

Summer precipitation for the England and Wales region, 1201–2000 CE, from stable oxygen isotopes in oak tree rings

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ABSTRACT: Oxygen isotope ratios from oak tree rings are used to extend the May–August precipitation totals of the England and Wales precipitation series back to 1201 CE. The agreement between instrumental and reconstructed values is unusually strong, with more than half of the variance explained and standard verification tests passed. The stability of this relationship is confirmed using split-period calibration and verification. This allows the reconstruction to be variance-scaled to the full length of the instrumental series back to 1766. Direct comparison with historical reports of very wet and dry summers show good agreement. Near-constant replication, with a minimum of 10 timbers sourced from historic buildings across central southern England ensures signal strength does not change over time. Summers during the late 20th century appear anomalously dry and those of the 21st century very close to the pre-20th century average with no evidence in the record of prolonged ‘megadroughts’ across England and Wales. © 2020 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: dendrochronology; Holocene; hydroclimate; palaeoclimate; *Quercus*

Introduction

In a warming world, changes in regional precipitation patterns are likely to have a larger direct impact on the environment and society than changes in temperature. Placing recent changes in hydroclimate within a long-term context requires high quality reconstructions based on proxy evidence, but these are difficult to produce, particularly for relatively moist, climatically temperate mid-latitude regions (PAGES hydro2k Consortium, 2017). Recent attempts to reconstruct UK rainfall using oak ring-width data (Wilson *et al.* 2013; Cooper *et al.* 2013), for example, produce reconstructions with statistical properties that do not resemble regional precipitation (Bothe *et al.* 2019). Pilot studies using tree ring stable oxygen isotope ratios have produced more promising results, but were based on limited sample replication (Rinne *et al.* 2013) or used samples drawn from across a very wide area (Young *et al.* 2015). However, Loader *et al.* (2019) have recently produced an 800-year oak oxygen isotope chronology, primarily for the purpose of dating timber structures (McCarroll *et al.* 2019; Loader *et al.* 2020), that is well- and evenly replicated and comprises samples drawn consistently from across the same region of central southern England, centred on Oxfordshire (Fig. 2 of Loader *et al.* 2019). Here we compare that chronology with regional instrumental precipitation series and use it to extend the England and Wales precipitation (EWP) series (Wigley *et al.* 1984; Wigley and Jones, 1987; Alexander and Jones 2000; Simpson and Jones 2014) back to 1201 CE.

Material and methods

The construction of the 800-year oxygen isotope chronology is described in detail elsewhere (Loader *et al.* 2019). Briefly, it is mainly the average of two independent annually resolved chronologies, each comprising the latewood alpha-cellulose of five independently dated tree rings from different trees or historic timbers drawn from across the same region of south central England. Where there were insufficient samples available at the time the pools were constructed, individual timber samples have been added to maintain near-constant (10 or 11-tree) sample replication throughout. The samples used for each year are identified in the supplementary information (Tables S1 and S2).

We compare the isotope chronology with regional rainfall data obtained from the UK Meteorological Office (Alexander and Jones, 2011) using standard split-period calibration and verification tests, including reduction of error, coefficient of efficiency and a test for the capture of extremes (McCarroll *et al.* 2015). We also use running 51-year windows to compare the statistical properties of the reconstruction with the instrumental series (Bothe *et al.* 2019). The final reconstruction of May to August precipitation is produced by variance scaling against the full EWP series (1766–2000 CE). Scaling over alternative periods, avoiding the early instrumental data or recent climatic change, makes very little difference (Table S3).

Calibration and verification

The oxygen isotope chronology was compared with rainfall totals for individual months and combinations of consecutive months (Table 1) for each of the five rainfall regions of England and Wales defined by Wigley *et al.* (1984). No

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Table 1. Strength of correlation (Pearson's correlation coefficient) between the isotope series and the five rainfall regions of England, and the England and Wales precipitation series (EWP), for individual months and their combinations. The start year for the period of comparison is provided

	Start	MAY	JUN	JUL	AUG	JUN-JUL	JUN-AUG	MAY-JUL	JUN-AUG	MAY-AUG
NWEB	1873	-0.14	-0.24	-0.46	-0.34	0.00	-0.52	-0.53	-0.56	-0.59
NEEP	1873	-0.20	-0.22	-0.46	-0.38	-0.50	-0.58	-0.56	-0.59	-0.63
SWEP	1873	-0.19	-0.36	-0.46	-0.38	-0.56	-0.56	-0.60	-0.62	-0.65
SEEP	1873	-0.18	-0.35	-0.47	-0.42	-0.55	-0.59	-0.60	-0.63	-0.66
CEP	1873	-0.25	-0.34	-0.51	-0.47	-0.59	-0.67	-0.66	-0.68	-0.73
EWP	1873	-0.22	-0.35	-0.52	-0.45	-0.61	-0.65	-0.67	-0.68	-0.73
EWP	1820	-0.20	-0.40	-0.50	-0.43	-0.61	-0.63	-0.67	-0.67	-0.72
EWP	1766	-0.23	-0.39	-0.51	-0.38	-0.62	-0.61	-0.67	-0.67	-0.72

Note: The five rainfall regions of England are Northeast (NEEP), Southwest (SWEP), Southeast (SEEP) and Central (CEP).

Table 2. Split-period verification test results, including reduction of error (RE) and coefficient of efficiency (CE). All dates are CE.

Calibration	R ²	Verification	R ²	RE	CE
2000–1883	0.50	1882–1766	0.50	0.56	0.50
1882–1766	0.50	2000–1883	0.50	0.57	0.50
2000–1910	0.52	1909–1820	0.52	0.50	0.47
1909–1820	0.52	2000–1910	0.52	0.51	0.48
2000–1937	0.50	1936–1873	0.54	0.57	0.54
1936–1873	0.54	2000–1937	0.50	0.53	0.49
2000–1820	0.54	1819–1766	0.53	0.54	0.49

strong correlations were found with any months beyond May to August or for any months or combinations of months for the year preceding tree ring formation. For all regions the strongest correlation is obtained when the total rainfall of

May to August is used, with July always the strongest single month. The strongest correlations are with the central England region, but all regions give strongly significant correlations with May to August. The correlation with the EWP series, which combines data from all five regions, is as strong as that with the central England division, when measured over the same period (1873–2000 CE). The EWP series extends to 1766 CE, though the number of stations, and therefore the standard error, improves after 1820 CE (Murphy *et al.* 2019). Extending the calibration back to 1820 CE hardly changes the strength of the correlations and they remain stable even when the calibration is extended back to 1766 CE (Table 1). Using the full length of the EWP series, May to August precipitation explains more than 50% of the variance in the oxygen isotope chronology ($R^2 = 0.52$, $n = 235$). Spatial field correlations confirm a strong match with the precipitation of the EWP region (Fig. S2).

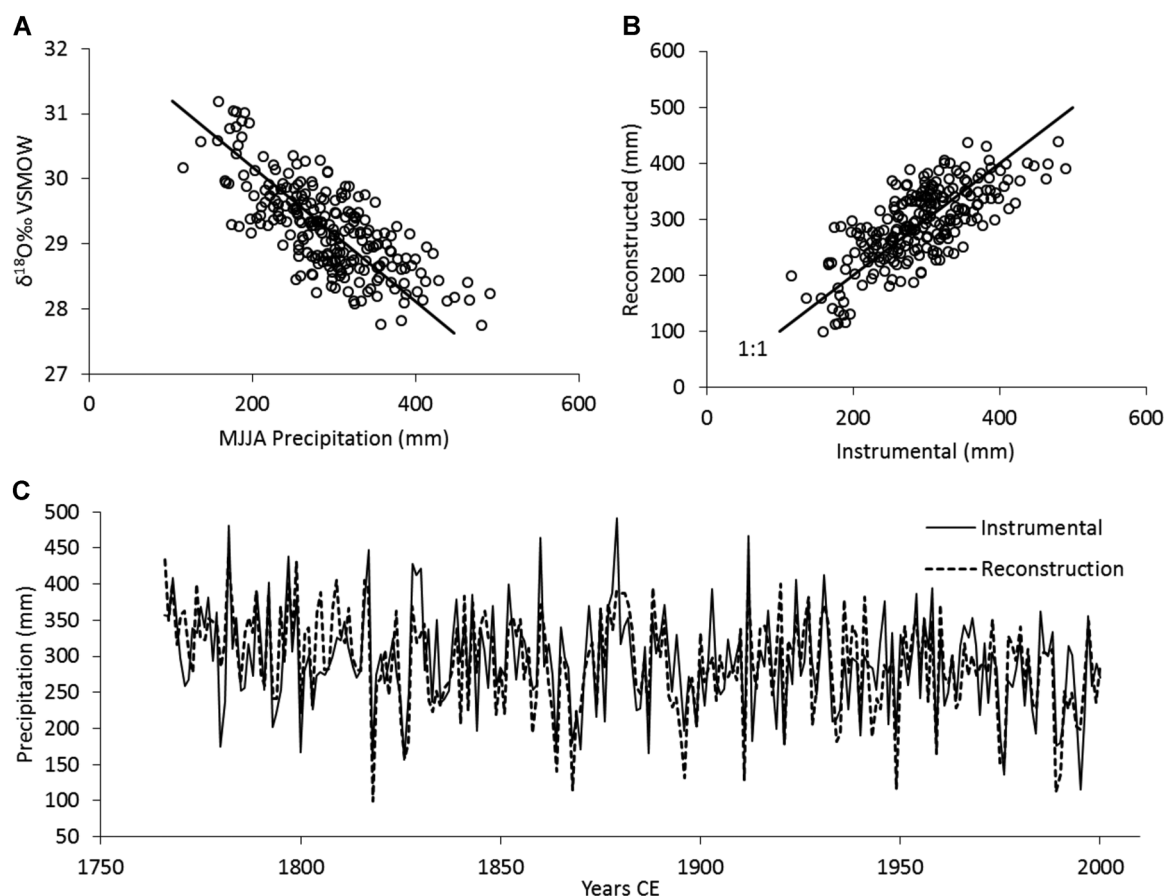


Figure 1. Reduced major axis regression of stable oxygen isotope ratios against measured May–August (MJJA) precipitation sum for England and Wales (A) and the resultant variance-scaled reconstruction for the calibration period (B and C).

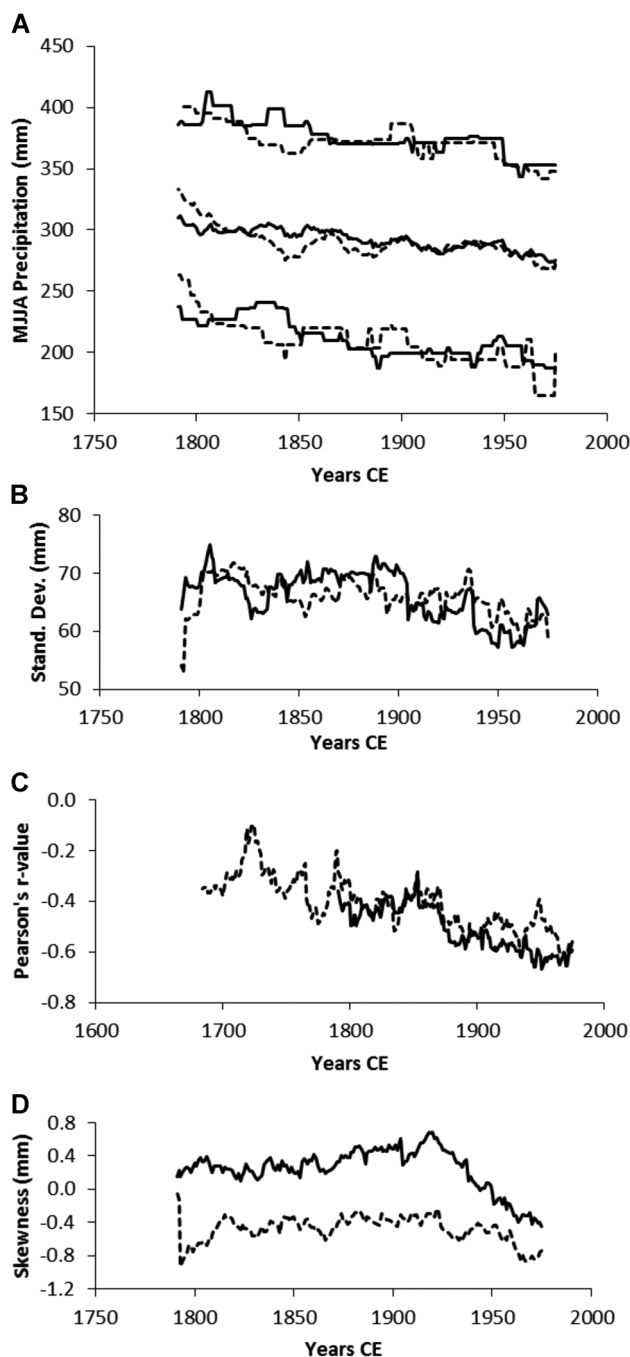


Figure 2. Comparison of the statistical properties of moving (centred) 51-year windows for the instrumental and reconstructed series (May–August (MJJA) precipitation). A: mean, 90th and 10th percentiles, B: standard deviation (mm), C: Pearson's correlation with central England temperature (MJJA, 1766–2000 CE and 1659–2000 CE, respectively), D: skewness (mm). Solid lines are instrumental data, dashed lines are proxy reconstructions.

Split-period verification tests (Table 2) applied over the full length of the EWP record, for May to August precipitation, produce very strong and consistent results that are weakened slightly by truncating the record at 1820 CE and not substantially improved by truncating at 1873 CE. Murphy *et al.* (2019) have argued that the early part of the EWP series, before 1820 CE, may overestimate summer rainfall, but our reconstruction does not strongly diverge from the instrumental data before 1820 CE and if calibration is based on the period after 1820 CE the verification statistics for the earlier period remain excellent (Table 2). We conclude from the stability and strength of the calibration and verification statistics that the full

EWP record is a suitable target upon which to base a hydroclimate reconstruction.

The isotope series can be converted into a precipitation reconstruction using simple linear (least squares) regression where the isotope data are treated as the independent variable, but this inevitably results in a reconstruction that has less variance than the instrumental data, and which is thus strongly biased towards the mean (McCarroll *et al.* 2015). Where the intention is to use proxy data to extend the range of an instrumental series, as in this case, a more useful approach is to scale the proxy data so that they have the same mean and variance as the target data over the full range of overlap. This approach, which is equivalent to reduced major axis regression, produces a reconstruction that is not biased towards the mean, and which is capable of expressing the full range of past climate (Fig. 1). The cost, in terms of increased error, is a function of the strength of correlation between proxy and target, with an unbiased scaled reconstruction explaining about 44% of the variance, as opposed to about 52% for a biased reconstruction based on regression.

The ability of a reconstruction to capture the correct 10% of extreme years can be tested using the extreme-value capture test (McCarroll *et al.* 2015; Wise and Dannenberg, 2019), based on the binomial distribution. In this case the reconstruction captures 10 of the 23 wet extremes and 13 of the dry extremes. The probability of capturing at least 10 of 23 extremes, where the chance probability is 10% ($p = 0.1$), is much less than one in a thousand. By contrast, a reconstruction based on regression would capture only two of the wet extremes. The variance-scaled reconstruction is thus good at capturing both wet and dry extreme years, but there is some asymmetry in performance, with the best results obtained for dry years (Fig. 1B).

By comparing the properties of moving 51-year windows, after conversion into Standardised Precipitation Indices (SPI), Bothe *et al.* (2019) demonstrated that previous reconstructions of UK precipitation have statistical properties inconsistent with instrumental measurements. Conversion into SPI units involves fitting a distribution function to each window and allows measurements and reconstructions with different mean and/or variance to be compared. In this case it is unnecessary because variance scaling ensures that the measured and reconstructed values are directly comparable. In contrast to earlier UK precipitation reconstructions, when compared with the instrumental series, the scaled reconstruction does not show strong divergence in the mean, the 90th and 10th percentiles (Fig. 2A), or in standard deviations (Fig. 2B). The 51-year moving correlation between May to August precipitation and the measured central England temperatures for the same window is consistently negative and increases in strength over time. The same pattern is seen in the reconstruction (Fig. 2C). The only clear difference between the statistical properties of the measured and reconstructed series is in skewness, with 51-year windows showing opposite signs for most of the record (Fig. 2D). The skewness values for the full calibration period also differ in sign (0.18 and -0.41). This difference is related to the asymmetry with which the magnitudes of extremely wet and dry years are captured and is discussed later. The full reconstruction, 1201–2000 CE is presented in Fig. 3.

Discussion and conclusions

The unusually strong calibration and verification results suggest that stable oxygen isotope ratios from the latewood

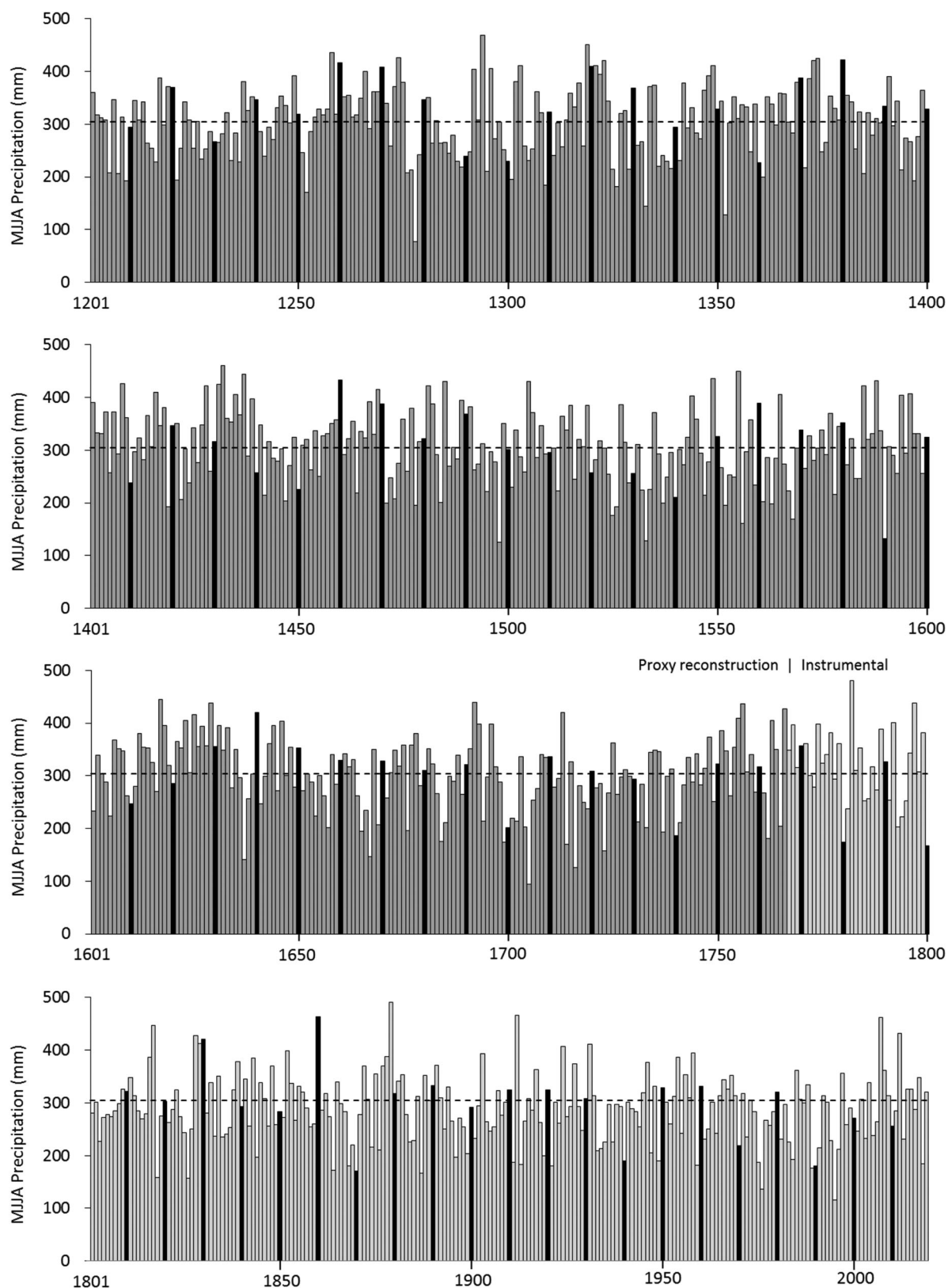


Figure 3. May–August precipitation sums for England and Wales, 1201–2000 CE. The period 1766 to 2000 is the England and Wales precipitation series; before 1766 the values are reconstructed using stable oxygen isotope ratios from oak tree rings. The dashed line is the pre-20th century average. Final years of decades are marked in black. An alternative version of this figure, using only the reconstruction, is included in the supplementary information (Fig. S1).

alpha-cellulose of UK oak trees provide an excellent proxy for May to August precipitation. Rainfall amount does not directly control the variation in isotope ratios; the signal arises principally because the rain that falls during wet and dry summers carries a different isotopic signal (Saurer *et al.* 1997;

Robertson *et al.* 2001; Darling and Talbot, 2003; Barbour, 2007; Treydte *et al.* 2014) and that signal is incorporated into the trees irrespective of whether they are growing under any environmental stress (Young *et al.* 2015). By using only the alpha-cellulose of the latewood that is formed in summer

(McCarroll *et al.* 2017), the signal is constrained to the late spring and summer of the year in which the tree ring is formed (Table 1). Since there is no evidence of age-related trends in the isotope data (Duffy *et al.* 2017, 2019), there is no need for statistical de-trending, thereby avoiding the potential loss of low-frequency climate signals (Cook *et al.* 1995). The result is a reconstruction that agrees very well with the full EWP series and which has statistical properties that are consistent with instrumental measurements (Fig. 2).

The largest difference between the instrumental measurements and the reconstruction is an apparent reduction in the skill with which the reconstruction captures the full magnitude of rainfall during the wettest summers (>400 mm). A likely explanation for this is that the isotope chronology is based only on timbers from central southern England rather than extending into the wetter areas of western England and Wales.

The reconstruction is particularly unusual in that the replication is near constant throughout. Assigning clearly defined uncertainty is difficult because of the pooling approach and asymmetry in capturing the magnitude of extreme years, but there is no reason to assume a decline in signal strength prior to the calibration period. The EWP series begins in 1766 CE but earlier documentary evidence provides additional verification. Almost all droughts and dry summers identified by Stone (2014) and Pribyl and Cornes (2019) appear in the reconstruction with below-average rainfall, in particular those identified as extremely dry, including 1252, 1325–1326, 1333, 1473, 1540 and 1684–1685 CE. For agrarian societies, runs of wet summers, leading to consecutive harvest failures, could be catastrophic (Campbell, 2010). Most notable is the period between 1314 and 1325 CE which corresponds with the ‘agrarian crisis’ that ravaged the population of Europe (Kershaw 1973; Pribyl 2017). The 1430s are also exceptionally wet in the reconstruction, which corresponds with the most severe famine of the 15th century (Camenisch *et al.* 2016; Pribyl 2017). The early part of the 17th century, during the Little Ice Age also appears to have been a time of very wet summers. In contrast, the summers of the late 20th century appear to have been unusually dry when placed in a long-term context, and are perhaps not the best choice of reference period against which to compare recent years (Kendon *et al.* 2019). Although the summers of the 21st century have been described as unusually wet (de Leeuw *et al.* 2016), the average May to August precipitation over that period (303 mm) is almost identical to the reconstructed average before the 20th century (304 mm). It is the late 20th century that is anomalous, with the last 40 years representing the driest such period across the full record. We see no evidence for long megadroughts (Cook *et al.* 2015) in our reconstruction of EWP prior to the period of instrumental observations.

Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Figure S1. May to August (MJJA) precipitation sums for England and Wales, 1201–2000CE, reconstructed using stable oxygen isotope ratios from oak tree rings. The dashed line is the pre-20th century average. Final years of decades are marked in black.

Figure S2. Spatial field correlation of reconstructed MJJA precipitation and CRU TS4.03 May to August precipitation 1901 to 2000 ($p < 1\%$).

Figure S3. Spatial field correlations with the gridded mean temperature of July and August (HadCRUT4.6 SST/T2m anom

1850:2000 $p < 1\%$). Upper: Oxygen isotope chronology, Lower: EWP totals for May to August.

Table S1. Tree and timber samples used in constructing the oxygen isotope chronology.

Table S2. Samples included in each year of the oxygen isotope chronology used to reconstruct England and Wales precipitation. Samples included in Pools one and two in green and blue respectively and samples measured individually in grey. Source and location of each sample is listed in Table S1.

Table S3. Properties of variance-scaled reconstructions based on different calibration periods, excluding both early instrumental data and the recent period of rapid anthropogenic climate change.

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Data availability statement

We are required to archive all of the data in the NERC repository under a non-commercial licence (<https://doi.org/10.5284/1078324>).

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