Asymmetric climatic warming improves California vintages

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Air temperature warming along coastal California from 1951-1997 has benefited the premium wine industry, as catalogued in larger yields and higher quality from Napa/Sonoma valleys. Climatic changes were asymmetric, with greatest warming at night and during spring. Warming was associated with large increases in eastern Pacific sea surface temperatures (SSTs) and higher atmospheric water vapor. Although the average temperature warming trend was modest (1.13ºC/47 yr), there was a 20 day reduction in frost occurrence and a 65 day increase in frost-free growing season length. Because regional scale SSTs persist for 6-12 months, predicting vintage quantity and quality from previous winter conditions appears possible.

Recent climatic warming trends, when expressed as annual average increases, tend to be modest (<1.0ºC/100 yr) (1) and may appear to be insignificant. However, the warming trends are asymmetrical: night minimum temperatures (Tmin) are rising faster than daytime maximum temperatures (Tmax), and seasonally, warming is usually greatest in winter or spring (2). Higher Tmin and spring warming affect mid-latitude ecosystems (3), particularly agriculture (4), through a reduction in frost frequency and longer growing season length (GSL) (5). Overall biospheric impacts depend on the timing of plant physiological requirements and the seasonality and magnitude of the asymmetric warming (6).

Grapes grown for wine production (winegrapes, *Vitis vinifera*) respond more directly to long-term climatic variations than more intensively managed crops, because they are less irrigated and fertilized, minimally genetically engineered, and long-lived (>50 years). Within the U.S., California produces 90% of all wine and dominates the $16 billion/yr retail wine industry (7). Since the early 1950s, winegrape growers in California have seen dramatic increases in premium wine quality, grape yield, and crop value (7). Given that high quality wines are associated with: (a) low frost damage in mild winters (January, February, March: winter); (b) early and even budburst, flowering, and development during warm springs (April, May, June: spring), and (c) optimal maturation with low summer temperature variability (July, August, September: summer) (8, 9), the question arises: have regional climatic changes helped the California wine industry?

The premium California wine producing areas of Napa and Sonoma valleys are strongly influenced by maritime weather systems. Trends (1951-1997) in annual average Pacific sea surface temperatures (SSTs) and California coastal average air temperatures (Tave) showed significant warming and co-variability (Fig. 1) which we suggest is associated with a water vapor feedback. To test whether increased SST affects atmospheric water vapor (measured by dewpoint temperature (Tdew)), we analyzed 1951-1997 daily meteorological records for the San Francisco airport (40 km south of Napa/Sonoma; long-term Tdew observations are not available in Napa/Sonoma). Annual Tdew increased 0.94ºC/47 yr ($p=0.015$) and was positively related to SST (Fig. 2). Monthly Tmin and Tdew from 1951-1997 were strongly correlated ($R=0.96$, $p<0.001$), suggesting a tight coupling between the two variables. Higher atmospheric water vapor may also lead to increased cloud cover; hourly observations of 1951-1993 cloud cover, aggregated to day and night values, showed a 3.4%/43 yr increase in nighttime cloud cover ($p=0.055$) and no change in daytime cloud cover.

Analysis of daily climatic data (Fig. 3) from four Napa/Sonoma sites (10) grouped into one regional average showed asymmetric warming, diurnal temperature range (DTR) compression, and frost reduction. Figures 1, 2, and 3 depict regional warming trends that are consistent with other results (5) and associated with warmer SSTs. Warming was also highly seasonal (Fig. 4). Average spring temperature increase was nearly double that in the rest of the year. Consistent with earlier studies (2), summer DTR showed the largest decline due to small but insignificant decreases in Tmax concomitant with Tmin increases.

Reported as annual averages, the observed changes in Napa/Sonoma are modest (1.13ºC/47 yr for Tave), but biological (11) and hydrological (12) consequences can be extensive. For example, the 2.06ºC/47yr increase in Tmin translated to a 71% decline in frost frequency (28 days/yr to 8 days/yr, $p<0.001$) and a 25% increase in frost-free GSL (254 days/yr to 320 days/yr, $p<0.001$). Enhanced water vapor shown by increases in Tdew, along with small changes in Tmax, resulted in an estimated 7%/47 yr reduction in growing season (March – October) vapor pressure deficit (VPD, $p=0.042$) (13). Lower VPDs reduce evaporative demand and water stress and increase plant carbon assimilation.

Springtime warming advances the start of the growing season (14), but since long-term data on Napa/Sonoma vine phenology were not obtainable, we estimated the day of winegrape flowering with a degree day summation (DD) (15). The DD approach predicted a 0.49 days/yr advance in flowering between 1951 and 1997 (Fig. 5a, $p<0.001$). Jones (9) observed similar climate-induced advancement of winegrape flowering and other phenological stages in Bordeaux, France. Flowering in a network of honeysuckle (*Lonicera korolkowii*) plants located around Napa/Sonoma advanced 0.71 days/yr (Fig. 5b), suggesting that the DD predictions are representative of observed regional biological responses.

Of all the observed changes in climate, spring warming and the decline in frost days and summer DTR are the most significant for wine quality (Table 1) (8). Wine quality ratings by Sotheby (16), available for California wines from 1963-1996 and dominated by north coast wines, increased by 0.22 points/yr (Fig. 6, $p=0.022$). Other rating systems show similar trends (16). Wine ratings have a major impact on wine value. For example, analysis of Wine Spectator data showed that for 1995 Napa wines, a rating increase of 10 points translated to a 220% per bottle price increase (17). In Napa valley, consequent with increasing quality, the value of the grape crop increased from $640/ha in 1958 to $19,600/ha in 1997 (18). Grape yield grew from 7 ton/ha to 10 ton/ha from 1958-1997 (18), suggesting that high yield and high quality are not mutually exclusive.

Among the variables listed in Table 1 and their derivatives, stepwise regression selected total winter frosts as a significant predictor of wine quality ($R=0.63$, $p<0.001$). While an R of 0.63 indicates that other factors (e.g., technology, vineyard management) contribute substantially to wine quality, the strength of the frost – wine quality relationship is its ability to track both high (inter-annual) and low (secular) frequency changes (Fig. 6). All parameters shown in Table 1 exhibit a pronounced increase over the 1951-1997 record, especially since the 1976-1977 shift in Pacific climate (Fig.1) (19). Before 1976, a number of vintages had poor ratings associated with frequent winter frosts. However, after 1976, ratings steadily improved with the near disappearance of winter frosts (Fig. 6), except during 1979 and 1989 when the number of severe frosts ($T_{min} < -3$ºC) was relatively high. Warmer SSTs after 1976, coupled with low sea level pressures dominating the California coast during 1977-1988 (20), resulted in an unprecedented string of years with high quantity and quality. Similar warming trends accompanied better sugar:acid ratios in Bordeaux, leading to higher wine quality over the last two decades (9). Variability in annual Tmin, which is directly related to many factors affecting wine quality (Table 1), was weakly related to the winter southern oscillation index ($R=0.42$, $p=0.0040$) (21), suggesting a global teleconnection.

Other wine-producing regions, such as Australia, South Africa, and Chile may be reaping the benefits of observed Tmin warming trends of similar or higher magnitudes (22). Unfortunately, along with the positive effects from recent climatic changes, there could be future negative impacts for the wine industry. Although Napa/Sonoma humidity levels are currently optimal (8), trends toward increasing humidity and air temperature suggest that in the future, the risk of fungal and vector borne disease outbreaks may increase (5). Pierce's disease, a fatal bacterial (*Xylella fastidiosa*) disease transmitted by sharpshooter beetles (Cicadellidae family) and apparently limited by frost occurrence (23), is increasing in Napa/Sonoma. Climatic change may therefore require increased investment in pesticide application and disease-resistant rootstock. In summary, Napa/Sonoma has experienced three highly beneficial climatic changes which appear to have increased yield and improved quality: 1) winter warming reduced frost; 2) spring warming stimulated growth; and 3) reduction in summer DTR produced optimal maturation.

Table 1. Climatic variables important for wine quality (8, 9): 1951-1997 increases and mean (standard deviation, σ) before and after the 1976-1977 regional Pacific climate shift (Fig.1) (19). All differences between periods were significant at the 1% level (t-test).

Parameter	1951-1997 changes	1951-1976 mean (σ)	1977-1997 mean (σ)
Winter Tmin (^oC)	2.39	3.74 (0.88)	5.06 (1.16)
Spring Tmin (^oC)	2.44	8.04 (0.63)	9.42 (0.77)
Summer DTR (^oC)	-3.14	19.0 (0.85)	17.5 (0.98)
Frost-free GSL (days)	65	272 (18)	311 (29)
VPD (kPa) (13)	-0.159	2.41 (0.12)	2.29 (0.15)

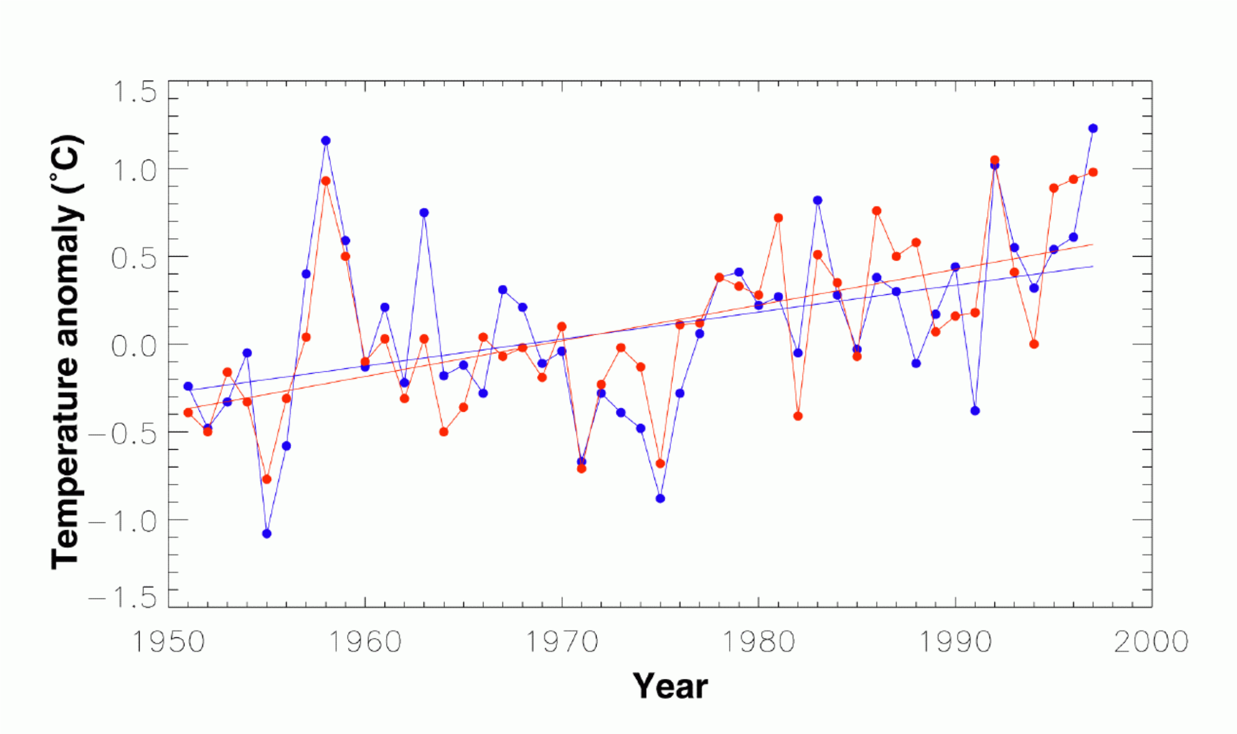

Figure 1. Standardized anomalies of coastal California average air temperatures and Pacific SSTs (24). SSTs (blue line and circles) are from a 5º x 5º grid centered at 35N 125W (0.71ºC/47 yr, $p=0.0030$); air temperatures (red line and circles) are north and central coast divisional averages (0.94ºC/47 yr, $p<0.001$). The increased post-1976 warming trends are part of a well-documented shift in Pacific climate (19). The strong correlation ($R=0.80$) suggests that land and ocean warming is coupled (25, 26) through a water vapor feedback. Moist Pacific air resulting from warmer SSTs, combined with shifts in sea level pressures leading to increased southwesterly winds (27), increases coastal atmospheric humidity and dewpoint temperature (Tdew). Higher Tdew leads to higher Tmin through the latent heat of condensation. Finally, enhanced water vapor increases cloud cover, further increasing Tmin through re-radiation of longwave energy.

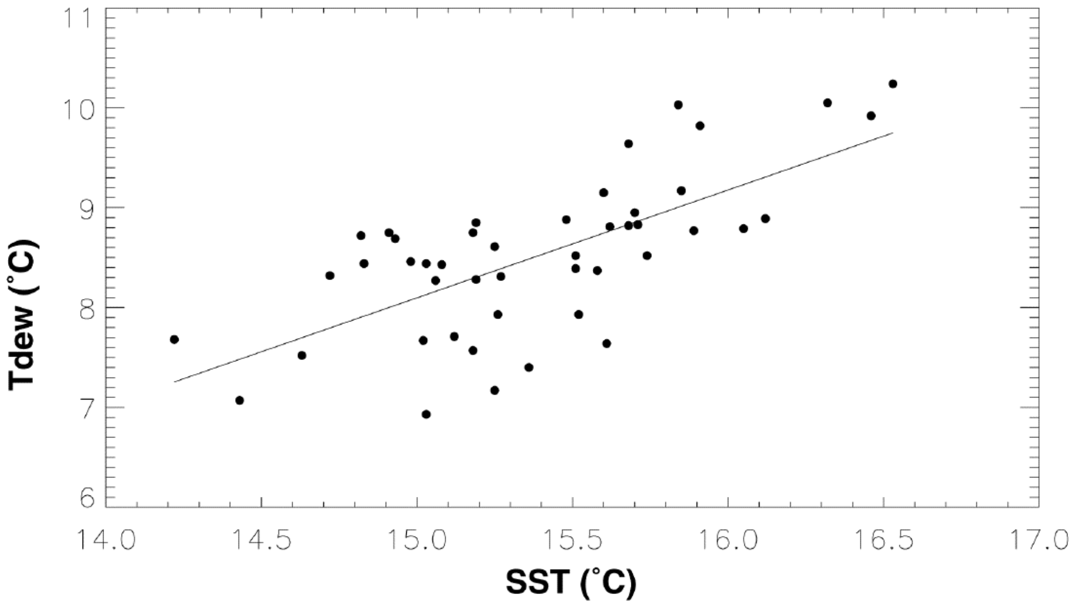

Figure 2. Annual Pacific SST vs. annual Tdew at the San Francisco airport from 1951-1997. The positive correlation between SST and Tdew ($R=0.70$, $p<0.001$) is a likely explanation for the observed enhancement of water vapor and increased temperature along coastal California (28). The reported decline in evaporation rates over the western U.S. (29) is consistent with reduced evaporative demand caused by increased atmospheric water vapor.

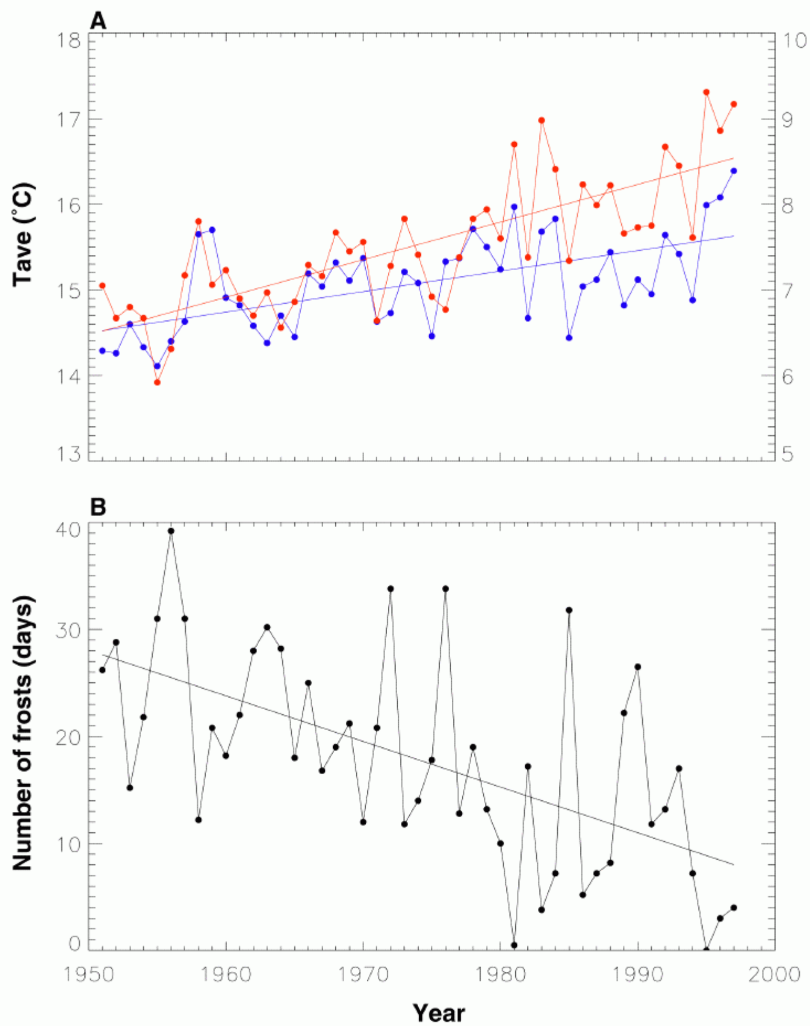

Figure 3. Napa/Sonoma climatic changes. (**A**) Tave increased 1.13ºC/47 yr ($p<0.001$, blue line and circles) with nearly all warming caused by increasing Tmin (2.06ºC/47 yr, $p<0.001$, red line and circles). Consequently, DTR declined by 1.87ºC/47 yr ($p<0.001$). Contribution of Tmin to Tave increase is higher than in global trends. (**B**) Napa/Sonoma frost decreased 71%/47 yr ($p<0.001$). If current trends continue, Napa/Sonoma will become a frost-free climate, indicating a fundamental shift in ecosystem function.

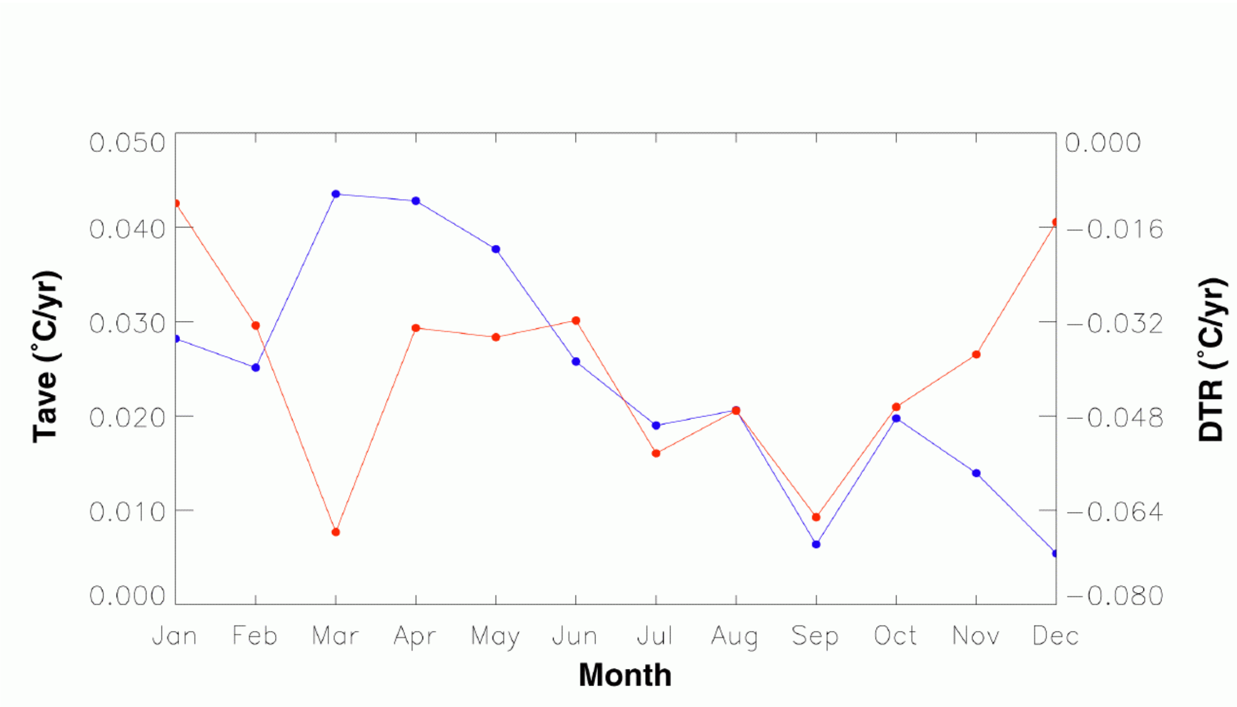

Figure 4. Napa/Sonoma monthly Tave and DTR trends from 1951-1997. Tave trends (blue line and circles) were significant at the 5% level in all months except December. DTR trends (red line and circles) were significant in March, May, July, August, September, and October. Tmax declined during summer months and increased during spring, but changes were not significant in any month. Spring warming and a decline in summer DTR, consistent with global trends, are favorable for winegrape cultivation (Table 1). The large DTR decline in March was accompanied by the highest monthly increases in nighttime cloud cover (18%/47 yr, p=0.010), Tdew (2.73ºC/47 yr, p<0.001), and Tmin (3.62ºC/47 yr, p<0.001) along with a small but insignificant increase in precipitation.

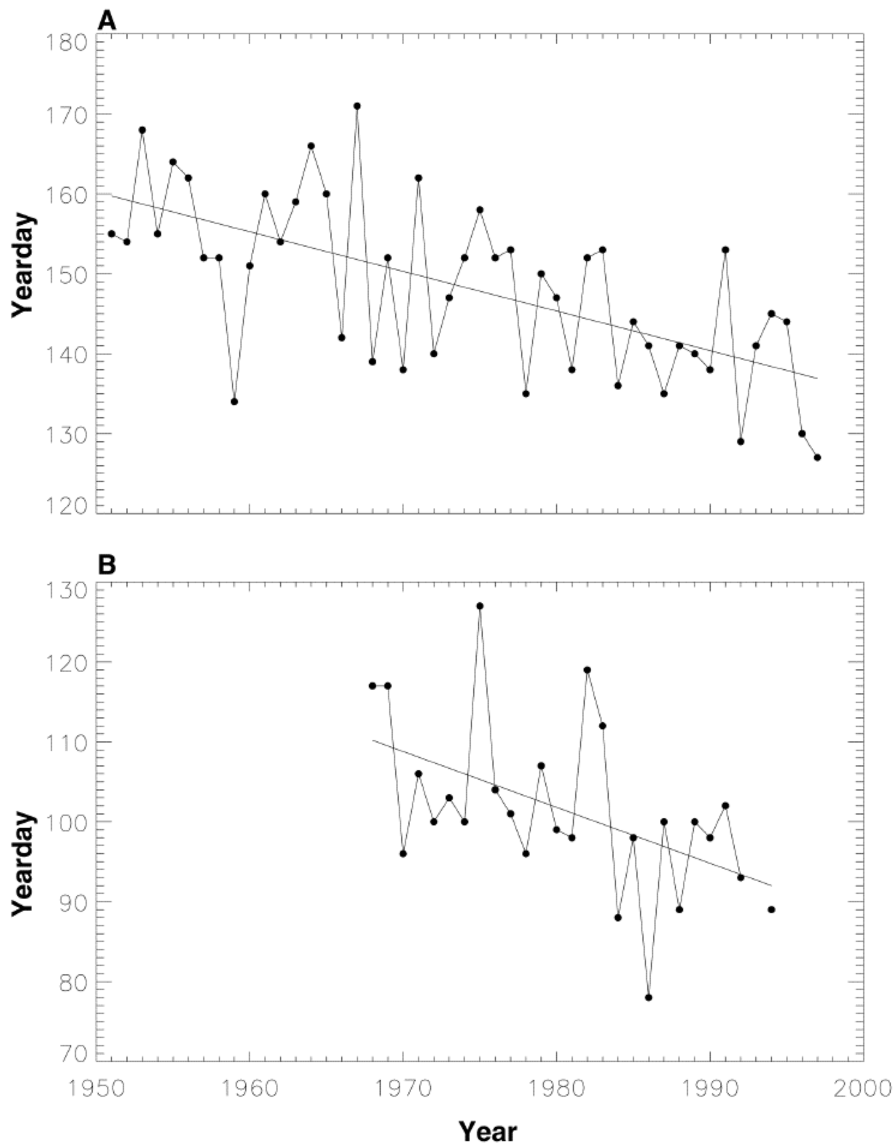

Figure 5. Estimated and measured Napa/Sonoma phenological trends. (**A**) Estimated winegrape flowering date. In northern California, flowering in winegrapes generally occurs when vines accumulate approximately 425 degree days (DD) with a Tave base temperature of 10ºC (15). Flowering advanced by 23.3 days between 1951 and 1997. (**B**) Measured honeysuckle flowering date (average date from four stations, 1993 missing) (11). Flowering advanced by 18.5 days between 1968 and 1994. Estimated winegrape flowering and measured honeysuckle flowering are correlated (R=0.58, p<0.001), suggesting that in spite of microclimate differences, both datasets show similar responses to climatic variability.

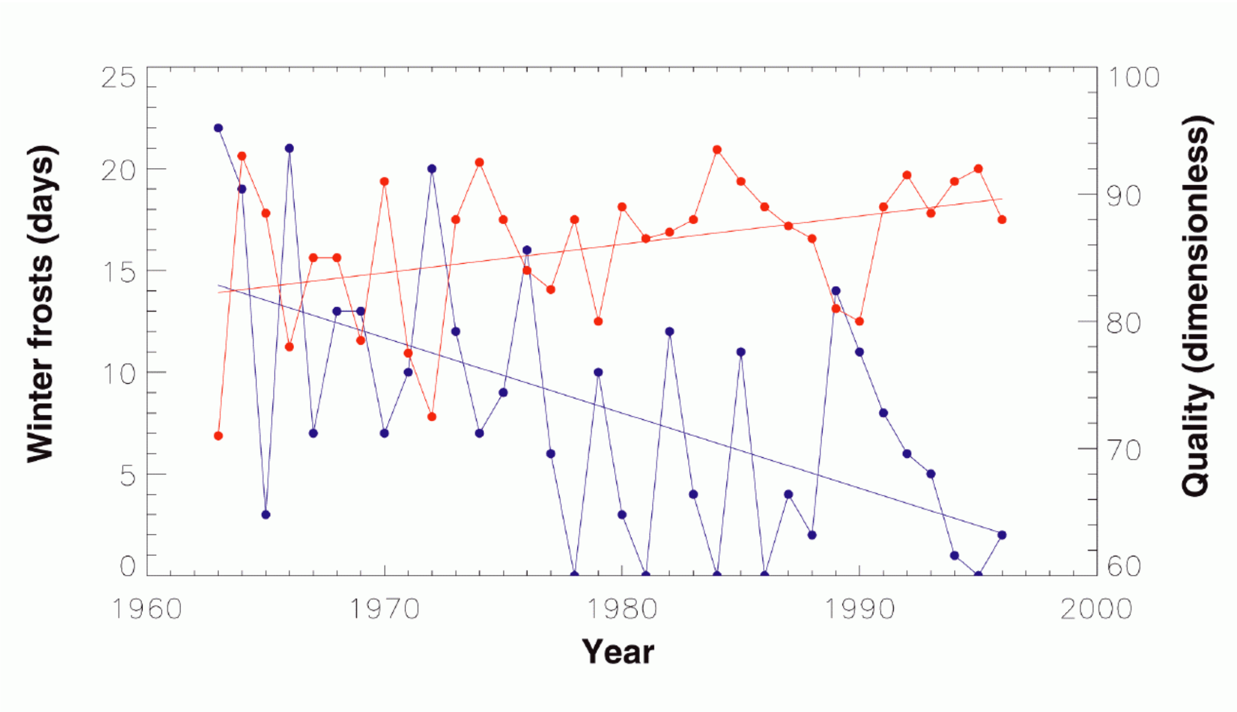

Figure 6: Observed relation between winter frost frequency and wine quality ratings (16). Buds damaged by frosts (blue line and circles) delay subsequent phenological events, leading to uneven maturity and poor wine quality (red line and circles) (30). Decoupling between quality and number of frosts during the 1980s is associated with an absence of severe frosts (Tmin < -3ºC). In addition to improving crop quality by reducing frost damage, a low number of frosts generally forecasts a favorable year for Napa/Sonoma wine production, including warm springs and low growing season DTR.

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13. We calculated VPD as the difference in vapor pressures at Tdew and Tmax. Calculation of VPD with a sine curve approximation of daytime temperature would have produced larger estimates of VPD decreases, but VPD at Tmax is more indicative of the most extreme diurnal water stress. Based on a high correlation (R=0.96, Tdew=-0.35 + 0.98Tmin) between observed Tdew and Tmin in a short-term (1995-1997) surface airways record at the Napa airport we assumed that Tmin = Tdew at Napa/Sonoma.

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16. Wine ratings produced immediately after production, such as the Sotheby (T. Stevenson, *The New Sotheby's Wine Encyclopedia* (DK Publishing Inc., New York, 1997)) and Wine Spectator ratings (J. Laube, *Wine Spectator's California Wine* (Wine Spectator Press, New York, 1996)) are more indicative of climatic influences than are ratings updated on a yearly basis. However, annually updated ratings, such as the Wine Advocate vintage charts for north coast California wines (R. Parker, “The Wine Advocate's vintage guide, 1970-1997” (http://www.winetech.com/html/vintchrt.html, 1997)) show similar trends, as do all long-term datasets of California wine quality. Since long-term current year ratings were not available specifically for north coast wines and because the Laube ratings are on a limited 1-5 scale, we used the Sotheby system for the remainder of the analysis (1-100 scale).

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31. This work was performed while RRN was a National Research Council Fellow at NASA/Ames Research Center. We thank Lee Johnson and Dave Peterson of NASA/ Ames and David Graves of Saintsbury Winery for their insights. Funding from NASA's Earth Science Enterprise supported this research through an Earth System Science Fellowship to MAW and grants to SWR and JCC. DRC was supported by grants from the NOAA Office of Global Programs.

Supplementary Figures

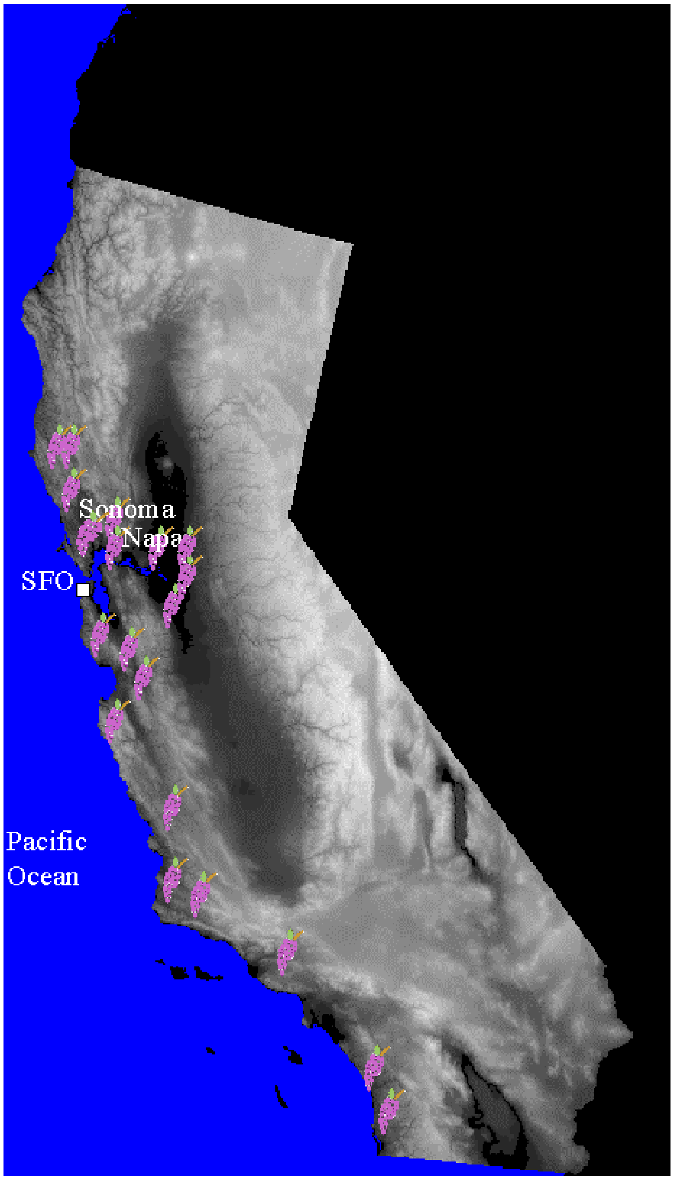


Figure 1 (supl). Premium wine producing regions of California (1). A strong maritime influence is usually needed to produce premium wines in California. Therefore, it is conceivable that changes over the eastern Pacific will have a significant impact on the California premium wine industry**.**

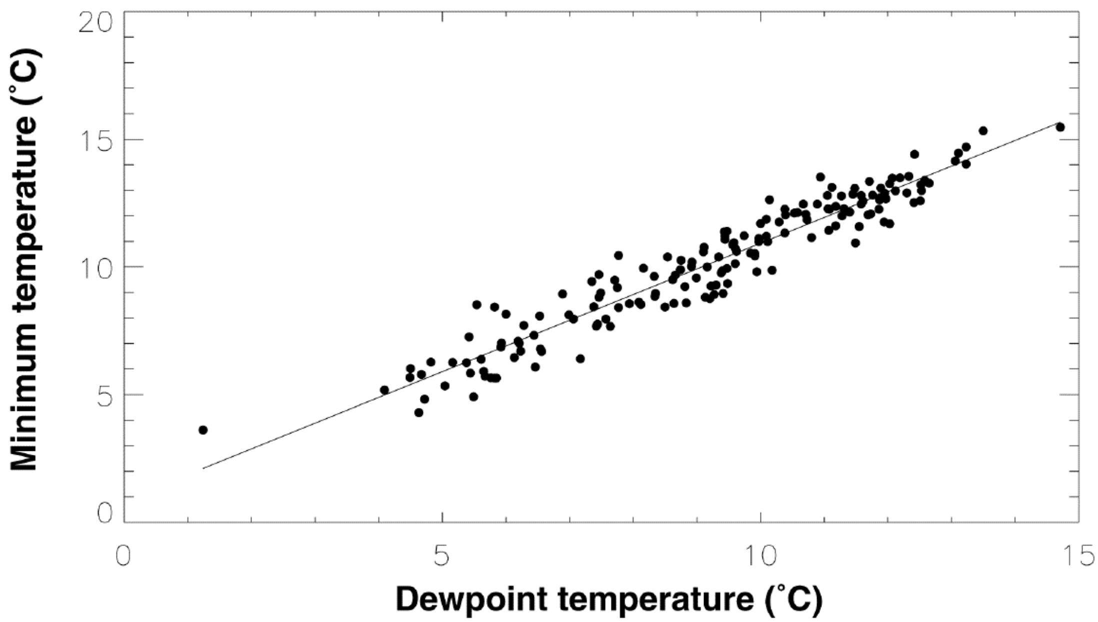


Figure 2 (supl). Relationship between monthly (1951-1997) dewpoint temperature and monthly night minimum temperature at the San Francisco airport (R=0.96). This well known climatological relationship implies that enhanced atmospheric water vapor generally leads to an increased minimum temperature through the latent heat of condensation (2).

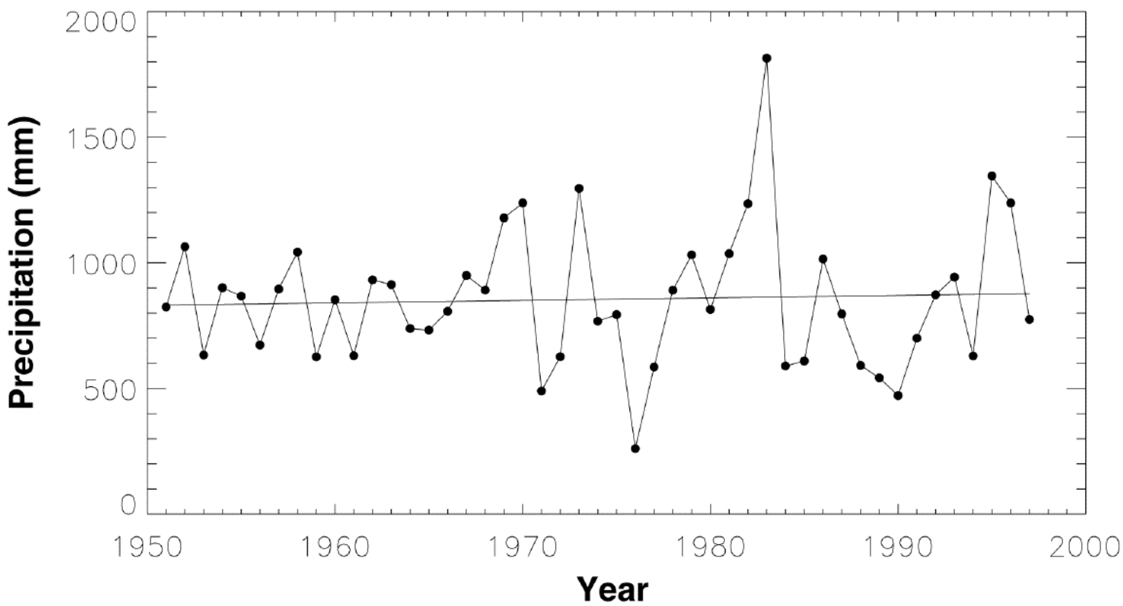


Figure 3 (supl). Annual total precipitation trends (1951-1997) over Napa/Sonoma. We did not observe significant changes in monthly or annual precipitation, while other regions in California showed a 10-20% reduction (3). March showed a small increase (insignificant) which also corresponded to a large decline in DTR.

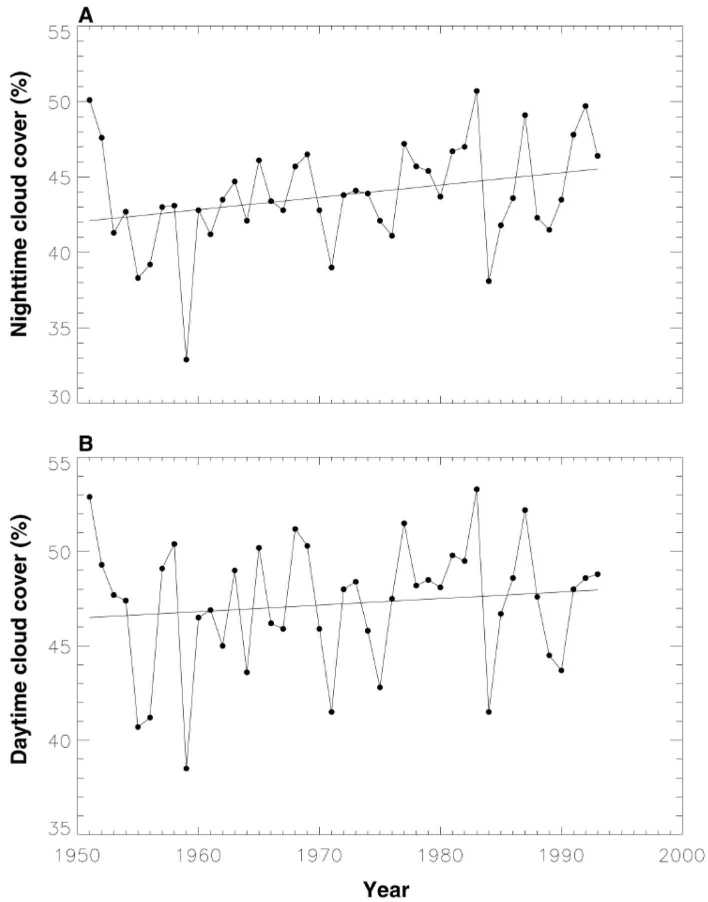


Figure 4 (supl). Annual average cloud cover trends at the San Francisco airport. (**A**) Average nighttime cloud cover was derived from hourly cloud cover observations between 7PM and 7AM for 1951-1993. The increases in nighttime cloud cover (3.4%/47 yr, p=0.055) are consistent with earlier reports (4) and suggest a possible mechanism for the decline in DTR. Increases in Tdew along with nighttime cloud cover are consistent with a water vapor feedback. Together, Tdew and nighttime cloud cover explained 65% of the variability in annual Tmin at the San Francisco airport. (**B**) Average daytime cloud cover was derived from hourly cloud cover observations between 7AM and 7PM for the years 1951-1993. Unlike nighttime cloud cover, no trends were found in daytime cloud cover, implying that there was no change in incident solar radiation.

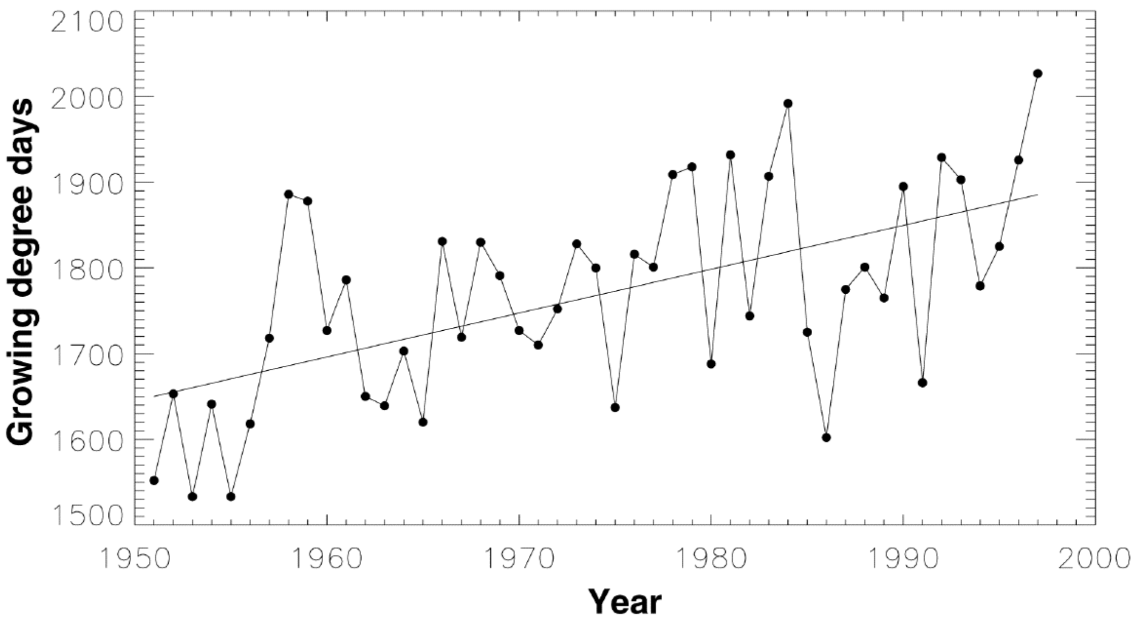


Figure 5 (supl). Growing season (March-October) degree day (DD) accumulation trends. DD are accumulated heat units widely used in agriculture to predict phenological events (budbreak, flowering, and harvest) and pest and disease outbreaks. Observed warming trends increased growing season DD totals and accumulation rates. A 14% increase in growing season DD was estimated from 1951-1997, indicating higher sugar accumulation and improved quality (5, 6). DD summations also showed that 1600 DD, the amount required for harvesting grapes for wine making in Napa/Sonoma, were accumulated 20-25 days earlier in 1997 than in 1951. Faster accumulation allows vineyard managers to leave the grapes on the vines until the optimal balance of sugars and acids is achieved.

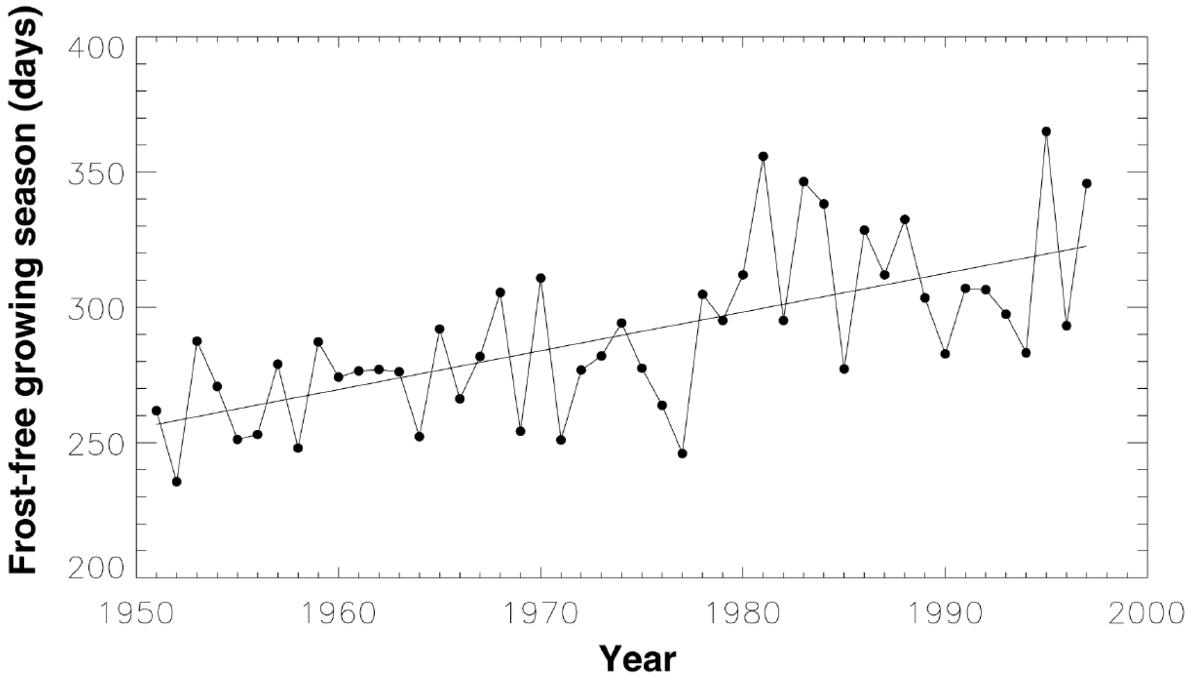


Figure 6 (supl). Frost-free GSL trends. A remarkable 65 day increase in frost-free GSL was caused by a strong decline in already irregular frosts over Napa/Sonoma. Longer growing seasons allow vineyard managers greater flexibility in various viticultural operations (pruning, harvest, etc.). Additionally, implications of such changes are profound for natural ecosystems, especially for species composition in communities as well as for carbon cycles (7).

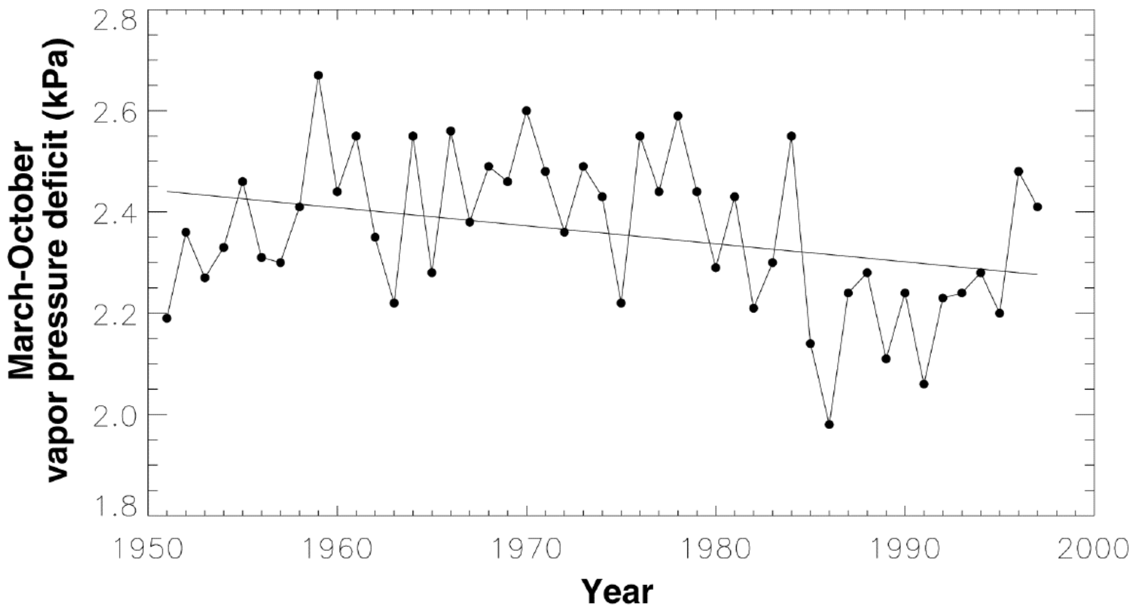


Figure 7 (supl). Growing season (March-October) VPD trends. Significant increases in atmospheric water vapor coupled with small summer reductions in Tmax resulted in an estimated 7% decline in VPDs. As they are computed using Tmax, the reported VPDs reflect the maximum diurnal VPD. Given the strong diurnal variation in Tmax and small variation in water vapor, it is likely that on average, the VPD reductions would be greater than 7%. Low VPDs imply low evapo-transpirational demands and consequently, low potassium uptake by the roots. High potassium levels in wine grapes, caused by high root uptake, are associated with poor quality wines (8).

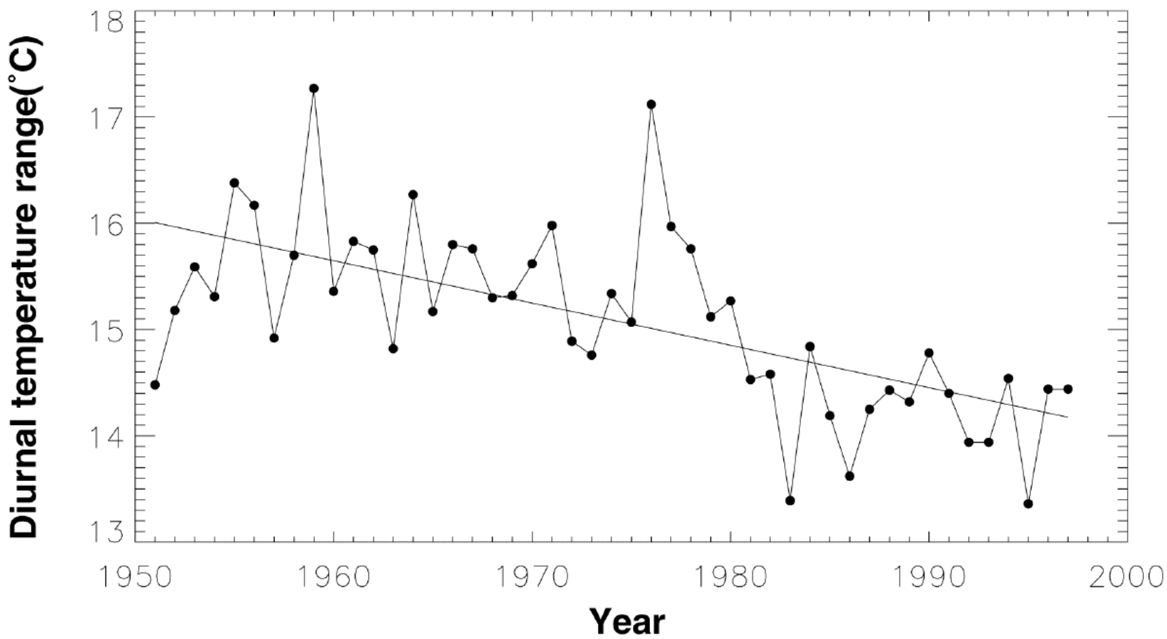


Figure 8 (supl). Annual average DTR trends. Asymmetric warming led to a 1.87ºC/47 yr compression of the DTR. Temperature variability and temperature extremes, as measured by Gladstones' temperature variability index (TVI) (8), are related to wine quality. Low TVIs favor high-quality wines. In Napa/Sonoma, the TVI declined from 36.1 in 1951 to 31.4 in 1997. TVI values under 30 indicate that any variety of table wine may be produced. Even within a vineyard, sites with higher Tmin and low DTR as a result of soils or topography are regularly associated with high quality wines (1). TVI = ∑ ((TDmax – TDmin)+(TMmax – TMmin)), where TD and TM represent daily and monthly values between March and October.

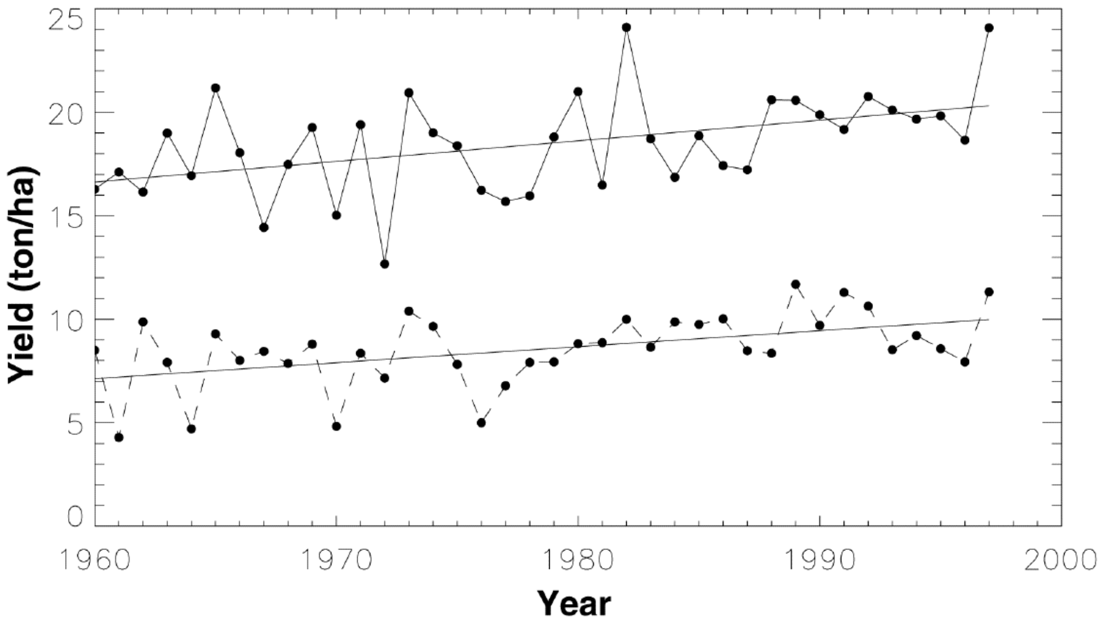


Figure 9 (supl). Napa and California yield trends. Between 1960 and 1997, Napa yields (9) increased 33% (dashed line and circles) while California yields (10) increased 22% (solid line and circles). After 1976, Napa and California yields increased monotonically. California yields are consistently higher than Napa yields because they include central valley jug wine and table grape production, which, for management reasons, have a much higher yield than premium wine grapes. Additionally, Napa and California yields are correlated ($R=0.57$, $p<0.001$), suggesting that regional climatic variation influences crop yield and that recorded yield increases are not purely due to management practices.

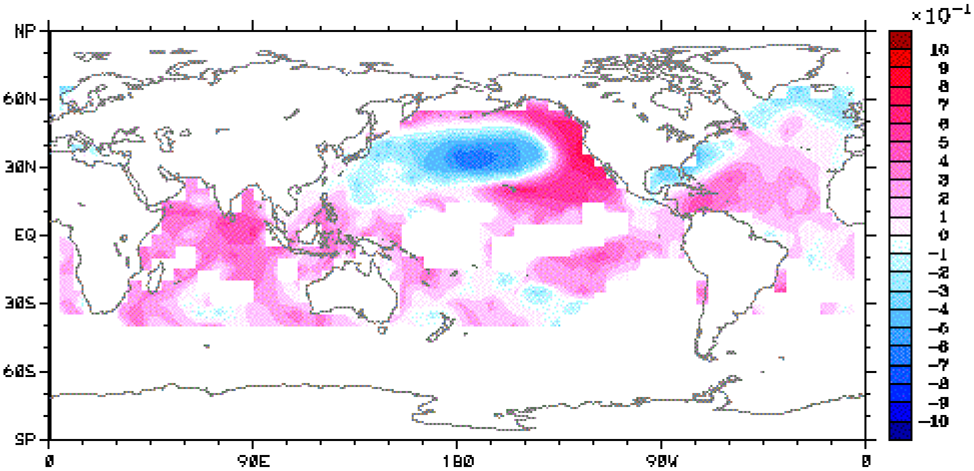
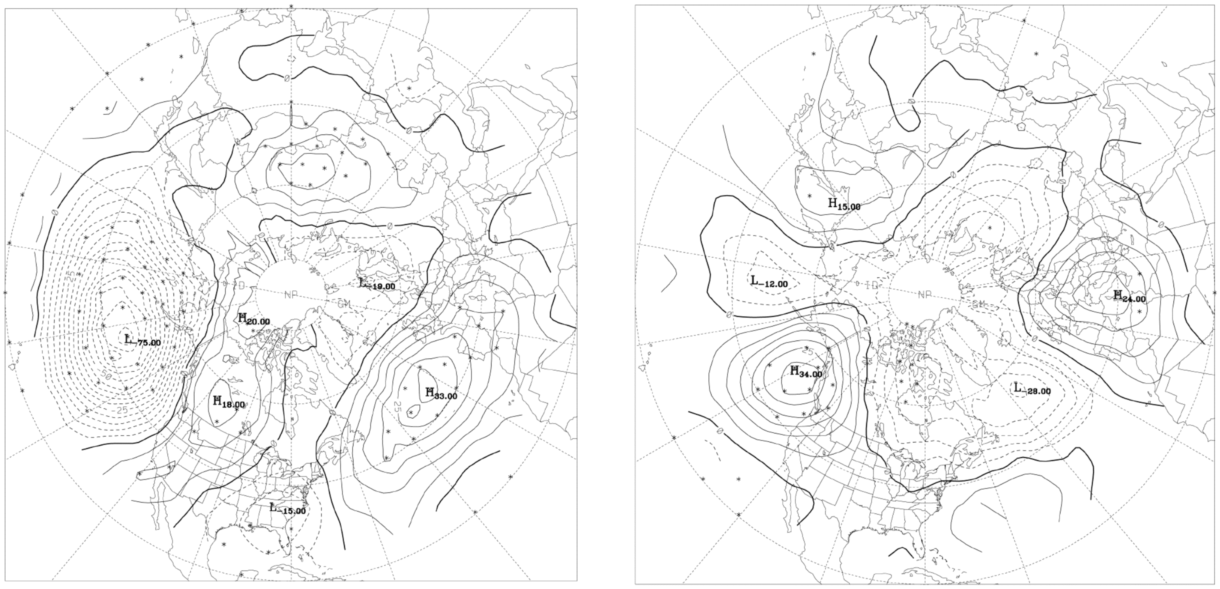


Figure 10 (supl). Correlations between coastal California Tave and SSTs (11) during winter (1946-1998) at each 5º x 5º grid cell. The positive relation between coastal land temperatures and near-coast SSTs suggests a strong maritime influence over the wine producing areas. Warmer winter SSTs, because of their persistence, also lead to warmer spring temperatures. This suggests that given winter SSTs, reasonable prediction of next-year wine quality may be possible. Warmer winter SSTs, on average, lead to higher quality wines from coastal California.



(A) (B)

Figure 11 (supl). Winter anomalies of 700 mb pressure heights (m) (11) for high and low frost years in Napa-Sonoma. We calculated the average number of annual frosts and divided the 1951-1997 dataset into above and below average scenarios. For the ten most extreme years within each scenario, we then calculated the composite 700 mb pressure patterns. Winters with low frost occurrence (**A**) are dominated by Pacific low pressure systems while winters with high frost occurrence (**B**) are dominated by Pacific high pressure systems. Since 1976, low pressure systems have become more frequent (12) bringing warm and moist southwesterly winds over the California coast.

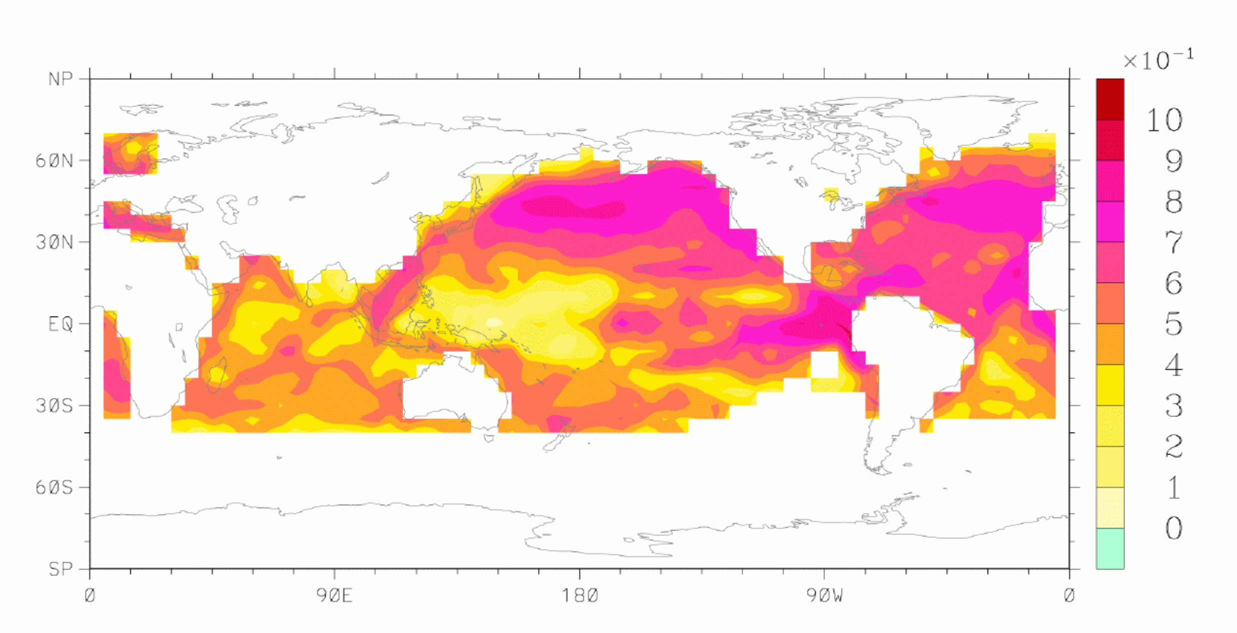


Figure 12 (supl). Correlation between SST and specific humidity (q, g/m^3) (11) at each 5º x 5º grid cell from 1946-1998. Data are smoothed with a three-month low pass filter. Increasing q is closely associated with increasing SST along the western coast of the U.S. Our analysis of the connection between SSTs and Tdew at the San Francisco airport is consistent with strong correlations between SSTs and q (shown here), along with recently reported correlations between q and temperature warming along coastal California (2).

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