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A millennial long March–July precipitation reconstruction for southern-central England

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Abstract We present a millennial long dendroclimatic reconstruction of spring/summer precipitation for southern-central England. Previous research identified a significant moisture stress signal in ring-width data measured from oak trees growing in southern England. In this study, we build upon this earlier work, specifically targeting south-central England, to derive a well replicated oak ring-width composite chronology using both living and historical material. The data-set includes 352 living trees (AD 1629–2009) and 1540 individual historical series (AD 663–1925). The period expressed by at least 50 trees in any year is AD 980–2009. Calibration experiments identify the optimal seasonal predictand target as March–July precipitation (1901–2007: $r^2 = 0.33$). However, comparison with the long Kew Gardens precipitation record indicates a weakening in tree-growth/climate response from $\sim$1800 to 1920 which we speculate may be related to smoke and sulphur dioxide (SO_2) emissions at that time which may have also contributed to a decrease in tree productivity. The time-series derived using the regional curve standardisation method to capture lower frequency information shows a mediaeval period with alternating multi-decade-long dry and wet periods, with AD 1153–1172 being the wettest reconstructed 20-year period in the whole record. Drier conditions are prevalent from $\sim$1300 to the early sixteenth century followed by a period of increasing precipitation levels. The most recent four centuries of the record appear similar to the mediaeval period with multiple decade-long dry and wet periods. The late twentieth century is the second reconstructed wettest period. These centennial hydroclimatic trends are in broad agreement with independent regional scale hydroclimatic reconstructions from tree-ring (East Anglia), historical, speleothem and peat water level proxy archives in the United Kingdom and appear coupled with reconstructed sea surface temperature changes in the North Atlantic which in turn influence the Atlantic meridional overturning circulation and westerly airflow across the UK.

Keywords Hydroclimate · Precipitation · Reconstruction · Tree-rings · Oak · Southern England

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1 Introduction

Over the last two decades the focus on studying past hydroclimatic variability has largely been secondary when compared to the study of temperature change even though precipitation probably has a greater influence on economic and agricultural stability than temperature. This is especially true for temperate Europe, where there is a predominance of local/regional based reconstructions of temperature (e.g. Hughes et al. 1984; Briffa et al. 1988,

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1992; Eronen et al. 2002; Grudd et al. 2002; Gunnarson and Linderholm 2002; Wilson et al. 2005a; Büntgen et al. 2006, 2008; Grudd 2008; Dobrovolný et al. 2009; Leijonhufvud et al. 2010; Loader et al. 2011) but very few precipitation reconstructions. Despite the successful development of spatially almost complete millennial long tree-ring based estimates of precipitation and drought indices for much of North America (Cook et al. 2004, 2010), similar spatial analyses are not yet possible for Europe when using tree-ring data alone (Büntgen et al. 2010a). This predominantly results from the paucity of long (>500 years) moisture sensitive tree-ring records (Brázdil et al. 2002; Wilson et al. 2005b; Helama et al. 2009; Büntgen et al. 2010b, 2011) although multi-proxy studies have derived 500-year long spatial hydroclimatic information for Europe (Pauling et al. 2006) and the Mediterranean region (Nicault et al. 2008). Büntgen et al. (2010a) recently highlighted the difficulty of deriving spatially complete reconstructions of past hydroclimate across Europe and emphasised the need for a denser network of moisture stressed tree-ring chronologies to be derived and compiled, especially focusing on the use of historical tree-ring material to extend living tree chronologies (Wilson et al. 2004).

There are no long (>500 years) published annually resolved proxy records of past precipitation for the United Kingdom (UK) although long-term changes in hydroclimate have been examined using speleothems (NW Scotland—Proctor et al. 2000, 2002) and water table estimates using testate amoebae (Multiple regions in the UK—Langdon et al. 2003; Charman and Hendon 2000; Charman et al. 2006). These archives, however, need to be interpreted cautiously due to uncertainties in age-depth modelling and complex interactions between temperature and precipitation within the proxy record. Some qualitative past climatic information has also been developed using historical documents for England (Lamb 1965; Ogilvie and Farmer 1997). With the relative sparse amount of hydroclimate proxies in the UK, tree-rings could therefore provide an important proxy data source for reconstructing past interannual, multi-decadal and possibly longer time-scale hydroclimatic variation for the UK.

During the late 1970s, for archaeological purposes, several British tree-ring laboratories produced long oak ring-width (RW) chronologies for different regions around the UK using both living and historical samples. While dendrochronological dating of oak samples was established early on, the question arose as to whether such data could be used to derive information on past climate. Hughes et al. (1978) found that oak trees growing in Ireland, Scotland and Wales could sometimes show a significant climate response and that such data could be used to explore temporal and spatial climatic changes. However, Pilcher and Baillie (1980) found no strong climatic influence on oak growth when examining eight oak chronologies from around the UK (three from Scotland and five from England). Briffa (1984), Jones et al. (1984) and Briffa et al. (1985) expanded on the Hughes et al. (1978) work and showed that reasonably calibrated ($r = \sim 0.5$–~ 0.6) indices of aridity (soil moisture) and streamflow could be developed from oak RW data, especially in southern and central England. Kelly et al. (2002), however, using a pan-European oak ring-width network, highlighted the mixed nature of the climatic signal in extreme (i.e. wide and narrow) ring-width years. They found a close coupling between the spatial pattern of extreme signature years and the spatial influence of the Arctic Oscillation and its influence upon westerly airflows across north-western Europe. Kelly et al. (2002) concluded that wide rings in Oak were related to increased wintertime westerly air flow across the North Atlantic and enhanced cyclonic activity over northern Europe resulting in abundant soil-moisture during the growing season. Thinner rings, on the other hand, appeared to result from both colder winter conditions and enhanced anticyclonic activity reducing soil-moisture in the growing season.

Despite the complexities of the climate signal within British oak RW data (Pilcher and Baillie 1980; Hughes et al. 1978; Briffa 1984; Kelly et al. 2002), the recent central European studies by Büntgen et al. (2010b, 2011) indicate that such data remain the best chance to reconstruct past mean state changes in hydroclimate for the UK at interannual and longer time-scales and will help place recent hydroclimatic changes into a longer term context (Marsh et al. 2007). This paper, along with an independent companion paper (Cooper et al. 2012), present the first attempts at compositing both living and historical tree ring data to derive millennial length precipitation reconstructions for southern England.

2 Tree-ring data

It is often considered "best practice" in dendroclimatology to target stands of trees where tree-growth is limited by one dominant climate parameter (e.g. upper tree-line for temperature, lower tree-line for precipitation, Fritts 1976). However, when utilising historical tree-ring material, as the original provenance of tree growth is not known, such strategic sampling is often not possible (Wilson et al. 2004). In the United Kingdom, to exacerbate further this problem, very few locations exist where "natural" oak woodland exists. In fact, arguably, there is no British woodland where management has not affected tree-growth in some way. This causes a difficult dilemma for the dendroclimatologist who, on one hand, wants to optimise the desired climate signal to be reconstructed—normally facilitated through careful site selection—but on the other, wants to ensure as a homogeneous a common signal as possible back in time. Although previous work in England clearly identified some oak ring-width chronologies to have a significant moisture stress signal (Hughes et al. 1978; Briffa 1984; Jones et al. (1984) and Briffa et al. (1985)), some sites, for a variety of ecological and management specific reasons, show little or no significant relationship with hydroclimatic variables. Therefore, as some living sites (of known provenance) do not express a significant climate signal, it is likely that some historical tree-ring data (of unknown provenance) will also not cohere strongly with climate.

In some rare situations it is possible to split historical tree-ring data into "climatically" and "non-climatically" sensitive groups (Wilson et al. 2004; Wilson and Topham 2004) using the changing statistical properties of tree ring-width chronologies along elevational/ecological gradients (Wilson and Hopfmueller 2001). Such an empirical approach to data splitting, however, is not possible when using oak ring-width data in England as the oak tree response does not consistently vary with the slight elevational differences observed between sites. Therefore, for this study, we adopt a conservative approach and simply aim to use all available oak ring-width data (living and historic) from central-southern England (an area broadly bounded by 51°–52.30°N and 2.5°–0°W), a region where many oak ring-width chronologies have been shown to express a degree of correlation with spring/summer hydroclimate parameters (Briffa 1984; Briffa et al. 1985). The pool of historical Oak ring-width data, from which the data for this study was collated, has been collected by multiple individuals and tree-ring laboratories over the last 25-years (see Acknowledgements). The only criteria for data inclusion are that (1) the ring-width data are derived from oak (*Quercus petraea* Liebl. or *Q. robur* L.) and (2) the ring-width series crossdate dendrochronologically (i.e. correlate) enabling precise dating therefore signifying a common regional growth signal. Data collation was also made to ensure that for every year for the last 1000 years, a minimum of 50 series replication was attained to ensure a robust utilisation of the regional curve standardisation method (Mitchell 1967; Cook et al. 1995; Briffa et al. 1996; Esper et al. 2003; Briffa and Melvin 2010).

A total of 352 living ring-width series from 15 sites and 1540 historical ring-width series were identified, with a substantial amount of the data spatially weighted to Oxfordshire, Hampshire, and Wiltshire (Table 1; Fig. 1). Note that in the north-west part of the target area, living data were available from Ludlow (Fig. 1; Table 1). As these data were located some distance from the main cluster of data, we also ensured that a reasonable amount of historic data was included from this part of the country (Shropshire).

Table 1 Summary information for the individual living ring-width chronologies

Site name	ITRDB/ other code	County	Region	No. of series	Full length	Latitude (N)	Longitude (E)	Elevation (m)	RBAR	EPS	N (EPS 0.85)
Ludlow	LUD	Shropshire	CENT	15	1823–1978	52.21	−2.44	185	0.485	0.93	6.0
Stoneleigh Abbey	STO	Warwickshire	CENT	16	1701–1998	52.20	−1.32	70	0.241	0.84	17.8
Bradfield	BRAD	Warwickshire	CENT	10	1879–1984	52.15	−1.15	130	0.420	0.88	7.8
Charlbury	CHA	Oxfordshire	SE	17	1828–1979	51.52	−1.30	130	0.473	0.94	6.3
Yanworth	YAN	Gloucestshire	SE	24	1738–1979	51.49	−1.54	180	0.427	0.95	7.6
Oakley	OAK	Oxfordshire	SE	16	1847–1978	51.48	−1.07	70	0.455	0.93	6.8
Wytham Woods	WYT	Oxfordshire	SE	22	1766–1999	51.46	−1.20	130	0.396	0.94	8.7
Brasenose Wood	BSN	Oxfordshire	SE	41	1757–2009	51.44	−1.11	100	0.348	0.96	10.6
Radley	RAD	Oxfordshire	SE	18	1812–1979	51.42	−1.13	70	0.531	0.95	5.0
Hardwick Estate	HWK	Oxfordshire	SE	21	1764–1999	51.30	−1.02	140	0.301	0.90	13.2
Mapledurham Estate	MPL	Oxfordshire	SE	73	1751–2009	51.29	−1.01	100	0.252	0.96	16.8
Savernake	SAV	Wiltshire	SW	23	1725–2006	51.24	−1.42	170	0.301	0.91	13.2
Salisbury	SALS	Wiltshire	SW	10	1797–1968	51.24	−1.42	170	0.457	0.89	6.7
Bath	BATH	Somerset	SW	14	1754–1979	51.22	−2.19	45	0.373	0.89	9.5
Crabwood	CBW	Hampshire	SE	31	1629–2009	51.04	−1.23	120	0.315	0.93	12.3

RBAR = mean inter-series correlation; EPS = expressed population signal; N (EPS 0.85) is the theoretical number of trees needed to acquire an EPS value of 0.85

3 Methods

3.1 Spatial signal assessment

The relatively large spatial coverage of both the living and historic data (Fig. 1) begs the question as to whether it is appropriate to pool all the ring-width data into one regional composite record. This is especially important to address as the dominant control on growth is moisture availability (Briffa 1984; Jones et al. 1984 and Briffa et al. 1985) and the variability of precipitation is more spatially heterogeneous than temperature. Wigley et al. (1984a), using principal component analysis of seasonal precipitation station series from England and Wales over the 1861–1970 period, identified 5 coherent regions of distinct precipitation variability (their central, South-West and South-East regions are shown in Fig. 1). However, their first principal component (explaining ~50% of the overall variance) for both the winter and summer seasons was weighted roughly to the same region covered by the ring-width data collated in this study. This result, in itself, provides a strong rationale for pooling all the data together to derive one large composite ring-width chronology for the south-central England region.

Prior to any analysis, the 15 site ring-width chronologies were detrended using a 100-year cubic smoothing spline (Cook and Peters 1981) after appropriate power transformation of the raw data to minimise end-effect index inflation (Cook and Peters 1997). To assess the common signal between the chronologies, between chronology correlation and principal component analysis were then undertaken over the 1880–1968 period. Over the same period, to assess their potential as precipitation proxies, simple correlations were also generated between each chronology and March–July precipitation using the appropriate regional precipitation series for their location (Alexander and Jones 2001)—based on regions defined by Wigley et al. (1984a). March–July is the optimal seasonal hydroclimatic parameter identified for dendroclimatic reconstruction (see later).

3.2 Large scale composites

The aim of this study is to derive a regional-scale composite chronology which will maximise the common signal in the ring-width data and minimise site specific effects. Firstly, focussing on the three hydroclimate regions of Alexander and Jones (2001), initial regional composites

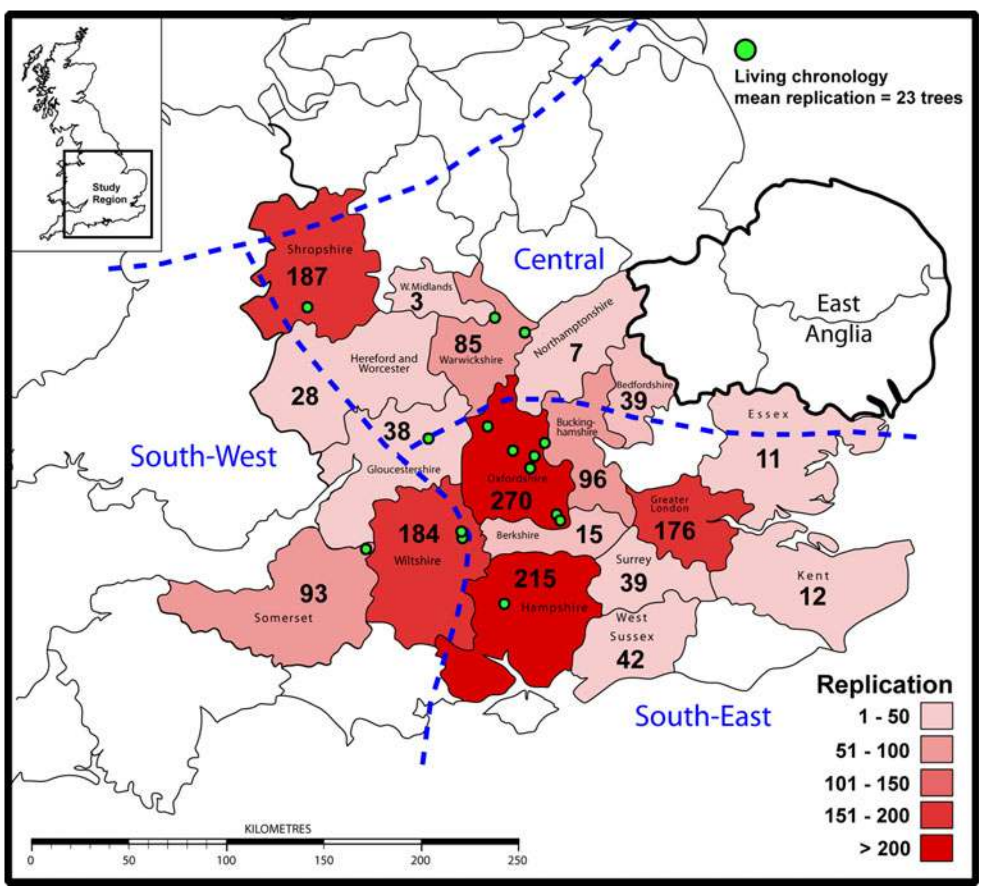


Fig. 1 Location map of living-tree chronologies used in this study and the number of historical tree-ring series used for each county. The *blue dashed lines* denote the divisions of the UK Meteorological Office regional precipitation series (Alexander and Jones 2001). East Anglia denotes the region targeted for the independent Cooper et al. (2012) study

were derived for the combined South-West and central (hereafter referred to as SW-CENT) and South-East (hereafter referred to as SE) regions to ascertain whether the inclusion of the ring-width data away from the main SE region would improve the overall "expressed" signal strength and modelled climate signal in the final large scale composite. The data for both these regional composite records were detrended in the same way as for the individual living site chronologies (e.g. 100-year spline). Correlation analysis was used to explore the stability of the coherence between these two composite series through time while correlation response function analysis, over the periods 1873–1939 and 1940–2006, explored the temporal stability of the response of these data to precipitation. Spatial correlations were also made against gridded precipitation data (Schneider et al. 2008) to identify the spatial response of the ring-width data.

Two chronology versions were developed for the full south-central England composite oak data-set. To maximise high-mid frequency common variability, the ring-width data were initially detrended using the 100-year spline approach used above (hereafter referred to as SPL100). However, such a data-adaptive approach to detrending is not appropriate for capturing potential longer time-scale information (Cook et al. 1995). Therefore, the ring-width data were reprocessed using the regional curve standardisation (RCS) method (Mitchell 1967; Cook et al. 1995; Briffa et al. 1992, 1996; Esper et al. 2003; Briffa and Melvin 2010) which can potentially capture secular-scale variability at frequencies greater than the mean length of the samples. The derivation of the RCS chronology is detailed in the "Appendix" and is hereafter referred to as RCSsf.

3.3 Dendroclimatic reconstruction: calibration and verification

Utilising the results from the correlation response function and spatial correlation analyses, calibration and verification of the full Oak composite record was made against the optimal season derived from a gridded area representative of the spatial correlations greatest influence. A classical split period (1901–1954 and 1955–2007) approach was adopted for calibration and verification. Calibration was performed on one independent period and verification undertaken on the other. Calibration of the oak ring-width composite was made using simple linear ordinary least squares regression while verification was made using the stringent coefficient of efficiency (CE) statistic (Cook et al. 1994) to assess temporal stability of the calibrated relationship. CE is a measure of shared variance between the actual and modelled series and any value over zero indicates robust reconstructed values when compared to independent climate data not used in the calibration period. Calibration and verification was conducted separately using both SPL100 and RCSsf versions of the Oak composite chronology to determine the influence of the different detrending methods on reconstruction robustness.

Further validation of the calibrated Oak signal was possible using the long instrumental precipitation record from Kew Gardens, London (1697–1999) which is situated within the met office South-East region and located ~50 km to the south-east of Oxfordshire where most of the living chronologies are located (Fig. 1). To assess the long-term temporal stability of the calibrated signal, running 31-year correlations were calculated between the oak composite chronology and Kew data in addition to the gridded data used for calibration (Schneider et al. 2008; Fig. 7) and the SE regional data (Alexander and Jones 2001). A Kalman filter analysis (Visser and Molenaar 1988) was also undertaken between the oak composite chronologies and the long Kew Gardens precipitation record to further assess the temporal stability of the calibrated signal.

4 Results

4.1 Spatial signal assessment

Table 2 presents the correlation matrix between the 15 living ring-width chronologies using the SPL100 chronologies as well as their 1st differenced transforms. On the whole, the between series correlations are weaker for the SPL100 chronologies, suggesting a degree of weaker common variability in the lower (mid) frequencies which may likely be related to varying site ecologies, localised disturbance and different management practices across the study region. It is only possible to maximise the common (presumably climate) signal, and minimise this site-specific non-climatic ecological/management related "noise" by sampling many sites and ensuring consistently high replication, as done in this study.

Figure 2a graphically presents the principal component analysis and highlights those chronologies that weigh most strongly on the first three eigenvectors (which together explain almost 70% of the total variance—Table 3). Overall, there is a loose agreement between the loadings and the hydroclimatic regions identified by Wigley et al. (1984a). PC1 represents the chronologies that are clustered within the South-East region, PC2 represents the South-West region while PC3 expresses mostly those sites from the central region.

The significance of the correlation (1880–1968) between each ring-width chronology and March–July precipitation (optimal season for reconstruction—see later) is shown in

Table 2 Correlation matrix (1880–1968) between the 15 oak ring-width chronologies—SPL100 (upper) and 1st differenced (lower) versions

	LUD	STO	BRAD	CHA	YAN	OAK	WYT	BSN	RAD	HWK	MPL	SAV	SALS	BATH	CBW	SPL mean
LUD		0.38	***0.11***	0.34	0.23	0.47	0.40	0.36	0.25	0.32	0.43	0.43	***0.17***	0.21	0.20	0.31
STO	0.54		0.35	0.62	0.41	0.59	0.37	0.58	0.53	0.54	0.52	0.43	0.50	0.46	0.50	0.48
BRAD	0.38	0.37		0.33	***0.15***	0.23	***0.12***	0.22	0.19	0.28	0.28	0.31	0.39	0.30	0.19	0.25
CHA	0.49	0.63	0.39		0.44	0.68	0.55	0.69	0.69	0.63	0.65	0.45	0.53	0.57	0.52	0.55
YAN	0.26	0.42	0.20	0.50		0.34	***0 17***	0.25	0.22	0.22	***0.09***	0.47	0.58	0.32	0.37	0.30
OAK	0.45	0.60	0.49	0.70	0.35		0.59	0.73	0.75	0.57	0.64	0.36	0.34	0.51	0.48	0.52
WYT	0.55	0.62	0.43	0.78	0.33	0.78		0.66	0.60	0.36	0.73	0.32	***0.17***	0.20	***0.16***	0.39
BSN	0.51	0.66	0.48	0.77	0.36	0.75	0.87		0.75	0.58	0.69	0.32	0.39	0.46	0.41	0.51
RAD	0.38	0.51	0.39	0.73	0.28	0.74	0.79	0.81		0.65	0.66	0.29	0.43	0.46	0.57	0.50
HWK	0.50	0.43	0.47	0.65	0.32	0.59	0.66	0.66	0.67		0.61	0.34	0.36	0.50	0.58	0.47
MPL	0.60	0.59	0.46	0.73	0.32	0.75	0.82	0.80	0.74	0.77		0.38	0.22	0.35	0.31	0.47
SAV	0.51	0.50	0.42	0.62	0.54	0.49	0.55	0.56	0.41	0.67	0.58		0.42	0.27	0.24	0.36
SALS	0.35	0.42	0.37	0.63	0.45	0.45	0.56	0.56	0.56	0.61	0.51	0.55		0.62	0.62	0.41
BATH	0.28	0.37	0.42	0.58	0.27	0.49	0.48	0.55	0.49	0.62	0.53	0.48	0.70		0.71	0.42
CBW	***0.17***	0.31	0.25	0.55	0.23	0.43	0.48	0.47	0.58	0.64	0.50	0.41	0.70	0.66		0.42
1st diff mean	0.43	0.50	0.39	0.62	0.34	0.58	0.62	0.63	0.58	0.59	0.62	0.52	0.53	0.49	0.46	

Bold and italicised text denotes values *not* significant at the 95% confidence level. Correlations of 0.35, 0.47 and 0.73 equate to T values (Baillie and Pilcher 1973) of 3.5, 5 and 10 respectively

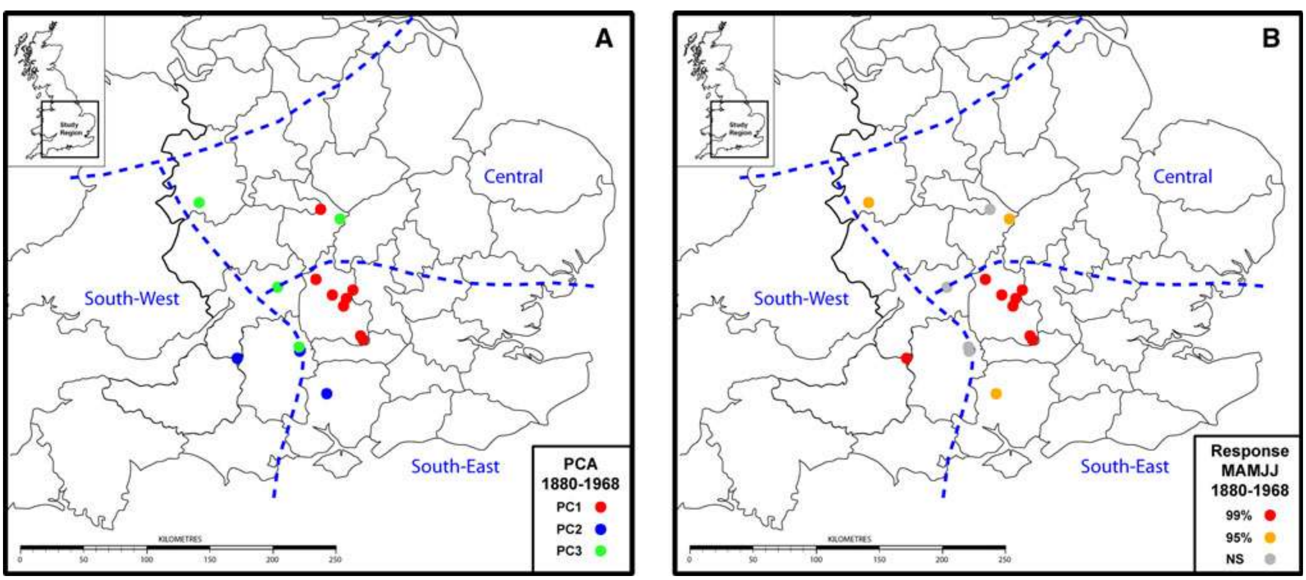


Fig. 2 **a** Principal component analysis (1880–1968, Table 3): loadings of chronologies on their dominant PC; **b** significance levels of the correlations (1880–1968) between each chronology and the appropriate regional precipitation series (Alexander and Jones 2001) for the March–July season

Fig. 2b. The coherence of the chronologies with precipitation is variable between sites with the strongest correlations being noted for most of the chronologies that load on PC1 (Fig. 2a). These results, at face value, suggest that optimal calibration would be performed using only those chronologies that are located in the SE region.

4.2 Large scale composites

To test the validity of using the living and historic data from the South-West and central regions where the climate response is weaker (Fig. 2b), a composite record was derived for this combined region (SW-CENT) and compared to the SE regional composite (Fig. 3a). In the twentieth century, the coherence between the two records is strong and time-stable (1873–1939 r = 0.73; 1940–2006 r = 0.77) suggesting a good degree of common signal. Despite the replication of the SE and SW-CENT composites varying through time (Fig. 3b), running 31-year correlations between the two series remain high (Fig. 3c) over most of the last millennium with correlation values only falling below 0.5 prior to ~1130 when replication in both data-sets starts to decrease (Fig. 3b). Figure 3d compares the composite chronologies after being smoothed with a 15-year spline. Although they compare quite well (r = 0.61), running 101-year correlations (Fig. 3c) indicate periods (centred on the ~1130s, ~1480s, ~1650–1690 and ~1900s) where the decadal common signal between the regional records is weaker, suggesting that higher replication may be required to derive a robust estimate at mid-frequencies.

Figure 4a–d present correlation response functions (1873–1939 and 1940–2006) for the two regional ring-width composite records against monthly precipitation data for the SE region as this data-set results in the strongest results for both composites (Alexander and Jones 2001). The response of both records is stronger for the later period showing significant correlations with March, April, June and July precipitation. SW-CENT expresses a similar response except correlations with July are not-significant at the 95% C.L. The correlations of SE and SW-CENT to March–July precipitation are 0.64 ($p < 0.001$) and 0.62

Table 3 Principal component analysis (1880–1968) loadings for each chronology

	PC1	PC2	PC3
	47.80%	12.00%	8.30%
MPL	**0.87**	0.12	0.16
WYT	**0.84**	-0.07	0.18
BSN	**0.80**	0.33	0.13
RAD	**0.76**	0.47	0.01
OAK	**0.75**	0.34	0.22
CHA	**0.63**	0.49	0.33
HWK	**0.59**	0.51	0.09
STO	**0.47**	0.44	0.43
CBW	0.23	**0.84**	0.09
BATH	0.24	**0.80**	0.15
SALS	0.05	**0.73**	0.48
SAV	0.26	0.08	**0.80**
YAN	-0.02	0.38	**0.70**
LUD	0.48	-0.13	**0.55**
BRAD	0.10	0.30	**0.38**

The percentage values denote the amount of variance each rotated PC explains of the original data matrix

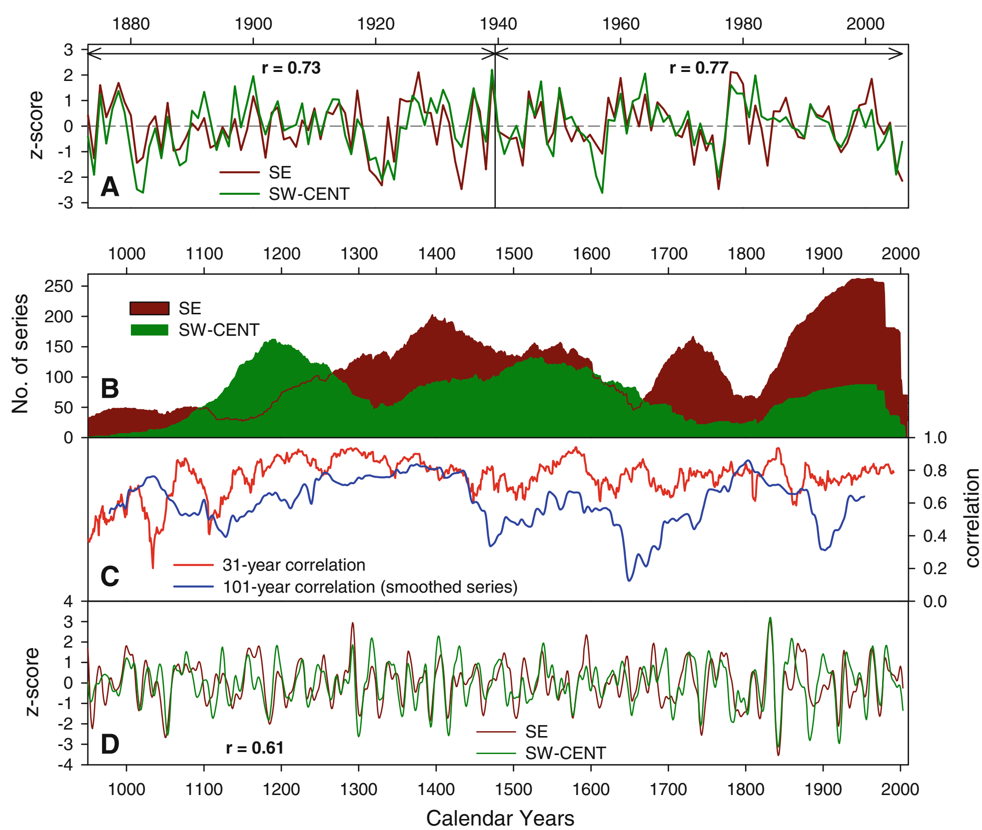


Fig. 3 **a** Comparison (1873–2006) of the SE and SW-CENT regional Oak composite ring width chronologies; **b** series replication of the SE and SW-CENT data-sets; **c** running 31-year (unfiltered) and 101-year (15-year spline smoothed series) correlations; **d** normalised smoothed 15-year spline versions of the SE and SW-CENT composite chronologies

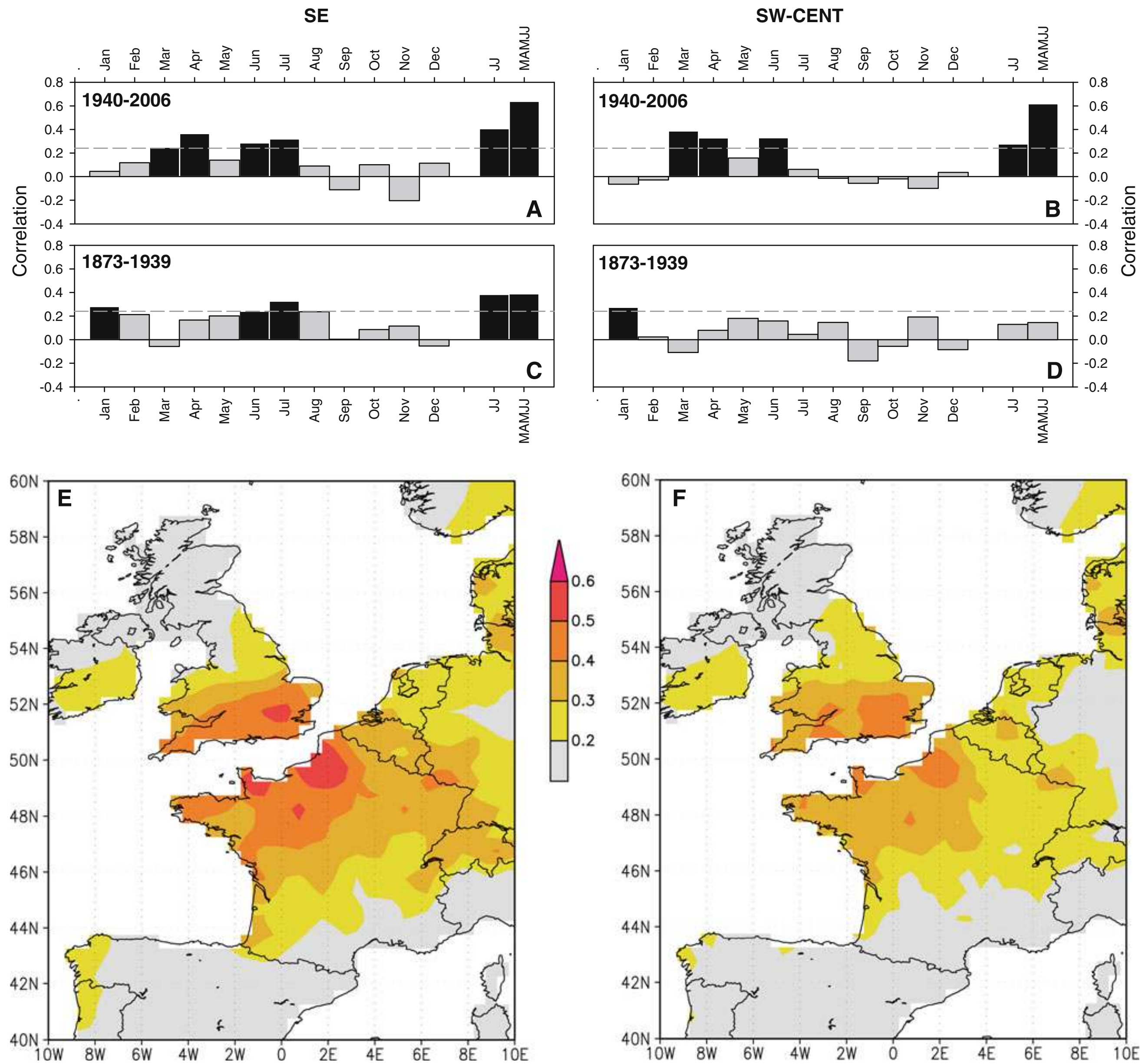


Fig. 4 **a**, **b** Correlation response functions analysis for the SE and SW-CENT composite series over the 1940–2006 period; **c**, **d** as **a** and **b** but for the 1873–1939 period. Horizontal *dashed lines* denote correlations (≥0.24) significant at the 95% confidence limit; **e** spatial correlation analysis between the SE composite series and gridded precipitation data (Schneider et al. 2008) for the Mar-July season; **f** as **e** but using the SW-CENT composite series

($p < 0.001$) respectively. These correlations, however, weaken markedly over the earlier period to 0.39 ($p = 0.001$; Figure. 4c) and 0.14 ($p = 0.26$; Fig. 4d). This significant weakening in response of the ring-width data to late nineteenth/early twentieth century precipitation is examined later in the paper. Finally, Fig. 4e, f show the spatial correlations (1901–2007) of the two regional composites with gridded precipitation data (GPCC-version 4—Schneider et al. 2008) over the NW European sector. As expected, the correlations are stronger using the SE regional ring-width data, but the general spatial pattern for both records is similar. Intriguingly, despite most of the tree-ring data coming from southern central England (Fig. 1), significant correlations are also noted against gridded precipitation data in northern France. This observation is important when addressing the weakening in response and deriving a stable calibration/verification model (see later).

The results above demonstrate that there is generally a strong common signal between the individual ring-width chronologies (Table 2), especially when multiple sites are averaged together to form regional composites (Fig. 3).

Importantly, the bulk of the oak ring-width data represent the same general region expressed by the dominant mode of summer precipitation variability (PC 1 explaining ∼50% of overall variance) in England and Wales (Wigley et al. 1984a). However, the response to precipitation of the ring-width data from the SW and CENT regions is significantly weaker than those from the SE region. Although it is tempting to utilise only the SE regional ring-width data, we believe that such an approach would be flawed as the exact provenance of the historical material is not known, although most historical construction material is likely to have been felled locally (Miles 2006). Despite this, the common signal between the SE and SW-CENT chronologies (Fig. 3c, d) remains consistently strong over most of the last millennium. Therefore, we adopt a prudent approach and utilise the whole tree-ring data-set (1892 ring-width series) to maximise the replication and common signal strength of the full composite record.

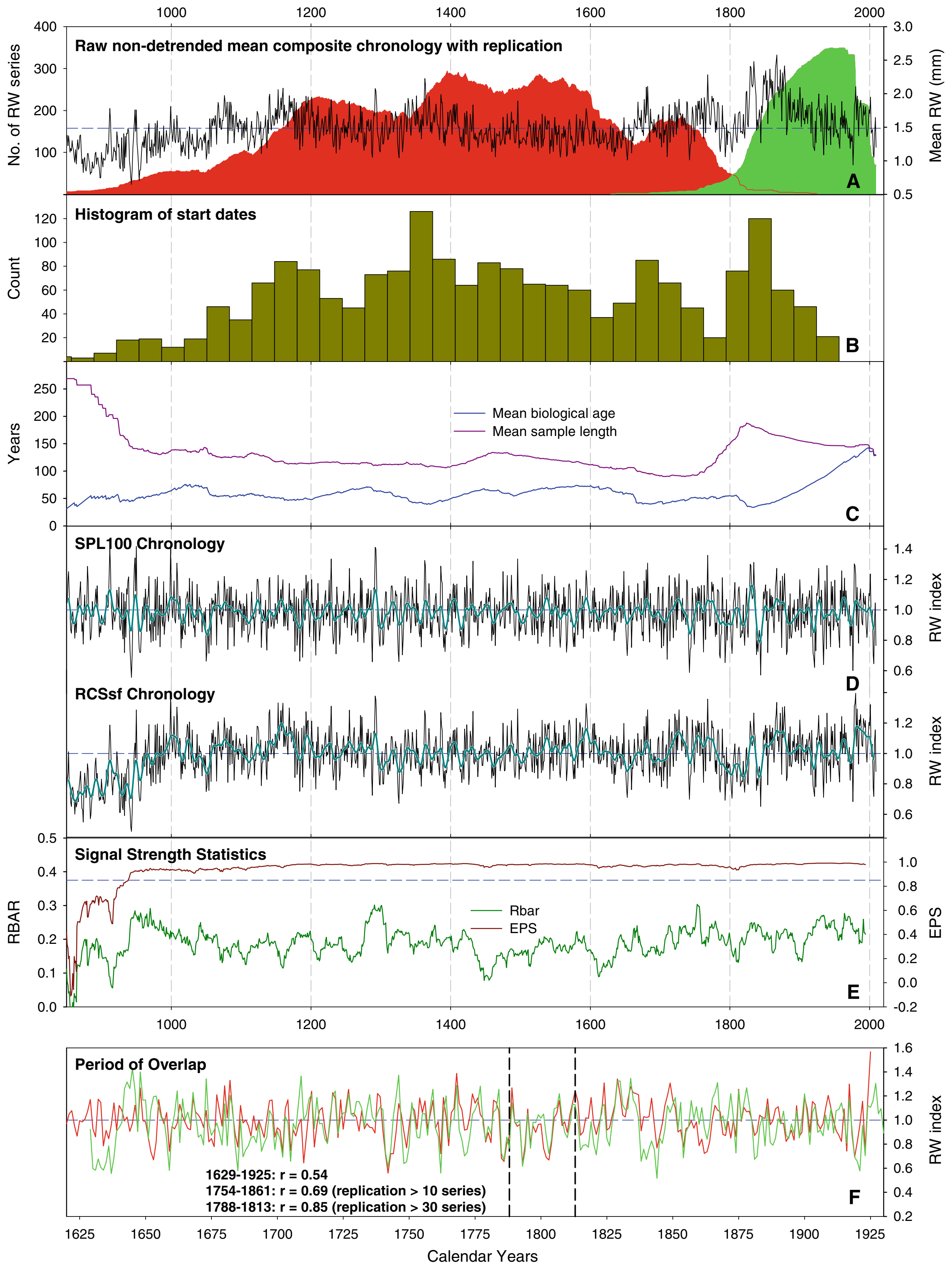
The south-central England oak data-set is highly replicated (Fig. 5a) with the period from AD 980–2009 represented by at least 50 trees although many periods have substantially more. Figure 5b presents a histogram of the start dates of the individual series, with peaks coinciding with above average ring-widths (Fig. 5a). This highlights the higher juvenile ring-width values expressed by the 'classic' negative exponential decreasing trend (Fritts 1976) that would be expected from trees adding on a roughly similar amount of wood each year on an expanding girth and emphasises the need for detrending the raw ring-width data. On the whole, the mean age of the samples at any 1 year (∼60 years) is relatively constant through time (Fig. 5c) although there is an inevitable increase in age (>100 years) in the late twentieth century as very young living trees were not sampled for this study. The mean length of the samples is also relatively constant (∼110 years) through time which restricts the amount of potential low frequency information that can be gleaned from such data when using data-adaptive detrending methods such as a 100-year cubic smoothing spline (Cook et al. 1995). This is clearly seen in Fig. 5d where the SPL100 chronology only expresses interannual to multi-decadal variability as any potential centennial variability has been removed through the detrending process. The signal-free RCS (RCSsf) generated ring-width composite chronology shows marginally more multi-decadal and longer scale variability.

Unsurprisingly, due to the high sample replication, the "expressed" signal strength is very good with Expressed Population Signal (EPS) (Wigley et al. 1984b) values greater than 0.85 extending back to the middle of the tenth century AD (Fig. 5e). However, the mean inter-series correlation (RBAR) values are much lower for the composite as a whole (mean = 0.18) compared to the individual site chronologies (RBAR = 0.38, Table 1). This again highlights the variable site specific signal of some sites (see Table 2) and the therefore weaker common regional signal in the large-scale composite compared to individual sites. However, even with an RBAR of 0.18, an EPS of 0.85 can be attained with ∼25 ring-width series and as replication is much higher than this for much of the record, it can be stated that the "expressed" signal strength in the composite series is numerically acceptable for dendroclimatic purposes at high- to medium-frequency timescales.

Finally, some validation of the historical ring-width data was provided by comparing these data with the living data over the period of overlap (Fig. 5f). Such a comparison must be made cautiously however as the replication of the historical (living) data decreases forward (backward) in time and so when replication is low in one or both of the records, such a comparison may not appear robust. Comparison across the overlap period, however, is a crucial step to assess the homogeneity of the common signal between living and historical TR data (Wilson et al. 2004; Wilson and Topham 2004). Overall, the living and historical standard chronologies agree very well. Over the period 1754–1861 where replication is greater than 10 trees in both data-sets, the inter-series correlation is 0.69. This value increases to 0.85 over the 1788–1813 period where replication is >30 trees. This latter result agrees empirically with the independent EPS analysis which shows that a minimum of 25 trees is needed to acquire a reasonable signal representative of the theoretical population chronology. A similar comparison is discussed and shown in the "Appendix" (Fig. 11e) for the RCSsf detrended data.

4.3 Dendroclimatic reconstruction: calibration and verification

Figure 4 shows that not only does the correlation of the oak ring-width data with mean March–July precipitation for the SE region (Alexander and Jones 2001) weakens back in time, but that the spatial correlations (Fig. 4e, f) are also significant against gridded data from northern France. Similar spatial correlations (Fig. 6—upper figures) are observed using the full SPL100 composite (Fig. 5d) with gridded precipitation indices (Schneider et al. 2008) for the 1901–1954 and 1955–2007 periods. For the latter period, the region of greatest response is centred over SE England (specifically the Greater London region), while for the earlier period, the greatest response is located over northern France. Over the full 1901–2007 period, reasonable correlations are noted for both these locations. This is an intriguing result, also noted using East Anglian (Fig. 1) Oak ring-width data (Cooper et al. 2012), which is not observed when undertaking the same spatial correlation


Raw non-detrended mean composite chronology with replication
No. of RW series
Mean RW (mm)
A
Histogram of start dates
Count
B
Years
Mean biological age
Mean sample length
C
SPL100 Chronology
RW index
D
RCSsf Chronology
RW index
Signal Strength Statistics
RBAR
EPS
Rbar
EPS
E
Period of Overlap
1629-1925: r = 0.54
1754-1861: r = 0.69 (replication > 10 series)
1788-1813: r = 0.85 (replication > 30 series)
F
RW index
Calendar Years

◀ **Fig. 5** Summary information for the full south-central England Oak composite oak ring-width record: **a** raw ring width chronology and replication of the historical and living data; **b** histogram of start dates of the individual series; **c** plots of mean biological age and mean sample length; **d** SPL100 and RCSsf chronologies (with 15-year spline filter); **e** running 31-year plots of mean inter-series correlation coefficient (RBAR) and expressed population signal (EPS) for the SPL100 chronology; **f** full period overlap comparison between the historic and living SPL100 chronologies. See the "Appendix" for the RCSsf chronology comparison between the living and historic data

analysis using the instrumental data (lower figures in Fig. 6). Therefore, to ensure that the temporally changing spatial response noted for the ring-width data is incorporated into the dendroclimatic modelling, calibration was conducted using the grid 49°–52°N0 to 2°W–2°E (box in Fig. 6), an area which incorporates SE England as well as northern France.

Figure 7 present calibration results for both the SPL100 and RCSsf chronology versions—the latter results presented in parentheses. Over the early (1901–1954) and late (1955–2007) periods, the calibration r^2 is 0.28 (0.27) and 0.37 (0.40) respectively. The CE values over the respective verification periods (1955–2007 and 1901–1954), which can be treated as the true r^2 of the regression equations (Cook et al. 1994), are 0.35 (0.37) and 0.26 (0.24), indicating a robust reconstruction for both chronology versions. The noted weakening of the signal in the early period (Figs. 4, 5, 6) is now non-significant when the gridded data from northern France are included in the calibration predictand data.

Over the full period, both versions of the oak chronology explain 33% of the precipitation variance which is typical of similar tree ring-width based reconstructions of hydroclimate from other regions in Europe (Büntgen et al.

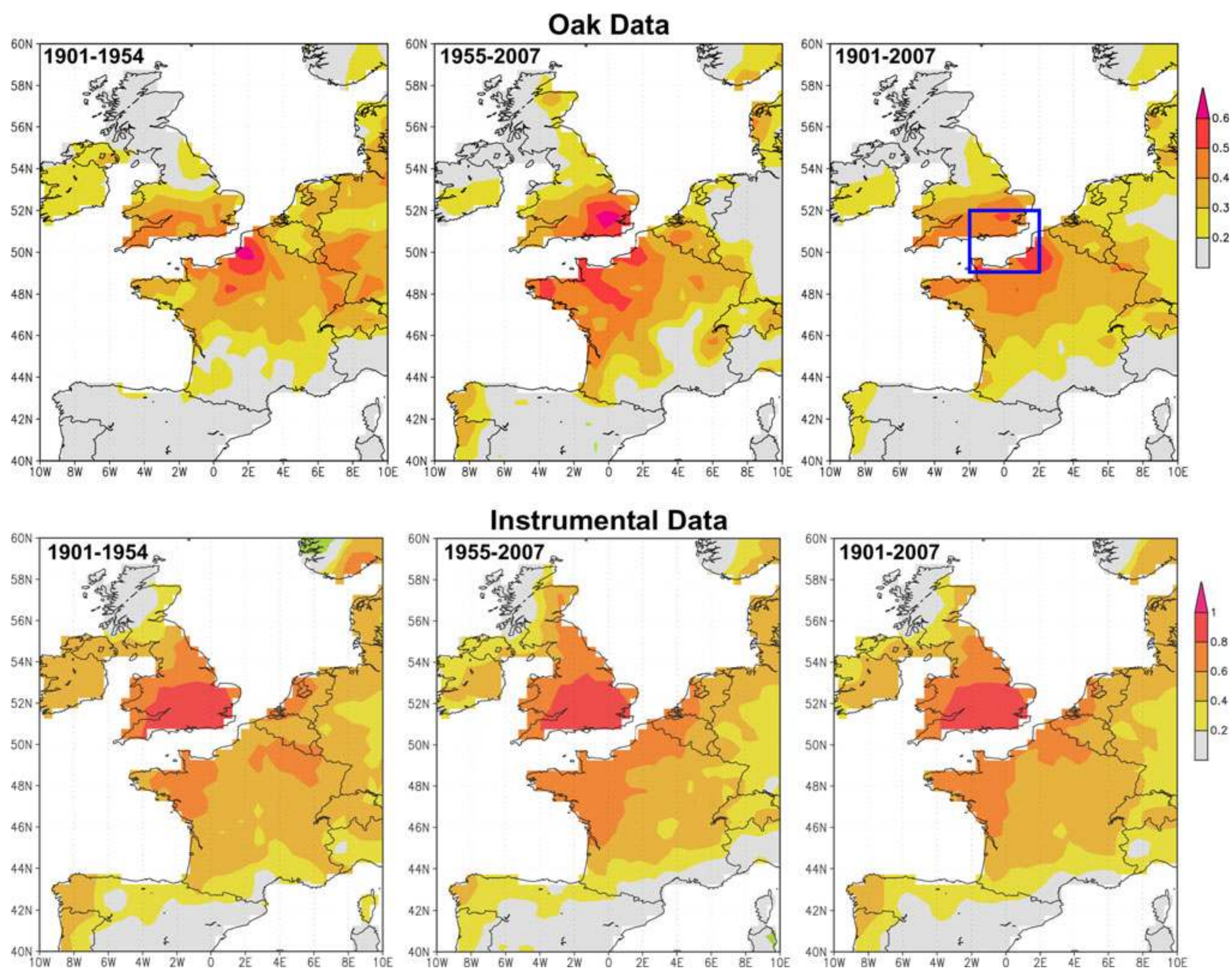


Fig. 6 *Upper figures* spatial correlation analysis between the full Oak composite chronology and gridded precipitation data (Schneider et al. 2008) for the March–July season for the 1901–1954, 1955–2007 and for the full period. The *blue box* denotes the spatial grid (49°–52°N to 2°W–2°E) used for calibration in Fig. 7. *Lower figures* as upper figures but using the gridded precipitation data from the same region as the ring width data (51–52.30°N 2.5 to 0°W)

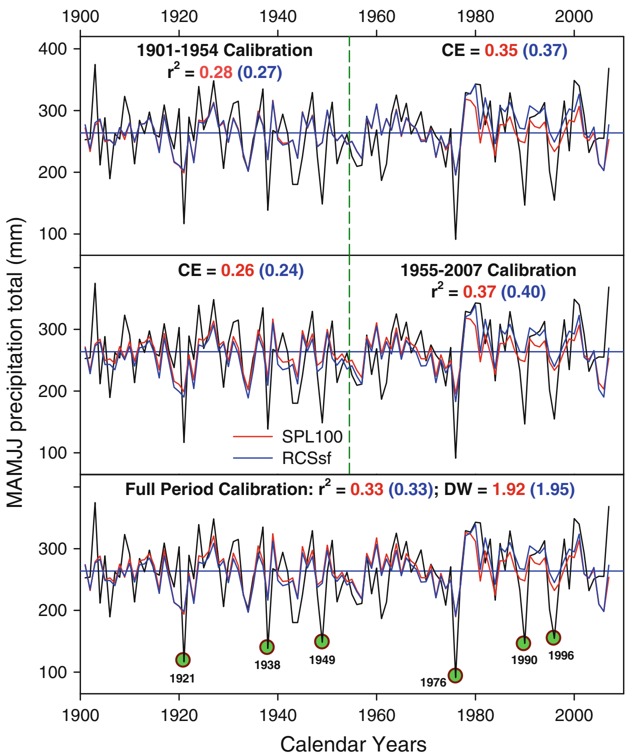


Fig. 7 Split period and full calibration and verification results for the SPL100 and RCSsf chronology versions. The circles in the lower panel highlight extreme dry years poorly modelled by the RW data

2010a; Cooper et al. 2012) and earlier oak based UK studies (Briffa 1984; Jones et al. 1984; Briffa et al. 1985). The Durbin-Watson (DW) (1951) statistic, a measure of 1st-order autocorrelation in regression model residuals, is 1.92 (1.95) indicating that the model residuals show no significant autocorrelation and that the reconstruction captures decadal variability well. However, from Fig. 7, the calibrated oak data do not appear to track the extreme dry years (1921, 1938, 1949, 1976, 1990 and 1996) in the instrumental record particularly well suggesting that the oak ring-width data are limited in their ability to reconstruct extreme seasonal drought events. This observation is partly related to the reduced variance of the reconstructed series compared to the predictand data when using OLS regression (Esper et al. 2005). We note also that calibration experiments were performed against the self-calibrating palmer drought severity index (van der Schrier et al. 2006) for the season of highest correlation (June–August season) over the 1901–2002 period for the same gridded area (49°–52°N to 2°W–2°E). However, compared to the precipitation results, the calibration was weaker ($r^2 = 0.27$ (SPL100) and 0.21 (RCSsf)) with significant autocorrelation noted in the model residuals (DW = 1.14 and 1.39).

Although the English oak composite series arguably calibrate and verify well against the gridded precipitation data incorporating SE England and Northern France (Fig. 7), the weakening in response in the early period deserves more attention. Comparison against the longer Kew Gardens record (1697–1999) allows the assessment of the long term stability of the calibrated signal. Figure 8a, b presents the running 31-year correlation and Kalman filter analysis between the varying instrumental precipitation series and the SPL100 and RCSsf chronologies. In the latter half of the twentieth century, the response of the oak ring-width data is strong with correlations exceeding 0.7. However, going back in time, the correlations weaken markedly to zero around 1900. Between 1800 and 1900 the correlation between the oak data and Kew Gardens precipitation is variable, but again becomes significant (95% C.L.) prior to 1800. The Kalman filter time-varying regression coefficients follow the same general long-term trend of the correlation values. However, although the values are weaker through the nineteenth century, the relationship with Kew Gardens precipitation remains significant suggesting only a weakening in signal at this time rather than a complete breakdown in response.

5 Discussion

5.1 Response instabilities through time

There is currently much debate within the dendroclimatic community with respect to the temporal stability of climate signals within temperature sensitive tree-ring chronologies from some sites around the Northern Hemisphere (D'Arrigo et al. 2008 and references therein). Although the ring-width data discussed here are moisture sensitive, the issue is not dissimilar and it is paramount that such response instabilities are examined and plausible hypotheses derived to explain these phenomena to avoid an uninformed over-interpretation of a dendroclimatic reconstruction. We therefore propose and discuss three hypotheses that might account for this temporal instability in the modelled climate signal of the oak ring-width data:

1. As mentioned earlier, the oak trees were not strategically sampled from climatically sensitive stands (e.g. lower tree-line, or based on site soil characteristics) where it might be expected that one climate parameter dominates tree growth. Therefore, it is possible that the climatic factors affecting growth may vary through time as the balance of limiting factors change due to changing climate. The nineteenth century was one of the coldest periods over the last 350 years (Manley 1974; Parker et al. 1992, 2005) and it is possible that the cooler temperatures at this time may have induced a partial temperature response in the trees (see also

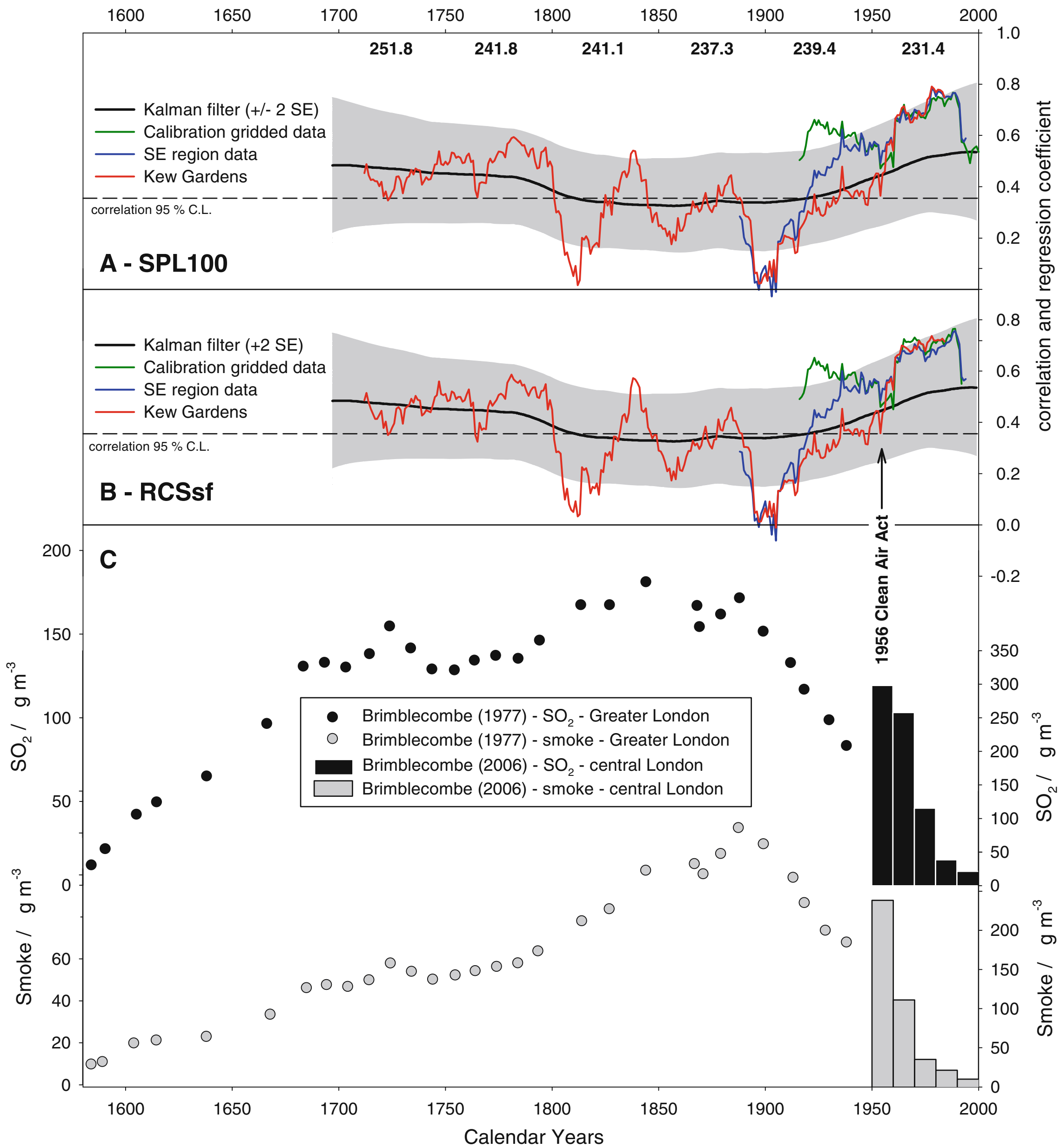


Fig. 8 **a** Running 31-year correlation plots between the SPL100 chronology and the gridded data used for calibration (Fig. 6), the SE regional data (Alexander and Jones 2001) and the Kew Gardens precipitation data for the MAMJJ season. Also shown are the results from a Kalman filter analysis (Visser and Molenaar 1988) with the Kew Gardens precipitation data. Prior to analysis the instrumental data were high-pass filtered with a 100-year spline for consistency with the SPL100 chronology; Upper bold values are 50 year interval precipitation totals (mms) for MAMJJ; **b** as **a**, but for the RCSsf chronology and unfiltered instrumental data; **c** scatter plots and histograms showing modelled (Brimblecombe 1977—Greater London) and measured (Brimblecombe 2006—Central London) SO_2 and smoke levels for the last four centuries

Cooper et al. 2012). However, correlation response function analysis, calculated using 50-year blocks from 1697 to 1999 (analysis not shown) with the central England Temperature record (Manley 1974; Parker et al. 1992, 2005) shows no significant response with monthly temperature. Thus if any influence from cooler temperatures occurred during this time, it is likely only to be relevant for individual years.

Figure 8a shows total mean March–July precipitation amounts for 50 year periods since 1700. From a moisture limiting point of view, although the 1950–1999 period was the driest period (231.4 mm) on record, precipitation levels are not significantly different to the other 50 year periods throughout the whole Kew record, so it is unlikely that the trees were markedly less moisture stressed during the nineteenth century due to higher precipitation levels.

2. The long term precipitation data from Kew Gardens was extracted from the non-corrected database of the global historical climate network (Peterson et al. 1997). Therefore, it cannot be discounted that there could be unknown homogeneity problems in the earlier portions of this instrumental series. Recent studies have shown that deviations between tree-ring proxies and earlier instrumental data are, in some specific situations, related to problems in the instrumental data rather than the proxies themselves (Wilson et al. 2005a, b; Frank et al. 2007). The deviation in correlations prior to ~1950 shown in Fig. 8a, b using the calibration grid, SE regional and Kew Gardens data may imply quality issues in one or all of the records, especially as the inclusion of data from northern France improves the calibrated signal (Figs. 6, 7). However, comparison (not shown) between long precipitation station records from Northern France and Kew Gardens does not show a systematic decrease in between-series coherence going back into the nineteenth century. Therefore, the weakening in oak response is likely not related to quality issues in the Kew instrumental data.
3. Finally, we believe that the influence of the British Industrial Revolution and accompanying pollution might also have some effect on the long-term variability of Oak growth in southern Britain. The industrial revolution started in England in the late eighteenth century and the period of weakest response of the oak data with Kew Gardens (nineteenth century) coincides with peak coal burning and associated sulphur dioxide (SO_2) pollution. Such pollution is known to affect conifer growth in central Europe (Wilson and Elling 2004; Elling et al. 2009) and it is likely that such pollution could also affect the growth of oak trees (Rinne et al. 2010). Unfortunately, there are no direct measurements of air pollutants over the last four centuries for central England with only modelled estimates of sulphur dioxide and smoke for the London region being available (Brimblecombe 1977, 2006). The lower panels in Fig. 8b show modelled (Brimblecombe 1977 for Greater London) and measured (Brimblecombe 2006 for central London) SO_2 and smoke levels for the last four centuries. The modelled SO_2 and smoke levels (~1580–1940—Brimblecombe 1977) were calculated based on coal usage and population changes in the Greater London region, while the more recent data represent actual measured SO_2 and smoke levels from central London. The difference in the two regions explains the higher values for the more recent data-set as pollution is more concentrated in central London compared to the more dispersed values of the larger Greater London area (Brimblecombe personal communication 2010).

It should be noted that the pollution data from London do not specifically represent pollution from central England. However, Viles (1996) discusses the effect of the building of the Oxford canal (1790), the great western railway (1844) and the London and north western railway (1851) which transformed Oxford from a "quiet university and market town to a large commercial and industrial centre". By the late eighteenth century Oxford was the 9th largest town in England and major gas works, ironworks and paper mills were built in the early nineteenth century (Viles 1996). By the mid-nineteenth century, there was considerable decay of the stonework of many of the older university buildings and observers at the time complained about the "smell of coal smoke" around Oxford (McLynn 1990). By the mid-twentieth century, pollution levels were already declining with SO_2 level falling from ~130 to ~70 $\mu g\ m^{-3}$ from the 1950s to 1960s with similar reductions in smoke levels (80–40 $\mu g\ m^{-3}$; Viles 1996). Although these levels are about one third of those of central London (Fig. 8b), the overall trends in pollution changes in Oxford over the last 400 years appear qualitatively similar (Viles 1996).

Despite the regional difference in representation between the pollution (from London and Oxford) and the more rurally located tree-ring data, the greater SO_2 and smoke pollution levels in the nineteenth century (Fig. 8b) coincide with the period of weakest climate response (Fig. 8a, b). The increase in response into the twentieth century also parallels the decrease in pollution levels. The period of greatest climate response clearly jumps upwards in the late twentieth century coinciding with the 1956 clean air act (Brimblecombe 2006) and resultant steep decline in SO_2 and smoke pollution. Although these qualitative observations do not provide definitive proof that pollution is the sole cause of the weakening in climate response of the oak data, they do suggest some coincidence at least and suggest that the pollution hypothesis should be more fully explored by testing the effects of such pollution on oak growth.

5.2 Dynamical validation of the 1000 year precipitation reconstruction

If the main reason for the weakening in response in the nineteenth century is indeed related to pollution, it can be hypothesised that prior to the industrial revolution, the climate signal in the oak data should improve when pollution levels are much lower or non-existent. Certainly there is an encouraging improvement in the correlation of

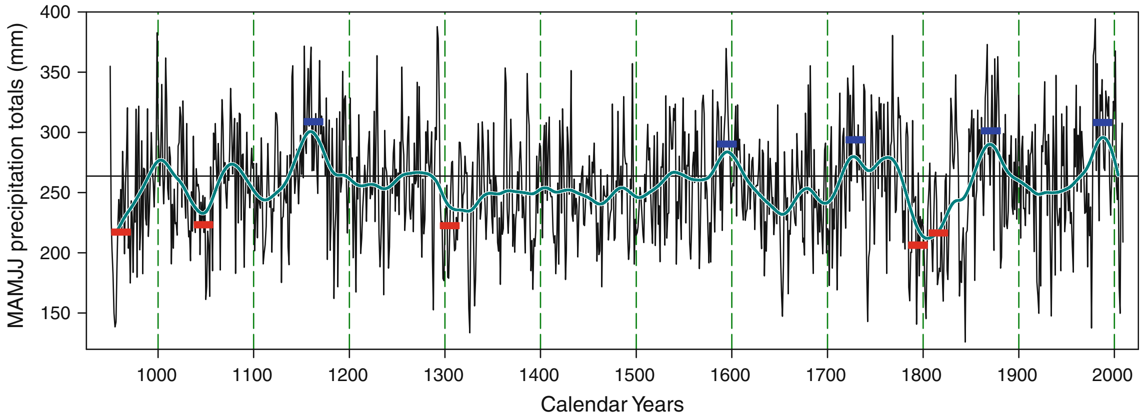


Fig. 9 Final scaled (Esper et al. 2005) composite RCSsf Oak chronology showing the reconstructed 5 driest and 5 wettest 20 year periods since AD950. See "Appendix" for derivation of this series. Smoothed time-series is a 50-year cubic smoothing spline. The horizontal line is the twentieth century precipitation average

the oak data with Kew Gardens precipitation in the eighteenth century (Fig. 8a, b) although they never attain the high values of the late twentieth century.

As the RCSsf version of the Oak chronology calibrates similarly to the SPL100 version and is theoretically less biased with respect to the capture of potential low frequency information, all further discussion focuses on the RCSsf version. The driest inferred periods from the RCSsf series (Fig. 9) are represented by the two 20 year periods 1785–1804 and 1806–1825 (Table 4). It should be emphasised however, that comparison with the Kew Gardens precipitation series shows weak coherence during the late eighteenth and early nineteenth centuries (Fig. 8a, b) and over the 1785–1825 period, the RCS series expresses precipitation values ~0.9 standard deviations below those expressed by the Kew data. It is therefore possible that conditions were not as dry as expressed by the reconstruction for this period and some other factor (e.g. pollution, or cooler climate etc.) could have reduced overall tree productivity during this period. The next three driest 20 year periods are in the medieval period at 952–971, 1295–1314 and 1038–1057 punctuated by the wettest 20-year period 1153–1172. 1978–1997 shows similarly wet conditions to the mid-twelfth centuries century wet period and the next three wettest decades are 1861–1880, 1720–1739 and 1585–1604.

Validating the pre-1700 period in the precipitation reconstruction can only be made by comparison with other proxy records. As stated earlier, however, there are few proxies of past hydroclimate in the United Kingdom. An independent oak ring-width record (310 living and 413 historical series) has been concurrently developed for East Anglia (Fig. 1—Cooper et al. 2012) which has similarly been calibrated against March–July precipitation. This series, which was also processed using the RCS methodology, correlates with the south-central Oak RCSsf composite at 0.59 and provides an important tree-ring based series for independent validation of the inter-annual to lower frequency signal. From north-west Scotland there is a speleothem growth rate record that extends back several thousand years which is related to both mean annual temperature and mean annual precipitation (Proctor et al. 2000, 2002). Charman and Hendon (2000) reconstructed water table estimates using testate amoebae from northern England peat bogs while Lamb (1965) derived a qualitative index of past precipitation and temperatures using historical documentary information. None of these latter records are annually resolved and only provide past climatic information at decadal and longer time-scales.

Table 4 The five driest and wettest 20-year periods (MAMJJ totals in mm) in the RCS Oak composite series (Fig. 9)

20 year period	Driest
1785–1804	207.2
1806–1825	217.2
952–971	217.7
1295–1314	222.6
1038–1057	223.8
20 year period	**Wettest**
1153–1172	308.9
1978–1997	308.2
1861–1880	301.2
1720–1739	294.2
1585–1604	290.5

Figure 10 compares the oak based RCSsf precipitation reconstruction with the other hydroclimatic proxy records described above. To account for the low resolution of the non-tree-ring records, the series have been smoothed with a 50-year cubic smoothing spline and standardised to

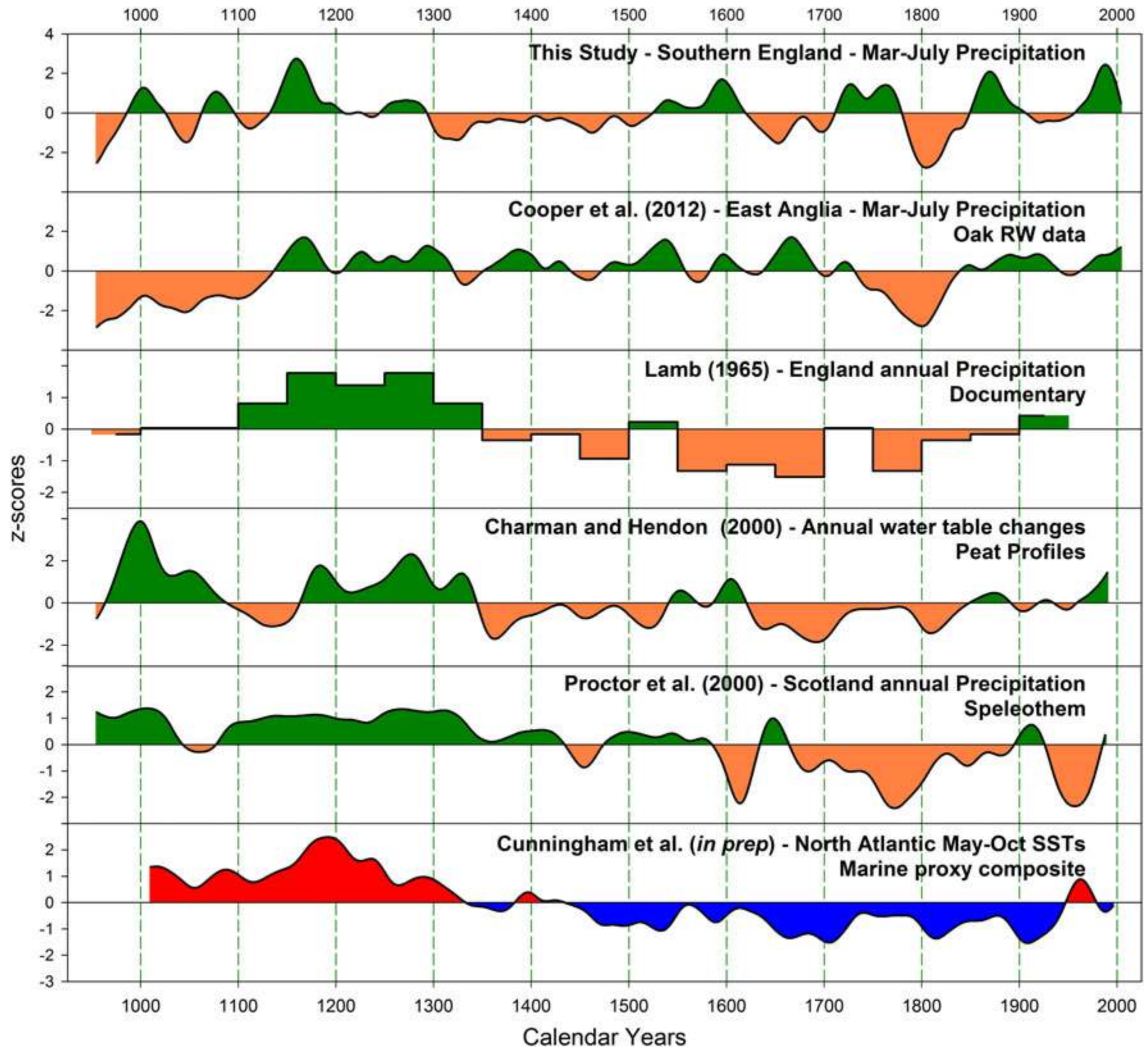


Fig. 10 Comparison of 6 proxy based reconstructions. All are hydroclimate reconstructions except the lower panel which presents estimates of sea surface temperatures for the North Atlantic. All series have been smoothed with a 50-year cubic smoothing spline except the Lamb (1965) series which is presented as the original 50-year block means. The series have been normalised to z-scores over their common period

z-scores over the common period. The Lamb (1965) record is presented as the original published 50-year blocks (see also Cooper et al. 2012). Overall, there appears to be qualitative broad agreement between the different proxy records. All records portray a consistent wetter mediaeval period from the twelfth centuries to fourteenth centuries. The start, end and duration of this wetter period is not entirely consistent between the records, with the speleothem and peat records showing wet conditions starting in the 10th/11th century while the southern England and East Anglian oak data suggest drier conditions during this time. The speleothem, peat and historic records also suggest that the drying observed following this mediaeval "wet period" occurred later than observed in the southern England tree-ring data. The East Anglian tree-ring data show slightly wetter conditions until the beginning of the eighteenth century. Ignoring potential dating errors in the non-annual proxy archives, it should be emphasised that the differences between the records could also be related to differences in seasonality with the southern England Oak data representing a spring/summer signal, while the other records also include winter.

All the hydroclimatic records, except East Anglia, show generally drier conditions between ~1400 and ~1900 (Fig. 10). Again, the start and end dates of this dry period differ between the records, but a common dry period is noted in the tree-ring, historical and peat records from the seventeenth to early nineteenth centuries. All records show a general trend towards wetter conditions from the eighteenth to nineteenth century with both the tree-ring and peat records expressing wet periods in the latter half of the nineteenth and twentieth centuries. The inferred dry period in the mid twentieth century in the speleothem record has been directly attributed to North Atlantic Oscillation (NAO) variability (Proctor et al. 2000) which has a greater impact on hydroclimate variability in north-west Scotland compared to southern England (Cooper et al. 2012).

The lowest plot in Fig. 10 is a marine based composite reconstruction (Cunningham et al. in preparation) for summer (May to October) sea surface temperatures (SSTs), utilising marine proxy data (e.g. Molluscs, foraminifera and alkenones) from the North Eastern Atlantic region. On multi-decadal to longer time-scales, warm SSTs appear to generally coincide with the wetter periods expressed in the UK hydroclimatic proxies with the transition from warm to cooler SSTs occurring in the fourteenth century. Similarly, dry periods generally agree with cooler reconstructed SSTs in the North Atlantic—the late seventeenth century not only being the driest period in most of the hydroclimatic proxies, but also one of the coldest in the SST record. These observations suggest broad scale influences of SSTs in the North Atlantic on hydroclimate across the UK. The overall agreement of the six individual proxy records in Fig. 10 is encouraging in light of the different proxy types and seasons they portray. In general, the overall secular trends they portray: wetter/warmer mediaeval period and a drier/colder "Little Ice Age" agree well with the dynamical hypothesis where, during the mediaeval climate anomaly (MCA), La Niña–like conditions predominated in the Pacific ocean inducing an intensified Atlantic meridional overturning circulation which resulted in a persistent positive mode in the NAO (Graham et al. 2007; Seager et al. 2007; Trouet et al. 2009). This period was also a time of generally warmer conditions, related in part to increased solar activity and fewer volcanically induced cooling episodes, which may have contributed to an intensification of the hydrological cycle over the northern Atlantic and resulted in wetter conditions over the British Isles.

6 Conclusion

A recent review of published tree-ring based hydroclimate reconstructions in Europe highlighted the relative sparse nature of such records (Büntgen et al. 2010a) and emphasised the need to target new locations and to explore the potential of utilising historical tree-ring material to extend records beyond the living cohort (Wilson et al. 2004). This paper, as well as the companion East Anglian oak series (Cooper et al. 2012), addresses these issues from a British perspective by compiling a highly replicated oak tree-ring data-set for southern-central England—a region where previous research has shown oak ring-width data to portray a reasonable coherence with hydroclimatic parameters (Briffa 1984; Jones et al. 1984; Briffa et al. 1985). The ring-width data-set comprised 352 living and 1540 historical series and was compiled from material sampled across a large region of southern England to maximise the large-scale common signal while minimising the site specific, ecological and management effects. The strongest climate-growth response was found with March–July precipitation ($r^2 = 0.33$) over the 1901–2007 calibration period. However, despite robust calibration and verification in the twentieth century (Fig. 7), when compared to the long Kew Gardens precipitation record, the strength of the calibrated signal is not time stable, exhibiting reduced coherence with the 1800–1920 earlier instrumental period (Fig. 8). This period coincides with the transition across much of Europe from rural to large-scale industrial economies and we hypothesise that this weakening in response is partly related to smoke and sulphur dioxide (SO_2) emissions at that time which may have also contributed to a decrease in tree productivity. The distinct improvement in response noted in the latter half of the twentieth century after the 1950s Clean Air Act supports this hypothesis.

The full March–July precipitation reconstruction (AD 950–2009—Fig. 9) shows a mediaeval period with alternating multiple decade-long dry and wet periods, with AD 1153–1172 being the wettest reconstructed 20-year period in the whole record. A prolonged 200-year relatively stable drier period then occurred from $\sim$AD1300. The sixteenth century generally shows an increasing precipitation trend while the most recent four centuries of the record appear similar to the mediaeval period with multi-decade-long dry and wet periods. The late twentieth century is the second reconstructed wettest period on record. Comparison to other independent UK based hydroclimatic reconstructions (Fig. 10) shows broad scale similar patterns with a wetter mediaeval period from the eleventh to thirteenth century (peaking in the mid-late twelfth centuries century), a prolonged period of drier conditions until the eighteenth/nineteenth centuries and the recent period showing generally wetter conditions. These broad scale centennial trends appear to cohere well with reconstructed SSTs from the North Atlantic region suggesting that moisture variability across the United Kingdom is partly coupled with North Atlantic SSTs, presumably related to changes in the Atlantic meridional overturning circulation and its effect on the North Atlantic Oscillation and westerly airflow across the UK (Graham et al. 2007; Seager et al. 2007; Trouet et al. 2009).

On-going analyses are exploring whether earlywood vessel area and stable isotope chronologies are less affected by localised air-pollution and can therefore be used to supplement or improve upon the results presented here (Loader et al. 2008). Of particular importance is the loss in calibrated signal in the eighteenth and nineteenth centuries. If pollution is indeed the main cause for this phenomenon then presumably similar response changes may well be observed in other long living/historical composite oak ring-width records across central Europe (Büntgen et al. 2010b, 2011). Such records will be important for deriving spatial reconstructions of hydroclimatic variability but a robust assessment of the stability of their climate response is required before such data-sets can be combined for large pan-European spatial reconstructions.

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Appendix: regional curve standardisation (RCS)

When using the RCS method it is assumed that the realignment of growth measurement series by ring age removes the effects of the common forcing by calendar year on the shape of the RCS curve (Briffa 1992; Briffa and Melvin 2010). This requires the rings for each ring age to be taken from a wide age distribution over time—i.e. through the use of sub-fossil trees—and failure to achieve this wide distribution over time may introduce systematic bias in resulting RCS chronologies. Figure 5c shows that there is, on the whole, a reasonably stable mean biological age through time. However, the age distribution changes in the recent period where the balance of samples shifts towards older trees. This shift in mean biological age can result in a bias in the recent portion of any chronology derived using the RCS method. Figure 11 also presents the mean age aligned regional curve using all the ring-width data. The classic negative exponential common growth form is clear. However, the 1 standard deviation range around this curve indicates the large variability in growth rates in the data. This is not surprising as the data have come from multiple locations around south-central England where differing site ecologies can affect local growth rates markedly. Using just one cambial age-aligned regional curve for RCS results in a biased long term chronology which steadily shows an increasing trend from the mediaeval period to present (not shown). To overcome this heterogeneous bias in the raw data, we experimented with multiple approaches to RCS—three of which are detailed here: (1) the ring-width data, for both the living and historic groups, were split into groups of common high/low growth rates related to the first 40 years of growth of each series. For illustration, the resultant four regional curves are shown in Fig. 11b. These curves were smoothed using a smoothing spline of 10% their length and this smoothed function used to detrend the raw ring-width data in each respective group. The detrended indices from each group were then pooled and averaged to derive the final RCS chronology; (2) As method 1 above, but the raw ring-width data were first adjusted using an adaptive power transform (Cook and Peters 1997) prior to the detrending; (3) The previous two RCS versions can potentially produce spurious results because in their derivation, the influence of the common signal between the trees (i.e. the large scale climate signal) can bias the "shape" of the age-aligned curves used to detrend the data. The potential occurrence of this systematic bias is reduced here by the use of the "signal-free" method (SFM) (Melvin 2008). In SFM, iterative methods are used to estimate and remove the common signal from the measurement series prior to developing an RCS curve.

Figure 11c compares the three RCS variants. The periods of greatest difference between the series (pre 1050 and around the 1800s) are highlighted using the standard deviation between each annual value of the three versions (Fig. 11d) highlighting the sensitivity of using different RCS approaches. For Figs. 9 and 10, we use the SFM version (defined as RCSsf) which calibrates ($r^2 = 0.33$; DW = 1.95) similarly with the gridded precipitation data as the 100-year spline detrended standard chronology (Fig. 7). Figure 11e shows the overlap between the living and historical SFM chronologies (similar to the spline version in Fig. 5f). The "noisier" nature of the RCS approach is clear when replication is low, but the 1788–1813 period, expressed by at least 30 trees in both data-sets, clearly shows that despite the period around 1800 being particularly sensitive to varying RCS approaches (Fig. 11d), the relative levels between the living and historic chronologies are similar,

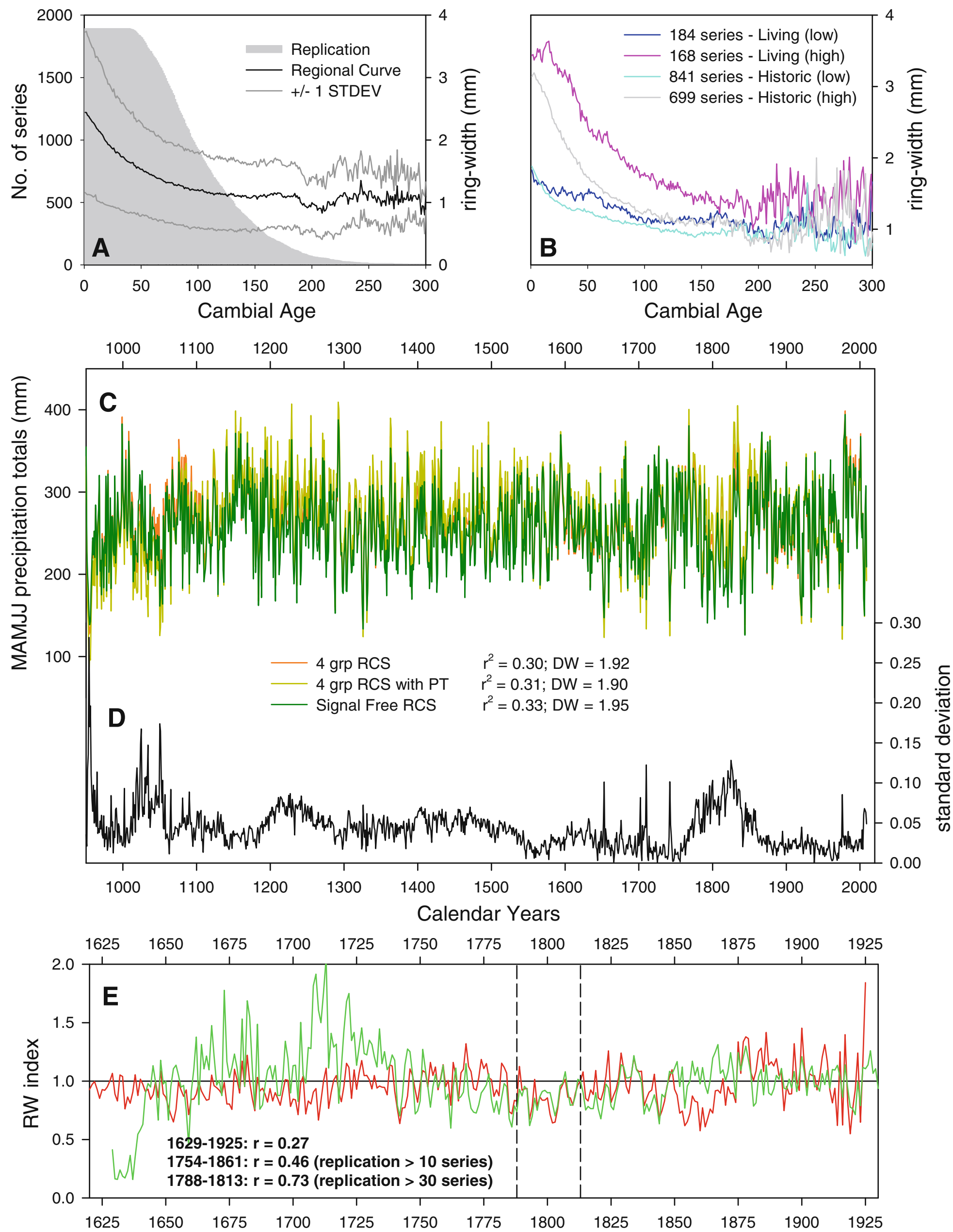

Fig. 11 **a** Cambial age aligned regional curve using all living and historical oak ring-width data; **b** age aligned curves for the growth level split living and historic groups; **c** three example RCS chronologies (see "Appendix" text for details). Each series has been scaled (Esper et al. 2005) to MAMJJ precipitation totals. R^2 and Durbin Watson results for these calibrations are shown; **d** Standard deviation calculated between the three RCS variants; **e** full period overlap comparison (as Fig. 5f) between the historic and living standard chronologies after the "signal-free" RCS detrending

indicating no relative bias between the living and historic data.

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