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A tree-ring reconstruction of East Anglian (UK) hydroclimate variability over the last millennium

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Abstract We present an annually resolved reconstruction of spring-summer precipitation variability in East Anglia, UK (52–53°N, 0–2°E) for the period AD 900–2009. A continuous regional network of 723 living (AD 1590–2009) and historical (AD 781–1790) oak (*Quercus* sp.) ring-width series has been constructed and shown to display significant sensitivity to precipitation variability during the March-July season. The existence of a coherent common growth signal is demonstrated in oaks growing across East Anglia, containing evidence of near-decadal aperiodic variability in precipitation throughout the last millennium. Positive correlations are established between oak growth and precipitation variability across a large region of northwest Europe, although climate-growth relationships appear time transgressive with correlations significantly weakening during the early twentieth century. Examination of the relationship between oak growth, precipitation, and the North Atlantic Oscillation (NAO), reveals no evidence that the NAO plays any significant role in the control of precipitation or tree growth in this region. Using Regional Curve Standardisation to preserve evidence of low-frequency growth variability in the East Anglian oak chronology, we produce a millennial length reconstruction that is capable of explaining 32–35% of annual-to-decadal regional-scale precipitation variance during 1901–2009. The full length reconstruction indicates statistically significant anomalous dry conditions during AD 900–1100 and circa-1800. An apparent prolonged wetter phase is estimated for the twelfth and thirteen centuries, whilst precipitation fluctuates between wetter and drier phases at near centennial timescales throughout the fourteenth to seventeenth centuries. Above average precipitation reconstructed for the twenty-first century is comparable with that reproduced for the 1600s. The main estimated wet and dry phases reconstructed here appear largely coherent with an independent tree-ring reconstruction for southern-central England.

Keywords East Anglia · Oak · Tree-rings · Precipitation · Millennial reconstruction

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1 Introduction

In its fourth assessment report (AR4), the Intergovernmental Panel on Climate Change (IPCC) reaffirmed previous model projections in predicting trends towards increased hydroclimate variability in the mid-latitude northern hemisphere over the course of the twenty-first century (IPCC 2007). Rising mean annual air temperatures of 1.5–3.5°C (SRES B1-A2), increased evapotranspiration, and reduced summer precipitation (>20%), will likely

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combine to increase the frequency of intense short-term (3–6 month) summer desiccation in southern and eastern England over the next 100 years, with likely detrimental consequences for agricultural output (Parry et al. 2004). Projected increases in winter precipitation of 10–20% by 2090–2099 (SRES A1B) will likely reduce the intensity of longer term (>6 months) hydrological drought due to enhanced winter recharge (Blenkinsop and Fowler 2007), although the frequency and severity of extreme meteorological events will very likely increase in all seasons over forthcoming decades (IPCC 2007).

The impacts of extreme hydrological and meteorological events may already be being felt across Europe when one considers the European-wide drought of 2003 (Fink et al. 2004) and severe central-European flooding in 2002 and 2005 (Kundzewicz et al. 2005; Jaun et al. 2008; Gaume et al. 2009). Whilst the social and economic impacts of adapting to potentially damaging hydroclimatic changes may prove costly for future governments and societies to tackle (Stern 2006), it is important to view these projections within a longer-term historical context in order to enhance our understanding of their relative significance within the 'natural' climate system. In recent decades a considerable volume of published literature has done just that. Long instrumental records (Lamb 1965; Wigley and Atkinson 1977; van der Schrier et al. 2006, 2007; Briffa et al. 2009), multiple proxy series (Proctor et al. 2000, 2002; Linderholm and Chen 2005; Masson-Delmotte et al. 2005; Touchan et al. 2005; Wilson et al. 2005, 2012; Helama et al. 2009; Büntgen et al. 2010), and combinations of the two (Casty et al. 2005; Pauling et al. 2006), have been developed to produce multi-centennial precipitation reconstructions for Europe and North America (Cook et al. 2004, 2010) stretching back over the past millennium, including a notably long 2,500-year dendroclimatic summer precipitation reconstruction for central Europe (Büntgen et al. 2011).

However, there has until now been no study of long-term, high-resolution hydroclimate variability within southern and eastern England, this despite the relative abundance of historical tree-ring material available in the form of historical building timbers. Previous short timescale dendroclimatic studies in the United Kingdom (Hughes et al. 1978; Pilcher and Baillie 1980; Pilcher and Gray 1982; Briffa 1984; García-Suárez et al. 2009) demonstrated, with varying degrees of success, the potential usefulness of oak ring-widths as a source of high-resolution hydroclimate information, despite the temperate maritime climate where tree growth might be expected to exhibit complacent (i.e. low variability) growth behaviour (Pilcher and Gray 1982). Hence, there remains untapped potential to utilise the pool of living and historical, centuries old oak ring-width material to reconstruct a continuous, annually resolved history of precipitation variability within the UK over the past 1,000-years. This paper addresses this potential by focusing on spring and summer (March–July) precipitation in East Anglia, whilst a companion paper (Wilson et al. 2012) has derived a similar, but independent, oak ring-width based precipitation reconstruction for southern-central England. These two papers represent the first steps towards a longer term goal of producing independent and spatially distinct millennial timescale hydroclimate reconstructions for each of five England and Wales precipitation regions first identified by Wigley et al. (1984a).

2 Data and methods

2.1 Sample collection

The geographical focus for this study is East Anglia (52–53°N, 0–2°E)—a well-defined region of eastern England comprised of the counties Norfolk, Suffolk, and Cambridgeshire (Fig. 1 and supplementary material Table SM1). This area was chosen because of its potential for yielding large volumes of historical building timbers, and because the entire area falls neatly within the central England coherent precipitation region (Wigley et al. 1984a; Alexander and Jones 2001) where relatively spatially homogeneous precipitation is expected across all sites. A total of 310 increment cores were taken from trees spread across nine locations to construct a modern 'living-tree' section of the chronology with sample replication spatially weighted on Norfolk. All sampling locations are at elevations between 10 and 90 m above sea level at sites experiencing a temperate maritime climate, with a range of soils present, from seasonally wet, base-rich, clay to free-draining, acidic, sandy loam (Table SM2). A single core was taken at breast height from each mature oak (>50 years old) using a 4 mm diameter increment corer. The cores were mounted, sanded, and the ring-widths measured and cross-dated using standard dendroclimatic techniques (Pilcher and Baillie 1980) to produce a 419-year long oak chronology for AD 1590–2009.

The modern series was then extended back to AD 781 through the incorporation of data from 413 historical construction timbers from 21 sites across the region, with the greatest number of samples again derived from Norfolk. These historical structural materials comprised a mix of wall and door panelling, roof beams, ceiling boards, and structural supports from country houses, cathedrals, university colleges, agricultural barns, medieval bridges, and a castle priory (Hillam 1980; Groves 1993; Arnold et al. 2005). After cross-dating and averaging, these samples formed a 1,009-year long historical chronology spanning AD 781–1790. Whilst determining the exact provenance of

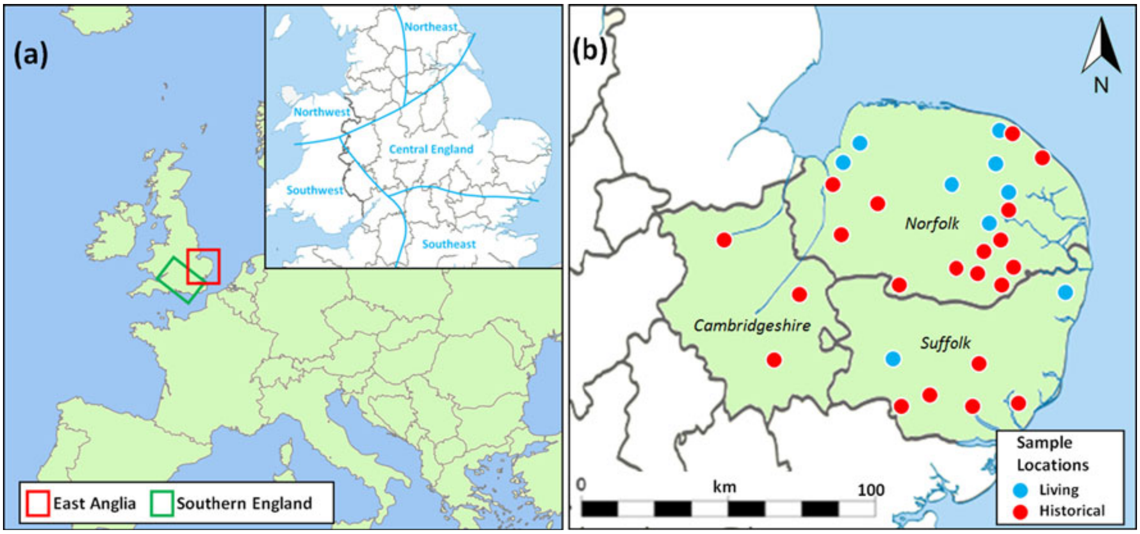

Fig. 1 Location map of the living and historical East Anglian oak chronologies within **a** Europe and **b** eastern England, with inset map showing the England and Wales precipitation regions (Wigley et al. 1984a). Also shown is the location of the southern-central England companion study by Wilson et al. (2012). Refer to Table SM1 for further details

historical timber has inherent uncertainties due to the paucity of historical records for specific timbers, the regional nature of this reconstruction, combined with robust cross-dating, means we can be reasonably confident the oak material came from locations within eastern England. It should be noted, however, that the exact species of individual wood samples remains unknown due to the native British oaks—*Quercus robur* L. (Pedunculate oak) and *Quercus petraea Liebl*. (Sessile oak)—being morphologically similar and readily cross-pollinating to form hybrids of *Quercus* × *rosacea* with intermediate traits of both parents (Jones 1958).

2.2 Climate data

To maintain optimal spatial coherence between the instrumental climate data used for calibration and the locations of the oak chronologies, we opted to use a 1901–2009 monthly 0.5° × 0.5° latitude/longitude gridded precipitation dataset for the region 49–53°N, 0–2°E (CRUTS3.1; Mitchell and Jones 2005), which, for reasons to be discussed, included data for northern France. We also selected a monthly Central England Temperature record (CET) spanning the period 1659–2009 (Manley 1974; updated by the UK Meteorological Office). Mean precipitation for this region is 56.8 mm per month since 1901, displaying a weak seasonal cycle towards greater precipitation in late autumn and winter and lower rainfall during spring (Fig. 2a). Annual mean temperature is ~9.6°C with the coldest and warmest mean temperatures occurring during January (4.0°C) and July (16.1°C) respectively. March–July (MAMJJ) time series of these records reveals a clear trend towards warmer conditions in England over the last 109 years, with mean temperatures rising from 10.6°C (1901–1910) to 11.9°C (2000–2009), with the greatest increase (+1.5°C) occurring during April (Fig. 2b). Conversely, precipitation can be seen to fluctuate considerably from decade-to-decade around the long-term MAMJJ mean (247 mm) with no statistically significant long-term seasonal or annual trends when calculated over the last century. Additional long precipitation records were obtained for later analysis from recording stations at Kew (51°28′N, 0°17′W; 1697–1999) and Pode Hole (52°46′N, 0°12′W; 1726–2010), as well as a composite Central England series (Wigley et al. 1984a; Alexander and Jones 2001; updated by the UK Meteorological Office; 1873–2009).

2.3 Chronology construction

2.3.1 Living oak series

Assembling all ring-width material from the central England precipitation region means that all trees should, if precipitation sensitive, exhibit a common pattern of growth behaviour both before and during the period of instrumental climate records. Determining a common tree growth "signal" amongst the living (modern) series is an essential first step in long chronology development in order to be able to justify the later averaging of all modern and historical material within a single regional composite. Table 1 shows the results of a simple cross-correlation matrix of the nine modern site series computed over their 1879–1981 common period. These correlations were calculated using individual site chronologies that have

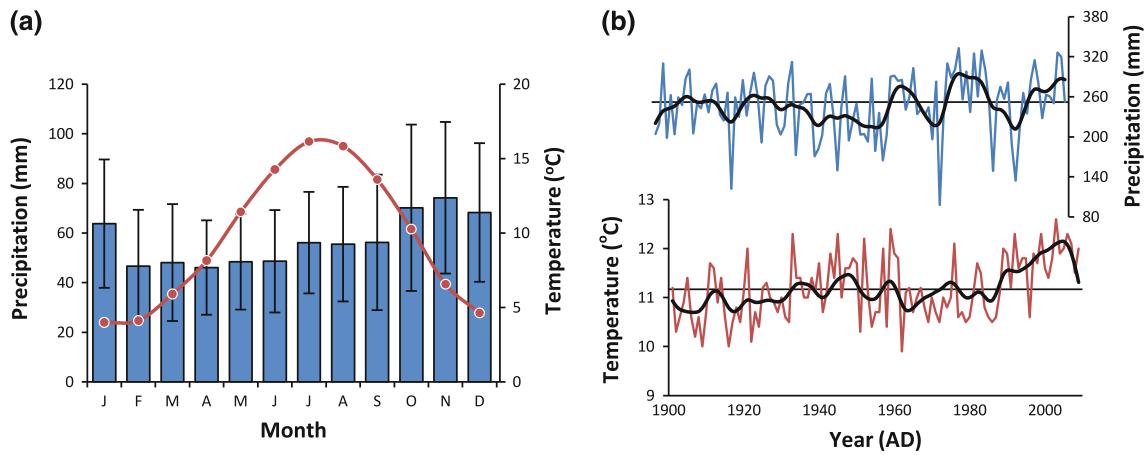

Fig. 2 Regional climate data plots of **a** monthly mean Central England Temperature (CET) and gridded (49–53°N, 0–2°E) precipitation with ±1 standard deviation; **b** associated MAMJJ time series for the period 1901–2009, also smoothed with a 10-year low-pass filter to emphasise decadal variability

Table 1 Cross-correlation matrix of the nine modern oak chronologies over the 1879–1981 common period, separately detrended with a 10-year (right) and a 100-year (left) high-pass spline ($p < 0.05$)

	Babingley	Blickling	Bradfield	Felbrigg	Foxley	Hethersett	Hevingham	Sandringham	Sotterley
Babingley		0.57	0.43	0.59	0.62	0.50	0.46	0.60	0.48
Blickling	0.49		0.46	0.64	0.69	0.69	0.61	0.58	0.59
Bradfield	0.43	0.42		0.46	0.50	0.52	0.52	0.49	0.49
Felbrigg	0.58	0.64	0.46		0.63	0.53	0.47	0.61	0.55
Foxley	0.65	0.48	0.46	0.51		0.63	0.66	0.65	0.63
Hethersett	0.46	0.65	0.48	0.60	0.64		0.57	0.70	0.72
Hevingham	0.47	0.43	0.42	0.46	0.58	0.55		0.57	0.48
Sandringham	0.50	0.33	0.48	0.45	0.59	0.65	0.60		0.58
Sotterley	0.49	0.58	0.44	0.54	0.57	0.71	0.42	0.51	

been detrended with separate 10- and 100-year high-pass smoothing splines to assess inter-site growth coherence at both high- and medium-frequency timescales. The results demonstrate a high level of common growth variability is present across all sites, with marginally stronger correlations at the higher frequency. On multi-decadal or centennial timescales local site management practises can often impart substantial levels of non-climatic "noise" upon the ring-width series, thereby weakening the apparent coherency of the regional tree growth signal (Briffa 1984). However, the presence of a strong common medium-frequency signal in this study suggests that either all sites have been subjected to comparable management regimes or, more-likely, that the noise representing such practises has cancelled out during the averaging of local site series, leaving potentially regional-scale growth-forcing factors to dominate the pattern of growth variability.

Assessing this further, we undertook a principal components analysis (PCA) of the chronology data (Fig. 3) involving a mathematical transformation of the standardised ring-width measurements into a group of orthogonal eigenvectors which describe the major modes of variance within the multiple chronologies composing the overall data set. During the 1879–1981 common period, all nine modern chronologies load positively on PC1, which explains 60.3% of the total variance, and therefore essentially represents the dominant mode of growth variability expressed across all sites. PC2, which explains just 9.3% of variance, reveals a mixed spatial signal with positive and negative loadings at four and five sites respectively. It is likely that this spatial disparity represents either site specific species differences or the impacts of local management practices, the effects of which (like patterns of variability represented by higher order PCs) will be largely removed when the chronology data are averaged across all sites. The lowest positive loadings on PC1 and strongest negative loadings on PC2 occur for Bradfield Woods in Suffolk which is geographically isolated from the main

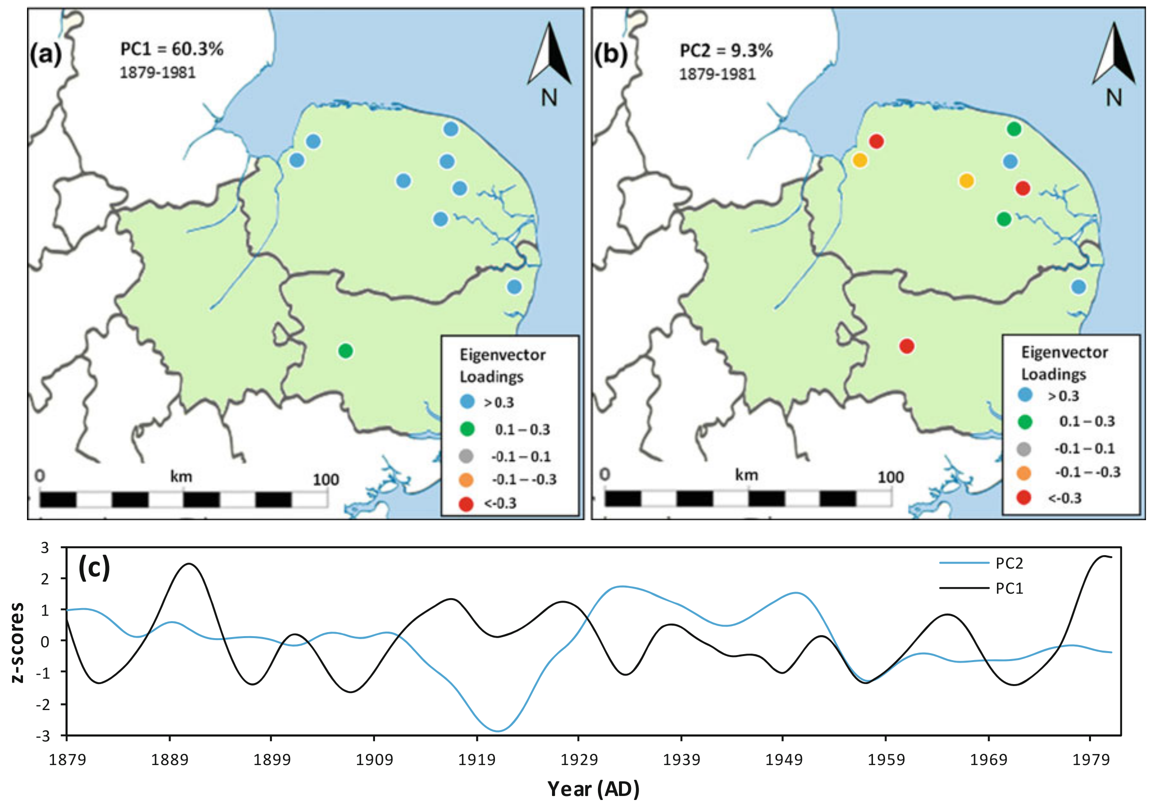

Fig. 3 Eigenvector loadings for the **a** first and **b** second principal components of the nine modern oak chronologies detrended with a 100-year high-pass spline, with **c** associated 1879–1981 common period amplitude time series, smoothed with a 10-year low pass filter

group of sites in Norfolk. Site separation distance accounts for some 31.7% of the variation in inter-site correlation strength ($p < 0.05$), with correlation reducing by 0.19 per 100 km increase in distance (Fig. SM1). This isolation therefore helps explain Bradfield's apparent poorer growth coherency with the other chronologies, and demonstrates the potential problem of incorporating ring-width data from too large an area when developing regional composite chronologies.

2.3.2 *Full composite chronology*

The existence of a strong common high-frequency growth signal amongst the available modern series justifies the extension of the living chronology with cross-dated and averaged historical material from the same region (Fig. 4a). However, due to the early social and economic development of the United Kingdom, there are likely no woodlands in East Anglia which have not been disturbed by human activity in one way or another. Many of England's woodlands have been intensively managed over the last 1,000-years through "coppice-with-standards" regimes (Jones 1958; Bridge et al. 1986), a process which creates characteristic gap-phase suppression and release cycles at multi-decadal timescales in tree ring-widths due to alterations in biotic and abiotic conditions. Additionally, agricultural practises in close proximity to field margin oaks, particularly since the 1950s, may have acted to mask some element of true climatic variability through external disturbances (e.g. fertilizer enhancement) altering tree growth. Therefore, in order to reduce the risk of both natural and anthropogenic disturbance signals from imparting undesirable non-climatic noise upon the chronology, it is advantageous to maintain high sample replication through time such that tree specific noise will be minimised, leaving the remaining growth signal to be potentially better representative of climate forcing. One measure of sufficient sample replication is the Expressed Population Signal (EPS), which gauges the extent to which a chronology represents the hypothetical noise-free signal, by expressing estimated chronology signal strength as a fraction of total chronology variance (Briffa and Jones 1990). It is defined as:

$$\mathrm{EPS}\,(t) = t * \mathrm{RBAR}/t * \mathrm{RBAR} + \,(1 - \mathrm{RBAR})$$

where t is the number of tree series averaged and RBAR is the mean inter-series correlation coefficient. EPS values range from zero to one, and whilst there is no definitive acceptable value, 0.85 has been suggested a desirable level to obtain (Wigley et al. 1984b). It should be stressed that in

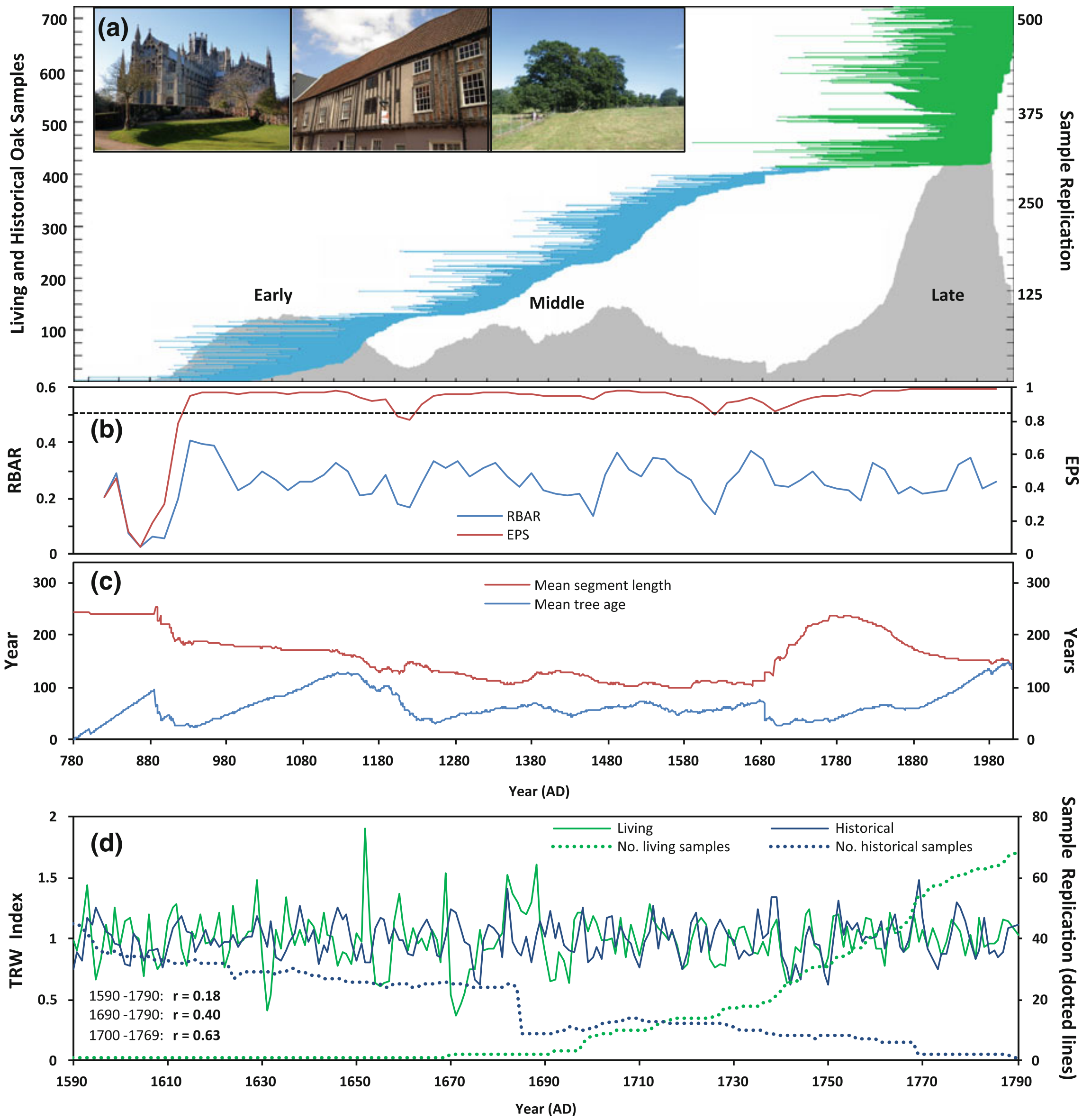

Fig. 4 Summary plots of the composition and high-frequency quality of the East Anglian oak chronology (AD 781–2009). **a** Temporal distribution of modern (*green*) and historical (*blue*) oak samples aligned according to end year with annual sample replication in *grey*. **b** 31-year running RBAR and EPS statistics with critical 0.85 EPS (*dotted line*) for the 10-year high-pass smoothed chronology. **c** Temporal variation in mean sample length and mean tree age. **d** 1590–1790 common overlap period between the modern and historical chronologies, with appropriate sub-sample replication (*dotted lines*)

so much as the RBAR is influenced strongly by chronology variance represented on interannual rather than multi-decadal timescales, the EPS measures chronology strengths at high rather than low frequency timescales. Figure 4b shows how, by virtue of sufficient sampling density, the EPS of the composite chronology is maintained above the 0.85 threshold for most of the last 1,200 years (chronology mean of 0.89). Periods where the EPS falls below 0.85 (~1215 and pre-920) due to low sample replication should be interpreted cautiously. Figure 4b also shows the 31-year running RBAR, which has an average value of 0.26 for the full length chronology. This level of inter-annual to decadal timescale regional common variance is comparable with that obtained in other published studies (Büntgen et al. 2010; Tegel et al. 2010; Wilson et al. 2012) and strongly suggests a wider climatic forcing of oak growth across East Anglia. However, due to low localised RBAR and EPS in the early section of the chronology, data pre-AD 900 were not considered to be of sufficient statistical quality for hydroclimate reconstruction and were therefore omitted.

An accurate assessment of the suitability of the historical material for composite chronology construction can

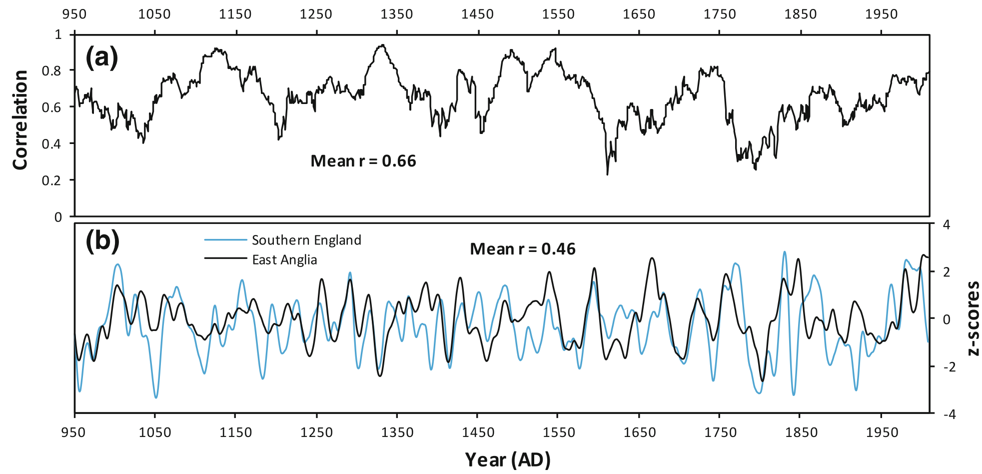

Fig. 5 Comparison of regional oak chronologies. **a** 31-year running correlations between the 20-year high-pass East Anglian chronology and the independent southern-central England oak series (Wilson et al. 2012). **b** AD 950–2009 time series of the two English oak chronologies band-pass filtered to maintain tree growth variability between 20 and 100-years

only be made by comparing it directly with the modern ring-width series during the 1590–1790 period of overlap. Whilst sample replication falls to its lowest point in 1685 during the transition between historical and modern series, Fig. 4d demonstrates that where sample replication of both series remains above 6 samples (1700–1769), correlation between the living and historical series is strong ($r = 0.63$, $p < 0.01$), thereby emphasising a high level of common growth variability through time and validating the extension with historical material. Mean sample segment length (Fig. 4c) generally declines over time from AD 781, before increasing again during the eighteenth/nineteenth centuries, and has a mean over the length of the chronology of ~160 years. Although this is longer than quoted in other oak hydroclimate reconstructions (Büntgen et al. 2010; Wilson et al. 2012) it still limits the degree to which low frequency climate variance can be extracted via so-called "data adaptive" methods of standardisation (i.e. removal of non-climatic trends in measured tree-ring series)—what has been termed the "segment length curse" (Cook et al. 1995). A plot of mean sample tree age through time (chronology average of 65 years) exhibits the classic twentieth century increase in response to targeted sampling of older, mature stands to construct the modern section of the chronology (Fig. 4c). Sample tree age also peaks during the twelfth century, when sample cores were predominately derived from Peterborough Cathedral, indicating the use of mature trees during construction of the cathedral bell tower, nave, and presbytery.

A quantitative assessment of the high- and medium-frequency chronology robustness can be made by comparing growth coherency with an independent oak chronology for southern-central England (Wilson et al. 2012). Although most of the ring-width series used to construct this chronology were obtained from locations several hundred kilometres from East Anglia, we would nevertheless expect to find some degree of coherence as many of the ring-width samples were derived from the same central England precipitation region. Figure 5a shows that between AD 950–2009, mean correlation between the two chronologies (using 20-year high-pass filtered data) was 0.66 ($p < 0.05$) with the weakest correlations observed during the early seventeenth and late eighteenth centuries, and the strongest coherence apparent circa-1130, 1320, 1480-1550, and circa-1740. Band-pass filtering to emphasise tree growth variability between 20 and 100 years (Fig. 5b) reduces the correlation to 0.46 ($p < 0.05$), although this nevertheless still demonstrates a very reasonable degree of common medium-frequency growth coherence, and is suggestive of a wider oak growth forcing mechanism. As such, periods of reduced correlation between the two chronologies may represent an expression of reduced precipitation control on regional oak growth at this time, with the reverse during periods of enhanced correlation. Certainly, this hypothesis holds true during the instrumental period, where an increase in twentieth century correlation coincides with an increase in oak precipitation sensitivity of both series (Sect. 3.1).

2.3.3 Aperiodic tree growth behaviour

Following previous unpublished work by Cooper (2011), who found evidence of approximately decadal timescale "aperiodic" behaviour within the growth rings of modern East Anglian oak chronologies, a 10-year band-pass filter was applied to each of the 30 site chronologies used in this study and the resulting smoothed series overlaid to examine the extent to which such aperiodicity is present throughout the entire 1,100-years (Fig. 6). Although temporally variable, there are obvious periods of pronounced and coherent aperiodic behaviour during the course of the last millennium when growth across most sites is strongly in-phase resulting in a prominent near-decadal growth pattern in the mean series. This is true for most of the eleventh century, as well as during ~1310–1430,

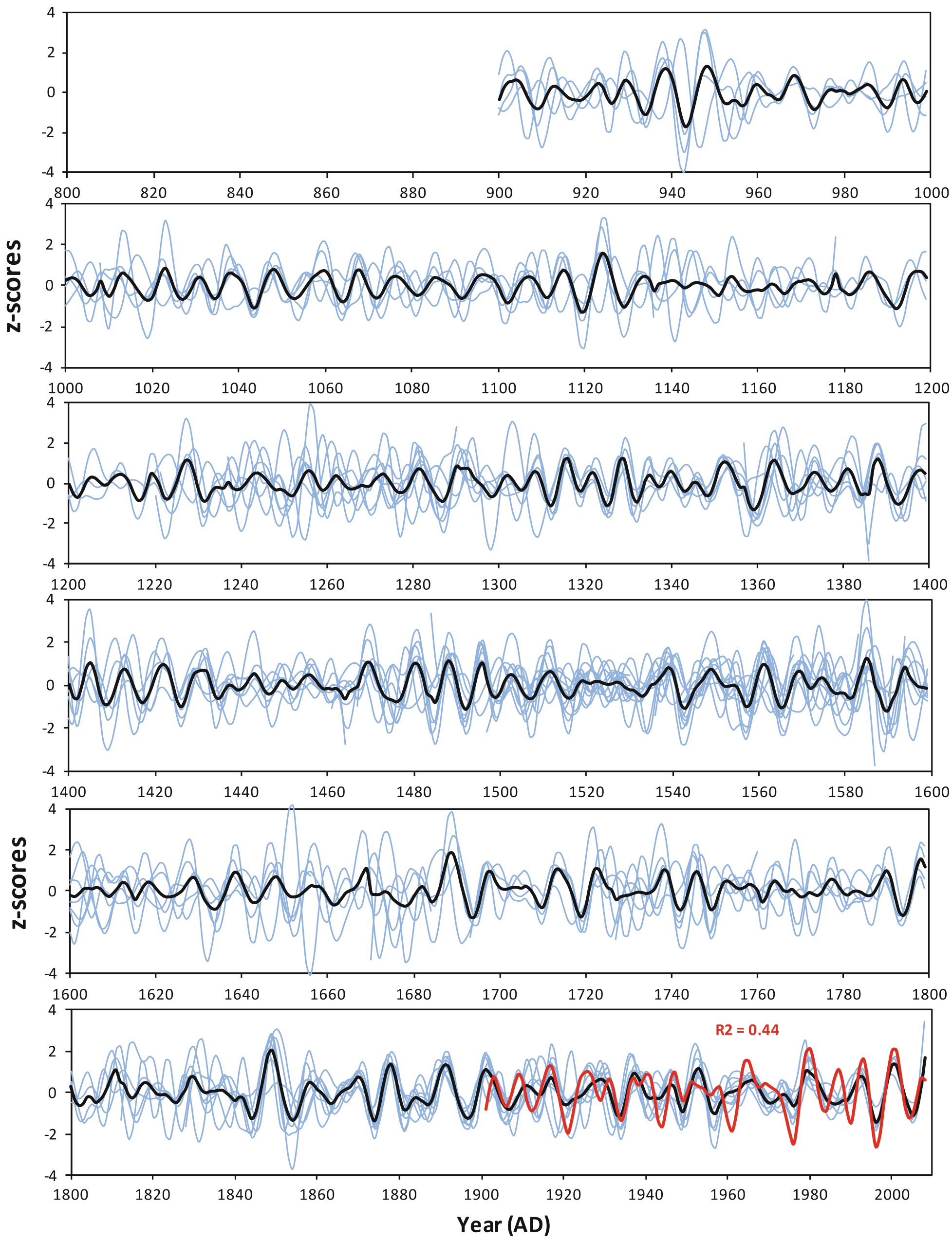

Fig. 6 Evidence of aperiodic growth behaviour within the East Anglian chronology. 10-year band-pass filtered time series of the individual site ring-width series (*blue*), mean series (*black*), and instrumental MAMJJ precipitation (*red*), for the period AD 900–2009

~1470–1510, ~1840–1910, and ~1950–2009. The significance of this behaviour becomes more apparent when overlaying the 10-year band-pass filtered MAMJJ precipitation series, which correlates strongly (r = 0.66; $p < 0.05$) and is capable of explaining 44% of smoothed tree growth variance during the instrumental period. This correlation increases substantially during the last two decades when precipitation variance shares 77% of the tree growth variability between 1989 and 2009. Given such robust correlations, one can speculate that periods of strong aperiodic growth over the rest of the millennium may have been driven by similar near-decadal variability in precipitation. Likewise, periods where such aperiodicity breaks down may be a consequence of either reduced oak precipitation sensitivity when rainfall was not the dominant control on growth, or due to a break down in the near-decadal periodicity of precipitation itself. Certainly, the periods of strong aperiodicity, such as the late-twentieth century, correspond highly with the periods of greatest correlation between the East Anglian and southern England chronologies (Fig. 5), with the reverse true during periods of weaker aperiodicity, thus providing considerable support for the idea of a variable strength precipitation control of oak growth over time.

2.3.4 Regional curve standardisation (RCS)

Having developed a millennial length chronology that is robust at the high-and medium-frequency timescale, the ring-width data were reprocessed to produce a chronology preserving a greater amount of the low-frequency growth variability that is required for millennial timescale climate reconstruction. Unfortunately, the complexity of tree growth influences makes the extraction of low-frequency climate information from tree-ring series problematic (Cook et al. 1990). The most significant obstacle is the necessary removal of the non-climatic, biological, age-related growth trends caused by photosynthetically synthesised materials being distributed around an ever increasing circumference as the tree grows (Briffa 1995). Standardisation is the method by which these age-related growth trends are removed. However, traditional methods sometimes fail to distinguish between biological trends in the ring-width series and those caused by low-frequency climatic variability (Briffa et al. 1996). This frequently results in the partial loss of the low-frequency climate signal, thereby compromising the validity of the chronology as it no longer represents the complete spectrum of climate forcing. As such, an alternative approach utilized here is Regional Curve Standardisation, which has the potential to preserve more low-frequency growth variability (Briffa et al. 1992; Briffa and Melvin 2011). RCS expresses measured ring-width data as deviations from an expectation of ring-width as a function of tree age for a particular tree species growing in a specific region. This expectation is represented by an empirically derived function applied to averages of ring-width series that have been aligned according to their biological age. It is most suited to studies which contain a large number of long samples from comparable sites within a region, such as building timbers or sub-fossil material, and which display a roughly uniform distribution over a long time. Because the averages of RCS indices for individual trees can vary through time and are not constrained to equal 1.0 over the time-span of each sample series, the resulting chronology can potentially capture growth variability at frequencies greater than the mean length of individual cores. This enables RCS to preserve considerably more low-frequency variability compared to traditional "data-adaptive" statistical standardisation models (e.g. fitting negative exponential curves to individual tree measurement series) which impose more restricted frequency constraints on the information contained in the standardised series (Briffa et al. 1996). This can be seen in Fig. 7, which shows the East Anglian chronology detrended using three different standardisation techniques: a 10-year high-pass smoothing spline, a 100-year high-pass smoothing spline, and by RCS. The 10- and 100-year high-pass smoothing splines preserve only the high- and medium-frequency tree growth variability, and whilst they provide a convenient expression of decadal timescale tree growth fluctuations, they are of limited use for long timescale climate reconstructions. In contrast, the application of the RCS approach using multiple parallel, "signal-free", sub-RCS curves, can been seen to preserve a greater proportion of the low-frequency growth variability required for millennial timescale reconstructions. From here on in we refer solely to the RCS version of the chronology. Further details of the precise RCS methodology are discussed in the Appendix.

2.3.5 Correlation and regression

The precipitation sensitivity of the RCS chronology was assessed through a simple form of response function analysis, relating the dependant ring-width variables to independent climate data series using simple correlation (Fritts 1976; Briffa and Cook 1990). From the sign and strength of the resulting associations it is possible to infer which climatic variables are most strongly associated with, and are hence the likely critical drivers of, oak growth in East Anglia. Because ring-width is frequently a predisposed function of both previous year's growth and current year climate variability, response functions are displayed as a function of climate in the preceding as well as current years of tree growth (Briffa 1995). Whilst response functions can provide a general indication of the potential climate influence on ring-width variability, any growth relationship demonstrated by correlation or regression against, what are in effect, arbitrary defined monthly mean climate variables, does not necessarily demonstrate a clear causal relationship (Pilcher and Gray 1982; Briffa and Cook 1990). Once an optimal climate response window had been identified, we used the traditional split period (early-late) ordinary least squares (OLS) linear regression approach to calibrate the precipitation reconstruction. The strength of the calibrations during the verification period were assessed via the variance explained (R^2), sign test, and coefficient of efficiency (CE) (Cook et al. 1994), whereby positive CE values indicate a robust calibration. In addition, the Durbin-Watson statistic (DW) (Durbin and Watson 1951) was used as a measure of 1st order autocorrelation in the regression residuals, whereby a DW of 2 conforms to no 1st order autocorrelation, whilst >2 (<2) indicates negative (positive) autocorrelation and is therefore suggestive of a systematic misfit between the predictand and predictor variables. The relative merits of various regression based approaches to climate reconstruction have previously been discussed (Esper et al. 2005; Bürger et al. 2006) and emphasised the substantial reconstruction variability between calibrations derived using differing regression techniques. Consequently, we also

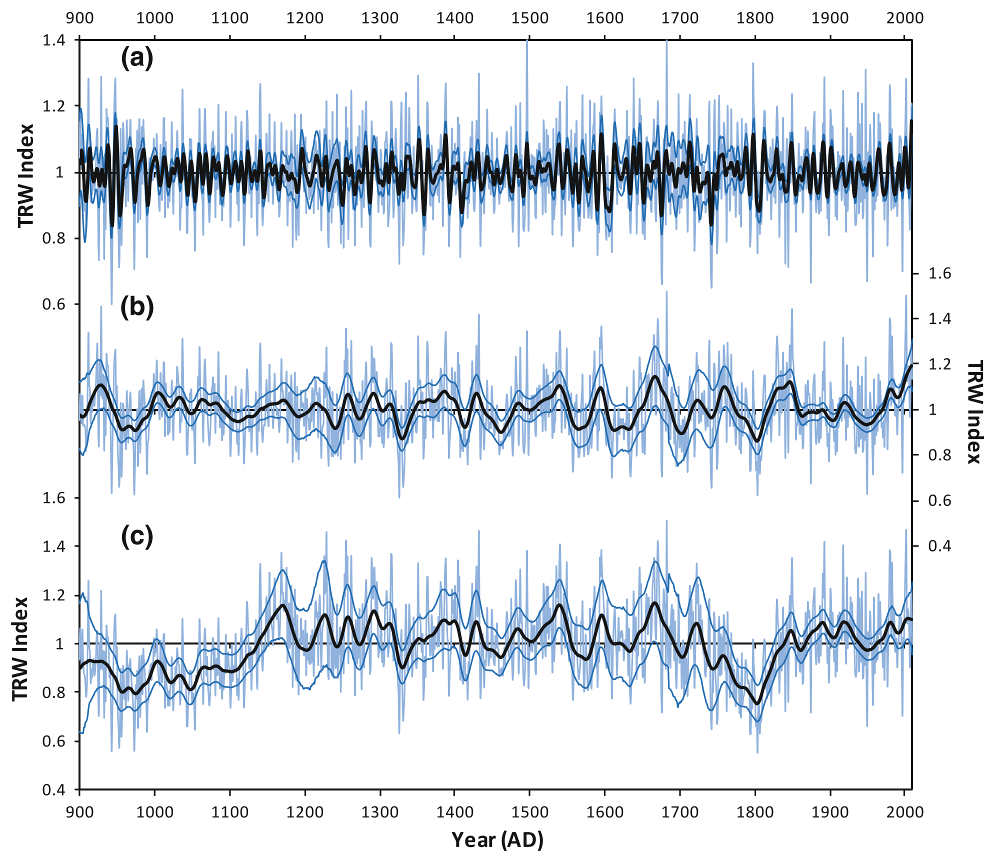

Fig. 7 Different frequencies of East Anglian oak growth variability preserved via various standardisation methods. **a** 10-year high-pass chronology smoothed with a 10-year low pass filter. **b** 100-year high-pass chronology smoothed with a 30-year low-pass filter. **c** Mean of three age dependant and "signal-free" regional curve standardisation curves, also shown smoothed with a 30-year low pass filter. *Dark blue error bars* represent the ±2 standard errors of the smoothed chronology

decided to test the "scaling" regression approach by simply adjusting the mean and standard deviation of the chronology to match those of the contemporaneous instrumental precipitation series, enabling us compare the result with the OLS regression.

3 Results and discussion

3.1 Climate response

Correlation of the RCS chronology against gridded (49–53°N, 0–2°E) instrumental precipitation reveals positive associations during most months and seasons in both current and previous years, with the exception of previous year July (Fig. 8a). High precipitation totals during the spring and summer of the growth year are the most influential periods for accelerating oak growth, with significant ($p < 0.05$) monthly associations evident for March, April, May, and July. Significant positive correlations were also established with precipitation during November and December of the previous year, emphasising the importance of winter soil moisture recharge in promoting strong tree growth in the following year. Strong correlations were produced against an October–August water year period (r = 0.52), as well as for the combined 3 months of spring (r = 0.47), whilst the strongest correlation was produced using a combined March-July season (r = 0.56). We subsequently took this to be the optimal response window for climate reconstruction. These correlations compare favourably with other published oak reconstructions (Büntgen et al. 2010, 2011; Wilson et al. 2012), whilst near identical correlations obtained against the 10- and 100-year high-pass detrended chronologies (Fig. SM2), emphasise the robustness of the climate-growth relationships, irrespective of standardisation procedure.

Moving 31-year period correlations against the four local precipitation series and the CET record reveal significant temporal variability in the short-term (virtually interannual) growth-climate relationships (Fig. 8b). Correlations with MAMJJ precipitation fluctuate between significant and non-significant associations during most the eighteenth and nineteenth century, before declining to the lowest level circa-1900 (r = ~0.20). Correlations increase strongly during the early twentieth century and attain maximum values (r = 0.75) by the twenty-first century after a slight reduction in strength during the 1970s. Although largely insignificant ($p > 0.05$), correlations against CET fluctuate between positive values during the late seventeenth, mid-eighteenth, mid-nineteenth, and

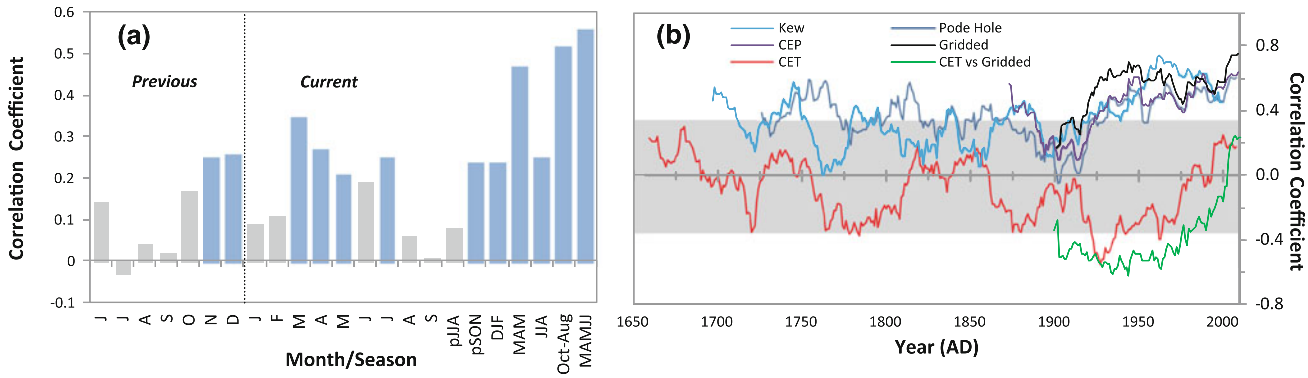

Fig. 8 Empirical demonstration of chronology climate sensitivity. **a** Correlation coefficients for monthly and seasonal measures of East Anglian precipitation variability calculated for the period 1901–2009. Significant correlations ($p < 0.05$) are shown in *blue*. **b** Moving 31-year period correlations between the East Anglian chronology and MAMJJ CET and Kew, Pode Hole, gridded, and central England precipitation (CEP) series. Also shown is the running correlation between CET and gridded precipitation. *Grey shading* represents non-significant correlation 95% significance level

twenty-first centuries, and negative values during the rest of the period, most significantly during the 1920s–1930s. An explanation for the temporally changing sensitivity of oak growth to temperature variability can be found when one examines the relationship between CET and precipitation. This demonstrates a distinct shift in the association between these two climatic variables from a warm/dry and cold/wet negative relationship of the early and mid-twentieth century, towards a warm/wet and cold/dry positive association over the last 10 years. Consequently, higher spring-summer temperatures are currently associated with higher precipitation, which in turn is responsible for increasing oak growth, hence the trend towards positive correlations between CET and oak growth over the last decade. Conversely, during the 1920–1930s increases in temperature were associated with decreases in rainfall which acted to reduce oak growth, hence the strong negative correlations between East Anglian oak growth and temperature at this time. It is, therefore, reasonable to assume that other periods when oak growth correlated positively with temperature (e.g. the late-seventeenth century) were also periods when temperature and precipitation were positively correlated. These intriguing findings highlight, not only the complex nature of tree growth forcing, but also the complex nature of climate variability in the UK. It is possible that at various times over the last 300 years oak growth may be better represented by a combination of both temperature and precipitation forcing, although correlations with the scPDSI (Wells et al. 2004) and SPEI (Vicente-Serrano et al. 2010) drought indices yielded weaker responses than demonstrated for precipitation alone (Fig. SM3). This is perhaps not surprising given that East Anglian oak is not at the geographical limit of its range and therefore has the potential to exhibit somewhat complex physiological growth behaviour resulting in many temporally unstable relationships against multiple climate parameters. A pattern of reduced precipitation sensitivity is also demonstrated in the southern-central England oak chronology (Wilson et al. 2012) over the last century, which the authors speculate could be due to either poor quality early instrumental data or a peak in smoke and SO_2 air pollution during nineteenth century industrialisation detrimentally affecting oak growth during this time. In any case, it is apparent that further research is required beyond the scope of the current paper to fully understand the causes of this temporal instability.

3.2 Spatial field analysis

Spatial field correlations comparing the RCS chronology and a gridded 0.5° × 0.5° latitude/longitude MAMJJ precipitation dataset for Europe (CRUTS3.1; Mitchell and Jones 2005) for the period 1901–2009, reveal significant ($p < 0.1$) associations with precipitation across England, northern France, Benelux, western Germany and Denmark which weaken in a NW–SE direction (Fig. 9—upper). This pattern closely corresponds with the spatial correlations derived against the instrumental gridded series (49–53°N, 0–2°E), thus emphasising the robustness of East Anglian oak growth as a hydroclimate proxy for this region (Fig. 9a). Comparison of early (1901–1955) and late (1956–2009) period correlations reveals some temporal instability in climate-growth relationships across parts of western Europe as precipitation sensitivity increases during the latter half of the twentieth century. The region of strongest correlation occurs over northern France, particularly during the early period, suggesting that East Anglian oak growth represents a better hydroclimate proxy for northern France than for East Anglia itself. Whilst we have no definite explanation as to why this should be the case,

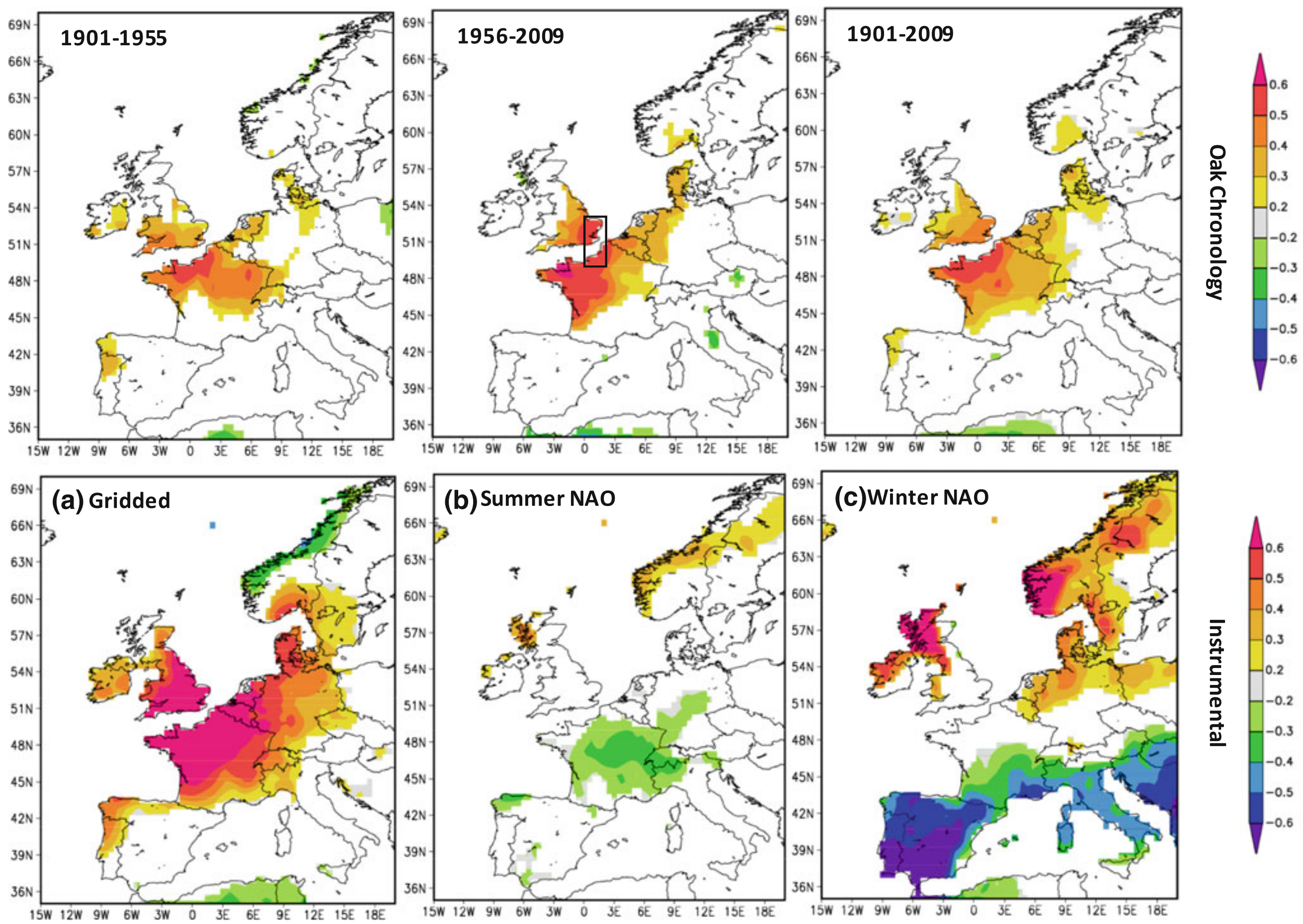

Fig. 9 European spatial correlation. *Upper panels* show field correlations of 0.5° × 0.5° gridded MAMJJ precipitation for Europe (CRUTS3.1; Mitchell and Jones 2005) against the RCS East Anglian oak chronology during early, late, and full length periods. The *black box* denotes the gridded (49–53°N, 0–2°E) instrumental precipitation series used for calibration. *Lower panels* show **a** European scale MAMJJ precipitation against the gridded (49–53°N, 0–2°E) instrumental precipitation series; **b** July–August precipitation against high summer (JA) Gibraltar-Iceland NAO index (Jones et al. 1997); **c** December–March precipitation against winter (DJFM) Gibraltar-Iceland NAO index (Jones et al. 1997). All correlations significant at $p < 0.1$ and shown for the period 1901–2009

very similar findings in the southern-central England oak chronology (Wilson et al. 2012) provides further evidence in support of some, as yet unknown, indirect association between English oak growth and precipitation over northern France. It is for this reason that gridded precipitation data for a larger region incorporating northern France (49–53°N, 0–2°E) was chosen for calibration. The temporal instability of the climate-growth relationship is also significantly reduced by using this gridded dataset instead of data solely for East Anglia (52–53°N, 0–2°E) (SM4).

A potential candidate driver behind the large scale spatial coherence of oak growth and precipitation across western Europe is the North Atlantic Oscillation (NAO). Positive index phases of the winter NAO are associated with enhanced winter moisture transport (50–200 mm per season) over northwest Europe, particularly Scandinavia, and drier conditions over southern Europe and the Mediterranean, with the reverse true during negative phases (Hurrell et al. 2001; Trouet et al. 2009). Although it has reduced impact on climate in the North Atlantic sector due to a shift in its position and strength, positive index phases of the summer NAO are associated with anomalous easterly winds driving warm, dry air from continental Europe across the UK resulting in likely increased soil moisture deficit (Folland et al. 2009). However, because eastern England sits between the major zones of precipitation fluctuations that accompany NAO phase transitions, precipitation in East Anglia is not strongly correlated with either summer or winter NAO (Fig. 9b, c). Consequently, moving 31-year correlations between the East Anglian oak chronology and an 1821–2009 NAO reconstruction based on Gibraltar and south-west Iceland surface pressure data (Jones et al. 1997), reveals no significant associations during any months or seasons at either annual or decadal timescales (Fig. SM5). However, this is not to say that oak growth is not indirectly sensitive to variations in surface

Table 2 Split period calibration and verification statistics for the ordinary least squares (OLS) linear regression and scaling reconstruction approaches, displayed for both annual and decadal smoothed timescales

		Verification 1901–1955				Calibration 1956–2009		Full period 1901–2009		
		r	R^2	CE	Sign-test	r	R^2	R^2	SE	DW
OLS	Annual	0.50	0.25	0.22	37/18 ($p = 0.01$)	0.61	0.37	0.32	21.7	1.78
	Decadal	0.36	0.13	0.12	33/22 ($p = 0.18$)	0.67	0.45	0.35	10.5	N/A
Scaling	Annual	0.50	0.25	−0.05	36/19 ($p = 0.03$)	0.61	0.37	0.32	38.7	1.91
	Decadal	0.36	0.13	−0.68	34/21 ($p = 0.10$)	0.67	0.45	0.35	17.7	N/A

CE coefficient of efficiency, *SE* standard error, *DW* Durban-Watson statistic

pressure. In an analysis of pan-European "signature" years in oak ring-width series, Kelly et al. (1989, 2002) established that years of common positive oak growth across western Europe (positive signature years) were associated with enhanced cyclonic activity over northern Europe. This causes increased westerly air flow across the North Atlantic, leading to higher precipitation and abundant soil moisture over the UK. Conversely, years of common reduced oak growth across western Europe (negative signature years) were associated with colder, drier conditions as a result of enhanced ridging (blocking anticyclones) during the spring months. We observe a similar low (r = 0.3–0.4), but nonetheless weakly significant ($p < 0.1$), correlation between East Anglian oak growth and a gridded 5° × 5° latitude/longitude European scale MAMJJ mean sea-level pressure (SLP) time series over the period 1899–2009 (Trenberth and Paolino 1980) (Fig. SM6). Furthermore, Lopez-Moreno and Vicente-Serrano (2008) demonstrate that negative NAO phases have increasingly been associated with drier conditions across southern England and northern France during the latter half of the twentieth century, whilst positive phase moisture availability has remained relatively constant. It is therefore at least possible that the decline in negative phase moisture availability may partly be responsible for the increased oak growth precipitation sensitivity we see during the second half of the twentieth century, through an enhancement of soil moisture stress.

3.3 Model calibration and verification

During the calibration period (1956–2009), tree growth variability was able to explain 37 and 45% of annual and decadal MAMJJ precipitation variance respectively using OLS regression against the gridded precipitation series (Table 2). Corresponding verification period (1901–1955) CE of 0.22 and 0.12 indicate a successful reconstruction, although the results emphasise the substantially weaker oak growth climate sensitivity during the early period, particularly at the decadal timescale. Over the full period (1901–2009) oak growth was able to explain 32 and 35% of annual and decadal precipitation variability respectively which is comparable with other European oak ring-width reconstructions (e.g. Büntgen et al. 2010, 2011; Wilson et al. 2012). At both interannual and decadal timescales regression residuals were normally distributed and showed no significant temporal trend over the full period ($R^2 = 0.01$ and 0.05 respectively) with a DW value of 1.78 indicating an absence of any significant autocorrelation in the annual residuals. However, due partly to the regression based variance reduction associated with the OLS regression approach, the magnitude of precipitation in extreme years (e.g. 1921, 1976, 1987, 1990, 1996, and 2007) tended to be underestimated in the reconstruction (Fig. 10). It is apparent from the number of extreme spring-summer seasons in the last 40 years that there has been a substantial increase in instrumental precipitation variability since the 1970s, especially at the decadal timescale. This increased variability has likely exerted a stronger precipitation control on oak growth over recent decades which may be responsible for the improved reconstruction fidelity apparent during the later calibration period. The scaling regression approach was also tested (Fig. SM7), but negative verification period CE value of −0.05 and −0.68 at the annual and decadal timescale respectively strongly indicate that this method is insufficiently robust for climate reconstruction and was therefore not pursued further. See supplementary material Figures SM7–SM12 for further details of the regression approaches explored here.

3.4 Millennial reconstruction

The millennial length MAMJJ precipitation reconstruction indicates anomalous dry conditions during AD 900–1100, with estimated precipitation (∼200 mm $year^{-1}$) significantly ($p < 0.05$) below the long-term mean of 238 mm $year^{-1}$ (Fig. 11). An apparent prolonged wetter phase is estimated for the twelfth and thirteenth centuries where smoothed rainfall totals increase to the maximum levels estimated for the entire 1,100 years (∼270 mm $year^{-1}$), although these are not statically significant ($p < 0.05$). Estimated precipitation then fluctuates between

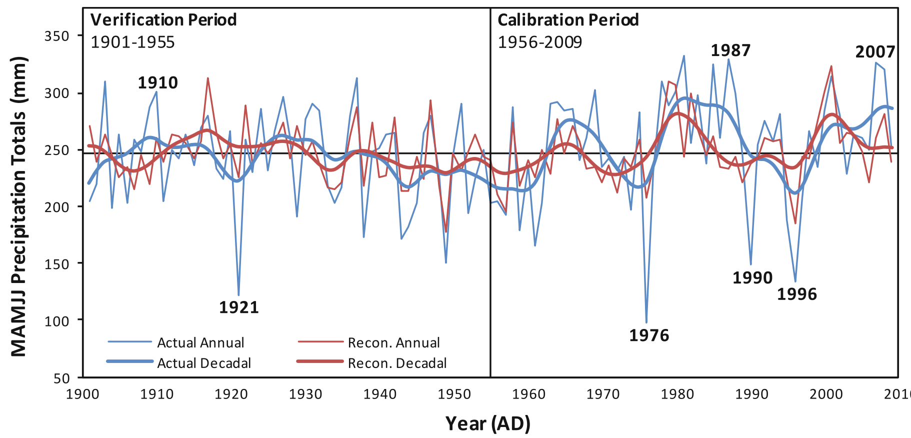

Fig. 10 Split period calibration and verification procedure for the OLS regression reconstruction of MAMJJ precipitation over the period 1901–2009. Calibration shown for both annual and decadal smoothed timescales, with labelled extreme years clearly underestimated by the model. See Table 2 for statistics

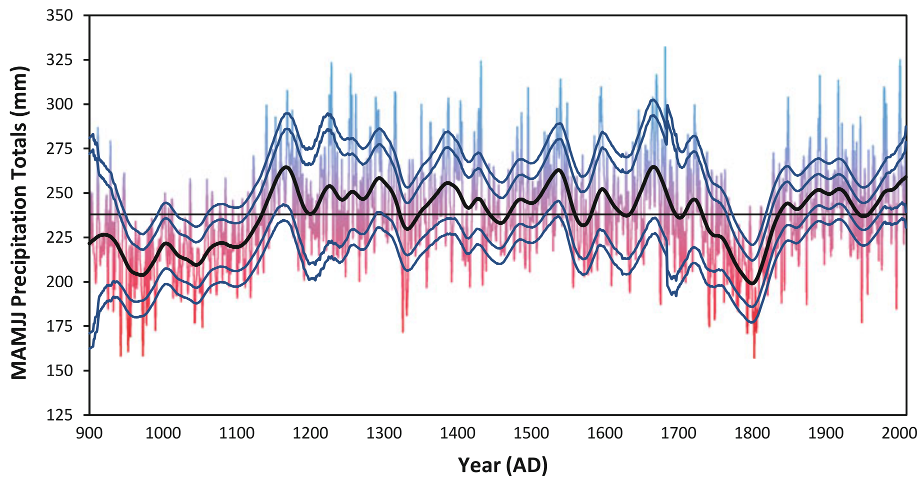

Fig. 11 Annually resolved reconstruction of East Anglian MAMJJ precipitation (mm) for the period AD 900–2009, shown smoothed with a 50-year low-pass filter. *Dark blue error bars* represent the ±2 standard errors of the chronology (*inner*) and OLS regression (*outer*) for the 50-year low-pass filtered chronology

wetter and drier phases at near centennial timescales throughout the fourteenth to seventeenth centuries. A distinct shift from wetter to drier conditions between the first and second halves of the sixteenth century is visible, a trend also detected in a study of sixteenth century European oak data (Briffa et al. 1999), where the authors attribute reduced growth after AD 1570 to anomalously high spring/summer pressure and warm, dry conditions occurring over west-central Europe. Another period of significant East Anglian dryness is reconstructed from ~1750 to 1830 which is of comparable magnitude to that reconstructed for the tenth century, and represents the driest period since that time. With the exception of a dip during the 1940s, precipitation increases during the late nineteenth and twentieth centuries to above average values, such that reconstructed precipitation for the twenty-first century is comparable with that reproduced for the 1600s (~260 mm year^{-1}).

Eighteen of the twenty driest reconstructed years occurred in two phases between 943 and 1054 and 1742–1806, with the driest year in 1803 (157 ± 31 mm) (the uncertainty being due in part to error in the oak chronology and partly that associated with the standard error of the OLS regression). The twenty wettest years occurred between 1169–1316, 1432–1682, and 1892–2001, with the wettest year occurring in 1682 (332 ± 78 mm). During the instrumental period (1901–2009) the reconstruction successfully estimates 10 of the 20 driest years in the instrumental record (Table SM3), and 8 of the 20 wettest years (Table SM4), implying greater oak growth sensitivity to years of low precipitation. This is further emphasised when comparing the reconstruction with a MAMJJ sea level pressure (SLP) time series (Trenberth and Paolino 1980) for the same region (49–53°N, 0–2°E), which correlates at −0.37 ($p < 0.1$) during 1901–2009. The reconstruction successfully estimates 8 of the 20 highest pressure (i.e. driest) spring-summer seasons (Table SM5), compared to just 6 of the 20 lowest pressure (i.e. wettest) seasons (Table SM6). Although some of the largest residuals are observed during extreme dry years (e.g. 1921, 1976, 1996), the underrepresentation of very wet years in the reconstruction indicates a probable physiological maximum limit to which oak growth responds to very wet years, such that once soil moisture availability has risen above a certain threshold, further increases in rainfall

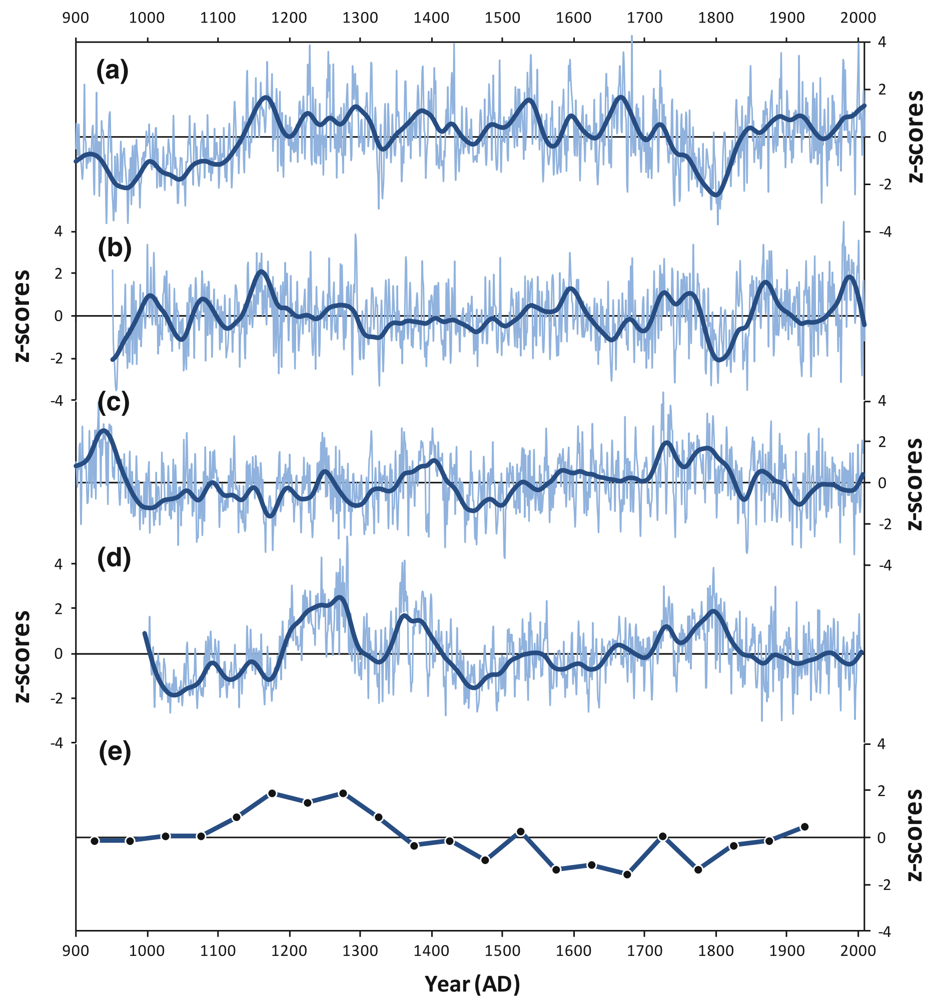

Fig. 12 Comparison of independent millennial length precipitation reconstructions. Normalised, 50-year low-pass smoothed oak ring-width reconstructions of **a** East Anglian MAMJJ precipitation (this study); **b** MAMJJ precipitation for southern-central England (Wilson et al. 2012); **c** AMJ precipitation for central Europe (Büntgen et al. 2011); **d** JJAS precipitation for Germany (Büntgen et al. 2010). **e** Also shown is an early estimation of 50-year average September-to-June England and Wales precipitation deduced from various documentary series (Lamb 1965)

have little or no effect in enhancing tree growth (see also Briffa 1984).

3.5 Reconstruction validation

Due to the current paucity of annually resolved millennial timescale precipitation reconstructions for East Anglia and the United Kingdom as a whole, it is not currently possible to comprehensively validate this reconstruction. However, of the existing independent millennial length precipitation reconstructions available for western Europe, four are presented in Fig. 12 as normalized, 50-year smoothed time series alongside the East Anglian reconstruction. These include three oak ring-width based precipitation reconstructions for southern-central England (Wilson et al. 2012), central Europe (Büntgen et al. 2011) and Germany (Büntgen et al. 2010), together with a documentary 50-year-average reconstruction of September-to-June precipitation for England and Wales (Lamb 1965). Immediately apparent is the good coherence ($r = 0.60/0.43$ at annual/50-year low-pass smoothed timescales) between the East Anglian and southern England reconstructions over much of the past millennium. Enhanced precipitation is common to both regions during the late twelfth, sixteenth, nineteenth and twentieth centuries, whilst prominent drier conditions are reconstructed for ~1780–1840 and to a lesser extent during the early 1300s and for parts of the tenth and eleventh centuries. These trends are broadly consistent with Lamb's England and Wales reconstruction of a wet twelfth–thirteenth century, a drier eighteenth century, and a trend towards average rainfall for the early twentieth century. However, care should be taken interpreting the Lamb (1965) documentary reconstruction which, as well as not being annually resolved, is partly based on a climatic index compilation produced by Britton (1937) using non-contemporary weather chronologies written substantially later than the events which they described. It has also been suggested (Ogilvie and Farmer 1997) that at least some of the climate indices formulated by Lamb for the medieval period are unreliable as they may in fact relate to other parts of Europe. It therefore seems that Lamb's "idealised" wet Medieval and dry Little Ice Age periods for the

England are more complex and less well defined than the reconstruction would suggest. That said, where Lamb (1965) does refer to individual years, such as 1236 and 1238 being unusually hot and dry and 1314 being very wet, our East Anglian reconstruction compares favourably by estimating below and above average rainfall respectively.

Despite differences in the geographical area and chosen seasonal reconstruction window, some of the broad trends of the East Anglian reconstruction are apparent in mainland Europe (Fig. 12c, d). Both European oak studies estimate below average spring-summer rainfall during 1000–1150 AD, with pronounced above average rainfall reconstructed for the thirteenth century in Germany. Above average rainfall in central Europe and Germany is also similar to that in East Anglia during the late fourteenth and early fifteenth centuries, although the prominent dryness circa-1800 is not evident here. This East Anglian reconstruction also bears a strong resemblance to a Finnish pine (*Pinus sylvestris* L.) based reconstruction (Helama et al. 2009) which reconstructs dry spring-summer conditions during the tenth–eleventh centuries and circa-1800, and wetter conditions during the twelfth century. Whilst Helama et al. (2009) attributed this to the combined influence of the El-Niño Southern Oscillation (ENSO) and NAO, no such relationship was detectable in this East Anglian study.

The trend towards an increasingly wetter spring-summer season over the last 50 years in East Anglia would initially appear at odds with a recent examination of long instrumental drought and precipitation records for Europe (Briffa et al. 2009) that demonstrated evidence of a robust trend towards more frequently occurring summer drought in south-east England during this period. However, that work explored a drought metric (scPDSI) that is affected not only by precipitation, but also by rising temperatures. The latter were shown to be a major driver of a recent reduction in soil moisture and so the two records are not necessarily mutually exclusive. Thus in summary, the broad correspondence demonstrated in the existing independent precipitation proxies compared here provides some validation of the reconstructed spring-summer precipitation trends estimated for East Anglia over the past 1100 years.

4 Conclusions

Amid mounting concerns about the possible impacts of future hydroclimatic change on terrestrial ecosystems and human society, it has become ever more important to gain a thorough understanding of past climatic variability as a benchmark against which to gauge current and possible future changes to the climate system. This study and a companion paper by Wilson et al. (2012), are intended to go some way towards this by presenting the first two, accurately dated and annually resolved reconstructions of spring-summer hydroclimate variability in England spanning the last millennium. This study is based on a continuous regional oak chronology using material gathered from 30 different sites across East Anglia. These data appear to show a coherent high-frequency growth signal persisting over the last 1100 years, and are strongly correlated with precipitation variability during a 5-month period spanning March–July. There is clear evidence that near-decadal variability in precipitation is forcing near-decadal aperiodic growth behaviour in East Anglian oaks over much of the last millennium. A significant increase in the year-to-year sensitivity of oak growth to precipitation variability is apparent during the course of the twentieth century, whilst a time transgressive relationship between precipitation and central England temperature has had knock-on consequences for the apparent association between oak growth and temperature variability. Patterns of widespread coherent oak growth response to precipitation variability across northern France, Benelux, western Germany and Denmark correspond strongly with the spatial distribution of East Anglian instrumental precipitation, and emphasise the value of East Anglian oak growth as a sensitive hydroclimate proxy for this region. However, we find no evidence to suggest that larger scale synoptic variability in the form of the North Atlantic Oscillation has significantly influenced either measured precipitation or oak growth in East Anglia over the last century.

After standardising the oak data using Regional Curve Standardisation to preserve low-frequency climate variability, the chronology was calibrated against gridded (49–53°N, 0–2°E) instrumental precipitation using ordinary least squares linear regression to produce a precipitation reconstruction capable of explaining 32 and 35% of annual-to-decadal precipitation variability respectively during the full 1901–2009 instrumental period. The tree-growth/precipitation association is weaker during the 1901–1955 period, particularly at the decadal timescale, but the earlier regression estimates still provide useful information about past precipitation variability. A tendency for the reconstruction to underestimate extreme years, especially wet years, is consistent with an interpretation of a physiological maximum limit to which oak growth responds to very wet years once soil moisture availability has risen above a certain threshold. The full MAMJJ precipitation reconstruction indicates significant ($p < 0.05$) anomalous dry conditions during AD 900–1100 and again during 1750–1830. An apparent prolonged wetter phase is estimated for the twelfth and thirteenth centuries, whilst precipitation fluctuates between wetter and drier phases at near centennial timescales throughout the fourteenth to seventeenth centuries. Reconstructed precipitation for the twenty-first century is above the millennial average and is comparable with that reproduced for the 1600s. The most prominent wet and dry periods reconstructed here show good similarity with other independent hydroclimate proxy reconstructions for the United Kingdom and central Europe, in particular with the spring-summer oak ring-width based reconstruction for southern-central England (Wilson et al. 2012).

Despite the UK's temperate maritime climate, this study has demonstrated the value of utilising both living and historical oak ring-width series to reconstruct regional hydroclimate variability in East Anglia over the last millennium. Due to the paucity of existing annually resolved precipitation reconstructions for the UK, future work might usefully focus on producing distinct millennial timescale oak chronologies for each of the other three (southwest, northwest, northeast) England and Wales coherent precipitation regions identified by Wigley et al. (1984a). This would enable further independent validation of the existing hydroclimate reconstructions and provide greater insight into the spatial variability of historical precipitation trends across the UK, particularly with respect to assessing the robustness of the anomalous dry conditions reconstructed here for the tenth and eleventh centuries. Until such time, the low frequency aspect of this paper should be considered preliminary and interpreted cautiously.

4.1 Data

Supporting material is available online at the Climatic Research Unit website (http://www.cru.uea.ac.uk/cru/data/). Ring-width data will be made available online at the International Tree-Ring Data Bank (ITRDB). Climate data can be accessed from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) Climate Explorer (http://climexp.knmi.nl).

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Appendix

Regional curve standardisation

Regional Curve Standardisation is advantageous over other "data-adaptive" standardisation approaches focussed on long-timescale climate reconstructions because it has the potential to preserve low-frequency growth variability in tree-ring chronologies. However, in preserving this low-frequency growth variability RCS is more susceptible to the influence of medium- and low-frequency non-climatic induced growth behaviour that may bias the final standardised chronology. In this respect, the RCS chronology carries greater uncertainty in terms of whether the expressed tree-growth variability is genuinely climatically forced or not, with obvious knock-on consequences for the interpretation of millennial timescale reconstructed climate variability. The biasing effects that may occur in RCS chronology production are discussed in Briffa and Melvin (2011). These include biasing by the residual climate signal in age aligned samples ("trend-in-signal bias") and the "differing-contemporaneous-growth-rate bias". In an effort to mitigate these limitations in practise, a form of RCS involving the use of "signal-free" RCS curves was employed in this study, along with the use of multiple parallel sub-RCS curves (Fig. 13). The former involves smoothing the tail of the RCS curves, removing climate signal contamination that would otherwise distort the beginning and end of the resulting chronology (Melvin and Briffa 2008). The latter involves deriving a set of standardisation functions based on sub-divisions of the total data set according to differences in overall growth rate of the constituent trees. Here, we used 3 sub-RCS curves, as advocated by Melvin (2004), and although this approach can, in itself, possibly lead to the loss of some lower

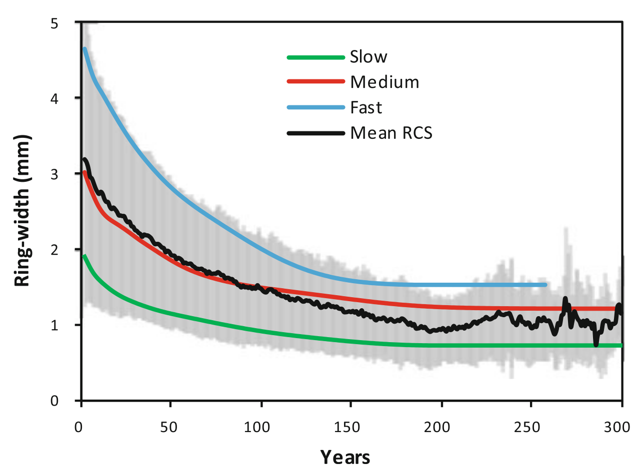

Fig. 13 Three age-aligned, signal free, RCS curves for slow, medium, and fast growth rate trees, with mean RCS and its ±1 standard deviation (*shading*)

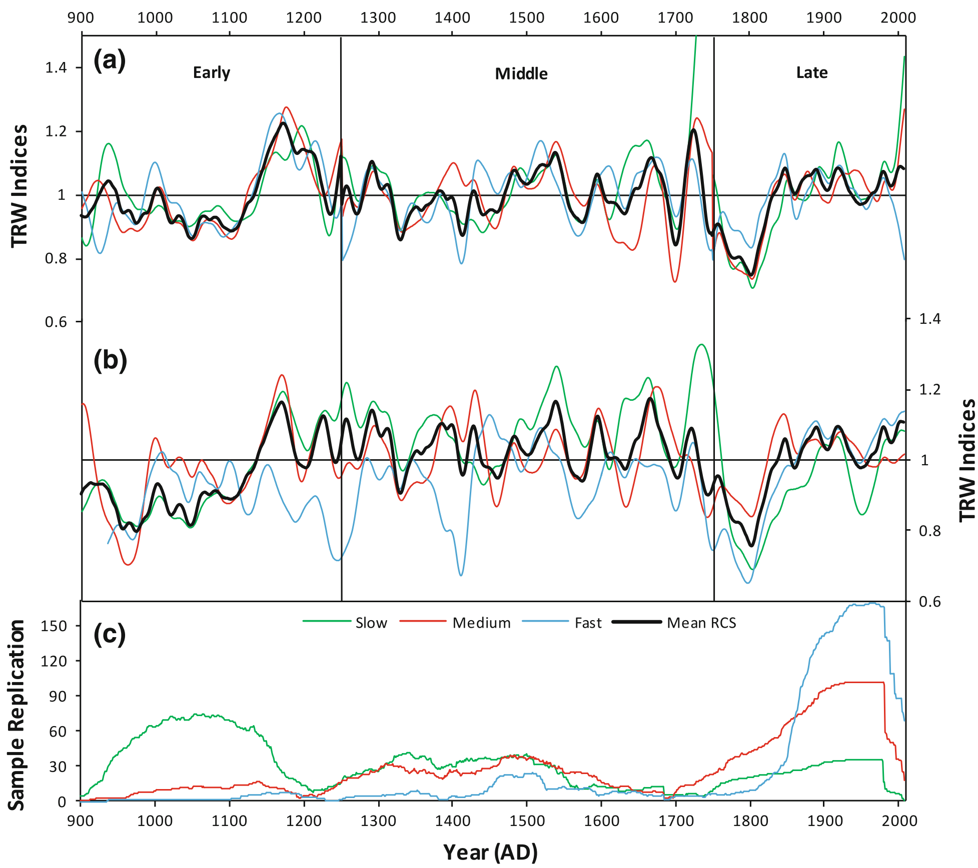

Fig. 14 **a** Three sub-set RCS chronologies derived for early (900–1249), middle (1250–1749), and late (1750–2009) periods identified on the basis of source location of samples (see Fig. 4) using ring-width indices only for the stated period. **b** Individual RCS chronologies for the entire standardised data set (900–2009), with the RCS indices separated according to relatively fast, medium, and slow growing trees, with the overall mean RCS chronology in *black*. All RCS curves are shown smoothed with a 30-year low-pass filter. **c** Changing sample replication over time for the full RCS chronology for trees characterised as fast, medium, and slow grown, derived via multiple RCS detrending over a fraction of total chronology length (Briffa and Melvin 2011)

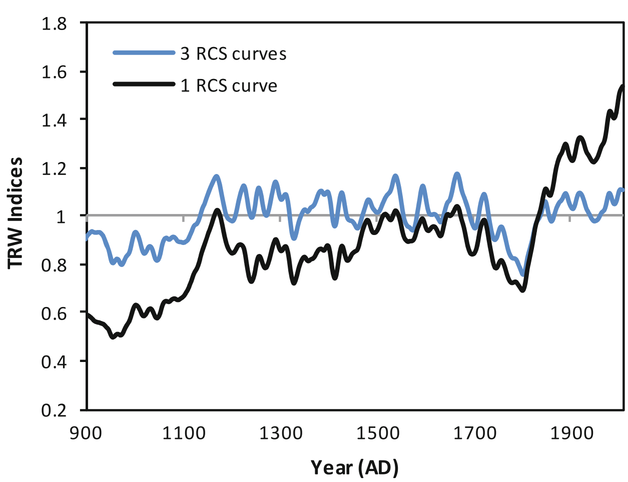

Fig. 15 Standardising the East Anglian chronology with a single RCS curve results in an upward sloping "differing-contemporaneous-growth-rate" bias compared to standardising with 3 RCS curves

frequency variability, the production of a set of corresponding sub-chronologies represents a form of robustness testing where the sensitivity to data selection is examined. This allows the degree of common growth behaviour produced using different sub-sets of the data to be compared through time.

Shown in Fig. 14 are three subset chronologies for the early (900–1249), middle (1250–1749), and late (1750–2009) periods identified on the basis of source location of material, with each sub-chronology detrended using multiple sub-RCS curves. The reason for doing this is to assess whether the prominent ring-width declines pre-1120 and circa-1800 were robust and not artefacts of the data selection and standardisation procedure. The resulting mean growth for each subset chronology (Fig. 14a) can be seen to exhibit approximately the same growth patterns as the full RCS series (Fig. 14b), thus providing some validation that these growth trends are real and potentially representative of a climatically induced reduction in regional oak growth. That said, there does appear to be some low-frequency ambiguity during the period 1350–1450 AD, whereby the full RCS chronology shows above average growth whilst the middle subset chronology reconstructs below average growth during this period. This is in common with the Wilson et al. (2012) reconstruction which also shows below average growth during this time. The exact cause of this discrepancy is currently unclear, and we therefore recommend that future work focus in greater detail on the application of the RCS procedure in a joint comparison of the two data sets. We would even suggest that future work should look at combining the East

Anglian and southern-central England chronologies into a single regional reconstruction.

To further test the validity of the RCS reconstruction, where substantial differences arose between the RCS curves of the fast, medium, and slow growing trees, the relevant anomalous cores were removed from the chronology and the mean curve replotted to determine if this irregular growth was biasing the overall chronology. On all occasions, removal of these cores had negligible effects as spurious growth trends were always associated with low sample replication. For example, the circa-1410 decline in fast growing tree indices coincides with just 4 fast growing trees, the circa-1250 decline with just 1–2 trees, and the circa-1730s peak in slow growing trees with just 5 trees (Fig. 14c).

An additional, but related, issue with RCS concerns the "modern sample bias" (Briffa and Melvin 2011) whereby coring for the modern section of the chronology sometimes targets only the large dominant trees within a stand. In such scenarios, coring trees on the basis of trunk radius means any young trees deemed large enough to sample must have grown much faster than similar sized, slower growing, older trees. Because the trees are standardised with reference to a single overall average expectation of growth as a function of tree age (simple RCS), this results in the older section of the chronology having lower than 'expected' growth rates whilst the younger section has faster growth rates. Thus, exclusion of the fastest growing trees from the early period, and the slowest growing trees from the recent period, contributes to an early negative and late positive bias in the chronology and, potentially, an upward sloping chronology signal, regardless of underlying climate influence (Briffa and Melvin 2011). Little bias occurs in the middle of the chronology as fast and slow biases tend to cancel out, but this is not possible at the ends and results in so-called "end effect bias". Figure 14c demonstrates this with the East Anglian material, whereby sample replication of faster growing trees increases through time, peaking in the twentieth century, whilst that of slower growing trees is seen to decline over time having peaked during the eleventh century. Consequently, detrending with a single RCS curve (Fig. 15) results in an upward slope in ring-width indices towards the modern period as the RCS curve is too shallow for fast growing trees and too steep for slow growing samples (Briffa and Melvin 2011), hence the requirement to use multiple sub-RCS curves as has been done here.

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