

Did Climate Matter? The Little Ice Age and European Growth

Morgan Kelly
University College Dublin
Dublin 4

and

Cormac Ó Gráda
University College Dublin
Dublin 4

*For presentation at the NBER Climate Change: Past and Present Conference,
May 30-31, Cambridge MA. Preliminary: not for citation.*

Did Climate Matter? The Little Ice Age and European Growth

Morgan Kelly and Cormac Ó Gráda

1. Introduction.

Traditional accounts of the collapses of ancient civilizations have focused on economic and socio-political causes. Today there is an increasing tendency to invoke exogenous factors, and especially the impact of climatic trends. In a world where the scope for the division of labor is limited by population and by society's surplus over biological subsistence, a mild climate can support greater social complexity. A shift toward more inclement climate, whether in the form of more frequent droughts or colder temperatures, constrains cultivation and agricultural productivity, and may lead to violent competition within and without for increasingly scarce resources.

While climate is now invoked to explain the rise and decline of whole civilizations – ranging from classic Mayan to Roman, from Anasazi to Mesopotamian¹ – our focus here is the more modest claim, going back to Utterström (1955) and Lamb (1965; 1995: 187-241), that in northern Europe an expansionary Medieval Warm Epoch was followed by a contractionary Little Ice Age that lasted to the nineteenth century. In the absence of direct measurements of weather conditions – moderately accurate alcohol thermometers only came into use in the late 1650s – these writers had to rely on ambiguous anecdotal evidence such as the ending of grape growing in southern England or the extinction of Norse colonies in Greenland. Now, however, thanks to the global warming debate, a large number of annual climatic reconstructions are available that potentially allow us to estimate how much weather actually varied. But before we can use these reconstructions we need a way to assess how reliable they are.

In this paper we look at how various climate estimates vary with medieval grain yields, using the extensive harvest records that survive from English manors for the period 1270 to 1450. This allows us to assess which climatic reconstructions most actually reflect weather conditions in north-western Europe; and also to estimate how much weather mattered through its impact on harvests. We find that yields of the most weather sensitive grain, wheat, were strongly affected by summer weather conditions; both temperature as measured by Low Countries Temperature series of Van Engelen, Buisman and IJnsen (2001), and rainfall as measured by the thickness of annual growth rings of English oaks. However, instead of the expected long cycles of medieval warmth and subsequent cold, we find that summer and winter temperature and rainfall each year were effectively independent draws from an unchanging distribution. In other words, climate in north-western Europe between the thirteenth and nineteenth centuries was constant, and whatever variations in economic growth that occurred in this time were not due to climatic swings. This does not mean, of course, that every decade had identical weather. Just as coin tossing games show long runs with excesses of heads or tails, so some periods like the early fourteenth and late seventeenth centuries saw disproportionate numbers of bad summers and poor harvests.

The rest of the paper is as follows. Section 2 compares the candidate weather reconstructions with measured English weather after the seventeenth century; while Section 3 compares these weather reconstructions with yields of wheat and other grains on medieval English manors. We demonstrate the absence of autocorrelation from the best performing weather reconstructions in Section 4, and look at the impact of weather on real wages in Section 5. Section 6 concludes with speculations on the implications for economic change in the early modern era.

2. *Reconstructing Past Weather.*

To estimate weather before the start of systematic records in the late seventeenth century requires proxies for temperature and rainfall. We start by looking at how several temperature reconstructions match observed English weather conditions after records become available in the late seventeenth century; and in the next section use medieval cereal yields to assess how well they perform before this. We focus on three estimates of weather conditions in northern Europe. First is the Low Countries Temperature series of Van Engelen, Buisman and IJnsen (2001) which runs almost continually from 1200 (starting from 825). It relies primarily on weather diaries and on records of river tolls and water mills to estimate for how long each year waterways were unusable because of winter ice or summer drought. The second weather reconstruction is by Chuine *et al.* (2004) who use Le Roy Ladurie's (1971) series of the starting dates of Pinot Noir grape harvests to estimate Burgundy spring and summer temperatures back to 1370. This series reports April – August temperature anomalies with reference to the 1960-1989 period for the city of Dijon. The third series is the thickness of annual growth rings of English oaks: oak trees like wet summers, so a large growth ring implies poor conditions for growing wheat and other grains. We also include one Northern hemisphere temperature reconstruction, the early estimate of Mann, Bradley and Hughes (1999) which places more weight on European data than later studies and has a correspondingly closer fit to measured English temperature.

Table 1 shows how well these proxies match recorded English weather conditions. For 1660-1880 we see that Dutch summer temperature follows English temperature, but the R^2 is perhaps lower than might be expected: a major lesson of the global warming debate is that weather conditions vary considerably over quite short distances, so that changes in estimated average temperature

across the Northern Hemisphere are a poor guide to variations in any particular area (Mann and Jones, 2003). The correlations with French summer temperature and Northern Hemisphere temperature are lower still: if English summer temperature is regressed on all three temperature measures, although the French and Northern Hemisphere temperatures remain statistically significant, they add little explanatory power to the regression, improving the R^2 by only 2 percentage points compared with using Dutch temperature alone. After 1766, when reliable rainfall statistics for England become available, it can be seen that oak trees grow strongly when a wet summer follows a cold, wet winter.

-
-

<i>Table 1: Weather proxies and measured weather</i>							
	Sum. temp	Win. Temp	Sum. Rain	Win. rain	R2	DW	BP
Oak rings	0.169 (0.117)	-0.307** (0.063)			0.149	1.152	0.581
Dutch summer	0.881** (0.038)				0.628	1.464	0.005
Dutch winter		1.186** (0.033)			0.800	1.850	0.000
French summer	0.475** (0.059)				0.200	1.660	0.148
N Hemisphere	0.037** (0.009)	0.012* (0.005)			0.052	0.593	0.461

Regression of oak ring width; Dutch summer and winter temperature Van Engelen, Buisman and IJnsen (2001); French summer temperature Chuine et al. (2004); and Northern Hemisphere temperature Mann, Bradley and Hughes (1999) on measured English temperature (1660–1980) and rainfall (1766–1980). Andrews (1991) HAC standard errors in parentheses.
 * denotes significance at 5 percent, ** at 1 percent.
 BP is p -value of studentized Breusch-Pagan heteroskedasticity test. Intercepts not reported.

-

3. Weather and Grain Yields.

To assess the validity of these weather series before the start of instrumental records in the late seventeenth century we look at their ability to account for variations in cereal yields. Medieval English manors kept detailed accounts of amounts of grain sown and harvested that provide perhaps the best records of crop yields before the collection of official statistics and the appearance of agricultural research stations in the nineteenth century.

We use a new dataset of crop yields on manors in the south and east of England between 1211 and 1450 compiled by Campbell (2007). Table 2 gives the mean, standard deviation, autoregressive coefficient, and Ljung-Box statistic of gross yield per seed (the ratio of grain harvested to grain sown) for the 4 main cereals for the period 1270–1450, each annual observation being the median across all manors in our sample. While accounts go back to 1211, Campbell (2007) questions their reliability in early years, in particular the recording of grain received from tithes that appears in some years to have been added to harvest totals. After 1450, manorial production becomes rare and records correspondingly sparse.

□

<i>Table 2: Summary statistics for grain yields and prices, 1270–1450</i>							
□	Gross □ Yield □				Price □		
□	Mean □	SD □	□ □	L-B □	Mean □	SD □	□ □
Wheat □	3.586 □	0.558 □	0.162 □	0.093 □	5.92 □	2.022 □	0.552 □
Rye □	3.707 □	0.863 □	0.265 □	0.018 □	4.351 □	1.726 □	0.526 □
Barley □	3.398 □	0.503 □	0.443 □	0.000 □	4.003 □	1.303 □	0.524 □
Oats □	2.576 □	0.465 □	0.679 □	0.000 □	2.401 □	0.592 □	0.587 □
Mean, standard deviation, and autoregressive coefficient for gross yields per seed, and nominal price (shillings per bushel); 1270–1450 L-B is the <i>p</i> -value of the Ljung-Box statistic.							

□

□

Figure 1. Scatter-plots and box-plots of net grain yields 1268-1480

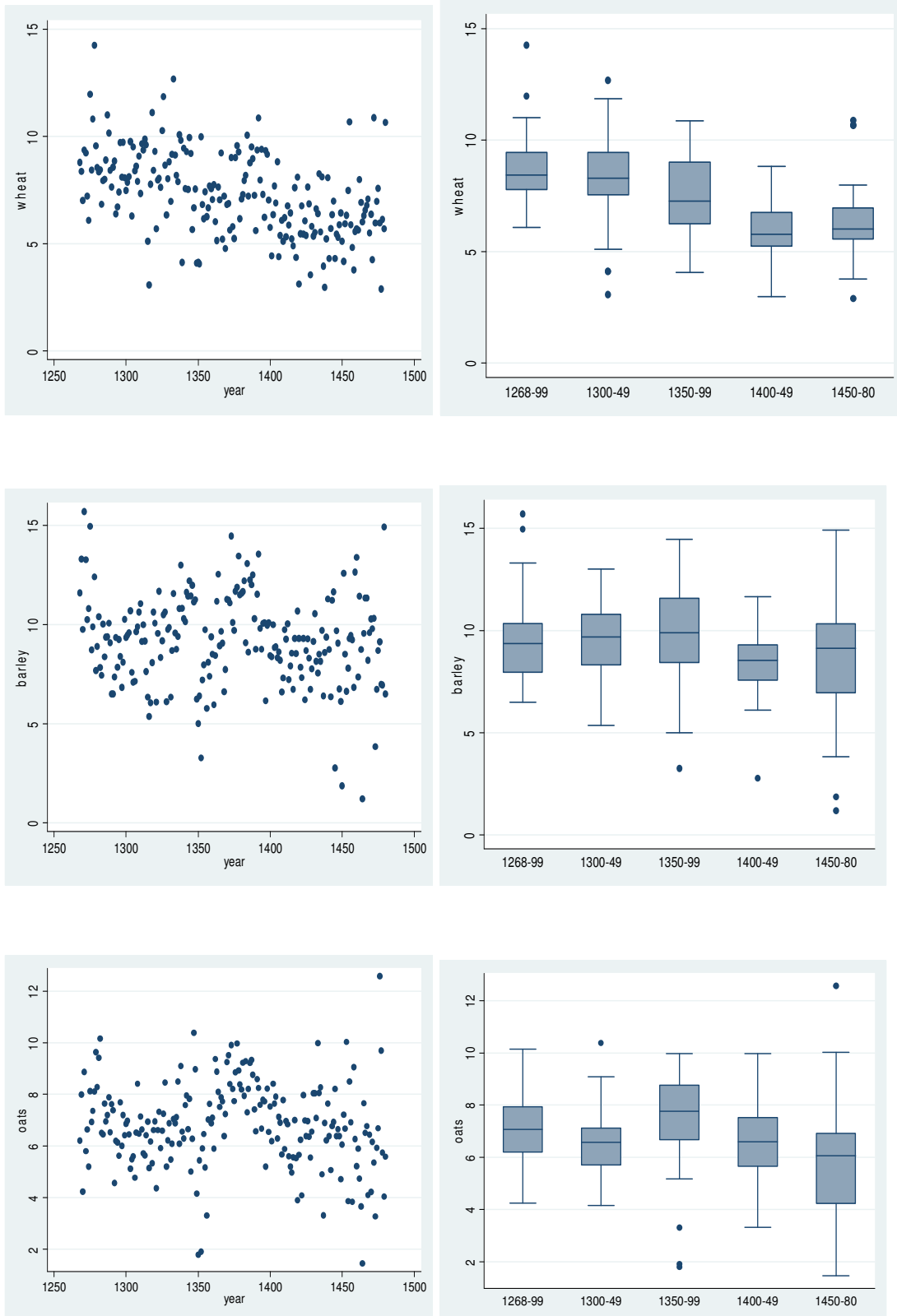


Figure 1 plots the net yield (in bushels per acre) of wheat, oats, and barley between the 1260s and the 1490s. It can be seen that yields tended to be low and variable. By comparison, in Britain from 1884–1939 mean yields for wheat, barley and oats were 32, 34, and 15 with respective standard deviations of 2.2, 1.9, and 1.8 (Mitchell, 1988). To estimate the impact of weather on yields we ran a regression of log yield ratios on weather, allowing intercepts and slopes to vary across manors:

$$\log Y_{it} = (\beta_0 + \beta_{0i}) + (\beta_1 + \beta_{1i})(s_t - \bar{s}) + (\beta_2 + \beta_{2i})r_t + \varepsilon_{it}$$

where Y_{it} is gross yield per seed on manor i in year t , $(s_t - \bar{s})$ is the deviation of estimated summer temperature from its mean value (15.3 degrees Celsius), and r_t is tree ring thickness expressed in standard deviations from its mean. The intercept and slope have components that vary idiosyncratically across manors $\beta_{ji} \sim N(0, \sigma^2_{\beta_j})$. It follows that the intercept is the log yield ratio in a year with average weather, while the slope coefficients are the average percentage changes in yield due to a one degree change in summer temperature and a one standard deviation change in oak ring thickness. We estimate by restricted maximum likelihood (Pinheiro and Bates, 2000, Ch. 2).

While intercepts, which denote average yield, vary widely across manors, there is little evidence for variation of slopes: comparing log-likelihood of regressions with fixed and variable slopes produced an improvement in fit that was significant at conventional levels only for the case of summer temperature on wheat, and even then the improvement in fit is small. For the results reported in Table 3, only the intercept varies across manors.

□

Table 3: Cereal yields and weather, 1211–1500

	<i>Intercept</i>	<i>Summer</i>	<i>Rings</i>	<i>Loglik</i>	R^2	σ_a	<i>N</i>	<i>Manors</i>
Wheat	1.223** (0.020)	0.050** (0.005)	-0.057** (0.004)	-2389	0.296	0.204	8439	112
Rye	1.286** (0.029)	0.048** (0.017)	-0.032** (0.015)	-597.2	0.133	0.137	1134	29
Barley	1.181** (0.020)	0.004 (0.005)	-0.009** (0.004)	-2231.4	0.248	0.193	7572	104
Oats	0.874** (0.014)	0.020** (0.005)	-0.004 (0.004)	-2648.2	0.152	0.142	8290	116

Mixed effects regression of log cereal yield ratio on on estimated summer temperatures (deviation from mean value of 15.3 Celsius) and oak ring thickness. Intercept varies across manors: σ_a is its standard deviation. N is number of observations and Manors is the number of manors. R^2 is the pseudo- R^2 for each regression. Standard errors in parentheses.
* denotes significance at 5 percent, ** at 1 percent.

Using the probably less reliable observations from before 1270 did not change the results in any important way, so all years were included. The small number of observations for some manors led to occasional difficulties with convergence, so we include only manors with at least 20 observations. Given the mild climate of the southern England, our expectation was that slight variations in temperature and rainfall each year would hardly affect yields outside well known periods of severe weather such as the heavy rains of 1315–16. In fact, wheat yield turns out to be strongly affected by weather: a one degree rise in summer temperature (equivalent to a change of 1.5 standard deviations) increases average yield by 5 per cent, while a one standard deviation increase in oak ring thickness is associated with a fall of 5.6 per cent in average output. As mentioned, the effect of summer temperature varies considerably across manors: estimated slopes range from zero to 0.12 with the strongest effects on manors with the highest yields: the correlation between estimated slopes and intercepts is 0.6.

□

<i>Table 4: Correlation between annual yields (above diagonal), and nominal prices (below diagonal) of cereals, 1270–1450</i>				
	Wheat	Rye	Barley	Oats
Wheat		0.477	0.388	0.237
Rye	0.884		0.370	0.305
Barley	0.852	0.831		0.599
Oats	0.811	0.761	0.876	

One thing we know for certain about our weather estimates is that they are measured with error, and their coefficient estimates suffer in consequence from attenuation bias. Using the textbook errors in variable formula, based on the known relationship of the variables after 1766, a regression using Dutch summer temperature and oak ring thickness as proxies for English summer temperature and rainfall respectively will produce coefficients that are 70 per cent and 48 per cent respectively of their true values, and to the extent that medieval estimates are less accurate than these later observations, the underestimate will be correspondingly larger.

Other crops were less sensitive to weather, in the order that we would expect. Rye has coefficients of 0.05 and -0.03 for temperature and tree rings; barley appears unaffected by summer temperature, and has a coefficient of only -0.01 for tree rings; and oats show no measurable effect of weather at all. This varying sensitivity is reflected in the autoregressive coefficient in Table 2 where annual wheat yields are effectively independent of each other, while less weather sensitive crops showing increasing autocorrelation. We see then in terms of weather risk, oats offered the best insurance, and had the added advantages of growing on poorer soil than other grain, and producing more calories per acre. We know from medieval accounts that the staple food of servants, outside harvest time, was dredge, a mixture of barley and oats (Dyer, 1988); and we show elsewhere that oat yields have the strongest predictive

power for death rates at all levels of medieval society, while Appleby (1979) argued that one of the reasons why England suffered less from famine than France during the late seventeenth and eighteenth centuries was because of its greater reliance on spring grains (Kelly and Ó Gráda 2009). Consequently, while weather strongly affected wheat yields, it does not appear to have had a large impact on the spring grains on which ordinary people relied.

4. *Climate since the Middle Ages.*

Medieval cereal yields suggest, then, that the Low Countries temperature estimates and oak ring thickness give us a reliable picture of weather conditions back to the thirteenth century. We therefore examine these series for long swings to see how climate varied during this period. Figure 2 shows estimated summer and winter temperature between 1201 and 2000 (actual temperatures after 1660, and estimated using a Kalman filter on the corresponding Dutch series before this), and oak ring thickness, measured in standard deviations from the mean, for the same period.

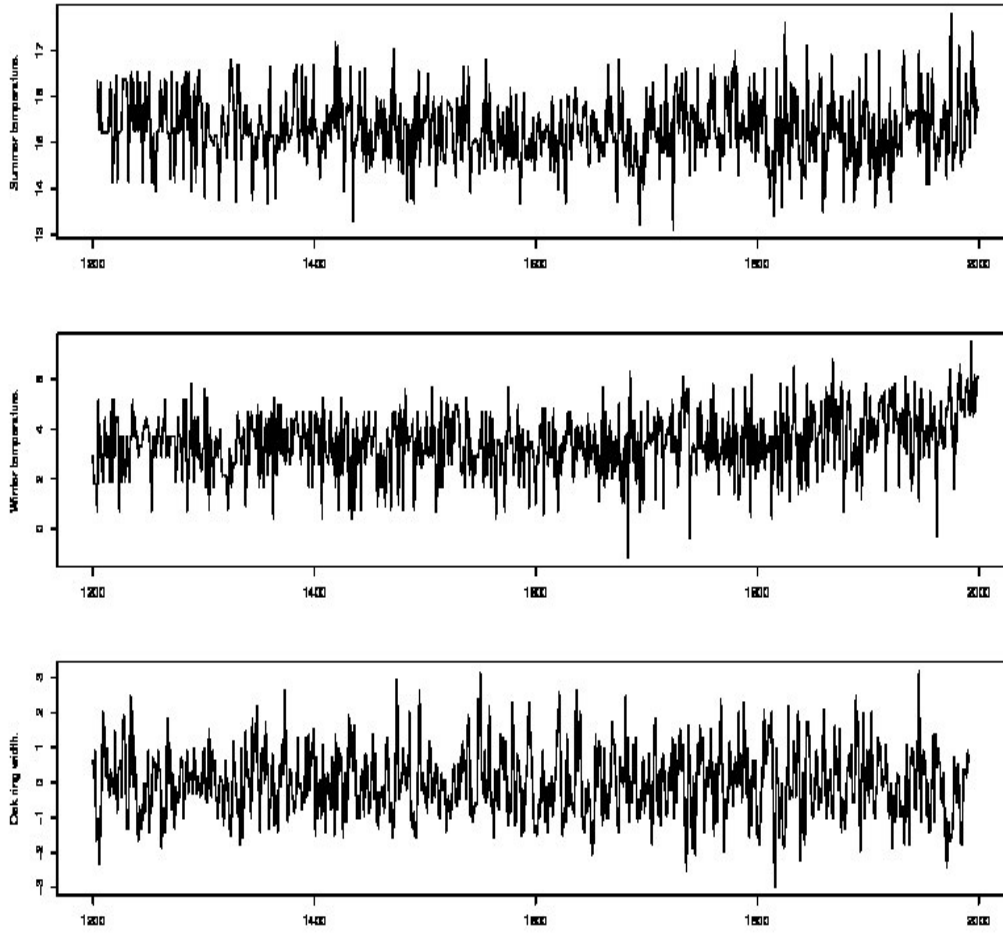


Figure 2: Estimated summer and winter temperature and oak ring thickness, 1201–2000

<i>Table 5: Summary statistics for annual weather until 1900</i>							
	Start	Mean	SD	ρ	SE	R ²	L-B
	Temperature						
English Summer	1660	15.26	0.79	0.102	0.065	0.010	0.111
English Winter	1660	3.49	1.35	-0.031	0.065	0.001	0.626
Dutch Summer	1200	16.25	0.93	0.121	0.038	0.015	0.001
Dutch Winter	1200	1.73	1.62	-0.031	0.038	0.001	0.410
Burgundy Summer	1340	-0.09	0.98	0.152	0.043	0.023	0.000
N. Hemisphere	1200	-0.14	0.12	0.615	0.03	0.38	0.000
	Rainfall						
English Summer	1720	444.93	87.79	0.114	0.087	0.013	0.183
English Winter	1720	461.89	86.21	0.02	0.087	0.000	0.182
Oak Rings	1200	0.02	1.00	0.331	0.036	0.109	0.000
Mean, standard deviation, and autoregressive coefficient, standard error and R2 for historical weather series. L-B is the p-value of the Ljung-Box test for randomness.							

Table 5 reports the results of first order autoregressions for each weather series until 1900, and it can be seen that there is little autocorrelation in most cases. Ljung-Box statistics show that annual data are random for English summer and winter temperature and rainfall, and Dutch winter temperature. The apparent temporal dependence in Dutch summer temperature estimates is generated by estimates prior to 1400: when these are omitted the Ljung-Box test indicates randomness. Similarly for the French temperature estimates, temporal dependence arises from observations before the mid-seventeenth century – suggesting that the decision of when to harvest grapes was influenced by the date of last year’s harvest – and disappears after this when temperatures measured by thermometer are used. There are only two cases where departures from randomness are robust. The first is the Mann, Bradley and Hughes (1999) Northern Hemisphere temperature series which, we have seen, had no

explanatory power for cereal yields, and appears to be driven by variations in conditions at high latitudes where there is evidence of long swings in climate (Dawson *et al.*, 2007). The second is the oak ring series which reflects the fact that oak trees are large, slow growing organisms (using innovations in oak ring thickness rather than actual thickness gave substantially identical results in predicting cereal yields). The estimated power spectra of all series except Northern Hemisphere temperature were flat. Table 6 reports regressions of annual weather conditions on dummies for each half century. It can be seen that the instrumental weather series, oak rings and reconstructed Dutch series show no pattern, except perhaps for winters in the late seventeenth century, before the late twentieth century when winters become milder and wetter. In summary, then, Figure 2 and Tables 6 show no long run trends in weather before the late twentieth century, and give no indication of a Medieval Warm Era or Little Ice Age. Instead, the annual observations are effectively independently, identically distributed for summer and winter temperature and rainfall.

Table 6: Regressions of weather series on half century dummy variables

	English Summer	English Winter	Dutch Summer	Dutch Winter	Burgundy Summer	NH	Rain Summer	Rain Winter	Oak Rings
C13.1			0.299 (0.189)	-0.556 (0.328)		0.107** (0.022)			-0.05 (0.201)
C13.2			0.182 (0.182)	-0.216 (0.322)		0.141** (0.021)			-0.113 (0.197)
C14.1			-0.071 (0.186)	-0.752* (0.328)		0.126** (0.022)			-0.094 (0.201)
C14.2			0.016 (0.182)	-0.167 (0.322)	0.688** (0.209)	0.158** (0.021)			0.101 (0.197)
C15.1			0.105 (0.186)	-0.595 (0.328)	0.535** (0.185)	0.093** (0.022)			-0.046 (0.201)
C15.2			-0.139 (0.182)	-0.507 (0.322)	0.197 (0.181)	-0.046* (0.021)			-0.101 (0.197)
C16.1			-0.039 (0.186)	-0.218 (0.328)	0.264 (0.185)	0.086** (0.022)			-0.159 (0.201)
C16.2			-0.344 (0.182)	-0.637 (0.322)	0.061 (0.181)	0.066* (0.021)			0.127 (0.197)
C17.1			-0.147 (0.185)	-0.518 (0.327)	0.32 (0.184)	0.039 (0.022)			-0.173 (0.2)
C17.2	-0.263 (0.167)	-0.893** (0.275)	-0.196 (0.183)	-0.824* (0.323)	0.581** (0.182)	0.01 (0.022)			-0.146 (0.198)
C18.1	0.243 (0.159)	-0.129 (0.262)	-0.104 (0.185)	0.039 (0.327)	0.212 (0.184)	0.043* (0.022)			-0.084 (0.2)
C18.2	0.265 (0.157)	-0.508 (0.259)	0.002 (0.183)	-0.465 (0.323)	-0.017 (0.182)	0.107** (0.022)	41.556* (18.417)	-31.193 (19.526)	-0.054 (0.198)
C19.2	-0.033 (0.159)	-0.372 (0.262)	-0.308 (0.185)	-0.535 (0.327)	-0.096 (0.184)	-0.004 (0.022)	6.711 (16.784)	-11.683 (17.642)	-0.047 (0.20)
C20.1	0.033 (0.159)	0.375 (0.262)	-0.184 (0.185)	0.249 (0.327)	0.18 (0.184)	0.142** (0.022)	-18.711 (16.784)	31.96 (17.642)	-0.084 (0.20)
C20.2	0.261 (0.157)	0.669* (0.259)	0.037 (0.183)	0.637* (0.323)	0.264 (0.182)	0.311** (0.025)	-10.453 (16.615)	40.567* (17.464)	-0.351 (0.207)
SER	0.795	1.309	0.923	1.633	0.919	0.109	83.90	88.19	1.002
R ²	0.048	0.122	0.031	0.053	0.055	0.055	0.33	0.05	0.081
0.012DW	1.88	2.04	1.82	2.06	1.83	0.96	1.90	1.98	1.34
BP	0.416	0.887	0.725	0.146	0.091	0	0.321	0.722	0.005

Regression of annual weather series on half century dummies. First half of nineteenth century is used as the reference point. BP is p -value of Breusch-Pagan heteroskedasticity test. Standard errors in parentheses.

* denotes significance at 5 per cent, ** at 1 per cent.

Fitting an ARMA (1,1) process improved the fit of the temperature series in a statistically significant but practically unimportant way. For example, for English summer temperature from 1660 to 1900, the AR and MA coefficients are 0.74 and -0.64 , both significant at 1 per cent; however the squared correlation between the fitted and actual values rises to only 0.02.

5. *Weather, Yields and Prices.*

While weather does not appear to exhibit long run trends, it did vary substantially from year to year, and we want to see how much these variations affected real wages. We first examine how harvest yields affected prices, and then look at how weather variations affected real wages.

5.1. *Harvests and prices.*

Assuming a fairly constant demand curve and a supply curve that shifts with weather and other conditions, annual combinations of price and yield can be used to trace out a demand curve.² While Davenant's famous schedule of wheat prices for seventeenth century England implies a demand elasticity in the region of 0.4 (Wrigley, 1989), the magnitude of the price elasticity of wheat demand in the nineteenth century has been the subject of some dispute; with Fogel (1992) finding an elasticity of below 0.2 with English data, and Persson (1999) estimating an elasticity of 0.6 with French and Swedish data.

Table 7 reports the results of a regression of nominal cereal prices (in shillings per bushel) on net yield ratios (both in logs) from 1270 to 1450, a period with no trend in prices. What is immediately apparent is that current wheat prices reflect not only the current harvest, but the harvest in the previous year.

<i>Table 7: Effect of yields on cereal prices, 1270–1450</i>							
	<i>Intercept</i>	<i>Yield</i>	<i>Lag Yield</i>	<i>Wheat</i>	<i>Lag Wheat</i>	<i>R²</i>	<i>DW</i>
Wheat	2.766** (0.114)	-0.799** (0.088)	-0.321** (0.052)			0.498	0.762
Rye	2.443** (0.131)	0.120 (0.100)	0.066 (0.089)	-0.843** (0.145)	-0.449** (0.088)	0.435	0.830
Barley	2.283** (0.104)	-0.155** (0.063)	-0.026 (0.069)	-0.507** (0.102)	-0.339** (0.057)	0.402	0.838
Oats	1.468** (0.109)	-0.162** (0.053)	-0.051 (0.037)	-0.367** (0.081)	-0.208** (0.046)	0.399	0.849

Regression of the price of each cereal on its own net yield ratio and the wheat net yield ratio in the current and previous years. All variables are in logs. Because of missing observations, the rye regression ends in 1377. Andrews (1991) HAC standard errors in parentheses.
* denotes significance at 5 percent, ** at 1 percent.

This points to a basic inefficiency in grain markets at this time, stemming from rigid supply. With annual wheat yields effectively independent, a poor harvest this year implied high prices on average next year, creating an incentive to expand output. That these gains to increased production were not driven to zero means that producers had a limited ability to expand supply. We shall see below that this supply rigidity disappears around the middle of the sixteenth century. Table 7 shows that a ten per cent fall in wheat yields would increase prices by 8 per cent in the current year and 3 per cent the next. This elasticity of 1.1 of price with respect to output, implies a demand elasticity of 0.9, well above nineteenth century figures. Looking at other grains, it is evident that their market is dominated by supply variations in the wheat market. While barley and oat prices show modest changes in response to their own yields, rye is not affected at all, and the main determinant of price in every case is wheat yields. This behavior is illustrated in Table 4 which shows that while correlations in

yields of different cereals were modest, correlations in their prices are in the range 0.8 to 0.9. If the wheat regression is run from 1211 to 1269 there is no significant relationship between yields and prices,³ supporting the view that early yields are badly mis-measured. If we use the regression coefficients from Table 7 to predict the prices we would expect from 1211–1269 had the yield data been true, the predicted prices are typically below recorded prices, further evidence that many early yields in Figure 1 above are over-estimated.

5.2. *Weather and Living Standards.*

While systematic data on grain yields end in the fifteenth century, we can continue to track the effect of weather on living standards using real wages in the form of Allen's wage series for building labourers in the south of England from 1301 to 1800. To eliminate the effect on real wages of long run factors such as population and technology we take first differences of the series.⁴ Table 8 shows a regression of changes in log wages on changes in estimated summer temperature and tree ring width from 1302 to 1800. We deflate the nominal series in two ways: first, using Allen's own basket of goods to give a standard real wage; and secondly using the price of wheat to give a wheat wage.

To test if the same regression relationship held between the Middle Ages and the Industrial Revolution, we apply an Andrews (1993) SupF test. This gives no evidence of a structural break in the real wage series, but indicates a break in the wheat wage regression in the 1560s, around the time of the price revolution. The relative infrequency of nominal wage changes in this period means that most of the variation in real wages comes from price changes. As Table 8 shows, wages were volatile, with a standard deviation for annual real

wages changes around 10 per cent; while for wheat wages the standard deviation falls from around 30 per cent before 1560 to around 25 per cent afterwards.

<i>Table 8: Effect of weather on living standards, 1302–1800.</i>							
	Oak	Lag Oak	Summer	Lag Summer	SER	R2	BP
Real Wage							
1302- 1800	-0.171** (.0041)	-.0112** (.0041)	.0113* (.0056)	.0127* (.0056)	.0990	.0531	.2173
Wheat Wage							
1302- 1559	-.0645** (.017)	-.0287** (.0171)	.0466** (.0219)	.084** (.022)	.02836	.1102	.3397
1560- 1800	-.0401** (.0142)	-.0116 (.0143)	.0431* (.0210)	-.0225 (.0208)	.2490	.0730	.1569
Regression of annual change in log real wage and wheat wage on current and lagged changes in oak ring thickness and estimated summer temperature. Standard errors in parentheses. * denotes significance at 5 percent, ** at 1 percent. BP is <i>p</i> -value of Breusch-Pagan heteroskedasticity test. Intercepts not reported.							

Although weather variables have a significant effect on real wages before 1800, the coefficients are small (but not negligible): a one standard deviation fall in oak ring thickness, or 1 degree Celsius rise in summer temperature increase real wages by around 1 per cent. However, for wheat wages the effects are substantial: before 1560, a one standard deviation fall in oak rings increases the wheat wage by 6 per cent in the current year, and 3 per cent in the following year; while a one degree rise in summer temperature increases it by 5 per cent in the current year and 8 per cent in the next. After 1560, similar changes cause wheat wages to rise by 3 per cent in the current year, with negligible effects the following year.

What is notable is that the previous year's weather and, by implication, harvest, cease to affect wheat wages after 1560, which is consistent with an improvement in the efficiency of the grain market. The year after a poor harvest, supply now rises sufficiently to drive gains from further expansion of planting to zero.

6. Implications.

It is nearly three decades ago since de Vries (1981: 624) claimed that historians were 'psychologically ready, even eager' to accept climate change as 'a vehicle of long-term historical explanation'. Only more recently, however, have historians and economists begun to combine historical, economic, and meteorological data in arguing for a link between secular climate change and economic trends in Europe (e.g. Steckel 2004; Koepke and Baten 2005; Campbell 2008).

The claim that shifting climate had a significant impact on economic trends in pre-contemporary Europe faces two hurdles. We have been concerned mainly with the first; establishing whether there was significant climate change. That such a change took place is widely accepted,⁵ but we find differently. Our claim that annual weather was effectively a random draw from a distribution that remained fixed between the Black Death and the early twentieth century is necessarily based in part on proxy meteorological measures. Our confidence in these data is boosted, however, by their ability to help account for the variations in medieval English crop yields, early modern real wages, and post-1660 instrument-derived meteorological data. Our findings are supported by research on the lengths of European glaciers prior to global warming from c. 1900. Data on the lengths of three Alpine glaciers, extending back to the sixteenth and seventeenth centuries, also imply climatic stasis before the late nineteenth century (see Figure 3).⁶

None of this rules out the likelihood of extreme weather events or short-term climatic anomalies such as those analyzed by Baillie (1999) and Campbell (2009). That runs of bad years such as those in the 1310s, the 1590s, or the 1690s caused severe hardship and dislocation in the short run is indisputable. Nor does it rule out the possibility that a medieval warm era (MWE) preceded the centuries of secular stationarity (in the statistical sense) described above. However, meteorologists have so far been unable to define such a MWE with any precision (Bradley, Hughes, and Diaz 2003).

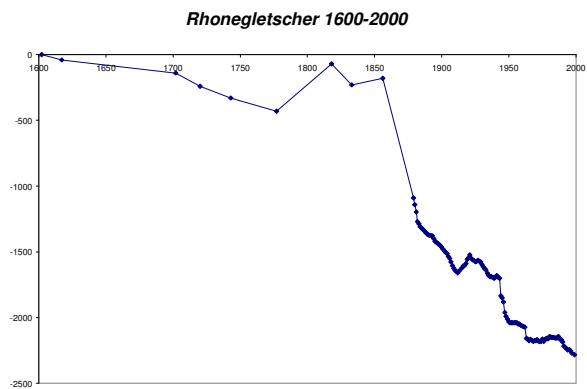
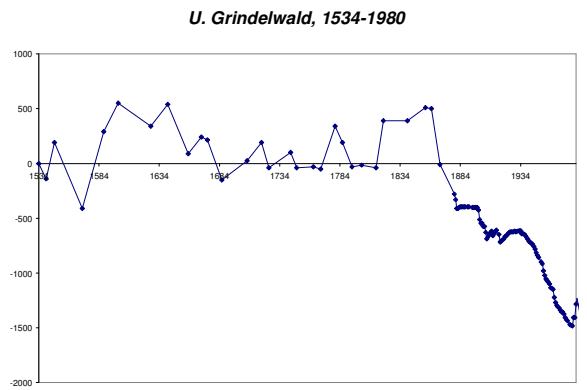
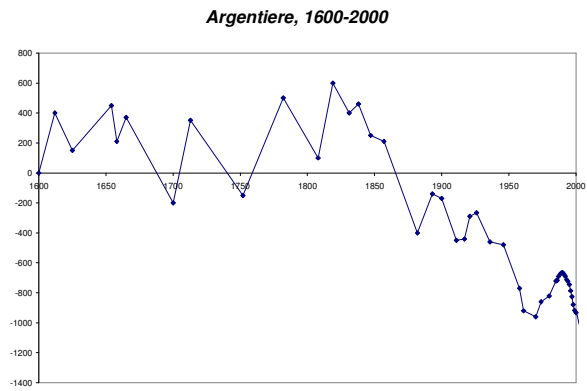
The second hurdle is to find a link between changes in climate and economic conditions. Steckel (2004) has linked the discovery of a downward trend in average adult heights to a cooling trend that 'caused havoc' in northern Europe for several centuries, while Komlos (2003: 181) attributes his finding of a 'very large' increase in French heights in the early eighteenth century to 'a very substantial rise in temperatures'. Fagan (2000) claims that deteriorating climate compromised the cultivation of wheat, always a 'tricky' crop in cooler climates, and reduced the growing season in England by about three weeks by 1500 and by 'as much as five' by the seventeenth century.

The connection between worsening climate and worsening economic conditions still lacks firm empirical support, however. Indeed, several pointers argue against it. First, a period of falling temperatures should have had most impact on the populations of marginal areas such as the Nordic countries and Switzerland – as often claimed for Greenland. Yet demographic trends imply that those 'marginal' regions gained relative to Europe as a whole. Thus, the combined populations of the four Nordic countries probably more than doubled between 1500 and 1820, while that of Europe rose by less than half. Over the same period, the population of Switzerland rose about 150 per cent, its share of the European total increasing from 1.2 per cent in 1500 to 1.4 per cent in 1600, and 1.7 per cent in 1700.⁷

Recent evidence from England also implies that the economic impact of any Little Ice Age was modest at most. Deteriorating climate should have left its mark on crop mixes and crop yields in marginal regions. Tillage should have retreated at the expense of pasture and wheat at the expense of sturdier cereal crops. Ongoing research on output and productivity trends in early modern English agriculture, however, implies that wheat's share in the total cereal acreage held its own between 1350 and 1700, as did wheat yields relative to those of oats and barley over the same period (Apostolides *et al.* 2008). Moreover, Fagan's claim that cooler temperatures led to a shrinking growing season does not sit comfortably with the finding by Apostolides *et al.* (2008) of evidence for an increase of over half in the number of days worked per household in English agriculture between 1450 and 1600 (2008). Across the English Channel, de Vries and van der Woude (1997: 21) note the severity of Dutch climate in the early modern era, but declare its long-run consequences on agriculture to have been 'marginal in character'. Finally, the modest increases in total factor productivity reported by Allen (1999) for England and Hoffman (1997) for France during the 'Little Ice Age' are more consistent with an unvarying climate stasis than with deterioration.

None of this contradicts Le Roy Ladurie's once provocative, if now old-fashioned view that 'in the long term the human consequences of climate seem to be slight, perhaps negligible, and certainly difficult to detect' (Le Roy Ladurie 1971: 119).

Figure 3. Glacier Lengths, 1500-2000



Appendix: Data Sources and Estimation

- Monthly mean Central England temperature from 1659 are from <http://hadobs.metoffice.com/> and the monthly England and Wales precipitation series from 1766 are from [http://www.metoffice.gov.uk/research/hadleycentre/CRdata/Monthly/HadEWP act](http://www.metoffice.gov.uk/research/hadleycentre/CRdata/Monthly/HadEWP.act).
- The Low Countries temperature series of Van Engelen, Buisman and IJnsen (2001) are available at <http://www.climateaudit.org/data/documentary/vanengeln.txt>.
- Spring-Summer temperatures in Burgundy, expressed as the deviation from the 1960–1989 Dijon average from Chuine *et al.* (2004) are available at http://gcmd.nasa.gov/records/GCMD_NOAA_NCDC_PALEO_2005-007.html
- The Mann, Bradley and Hughes (1999) Northern Hemisphere temperature reconstruction, expressed as the deviation from the 1902–1980 average is available at http://www.ncdc.noaa.gov/paleo/pubs/mann_99.html.
- Average English oak ring widths were provided by Professor Michael Baillie, Palaeoecology Centre, The Queen’s University of Belfast.
- Crop yield data are from Campbell (2007): <http://www.cropyields.ac.uk>.
- Wage and price data are taken from Robert Allen’s database of prices And wages in London and Southern England, 1259–1914 (<http://www.nuff.ox.ac.uk/users/allen/>).
- Estimation was carried out using the *R* package. Panel regressions were estimated using the *lme4* module, vector autoregressions using the *vars* module,

coefficient stability using the *strucchange* module, and sensitivity to outliers using the *forward* module.

□

□

References □

Allen, R.C. 1999. 'Tracking the agricultural revolution in England'. *Economic History Review*. 52: 309-25.

Andrews, Donald W. K. 1991. "Heteroskedasticity and Autocorrelation Consistent Covariance Matrix Estimation." *Econometrica* 59: 817-858.

Andrews, Donald W. K. 1993. "Tests for Parametric Instability and Structural Change with Unknown Change Point." *Econometrica* 61: 821-856.

Apostolides, A., S. Broadberry, B. Campbell, M. Overton, and B. van Leeuwen. 2008. 'English Gross Domestic Product: some preliminary estimates', available at:
<http://www2.warwick.ac.uk/fac/soc/economics/staff/faculty/broadberry/wp/pre1700v2.pdf>

Appleby, Andrew B. 1979. "Grain Prices and Subsistence Crises in England and France, 1590-1740." *Journal of Economic History* 39: 865-887.

Baillie, Mike. 1999. *Exodus to Arthur: Catastrophic Encounters with Comets*. London: Batsford.

Bradley, R.S., M.K. Hughes, and H.F. Diaz. 2003. 'Climate in medieval time'. *Science*. Vol. 302, 17 October.

- Campbell, B. M. S. 2007. *Three Centuries of English Crops Yields, 1211–1491*.
WWW Document. URL <http://www.cropyields.ac.uk>.
- Campbell, B.M.S. 2009. 'Nature as historical protagonist', *Economic History Review*, forthcoming.
- Chuine, Isabelle, Isabelle Yiou, Nicolas Viovy, Bernard Seguin, Valerie Daux and Emmanuel Le Roy Ladurie. 2004. 'Grape ripening as a past climate indicator'. *Nature* 432(289–290).
- Clark, Gregory. 2004. "The Price History of English Agriculture, 1209–1914." *Research in Economic History* 22:41–123.
- Cowie, Jonathan (2007). *Climate change: biological and human aspects*. Cambridge University Press.
- Dawson, A. G., K. Hickey, P. A. Mayewski and A. Nesje. 2007. "Greenland (GISP2) Ice Core and Historical Indicators of Complex North Atlantic Climate Changes during the Fourteenth Century." *The Holocene* 17:427–434.
- de Vries, Jan. 1980. "Measuring the impact of climate on history: the search for appropriate methodologies." *Journal of Interdisciplinary History*, 10(4): 599–630.
- de Vries, Jan and Ad van der Woude. 1997. *The First Modern Economy*. Cambridge: Cambridge University Press.

- Dyer, Christopher. 1988. 'Changes in Diet in the Late Middle Ages: The Case of Harvest Workers'. *Agricultural History Review* 36:21-38.
- Fagan, Brian M. 2000. *The Little Ice Age: How Climate Made History, 1300-1850*. New York: Basic Books.
- Fogel, Robert W. 1992. "Second Thoughts on the European Escape from Hunger: Famines, Chronic Malnutrition, and Mortality Rates." In *Nutrition and Poverty*, ed. S. R. Osmani. Oxford: Clarendon Press.
- Hoffman, Philip. 1997. *Growth in a Traditional Society: The French Countryside 1450-1815*. Princeton: Princeton University Press.
- Kelly, M. and C. Ó Gráda. 2009. 'The Poor Law versus the Positive Check: Living Standards and Mortality in England since the Middle Ages.' Working Paper.
- Koepke, Nikola & Baten, Joerg, 2005. 'The biological standard of living in Europe during the last two millennia'. *European Review of Economic History*. 9(1): 61-95.
- Komlos, John, 2003. "An anthropometric history of early modern France." *European Review of Economic History*, 7(02): 159-189.
- Lamb, H. H. 1965. "The early medieval warm epoch and its sequel." *Palaeogeography, Palaeoclimatology, Palaeoecology* 1: 13-37.
- Lamb, H.H. 1995. *Climate History and the Modern World*. 2nd ed. London: Routledge.

- Le Roy Ladurie, Emmanuel. 1971. *Times of Feast, Times of Famine*. London: Allen & Unwin.
- Maddison, Angus. 2009. *Statistics on World Population, GDP and Per Capita GDP, 1-2006 AD*, available at <http://www.ggdc.net/maddison/>.
- Mann, Michael E. and Philip D. Jones. 2003. "Global Surface Temperatures over the Past Two Millennia." *Geophysical Research Letters* 30:1820.
- Mann, Michael E., Raymond S. Bradley and Malcolm K. Hughes. 1999. "Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations." *Geophysics Review Letters*. 26: 759-762.
- Mann, Michael E. 2002. "Little Ice Age." In M.C. McCracken and J.S. Perry, eds. *Encyclopedia of Global Environmental Change*. Chichester: Wiley.
- Mattmueller, Markus. 1987. *Bevolkerungsgeschichte der Schweiz. Teil 1: die fruhe Neuzeit, 1500-1700*. 2 vols. Helbing und Lichtenhahn: Basel.
- Mitchell, B. R. 1988. *British Historical Statistics*. Cambridge: Cambridge University Press.
- Persson, Karl Gunnar. 1999. *Grain Markets in Europe, 1500-1900: Integration and Deregulation*. Cambridge: Cambridge University Press.
- Pinheiro, Jose C. and Douglas M. Bates. 2000. *Mixed Effects Models in S and S-PLUS*. New York: Springer.

Steckel, R. 2004. "New Light on the "Dark Ages": The Remarkably Tall Stature of Northern European Men during the Medieval Era." *Social Science History*. 28:2: 211-29.

Tainter, Joseph. 1992. *The Collapse of Complex Societies*. Cambridge: Cambridge University Press.

Utterström, Gustav. 1955. "Climatic Fluctuations and Population Problems in Early Modern History." *Scandinavian Economic History Review* 3:3-47.

Van Engelen, A.F.V., J. Buisman and F IJnsen. 2001. "A Millennium of Weather, Winds and Water in the Low Countries." In *History and Climate: Memories of the future?*, eds. P. D. Jones, A. E. J. Ogilvie, T. D. Davies and K. R. Briffa. Boston: Kluwer Academic. Also available at: http://www.knmi.nl/kd/daggegevens/antieke_wrn/millennium_of_weather.pdf.

Weiss, H. and R.S. Bradley 2001. "What drives societal collapse?" *Science*, 291: 609-610.

Wrigley, E. A. 1989. "Some Reflections on Corn Yields and Prices in Pre-Industrial Economies." In *Famine, Disease and the Social Order in Early Modern Society*, ed. John Walter and Roger Schofield. Cambridge: Cambridge University Press.

ENDNOTES

¹ For useful surveys of theories that invoke climate to explain the collapse of historical societies see Tainter (1992: 44–50); Weiss and Bradley (2001); Cowie (2007).

² However, because a poor harvest would lower demand for labour at harvest time and therefore income, falls in yields would cause the demand curve to shift in somewhat, leading combinations of prices and quantities to overestimate the steepness of the demand curve. However, to the extent that wheat in this period was consumed by fairly affluent individuals who were not reliant on harvest work as a source of income, this effect may not be important.

³ We use Clark's (2004) prices: the correlation between these and Allen's price series from 1270 to 1450 is 0.95 although Clark's series appear to correspond to one year after they are labelled: his 1271 price matches Allen's 1270 price, etc.

⁴ Non-stationarity is not a problem in differencing these series: the Phillips-Perron Z-alpha statistic (which has a 5% critical value of -14.1) for the wheat wage is -53; and for the real wage is -13.8 which falls to -15.8 if the last decade is omitted.

⁵ Previous scholars have written of 'climatic conditions deteriorat[ing] considerably' (Komlos 2003), of a 'general cooling period of 500–600 years' (Steckel 2004), and even of European summers which by 1500 were 'about seven degrees Celsius cooler' than during the Medieval Warm Epoch (Fagan 2000).

⁶ We are grateful for Johannes Oerlemans and Paul Leclerq for the data described in Figure 3. See also Oerlemans 2001.

⁷ It is readily admitted that reliable demographic data are lacking for before the seventeenth or eighteenth centuries. Our Nordic population data taken from Maddison, and the Swiss demographic data from Mattmueller (1987: 1: 365).