To Dr Alastair Brown,

Please find, below, our responses to the reviewer comments on our recent paper submitted to *Nature Climate Change*, titled "Climate change decouples drought from early winegrape harvests in France". Below, you will find the original review comments in *italics*, our responses in plain text, and any substantive additions to the text in the main manuscript in **bold**.

Should you have any questions, please do not hesitate to contact us.

Kind Regards,

Benjamin Cook (corresponding author)
Elizabeth Wolkovich

Reviewer 1

"This paper addresses an important issue for the global wine industry namely the influence of climate change on grapevine Phenology and its central conclusion is of critical significance to the french and german wine industries that are in the main not irrigated. The work is also of significance to the majority of of the global wine industry that is irrigated because it confirms the quantitative influence of climate change on grapevine phenology central. Indeed an interesting point that the authors have not emphasised is that in this analysis of the unirrigated French industry and Webb et al's (2012)analysis of the irrigated Australian wine industry the basic temperature sensitivity of grapevine to climate change is the same - 6 days per degree C
The central conclusion is well supported by the data presented and I recommend that it be be published in Nature Climate change provided the authors can satisfactorily address some methodological questions that I have outlined below and also address some editorial issues in the manuscript"

We appreciate the reviewer's positive comments and their important point about the similarity between our findings and Webb et al. Thus, we have added text in the manuscript noting the similarity in our temperature sensitivities to Webb et al. 2012. Paragraph 5:
And the magnitude of the temperature sensitivity (–6 days per degree of warming) agrees with other estimates, including for irrigated vineyards in Australia[12].

“1. The central assumption in the use of the GHD - Core dataset from 1600 to 2007 is based on some sweeping assumptions that varieties and viticultural practise have remained relatively constant in the French and Swiss industries over this period. The following components of this assumption needs to be addressed before it can be accepted
“1. Was the Grape Harvest Day - CORE dataset corrected for variations in Baume'(sugar) levels on harvest day to a common Baume' level - while they are currently specified particular Appellations this is a range not a particular figure and of course influences harvest day”

Both this reviewer and the second reviewer make an important point regarding whether our results are highly influenced by shifts in viticulture practices over time. We completely agree with both reviewers that a number of major changes have occurred in French wine industry over periods of our study, including shifts in targeted sugar levels of grapes at harvest. Thus it is important that we show such shifts are not biasing our findings. To address these important points we have added additional text to the Methods section and new analyses to the Supplemental Materials.

With regard to the reviewer’s concern about Baume’ (sugar) levels in our analysis: this concern relates to the fact that management changes designed to select specific sugar levels in the fruit may affect harvest dates, sometimes independent of any environmental changes (such as climate). Unfortunately, there is no information on sugar levels from the Daux et al historical dataset that we use. It is therefore impossible to adjust the data to common Baume’ level. However, there are several reasons we believe the lack of this information does not compromise our analysis and interpretations of climate change impacts on harvest date:

1) Most of our results and discussion are based on the GHD-Core composite index, which was designed specifically to minimize the influence of local management changes. Baseline sugar levels are therefore likely to vary across the regions and varieties that make up this index. And any changes in harvest practice designed to select for specific Baume’ sugar levels are unlikely to be uniform across regions and grape varieties. The multi-region average of 8 sites in our

GHD-Core composite will thus minimize this and other local management effects, while maximizing the signal of large-scale climate forcing.

2) Temperature is the fundamental and direct driver of harvest dates in the Daux et al dataset. Any management induced shift in harvest dates (e.g., to select for fruit with specific sugar levels) would thus be expected to weaken the climate/harvest date relationship because harvest will be based on additional considerations besides climate influences on fruit maturation. However, the temperature sensitivity of GHD-Core is relatively stationary pre- and post 1980 (about -6 days per degree C of warming), indicating that the direct relationships between temperature and harvest date has not changed. This strongly suggests that any management effects that would shift the harvest date independent of climate are largely non-significant.

3) The only changing climatic relationship with harvest date is drought. There is no a priori reason, however, to believe that management changes based on Baume' levels would specifically change this relationship, while maintaining a stationary relationship with the primary driver (temperature).

While we do not believe the lack of Baume' information undermines our analysis, we have added additional text to the Methods section acknowledging that this information is unavailable, and making the same points above. In Methods, under "Grape Harvest Data":

Other analyses of climate change and historical grape harvest dates have attempted to adjust the recorded dates based on sugar levels (e.g., Baume and Brix levels, or, relatedly potential alcohol) in the fruit[12]. This is because management changes designed to select specific sugar levels in the fruit may affect harvest timing; such changes may be independent of climate climate or may be caused by climate change allowing growers to pick riper grapes[31]. Unfortunately, data on sugar levels are unavailable for the DAUX harvest date dataset (Garcia de Cortazar-Atuari, pers. comm.), and the relationship between harvest dates and sugar levels is not consistent across regions or even vineyards[32] making it difficult for us to estimate how sugar levels may have changed our core index. However, we believe lack of this information is unlikely to affect our results. First, the multi-site composite index we constructed, GHD-Core, is designed to maximize the large-scale climate sensitivity and minimize the effects of local management changes. Second, we see similar trends across regions where management for sugar

levels have not been similar (Supplemental Figures 4-11), suggesting climate is a far stronger signal than shifts in harvest for particular sugar levels. Next, we note that the harvest date sensitivity to temperature (the primary driver) in GHD-Core has a similar magnitude pre- and post-1980. Shifts in harvest timing to select for higher sugar levels would tend to delay harvest (given no change in climate), thus if these shifts were extreme we would expect the relationship between temperature and harvest date to weaken. As this does not occur, it is likely that any management driven shifts in harvest timing that have occurred have been relatively minor. Finally, we note that the only changing climate relationship is between harvest and drought. There is no a prori reason, however, to expect management shifts in harvest to change this relationship, while maintaining a significant relationship with the primary harvest driver (temperature).

"2. While the basic grape varieties within the French wine industry have remained constant over this period -significant changes have occurred through
1. The selection of superior clonal material with these varieties"

This is an important point that we agree deserves further discussion in the manuscript. In order to address this issue we consulted with a number French colleagues about when clonal selection began and when areas experienced major re-planting of superior clonal material. Major efforts to produce better clones occurred at the national levels via INRA (starting in the 1950s), then ANTAV (Association Nationale Technique pour l'Amélioration de la Viticulture), and finally by ENTAV (Etablissement National Technique Amélioration Viticulture). We found, however, that the actual replanting of vineyards with the improved clones is not documented well for many regions and occurred at different times for different regions and for different vineyards. As such it is difficult for us to directly assess possible impacts of clonal selection on phenology. However, as discussed above, we believe the impact of clonal selection is unlikely to impact our analyses because (1) the results are consistent across regions even though timing of clonal selection is noted, (2) our use of the GHD-Core Index deemphasizes local management changes, and (3) the phylloxera comparison we did (below), representing a much larger wholesale shift in planting across France, shows little impact on our climate sensitivities. We have added these discussion points to the Supplemental , under the new section 'Clonal Selection':

In the mid to late twentieth century vineyard managers began to re-plant many of their vineyards in order to produce higher quality wines through improved matching of varieties to local terroir and improved selection of clones of particular varieties (7). Such shifts in the composition of vineyards could introduce changes over time that would influence vine phenology and grape harvest dates. These shifts, however, occurred across different regions at different times (7), making it difficult for us to test for their impact on phenology through a comparison of different periods as we did for the phylloxera outbreak (see above). Two of our other findings, however, suggest the impact of changes in varieties and clones planted do not bias or affect our results. First, our findings are relatively robust when considered across different regions (Supplemental Figures 4-11) that—in addition to planting substantially different varieties and clones—had different timings of major re-plantings. Second, our analysis to test for possible effects of the phylloxera epidemic and subsequent replanting (see above) found no dramatic changes in climate sensitivities of harvest dates. As the replanting after phylloxera included planting of different varieties (including hybrids) we expect that if this change had no strong impact on climate sensitivity then the comparatively smaller change of clonal selection would not impact our findings. Finally, experimental studies show the impact of climate on vine phenology is greater than variety (8).

"2. Most importantly the use of American Vitus rootstocks in the French industry following its devastation by the root aphid Phylloxera in the late nineteenth century - the post 1900 datasets are derived from grafted vines whereas the pre 1900 dataset is from own roots vines.The potential significance of these major changes in viticultural practice need to be assessed and analysed in terms of their impact on the phenology of the vines"

We have added a new analysis to investigate the potential impact of phylloxera. From Supplemental Materials, "Phylloxera":

In the 1860s (3), an exotic species of aphid (*Daktulosphaira vitifoliae*, commonly known as grape phylloxera) was introduced to France. This resulted in a severe blight and destruction of many vineyards across France (3–7). Large-scale recovery of the vineyards and wine industry began in the late 1800s and early 1900s with the grafting of European vines onto phylloxera resistant rootstock from wild *Vitis* species native to the United States. There was thus a substantial shift in rootstock composition beginning

around the turn of the 20th century—alongside planting of many new varieties as well as hybrid grape varieties (3, 7)—changes that could possibly affect our interpretation of climatic effects on harvest date.

To investigate this, we calculated regression models between GHD-Core and JJA climate (temperature, precipitation, PDSI) from the climate reconstructions (instrumental data is not available prior to 1901) (Supplemental Figure 16) from before to after the outbreak and replanting. Across the three intervals: 1800–1850 (prior to the phylloxera epidemic), 1851–1900 (during the phylloxera epidemic), and 1901–1980 (after widespread grafting occurred) results are generally consistent. For temperature, sensitivities, range from –4.97 to –6.56 days $^{o}C^{-1}$ with R^2 values from 0.359 to 0.464, similar to results found in the instrumental regressions for this season (Supplemental Figure 13). Similar results are found for precipitation and PDSI, although precipitation is only marginally significant for 1800–1850 (PDSI is still highly significant for this period, however).

Given the lack of evidence for any systematic change in sensitivities pre- and post- phylloxera, we conclude that this event is unlikely to have significantly affected our climate based analyses and interpretations. Further, as the period of 1900-1980 included substantial changes in viticultural practices (e.g., widespread mechanization, French laws mandating planting and harvest limits through appellation d'origine controlee (AOC), and changes in varieties and clones planted— see below, (5, 6)), the lack of substantial changes in climatic sensitivities in this period compared to periods before suggests gross changes in viticultural management do not impact phenology strongly, as least when compared to the impact of climate on phenology.

"2. The diagrams and their captions need further clarification and explanation for reader assimilation

"1. Diagram 1 - the normalised histograms of anomalies for 2 periods 1600-1980 (blue) and 1981-2007 (pink) - what does the mauve colour represent ? - also DAUX dataset should be referenced to reference list"

We thank the reviewer for pointing this out. We have rewritten the caption to be more intuitive, as well as adding the reference to the DAUX dataset. New caption for Figure 1:

Left panel: GHD-Core time series of grape harvest date anomalies, composited from the Alsace (Als), Bordeaux (Bor), Burgundy (Bur), Champagne 1 (Cha1), Languedoc (Lan),

the Lower Loire Valley (LLV), the Southern Rhone Valley (SRv), and Switzerland at Lake Geneva (SWi) regional harvest date time series in the DAUX[4] dataset. All anomalies are in units of day of year anomalies, calculated relative to the average date from 1600–1900. Right panel: normalized histograms of GHD-Core harvest date anomalies from 1600–1980 (blue) and 1981–2007 (red).

"2. Diagram 2 - the purpose of this diagram is not clear nor explained in the caption"

Figure 2 was meant to illustrate the changing relationship between GHD-Core and climate in a spatially explicit way, meant as a supporting analysis to the regressions in Figure 3. We have modified the text to hopefully make the purposes of Figures 2 and 3 clearer. Beginning of Paragraph 5:
In addition to an overall trend towards earlier harvest dates, there are also substantial changes in the strength of the relationship between climate (temperature, precipitation, PDSI) and GHD-Core (Figures 2 and 3; for individual regional grape harvest date series, see Supplemental Figures 4-11). Most notably, the strength and significance of the moisture relationships (precipitation and PDSI) decline in recent years (Figure 2, bottom two rows; Figure 3, center and right columns), while the relationship with temperatures appears relatively stationary (Figure 2, top row; Figure 3, left column).

"3. Other minor editorial - page 2 para 1 - warmer temps..........vine phenological development from flowering to fruit maturation l and harvestvine phenology is affected by temperature throughout the full cycle - bud burst, flowering, verasion and maturity"

We have modified the text to make this correction. The new sentence now reads:
Specifically, warmer temperatures accelerate grape phenology over the full cycle of development (budburst, flowering, veraison, and maturity), while increased precipitation tends to delay winegrape phenology[13].

"*4. Final conclusions*
1. While I agree the authors have demonstrated that climate change is not acting on phenology in the absence of drought , I do agree that this is a fundamental change physiological change in

the grapevine ,in other areas we have found if drought also occurs it has an additive effort on accelerating phenology"

Our analysis was primarily speaking to the impacts of drought on phenology, as expressed through grape harvest dates. We fully agree that drought can affect wine grapes in other ways, and we have added some text acknowledging this. From the final paragraph:

Droughts are still likely to affect vine health and development and the wine industry independent of temperature effects, especially in wine growing regions that are significantly drier than France[12,26].

Reviewer 2

"Overall a very good piece of research and the article is generally well written. Some minor issues or clarifications needed. References are sufficient to cover the background research. Only tie that would be of interest is that a long term record of spring shoots in grapevines in Hungary has shown an interesting connection to spring temperatures, but which are not always well correlated with harvest dates. Fila et al (2015) and Kiss et al (2010)."

We were unaware of these references and thank the reviewer for pointing them out. While the inclusion of these datasets in our analysis is outside the scope of the current study, we have added the citation for Fila to the manuscript.

"I am pretty confident that the literature does not show that drought is the main driver of fruit maturation. Temperature, and even better accumulated heat, over the growing season is the main driver of fruit maturation. Rainfall in wine growing regions can be very beneficial during spring and even into MJJ as long as it is followed by relatively dry conditions into JAS. But drought is not the main driver."

We have modified the abstract to more clearly indicate that temperature is the primary driver:

Across the world, winegrape phenology has advanced in recent decades[1–3], in step with climate change induced trends in temperature---the main driver of fruit maturation---and drought.

"Also it is worth noting that the regions you are examining have historically not used irrigation and have much wetter summer climates than other mid-latitude wine regions on west coasts of continents (Chile, Australia, western US). Seasonally dry summers in Europe are typically good for fruit quality, but much drier conditions can both stress the vines producing poor fruit and result in much lower yields. The main point is that drought is not a main driver of harvest dates, but plays a much more complicated role depending on its timing, longevity, and severity. All you have done is look at them separately and noted stronger temperature effects and lower precipitation effects."

We agree that drought plays an important role aside from its impact on grape vine phenology. To that end, we have added a modified statement and references to the final paragraph of the paper.

Droughts are still likely to affect vine health and development and the wine industry independent of temperature effects, especially in wine growing regions that are significantly drier than France[12,26].

"For much research that I have seen, when you run a multivariable regression the temperature signal swamps the precipitation signal and results in any measure of moisture being not included in the regression. I would like to see some attempt to quantify the entire model with your data, would temperature, precipitation, and PDSI all stay in a multivariable regression model?"

We have added a multiple regression analysis to the Supplemental for both the 1901-1980 and 1981-2007 intervals, using instrumental temperature, precipitation, and PDSI as predictors. Indeed, the addition of the precipitation and PDSI terms do not add significant skill beyond temperature in the multiple regression model. This indicates that drought variability is not acting as a direct impact on wine phenology, but is instead acting indirectly through modulation of temperature effects, supporting our main hypothesis discussed in the Supplemental ("Temperature versus Moisture Comparisons "). We also note that, as with the univariate regressions, our multivariate regressions show big changes in the precipitation and PDSI sensitives, but not for temperature (reinforcing the fundamental conclusion in our manuscript). The multiple regression analysis is discussed in detail in the Supplement, and we have added some text to the main manuscript noting these results. From the Supplemental, “Multiple Regression Analyses”:

Temperature, precipitation, and PDSI are all significant predictors of grape harvest dates as analyzed by our univariate approach presented in the main text. We additionally investigated if our results would change when these variables were included in a multiple regression framework using climate data from the instrumental CRU climate grids (results shown in Tables 9 for 1901–1980 and Table 10 for 1981–2007). These results highlight that temperature is the dominant driver of grape harvest date, explaining most of the variation (R2) and being one of the top models (based on δAIC) for both time periods. Addition of precipitation and/or PDSI to a model containing temperature provides only small improvements in explanatory power, especially during 1901-1980 (AIC values generally increase when precipitation or PDSI are added). Additionally, precipitation and PDSI generally show a lower impact on harvest date (i.e., smaller and nonsignificant, at $p > 0.05$, model coefficients) when included in a model with temperature. These results provide further support to the hypothesis that the major impact of moisture variability is not on grape phenology directly but, instead, is through the modulation of temperatures (where drier equals warmer, via the mechanisms discussed previously).

These analyses also further highlight the shift in how climate affects harvest dates after 1980. Though nonsignificant, the regression coefficients for precipitation and PDSI before 1980 all indicate moisture delays harvest. After 1980, in four of the five multiple regression models these coefficients become negative. Further, the sign of the interaction between temperature and moisture shifts in all models after 1980, suggesting a fundamental change in the relationship of these climate variables, as discussed above in ‘Temperature versus Moisture Comparisons’. Shifts in the moisture predictors (and, where applicable, their interaction terms) between these two time periods are therefore similar, whether analyzed in a univariate or multivariate regression model.

Main manuscript, paragraph 6:

This may be due to direct drought impacts on fruit maturation by increasing abscisic acid production[12], but is more likely to occur through interactions between soil moisture and air temperature (see ‘Temperature versus Moisture Comparisons’ and ‘Multiple Regression Analyses’ in the Supplemental).

“Why was the data set not updated to 2014? The data is available and would make your work much relevant.”

The latest data available in the publicly accessible DAUX data set ends in 2007. Our analyses are based on the version archived at the NOAA Paleoclimate Data Center, downloaded from here:

https://www.ncdc.noaa.gov/cdo/f?p=519:1:0::::P1_STUDY_ID:13194

We contacted one of the main authors of the Daux et al. paper and creator of the published dataset, Iñaki García de Cortazar Atuarí, to inquire whether it would be possible to update the phenology dataset. He said data are not routinely updated into any central database and it would take many months to update just some of the series, while others may not be possible to update due to data sharing issues. Further, we note that two of our paleoclimate reconstructions (temperature and precipitation) actually end prior to the last date in the DAUX dataset (2002 for temperature; 2000 for precipitation). Some of our analyses (e.g., the anomaly compositing) are therefore limited not by the length of the DAUX data, but by the end date of the paleoclimate datasets. As with the DAUX data, we were unable to find an updated version of these paleoclimate datasets. Finally, we believe additional data is unlikely to fundamentally alter our findings given the strong signals in the paleoclimate reconstructions of temperature and PDSI, as well as the independent analyses of the instrumental data.

“Grapevine is one word.”

We have modified the text to remove all uses of “grape vine” as two words.

“Fila et al (2015) also show the effect of "the year without a summer" in spring vine shoots in Hungary.”

Actually, Fila et al find little evidence for Tambora in their reconstructed series. From their paper: *‘…in the reconstructed series there is little evidence of the effects of the Tambora eruption, which caused the famous “year without a summer” in 1816.’*

They attribute this to the major cooling from Tambora occurring during the summer, rather than the spring, when the shoots are recorded in the *Book of Vinesprouts.*

"Figure 1 caption needs to define the region acronyms, as it is now it is only defined in the Supplementary Information."

We have added the definitions for the region acronyms into the Figure 1 caption.

"Figure 2 needs to give the GHD-Core region box definition, not given until Figure 3."

We have added the GHD-Core region definition to the caption for Figure 2.