which chilling models perform best under novel climatic regimes in different regions of the world. Researchers in California and elsewhere have not dedicated much effort in recent years to making chilling models more accurate and to testing various models under different temperature regimes. In this age of imminent climatic change, reliance on models that have worked in the past might not be a viable option for many growers. Enhanced efforts to improve current chilling models and to better understand the biology of rest-breaking will thus be necessary to ensure efficient production of fruits and nuts in a warmer future.

5. Conclusions

The four chilling models tested predicted different rates of change in winter chill in California. While all models showed a decline, winter chill loss predicted by the currently common models, the Chilling Hours Model and the Utah Model, was much greater than losses predicted by the Positive Utah Model and the Dynamic Model. While available information is insufficient for deciding which model is most suitable for describing imminent changes in winter chill, our study clearly indicates that research on chilling models needs to be intensified, in order to prepare fruit and nut growers in California and other growing regions for the agroclimatic changes that lie ahead.

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