

## CHANGE POINTS AND TEMPORAL DEPENDENCE IN RECONSTRUCTIONS OF ANNUAL TEMPERATURE: DID EUROPE EXPERIENCE A LITTLE ICE AGE?

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We analyze the timing and extent of Northern European temperature falls during the Little Ice Age, using standard temperature reconstructions. However, we can find little evidence of temporal dependence or structural breaks in European weather before the twentieth century. Instead, European weather between the fifteenth and nineteenth centuries resembles uncorrelated draws from a distribution with a constant mean (although there are occasional decades of markedly lower summer temperature) and variance, with the same behavior holding more tentatively back to the twelfth century. Our results suggest that observed conditions during the Little Ice Age in Northern Europe are consistent with random climate variability. The existing consensus about apparent cold conditions may stem in part from a Slutsky effect, where smoothing data gives the spurious appearance of irregular oscillations when the underlying time series is white noise.

**1. Introduction.** The Little Ice Age is generally seen as a major event in European climatic history, causing Swiss glaciers to advance, the Thames in London to freeze, grape growing to disappear from England and wheat from Norway, and the Norse colonies in Greenland to perish. The goal of this paper is to estimate the magnitude and timing of climatic deteriorations during the Little Ice Age in Europe by using a variety of standard summer and winter temperature reconstructions: for Central Europe since 1500 [Dobrovolný et al. (2010)]; the Netherlands from 1301 [van Engelen, Buisman and IJnsen (2001)]; Switzerland from 1525 [Pfister (1992)]; and England from 1660 [Manley (1974)]. However, contrary to the existing consensus of a European Little Ice Age, we can find little evidence for change points or temporal dependence in the weather series that we examine.

Starting with standard classical tests for change points in mean temperature—Bai and Perron (1998) breakpoints and Venkatraman and Olshen (2007) binary segmentation, which we show can detect changes of one standard deviation lasting a generation, and 0.5 standard deviations lasting a century—we find that all winter series break around 1900, as does Central European summer temperature. However, there is no indication of any shift in mean temperature, apart from a brief fall in Switzerland during the 1810s, prior to this. Using the Bayesian change point analysis of Barry and Hartigan (1993), which has greater ability to detect

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short deviations, we find that while winters before 1900 are stable, there are occasional decades of markedly reduced summer temperature (the 1590s in Central Europe, the 1690s in England and the 1810s everywhere), but again no evidence of sustained falls in mean temperature.

However, temperature changes during a European Little Ice Age are more likely to have been gradual trends than discrete jumps. Therefore, the core of this paper consists of tests for temporal dependence; looking specifically at whether annual temperature in Europe displays conditional mean independence or martingale differences, given the past history of a stationary series  $\{Y_t\}$  with expectation  $\mu$ , the best forecast of its current value is its unconditional mean:  $E(Y_t|Y_{t-1}, Y_{t-2}, \dots) = \mu$ .

Developed in financial econometrics to test the Efficient Markets Hypothesis that changes in asset prices should be unpredictable, there are three principal categories of these tests: Portmanteau tests that look at the sum of autoregressive coefficients in the data; variance ratio tests that look at how fast the variance of a series grows as the number of observations rises; and spectral tests that look for departures from a straight line spectrum. While little known outside econometrics, these tests have considerable power to detect a wide variety of patterns of temporal dependence. We apply recent versions of the three types of test to European temperature series and find few departures from conditional mean independence, with these departures driven by pre-1700 reconstructions.

In summary, then, annual temperature reconstructions for Northern Europe do not appear to exhibit temporal dependence or structural breaks consistent with the occurrence of a European Little Ice Age. To avoid confusion about this result, it is useful to bear in mind that, in contrast to the hemispheric or global scale on which climatologists usually operate, the scale of our analysis is regional. A fundamental lesson of efforts over the past twenty years to construct estimates of global temperature is that conditions in individual regions are extremely noisy signals of global conditions. The fact that European weather has been fairly constant between the late Middle Ages and late nineteenth century no more implies that wider Northern Hemisphere temperatures were constant during this period than the absence of marked rises in European summer temperature during the twentieth century implies that global warming was not occurring. Similarly, the slowly changing nature of forcing variables that drive global climate (solar output, Earth orbit, land cover, greenhouse gas concentrations; with more rapid movements associated with volcanic activity) would lead us to expect that annual Northern Hemisphere temperatures display considerable autocorrelation, but this is not incompatible with the absence of autocorrelation that we find in Europe.<sup>1</sup>

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<sup>1</sup>The autocorrelation for the Climatic Research Unit's Northern Hemisphere series Jones et al. (2012) from 1850 to 1949 is 0.4 for July with  $p$ -value of  $p = 0.001$ , but  $-0.1$  for January with  $p = 0.2$ .

That our findings run counter to the existing consensus of a European Little Ice Age may reflect the fact that our analysis is based on unsmoothed data. This is in contrast to the common practice in climatology of smoothing data using a moving average or other filter to extract long run climate signals from noisy local weather observations. When data are uncorrelated, as the annual European weather series we examine appear to be, such smoothing can introduce the appearance of irregular oscillations: a Slutsky effect. For an example of this in climatology see Figure 2 in Mann (2002) where the fall in smoothed Central England temperature “which best defines the European Little Ice Age” is explicitly highlighted. We illustrate the Slutsky effect in Figure 5 below for the four temperature series: while annual temperatures are uncorrelated, when smoothed with a 30 year moving average the data appear to show marked episodes of lower temperature consistent with a European Little Ice Age.

The rest of the paper is as follows. The traditional view of the European Little Ice Age is outlined in Section 2, along with descriptions of the data sources. Section 3 applies classical and Bayesian change point tests to the temperature reconstructions and finds little evidence of sustained changes before the twentieth century, although there are some decades of markedly lower summer temperature. Section 4 looks for temporal dependence in annual temperature using tests of conditional mean independence, while Section 5 outlines the Slutsky effect.

Supplement A [Kelly and Ó Gráda (2014)], available online, finds similar behavior in other weather records: instrumental records from European cities since 1700; the reconstruction of average temperature across all of Europe since 1500 by Luterbacher et al. (2004); German weather since AD 1000 [Glaser and Riemann (2009)]; and English and Swiss precipitation. It also tests for the presence of changing volatility in the annual reconstructions examined here by testing for autoregressive conditional heteroskedasticity.

**2. The Little Ice Age.** Originally coined in by Matthes (1939) to describe the increased extent of glaciers over the last 4000 years, the term “Little Ice Age” now usually refers instead to a climatic shift toward colder weather occurring during the second millennium. There is a consensus among climatologists that much of the Northern Hemisphere above the tropics experienced several centuries of reduced mean summer temperatures, although there is some variation over dates, with Mann (2002) suggesting the period between the fifteenth and nineteenth centuries, Matthews and Briffa (2005) 1570–1900, and Mann et al. (2009) between 1400 and 1700.

Wanner et al. (2008) identify a fall in global temperatures between around 1350 and 1850 associated with variations in the Earth’s orbit, lowered solar output and several large volcanic eruptions. More recently, the PAGES 2k Consortium (2013) finds that timing of peak cold periods in the last millennium varies regionally, with Europe [where reconstructions are based on mountain and Scandinavian tree rings,

and the Dobrovolný et al. (2010) documentary reconstruction that we analyze here] showing a transition to a cooler climate around 1250.<sup>2</sup>

Our concern in this paper is not with the Little Ice Age globally or across the Northern Hemisphere, but its extent in Europe. A central lesson from efforts to reconstruct global temperature over the last 15 years is that regional climates vary widely and are therefore noisy signals of hemispheric climate, so that the findings that we present for Europe have no necessary implications for the behavior of average temperature over the wider Northern Hemisphere.

A combination of resonant images invoked by Lamb (1995) has linked the Little Ice Age firmly to Northern Europe. These include the collapse of Greenland's Viking colony and the end of grape-growing in southern England in the fourteenth century; the Dutch winter landscape paintings of Pieter Bruegel (1525–1569) and Hendrik Avercamp (1585–1634); the periodic “ice fairs” on London's Thames, ending in 1814; and, as the Little Ice Age waned, the contraction of Europe's Nordic and Alpine glaciers. Among historians, the idea that major economic and political events during the Little Ice Age, and particularly during the seventeenth century, were driven by worsening climate has generally been treated with scepticism [see, e.g., Appleby (1981) and de Vries (1981)], but a notable exception is Parker (2008) who attributes most of the political turbulence of the mid-seventeenth century, from the Irish Catholic uprising to the Mughal civil war, to a supposed worsening of climate during this period.

*2.1. Data sources.* In this paper we analyze weather reconstructions for Europe that are based on documentary sources. An immediate question is why more systematic proxies such as tree rings cannot be used instead. The answer is that tree rings accurately reflect annual weather conditions only in places where trees are at the edge of their geographical range, under stress because of cold or aridity; something that is not the case in most of Europe outside Scandinavia.<sup>3</sup>

Instead, for the period before 1700, when instrumental records begin, an abundance of material allows European temperatures to be reconstructed from documentary sources. For the sixteenth and seventeenth centuries, weather diaries and ships logs exist in considerable numbers. For earlier centuries, information about weather conditions is available from recorded harvest dates for grains, hay and grapes, and, in particular, from records of river tolls and water mills: how long each

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<sup>2</sup>If the European Little Ice Age occurred as a sudden and permanent jump to worse conditions, these start points precede most of the series analyzed here apart from the Netherlands series from 1301 and the German series from AD 1000 (in Supplement A [Kelly and Ó Gráda (2014)]). However, it is more likely that the Little Ice Age represents recurring episodes of worsened climate that should be detectable here.

<sup>3</sup>More controversially, McShane and Wyner (2011) argue that currently used proxies such as tree rings, lake sediments and ice cores have low explanatory power for recorded Northern Hemisphere temperature since 1850.

year were rivers unnavigable or mills unusable because waterways were frozen in winter or dried up in summer. A useful survey of these documentary sources is given by Brázdil, Pfister and Luterbacher (2005).

The two pioneering documentary reconstructions of regional European weather are monthly Swiss temperature and precipitation from 1525 [Pfister (1992)] and quarterly Netherlands temperature from 1301 [van Engelen, Buisman and IJnsen (2001)],<sup>4</sup> and we analyze both here. The current definitive reconstruction is the monthly Central Europe reconstruction since 1500 by Dobrovolný et al. (2010), which includes authors of most of the previous major European weather reconstructions and attempts to improve calibration of documentary records against instrumental records by trying to correct instrumental records for urban heat island effects and the impact of switching the location of thermometers from north-facing walls to modern louvered boxes. The monthly Central England series of Manley (1974) is based entirely on instrumental records, albeit with some heroic data splicing before 1700, and is included to look at weather in a more oceanic zone of Europe.

Documentary estimates of German temperature have been extended back to 1000 AD by Glaser and Riemann (2009) who label years as good, average or bad. Because these data are multinomial we analyze them separately in Supplement A [Kelly and Ó Gráda (2014)]. It is worth noting that although our early data are documentary, data for the eighteenth and early nineteenth centuries, which lie within most definitions of the Little Ice Age, are instrumental records.

*2.2. Reliability of documentary reconstructions.* How believable are these documentary reconstructions? With the exception of the Netherlands series, which provides detailed accounts of its construction (in Dutch), most studies give little detailed information on sources and methodologies used to translate documentary records into temperatures. However, we can still validate these series by seeing how they correlate with records of agricultural activity not used in their reconstruction.

The most detailed and extensive records of agricultural output in Europe before the establishment of research stations at the end of the nineteenth century are the accounts kept by English manors between the thirteenth and fifteenth centuries, which have been tabulated by Campbell (2007). The left-hand panel of Figure 1 plots Netherlands summer temperatures against the annual ratio of wheat harvested to wheat sown on 144 manors from the start of accurate records in 1270 (the earliest accounts start in 1211, but some of these early records claim anomalously high

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<sup>4</sup>Although these series start in AD 800, there are increasing numbers of missing observations as we go back past 1301 and the authors are less confident of their accuracy, putting them in wider bands that they denote by Roman rather than Arabic numerals. In running times series tests, missing observations during the 14th and early 15th centuries (30 for winter, 11 for summer) were set at the median value of the entire series.

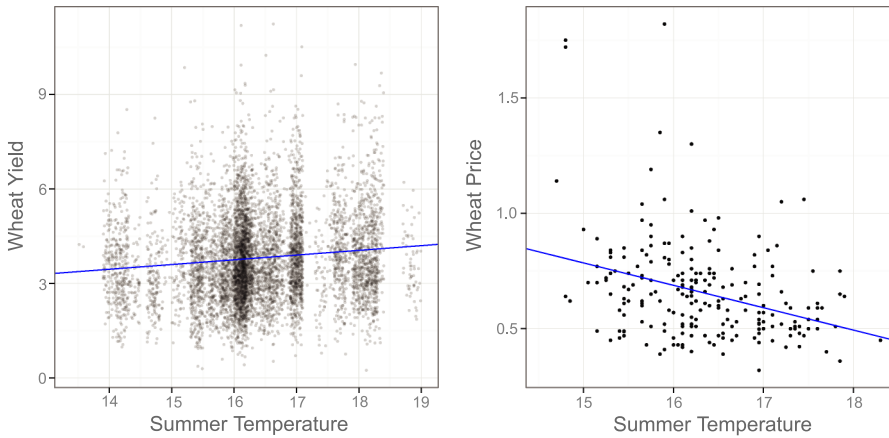


FIG. 1. (Left) wheat yield per seed on 144 English manors versus Netherlands summer temperature, 1270–1450. (Right) log English wheat price versus average Netherlands temperature over previous two years, 1213–1500.

yields that are not reflected in low wheat prices: including these records did not affect the results materially) and end in 1450 by when this pattern of seigneurial agriculture carried out by coerced labor had virtually disappeared. Points are jittered to separate overlapping ones.

It can be seen that yields move roughly in line with the Netherlands temperature estimates of van Engelen, Buisman and IJnsen (2001), although explanatory power in Table 1 is low: a one degree rise in summer temperature increases the average yield ratio by 5 per cent, while winter temperature has no impact. Estimating the regression with mixed effects to allow coefficients to vary across manors did not reveal large variation across manors or change the reported estimates markedly. As a further test of the validity of these results, we looked at the impact of temperature on the yields of barley and oats, which are known to be more weather resistant than

TABLE 1  
Regression of annual English wheat prices (1211–1450) and yields (1270–1450) on estimated Netherlands temperatures

	Intercept	Summer	Lag summer	Winter	Lag winter	RMSE	R <sup>2</sup>	N
Yield	0.504 (0.077)	0.046 (0.005)		0.001 (0.003)		0.369	0.016	6037
Price	5.771 (0.454)	-0.050 (0.019)	-0.048 (0.020)	-0.003 (0.012)	-0.010 (0.012)	0.261	0.076	164

Regression of annual English wheat prices and yields (both in logs) on current and lagged Netherlands summer and winter temperature. Standard errors in parentheses.

wheat, and found that summer temperature had a smaller effect on barley and none on oats.

English medieval agriculture was highly commercialized, and price series for wheat exist back to 1211 [Clark (2004)].<sup>5</sup> Wheat could be stored for a year after harvesting, so prices reflect the previous two years' harvests: one poor harvest had a limited impact, but successive harvest failures (such as occurred during the Great Famine from 1316–1317, when wheat prices rose to nearly three times their average level—shown by the two points in the northwest corner of the second panel of Figure 1) were lethal. We show elsewhere [Kelly and Ó Gráda (2014c)] that death rates at all levels, from unfree tenants to the high nobility, rose sharply after poor harvests, which caused epidemic disease to spread across society.

We analyze wheat prices from 1211 until 1500, a period during which the general price level was stable before the Price Revolution of the sixteenth century. Regressing log price on current and lagged summer and winter temperatures in Table 1, it can be seen that a one degree rise in summer temperature reduced prices by 5 per cent in the current and following year, while, again as we saw with yields, winter temperature has no discernible impact. In summary, then, its ability to predict medieval English wheat yields and prices suggests that the Netherlands temperature reconstruction is a reliable one.

**3. Change points in temperature since the Middle Ages.** To examine how weather deteriorated during the Little Ice Age, we analyze several widely used annual summer and winter temperature reconstructions up to 2000 for Western Europe: Central Europe from 1500; Netherlands from 1301; Switzerland from 1525; and England from 1660.<sup>6</sup> The Central Europe series is expressed as a deviation in degrees from the 1961 to 1990 average; monthly Swiss temperatures are assigned to an integer scale from plus three (very good) to minus three (very bad), while the Netherlands and English series are expressed in degrees Celsius. We subtract the mean of the Netherlands and English series prior to analysis, and look at summer (defined as the mean from June to August) and winter (defined as the mean from December to February) temperatures.

In this section we look for change points in average temperature series, focusing on the classical change point tests of Bai and Perron (1998) and Venkatraman and Olshen (2007) and the Bayesian test of Barry and Hartigan (1993). In climatological terms, changes in forcing variables are likely to be associated with long trends rather than changes in levels, and we look explicitly at tests for temporal dependence in annual temperature in the next section. However, changing means

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<sup>5</sup>We move Clark's price series back by one year to align them with calendar years rather than harvest years.

<sup>6</sup>We look at the Luterbacher et al. (2004) reconstruction of average temperature across all of Europe since 1500 and the Glaser and Riemann (2009) reconstruction of German temperatures since AD 1000 in Supplement A [Kelly and Ó Gráda (2014)].

associated with varying time trends are readily detectable with change point analyses used in this section.

To look at mean variations, we start with a simple one-way ANOVA to examine winter and summer temperature by a half century for each series, and then compare variance of temperature within decades with variance between decades, before moving on to change point tests.

3.1. *One-way ANOVA.* Temperature in year  $i$  during half-century  $j$  is assumed to be normally distributed  $y_{ij} \sim N(\alpha_j, \sigma_w^2)$ , while for mean temperature during half-century  $j$   $\alpha_j \sim N(\mu, \sigma_b^2)$ . To identify coefficients, each series is demeaned, and we constrain the mean temperatures over half centuries to sum to zero  $\sum_j \alpha_j = 0$ , and impose standard noninformative priors:  $\mu \sim N(0, 10,000)$ ,  $\sigma_b \sim U[0, 20]$ ,  $\sigma_w \sim U[0, 20]$ . This was estimated by MCMC in JAGS with 10,000 iterations, the first 2500 being discarded. Trace plots indicate rapid convergence on the posterior distribution, and the Gelman–Rubin diagnostic supports convergence.

Figure 2 shows little variation in summer temperature with most observations lying within 0.25 degrees C of the series mean. For winter series and Central European summers the rise around the late nineteenth century is evident.

3.2. *Intra-class correlation.* Given that variance appears fairly constant for most series (see Supplement A [Kelly and Ó Gráda (2014)]), it is worthwhile to compare the variance of temperature between periods with the variance within periods. We use the same specification, priors and number of iterations for annual temperature as in Figure 2, but use decades rather than half centuries as our period of analysis (the results are almost identical if we use half centuries), and end each series in 1900.

Table 2 reports the estimated standard deviation within decades  $\sigma_w$  and between decades  $\sigma_b$ , and also the intra-class correlation, the percentage of the variance of the series accounted for by between-class variance:  $ICC \equiv \sigma_b^2 / (\sigma_b^2 + \sigma_w^2)$ . It can be seen that the standard deviation of temperature between decades is low: of the order of one quarter of a degree Celsius. Similarly, the intra-class correlation is low, with between-decade variance accounting for one to three per cent of variance for winter temperature, and four to eight per cent for summer.

3.3. *Classical change point tests.* We now look at the stability of each series: can we find structural breaks in mean temperature corresponding to different phases of climate? We start with classical tests: the Bai and Perron (2003) procedure, implemented by Zeileis et al. (2002), which uses linear programming to find the optimal location of  $k$  breakpoints that minimize the sum of squared residuals, subject to a Bayes Information Criterion penalty for adding breakpoints; and the Venkatraman and Olshen (2007) circular modification of Sen and Srivastava



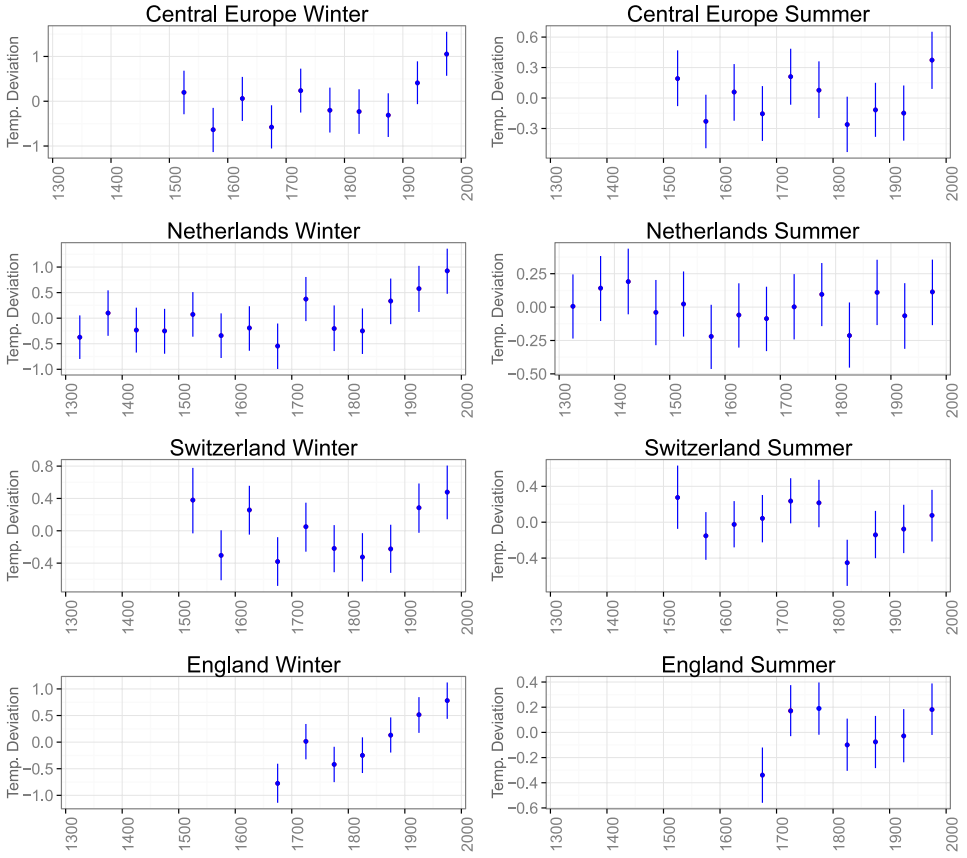


FIG. 2. Mean summer and winter temperature deviation by half century with 95 per cent credible intervals.

TABLE 2  
Within and between decade standard deviation of annual temperature series before 1900

	Winter			Summer		
	ICC	$\sigma_w$	$\sigma_b$	ICC	$\sigma_w$	$\sigma_b$
C. Europe	0.01 [0, 0.04]	1.92 [1.79, 2.06]	0.11 [0, 0.36]	0.04 [0, 0.1]	1.07 [1, 1.15]	0.19 [0.03, 0.36]
Netherlands	0.02 [0, 0.06]	1.64 [1.55, 1.74]	0.18 [0.01, 0.4]	0.04 [0, 0.1]	0.89 [0.84, 0.95]	0.17 [0.04, 0.29]
Switzerland	0.03 [0, 0.09]	1.15 [1.07, 1.23]	0.16 [0.02, 0.36]	0.05 [0, 0.13]	0.97 [0.9, 1.05]	0.2 [0.05, 0.37]
England	0.04 [0, 0.14]	1.34 [1.23, 1.47]	0.23 [0.01, 0.52]	0.07 [0, 0.2]	0.78 [0.71, 0.86]	0.21 [0.05, 0.38]

Intraclass correlation, between decade standard deviation and within decade standard deviation of annual temperature series. 95 per cent credible intervals in brackets.

(1975) binary segmentation which looks for the largest change in the partial sums of observations. The Bai–Perron test looks for instability in regression coefficients but, because we find little evidence for large or significant trends or autocorrelation in the weather series (see Section 4.1 below), we focus on shifts in the intercept or mean value here.<sup>7</sup> Climatology would lead us to expect shifts in temperature trends rather than in levels, but in Section 4.1 we find no indication of substantial trends or structural breaks in trends before 1900.

For these tests to be informative, we must know their power: are they capable of detecting shifts in mean temperature of the sort that might have occurred during a European Little Ice Age? We will examine the power of these tests to find changes of means in series which are independent draws from a normal distribution: we will see in Section 4 that our data are compatible with the assumption of no temporal dependence.

Starting with the case of a series of length 300 with a constant mean of zero (in all simulations the standard deviation is unity), in 1000 simulations, BP detected breaks in 1.8 per cent of cases and VO in 1.4 per cent, close to its nominal significance level of 1 per cent. In all cases here, the minimum segment length in BP is set to 15 per cent of the data series. Looking at the ability to detect changes, in 1000 simulations where 150 observations of mean zero are followed by 150 with a mean of 0.5, BP detected the break in 90 per cent of cases and VO in 64 per cent, while for 100 observations in each group the success rates are 71 per cent and 43 per cent. By contrast, the Bayesian change point analysis of Barry and Hartigan (1993), which performs better than classical tests in detecting short breaks, finds only around one quarter of 0.5 standard deviation changes halfway through a series of length 200 or 300.<sup>8</sup>

Looking at a series of 150 observations where the middle 50 are 1 standard deviation higher, BP detects 96 per cent and VO 95; for a rise of 0.75 the percentages detected are 71 and 65, while for a rise of 0.5 the detection rates were 28 and 22 per cent. For a rise in 33 observations in the middle of a series of 100, for a one standard deviation increase BP detected 84 per cent of cases and Segment 77; for a rise of 0.75 the rates are 52 and 40, while for a rise of 0.5 the detection rates are 21 and 13. In other words, binary segmentation and BP can detect changes of 1 standard deviation in annual temperature (roughly 1 degree Celsius for summer temperatures in Northern Europe) that last a generation and fairly reliably detect 0.5 standard deviation changes that last a century.

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<sup>7</sup>The older CUSUM test [implemented by Zeileis et al. (2002)] performed poorly in simulations, only detecting half as many breaks in short series as Bai–Perron, and we do not report its results here. Because we are using seasonal averages, and only have annual data, the Dierckx and Teugels (2010) test for changes in the parameter of the Pareto distribution generating extreme values is not applicable.

<sup>8</sup>For a change in the posterior mean to be detectable by eye, it requires a posterior probability of a change point of at least 0.15, which, looking at the maximum posterior probability for 10 observations on either side of the break, occurs in around 25 per cent of simulations.

TABLE 3  
*Change points in mean winter and summer temperatures*

	Start	Winter		Summer	
		BP	VO	BP	VO
C. Europe	1501	1909	1909	0	1982
Netherlands	1301	1861	1897	0	0
Switzerland	1525	1910	1911	0	1813, 1818
England	1660	1910	1911	0	0

Change points in mean winter and summer temperatures identified by Bai–Perron breakpoints and Venkatraman–Olshen binary segmentation.

Table 3 reports the change points detected in our four series of summer and winter temperature using BP and VO. In all cases we find a break in winter temperatures around the start of the twentieth century, but no indication of any change before that. For summer temperature, England and the Netherlands show no change points. Central Europe shows a rise in the late twentieth century, while Switzerland records a shift between 1813 and 1818; we return to this below.

In summary, classical change point tests suggest that if sustained falls in temperature did occur in Europe during the Little Ice Age, their magnitude was below half a standard deviation.

*3.4. Bayesian change points.* The breakpoint and segmentation methods perform well in detecting long-lasting changes in series, but do less well at finding shorter breaks. We therefore consider the Bayesian change point analysis of Barry and Hartigan (1993) implemented through the MCMC approximation of Erdman and Emerson (2007). Figure 3 shows the estimated mean of each series inside a 95 per cent credible interval, with the posterior probability of a change point plotted below, all estimates being carried out using the default values of Erdman and Emerson (2007).

It is evident that winter temperatures are stable until the twentieth century when they rise markedly, particularly for England. While designed to detect changes in means, upward trends associated with post-industrial warming in the twentieth century are readily apparent. For summers, the older reconstructions for Netherlands and Swiss temperature show little variation before the twentieth century, apart from a rise in the late eighteenth century for the Netherlands, and a drop in the 1810s for Switzerland.

The English and the Central European series, while not showing sustained changes before 1900, do show considerable volatility around their mean, with episodes of sustained falls in summer temperature lasting around a decade. The most notable of these, that also appears in many of the city series included in the

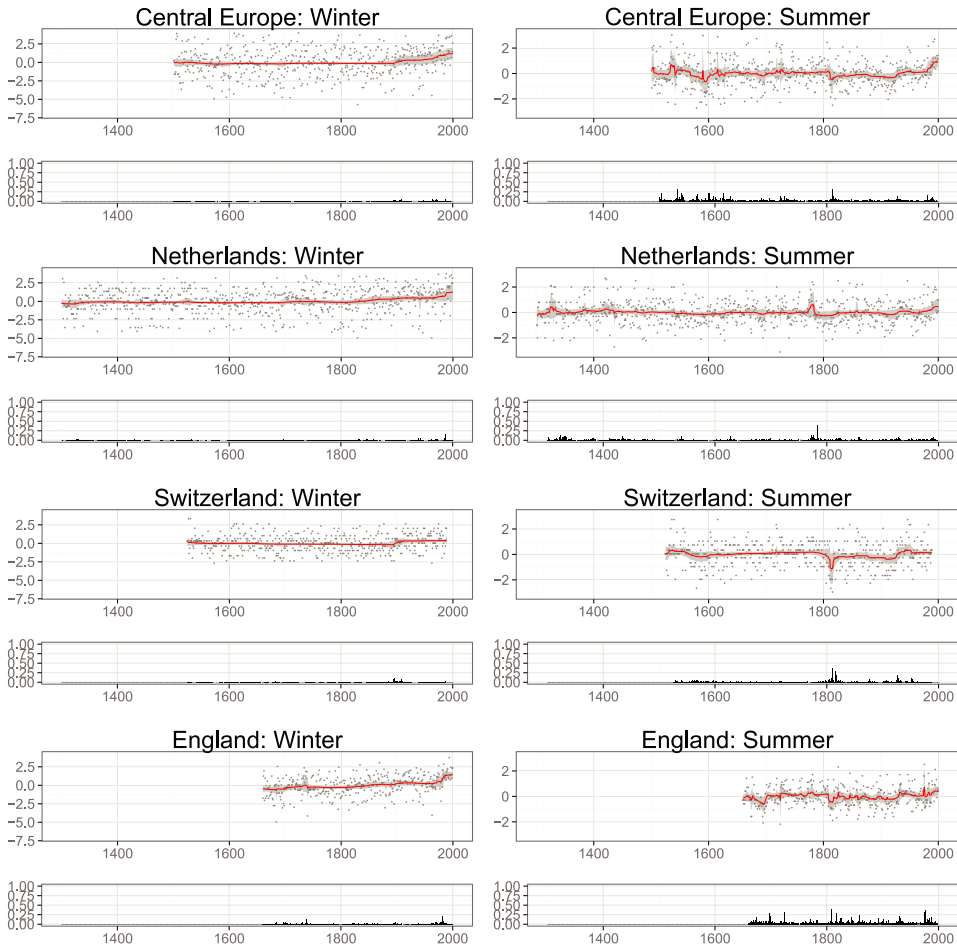


FIG. 3. Posterior mean and probability of breakpoint for temperature deviation series using the Barry and Hartigan product partition model.

Appendix, occurs in the 1810s when temperatures in England were below average every year between 1809 and 1817, and in Central Europe between 1812 and 1818. Similarly, temperatures in Central Europe were below average every year from 1591 to 1598, and in England from 1687 to 1698.<sup>9</sup> While summer temperatures do not show the prolonged changes that one would expect during a Little Ice Age, there are occasional decades of notably worse weather.

<sup>9</sup>It is notable that some of these falls occur in the same decade as well-known episodes of volcanism such as Tambora in 1815, and Hekla, Amboina and Serua in 1693–1694, although in both cases the temperature falls precede the volcanic episodes by several years.

TABLE 4  
*Regression of annual temperature reconstructions on lagged temperature and trend*

	Start	Intercept	Lag temperature	Trend	RMSE	R <sup>2</sup>
<i>Summer</i>						
C. Europe	1501	-1.145 (0.199)	-0.108 (0.050)	0.000 (0.001)	1.908	0.012
Netherlands	1302	-0.267 (0.136)	-0.039 (0.041)	0.000 (0.000)	1.649	0.004
Switzerland	1526	-0.266 (0.119)	-0.138 (0.051)	-0.001 (0.001)	1.144	0.028
England	1661	-0.601 (0.179)	-0.051 (0.065)	0.003 (0.001)	1.342	0.020
<i>Winter</i>						
C. Europe	1501	-0.083 (0.109)	0.112 (0.050)	0.000 (0.000)	1.077	0.016
Netherlands	1302	0.053 (0.074)	0.100 (0.041)	0.000 (0.000)	0.904	0.012
Switzerland	1526	0.100 (0.102)	0.063 (0.052)	-0.001 (0.000)	0.981	0.012
England	1661	-0.034 (0.104)	0.102 (0.065)	0.000 (0.001)	0.795	0.011

Regression of annual temperature on lagged temperature and a trend. Standard errors in parentheses. All series end in 1900.

**4. Temporal dependence in temperature.** While European temperatures do not show much sign of discrete changes, Little Ice Age events are more likely to have been associated with gradual changes.<sup>10</sup> We therefore examine the temperature reconstructions for temporal dependence. We start with a simple first order autoregression with trend, and then consider tests of conditional mean independence that are sensitive to a range of higher order and nonlinear dependencies.

4.1. *First order autoregressions.* Table 4 gives the results of a first order autoregression with trend  $y_t = \alpha + \beta y_{t-1} + \gamma t$  for each weather series. We shall see below that this specification is adequate: there is little indication of higher order dependencies or nonlinearities in the data. Each series is ended in 1900 and a [Bai and Perron \(2003\)](#) procedure does not indicate a structural break in any regression associated with changes between rising and falling trends of temperature.

<sup>10</sup>In addition, as a referee observes, change points may be eliminated in documentary reconstructions if their authors splice data together by assigning early reconstructions the same mean as later instrumental observations. Such homogenization will not eliminate the temporal dependence that we test for in this section.

For every series the regression  $R^2$  is below 0.03. The size of autocorrelation is small in every case, and only a few series show statistically significant autoregression at conventional levels. Central European and Netherlands winters show significant correlation but with a coefficient around 0.1: a one degree rise in temperature one year increases average temperature the next winter by an almost imperceptible tenth of a degree. The significance of the Netherlands series is caused by reconstructions from the fourteenth century and disappears from the fifteenth century onward, while significance for the Central Europe series disappears after 1700. Similarly, the small negative autocorrelation in the Central Europe and Swiss winter series disappears when noninstrumental observations before 1700 are excluded.

4.2. *Conditional mean independence.* While these temperature reconstructions do not, with some exceptions for early periods, display first order autoregression, there remains the possibility that the series show some other form of dependence, either higher order linear or nonlinear. To investigate this possibility, we analyze our weather series for what statisticians call conditional mean independence and financial econometricians, who developed these tests to see if changes in asset prices are unpredictable, call martingale differences. Specifically, for a stationary series  $\{Y_t\}$ , let  $I_t = \{Y_t, Y_{t-1}, \dots\}$  denote the information set at time  $t$ . Under martingale differences  $E(Y_t | I_{t-1}) = \mu$  [Escanciano and Lobato (2009a)].

4.2.1. *Tests.* Martingale differences imply zero autocorrelations  $\rho_i$  for order  $i > 0$ . This leads to the standard Ljung–Box Portmanteau test based on the sum of the first  $p$  squared autocorrelations  $T \sum_{i=1}^p \tilde{\rho}_i^2$ , where  $\tilde{\rho}_i = \rho_i \sqrt{(T+2)/(T-i)}$  and  $T$  is the number of observations. We apply the modification of Escanciano and Lobato (2009b) where correlations are divided by sample autocovariances of the squared series to provide robustness against heteroskedasticity, and  $p$  is chosen by a data-dependent procedure where a penalty term is subtracted that switches between Akaike and Bayes Information Criteria.

The second test we apply is a variance ratio test, based on the idea of Lo and MacKinlay (1989) that, for uncorrelated series, estimated variance should rise in proportion to the length of the series:  $AVR = 1 + 2 \sum_{i=1}^{p-1} (1 - i/p) \rho_i$ . We apply the Kim (2009) modification where  $p$  is chosen by a data dependent procedure, and the distribution of the test statistic is derived by applying a wild bootstrap, where each term  $Y_t$  of the original series is multiplied by a random variable with zero mean and unit variance.

The third class of tests for temporal dependence in time series are tests for the departure of the series spectrum from linearity. In econometrics these originate with Durlauf (1991), and we report the generalized spectral test of Escanciano and Velasco (2006).

4.2.2. *Results.* Looking at the small sample properties of these tests for samples with 100, 300 and 500 observations, Charles, Darné and Kim (2011) find that the reported size of all tests is approximately correct and that against models of linear dependence, the automated variance ratio test shows highest power, while against a variety of nonlinear processes, the generalized spectrum test works best. The temperature series here do not appear to exhibit nonlinearity: applying a Teraesvirta–Lin–Granger (1993) test for nonlinearity in means using the code of Trapletti and Hornik (2010) led to  $p$ -values in excess of 0.09 for all series, with values above 0.5 in most cases.

Table 5 reports the  $p$ -values of the three temporal dependence tests for each temperature series, calculated using the default values of Kim (2010). The first block reports results for each series from 1701 to 1900; the second is for all years after 1701; the third has each series from its start (1500 for Central Europe, 1301 for the Netherlands, 1525 for Switzerland and 1660 for England) until 1700; while the final block gives results for the pre-1901 period.

TABLE 5  
*Tests for conditional independence in means*

	Summer			Winter		
	$Q$	VR	Spec	$Q$	VR	Spec
			1701–1900			
C. Europe	0.23	0.06	0.43	0.29	0.00	0.78
Netherlands	0.13	0.05	0.10	0.30	0.24	0.86
Switzerland	0.53	0.43	0.25	0.17	0.12	0.29
England	0.42	0.42	0.51	0.46	0.60	0.62
			1701–2000			
C. Europe	0.01	0.02	0.01	0.32	0.32	0.83
Netherlands	0.05	0.01	0.10	0.63	0.64	0.62
Switzerland	0.01	0.26	0.19	0.71	0.74	0.47
England	0.22	0.14	0.32	0.00	0.04	0.04
			<i>pre</i> -1701			
C. Europe	0.03	0.01	0.01	0.07	0.00	0.09
Netherlands	0.24	0.00	0.29	0.61	0.92	0.85
Switzerland	0.02	0.25	0.03	0.45	0.36	0.20
England	0.16	0.15	0.40	0.06	0.04	0.05
			<i>pre</i> -1901			
C. Europe	0.03	0.02	0.02	0.04	0.00	0.23
Netherlands	0.01	0.00	0.00	0.38	0.41	0.58
Switzerland	0.19	0.13	0.54	0.01	0.65	0.01
England	0.00	0.03	0.09	0.62	0.79	0.48

$p$ -values for tests of conditional independence of means of temperature series until 2000.  $Q$  is a robustified portmanteau test with automatic lag selection. VR gives the wild bootstrap test results for an automatic variance ratio test. Spec is a generalized spectral test.

It can be seen that for 1701–1900 (a period whose start lies in conventional definitions of the Little Ice Age) the only test that rejects conditional mean independence at conventional levels is the VR test for European winters. This seems to result from excessive sensitivity of the VR test: this series has a first order autoregressive coefficient of  $-0.06$  with a  $p$ -value of  $0.36$ ; and if the residuals from this first order autoregression are tested, the VR test returns a  $p$ -value of  $0.82$  (with the automatic Portmanteau and generalized spectrum test giving similar values), indicating that the first-order specification is adequate. Adding in twentieth-century observations in the second block, the only series to show systematic departures from conditional mean independence are Central European summers and English winters, both of which rise notably after 1900.

The excess sensitivity of the VR test also appears in the pre-1701 Central Europe winter data: the coefficient of a first order autoregression is  $-0.14$  with a  $p$ -value of  $0.05$ , and applying the VR test to residuals gives a  $p$ -value of  $0.97$ . For the summer data, the coefficient of a first order autoregression is  $0.12$  with a  $p$ -value of  $0.09$ , and applying the VR test to residuals gives a  $p$ -value of  $0.82$ . We find similar behavior in pre-1701 Netherlands temperatures: the coefficient of a first order autoregression is  $-0.04$  with a  $p$ -value of  $0.38$ , and applying the VR test to residuals gives a  $p$ -value of  $0.87$ .

The weak correlation of annual Northern European temperature series is in marked contrast to the strong autocorrelation in the CRU Northern Hemisphere temperature series since 1850 which has first order autocorrelation  $0.6$  and significant partial autocorrelations out to lag four [McShane and Wyner (2011)], highlighting once again the importance of spatial variation in climatic patterns.

**5. The Slutsky effect.** As we noted in the [Introduction](#), our failure to find change points or temporal dependence in European weather possibly reflects the fact that we are analyzing unsmoothed data. By contrast, climatologists tend to smooth data using a moving average or other filter prior to displaying. When data are uncorrelated, as annual European weather series appear to be, smoothing can introduce the appearance of irregular oscillations: a Slutsky effect.

Confusingly, there are two different definitions of the Slutsky effect in common use.<sup>11</sup> First there is the formal sense, going back to Slutsky (1937), that applying a filter to a white noise series will generate *regular* cycles corresponding to peaks in the transfer function of the filter. For an  $m$  period moving average, for example, the transfer function is

$$f(\omega) = \frac{1}{m^2}(1 - \cos m\omega)/(1 - \cos \omega),$$

which, for  $m = 25$ , has its largest peak, after zero, around 17.5 years: too short, clearly, to generate Little Ice Age behavior.

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<sup>11</sup>We are grateful to a referee for pointing this out.



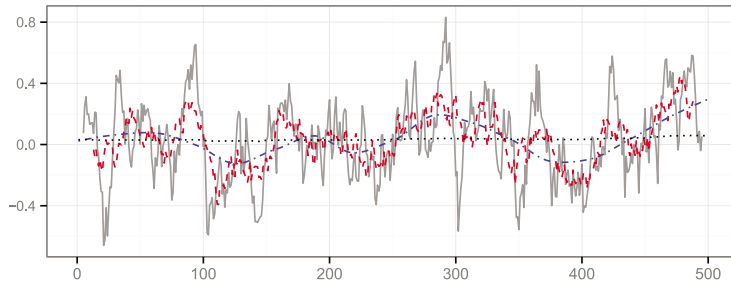


FIG. 4. *Slutsky effect: 500 independent, standard normal random numbers smoothed with a 10 period moving average (solid line); 25 period moving average (dashed line); and loess smoother with span of one third (dotdash line). The central dotted line gives the posterior mean estimated by a Barry–Hartigan change point procedure.*

The second sense, and the one that we invariably use here, is the colloquial one that applying a moving average to a white noise series will generate the appearance of *irregular* oscillations, as the filter is distorted by runs of high or low observations.<sup>12</sup> The intuition behind the Slutsky effect is straightforward: just as tossing a fair coin leads to long sequences with an excess of heads or tails, so random sequences in general will occasionally throw up some unusually high or low values in close succession that will distort a smoothing filter. In climatology, Burroughs [(2003), page 24] briefly discusses the Slutsky effect, in the second sense, in an early chapter on statistical background and gives a diagram illustrating how applying a moving average to a series of random numbers will give the appearance of irregular cycles, but does not subsequently investigate whether it can be the source of perceived climate cycles.

The Slutsky effect is illustrated in Figure 4 which gives smoothed values of 500 independent standard normal variables, using moving averages of 10, 25 and 50, and R's loess filter with smoothing span of one third.<sup>13</sup> It can be seen that a notable downward dip appears to occur after observation 100, and particularly between observations 300 and 400, which is followed by a marked upward trend. By contrast, the posterior mean estimated by a Barry and Hartigan (1993) change point procedure, which we have seen to be particularly useful for detecting short changes in the mean value of a series, shows little variation.

The Slutsky effect is illustrated in Figure 5 for the four temperature series, each smoothed with a 30 year moving average. The longest, Netherlands series, appears

<sup>12</sup>This is the definition given, for instance, at <http://mathworld.wolfram.com/Slutzky-YuleEffect.html>.

<sup>13</sup>The variables were generated in R with seed set to 123. The loess smoother applies a polynomial regression of order two to points within the smoothing span, with observations within the window being averaged with tri-cubic weights. The loess smoother behaved almost identically to the Butterworth low pass filter with threshold of 0.025, except at the boundaries where the latter showed characteristic attenuation toward zero.

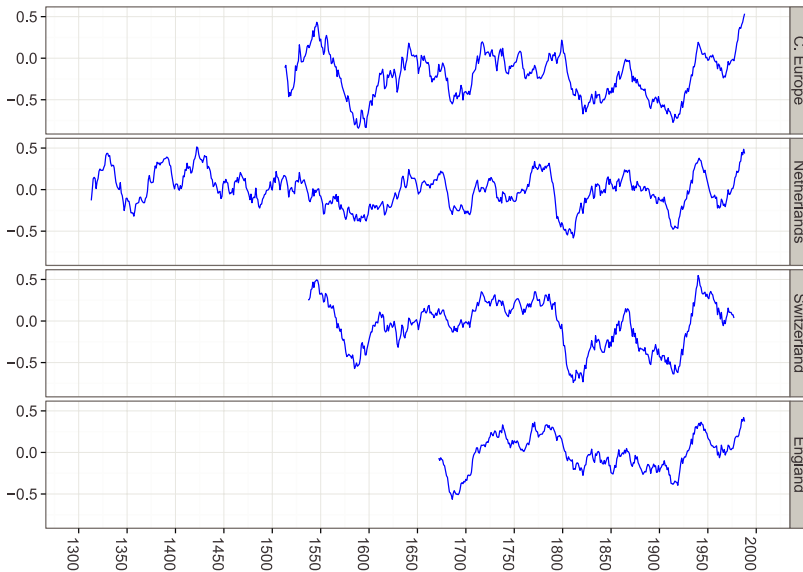


FIG. 5. Slutsky effect in European summer temperature deviation reconstructions, 1301–2000 smoothed with a 30 year moving average.

to show a cooling trend from the mid-fifteenth to the early nineteenth centuries, with markedly cold episodes in the late sixteenth, late seventeenth and early nineteenth centuries. Particularly interesting is the Central Europe series in the top panel. The temperature pattern resembles the [PAGES 2k Consortium \[\(2013\), Figure 2\]](#) European reconstruction (notably the troughs in the late 1500s and 1600s, and the early 1800s) which is based on the same series along with tree rings from the Pyrenees, Alps, Balkans and Scandinavia.

Glaciers may be seen as a physical embodiment of a Slutsky effect: their extent represents a moving average process of temperature and precipitation over preceding years, and can show considerable variation through time even though the annual weather processes that drive them are independent draws from a fixed distribution. For example, while annual Swiss winter temperature and precipitation are close to white noise until the late nineteenth century (see Supplement A [Kelly and Ó Gráda (2014)] for precipitation results), Swiss glaciers fluctuate considerably, expanding from the mid-fifteenth century until 1650, contracting until 1750 and then expanding again until 1850 [Matthews and Briffa (2005), pages 18–19].

**6. Conclusions.** Our intention was to estimate the extent and timing of climate changes during the European Little Ice Age. To our surprise, despite multiple tests, standard temperature reconstructions give little indication of temporal dependence or sustained structural breaks in European weather before the late nine-

teenth century. If Europe experienced a Little Ice Age, the weather reconstructions analyzed suggest that temperature falls were of the order of less than half of one standard deviation.

Our findings are a reminder that some of the changes claimed by [Lamb \(1995\)](#) to be consequences of the Little Ice Age may have other possible causes. The freezing of the Thames—which for most people is the most salient fact about the Little Ice Age—was due to Old London Bridge which effectively acted as a dam, creating a large pool of still water which froze twelve times between 1660 and 1815 [[Schneer \(2005\)](#), page 70]. Tidal stretches of the river have not frozen since the bridge was replaced in 1831, even during 1963 which is the third coldest winter (after 1684 and 1740) in the Central England temperature series that starts in 1660.

For Greenland's Vikings, competition for resources with the indigenous Inuit, the decline of Norwegian trade in the face of an increasingly powerful German Hanseatic League, the greater availability of African ivory as a cheaper substitute for walrus ivory, overgrazing, plague and marauding pirates probably all played some role in their demise [[Brown \(2000\)](#)]; and even if weather did worsen, the more fundamental question remains of why Greenland society failed to adapt [[McGovern \(1981\)](#)]. The disappearance of England's few vineyards is associated with increasing wine imports after Bordeaux passed to the English crown in 1152, suggesting that comparative advantage may have played a larger role than climate.

Similarly, the decline of wheat and rye cultivation in Norway from the thirteenth century may owe more to lower German cereal prices than temperature change [[Miskimin \(1975\)](#), page 59]. Moreover, with worsening climate we would expect wheat yields to fall relative to the more weather-robust spring grains barley and oats, whereas [Apostolides et al. \[\(2008\), Table 1\(A\) and \(B\)\]](#), find that between the early fifteenth and late seventeenth century, wheat yields show no trend relative to oats and rise steadily relative to barley.

Finally, demography supports our reservations about a European Little Ice Age. We would expect Northern Europe to have shown weak population growth as the Little Ice Age forced back the margin of cultivation. In fact, while the population of Europe in 1820 was roughly 2.4 times what it had been in 1500, in Norway the population was about 3.2 times as large, in Switzerland 3.5 times, in Finland 3.9 times and in Sweden 4.7 times as large as in 1500 [[Maddison \(2009\)](#)].

In summary, this paper makes two points: one methodological, one historical. First, smoothing white noise or near white noise data is problematic, but the most reliable and informative results, both in terms of avoiding spurious oscillations and detecting real breaks, are given by the [Barry and Hartigan \(1993\)](#) procedure. Second, although most people have strong priors that Europe experienced bouts of markedly worse weather during the Little Ice Age, such episodes are not apparent in standard temperature reconstructions.

## APPENDIX: DATA SOURCES

- Central European temperature reconstructions from 1500 by Dobrovolný et al. (2010) are available at <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/historical/europe/dobrovolny2010temperature.xls>.
- The Netherlands temperature series of van Engelen, Buisman and IJnsen (2001) are available at [http://www.knmi.nl/klimatologie/daggegevens/antieke\\_wrn/nederland\\_wi\\_zo.zip](http://www.knmi.nl/klimatologie/daggegevens/antieke_wrn/nederland_wi_zo.zip).
- Swiss summer and winter temperature and precipitation from Pfister (1992) are available at <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/historical/switzerland/clindef.txt>.
- Monthly mean Central England temperature from 1659 are from <http://hadobs.metoffice.com/hadcet/cetml1659on.dat>, and the monthly England and Wales precipitation series from 1766 are from [http://hadobs.metoffice.com/hadukp/data/monthly/HadEWP\\_monthly\\_qc.txt](http://hadobs.metoffice.com/hadukp/data/monthly/HadEWP_monthly_qc.txt).

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## SUPPLEMENTARY MATERIAL

**Supplement A: Additional weather series** (DOI: [10.1214/14-AOAS753SUPPA](https://doi.org/10.1214/14-AOAS753SUPPA); .pdf). This supplement analyzes additional weather series: European cities since 1500; European average temperature since 1500; German temperature since AD 1000; and English and Swiss precipitation. It also examines the variance of the temperature series examined here.

**Supplement B: Data and code** (DOI: [10.1214/14-AOAS753SUPPB](https://doi.org/10.1214/14-AOAS753SUPPB); .zip). This file contains the data and R code used in the paper.

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