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RESEARCH ARTICLE

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A 4-week advance in the growing season in Napa Valley, California, USA

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Abstract
The growing season start and duration, along with other temperature-related measures of importance to premium wine grapes in Napa Valley, California have changed as climate over the western United States has warmed. The growing season start has varied from year to year with a standard deviation of about 3 weeks, but over the 1958–2016 record a linear fit to the time sequence shows it advanced by more than 4 weeks. Over the study period, advances in the growing season were strongly influenced by temperature increases beginning in the late 1960s with warm anomalies generally persisting through recent years. The date upon which the growing season accumulated 1400 growing degree-days also shifted earlier by about 4 weeks. Other measures swung to a warmer status, including the mean temperature of the last 45 days of the growing season, which warmed by over 1.5°C. Warming days and especially warming nights contributed to the growing season advance as well as trends towards warmer expressions of other viticultural measures. Years with earlier and warmer growing seasons experienced a substantial reduction in the number of daily cool extremes, and an increase in daily warm extremes, including the number of days whose temperature reaches or exceeds 35°C.

KEYWORDS
California, climate change, climate variation, growing season, Napa Valley, phenology, temperature, viticulture

JEL CLASSIFICATION
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1 | INTRODUCTION

Napa Valley, located north of San Francisco Bay in the transitional climate between California's coast and Central Valley (Figure 1) is one of the premiere viticultural regions of the world. Wine grapes, reported as the world's most valuable crop (Wolkovich et al., 2018), contribute substantially to California's agricultural economy. Napa Valley's wine grapes and wines are dependent upon its Mediterranean climate with warm dry summers and cool wet winters (Skinner, 2003). Napa Valley shares characteristics of both interior and coastal climates of the central California

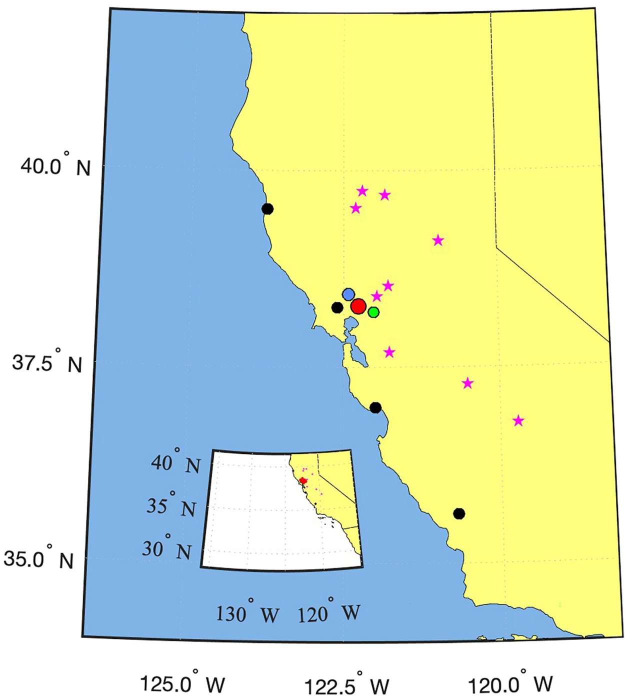

FIGURE 1 Napa State Hospital (large red dot) and Oakville CIMIS (large blue dot) stations, nearby COOP stations (blue diamonds), Fairfield dew point temperature station (green dot), Oakland radiosonde (black square with blue outline), Inland USHCN stations (lavender stars) and Coastal USHCN stations (black dots). White area in smaller inset map shows domain of eastern North Pacific SST. [Colour figure can be viewed at wileyonlinelibrary.com]

region. Temperature, including short-term daily to interannual fluctuations and longer-term multi-year to several decade variation, is particularly important to the premium wine grapes produced in Napa Valley.

Temperature variations affect plant development (e.g., Kukal & Irmak, 2018). Temperature influences are pronounced upon wine grape growth and various aspects of grape composition, which influences wine quality (e.g., Gladstones, 1992; Nicholas et al., 2011; Winkler et al., 1974). Having an accurate sense of seasonal evolution is vital to planning viticultural activities and making winemaking decisions (Fraga et al., 2012), and it is noteworthy that prominent markers of vine phenology, for example, the timing of budbreak, flowering, and the onset of ripening known as véraison, can be predicted by temperature-based models (Parker et al., 2011).

Wine quality has numerous sensitivities to temperature variations, from daily extremes to decadal fluctuations and changes. Unseasonal early springs can lead to greater frost risk as vines begin growing sensitive tissues when temperatures can still drop below freezing. Anomalously warm nights can alter fruit composition, mainly through increased sugar concentration and decreased acidity, producing wines with higher alcohol but potentially with underdeveloped flavour (Gaiotti et al., 2018; Nicholas, 2015). Detrimental effects of high summer heat include lower anthocyanin and tannin concentrations (Gaiotti et al., 2018), which are important determinants of wine colour and texture. At their extreme, when temperatures reach or exceed 35°C, metabolic processes decline (e.g., Valladao et al., 1995; White et al., 2006). Seasonal temperature variations, strongly related to cumulative degree-day measures, govern wine grape phenology (e.g., Gladstones, 1992; Parker et al., 2011). Ideal grape composition, with regard to sugar/acid ratio, colour, and aromas, is obtained when grape ripening occurs under moderate temperatures (Nicholas et al., 2011; Spayd et al., 2002). Thus, warm temperatures at the end of the growing season can have undesirable effects, since cool temperatures then are beneficial in allowing grapes to develop optimal composition and flavour (van Leeuwen & Destrac-Irvine, 2017).

Climate change is underway and will likely increasingly affect all regions (e.g., IPCC, 2021) including Mediterranean climates, which may be especially vulnerable (Polade et al., 2017; Xoplaki et al., 2003). Temperatures in California vary considerably on monthly and seasonal time scales (Alfaro et al., 2006; Dias et al., 2018), and over multiple years and decades (Higgins et al., 2002). Additionally, longer term warming has occurred over the last several decades (Cordero et al., 2011), partly in response to anthropogenic climate change (e.g., Barnett et al., 2008; Williams et al., 2019). Adding to terrestrial heat waves, recent prolonged warm events have been observed in the eastern North Pacific (e.g., Bond et al., 2015). Over California and the western United States, temperatures in winter and spring have warmed significantly since the 1950s (Abatzoglou & Redmond, 2007; Bonfils et al., 2008). Cordero et al., 2011 found widespread seasonal and annual warming of nights and days in California over 1918–2006 and 1970–2006. In coastal California, warming in summer has been stronger in nighttime where increased daytime maximum temperatures at some locations have been suppressed by enhanced daytime marine layer ventilation (Clemesha et al., 2017; Cordero et al., 2011; Iacobellis & Cayan, 2013; Lebassi et al., 2009), reinforcing results from Nemani et al. (2001) and Jones and Goodrich (2008). Increased humidity in irrigated agricultural settings has been shown to reduce daytime maximum temperatures (Lobell & Bonfils, 2008). Gershunov et al. (2009) found that nighttime-accentuated heat waves associated with anomalously humid air masses have emerged in California since the 1980s, echoing results obtained globally (Alexander et al., 2006).

This paper investigates within-season to interannual variability and longer-term changes in temperature-driven viticultural measures in Napa Valley. As temperatures have warmed over this period, the overriding question we address is: *how has the growing season and other* *important viticultural measures fluctuated and changed over recent decades?*

2 | OBSERVATIONAL DATA

We used temperature data from two weather stations in Napa Valley and from a broader weather network, as well as sea surface measures from 1958 to 2016. Temperature observations for Napa Valley are represented primarily by the Napa State Hospital record and the Oakville California Irrigation Management Information System (CIMIS) temperature record. Temperature and other weather and climatic variables from surrounding locations are also included.

The Napa State Hospital station (10.6 m elevation) provides the principal weather station record within Napa Valley employed in this study (Figure 1). Data used begins November 1957 and ends December 2016; for brevity this period is referred to as 1958–2016. From 1985 through 2016, temperature at Napa State Hospital was recorded electronically by a Maximum-Minimum Temperature System (MMTS), approximately 2 m above a lawn within 3 m of the north wall of the Napa State Hospital Fire Station and within 2 m of an asphalt road. Before 1985, temperature instrumentation is not specified in NOAA metadata, but a visit to the site suggests that it was measured with a maximum-minimum liquid-in-glass thermometer from a Cotton Region Shelter that remains located approximately 5 m from the south side of the Fire Station. Because of its proximity to the Fire Station and in recent decades adjacent to the paved road, this record likely has a warm bias, so the primary temperature record used here is a modified version of the Napa State Hospital record using adjustments from the USHCN Napa record, described below. The unadjusted Napa State Hospital temperature record is contained in the GHCN dataset.

The temperature record at Oakville (57.9 m elevation, approximately 27 km north of Napa State Hospital, Figure 1) is from a California Irrigation Management Information System (CIMIS; station https://cimis.water.ca.gov/Stations.aspx), with a record beginning in March, 1989. The CIMIS weather data (Hidalgo et al., 2005; Pathak et al., 2016) is recorded at hourly time steps, so the maximum and minimum hourly values were identified for each 24 h period and used to approximate the daily Tmax and Tmin. The Oakville CIMIS record is relatively short, so we use it to evaluate and confirm various statistical properties and results from the longer Napa State Hospital record, and only comparatively its multi-decade variation.

Quality control of Napa State Hospital and Oakville CIMIS Tmax and Tmin data was performed to remove outliers and fill missing values, as described in Supporting Information, Part 1.

2.1 | Global Historical Climatology Network temperature

Daily Tmax and Tmin were obtained from the Global Historical Climatology Network (GHCN) (Menne et al., 2012) dataset for Napa State Hospital and other GHCN stations in Central California, most of which also were in the form of monthly means within the United States Historical Climatology Network (USHCN) dataset described below. An adjusted version of Napa State Hospital GHCN record (Supporting Information, Part 2) is employed in most of the analyses herein.

2.2 | United States Historical Climatology Network temperature

USHCN monthly records, from a subset of stations within the GHCN dataset, have been identified to quantify national and regional temperature changes in the continental United States (Menne et al., 2009; Vose et al., 2012).

The USHCN monthly mean dataset contains adjustments that have been implemented to mitigate spurious temperature variation that has been attributed to changes in instrumentation (Menne et al., 2010; Pielke Sr. et al., 2007), weather station exposure (Fall et al., 2008), and time of observations (Menne et al., 2009). Menne et al. (2010) found that USHCN temperature trends since 1980 were not inflated due to poor instrument siting, and Vose et al. (2012) found that trends over the conterminous United States are comparable to trends estimated from atmospheric reanalyses, which did not assimilate surface temperature observations. However, Pielke Sr. et al. (2007) noted that the USHCN adjustments, derived from associations with surrounding stations (Menne & Williams Jr., 2009) produce a false degree of consistency. In comparison to those from unadjusted records, Fall et al. (2011) showed that over the conterminous United States Tmax trends from adjusted temperature records increased, while Tmin trends decreased.

The Napa State Hospital monthly Tmax and Tmin record (Figure 2), 1958–2016, along with other stations employed (Figure 1), are from the monthly USHCN version 2.5. USHCN monthly mean Tmax and Tmin are used to adjust the GHCN daily record to conform to the corresponding USHCN monthly means. The adjustments seen in Figure 2, described in Supporting Information, Part 2, resulted in diminished Tmin trends and increased Tmax trends, consistent with Fall et al., 2011 findings from the broader USHCN network.

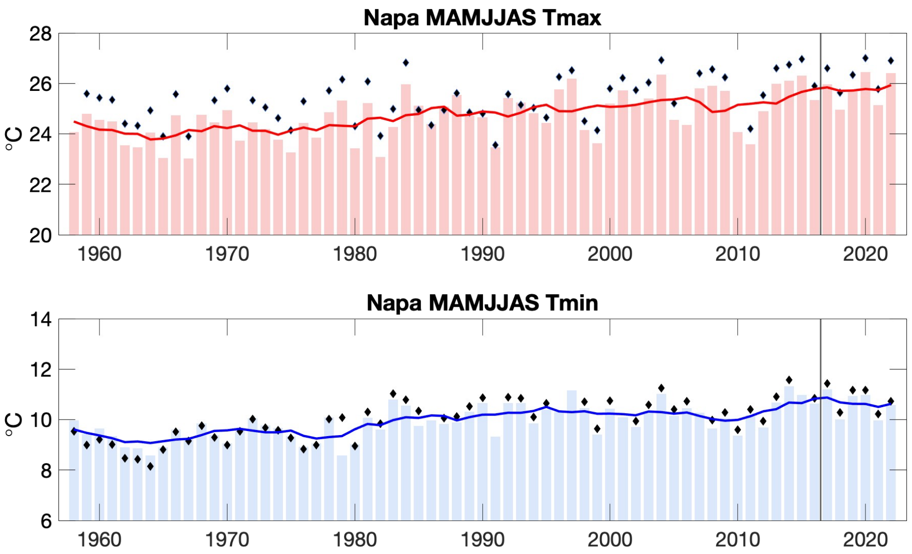

FIGURE 2 Bars: March–September average Napa Tmax (above) and Tmin (below) time series (°C) derived from USHCN monthly data, with 7 year running means designated by lines. Dots show the unadjusted GHCN values. Analyses herein consider 1958–2016; subsequent data from 2017 to 2022 is plotted to right of vertical line. [Colour figure can be viewed at wileyonlinelibrary.com]

2.3 | Daily temperature extremes

Contributions of daily extremes to seasonal viticultural measures were evaluated using the occurrence of Tmax or Tmin at or above its 95th or 99th percentile, or at or below its 5th and 1st percentiles (called T99, T95, T05 and T01 extremes of Tmax or Tmin; Supporting Information, Part 4). These percentiles were determined for particular seasonal or monthly periods based on the activity of each of several viticultural measures described below from (1958–2016) Napa GHCN adjusted daily Tmax and Tmin. Analogous threshold values were also determined from daily anomalies of Tmax and Tmin. Using the T95, T05, T99 and T01 percentile values, the proportion of the respective extreme days was tallied for the upper or lower third of years for each of the selected viticultural measures.

2.4 | Sea surface temperature

Area average sea surface temperature (SST) monthly values and anomalies were developed. SST along the coast adjacent to California was employed as an index of regional marine air mass influences. Using COBE 1° gridded SST dataset (Japan Meteorological Agency, 2006), area average coastal SST during November 1957–2016 was constructed from the Pacific coast westward to 137.5° W and from 27.5° N to 41.5° N (Figure 1, inset).

3 | VITICULTURAL MEASURES

Analyses of viticultural measures were conducted, primarily, over November 1957 through December 2016, represented by cooperative observer (COOP) and other ancillary records. The starting point of this period was the beginning of consistently sampled (0Z and 12Z) Oakland radiosonde data. A shorter period, 1989–2016, corresponds to the Oakville CIMIS weather station temperature record.

Here we adopted a set of bioclimatic measures identified from previous studies describing associations of wine grapes with temperature-related weather and climate variables. As listed below, three of these measures record seasonality, two measures record temperature during the latter portion of the growing season, and two measures register temperature extremes:

1. A growing season measure oriented towards grapevine development, where the start day of the growing season was defined as the first day of a series of days having daily mean temperature ≥10°C (Gladstones, 1992) with no more than 3 days of interruptions.
2. End day 1400, a measure of time to grape maturity was defined as the number of days from the start of the growing season until the sum of daily mean temperature excess over a base temperature of 10°C reached 1400°C degree-days, based on Gladstones (1992) determination for the premium varieties of grapes such as those grown in Napa Valley. Associated with start and end day, the length of the 1400 degree-day growing season is the duration from start day to end day. For completeness, the length of the entire growing season, that is, until daily temperatures consistently dip to 10°C or below is also recorded.
3. Mean temperature of the last 45 days of the growing season before 1400 degree-days were reached, called T45, as the temperature during the latter period of the growing period is a determinant of grape flavour and colour characteristics (Nicholas et al., 2011; Wolkovich et al., 2018).
4. The cool night index (Tonietto & Carbonneau, 2004), representing nighttime temperatures during grape

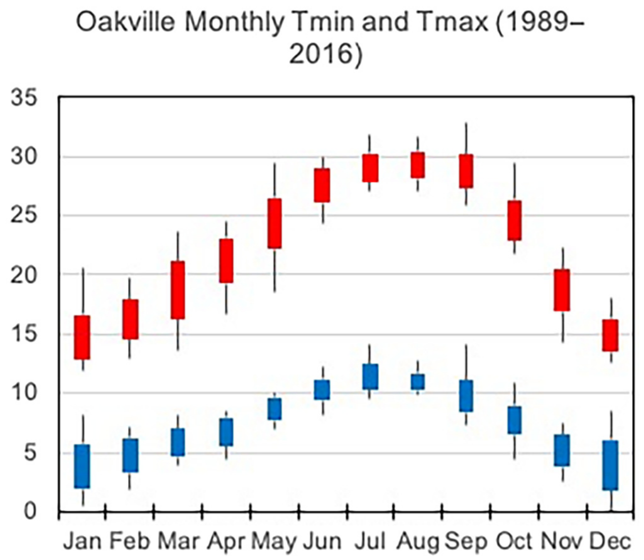

FIGURE 3 Climatology (°C) of Oakville monthly temperature, 1989–2016. Bars delineate ± 1 standard deviation from monthly mean value. Whiskers attach to highest and lowest extreme monthly values. [Colour figure can be viewed at wileyonlinelibrary.com]

maturation, is the average Tmin during September (Sep Tmin).

5. Number of days having Tmax ≥35°C, called XT35, which has been identified as a threshold above which metabolic processes decline (e.g., Valladao et al., 1995; White et al., 2006).
6. Number of frost days, represented by days whose Tmin ≤0°C.

Statistics derived from the yearly time series of each of the viticultural measures are shown in Supporting Information, Part 3.

4 | RESULTS

4.1 | Variability of viticultural measures

Daily mean temperature has often been used in previous climatic studies involving wine grapes, but Tmax and Tmin exhibit important differences in their climatologies (Figure 3) and exhibit a degree of independent variation (Supporting Information, Part 3), so here their associations are considered separately.

The days of each year's growing season start, when the year reached 1400 growing degree-days, and end of the entire growing season are plotted in Figure 4 and tabulated along with statistics of other viticultural measures in Table 1. Following the temperature climatology obtained from Napa 1958–2016 adjusted GHCN and other records (Supporting Information, Part 3), the start of the growing season was March 16, but varied interannually with a standard deviation of 29 days. The growing season reached 1400 degree-days, on average, on October 5, having occurred as late as day 312 (November 8, 1975) and as early as day 254 (September 11) in 1997 and 2014. Because temperature is cooler in the early portion of the growing season, a given day earlier in the season tends to have a lesser contribution to the seasonal total growing degree-days than days in the mid and end of growing season. Thus, a large deviation in start day at the beginning of the growing season has a relatively small contribution to the seasonal total degree day variation. Consequently, a growing season with an earlier start tends to have a longer 1400 degree-day growing season length than does a growing season with a later start, and because of this, the end of the growing season exhibited a markedly smaller standard deviation (only 14.5 days) than did the start of the growing season. T45, the mean temperature during the 45 days leading up to and including the final day when the growing season reaches 1400 degree-days, varies interannually with standard deviation 1.2°C, quite similar to standard deviations of August and September monthly means (Figure 3).

The entire growing season ended, on average, on December 2 (Figure 4). In contrast to the large variation of the growing season start whose standard deviation is 29 days, the entire growing season end has a standard deviation of only 13 days, likely due to the relatively small contribution to total degree days from cool early spring temperatures and to the steep decline in temperature, especially Tmax, from late autumn to winter in comparison to a more gradual increase in temperature from winter to spring.

Concerning the cool night index, September Tmin averaged 11°C, with a standard deviation of 0.9°C. Over the 59 year record, XT35, the number of days with Tmax ≥35°C, averaged 5.7 days/year^{-1} with a standard deviation of nearly 3 days. An average of 16 days per year registered Tmin ≤0°C, with a standard deviation of 9 days. The distributions of the yearly XT35 and the yearly number of days with Tmin ≤0°C were positively skewed (also exhibited by the Oakville statistics, Supporting Information, Part 2), reflecting the occurrence of a few years with large numbers of these extreme days.

Several viticultural measures are correlated at levels that exceed 95% statistical significance (Table 2). These correlations reflect common dependences on Tmax and Tmin anomalies, and also indicate that early season temperature anomalies carry through to various seasonal aggregate measures, that how anomalous temperatures may persist through subsequent months. The growing

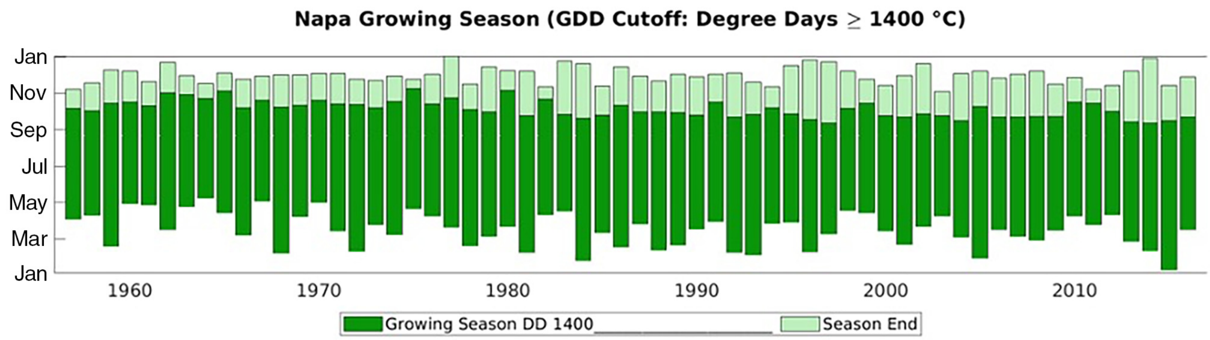

FIGURE 4 Each year's growing season start day (lower edge of dark green bar) through day when growing season reaches 1400 growing degree-days (upper edge of dark green bar) and ensuing period until growing season ends (top of light green bar). Plot illustrates large variation of start day, and shift towards earlier start day and end day of 1400 growing degree-day season. From Napa 1958–2016 USHCN data. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Viticultural Statistics based on Napa adjusted GHCN 1958–2016 temperature record.

Napa GHCN-adjusted (1958–2016)	Mean	SD	Trend (per year)
Start day	March 16	29.4 days	**−0.557** days/year^{-1}
End day (1400)	October 5	14.5 days	**−0.536** days/year^{-1}
Length (1400)	202.7 days	24.9 days	0.022 days/year^{-1}
T 45 (1400)	18.9°C	1.16°C	**0.032**°C/year^{-1}
End day (whole)	December 2	13.4	−0.060 days/year^{-1}
Length (whole)	262.1 days	34.0	**0.499** days/year^{-1}
XT35	5.8 days	3.27 days	**0.047** days/year
Sep Tmin	11.3°C	0.91°C	0.110°C/year^{-1}
Days w $T < 0$	15.8 days	9.05 days	−0.060 days
GDD (April–October)	1586°C	120°C	**4.47**°C days/year^{-1}

Note: Trends significant (Mann–Kendall test) at 95% confidence level shown in bold.

TABLE 2 Correlation between Annual Viticultural Measures 1958–2016.

	End day (1400)	Length (1400)	T45 days (1400)	XT35 days	Sep Tmin	Days w $T < 0$°C	GDD
Start day	**0.53**	**−0.87**	**−0.26**	0.05	−0.05	0.08	**−0.53**
End day (1400)		−0.04	**−0.70**	**−0.38**	**−0.32**	0.11	**−0.95**
Length (1400)			−0.11	**−0.28**	−0.13	−0.04	0.07
T45 (1400)				**0.40**	**0.59**	−0.18	**0.69**
XT35 days					0.12	−0.12	**0.33**
Sep Tmin						−0.03	**0.35**
Days w $T < 0$							−0.16

Note: Correlation coefficients significant at 95% confidence are bold.

season start is correlated ($r = 0.53$) with the end day of the 1400 degree-days growing season and negatively correlated ($r = -0.87$) with the length of the 1400 degree growing season, so earlier growing season start associates with earlier 1400 degree-day growing end but with a longer duration until the end of the 1400 degree-day growing season. Additionally, the growing season start date is negatively correlated ($r = -0.53$) with annual total growing degree-days—warm temperature anomalies in the early season tend towards higher annual total annual degree-days and vice versa. The end day of the 1400 degree-day growing season associated negatively and very strongly ($r = -0.95$) with annual total degree-days. An earlier (later) end day of the 1400 degree-day growing

TABLE 3 Correlation between Tmax and Tmin for Napa and Oakville, based upon daily and monthly data for October–March and April–September.

	Daily Napa (1958–2016)	Daily Oakville (1979–2016)	Monthly Napa (1958–2016)	Monthly Oakville (1979–2016)
ONDJFM	**0.45**	**0.34**	**0.75**	**0.61**
AMJJAS	**0.54**	**0.44**	**0.87**	**0.80**

Note: Bold indicates correlation is significance at 95%.

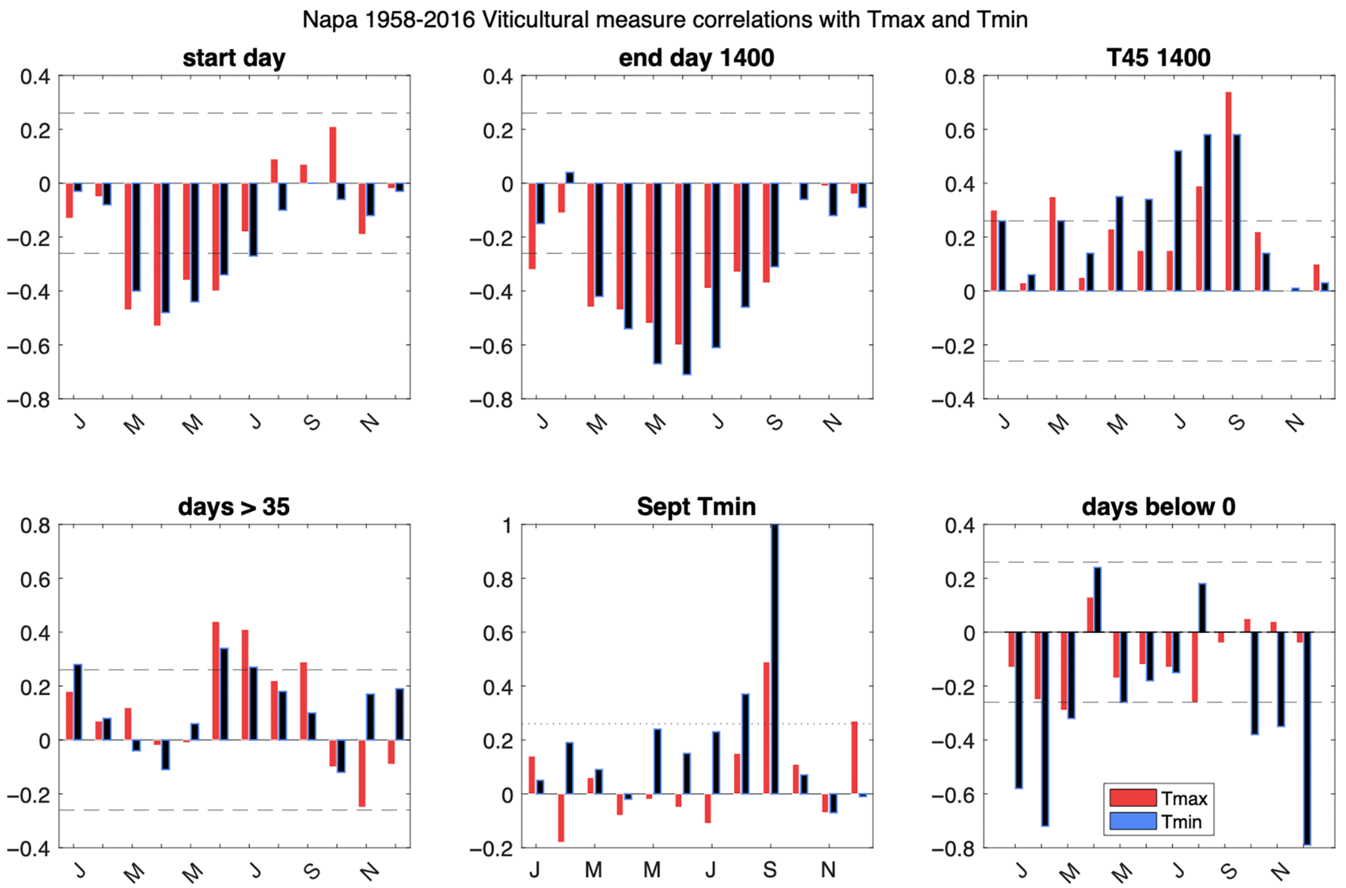

FIGURE 5 Correlations of Napa USGHCN monthly Tmax (thin, red) and Tmin (thick, blue) versus selected viticultural measures over 1958–2016: Start Day, End Day (1400 growing degree-days), T45, number of days >35°C, September Tmin and number of days ≤0°C. Two-tailed 95% significance levels ($r = \pm 0.26$) shown by dashed horizontal lines. [Colour figure can be viewed at wileyonlinelibrary.com]

season associates strongly ($r = -0.70$) with anomalously warmer (cooler) T45. T45 correlates positively with September mean Tmin ($r = 0.59$), and also with degree-days totalled over the entire growing season ($r = 0.69$).

4.2 | Association of viticultural measures with monthly Tmax and Tmin

Tmax and Tmin anomalies are positively and significantly correlated (Pearson correlations) at a moderate level from daily data and more strongly from monthly aggregated data (Table 3). Tmax and Tmin have different levels of anomalous variability at both daily and monthly time scales (Supporting Information, Part 3), probably arising from diurnally varying effects including energy balance and boundary layer structure (Davy et al., 2016; Rahn & Mitchell, 2016), marine layer influences (Lebassi et al., 2009) and coastal clouds (Iacobellis & Cayan, 2013). These daytime and nighttime influences would have different effects on the growing season and other viticultural measures, so in the analyses herein Tmax and Tmin contributions are considered separately.

To investigate temperature ingredients of particular viticultural measures, we consider how they are correlated (Pearson correlations) with anomalous Napa Tmax

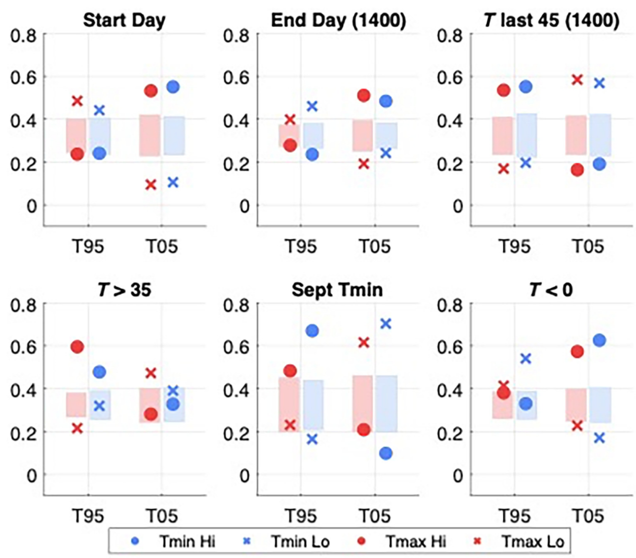

FIGURE 6 Fraction of warm (T95) and cool (T05) daily extremes that occurred within one third of years whose growing season Start Day or whose growing season reached 1400°C degree-days earliest or latest. Pale envelope shows 5th to 95th percentile fractions obtained in a random shuffling exercise. Dots represent fraction of observed occurrences during years having high third of each measure and X's represent fraction observed during years having low third. [Colour figure can be viewed at wileyonlinelibrary.com]

and Tmin (Figure 5). The growing season start is essentially unaffected by Tmax and Tmin during December, January and February. The start date is most strongly associated with March–May temperatures, consonant with the start date mid-March mean and its 29-day standard deviation. These correlations are negative, for example, warm anomalies of Tmax and Tmin in these spring months associate with earlier start of growing season. Interestingly, May and June exhibit relatively high correlations, indicating that anomalously warm (early) or cool (late) spring starts may carry over into subsequent months. Correlations of growing season start day with Tmax in March and April were stronger than those with Tmin. Growing season end dates are even more strongly correlated with monthly temperature anomalies in May through July. Significant Tmax and Tmin correlations extend from April through September, reflecting their cumulative influence on the progression of the growing season to its end point (average in early October). As with the start date, correlations are negative, for example, warm anomalies of Tmax and Tmin in later spring and summer months are associated with earlier end of the 1400 degree-day growing season. In contrast to start day associations, growing season end day more strongly correlated with Tmin than with Tmax. Unsurprisingly, cumulative degree-days over the entire growing season correlated positively with Tmax and Tmin, with strongest correlations in March through August. Tmin correlations with growing degree-days were somewhat higher than those of Tmax in May, July and August.

T45 was most strongly correlated with monthly mean Tmax in August and especially September, and with Tmin in July, August, and September. Correlations formed with viticultural measures from Oakville 1989–2016 (not shown) were very similar. Anomalies in XT35 had positive correlations with monthly mean Tmax in June, July, August and September—not surprisingly since these are months with the highest overall mean Tmax (Supporting Information, Part 2). The number of days with Tmin ≤0°C had negative correlations with monthly mean Tmin in November through March, being strongest in December and February.

4.3 | Influence of daily extreme Tmax and Tmin on anomalous viticultural measures

Spells of extreme warmth (Gershunov et al., 2009; Guirguis et al., 2018; Pierce et al., 2018) and coolness are an important component of California climate. For nearly all of the viticultural measures, the occurrence of daily Tmax and Tmin extremes (Table S4.1) played a role in creating anomalous seasonal viticultural outcomes. To investigate a relatively large number of cases, contributions of extremes to the subsets of years containing the highest and lowest one third of each viticultural measure were considered. Within the one third of years having earliest growing season start date (Figure 6), nearly 50% of the 1958–2016 population of T95 warm extremes during March–May occurred, but less than 12% of the cool extremes occurred (see also Table 4). These observed fractions fall beyond the envelope of 95 to 5 percentile occurrence of extremes as determined by a random shuffle sampling exercise. For the third of years having latest growing season start (marked by solid dots in Figure 6), extreme occurrence during March–May had unusually many cool extremes. Numbers of warm extremes were diminished, though not enough to exceed statistical confidence limits. The more extreme daily T99 and T01 Tmax and Tmin yielded results similar to those for the T95 and T05 extremes. The proportion of extreme temperature anomalies occurring during the third of years with earliest and latest growing season start exhibited a similar pattern, but somewhat stronger, as those for the full temperature values (Supporting information, Part 4).

The one third of years that were earliest to reach 1400 degree-days included 40% of Tmax March–September T95 warm extremes and only 19% of Tmax T05 cool

TABLE 4 Percent of extreme daily temperatures occurring one third late/early low/high years. [Colour table can be viewed at wileyonlinelibrary.com]

Napa 1958–2016

	Start day				End day (1400)				*T* last 45 days (1400)			
	Late Tmax	Early Tmax	Late Tmin	Early Tmin	Late Tmax	Early Tmax	Late Tmin	Early Tmin	Low Tmax	High Tmax	Low Tmin	High Tmin
T99	29	44	16	**49**	30	39	**21**	**48**	**8**	**54**	**14**	**59**
T95	24	**49**	24	**44**	28	**40**	**24**	**46**	**14**	**48**	**18**	**50**
T05	**53**	**9**	**55**	**11**	**51**	**19**	**48**	**24**	**54**	**14**	**52**	**19**
T01	**65**	**2**	**53**	**7**	**59**	**16**	**54**	**18**	**49**	16	41	27

	XT35				September Tmin				*T* < 0			
	Low Tmax	High Tmax	Low Tmin	High Tmin	Low Tmax	High Tmax	Low Tmin	High Tmin	Low Tmax	High Tmax	Low Tmin	High Tmin
T99	**12**	**62**	21	**63**	22	**72**	**6**	**89**	46	36	**64**	24
T95	**22**	**60**	32	**48**	23	**48**	**16**	**67**	**41**	38	**54**	33
T05	**47**	28	39	33	**62**	21	**70**	**10**	23	**57**	**17**	**63**
T01	**52**	26	32	33	56	28	**83**	**0**	15	**64**	**9**	**75**

Note: T99, T95, T05 and T01 thresholds determined from Napa 1958–2016 daily Tmax and Tmin within following seasonal windows: Start day: March–May; End day: March–September; T45: August–September; September Tmin: September; XT35: June–September; *T* < 0: November–March. Bold numbers designates observed occurrence being significant wherein observed frequency is greater than 95th percentile or less than 5th percentile of distribution from random shuffle trials. Red shading designates significant extreme occurrence during anomalously warm-associated viticultural measures, with dark red representing significant numbers of T99 or T95 extremes and pale red for significant numbers of T01 or T05 extremes.

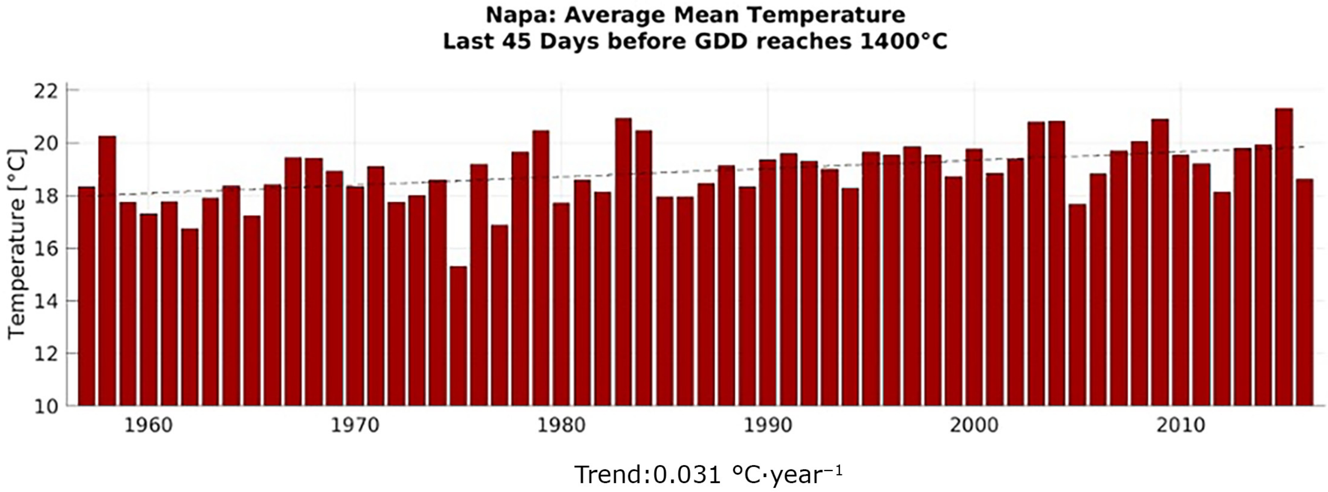

FIGURE 7 Time series of T45 (°C), the mean temperature over the 45 days leading up to the end of the 1400°C degree-day growing season for each year 1958–2016. Mean is 18.9°C; standard deviation is 1.16°C; and 1958–2016 trend is 0.031°C/year^{-1}. From Napa adjusted GHCN data. [Colour figure can be viewed at wileyonlinelibrary.com]

extremes; Tmin warm extremes were similarly tilted and also statistically significant (Table 4). The one third of years that were latest to reach 1400 degree-days had somewhat, though not significant, reductions in March–September warm extremes, but had markedly high numbers of cool extreme (T05) days. Extreme daily anomalies in March–September during years that were earliest (latest) to reach 1400 degree-days exhibited similar high (low) occurrence of warm extremes and low (high) occurrence of cool extremes (Table S4.3).

During years with one third highest occurrence of XT35, daily warm and cool Tmax and Tmin extremes tilted to higher and lower numbers of occurrence, and vice versa during years with lowest XT35 (Table 4 and Figure 5). Similarly, during years with one third highest September Tmin, daily warm and cool Tmin and Tmax

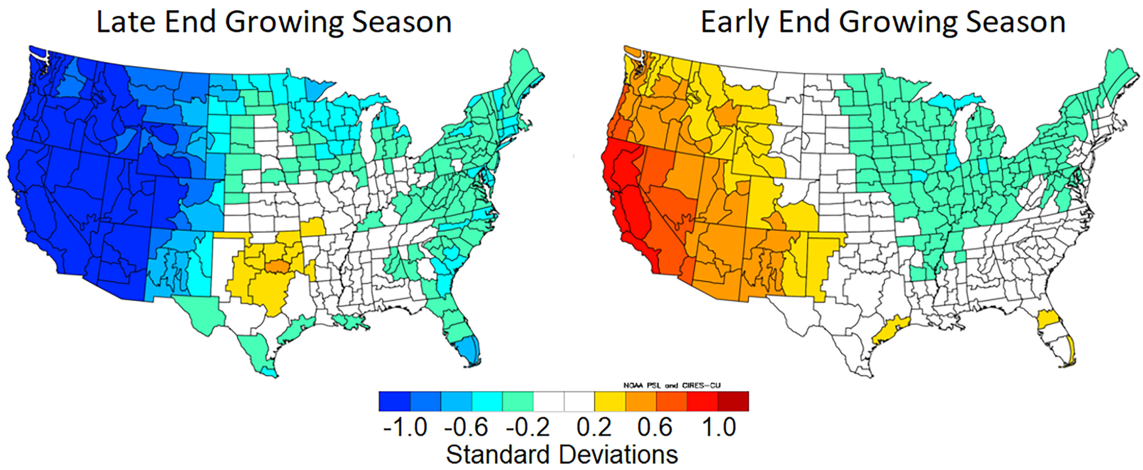

FIGURE 8 Average March–September mean temperature anomalies (°C) over the conterminous United States, for 20 years of latest (left) and earliest (right) end of Napa 1400 GDD season. Anomalies are formed from long term March–September averages over 1981–2010. Latest years are: 1975, 1980, 1965, 1962, 1963, 1977, 1964, 1982, 1967, 1970, 2010, 1974, 1991, 1960, 2011, 1959, 1999, 1972, 1976 and 1971; earliest years are: 1997, 2014, 2013, 2004, 2015, 1996; 1984, 1992, 2001, 2006, 2007, 2016, 2008, 2009, 1981, 2000, 2003, 1985, 1990 and 1993. Produced using U.S. NOAA Earth Science Research Laboratories Physical Sciences Laboratory plotting and mapping of NOAA/NCEI climate division temperatures https://psl.noaa.gov/data/usclimdivs/ [Colour figure can be viewed at wileyonlinelibrary.com]

extremes exhibited higher and lower occurrences than expected, and vice versa during years with one third lowest September Tmin.

The one third of years having highest T45 tended to occur during the latter half of the 1958–2016 record (Figure 7). The years with highest T45 included 48% or more of the entire population of August and September Tmax and Tmin T95 extremes and less than 20% of Tmax and Tmin T05 low extremes. The more extreme T99 and T01 Tmax and Tmin counts (Table 4) echoed those for the T95 and T05 extremes.

Extreme Tmax and Tmin anomalies, using thresholds determined similarly as those for the full values, also exhibited strong associations with the anomalous seasonal viticultural measures (Supporting Information, Part 4).

4.4 | Trends of viticultural measures and temperatures 1958–2016

Related to warming trends in monthly and seasonal temperatures over the six decades (Supporting Information, Part 5), viticultural measures also shifted. The amount of change was large, with most of the viticultural measures exhibiting trends registering statistical significance above the 95% level of confidence (Table 1). The start of the growing season and the end of 1400 degree-day growing season advanced by more than 4 weeks, as shown in Figure 4. These multi-decade changes exceed typical year to year standard deviations (Supporting Information, Part 3). T45 increased by 1.9°C (Figure 7), mostly reflecting summer warming, but to a lesser degree because the growing season shifted, on average, to a somewhat warmer part of late summer, which contributed about 0.2°C to this change. XT35 increased by 2.7 days per year, an increase of nearly 50% of its overall average. September Tmin increased by 0.65°C but also exhibited considerable interannual variability and did not register a statistically significant trend. The total growing season increased by 317 degree-days, a result of warmer temperatures during February through October (Supporting Information, Part 5). Related to this, the length of the total growing season increased by 35 days. The number of days whose Tmin ≤0°C diminished by 4.3 days, mostly from changes in winter months, amounting to a decline of more than 25% of overall average.

Reinforcing their expected relationships with warming monthly mean temperatures, shifts in the viticultural measures were supported by an increasing (decreasing) frequency of warm (cool) daily extremes (Supporting Information, Part 5). Warming trends occurred both in daytime and nighttime temperatures, with strongest monthly mean Tmax and Tmin increases occurring within March through September. Tmax and Tmin T95 occurrences during April to September increased from about 8 to 12 per year, passing the 95% significance level. Diminishing T05 occurrences in April–September were even stronger than T95 increases, decreasing from 12 or more per year to about 6 per year.

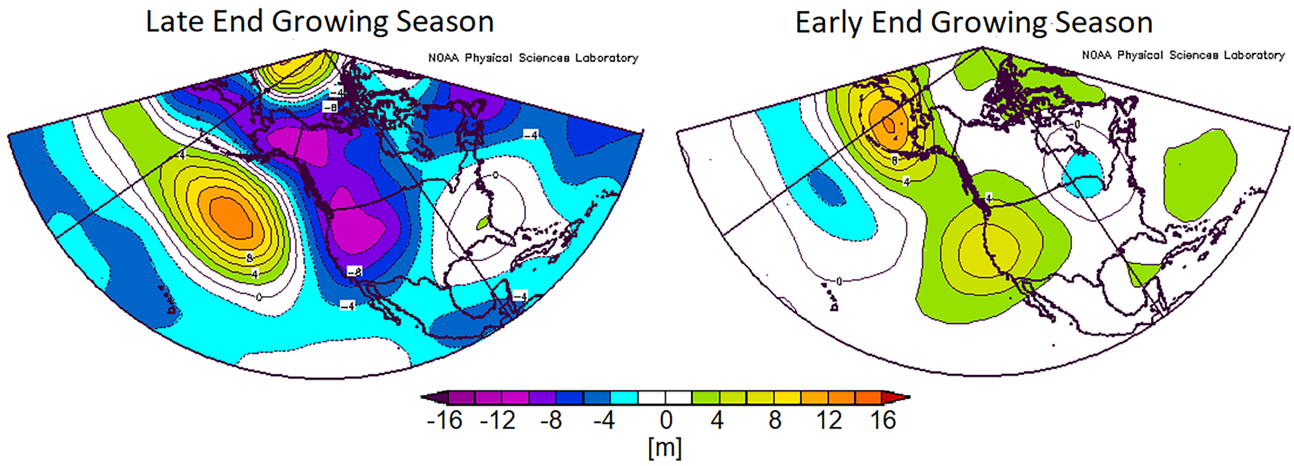

FIGURE 9 Average anomaly of March–September 700 hPa for 20 years whose end date of 1400°C degree-day season was latest (left) and earliest (right). Negative, positive 700 hPa anomalies associate with cool, warm surface temperature anomalies over the western United States shown in Figure 6. Latest and earliest years same as those listed in Figure 8. Produced using NOAA ESRL PSL plotting and mapping of NCEP Reanalysis data. [Colour figure can be viewed at wileyonlinelibrary.com]

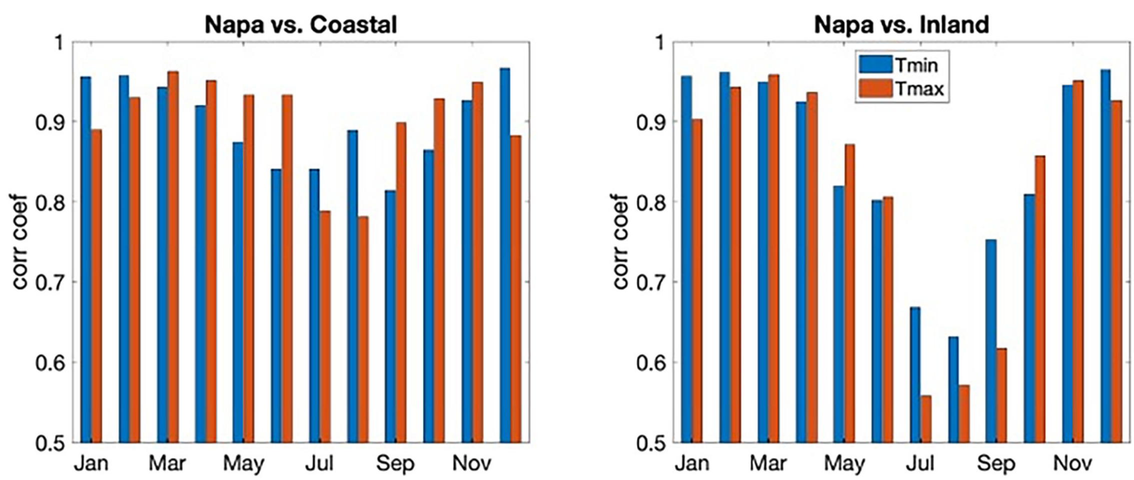

FIGURE 10 Correlations, Napa versus Coastal region (left) and Napa versus Inland region (right) monthly mean Tmin (blue) and Tmax (red), from records from 1958 to 2016. All correlations exceed 95% significance level. [Colour figure can be viewed at wileyonlinelibrary.com]

4.5 | Relationship to regional climate variations

To better understand causal factors, it is helpful to investigate how temperature-driven viticultural measures may be connected to climatic variables that extend beyond Napa Valley, including regional temperature, atmospheric circulation and sea surface temperature.

Considering seasonal time scales, composites of US divisional temperature anomalies (Karl & Koss, 1984) were formed by averaging, over March through September the one third of years within 1958–2016 being earliest and one third of years being latest to reach 1400 degree-days (Figure 8). The composite of these earliest years reveals warm anomalies throughout the western United States, with cool anomalies downstream over the eastern United States. Strongest positive temperature anomalies occur in California's coastal and nearby inland climate divisions, with lesser but still substantial temperature anomalies extending into western Nevada and southern Oregon. Conversely, the one third of years being latest to reach 1400 degree-days featured a roughly opposite pattern of cool anomalies. Cool temperatures are even more extensive than the strong warm anomalies associated with the earlier growing season, with strong negative anomalies occurring across the far West from the Pacific coast inland to about 110° W.

TABLE 5 Correlations, monthly Tmax and Tmin versus SST and Tdew and SST versus Tdew, within October–March and April–September.

	SST versus Tmax and Tmin				Tdew versus Tmax and Tmin				
	Napa (1958–2016)		Oakville (1989–2016)		Napa (1958–2016)		Oakville (1989–2016)		
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	SST versus Tdew (1958–2016)
ONDJFM	**0.37**	**0.44**	0.12	**0.37**	0.07	**0.62**	0.12	**0.59**	***0.28***
AMJJAS	**0.30**	**0.54**	0.14	**0.38**	−0.07	**0.51**	−0.15	**0.27**	***0.57***

	SST versus Tmax and Tmin				Tdew versus Tmax and Tmin			
	Coast		Inland		Coast		Inland	
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
ONDJFM	**0.39**	**0.47**	**0.28**	**0.47**	0.09	**0.63**	0.06	**0.59**
AMJJAS	**0.37**	**0.62**	0.14	**0.41**	0.06	**0.65**	−0.06	**0.27**

Note: Correlations significant at 95% confidence level are bold.

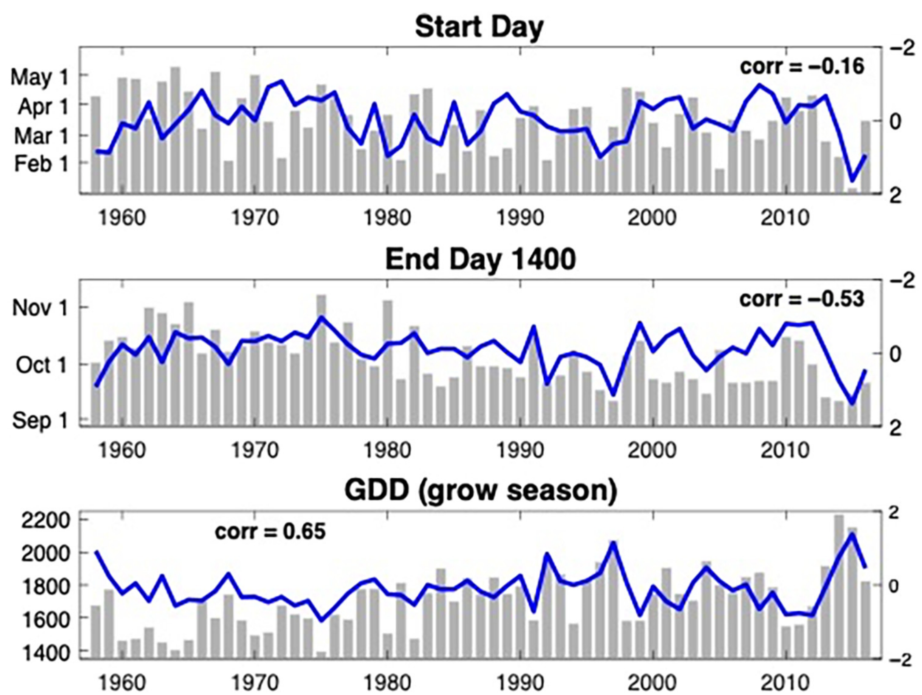

FIGURE 11 Coastal sea surface temperature anomaly (SST [°C]; blue lines) plotted together with viticultural measures (grey bars). Top: Start Day is paired with February–April SST; Middle: End Day of 1400 degree-day growing season is paired with March–September SST; Bottom: total annual growing degree-days (GDD) is paired with March–September SST. In top and middle panels, SST scale is inverted, but not in bottom panel. [Colour figure can be viewed at wileyonlinelibrary.com]

The broad regional patterns exhibited in the US temperature composites demonstrate that anomalous Napa growing season conditions are driven by large scale processes. An analogous composite of mid-troposphere geopotential height anomalies (Figure 9) indicates that the surface temperature anomaly patterns are associated with shifted or accentuated atmospheric planetary waves (Abatzoglou & Redmond, 2007; Strong & McCabe, 2017; Yu et al., 2019) and attendant signatures of anomalous horizontal advection, vertical motion and other processes which cause cooler- or warmer-than-normal air masses. The 700 hPa height patterns in Figure 9 are forms of the atmospheric circulation exhibiting strong positive anomalies over western North America, associated with high pressure and anomalous warm and anomalously early growing seasons, and conversely, strong negative anomalies associated with anomalous cool and anomalously late growing seasons.

From a tighter regional perspective, coastal air masses may also influence Napa temperatures (Nemani et al., 2001), so we investigate associations of Napa Tmax and Tmin with averages of Tmax and Tmin over the coastal and inland regions (Supporting Information, Part 2). Although in the October–June

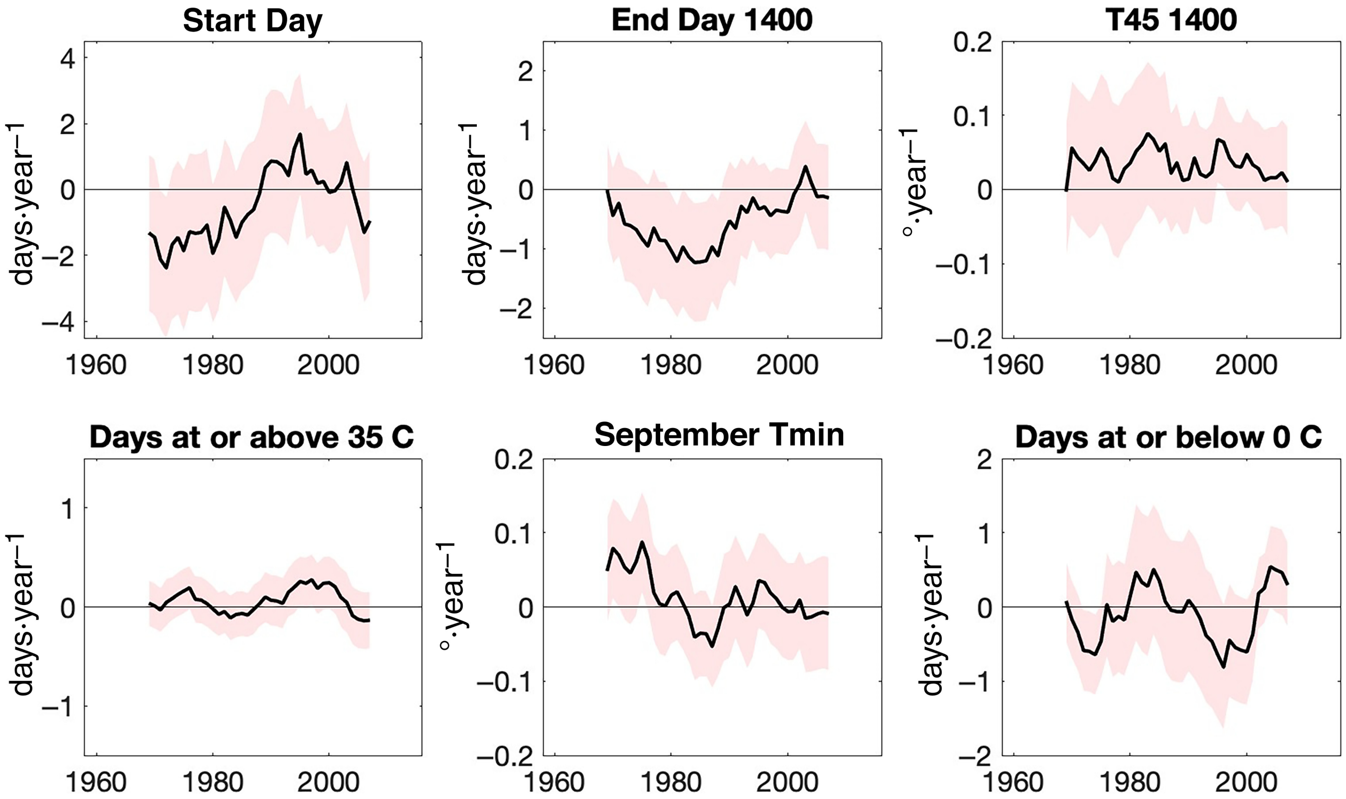

FIGURE 12 Twenty-one-year running linear trend determined for viticultural measures, including Start Day, End Day of 1400 degree-day growing season T45, XT35, September Tmin and days whose Tmin ≤0°C. Trend is computed for each 21-year period, sliding over 1958–2016 period and plotted on centre year of each 21-year period. Pale envelope shows 5%–95% confidence interval of each 21-year linear trend. [Colour figure can be viewed at wileyonlinelibrary.com]

cooler period, Napa and inland monthly Tmax and Tmin are strongly and significantly correlated ($r \geq 0.8$ for most cases), in the July–September warmer period their correlations drop considerably, especially for Tmax (Figure 10). On the other hand, Napa and coastal monthly Tmax and Tmin retain relatively high and statistically significant correlations ($r \geq 0.75$) throughout this summer ripening and grape maturity period—for example, Napa correlations are considerably higher with coastal temperatures than inland temperatures for both Tmax and Tmin.

Napa temperature associations with coastal temperature anomalies in summer are likely reinforced by prevailing westerly winds which carry marine influences to California's exposed coastal plains and valleys, including Napa Valley (Lebassi et al., 2009). Following findings by Nemani et al. (2001) that grape yields and wine quality in Napa related to nearby coastal ocean temperatures, associations with regional ocean temperatures (Figure 1) were investigated. To this point, monthly Oakville Tmax and Tmin anomalies are more strongly correlated with North Pacific SST anomalies than are inland temperature anomalies, although somewhat weaker than are coastal temperature anomalies (Table 5).

Viticultural associations with ocean temperatures are stronger for nighttime (Tmin) than daytime (Tmax), in agreement with results obtained by Alfaro et al. (2006). Also, Table 5 shows that Napa Tmin correlations with North Pacific SST anomalies are somewhat stronger in the warm season (AMJJAS) than in the cool season (ONDJFM).

Congruent with previous findings by Nemani et al., 2001, Napa minimum temperatures register positive correlations with humidity (Table 5), being somewhat more strongly correlated in ONDJFM ($r = 0.62$) than in AMJJAS ($r = 0.51$). Coastal minimum and maximum temperatures exhibit somewhat stronger correlations than do Napa with humidity and ocean temperatures, while Inland minimum and maximum temperatures exhibit weaker but still statistically significant correlations. Correlations between ocean temperatures and humidity (SST vs. Tdew) anomalies were higher during the warm half (AMJJAS) than the cool half year (ONDJFM).

Considering SST associations with viticultural measures, Figure 11 shows that anomalous coastal sea surface temperature correlated significantly with the date upon obtaining 1400 growing degree-days ($r = -0.53$) and with growing season total degree-days ($r = 0.61$). Thus anomalously warmer March–September SST associated with faster accumulation to 1400 degree-days and with greater degree-day accumulation over the entire growing season, and vice versa for anomalously cooler SST. While coastal ocean temperatures and coastal marine layer are linked to broader scale climate patterns including the El Niño/Southern Oscillation (e.g., Schwing et al., 2002) and the Pacific Decadal Oscillation (PDO; Mantua et al., 1997; Schwartz et al., 2014), direct correlations of viticultural measures with these natural climate modes are relatively weak (March–September growing degree days vs. PDO and Niño3.4 SST index were 0.21 and 0.18).

5 | DISCUSSION

Shifts in the viticultural measures were driven by positive and highly significant (Mann–Kendall test) trends in Tmax and Tmin (Figure 2 and Supporting Information, Part 5). However, over the shorter 1989–2016 period, trends of viticultural measures derived from the Napa adjusted record and the Oakville CIMIS record, while directed towards their warmer expressions, were quite strongly affected by interannual variation and generally did not reach the 95% statistical significance level. The contrast between the magnitude of trends from these two periods motivates a closer investigation of how changes unfolded within 1958–2016.

Linear trends calculated sequentially for each 21 years of the 1958–2016 record of several viticultural measures (Figure 12) indicate that warming and its influences have occurred throughout most of the record. Strongest changes in growing season Start day occurred between the early 1970's through the early 1990's. Warming-related trends centred in the late 1960's continued until the mid-1980's, followed by about 10 years of cooling, then followed, generally, by warming through 2006. T45 and XT35 trends were nearly all positive although they tapered to lower positive (T45) or slightly negative during the last few years of the record. The viticultural measure changes associated with a shift from cooler conditions from 1960 through about 1975 to more frequent warm anomalies and/or less intense cool anomalies after that. This period saw a decided increase in atmospheric CO_2 and other greenhouse gasses (https://keelingcurve.ucsd.edu/) and a marked increase in global surface temperature (Hansen et al., 2010). Since 1957, global mean surface temperature has risen by approximately 1°C (NASA global mean temperature; https://psl.noaa.gov/data/climateindices/), nearly the same as temperature over the contiguous United States (https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/national/time-series#). Also, the 1970's warming transition is a signature of the mid-1970's Pacific climate shift (Mantua et al., 1997; Miller et al., 1994), when atmospheric circulation over the North Pacific and North American morphed into a deepened Aleutian Low, positive Pacific North American pattern. Moving trends of the start day and the end day of 1400 degree day are correlated significantly ($r = -0.66$; $r = -0.68$) with analogous moving trends of the Pacific Decadal Oscillation. Consistent with North Pacific surface temperature associations, anomalously high pressure that formed over western North America supported the warming Tmax and Tmin (Figure 2 and tabulated in Supporting Information, Part 5) along with attendant responses in hydroclimate and phenology over much of the western United States (Cayan et al., 2001).

6 | SUMMARY AND CONCLUSIONS

Warming-driven shifts in Napa Valley viticultural measures are consistent with trends in grapevine phenology reported over international growing regions, ranging from 6 to 25 days earlier over numerous varieties and locations, which correlated strongly with warmer springs and summers (Duchêne & Schneider, 2005; Ruml et al., 2016; Webb et al., 2012). Daytime and nighttime warming contained in a USHCN-adjusted version of the 1958–2016 Napa State Hospital temperature record produces large shifts in temperature-related viticultural measures. The start of the Napa growing season shifted earlier by more than 4 weeks over those six decades. The end day, specified here as the accumulation of 1400 degree-days, advanced nearly at the same rate as the start date, so while the growing season advanced, the time required for grapes to mature remained about the same. T45, the temperature during the last 45 days of the 1400 degree-day growing season, became warmer by about 1.9°C, mostly because of the warming over the six decades and to a small degree because the shift of latter part of the growing season placed it into a somewhat warmer seasonal window than previously.

Anomalous Napa Valley growing season measures and temperatures have been strongly influenced by planetary scale atmospheric circulation patterns and have generally reflected large regional scale temperature patterns. Extreme daily temperatures have played an important role, wherein increased occurrences of warm extremes and decreased occurrences of cool extremes supported the overall warming-related trends of growing season and other viticultural measures.

The rate of warming and change in the viticultural measures in the Napa region has been uneven, with contributions from shorter term (daily to interdecadal) variability. Changes during the last three decades 1989–2016, were comparatively less than those that appear in the longer, earlier starting record, wherein much of the warming occurred between 1960 and 1990. This most active change period is synchronized with the major shift of climate over the Pacific and North America that occurred in the mid-1970's (Miller et al., 1994). Over this last 3 decades, although temperatures warmed somewhat and viticultural measures have shifted accordingly, the trends from 1989 to 2016 did not reach 95% significance levels. But, it is noteworthy that growing season temperatures in subsequent years have tended to remain anomalously warm (Figure 2).

Despite warming temperatures and commensurately shifting growing season measures, Napa premium wine grapes have remained highly successful (California Department of Food and Agriculture, 2021). Importantly, Napa seasonal temperatures were anomalously warm during four of the recent 6 years after the analysis period (Figure 2), a period when they were not buttressed by coastal ocean surface temperatures since the El Niño/Southern Oscillation was more often in its La Niña state and PDO was mostly negative. The longer term warming trend and more recent anomalous warmth strengthens the proposition that warming and related viticultural measure changes in Napa Valley have been reinforced by anthropogenic climate warming. With continued emissions of greenhouse gasses, we can anticipate that Napa Valley will undergo further warming. Results here provide a template for future changes in viticultural measures. The recent continued warmth, combined with projected further warming strongly suggests that an additional 0.5°C of warming is likely within the next 3 decades; even this moderate increase would equate to 95 more degree-days over the Napa 191 day mean growing season. Higher amplitude and more frequent within-season viticultural impacts could also be expected from extreme warm spells. Such an increase in heat would impose a challenge in producing premium quality wine (Diffenbaugh et al., 2011; Gambetta & Kurtural, 2021; Hannah et al., 2013; Jones et al., 2005; White et al., 2006), although different grape varieties respond differently to a given amount of warming (Wolkovich et al., 2017).

The nature of anomalous warm seasons within the six decades considered here can be useful in preparing for more frequent warmth and shifted growing conditions. However, additional long term, continuous temperature records from the Napa region are needed to validate the USHCN adjusted data employed in this study. Although the Oakville CIMIS record begins 1989, the interannual variation within this period is strong enough to distort the reckoning of long period trends (e.g., Figures 2, 3 and 6). Thus, the longer period results here are pinned to the USHCN homogenized record, but this propagates errors and uncertainty from neighbouring stations used in the USHCN adjustment. An effect to keep track of is the extent to which warming in Napa may more closely follow the more moderate levels projected along the California coast (Pierce et al., 2018) as suggested by correlations of shorter period variations shown in Figure 8, or rather, the higher amplitudes projected for the inland environment. Under these projections, by 2070, coastal warming may be exceeded by inland warming by 0.5°C or more.

Multi-decade changes and these uncertainties underscore the need for sustained observations that are unaffected by changing urban influences and other spurious effects (Karl et al., 1995; Redmond, 2000). Continuous meteorological and viticultural observations are needed to more accurately record and understand temporal and spatial variability, including long period changes in Napa Valley and its surrounding regions.

AUTHOR CONTRIBUTIONS

Daniel R. Cayan: Conceptualization; investigation; funding acquisition; writing – original draft; methodology; validation; visualization; writing – review and editing; project administration; supervision. **Laurel DeHaan:** Writing – review and editing; formal analysis; software; data curation; validation; visualization. **Mary Tyree:** Software; formal analysis; data curation; visualization. **Kimberly A. Nicholas:** Writing – review and editing; methodology; validation; visualization; funding acquisition.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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