

Climate change decouples drought from early wine grape harvests in Western Europe

Benjamin I Cook^{1,2} & Elizabeth M Wolkovich^{3,4}

¹*NASA Goddard Institute for Space Studies, New York City, NY, USA*

²*Ocean and Climate Physics, Lamont-Doherty Earth Observatory, Palisades, NY, USA*

³*Arnold Arboretum, Boston, MA, USA*

⁴*Organismic and Evolutionary Biology, Harvard University, Cambridge, MA, USA*

Climate change has advanced the timing of wine grape maturation and harvest dates (GHD) worldwide, with many regions witnessing advances of several weeks to over a month^{1–3}. Understanding the climatic drivers and longer-term context of recent GHD trends requires long-term records of both harvest dates and the associated climatic drivers, temperature and drought. Here, we combine long-term GHD records from across France⁴ with independent reconstructions of temperature⁵ and drought^{6,7} to investigate the climatic controls of early harvest dates from 1600–2007. We demonstrate that high temperatures and drought during the late spring and early summer (May–June–July) are the primary drivers of early harvests, but that in recent decades (1981–2007) drought has become largely decoupled from harvest timing. This decoupling is likely due to recent, anthropogenically forced warming trends providing large amounts of heat for fruit maturation; temperatures that, before significant anthropogenic warming, would have required a regional drought. Our results indicate that anthropogenic climate change may have fundamentally altered the drivers

of early winegrape harvests across France, with possible ramification for both viticulture management and wine quality.

Wine grapes (*Vitis vinifera* ssp. *vinifera*) are the world's most valuable horticultural crop, and there is emerging evidence that warming trends have advanced harvest dates in recent decades. For example, both Europe⁸⁻¹¹ and Australia¹² have witnessed shifts towards earlier harvests, with some regions advancing several weeks to over a month since the 1970s¹⁻³. Concomitant with these phenological changes have also been shifts in wine quality ratings¹³ and other metrics related to wine quality¹⁴, including sugar and acid levels at grape maturity⁸.

Both temperature and precipitation influence wine grape phenology, although wind, light, and other abiotic factors filtered through the local environment (i.e., *terroir*) may also play a role¹⁵. Warmer temperatures generally speed up grape vine phenological development from flowering to fruit maturation and harvest, while increased precipitation tends to delay these events¹⁶. Earliest harvests are thus generally found in years where the growing season is characterized by anomalously high temperatures and drought⁸.

Within these broad outlines, however, extreme temperature and precipitation events may have additional effects, depending on their timing and magnitude. For example, high temperatures can damage leaf and grape tissues^{15,17}, while heavy rain can burst grape clusters or promote rot¹⁶. An ideal harvest is thus typically favored by a long, warm summers with above average early-season rains, combined with a late season drought. This ensures the vines and grape have sufficient heat and moisture to grow and mature early on, with dry conditions later in the year shifting them away from vegetative growth and towards greater investment in fruit production

mid-season^{16,18,19}. Overall, both precipitation²⁰ and temperature¹⁹ appear to control wine quality and the timing of harvest^{11,12}, though temperature is sometimes suggested to be most critical to wine grape phenology^{13,21}.

Most previous investigations into climate change impacts on wine phenology have focused on recent, relatively short timescales (e.g., 30–40 years^{1,10,12}), and have not explicitly considered the stationarity (or lack thereof) of grape phenology and climate relationships. To address this gap, we analyze over 400 years of wine grape phenology records from Western Europe⁴, comparing against both instrumental climate data for the 20th century and proxy based reconstructions of temperature⁵, precipitation⁷, and the Palmer Drought Severity Index⁶ (PDSI) for the last several centuries.

From the GHD database of Daux et al 2012, we constructed a multi-site GHD index (hereafter, GHD-Core) by averaging harvest date anomalies from 7 individual sites across France and Switzerland (see Methods for more details). This series (Figure 1) shows pronounced variability on both inter-annual and centennial scales over the last 400 years. The latest GHD anomaly in the record is 1816, the so called ‘Year without a Summer’ following the eruption of Mount Tambora in Indonesia²², when cold conditions dominated continental Europe and harvest dates were +24.8 days late. The earliest date is 2003 (-33.4 days early), during one of the worst summer droughts and heat waves in recent history²³. During the first half of the twentieth century (1901–1950), harvest dates were modestly early (-4.49 days), while during the middle of the century (1951–1980) they were about average (-0.47 days). In recent decades (1981–2007), however, there has been a strong shift towards earlier harvest dates, with average GHDs during this interval of -10.6 days.

Harvest dates are significantly earlier (Student's t -test, $p \leq 0.0001$) in this recent period compared to the previous interval (1600–1980), and the average GHD anomaly even exceeds the baseline averaging period (1600–1900) standard deviation of -7.8 days.

Coinciding with this recent shift towards earlier harvest dates is also an apparent change in the strength of the relationships between GHD-Core and various climate variables in the CRU climate grids (for individual regional GHD series, see Supplemental Figures 4–10). Over the first half of the twentieth century (1901–1950), GHD-Core correlates negatively (Spearman's rank) with May-June-July (MJJ) temperatures across Western Europe (Figure 2, top row), indicating a strong tendency for earlier harvests during warmer conditions in late spring and early summer. Correlations are positive, though weaker, with MJJ precipitation (Figure 2, middle row) and PDSI (Figure 2, bottom row); droughts causing earlier harvests. These relationship generally persist into the middle of the century (1951–1980). In recent decades (1981–2007), the relationship with moisture essentially disappears.

In Figure 3, we compare the GHD-Core index against regional average climate for two periods: 1901–1980 and 1981–2007 (we tested a variety of breakpoints, but this seemed to fit the best). In both periods, MJJ temperatures are the single best predictor of harvest date anomalies in GHD-Core, explaining nearly 70% of the variance for 1901–1980. In the latter period, the strength of the relationship weakens ($R^2 = 0.57$) but, notably, the slope of the relationship remains about the same, between -6 and -7 days per degree of warming. This suggests that the temperature sensitivity of in GHD-Core is relatively stationary. This is in sharp contrast to the apparent changing relationship between GHD-Core and MJJ precipitation and PDSI. Both PDSI and precipitation are

positively correlated with GHDs from 1901–1980, indicating dry conditions during MJJ drive earlier harvests. This may be due to direct drought impacts on fruit maturation (ref XXXX), but is more likely due to indirect influences via land-atmosphere feedbacks, namely the tendency for dry conditions to lead to warmer temperatures and vice versa over this region (ref XXXX). Since 1981, however, this relationship has become insignificant and largely disappeared. Positive correlations over France pretty much universally disappear (Figure 2), and the regressions become insignificant and the slope of the regression lines pretty much flat (Figure 3).

We composite all years with early GHD, defined as 1 standard deviation or earlier (-7.8 days, calculated from the 1600–1900 base period). From 1600–1980, this gives us 68 years and 18 years from 1981–2007. Average PDSI for these early years prior to 1980 is -1.04, indicative of mild drought conditions; from 1981 onward, it's actually slightly positive (+0.85). Median PDSI before and after is -0.87 and 0.96. Pooled PDSI from before and after are significantly different ($p \leq 0.001$) based on Student's t-test and Wilcoxon Ranksum test, indicating strongly that extreme early years needed drought conditions in the past at least based on PDSI. For JJA precipitation, there are only 11 years after 1981. Before, mean precip anomaly was -12%; median -10%. After 1980, mean was -1.3% and median was -1.5%. Differences in precipitation are only marginally significant: Student's t-test one tail (before drier than recent) $p = 0.08$, Wilcoxon ranksum not significant. before 1980 is significantly drier than zero, after is not. Monte-Carol shows sensitivity to sampling.

To test for sampling uncertainty, we conducted 10,000 Monte-Carlo simulations in which we resampled (with replacement) PDSI, precipitation, and temperature from the early years before and after the 1980 break and recalculated our Student's t and Wilcoxon rank sum tests. Both before and after, we resampled the number of years available after 1981: 18 years (PDSI), XX years (precipitation), and XX years (temperature). For PDSI, 95% of the simulations were still significantly different Student's t-test; for Wilcoxon it was 89%.

Methods

Grape Harvest Data. We analyzed GHD data in the databased of grape harvest time series from western Europe compiled by Daux et al 2012 (hereafter, DAUX⁴). DAUX includes 27 regional composite time series of grape harvest dates compiled from local vineyard and winery records going back as far as 1354. Most of these series are from France, but also included are data from Switzerland, Spain, Luxembourg, and Germany (Supplemental Figure 1). These data are ideal for climate change research applications because management practices have changed very little over time and irrigation as a viticulture tool (which could complicate the interpretation of climate relationships) is largely absent, especially in France. Indeed, these data have been used previously to develop proxy-based temperature reconstructions for the region⁴.

Rather than focus our analysis on the individual regional GHD series, we created a composite average index from several regional series (GHD-Core). Using a multi-site composite series has two main advantages. First, every regional GHD series has missing values. By averaging multiple sites into a single composite index, we were able to ensure a serially complete time series back to

1600. Second, because viticulture management varies across grape varieties and regions, use of a composite average series should minimize the influence of local management effects and instead emphasize larger scale signals related to climate variability and change (the primary focus of our study).

From the 27 regional GHD series available, we chose 7 sites (Supplemental Table 1) to construct GHD-Core: Alsace (Als), Bordeaux (Bor), Burgundy (Bur), Champagne 1 (Cha1), the Lower Loire Valley (LLV), the Southern Rhone Valley (SRv), and Switzerland at Lemman Lake (Swi). All 7 regional series are over 80% serially complete back to 1800 and over 40% complete back to 1600 (Supplemental Table 2). After 1600, most years have at least 3-4 of these regional series represented; sample depth declines sharply prior to this date (Supplemental Figure 2). All analyses are thus restricted to the period from 1600–2007.

Prior to compositing, we converted each series to anomalous days per year, relative to their mean for 1600–1900. Despite the broad geographic range and climate gradients covered by these sites, there is good cross site correlation in the harvest dates (Supplemental Table 3; Supplemental Figure 3). Average harvest dates for all regional series, as well as GHD-Core and GHD-All (a composite average of all 27 sites), are anomalously early during the recent 1981–2007 interval relative to the baseline averaging interval of 1600–1900, ranging from on average 2 days (Cha1) to over 3 weeks (SWi) (Supplemental Table 4). There are also small differences across time in the inter-annual standard deviation in harvest dates (Supplemental Table 5), with most sites showing slightly reduced variability during the twentieth century compared to 1600–1900.

Climate Data and Reconstructions. Instrumental temperature and precipitation data for the twen-

tieth century (1901–2012) are taken directly from version 3.21 of the CRU climate grids²⁴. These data are monthly gridded fields, interpolated over land from individual station observations to a spatially uniform half degree grid. We also use a drought index, the Palmer Drought Severity Index (PDSI²⁵), derived from the CRU data²⁶. PDSI is a locally standardized indicator of soil moisture, calculated from inputs of precipitation and evapotranspiration. PDSI integrates precipitation over multiple months and seasons (about 12 months), so incorporates longer term changes in

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Competing Interests The authors declare that they have no competing financial interests.

Correspondence Correspondence and requests for materials should be addressed to B.I.C. (email: benjamin.i.cook@nasa.gov).

Figure 1 Left panel: time series of Grape Harvest Date (GHD) anomalies from GHD-Core, composited from the Als, Bor, Bur, Cha1, LLV, SRv, and SWi regional GHD time series in DAUX. All anomalies are in units of day of year, relative to the average date calculated from 1600–1900. Right panel: normalized histograms of GHD anomalies from GHD-Core for two periods: 1600–1980 and 1981–2007.

Figure 2 Point-by-point correlations (Spearman's rank) between GHD-Core and May-June-July temperature, precipitation, and Palmer Drought Severity Index (PDSI) for three periods: 1901–1950, 1951–1980, and 1981–2007. All climate data are from the CRU 3.21 climate grids, described in the Methods section. Prior to calculating the correlations, we linearly detrended both the climate data and GHD-Core.

Figure 3 Linear regressions between regional average climate variables (2°W–8°E, 43°N–51°N)