California Heat Waves with Impacts on Wine Grapes

Alexander Gershunov[1], Daniel R. Cayan[1,2] and Bernard Retornaz[3]

[1]Scripps Institution of Oceanography, University of California San Diego
[2]US Geological Survey
[3]Maison Louis Latour

ABSTRACT

Heat wave activity over the California region has undergone significant changes over the last two decades. Regional heat waves in recent years were more humid and their nighttime temperature expression has been greatly accentuated in recent years. These recent changes appear to be an acceleration of a long-term trend that is regionally consistent with global climate change. Humid heat and elevated nighttime temperatures, especially in the form of stronger, longer lasting and more spatially extensive heat waves can stress various aspects of society and environment. Agriculture is susceptible to humid heat, particularly in a region acclimatized to hot and dry summer days and cool nights: conditions ideal for wine grapes. Two decades of observations reveal potentially detrimental effects of increased heat wave activity in California upon state-wide wine production tendencies. In traditional "old world" wine-making regions, wine harvest dates are known to reflect, in part, average climate conditions over the growing season, in the sense that warmer seasonal temperatures tend to favor greater harvests. In California, however, we find an insignificant tendency for warm summers on average to favor smaller yields, especially for red wine grapes, while a much stronger relationship exists with extreme temperatures rather than with mean summertime temperatures—extreme hot events, especially those of the humid variety, have strongly associated with lower-yield harvests. This is a regional state-wide relationship. A further indication of heat wave impacts is a linkage between hot temperature extremes and *delayed* harvest dates of chardonnay grapes at a vineyard in the Carneros region of the Napa Valley. Possible reasons for these findings are discussed along with their implications and future research plans in *climenology* – the study of enology and climate.

INTRODUCTION

Climatic vacillations and trends are keenly recorded by Bacchus since time immemorial in grape harvests and in the quality of the wines they yield. Grapes absorb heat and sunshine, the fruit optimally thrive when days are warm and dry and nights are cool: conditions characteristic of Mediterranean-type summer climates found in several regions around the world. Grapes integrate climatic conditions during the warm growing season and, therefore, the warm season's climate signature is imprinted into the vines and eventually the wine. Traditionally, cool and rainy summers result in late harvests of immature fruit yielding weak sour wines. Hot and dry summers typically result in early harvests of mature fruit and abundant robust wines. The effects of average seasonal temperatures and related insolation on harvest dates are well known and quantified, so much so, that wine harvest dates are a prime example of historical proxy data used to reconstruct past climate (spring and summer average temperature and cloudiness/rainfall) in old-world traditional wine growing regions (e.g. Le Roy Ladurie 1967). It is also understood that extreme short-duration weather events, even if not clearly reflected in seasonal averages, can decisively impact the grape if they occur at key times during the growing season. Such is the case with heat waves, which tend to occur around the annual peak of temperature in July and August, around the time of veraison or grape ripening. Although dry heat is generally good for wine grapes, excessive and/or humid heat can stress the grapes' metabolism, delay ripening and promote withering. In the less traditional "new world", the relationships between harvest times, yields and quality may be complicated by non-traditional wine-making practices. Without focusing on grapevine chemistry or biology, we here provide empirical evidence of the effect of heat waves on wine grapes in California.

Excessive heat waves in California have been recently shown to be primarily of two types – (I) dry daytime heat and strong nighttime cooling typical for the region and (II) humid heat waves expressed most strongly in nighttime temperature anomalies (Gershunov et al. 2009, hereafter GCI09). Humid heat waves display a clear and accelerating upward trend culminating so far with the July 2006 event – the strongest heat wave recorded in at least six decades of station observations – twice as strong in minimum (nighttime) temperature as the previous type II record, 2003, which was at the time of its occurrence also unprecedented by a large margin. Even the daytime (maximum) temperature expression of the primarily nighttime humid 2006 event broke records set by type I events. The upward trend in California humid nighttime heat waves is reflected strongly in temperature intensity, duration, and spatial extent (GCI09).

Because nighttime heat waves have not been the typical form of heat waves in this semi-arid Mediterranean climate, they may exert greater stress on many living organisms acclimatized to dry daytime heat and cool nights. The 2006 heat wave, therefore, impacted the health of humans and animals, the ecosystem and energy supply (see references in GCI09) as well, as we shall see, wine grapes. Powerful impetus for impact quantification of humid heat waves on grapes, among other organisms, is provided by the fact that a regional intensification of humid heat waves is consistent with global warming via exceptional warming of the Pacific Ocean just west of Baja California (GCI09) that is enhanced by a regional cloud-feedback mechanism (Clement et al. 2009). This warming is associated with increasingly humid air that is transported northward to California by synoptic circulations responsible for large-scale regional heat wave activity (GCI09).

Below, we briefly describe the weather and grape data as well as the procedure for heat wave activity quantification locally and over the region. We then show some relevant features of heat wave activity and their observed changes. Red and white wine grape production is then described; environmental influences are quantified and related to regional heat wave activity. Finally, chardonnay harvest dates at one Napa Valley vineyard are examined together with local heat wave activity. In conclusion, results are briefly discussed in the context of winemaking practices, future climate challenges and topics for future research in *climenology,* our proposed term for the study of climate and winemaking.

DATA

Daily maximum and minimum temperature records are obtained, as in GCI09, from the National Climatic Data Center (NCDC 2003) but updated through summer 2008. Out of 353 weather stations in California, we chose 135 stations as representative of the State. These stations were quality controlled and selected as in GCI2009 but with somewhat denser coverage practical over California – the station with the most complete summertime records (1948-2008) in a 20km radius was chosen. In hilly terrain, typical of many vineyard locations, where elevation ranged at least 100m in a 20km radius, the highest elevation station with adequate data (no more than 15% of data missing over the 1948-2008 period) was also retained. This removed the urban bias present in the spatial distribution of stations and resulted in a generally uniform state-wide coverage.

Every year, the US Department of Agriculture publishes a publicly available report on all wine grapes officially crushed in the state of California (CDFA 2009). Information on tonnage and price is available for every year since 1988. The data are classified by red and white wine types in addition to raisin and table types. Grape crush in thousands of tons as well as price per ton for various types of grapes is utilized here for red and white wine types.

Harvest dates for chardonnay grapes grown at the Brown Ranch vineyard in northeast Carneros, Napa Valley, were obtained from Saintsbury Vineyards (http://www.saintsbury.com/) courtesy of David Graves.

Unfortunately, not enough recent data is available for Baja California, particularly for the Guadalupe valley, Mexico's primary wine region. However, its proximity to the State of California makes the state-wide results presented here relevant to impacts on wine making in Mexico.

RESULTS

Clearly, there has been a general warming across California particularly apparent in minimum temperatures (Figure 1). The summer (June, July and August, or *JJA*) 2006 stands out as the hottest summer in average nighttime temperatures (GCI09). Some of this warmth had to do with the late July 2006 heat wave that was accentuated in nighttime temperatures because the elevated greenhouse effect associated with extraordinary levels of humidity impeded radiational cooling (GCI09). This event powerfully marked most of California including, as we shall see, Napa Valley (Figure 2). Because stronger warming has occurred in nighttime or minimum temperature (Tmin) compared to daytime maximum temperature (Tmax), the diurnal temperature range (Tmax – Tmin) has been decreasing. This pattern has been largely typical of observed global warming (e.g. Easterling et al. 1997).

a) Average summertime Tmax b) Average summertime Tmin

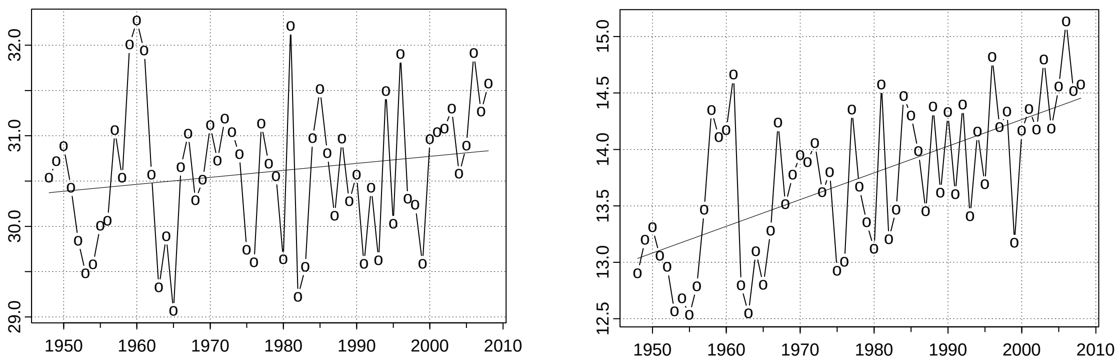

Figure 1. Maximum and minimum temperatures (Tmax and Tmin) averaged over summer (JJA) and 135 California stations.

a. Heat waves

We define heat waves from daily observed maximum and minimum temperatures, as in GCI09. Local Tmax and Tmin climatologies are constructed at each station using daily data from the 1950-1999 base period summers. For each summer, temperature exceedances over a high threshold (99th or 95th percentiles of the local baseline climatology) are summed up as degree days at each station and summer giving the local summertime heat wave activity index (HWAI). Figure 2 shows the data and thresholds at the Napa State Hospital station. Heat waves that exceed local thresholds can last from several days to two weeks. Not every summer registers local heat wave activity at the 99th percentile threshold. The late July 2006 event was unprecedented at many California stations. It the Napa station, it was not unprecedented in terms of its peak one-night intensity (June 14, 2000, was record high at 25ºC), but due to its overall magnitude (intensity and duration), local HWAI peaked in 2006 relative to this part of the record and this is reflected in Figure 7 below.

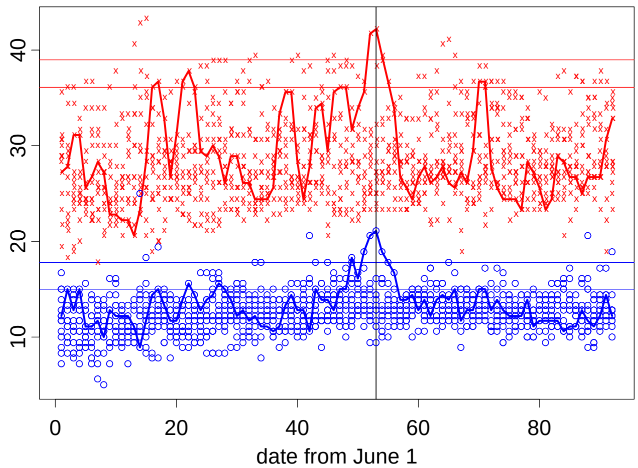

Figure 2. Minimum (Tmin, blue circles) and maximum (Tmax, red x's) temperatures as functions of summer date (from June 1 to August 31) observed at the Napa State Hospital meteorological station (38.27ºN, 122.25ºW) over the 14 years 1994-2007, the period of overlap with phenological observations at close-by Brown Ranch vineyard, Carneros (Figure 7). 2006 Tmin and Tmax are shown in blue and red curves, respectively. July 23, the peak date of the 2006 event is marked with the vertical line. Horizontal lines delineate the 95th and 99th percentiles of the 1950-1999 Tmin and Tmax climatologies.

Local HWAI computed at every station and averaged over all stations in California constitutes the regional California HWAI (CAHWAI, Figure 3). Regional nighttime-accentuated (Type II) heat waves are clearly on the rise, as discussed in detail in GCI09. The crucial causal difference between daytime and nighttime-accentuated heat waves is not atmospheric circulation, but rather the availability of humidity that is advected by the heat wave circulations. Heat wave circulations typically involve a high surface pressure dropping into the southern Great Plains and a low pressure developing concurrently along California's central coast. This synoptic configuration of surface pressure centers favors northward advection of air into California notably from a marine region west of Baja California that has been experiencing a pronounced warming (1.5°C since 1948) and a related warming and moistening of the air above it. Advection of this gradually warmer and especially moister air by episodic synoptic heat wave circulations is largely responsible for the rising trend in nighttime humid Type II heat wave events. Please refer to GCI09 for more detail.

a) CAHWAI95: 95th percentile threshold   b) CAHWAI99: 99th percentile threshold

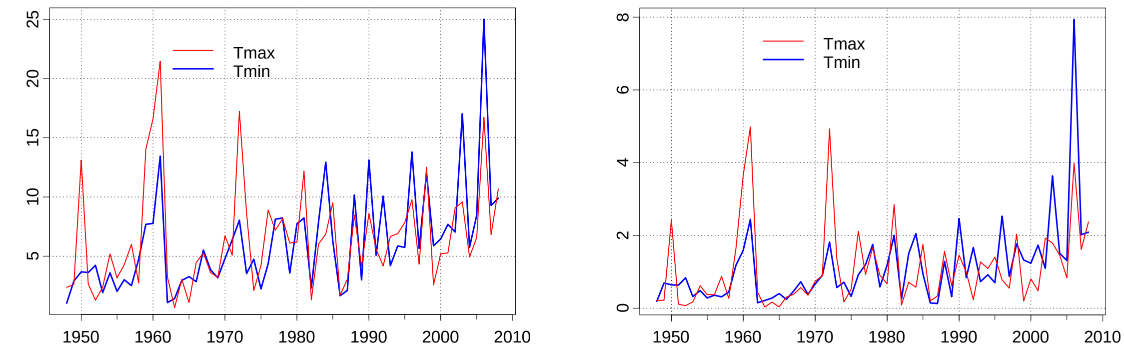

Figure 3. CAHWAI computed using the 95th (a) and 99th (b) percentile exceedance thresholds.

The more extreme CAHWAI99 index shows a steeper and apparently accelerating rate of increase compared to the milder CAHWAI95.

b. California grape crush

Figure 4 shows total tons of red and white wine grapes crushed in the entire state along with their prices averaged over all vineyards and varieties. In the following discussion, we use grape *crush* and *production* as interchangeable terms.

a) Red and white grapes crushed (K tons)   b) Red and white grape prices (USD/tonn)

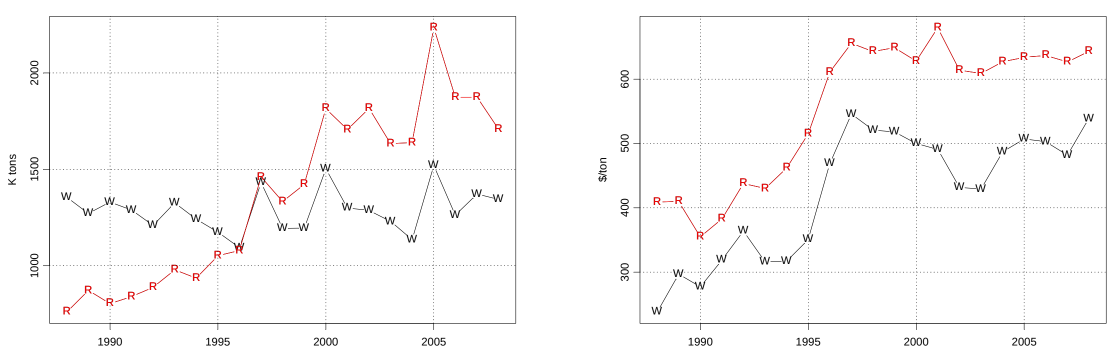

Figure 4. California Grape Crush Report data. Red and white grapes crushed (a: red and black curves, respectively) and red and white wine grape prices (b).

It is clear from Figure 4b that most of the variability in grape crush (Figure 4a) is due to wine style and other resource management decisions. Originally, more white wine grapes were grown in California. (IS THERE A HISTORICAL REASON FOR THIS? KIM?) As red wine grapes have always sold for a higher price (Figure 4b), the production of red wine grapes increased, while that of white wine grapes remained relatively constant since 1988. Probably [OR REFERENCE IF DEFINITELY. KIM?], more vineyards were planted to grow red wine grapes, perhaps at the expense of other agricultural commodities, but apparently not too much at the expense of white wine grapes whose production, although decreasing somewhat in the mid-nineties, subsequently recovered. Prices for both types of wine grapes increased the most in the early and mid-nineties. Possibly in response to the price of red wine grapes remaining higher than white wine grapes , production of red wine grapes increased most quickly in the second half of the 1990s, by about 80% in five years. The production increase lagged the price increase by about three years required for vines to take root and mature. Prices remained relatively stable since 1997 and the red wine production trend subsided since 2000 and stabilized at a level above that of white wine grape production. Although the red wine grape crush trend subsided, the year-to-year variability or production *volatility* increased since 1997 with an all-time peak in production registered in 2005, for both grape types. To remove trends due to economic decisions and accentuate the possible effects of environmental variability including that of climate on crush volatility, we produce a series of *innovations* or *gains*, i.e. changes in grape production from one year to the next (Figure 5).

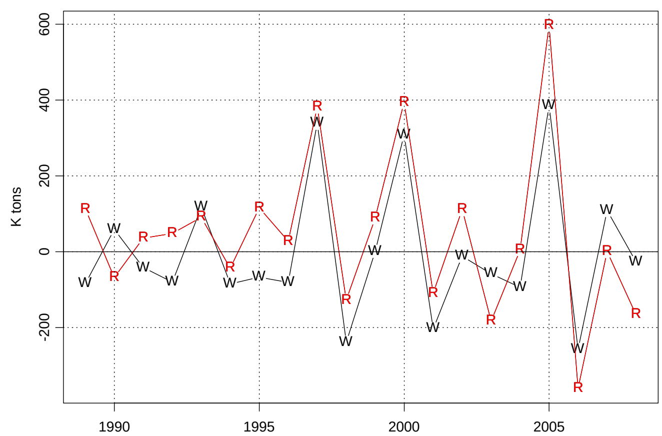

Figure 5. Red and white grape crush gains, i.e. production in year(n) – year(n-1).

The series of innovations in red and white wine grape crush (Figure 5) more clearly show a relative stability of production until a big gain in 1997 and strong volatility (i.e. large year-to-year changes) in production since then. Big jumps in innovations of red and white grape production are clearly in phase with each other which is to be expected if large-scale environmental factors are responsible for these jumps[1]. The largest year-to-year drop in production of both types of wine grapes occurred in 2006, while the second largest drop in red wine grape production occurred in 2003, the second most intense humid heat wave year. We next compare these gains with the daytime and nighttime statewide heat wave indices, the CAHWAI (Figure 6).

---

[1] It is also possible that environmentally-driven overproduction affects prices and production decisions the following year. However, this idea is not pursued here. Instead, we show how changes are related to heat.

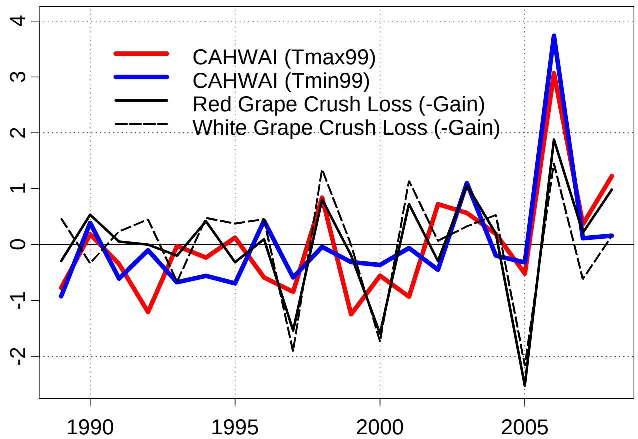

Figure 6. This figure combines figures 5 and 3b over their overlapping period. Grape crush gains are inverted for ease of visual interpretation. Units are scaled to standard deviations. Original magnitudes can be seen on Figures 3b and 5. The correlation coefficient (r) of CAHWAI (Tmin99, blue curve) with red wine grape crush gain (solid black curve) is -0.60, p = 0.0027, and that with white wine grape crush is -0.38, p = 0.047; correlations with Tmax99 as well as with Tmin95 and Tmax 95 are progressively lower, but all significant at the 95% confidence level, while correlations with average summertime Tmin and Tmax are not significant (-0.32 with red grape crush gain and only half that magnitude with white grape crush gain, for either Tmin or Tmax summertime average).

Large gains in grapes crushed were made in years with mild summers (1997, 2000, 2005) while big drops in 1997 and 2003 and 2006 clearly coincided with active heat wave summers. We know from GCI2009 (their Figures 12d and 13d) that summer 2001 saw strong humidity and nighttime-accentuated heat wave activity, although daytime temperatures were depressed due to convective cloudiness and even relatively widespread rainfall in early July. This mugginess together with reduced sunshine could have adversely affected the grapes in 2001.

We know that, traditionally, dry daytime heat is good for grapes. In California, where the bulk of wine grapes is nowadays grown in the very hot Central Valley, we see a weak state-wide tendency for cooler summers on average to yield bigger harvests. Too much heat appears to be harmful, as the much stronger relationship between grape crush and the more extreme CAHWAI99 clearly suggests. Moreover, it is specifically humid heat that appears to be particularly detrimental to wine grapes and red wine grapes are especially affected.

c. Napa valley harvest dates

Given results of Le Roy Laduire (1967) and the fact that heat builds up sugar in the grapes, we expected to see early harvest dates in particularly hot summers. However, results presented in Figure 7 suggest the opposite, at least for Chardonnay grapes at Brown Ranch vineyard of Saintsbury in northeastern Carneros.

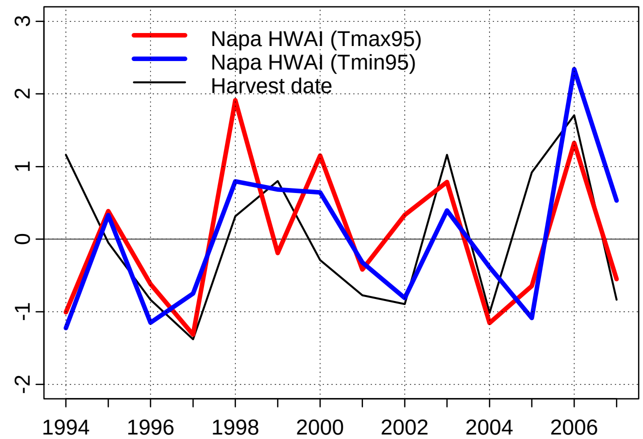

Figure 7. Local Napa Valley HWAI and Chardonnay harvest dates at nearby Brown Ranch vineyard, northeast Carneros, Saintsbury, Napa Valley. Indices are scaled to standard deviations. The HWAI data are scaled from original values displayed in Figure 3b, while harvest dates range from August 27 in 1997 and October 17 in 2006. Correlation coefficients of harvest date with nighttime and daytime heat wave activity are, respectively, 0.43 and 0.42 ($p = 0.065$).

Both nighttime and daytime HWAIs evaluated at Napa State Hospital weather station are correlated with Brown Ranch Chardonnay harvest dates at above 0.42 ($p = 0.065$). Fourteen years is a small sample and these correlations are only significant at the 90% confidence level. Obviously, many other environmental factors besides heat waves influence harvest dates, including those influencing earlier phenological milestones (e.g. bud break and veraison), factors such as summertime cloudiness and springtime climate, etc. Other grapes may possibly react differently to the same environmental pressures and other growers can make different harvesting decisions in the face of the same environmental pressures. Heat wave impacts differ from one event to another. We recognize that besides the types of heat waves (humid vs. dry), timing of events can also be very important vis a vis the grape's phenology or stages of maturity. We do not consider this important topic here. With the above caveats, heat waves do appear to make a difference, but why towards later harvests? Moreover and interestingly, average summertime Tmax and Tmin are uncorrelated with harvest dates of Brown Ranch Chardonnay.

DISCUSSION AND CONCLUSIONS

California statewide harvest records indicate that, heat waves often associate with lower-yield harvests. Furthermore, a record of chardonnay harvest timing from Carneros region of Napa Valley reveals that harvest dates associate in a seemingly counterintuitive manner—heat waves may actually provoke later harvests.

Although excessive heat builds up the grape's sugar level necessitating earlier harvests in traditional winemaking societies and making climate reconstruction from harvest date records possible (e.g. Le Roy Ladurie 1967), new world practices are less strict allowing irrigation and other practices considered anathema in traditional wine growing and making. Increased irrigation, of course, mitigates growing stress due to excessive heat. Among other new-world practices is the addition of water at grape crush to dilute the grapes' sugar levels. The only characteristic that cannot be easily manipulated is character. Character is a function of the grape's maturity and maturation slows down with slower metabolism. Metabolism is quick under optimal environmental conditions that include warm dry days and cool nights. Humidity acts to slow down metabolic processes in grapes at least (without considering direct biochemical influences) by disproportionately increasing nighttime temperature when daytime temperature is already at detrimentally high levels. Under such extreme conditions, new-world wine growers and makers, preferring to enhance the grapes' maturity and the character of the vintage apparently prefer to harvest later even at the risk of loosing a significant portion of the crop to heat stress. We do not know how prevalent this practice is, but certainly more so in California than in France, Spain, Italy, and other winemaking societies where the process is more strictly controlled by laws steeped in tradition. It is possible, therefore, that the effect of heat waves on the quantity of the harvest (Figure 6) is greater in new-world winegrowing regions, while their effect on the quality is less.

This fine point is somewhat speculative and warrants further research, perhaps as much with the palate as with less subjective statistical tools. Statistics should also be done in a way that is more sensitive to the complex geography of California. Heat waves can have different effects on grapes in the normally hot Central Valley where most wine grapes are grown, compared to the cooler coastal valleys of northern and central California – regions growing the higher quality grapes. Effects on different grape varieties should be considered separately. Furthermore, we do not adequately know how marine influences, including low-level stratus clouds, react to inland heat waves and modulate coastal temperatures. A more detailed study is certainly warranted focusing on California and northern Baja California including Guadalupe Valley, where the impacts of humid heat waves are expected to intensify in the future. It would also be extremely useful to compare similar results obtained in California and other winemaking regions, especially those steeped in "old world" winemaking traditions. What's more, because humid heat waves in California appear to be associated with ocean warming, particularly in the California current outflow region west of Baja California (GCI09), future enjoyment of respectable quantities of quality California wines necessitates further oceanographic exploration off the cost of Baja California.

ACKNOWLEDGMENT

Following a presentation given by Gershunov at CICESE in April 2008 on heat waves and their oceanic influences, Antoine Badan articulated concerns about impacts of humid heat waves on wine grapes and later expounded upon these in a fascinating and gracious chat over a bottle of his exquisite Chasselas. That chat provided inspiration for this work. We thank David Graves for making the chardonnay phonological data from Saintsbury's Brown Ranch available to us, Kimberly Nicholas Cahill for learned discussion, and Mary Tyree for data handling. We are also grateful to Hugo D'Acosta and several other winemakers in the Guadalupe Valley of Baja California for fruitful and tasteful discussions.

REFERENCES

CDFA, 2009: Grape crush report, preliminary 2008 crop. California Department of Food and Agriculture, Sacramento, CA, 9pp, [Available online at http://www.nass.usda.gov/Statistics_by_State/California/Publications/Grape_Crush/Prelim/2008/200802gcbnarr.pdf].

Clement, A.C., R. Burgman, and J.R. Norris, 2009: Observational and model evidence for positive low-level cloud feedback. *Science*, 325, 460-464.

Easterling, D. R., and Coauthors, 1997: Maximum and minimum temperature trends for the globe. *Science,* **277,** 364–367.

Gershunov, A., D. Cayan and S. Iacobellis, 2009: The great 2006 heat wave over California and Nevada: Signal of an increasing trend. *Journal of Climate*, 22, 6181–6203.

Le Roy Ladurie, E., 1967: Histoire du climat depuis l'an mil. Flammarion, 287pp.

NCDC, 2003: Data documentation for data set 3200 (DSI-3200): Surface land daily cooperative summary of the day. National Climatic Data Center, Asheville, NC, 36 pp. [Available online at http://www.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td3200.pdf].

USDA, 2008: California grape crush report. http://www.nass.usda.gov/Statistics_by_State/California/Publications/Grape_Crush/Prelim/2008/200802gcbnarr.pdf