Climate change decouples drought from early winegrape harvests in France

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*

Across much of the world, winegrape phenology has significantly advanced in recent decades[1–3]. Such trends appear in step with climate change induced trends in temperature and drought—the main drivers of fruit maturation. Fully understanding how climate change contributes to changes in harvest dates, however, requires analyzing winegrape phenology and its relationship to climate over a longer term context, including data predating anthropogenic interference in the climate system. Here, we investigate the climatic controls of early grape harvest dates from 1600–2007 in France (7 sites) and Switzerland (1 site), using historical harvest data[4] and independent reconstructions of temperature[5] and drought[6,7]. At these sites, early harvests occur with warmer temperatures (-6 *days* $^{o}C^{-1}$) and are delayed by wet conditions ($+0.07$ days mm-1; $+1.68$ days PDSI^{-1}) during late spring and early summer (May-June-July). In recent decades (1981–2007), however, harvest timing has become disconnected from moisture and drought. Historically, high summer temperatures in Western Europe, which would hasten fruit maturation, required drought conditions to generate extreme heat.

The relationship between drought and temperature in this region, however, has weakened in recent decades and, with enhanced warming from anthropogenic greenhouse gases, sufficiently high temperatures for early harvests can now occur regularly without drought. Our results suggest that anthropogenic climate change may have fundamentally altered the climatic drivers of early winegrape harvests in France, with possible ramifications for viticulture management and wine quality.

Winegrapes (*Vitis vinifera* ssp. *vinifera*) are the world's most valuable horticultural crop, and there is increasing evidence that warming trends have advanced winegrape harvest dates in recent decades[1,2,8–12]. Harvest dates are closely connected to the timing of grape maturation which is highly sensitive to climate during the growing season. Specifically, warmer temperatures accelerate grape vine phenological development from flowering to fruit maturation and harvest, while increased precipitation tends to delay winegrape phenology[13]. The earliest harvests thus generally occur in years where the growing season experiences warmer temperatures and drought[8].

Along with trends in harvest dates, there have also been apparent shifts in wine ratings[14] and other metrics of wine quality[8,15]. High quality wines are typically associated with early harvest dates in many regions[8,14], and are also favored by warm summers with above average early-season rainfall and late season drought. This ensures the vines and grapes 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[13,16,17]. Overall, both precipitation[18] and temperature[17] contribute to wine quality and the timing of harvest[11,12], though temperature is suggested to be most critical to winegrape phenology[14,19].

These shifting trends in viticulture have led to much recent research to better understand climate controls on winegrape phenology[11,12], especially grape harvest dates, and quality[14,18,19]. Most research has, however, focused on relatively short, recent timescales (e.g., the last 30–40 years[1,10,12]). There has thus been little consideration of the 1) longer term historical context of recent harvest date trends and 2) possible non-stationarities in the relationship between winegrape phenology and climate. We address these issues by conducting a new analysis using over 400 years (1600–2007) of harvest data from Western Europe[4]. From this database, we construct a multi-site grape harvest date index (hereafter, GHD-Core) by averaging harvest date anomalies from 7 regional harvest date time series across France and one site in Switzerland (see Methods for more details). We then analyze the variability and trends in GHD-Core, and compare against instrumental climate data over the 20$^{\text{th}}$ century[20] and proxy-based reconstructions of temperature[5], precipitation[7], and soil moisture (Palmer Drought Severity Index; PDSI)[6] (PDSI) back to 1600. We also test for associated shifts in wine quality for two sites (Bordeaux and Burgundy), using 100 years of wine quality ratings[21].

The GHD-Core series has pronounced variability from year to year and a strong trend towards earlier dates in the latter part of 20$^{\text{th}}$ century (Figure 1). The latest date in the record (Figure 1, left panel) is 1816, the so called 'Year without a Summer' following the eruption of Mount Tambora in Indonesia[22]. The eruption caused pronounced cooling over continental Europe during the growing season, with harvest dates in GHD-Core delayed over three weeks ($+24.8$ days). The earliest date in the record is 2003 (-31.4 days), coinciding with one of the worst summer heat waves in recent history[23]. Mean harvest dates were modestly early during the first half of the 20$^{\text{th}}$

century (1901–1950, -5.2 days), roughly average from 1951–1980 (-1.1 days), and substantially earlier during the most recent decades (1981–2007, -10.24 days) (Supplemental Table 4). The 1981–2007 mean date exceeds one full standard deviation of harvest date variability calculated from the baseline averaging period (1600–1900, ± 7.67 days) and is significantly earlier than the full previous interval (1600–1980; One Sided Student's t-test, $p \leq 0.0001$). The 1981-2007 period is also earlier than the earliest previous 27 year interval (1635–1661, -7.42 days), although results are only marginally significant (One Sided Student's t-test, $p = 0.075$).

There are strong and significant correlations between GHD-Core and the instrumental climate data, although the strength of the moisture relationships (precipitation and PDSI) declines in recent years (Figure 2) (for individual regional grape harvest date series, see Supplemental Figures 4–11). 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. Regional average (dashed box in Figure 2; 2°W–8°E, 43°N–51°N) MJJ temperatures are the single best predictor of GHD-Core (Figure 3), explaining 70% of the variance for 1901–1980 and only weakening slightly in the more recent period ($R^2 = 0.64$). Notably, the slope of the regression is similar before and after 1980 (harvest dates advancing approximately -6 days per degree of warming), suggesting that the temperature sensitivity of harvest dates is relatively stationary over time.

Correlations are positive, though weaker, with MJJ precipitation (Figure 2, middle row) and PDSI (Figure 2, bottom row), indicating earlier harvests during drought conditions. This may be due to direct drought impacts on fruit maturation by increasing abscisic acid production[12] or indi-

rectly through feedbacks between soil moisture and air temperature. Dry soils favor sensible over latent (i.e., evapotranspiration) heating, increasing soil and air temperatures and speeding up fruit maturation. Western Europe is a region where this soil moisture-temperature interaction is thought to be especially strong[24] (Supplemental Figure 12, top row). These moisture versus harvest date relationships persist through the middle of the century (1951–1980), but become insignificant in recent decades (1981-2007) (Figure 3).

To further investigate this apparent weakening of the harvest-drought relationship, we composited climate anomalies back to 1600 during early harvest years, defined as years when GHD-Core was -7.67 days early or earlier (one standard deviation). For this, we used June-July-August (JJA) average climate, the closest match available to the MJJ season in the seasonally resolved climate reconstructions. In the instrumental data, the relationships between GHD-Core and temperature and precipitation weaken during JJA compared to MJJ, while PDSI improves slightly (Supplemental Figure 13). All regressions prior to 1980 are still significant, however, and JJA comparisons between grape harvest date and moisture (precipitation and PDSI) show a similar weakening and loss of significance from 1981–2007. The temperature-moisture coupling relationships for 1901–1980 are stronger during JJA than MJJ, and both the precipitation and PDSI regressions with temperature becoming insignificant afterward (Supplemental Figure 14).

Compositing the early harvest dates in GHD-Core yields 72 years from 1600–1980; from 1981–2007, the composite ranged from 11–18 years, depending on the end date of the different climate reconstructions (Figure 4). As expected, early harvests are associated with warmer than average conditions in both intervals, increasing in intensity in the more recent period (consistent

with large-scale greenhouse gas forced warming trends over Europe). Composite precipitation and PDSI are dry during 1600–1980, with regional average precipitation -11% below normal and mean PDSI$= -1.1$ (indicative of a modest drought).

After 1980, the association between dry anomalies and early harvests effectively disappears, with regional average mean precipitation only slightly below normal (-1.3%) and PDSI actually wetter than average ($+0.86$). Differences in the early harvest PDSI composite pre- and post-1980 are highly significant (One Sided Student's t-test, $p \leq 0.001$), while only marginally significant for precipitation (One Sided Student's t-test, $p = 0.08$). However, a one sample Student's t-test comparing the precipitation anomalies against a mean of zero found that only the precipitation anomalies in the pre-1980 period are significantly below normal. These results were confirmed by a Monte-Carlo analysis to test for sampling uncertainties in the composite averaging (Supplemental Figure 15). These results further support our conclusion from the 20$^{\text{th}}$ century climate analyses, indicating that drought has become decoupled in recent decades as a significant driver of early harvest dates.

Two factors have likely contributed to the diminishing importance of moisture for winegrape phenology. The first is the apparent weakening of the soil moisture-temperature relationship over Western Europe in recent decades, which is especially apparent for JJA (Supplemental Figure 14). Prior to 1981, moisture variability (as represented by precipitation and PDSI) accounts for approximately 25% of the year to year temperature variability in this region. In more recent decades, however, these moisture-temperature regressions become insignificant. Second, with the strengthening of anthropogenic greenhouse gas induced warming, this added heating has made it easier

for summers to reach critical heat thresholds needed for early harvest dates. Previously, drought conditions would have been a necessary pre-condition to reach such extremes.

Climate and harvest timing are both thought to affect wine quality, but have generally been assumed to be stationary. But if the climatic constraints on winegrape phenology are changing, then environmental effects on quality may also be non-stationary. Using wine ratings for the Bordeaux and Burgundy regions[21], we analyzed harvest timing and climate effects on wine quality pre- and post-1980. In these regions the likelihood of higher quality wines increases with earlier harvests and higher temperatures (see Supplemental Table 6), and these harvest date and temperature effects are generally significant and of similar magnitude before and after 1980. Higher quality wines are also favored by dry conditions pre-1980 (Supplemental Table 7), but the relationship between PDSI and quality weakens considerably after 1980 (either becoming insignificant or seeing much reduced magnitudes in the ordinal coefficients). Thus, there has been a recent decoupling between wine quality and drought, similar to the results from our climate and grape harvest date analysis.

Our findings—suggesting a largescale shift in how climate drives early harvests across France and Switzerland—are generally consistent across regions (Supplemental Figures 4–11). This consistency is important for two major reasons. Firstly, winegrape varieties span a great degree of phenological diversity, and there may be related differences in their sensitivities to climate within and across regions[25]. Second, both the trends in harvest dates and changes in the climate constraints could be explained by viticultural management changes in recent decades, rather than shifts in environmental forcing. We find however, good cross-site correlations across the regional series

used to create GHD-Core (Supplemental Table 3; Supplemental Figure 3) and diverse regions—for example, Alsace, Champange, Burgundy and Languedoc—show findings similar to our overall results (Supplemental Figures 4–11, one notable exception was Bordeaux where climate relationships have been relatively stable over time). These regions span greatly differing varieties and management regimes that have generally not shifted similarly. This indicates some commonality to the climate signal across the regions, making it unlikely our results and interpretations are biased by one (or a few) of the grape harvest date series. Further, irrigation, the management activity that would be most likely to complicate our climate interpretations, is generally not allowed in France, making it highly unlikely that this could explain the reduction in moisture signal in recent years.

Our results indicate a fundamental shift in the role of drought and moisture availability as large-scale drivers of harvest timing and wine quality across France and Switzerland. Long-term grape harvest date records and wine quality estimates demonstrate that warm temperatures have been a consistent driver of early harvests and higher quality wines. Relationships with drought, however, have largely disappeared in recent decades, a consequence of large-scale shifts in the climate system that have decoupled high growing season temperatures from dry summers. Our results do not necessarily presage an inevitable future where wine quality is dominated by environmental changes. In reality, grape harvest date and wine quality depend on a number of factors beyond climate—including winegrape varieties, soils, vineyard management, and winemaker practices[26,27]. Our results do suggest, however, that the large-scale climatic drivers within which these generally local factors act has fundamentally shifted. Such information may be critical to wine production as climate change intensifies over the coming decades in France, Switzerland,

and other wine growing regions.

Methods

Grape Harvest Data. We analyzed harvest data in the database of regional winegrape harvest time series from Western Europe compiled by Daux et al 2012 (hereafter, DAUX[4]). DAUX included 27 regional composite time series of winegrape harvest dates, compiled from local vineyard and winery records going back as far as 1354. Most of these series were from France, but also included were data from Switzerland, Spain, Luxembourg, and Germany (Supplemental Figure 1). These data were ideal for climate change research applications because management practices have changed generally little over time and irrigation as a viticulture tool (which could have complicated the interpretation of climate relationships) was (and still is) largely absent, especially in France. Indeed, these data have been used previously to develop proxy-based temperature reconstructions for the region[4].

We created a composite average index from several regional series (GHD-Core) as the focus for our analysis. Using a multi-site composite series had two main advantages. First, every regional grape harvest date series had at least some 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 winegrape varietals and regions, use of a composite average series should minimize the influence of local management effects (which are unlikely to be synchronous across space) and instead emphasize larger scale signals related to climate variability and change (the primary focus of our study).

From the 27 regional grape harvest date series available, we chose 8 sites (Supplemental Table 1) to construct GHD-Core: Alsace (Als), Bordeaux (Bor), Burgundy (Bur), Champagne 1 (Cha1), Languedoc (Lan), the Lower Loire Valley (LLV), the Southern Rhone Valley (SRv), and Switzerland at Leman Lake (SWi). All 7 regional series were over 80% serially complete back to 1800 and all but one (Cha1) were over 60% complete back to 1600 (Supplemental Table 2). Importantly, all 8 sites had good coverage for the most recent period (1981–2007) when we conclude that drought controls on harvest date have significantly weakened. 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 (also the time period indicated by Daux et al 2012 as the most reliable).

Prior to compositing, we converted each harvest date series to days per year anomaly, relative to their local mean for 1600–1900. Despite the broad geographic range and climates gradients covered by these sites, there was 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), were anomalously early during the recent 1981–2007 interval relative to the baseline averaging period of 1600–1900, ranging from on average -2 days (Cha1) to over -23 day (SWi) early (Supplemental Table 4). There were 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 twentieth century (1901–2012) were taken from version 3.21 of the CRU climate grids[20]. These data were monthly gridded fields, interpolated over land from individual station observations to a spatially uniform half degree grid. We also used a drought index, an updated version of the Palmer Drought Severity Index (PDSI[28]) derived from the CRU data[29]. 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), and so it incorporates longer term changes in moisture balance beyond the immediate months or season.

To extend our analysis further back in time, we also used three largely independent proxy based reconstructions of temperature[5], precipitation[7], and PDSI[6]. The temperature and precipitation products are 3-month seasonal reconstructions (DJF, MAM, JJA, SON) using primarily historical documentary evidence over the last 500 years. The temperature reconstruction covers the period 1500–2002; the precipitation reconstruction covers 1500–2000. The PDSI reconstruction is summer season only (JJA) and is based entirely upon tree ring chronologies distributed across Europe. It covers the entire Common Era, up through 2012. Prior to comparisons with the grape harvest data, we anomalized all three reconstruction products to a zero mean over 1600–1900, the same baseline period used in the harvest date anomaly calculations.

Wine Quality Data & Analyses. We extracted wine quality data from Broadbent (2002)[21], which was ideal for our analyses in that it represented quality assessed by 1) a single observer who 2) attempted to correct for age since vintage in his ratings. Ratings were scaled from 0 to 5, with 0 indicating a 'poor' vintage and 5 indicating an 'outstanding' vintage. We extracted data

for the 1900-2001 vintages in Bordeaux and Burgundy (2001 being the last year of data in the book). We selected these two regions for analysis because they are two of France's major wine-growing regions, coinciding with two major time-series of grape harvest date included in GHD-Core, and represented the most serially complete time series (99% for red Bordeaux, 98% for white Bordeaux, 88% for Red Burgundy and 59% for white Burgundy, with almost all the missing data occurring before 1950). We fit ordered logit models to wine quality and CRU 3.21 climate data for each region by wine color (red or white), using the package `ordinal` in `R` 3.1.2[30].

1. Duchêne, E. & Schneider, C. Grapevine and climatic changes: a glance at the situation in alsace. *Agronomy for sustainable development* **25**, 93–99 (2005).

2. Seguin, B. & de Cortazar, I. G. Climate warming: Consequences for viticulture and the notion of 'terroirs' in europe. *Acta Horticulturae* 61–69 (2005).

3. Webb, L. B., Whetton, P. H. & Barlow, E. W. R. Observed trends in winegrape maturity in Australia. *Global Change Biology* **17**, 2707–2719 (2011).

4. Daux, V. *et al.* An open-access database of grape harvest dates for climate research: data description and quality assessment. *Climate of the Past* **8**, 1403–1418 (2012).

5. Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M. & Wanner, H. European Seasonal and Annual Temperature Variability, Trends, and Extremes Since 1500. *Science* **303**, 1499–1503 (2004).

6. Cook, E. R. *et al.* Old World Droughts and Pluvials During the Common Era. *Science Advances* (in revision).

7. Pauling, A., Luterbacher, J., Casty, C. & Wanner, H. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. *Climate Dynamics* **26**, 387–405 (2006).

8. Jones, G. V. & Davis, R. E. Climate Influences on Grapevine Phenology, Grape Composition, and Wine Production and Quality for Bordeaux, France. *American Journal of Enology and Viticulture* **51**, 249–261 (2000).

9. Schultz, H. R. & Jones, G. V. Climate Induced Historic and Future Changes in Viticulture. *Journal of Wine Research* **21**, 137–145 (2010).

10. Tomasi, D., Jones, G. V., Giust, M., Lovat, L. & Gaiotti, F. Grapevine Phenology and Climate Change: Relationships and Trends in the Veneto Region of Italy for 1964–2009. *American Journal of Enology and Viticulture* (2011).

11. Camps, J. O. & Ramos, M. C. Grape harvest and yield responses to inter-annual changes in temperature and precipitation in an area of north-east Spain with a Mediterranean climate. *International Journal of Biometeorology* **56**, 853–864 (2012).

12. Webb, L. B. *et al.* Earlier wine-grape ripening driven by climatic warming and drying and management practices. *Nature Climate Change* **2**, 259–264 (2012).

13. Jones, G. V. Winegrape Phenology. In Schwartz, M. D. (ed.) *Phenology: An Integrative Environmental Science*, 563–584 (Springer Netherlands, 2013).

14. Jones, G. V., White, M. A., Cooper, O. R. & Storchmann, K. Climate Change and Global Wine Quality. *Climatic Change* **73**, 319–343 (2005).

15. Mori, K., Goto-Yamamoto, N., Kitayama, M. & Hashizume, K. Loss of anthocyanins in red-wine grape under high temperature. *Journal of Experimental Botany* **58**, 1935–1945 (2007).

16. Chaves, M. M. *et al.* Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of Botany* **105**, 661–676 (2010).

17. Baciocco, K. A., Davis, R. E. & Jones, G. V. Climate and Bordeaux wine quality: identifying the key factors that differentiate vintages based on consensus rankings. *Journal of Wine Research* **25**, 75–90 (2014).

18. Van Leeuwen, C. *et al.* Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes. *Journal International Des Sciences De La Vigne Et Du Vin* **43**, 121–134 (2009).

19. Coombe, B. G. Influence of temperature on composition and quality of grapes. In *Symposium on Grapevine Canopy and Vigor Management, XXII IHC 206*, 23–36 (1986).

20. Harris, I., Jones, P. D., Osborn, T. J. & Lister, D. H. Updated high-resolution grids of monthly climatic observations –the CRU TS3.10 Dataset. *International Journal of Climatology* **34**, 623–642 (2014).

21. Broadbent, M. *Vintage Wine: Fifty Years of Tasting Three Centuries of Wine* (Harcourt Inc, 2002).

22. Oppenheimer, C. Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in Physical Geography* **27**, 230–259 (2003).

23. Rebetez, M. *et al.* Heat and drought 2003 in Europe: a climate synthesis. *Annals of Forest Science* **63**, 569–577 (2006).

24. Seneviratne, S. I., Luthi, D., Litschi, M. & Schar, C. Land-atmosphere coupling and climate change in Europe. *Nature* **443**, 205–209 (2006).

25. Parker, A. *et al.* Classification of varieties for their timing of flowering and veraison using a modelling approach: A case study for the grapevine species Vitis vinifera L. *Agricultural and Forest Meteorology* **180**, 249 – 264 (2013).

26. Jackson, D. I. & Lombard, P. B. Environmental and management practices affecting grape composition and wine quality-a review. *American Journal of Enology and Viticulture* **44**, 409–430 (1993).

27. van Leeuwen, C. *et al.* Why climate change will not dramatically decrease viticultural suitability in main wine-producing areas by 2050. *Proceedings of the National Academy of Sciences* **110**, E3051–E3052 (2013).

28. Palmer, W. C. Meteorological drought, Research Paper No. 45. *US Weather Bureau, Washington, DC* **58** (1965).

29. van der Schrier, G., Barichivich, J., Briffa, K. R. & Jones, P. D. A scPDSI-based global data set of dry and wet spells for 1901–2009. *Journal of Geophysical Research: Atmospheres* (2013).

30. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria (2014). URL `http://www.R-project.org/`.

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.

Author Contributions: BIC and EMW conceived of the paper and contributed equally to the writing. BIC conducted the climate analyses and processing of the harvest data, with contributions from EMW. EMW performed the wine quality analysis.

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

Acknowledgements I. García de Cortázar-Atuari for help with Daux data, H. Eyster, S. Gee & J. Samaha for extracting wine quality data.

Figure 1 Time series of grape harvest date anomalies from GHD-Core (left panel), composited from the Als, Bor, Bur, Cha1, Lan, LLV, SRv, and SWi regional harvest date time series in the DAUX dataset. All anomalies are in units of day of year anomalies, calculated relative to the average date from 1600–1900. In the right panel, we compare normalized histograms of anomalies from GHD-Core for two periods: 1600–1980 and 1981–2007.

Figure 2 Twentieth century analysis between climate obsevations and GHD-Core. Panels show 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 the climate data are from the CRU 3.21 climate grids, described in the Methods section.

Figure 3 Twentieth century analysis between climate observations and GHD-Core. Panels show linear regressions between GHD-Core and May-June-July climate variables from CRU 3.21, averaged over the main GHD-Core region (2°W–8°E, 43°N–51°N). The top row shows results from 1901–1980; the bottom row for 1981–2007. Calculating the regression statistics on the detrended data yielded nearly identical results, summarized in Supplemental Table 8.

Figure 4 Analysis between paleo-climate reconstructions and GHD-Core. Composite average temperature, precipitation, and PDSI anomalies from the various climate reconstructions (see Methods) from years with early harvest dates (≤ -7.67 days early).

Numbers in the lower left corners indicate the number of years used to construct each composite.