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Accumulated winter chill is decreasing in the fruit growing regions of California

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Abstract We examined trends in accumulated winter chill across the fruit growing region of central California and its internal coastal valleys. We tested the hypothesis that global warming is in motion in California and is causing accumulated winter chill to decrease across the fruit and nut growing regions of California. The detection of potential trends in accumulated winter chill (between 0 and 7.2°C) was determined using two complementary climate datasets. The California Irrigation Management Information System (CIMIS) contains hourly climate data and is suitable for computing accumulated chill hours and chill degree-hours. But, its longest data records extend back only to the 1980s. The National Weather Service Coop climate record is longer, extending beyond the 1950s at many sites. But its datasets only contain information on daily maximum and minimum temperatures. To assess long term trends in winter chill accumulation, we developed an algorithm that converted information from daily maximum and minimum temperature into accumulated hours of winter chill and summations of chill-degree hours. These inferred calculations of chill hour accumulation were tested with and validated by direct measurements from hourly-based data from the CIMIS network. With the combined climate datasets, we found that the annual accumulation of winter chill hours and chill degree hours is diminishing across the fruit and nut growing regions of California. Observed trends in winter chill range between -50 and -260 chill hours per decade. We also applied our analytical algorithm to project changes in winter chill using regional climate projections of temperature for three regions in the Central Valley. Predicted rates of reduced winter chill, for the period between 1950 and 2100, are on the order of -40 h per decade. By the end of the 21st century, orchards in California are expected to experience less than 500 chill hours per winter. This chronic and steady reduction in winter chill is expected to have deleterious economic and culinary impact on fruit and nut production in California by the end of the 21st Century.

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1 Introduction

California's diverse geography and microclimates enables it to serve as a venue for more than 350 field and vegetable crops and fruit and nut trees. From the perspective of the United States, California is nearly the sole producer of a large number of desirable and valuable fruits, nuts and vegetables. For example, California produces over 95% of the United State's apricots, almonds, artichokes, figs, kiwis, raisin grapes, olives, cling peaches, dried plums, persimmons, pistachios, olives, and walnuts (Anonymous 2003). And among this list, nuts and fruits like almonds and grapes have an annual economic value exceeding a billion dollars, each (Anonymous 2003).

California's ability to produce a large and diverse number of fruits and nuts stems, in part, from the Mediterranean climate that is experienced in many of its fertile interior valleys. There, typical climate conditions include a long growing season with ample sunshine and rainy, cool winters. The rainless summer provides ample sunshine for growth and inhibit infection by disease (Gutierrez et al. 2006). The cool wet winter period is dominated by a succession of winter storms from the Pacific ocean and is maintained between storms by periods of fog in many of the interior valleys (Holets and Swanson 1981; Suckling and Mitchell 1988; Underwood et al. 2004). Winter rain replenishes the soil reservoir and melt-water, from the snowpack on the surrounding Cascade and Sierra Nevada mountains, runs off and is stored in dams. This water is distributed during the growing season via a network of aqueducts and canals to provide irrigation water to the orchards during the rainless summers.

The sustenance of this rich, diverse and complex agricultural system is perceived to be vulnerable because the current climate in California is expected to warm over the next 50 to 100 years (Cayan et al. 2005; Hayhoe et al. 2004). The degree of warming will depend upon future patterns of fossil fuel combustion, deforestation, population growth, technological innovations. Based on various carbon emission scenarios, future CO_2 levels are expected to range between 600 and 1,000 ppm by 2100 and are expected to cause a 3 to 5°C increase in the mean global temperature (Friedlingstein et al. 2003; Fung et al. 2005). At the regional scale, climate simulations for California predict that a doubling of pre-industrial CO_2 levels, from 280 to 560 ppm, will produce up to a 3 to 4°C warming (Hayhoe et al. 2004; Izaurralde et al. 2003; Snyder et al. 2002). Regional climate simulations also predict a decrease in the extent and amount of winter snowpack on the mountains of California.

Regional analyzes of climate trends over agricultural regions of California and the western United States suggest that climate warming is already in motion. Cayan et al. (2001) analyzed data on the springtime blooming of lilac, a proxy for climate, and found that spring blooming is occurring earlier than in the past. These data provides indirect evidence that a warming trend is occurring across the western United States. Feng and Hu (2004) and McKenney et al. (2006) evaluated trends in agricultural climate statistics that were generated from a national climate monitoring network and database. They found that the growing season is lengthening by about a day per decade across North America and California (Feng and Hu 2004; McKenney et al. 2006). In regional climate analysis, Nemani et al. (2001) reported a warming trend in annual average temperature, exceeding 1°C over 47 years, along the coastal region of northern California. This warming was associated with a 20 day reduction in the last day of frost occurrence and a 65 day increase in the frost free growing period. And most recently Christy et al. (2006) examined daily maximum and minimum temperatures for stations in the irrigated San Joaquin Valley and the adjacent Sierra Nevada range. They report that minimum temperatures in the San Joaquin Valley,

Table 1 Number of hours below a threshold temperature required for dormancy for a selection of fruits and nuts

Fruit or Nut	Chill hours needed[a]
Almond	400–700
Apricot[b]	350–1,000
European pear	600–1,500
European plum	700–1,800
Fig	100–500
Grape	100–500
Kiwi[b]	400–800
Kiwi 'Twei' (female)	0–200
Kiwi 'Vincent' (female)	0–200
Nectarine[b]	200–1,200
Peach[b]	200–1,200
Persimmon	100–500
Pistachio	800–1,000
Pomegranate	100–200
Quince	100–500
Raspberry[b]	100–1,800
Sweet cherry (most)	600–1,400
Walnut[b]	400–1,500

Australasian Tree Crops Source Book, http://www.aoi.com.au/atcros/LM.html

[a] Chill hours means accumulated cold-season hours below 7°C

[b] Low-chill varieties exist which need less chilling

over the period between 1910 and 2003, are increasing by 0.25°C per decade. They, however, attribute these trends partially to changes in land use, which alter albedo, sensible heat transfer and evaporation.

A previous analysis on agricultural-climate interactions for California, by Hayhoe et al. (2004), focused primarily on trends in mean temperature. With respects to the functioning of vegetation and crop systems, mean temperature is not always the most significant and critical climate statistic to examine. More relevant climate statistics involve thresholds at the upper and lower tail of the probability distribution and information on the timing of certain temperature regimes (Porter and Semenov 2005). For example, phenology, the science that studies the timing of flowering, leaf expansion and fruit set, accelerates when winter minimum temperatures increase (Chmielewski et al. 2004). Crops yields can be ruined if frost occurs during the flowering and pollination period. Fruit quality can degrade if there is an extreme heat spell during the fruit-set period, such as the common burning of walnuts. And insect and disease infestations are more apt to occur if winter cold exposure is not sufficient (Gutierrez et al. 2006; Rosenweig and Hillell 1998).

We are concerned with the detection of trends in an agricultural temperature statistics buried within long-term climate data. These are the accumulation of chilling temperature and chilling hours during the winter period. Our interest in this topic is based on the fact that an extended period of cool temperatures, below a threshold temperature, is required for fruit trees to become and remain dormant and subsequently set fruit (Aron 1983). Winter chill is computed either as the number of hours below a critical temperature (chill hours) or in terms of the summation of the degrees below a critical temperature (chilling degree hours) (Aron 1975; Richardson et al. 1974.; Snyder et al. 1999; Zalom et al. 1983). In general, fruit tree species need to experience between 200 and 1,500 h below a base of

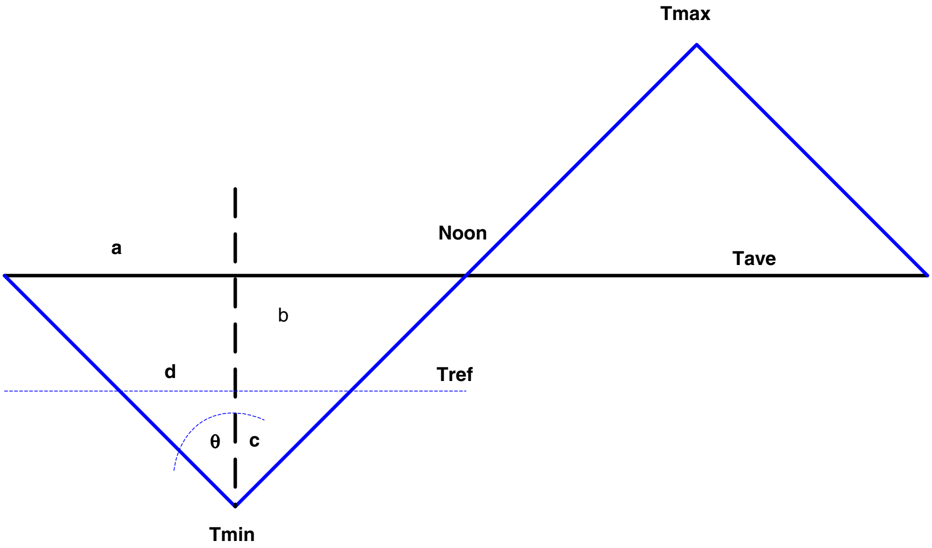
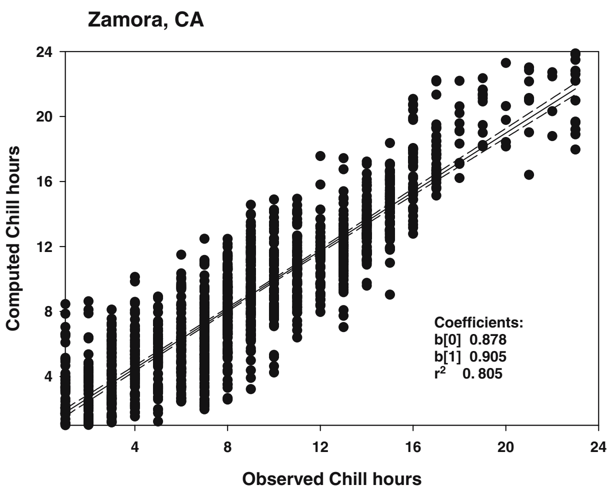


Fig. 1 Schematic of the idealized mean diurnal temperature course. *Line a* is 6 h in length, *line b* is the distance between average and minimum temperatures, *line c* is the distance between the reference and minimum temperature and *line d* is one-half the duration that temperature is below the reference temperature

7.22°C (or 45°F) during the winter to produce flowers and fruit (Egea et al. 2003; Rattigan and Hill 1986; Samish 1954). For additional information, a compilation of chill requirements for a selection of fruit and nut trees grown in California is listed in Table 1.

Under current climate conditions this dormancy is met, in part, because prolonged periods of fog occur during the winter in the Central Valley of California (Holets and Swanson 1981;Suckling and Mitchell 1988; Underwood et al. 2004) and enable the fruit and nut trees to experiences a sufficient period below the critical temperature threshold

Fig. 2 Comparison between daily chill hours measured with hourly temperature measurements and computed on the basis of daily minimum and maximum temperature measurements



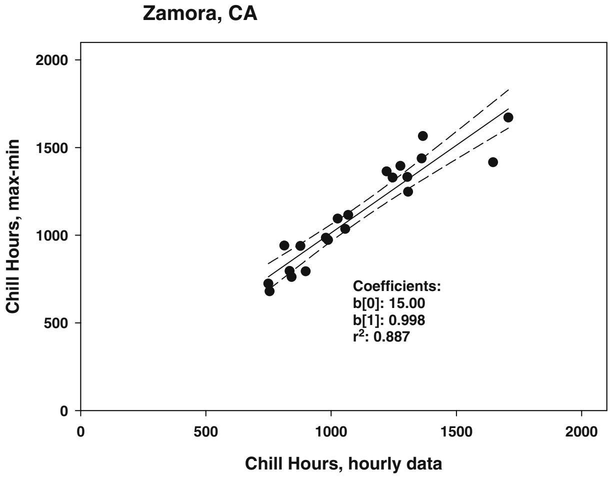


Fig. 3 Comparison between the annual accumulation of winter chill hours using hourly and maximum and minimum temperature measurements for Zamora, CA

(7°C). In the event of climate warming we hypothesize that regional and global warming will reduce the accumulated number of chill degree-hours and chill hours in the fruit and nut growing region of California. Moreover, the change in temperature may not be gradual. If prolonged periods of winter fog disappear, the Central Valley may experience larger diurnal swings in winter temperature and fewer hours below the critical temperature. If true, sustained production of high value nuts and fruits like almonds, cherries, and apricots, will be in jeopardy and deleterious economic, culinary and social consequences could occur.

In this paper, we examine trends in accumulated winter chill across the fruit and nut growing region of the Central Valley in California and its internal coastal valleys. We then apply our analysis to regional climate projections of temperature for three regions in the Central Valley for the period between 1950 and 2100. The hypothesis we are testing is that global warming is in motion and accumulated winter chill is decreasing across the fruit growing region of California.

2 Materials and methods

We based our analysis on a combination of hourly and daily climate data. The source of hourly climate data is the California Irrigation Management Information System (CIMIS) and the source of daily climate data is the National Weather Service Cooperative Network. Both datasets are available through the California Climate Archive (http://www.calclim.dri.edu/). The CIMIS data is ideal for computing accumulated winter chill hours. Unfortunately its data record is of a relatively short duration, starting in the 1980s, to be used for performing an extended climate analysis. The NWS coop database, on the other hand, allows us to investigate longer climate trends because many sites go back to the 1930s. But this database only produces information on daily maximum and minimum temperature. To alleviate the distinct negative attributes of two databases and utilize their respective positive attributes, we first develop an analytical equation for computing accumulated chill hours and chill degree-hours from maximum and minimum temperature measurement. Next we test and validate it against hourly

Table 2 Listing of the climate stations used in the analysis and regression statistics for the temporal trends in chill degree-hours and chill hours

		Lat	Long	Start year	Chill degree hours			Chill hours		
					Slope	R^2	*P*	Slope	r^2	*P*
Angwin	Cp	38.56	–122.43	1953	–12.7	0.032	NS	–2.62	0.0174	NS
Antioch	Cp	37.997	–121.808	1949	–4.4	0.01	NS	–0.193	0.00016	NS
Brentwood	Cm	37.938	–121.695	1987	–69.3	0.27	*	–26.4	0.379	**
Camino	Cm	38.750	–120.730	1984	26.1	0.03	NS	5.9	0.02	NS
Castroville	Cm	36.770	–121.770	1983	–103.3	0.34	**	–35.1	0.298	*
Chico	Cp	39.700	–121.810	1932	–7.116	0.0417	NS	–3.618	0.0811	*
Coalinga	Cp	36.150	–120.350	1940	–15.28	0.227	**	–4.511	0.213	**
Colusa	Cm	39.230	–122.020	1983	–167.5	0.59	**	–38.2	0.451	**
Davis	Cm	38.540	–121.780	1982	–82.9	0.37	**	–24.3	0.379	**
Durham	Cm	39.610	–121.820	1983	–44.6	0.19	*	–15.6	0.231	*
Firebaugh	Cm	36.85	–120.59	1982	–62.0	0.32	**	–18.75	0.278	**
Fivepoints	Cm	36.340	–120.110	1982	–55.6	0.26	*	–12.9	0.168	*
Fivepoints	Cp	36.340	–120.110	1955	–40.6	0.47	**	–10.47	0.344	**
Gerber	Cm	40.050	–122.160	1983	–68.1	0.32	**	–25.1	0.352	**
Healdsburg	Cp	38.619	–122.860	1932	–10.9	0.17	**	–2.78	0.136	**
Kettleman	Cm	35.870	–119.890	1983	–70.42	0.36	**	–22.5	0.33	**
Livermore	Cp	37.730	–121.690	1982	–45.84	0.38	**	–12.25	0.301	**
Los Banos	Cm	37.090	–120.760	1989	–36.5	0.03	NS	–13.6	0.034	NS
Manteca	Cm	37.840	–121.220	1987	–28.7	0.03	NS	–7.44	0.020	NS
Modesto	Cm	37.650	–121.190	1987	–78.4	0.25	*	–26.48	0.272	*
Nicholaus	Cm	38.870	–121.550	1983	–80.8	0.18	NS	–26.65	0.201	NS
Orland	Cp	39.740	–122.170	1949	–23.01	0.25	**	–6.711	0.234	**
Parlier	Cm	36.600	–119.500	1983	–59.01	0.24	*	–16.56	0.2	*
Red Bluff	Cp	40.177	–122.260	1959	–23.9	0.06	NS	–6.33	0.033	NS
Shafter	Cm	35.530	–119.280	1983	–59.0	0.25	*	–11.51	0.127	NS
Stratford	Cm	36.160	–119.850	1983	–56.34	0.191	*	–16.24	0.161	NS
Tracy	Cp	37.710	–121.460	1958	–25.2	0.26	**	–7.15	0.205	**
Visalia	Cm	36.300	–119.220	1983	–64.4	0.27	*	–18.9	0.242	*
Winters	Cp	38.525	–121.970	1952	–18.7	0.19	**	–5.51	0.177	**
Woodland	Cp	38.670	–121.680	1958	–31.1	0.31	**	–9.02	0.271	**
Zamora	Cm	38.810	–121.910	1983	–59.8	0.25	*	–19.55	0.219	*

CP denotes data from a Coop Station and CM represents data from a CIMIS Station. The regression slopes are tested for being significantly different from zero at the 5% and 1% probability level. Regression coefficients that are not significantly different from zero are denoted as NS.

*$P<0.05$ at the 5% level; **$P<0.01$ at the 1% level

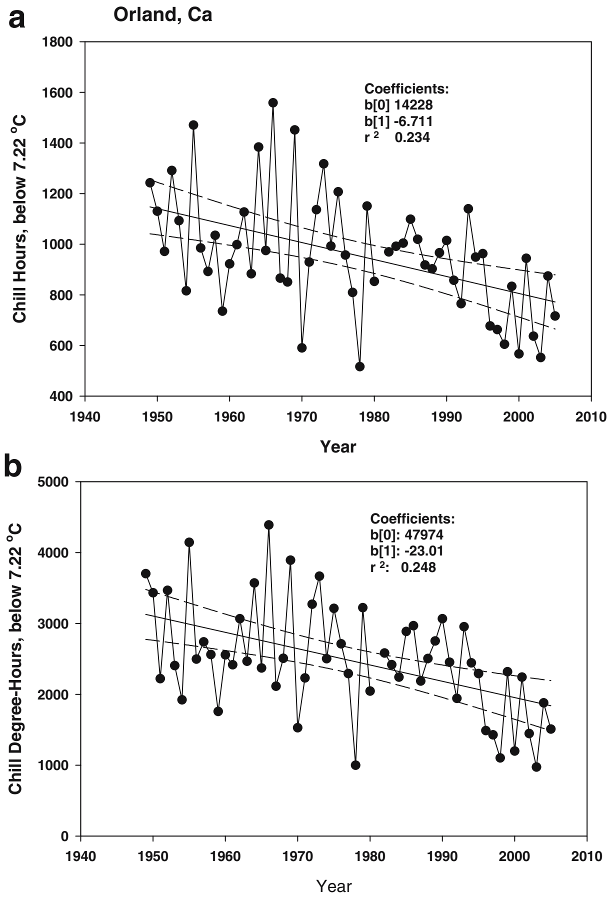
climate data. Then apply the algorithm to the longer Coop data record to examine if there are significant and negative trends in chill hours and chill degree-hours.

Winter chill-degree hours ($C_{d,h}$) and chill hours (C_h) were summed between November 1 and Feb 28. On a daily basis the number of chill hours is computed relative to a reference temperature, in this case 7.22°C or 45°F:

$$C_{d,h} = \sum_0^{24} T_{ref} - T(t) \quad (1)$$

Temperature differences were not summed if air temperature was below freezing or above the reference level.

Fig. 4 Long term trend in accumulated chill hours (*top panel*) and chill degree-hours (*bottom panel*) at Orland, CA. These data are derived from the National Weather Service Coop station



To compute cumulative chill degree hours from maximum and minimum air temperature measurements, we applied trigonometric concepts to an ideal diurnal temperature course (Snyder et al. 1999; Zalom et al. 1983). First we assumed that the diurnal temperature course can be described by two adjoined triangles, one between the daily mean and the minimum temperature and the other between the daily mean and the maximum temperature (Fig. 1). We know the length of segment **a** is 6 h and the length of segment **b** is the difference between the daily average and minimum temperatures. So we can compute the tangent of the angle θ as:

$$\tan\theta = \frac{a}{b} = \frac{6hr}{T_{ave} - T_{\min}} = \frac{d}{c} = \frac{d}{T_{ref} - T_{\min}} \tag{2}$$

The length of segment **c** is the difference between the reference and the minimum temperatures, so we can compute the length **d**, which is one-half the time below the reference temperature.

$$d = \tan\theta \cdot \left(T_{ref} - T_{\min}\right) \tag{3}$$

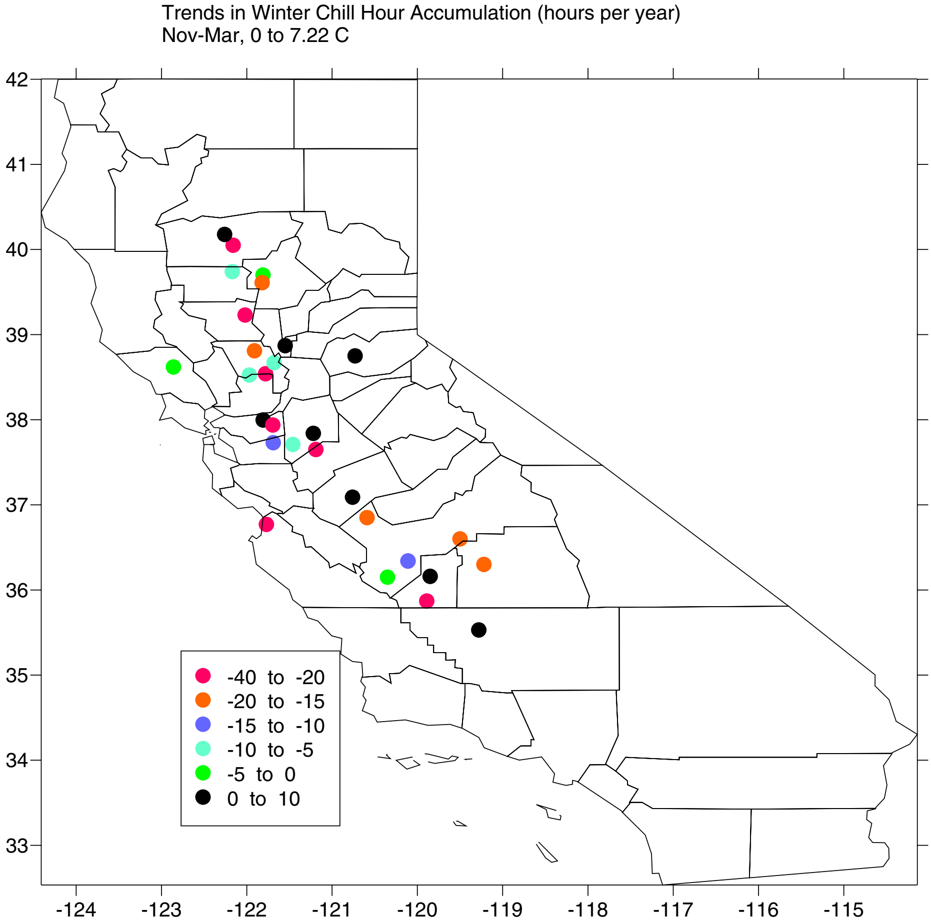


Fig. 5 Map of long term trends in the change in winter chill accumulation (hours per year) over the course of the dormant period. Data are derived from the California Climate Archive

The number of chilling hours (C_h) accumulated over a day is then computed as 2 times d. If T_{min} is below freezing we are then interested in hours between T_{ref} and 0°C. In this situation we compute the freezing duration.

$$f = 2 \cdot \tan\theta \cdot \left(T_{freeze} - T_{\min}\right) \tag{4}$$

We then compute the chilling period as the difference between 2 times d (Eq. 3) and f (Eq. 4). With information on C_h in hand, we next computed the summed chill degree hours ($C_{d,h}$), which is related to the area under the curve delineated in Fig. 1 bounded below line d.

$$\sum C_{d,h} = d \cdot 2 \cdot \left(T_{ref} - T_{\min}\right) \tag{5}$$

To evaluate how well this method works we compared estimates of daily chill hours based minimum and maximum temperature data with observations based on hourly meteorological data. A test case is shown in Fig. 2 for Zamora, CA. There is a slight bias between the two measures (slope is 0.905 and the intercept is 0.87), but overall the

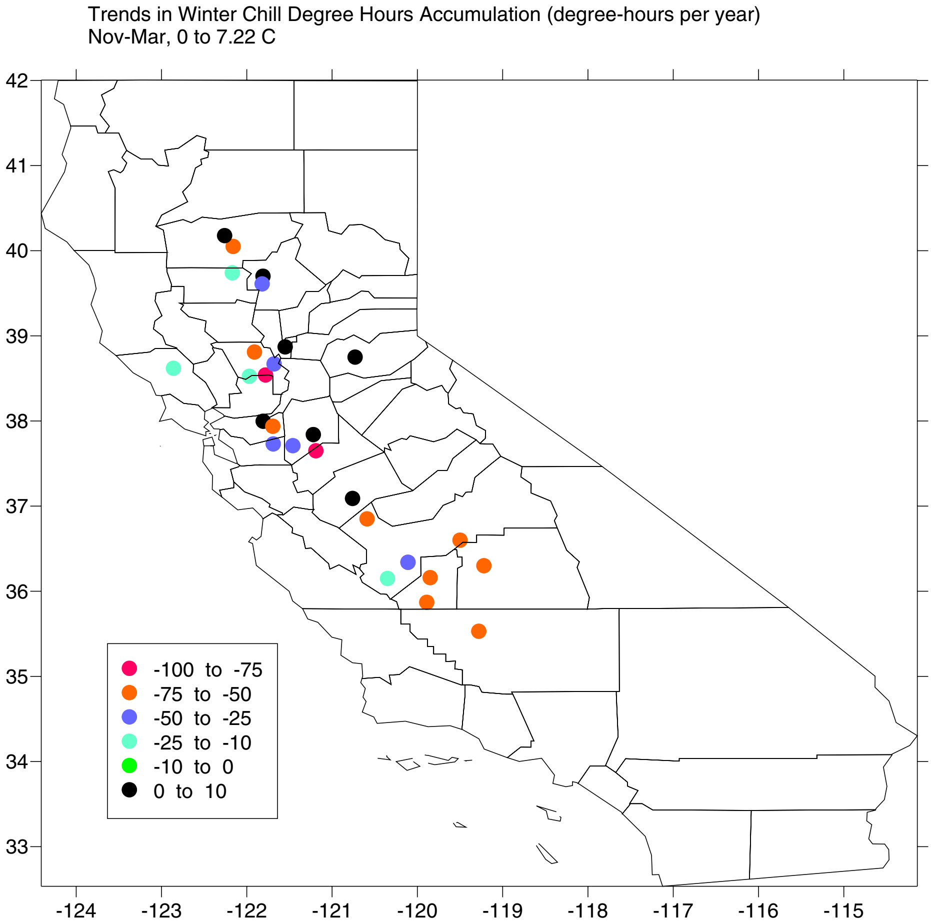


Fig. 6 Map of long term trends in the change in winter chill-degree accumulation (degree-hours per year) over the course of the dormant period. Data are derived from the California Climate Archive

correspondence between the two metrics is quite good (r^2=0.805). Next, we examine if this set of equations is suitable for the ensuing analysis by comparing the number of chill hours accumulated over the winter based on hourly meteorological data and minimum and maximum temperature data for a test case, Zamora, CA. Figure 3 shows excellent correspondence between accumulated winter chill based on hourly and daily maximum and minimum air temperature measurements (slope=0.998; intercept=15.0; r^2=0.887). In sum, the simple trigonometric relationships convert data from daily maximum and minimum temperatures into information that is produced with temperature data on hourly temporal resolution.

2.1 Climate scenarios

We investigate future trends in winter chill hours using regional climate projections for California based on the NCAR Parallel Climate model (PCM1) and NOAA's Geophysical Fluid Dynamic Laboratory (GFDL/CM2.1) climate models (Cayan et al. 2005). One case

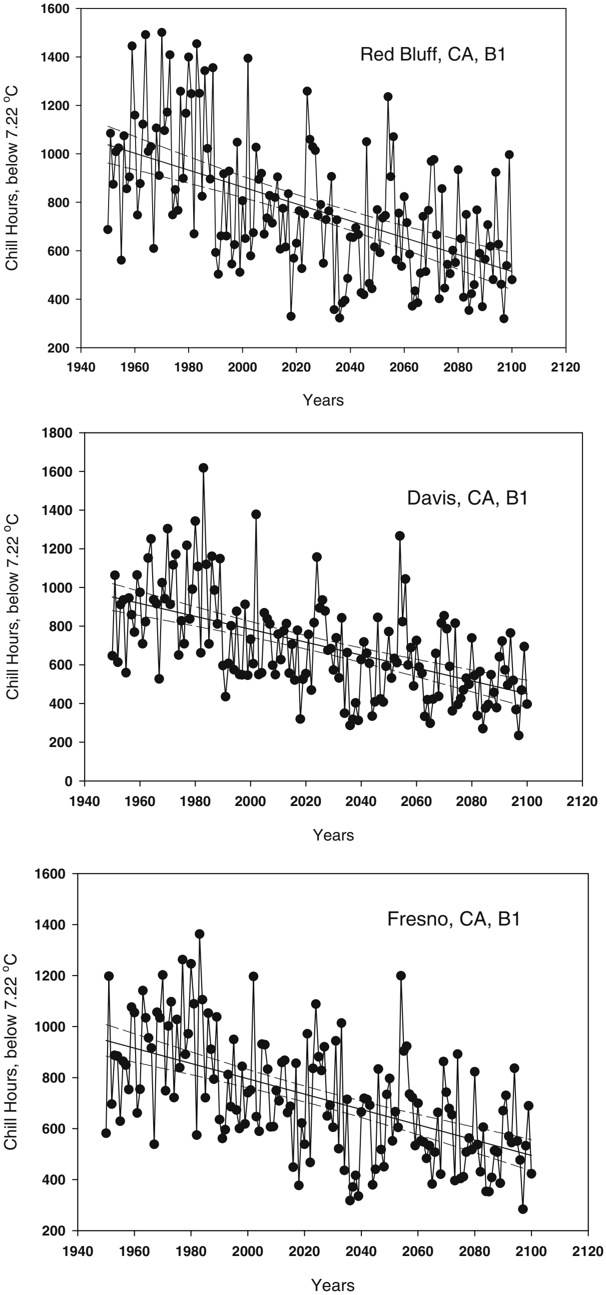
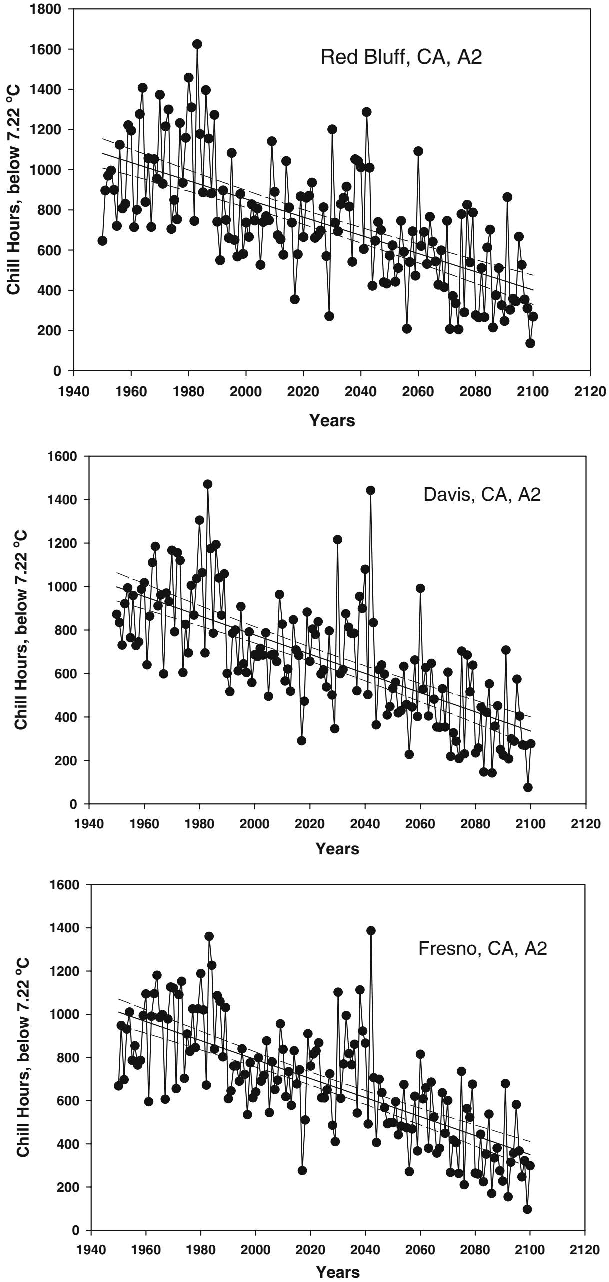


Fig. 7 Current and future projections of chill hour accumulation for three sites up and down the Central Valley (Red Bluff, Davis and Fresno). Climate projections were computed to 2100 for scenarios B1

involves the B1 emission scenario, that was derived for the Intergovernmental Panel on Climate Change (IPCC) assessment (Nakicenovic et al. 2000). It expects CO_2 to reach 500 ppm by 2100. The other case is the A2 emission scenario which expects CO_2 to reach 900 ppm by 2100. Grid-scale climates were disaggregated from the regional grid point and

Fig. 8 Current and future projections of chill hour accumulation for three sites up and down the Central Valley (Red Bluff, Davis and Fresno). Climate projections were computed to 2100 for scenarios A2



corrected to three locations up and down the Central Valley (Red Bluff, Davis and Fresno) with a technique developed for adjusting GCM output for long-range streamflow forecasting (Wood et al. 2002). The method was originally developed for studies examining the hydrologic impacts of climate change (Maurer and Duffy 2005; VanRheenan et al. 2004).

3 Results and discussion

3.1 Current trends in chill hours and chill degree hours

Using hourly data from the CIMIS project, we computed trends in accumulated chill hours and chill degree-hours at over thirty sites in the Central Valley and coastal valleys (Table 2). Results from an individual case are shown in Fig. 4. This site is near Orland, a location situated in the northern Sacramento Valley, and is an area surrounded with almond and olive orchards. The climate data set for the coop station near Orland started in 1948. At this station, significant and negative trends in both chill hours (Fig. 4a) and chill-degree hours (Fig. 4b) are evident in the 50 year climate record.

Applying this analysis to the thirty plus climate stations across the fruit growing valleys of California, we were able to produce maps of trends in chill hours (Fig. 5) and chill degree hours (Fig. 6). Most sites (except 8) are experiencing a significant and negative trend in winter chill hours with time (Table 2). In general, orchards are experiencing a loss in winter chill that ranges between 50 and 500 h per decade and between 100 and 1,000 degree-hours per decade. The greatest rates of change are interspersed throughout the Central Valley, as are sites with no significant trends. So no specific geographic pattern was detected with regards to where winter warming is and is not occurring.

The length of individual climate records did not have an influence on whether or not the regression slope was significantly different from zero. Both short and long climate records revealed cases with significant and insignificant trends in chill accumulation.

3.2 Future trends in chill hours and chill degree hours

To evaluate future trends in accumulated winter chill-degree hours, we applied our algorithm to time series of projected maximum and minimum temperatures in the Central Valley for the period between 1950 and 2100. Figure 7 shows negative trends in accumulated chill hours for the B1 scenario for Red Bluff, Davis and Fresno, sites in the north, central and southern portions of the Valley. These representative field sites are expected to lose between 3 and 3.5 chill hours per year. A greater loss in winter chill is expected with the A2 climate scenario. Figure 8 shows that sites across the Central Valley of California will lose between 4.3 and 4.5 chill hours per year.

Data derived from the climate model computations show that winter chill hours will continue to decrease from a baseline near 1,000 h, as observed in 1950, to about 500 h by 2100. Both climate scenarios indicate that the local winter climate will approach the critical thresholds of chill needed for winter dormancy by many value fruit and nut trees species (Table 1). In the future, one may need to substitute fruit species that need less chill hours (e.g. peaches for almonds) or develop new cultivars that require less winter chill.

Not considered well in the models, but superimposed upon the green-house effect evident in the measurement record, is the large scale effect of converting the Central Valley from a semi-arid grassland or desert into irrigated landscape. This land conversion causes the surface to have a lower albedo and more available energy for evaporating water and heating the air. Greater transpiration increases the humidity in the planetary boundary layer (McNaughton and Spriggs 1986), which enhances the downward directed longward energy flux (Christy et al. 2006; Monteith and Unsworth 1990). Together, these factors will contribute to warmer nights during the growing season. But the cited effects of land use conversion on the California climate should be greatest during the growing season, and secondary during the winter dormant period.

In closing significant and negative trends in accumulated winter chill are being observed across California and are projected to continue into the near and distant future. The production of high value fruits and nuts could be in jeopardy unless efforts are made to stem global warming, develop cultivars that require less winter chill or move orchards to higher elevations in the coastal and Sierra Nevada foothills.

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