

# Oxygen stable isotope ratios from British oak tree-rings provide a strong and consistent record of past changes in summer rainfall

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**Abstract** United Kingdom (UK) summers dominated by anti-cyclonic circulation patterns are characterised by clear skies, warm temperatures, low precipitation totals, low air humidity and more enriched oxygen isotope ratios ( $\delta^{18}\text{O}$ ) in precipitation. Such conditions usually result in relatively more positive (enriched) oxygen isotope ratios in tree leaf sugars and ultimately in the tree-ring cellulose formed in that year, the converse being true in cooler, wet summers dominated by westerly air flow and cyclonic conditions. There should therefore be a strong link between tree-ring  $\delta^{18}\text{O}$  and the amount of summer precipitation. Stable oxygen isotope ratios from the latewood cellulose of 40 oak trees sampled at eight locations across Great Britain produce a mean  $\delta^{18}\text{O}$  chronology that correlates strongly and significantly with summer indices of total shear vorticity, surface air pressure, and the amount of summer precipitation across the England and Wales region of the United Kingdom. The isotope-based rainfall signal is stronger and

much more stable over time than reconstructions based upon oak ring widths. Using recently developed methods that are precise, efficient and highly cost-effective it is possible to measure both carbon ( $\delta^{13}\text{C}$ ) and oxygen ( $\delta^{18}\text{O}$ ) isotope ratios simultaneously from the same tree-ring cellulose. In our study region, these two measurements from multiple trees can be used to reconstruct summer temperature ( $\delta^{13}\text{C}$ ) and summer precipitation ( $\delta^{18}\text{O}$ ) with sufficient independence to allow the evolution of these climate parameters to be reconstructed with high levels of confidence. The existence of long, well-replicated oak tree-ring chronologies across the British Isles mean that it should now be possible to reconstruct both summer temperature and precipitation over many centuries and potentially millennia.

**Keywords** Precipitation · Temperature · UK · Stable isotopes · Tree-rings

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## 1 Introduction

Whilst temperature has been the major focus of research surrounding the current and future effects of anthropogenic climate change, it is changes in precipitation that are likely to have a greater impact upon society, at least in the shorter term. Better modelling of the evolution of hydro-climate in a warming world will require long and reliable reconstructions of past precipitation; however such records are hard to obtain, especially for the highly populated temperate mid-latitude regions where moisture stress is typically low. Some progress has recently been made using the ring widths of oak trees as a measure of past changes in rainfall (Büntgen et al. 2010; Cooper et al. 2013; Wilson et al. 2013), but in most regions oak growth is not strongly constrained by any

single climate variable (e.g. Hughes et al. 1978; Pilcher and Gray 1982; García-Suárez et al. 2009) and so reconstructions based upon ring-widths need to be interpreted with some caution. Stable oxygen isotopes ( $\delta^{18}\text{O}$ ) from tree-rings have the potential to reconstruct both the isotopic ratio of precipitation (e.g. Robertson et al. 2001; Saurer et al. 1997; Waterhouse et al. 2002) and past precipitation amount (e.g. Masson-Delmotte et al. 2005; Treydte et al. 2006; Rinne et al. 2013). We therefore pursue the approach of using the  $\delta^{18}\text{O}$  composition of annual oak tree-rings which, we argue, is more strongly and consistently linked to summer rainfall amount in the UK than tree growth and could therefore be used to produce very long precipitation reconstructions.

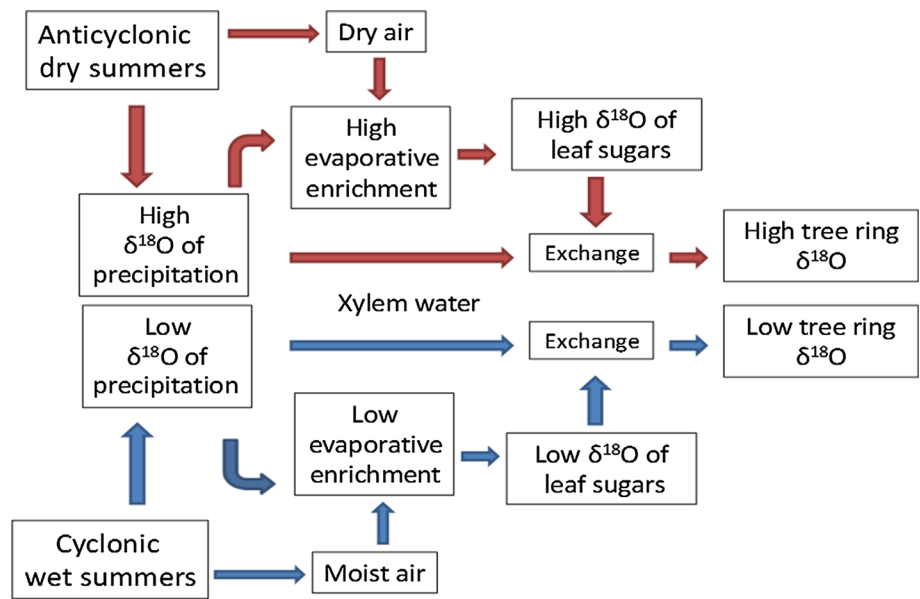
The UK and surrounding regions have some of the longest instrumental climate records in the world. These records provide clear evidence for the strong link between atmospheric circulation and summer precipitation amount over the UK. Using principle component analysis on 55 individual precipitation records from the UK, Éire, France, Belgium and the Netherlands over the period AD 1861–1970, Wigley et al. (1984) demonstrated that there is a strong common precipitation signal over what they defined as the ‘England and Wales precipitation (EWP) region’, with PC1 explaining 45.3 % of the variance in annual precipitation and 49.9 % in summer (June–August) precipitation. The link between circulation and precipitation can be demonstrated using Lamb’s UK weather types, which provide a method of classifying atmospheric circulation patterns (Lamb 1972; Jenkinson and Collison 1977; Jones et al. 2013). Summer (June–August) atmospheric total shear vorticity ( $Z$ ), which is a measure of the circulation of the atmosphere (positive values being cyclonic and negative anticyclonic), over the UK has a product moment correlation coefficient ( $r$ ) with the summer EWP at  $r = 0.82$  ( $p < 0.001$ ) over the period AD 1871–2012. The link between summer precipitation and atmospheric circulation across the UK can be further demonstrated by carrying out a spatial field correlation between summer EWP and 850 mb air pressure (van Oldenborgh et al. 2009; Trouet and van Oldenborgh 2013), the correlation of  $r > 0.80$  ( $p < 0.001$ ) over much of the southern British Isles (AD 1871–2010) confirms this relationship (see Fig. 6c).

Annual variations in the  $\delta^{18}\text{O}$  composition of tree-ring cellulose have two major controls: the isotopic ratio of the water drawn up through the roots and evaporative enrichment at the leaf surface (Roden et al. 2000), the former is primarily controlled by atmospheric circulation and the latter by the vapour pressure difference between the air and the leaf, and hence strongly linked to relative humidity. The dominating effect of atmospheric circulation on both the isotopic composition of precipitation and on air humidity allows us to hypothesise that the  $\delta^{18}\text{O}$  of tree-rings will produce a reliable record of changes in the amount of summer

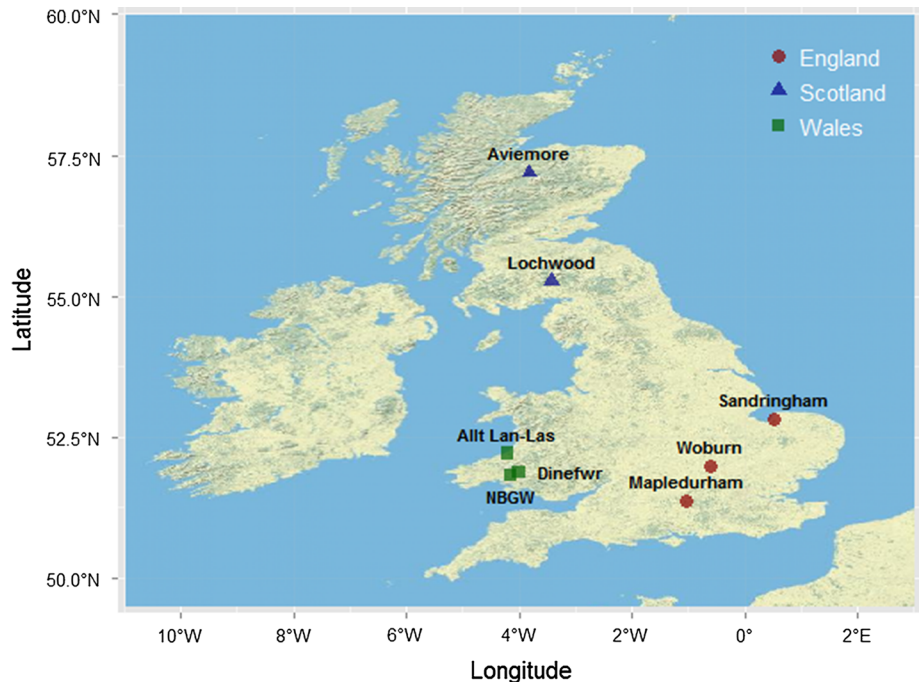
rainfall. The prevailing modes of circulation which control summer rainfall, air humidity and the isotopic signature of the precipitation should therefore be recorded in the wood of the annual growth rings of trees which use predominantly summer rainfall for growth (Treydte et al. 2014; Saurer et al. 2012). In dry British summers, characterised by the prolonged presence of ‘blocking’ anti-cyclonic conditions, the  $\delta^{18}\text{O}$  of the precipitation which trees use for growth is high and low air humidity leads to increased evaporation, further enriching the  $\delta^{18}\text{O}$  of leaf water. Under such conditions the sugars formed in the leaves of trees and ultimately the cellulose of latewood (summer-wood) cells should be isotopically enriched, the converse being true of wet summers dominated by cyclonic conditions with higher rainfall and higher air humidity (Fig. 1). We therefore predict a strong and consistent correlation between the stable oxygen isotope ratios of British oak tree-rings and amount of summer rainfall. We seek to test this hypothesis using a network of isotopic data from oak tree-rings (*Quercus robur*, *Q. petraea*) across the UK.

Stable carbon isotopes ratios ( $\delta^{13}\text{C}$ ) from tree-rings have been demonstrated to be a powerful proxy for climatic variability (e.g. Brien et al. 2012; Edwards et al. 2008; Gagen et al. 2007; Hafner et al. 2014; Heinrich et al. 2013; Hiltavuori et al. 2009; Kress et al. 2010; Liu et al. 2014). The  $\delta^{13}\text{C}$  measured in annual tree-rings essentially represents a balance between photosynthetic rate and stomatal conductance (McCarroll and Loader 2004). Where moisture stress is high (xeric environments) stomatal conductance is likely to dominate, and in mesic environments with low moisture stress photosynthetic rate should represent the most important control on  $\delta^{13}\text{C}$  variability. Photosynthetic rate is driven by solar radiation and in particular photosynthetically active radiation (PAR). Stomatal conductance is mainly controlled by the difference in vapour pressure between the ambient air and that within the intercellular spaces of a trees leaves. It therefore appears likely that for trees growing in environments with low moisture stress—such as the UK—climatic variables closely related to the amount of PAR the tree receives will most closely reflect the processes which control tree-ring  $\delta^{13}\text{C}$ , these include sunshine hours, cloud cover and temperature (Hari et al. 1981; Hari and Nöjd 2009; Hafner et al. 2014; Young et al. 2010, 2012a Gagen et al. 2007, 2011; Loader et al. 2013a). In the UK strong and highly consistent correlations between  $\delta^{13}\text{C}$  and growing season temperatures have been demonstrated, including pre-twentieth century records (Robertson et al. 1997; Loader et al. 2008, Rinne et al. 2010; Young et al. 2012b), and while it is recognised that the link between temperature and  $\delta^{13}\text{C}$  is largely an indirect one, the length of the instrumental temperature records available in the UK (up to c. 350-years) allow for rigorous examinations of this relationship.

**Fig. 1** Schematic diagram of the relationship between circulation, and therefore rainfall amount, and the stable oxygen isotopic composition of British oak tree-rings. The isotopic signature of precipitation is carried to the wood via sugar production in the leaf, where vapour pressure difference drives evaporative enrichment, but also more directly because of post-photosynthetic exchange between the oxygen atoms of the plant sugars and unaltered xylem (source) water



**Fig. 2** Map showing the locations of the eight oxygen isotope chronologies used in this study, NBGW stands for the National Botanic Garden of Wales



## 2 Data and methods

### 2.1 Sample collection and processing

Annually resolved stable oxygen isotope data have been assembled from eight locations in the United Kingdom (UK) (Fig. 2), with good replication (mean annual  $n = 34$ ) covering the period AD 1850–2012. Three of these data sets have previously been published: Lochwood (Loader et al. 2008), Sandringham (Robertson et al. 2001) and Woburn (Rinne et al. 2013) and sampling and analytical

methods are described in these supporting references. The other five are new series: Aviemore, Allt Lan-las, Dinefwr, Mapledurham, and the National Botanic Garden of Wales (NBGW). At Dinefwr and Mapledurham, sub samples were taken from cross sections cut from large fallen trees. At Aviemore, Allt Lan-las and the NBGW trees were sampled at c. 1.2 m using 5 mm increment borers.

In addition to  $\delta^{18}\text{O}$ , stable carbon isotope ratios ( $\delta^{13}\text{C}$ ) are used from three of the sites: Allt Lan-las, Mapledurham and Aviemore (Fig. 2). Details of the Allt Lan-las  $\delta^{13}\text{C}$  can be found in Young et al. (2010);  $\delta^{13}\text{C}$  results from the other

two data sets are new. All the data are from annually pooled tree-ring latewood. The annual pools comprise six trees at both Allt Lan-las and Mapledurham and seven trees at Aviemore.

After careful cross-dating against regional chronologies the latewood of individual rings were cut with a scalpel under magnification. For each year, the late-wood of between five and seven trees was pooled, a well-established method in tree-ring isotopic analysis (e.g. Treydte et al. 2006; Saurer et al. 2008). Annually pooled samples were then extracted to  $\alpha$ -cellulose using standard methods (Loader et al. 1997; Rinne et al. 2005). For  $\delta^{18}\text{O}$  isotopic analysis, between 0.30 and 0.35 mg of dry  $\alpha$ -cellulose was weighed into silver capsules. Stable oxygen isotope ratios were then measured online using a Thermo Scientific Flash high-temperature elemental analyser (HTEA) 1112 series, interfaced with a Delta V Advantage isotope ratio mass spectrometer (Thermo Scientific). For  $\delta^{13}\text{C}$  isotopic analysis, 0.30–0.35 mg of dry  $\alpha$ -cellulose were weighed into tin capsules for both the Allt Lan-las and Mapledurham sites and combusted online using a PDZ-Europa (Sercon) 20/20 isotope ratio mass spectrometer. For the Aviemore site 0.30–0.35 mg of dry  $\alpha$ -cellulose was weighed into silver capsules which were pyrolysed for simultaneous  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  measurement (Woodley et al. 2012b; Young et al. 2011b). Pyrolysis was carried out in a Thermo Scientific Flash high-temperature elemental analyser (HTEA) 1112 series interfaced with a Delta V Advantage isotope ratio mass spectrometer (Thermo Scientific). All isotope analyses were performed at Swansea University and results are expressed using the delta notation in parts per mille: stable oxygen isotopes relative to the Vienna Standard Mean Ocean Water (VSMOW) standard; and stable carbon isotope results to the Vienna Pee Dee Belemnite (VPDB) standard. Analytical error was typically:  $\delta^{18}\text{O}$ , <0.3 per mille (‰) ( $\sigma_n - 1$ ,  $n = 10$ ); and  $\delta^{13}\text{C}$ , <0.1 per mille (‰) ( $\sigma_n - 1$ ,  $n = 10$ ) (Boettger et al. 2007).

## 2.2 Age related trends

An important question to consider when using tree-ring proxies for climatic reconstruction is whether they are affected by trends related to tree age (Cook et al. 1995). There is only limited evidence for oxygen isotopes in tree-rings and most of it comes from species other than oak. Limited studies using pooled isotope measurements have suggested that there may be systematic differences between the  $\delta^{18}\text{O}$  of old and young trees [Treydte et al. 2006 (*Juniperus* sp.) and Esper et al. 2010 (*Pinus uncinata*)]. A more comprehensive study of *Pinus sylvestris* L. from annualised data of multiples trees found no significant age trends in either  $\delta^{18}\text{O}$  or  $\delta^{13}\text{C}$  (Young et al. 2011b). Labuhn et al. (2014) looked at age trends in oak trees in south-western

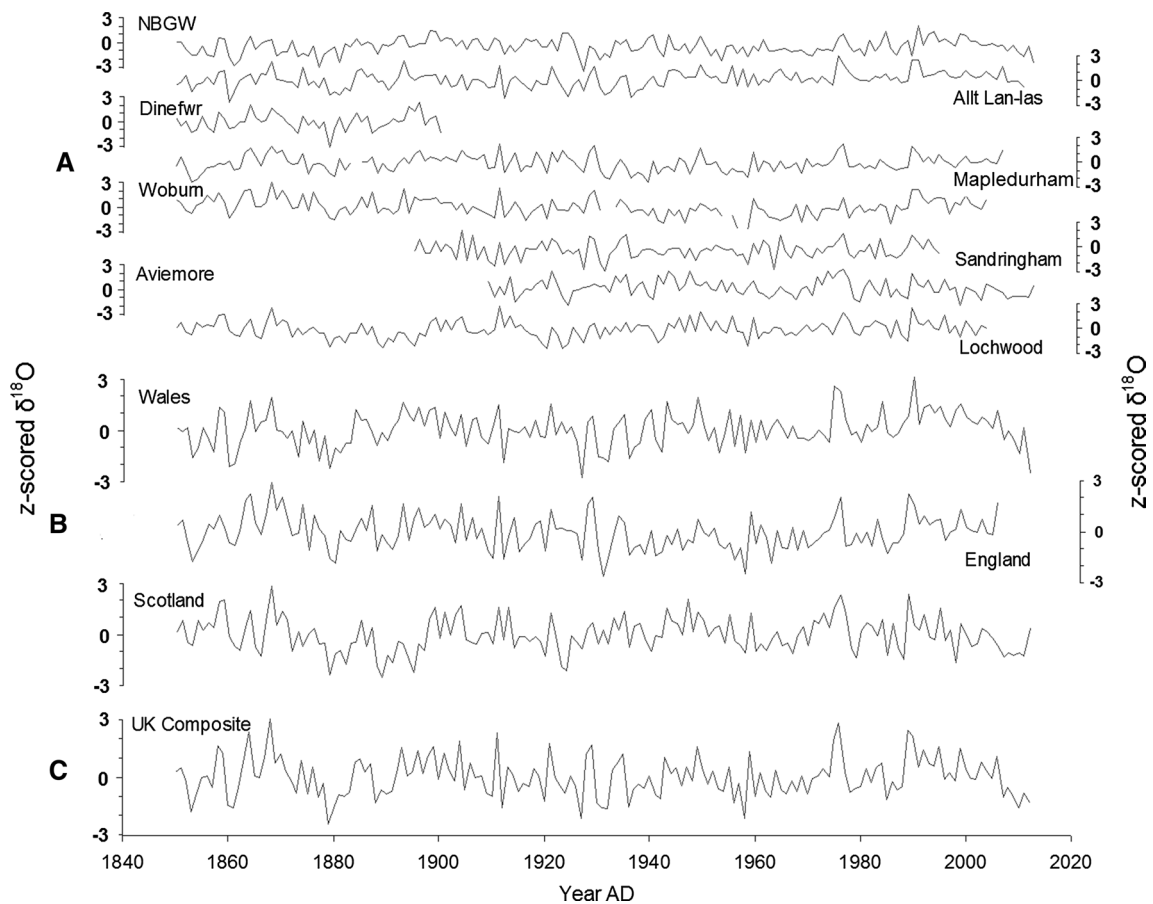
France: they identified a significant juvenile trend persisting for the first 20–30 years of growth but no other significant long term age related trends. A similar juvenile trend has also been identified for *Pinus sylvestris* L. tree-ring  $\delta^{13}\text{C}$  (Gagen et al. 2007). All of the data included in our study avoided the use of, at least, the first 30-years of tree growth and so should therefore avoid the juvenile effect described by Labuhn et al. (2014) and Gagen et al. (2007). Although it is not strictly possible to test for long term age related trends using pooled data, an examination of Fig. 3 shows that there are no obvious long-term trends in our results which are not directly attributable to climate (Fig. 6).

## 2.3 Chronology construction

The data sets do not all cover the entire calibration period of AD 1850–2012 (Fig. 3a), however a reasonable geographical coverage and sample depth is maintained throughout. Inter-correlations were performed between each of the individual  $\delta^{18}\text{O}$  series over the longest possible common period, except where the overlap was <30 years (Table 1). The data presented in Table 1 suggests that there is a common  $\delta^{18}\text{O}$  signal in oak trees from across the UK. There is a significant ( $p < 0.05$ ) inter-correlation between all the individual  $\delta^{18}\text{O}$  series (Table 1); except for Aviemore, the most northerly site, which does not correlate significantly with NBGW, Woburn or Mapledurham (Fig. 2). The Dinefwr site does not have a long enough overlap to test its relationship with either Aviemore or Sandringham.

The data assembled here were not originally collected with the aim of producing a UK oxygen isotope composite series, and so sampling is somewhat sub-optimal for this purpose; for example there are no sites between c. 53°N and 55°N (the English Midlands and the North of England). The data collected, however, represent a reasonable UK coverage and fall into three administrative regions of the UK, the countries of Wales, Scotland and England (Figs. 2, 3b). To avoid imparting a geographical bias to the final UK composite the data from the eight individual series (Fig. 3a) were first combined into three regional (country) chronologies (Wales, Scotland and England) (Fig. 3b). Data from the individual sites were z-scored (to a mean of zero and a standard deviation of one) over the longest possible common period and then a mean was taken. The resulting three regional chronologies share much variability in common (Table 1), especially the England and Wales chronologies ( $r = 0.63$ ,  $p < 0.001$ ). To produce the final UK  $\delta^{18}\text{O}$  composite the three regional chronologies were again z-scored over the longest possible common period (AD 1850–2006), and the mean of these series was then taken, and once again z-scored, to produce the final z-scored UK  $\delta^{18}\text{O}$  composite series (Fig. 3c). An alternative approach to combining





**Fig. 3** Oak stable oxygen isotope series ( $\delta^{18}\text{O}$ ) z-scored (mean of zero and standard deviation of one) for: eight individual sites (a); three regional composites (b); and UK composite (c)

discontinuous series would be to use anomalies from the mean over a common period (Jones 1994), which has the advantage of retaining the original units of measurement. However as the ultimate aim here is to scale the composite series to EWP it is necessary that the final composite  $\delta^{18}\text{O}$  series has a mean of zero and standard deviation of one (z-score) which would not be the case with anomalies from the mean.

Two corrections were applied to the stable carbon isotope series from Allt Lan-las (Wales) (Young et al. 2012b), Mapledurham (England) and Aviemore (Scotland). Firstly, for the anthropogenically induced decline in the  $\delta^{13}\text{C}$  of atmospheric  $\text{CO}_2$  since *c.* AD 1850, using the methodology proposed by McCarroll and Loader (2004); and secondly to account for changes in the behaviour of trees due to the increasing availability of atmospheric  $\text{CO}_2$  since *c.* AD 1850, following the methodology suggested by McCarroll et al. (2009), the so called PIN correction. These three corrected  $\delta^{13}\text{C}$  series were then combined into a single  $\delta^{13}\text{C}$  chronology (AD 1850–2010) by taking the mean of the three series z-scored over the longest common period

(the same procedure as for  $\delta^{18}\text{O}$ ); this mean was then once more z-scored to allow a direct comparison to be made with z-scored  $\delta^{18}\text{O}$  results. The intercorrelation between the three individual  $\delta^{13}\text{C}$  series can be seen in Table 2, there are significant correlations ( $p < 0.01$ ) between all the three series.

## 2.4 Climate calibration

To test suitability of oak tree-ring  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  for palaeoclimatic reconstruction standard tree-ring calibration statistics (NRC 2006) were used to test the strength and temporal stability of the relationship between: the  $\delta^{18}\text{O}$  composite series and summer EWP; and the  $\delta^{13}\text{C}$  chronology and Central England temperature (CET). For these tests the data set was split into, as near as possible, two equal parts and reduction of error (RE), coefficient of efficiency (CE) and the squared correlation coefficient ( $R^2$ ) were calculated (see NRC (2006) for a full review). Both RE and CE have a theoretical range of  $-\infty$  to 1, any number below zero is considered a failure (NRC 2006),  $R^2$  represents the

**Table 1** Matrix showing: top right *Pearson's product moment correlation coefficient* ( $r$ ) between each individual oxygen isotope series, composite oxygen isotope series, summer (June–August) England and Wales precipitation (EWP) and summer (June–August) Central England Temperature (CET), underlined values are not significant at  $p < 0.05$ , NA indicates series with insufficient overlap for meaningful calculations ( $n < 30$ ); bottom left, the period of overlap ( $n$ ) in years between each series

	NBGW	Lanlas	Dinefwr	Woburn	Mapledurham	Sandringham	Lochwood	Aviemore	Wales	England	Scotland	UK	EWP
NBGW		0.42	0.37	0.29	0.39	0.37	0.21	0.05	0.81	0.39	0.19	–0.39	–0.39
Lanlas	161		0.54	0.51	0.54	0.52	0.52	0.32	0.84	0.61	0.48	0.79	–0.58
Dinefwr	51	51		0.42	0.59	NA	0.29	NA	0.78	0.55	0.29	0.64	–0.52
Woburn	154	154	51		0.62	0.49	0.45	0.14	0.48	0.87	0.39	0.71	–0.51
Mapledurham	157	157	51	150		0.55	0.37	0.16	0.60	0.87	0.33	0.74	–0.51
Sandringham	100	100	6	96	100		0.32	0.34	0.56	0.81	0.38	0.72	–0.53
Lochwood	154	154	51	150	153	100		0.42	0.44	0.46	0.91	0.75	–0.49
Aviemore	104	102	0	91	98	86	95		0.22	0.23	0.85	0.53	–0.33
Wales	163	161	51	150	198	100	154	104		0.63	0.39	0.83	–0.60
England	157	157	51	150	156	100	154	98	157		0.43	0.85	–0.60
Scotland	163	161	51	150	156	100	154	104	163	157		0.75	–0.48
UK	163	161	51	150	156	100	154	104	163	157	163		–0.69
EWP	163	161	51	150	156	100	154	104	163	157	163	163	

proportion of the variance in isotopic ratios explained by variance in summer climate and has a range from 0 to 1.

Reconstructions of past climate based on the standard method of using the proxy data as the independent variable to predict the desired climate parameter almost inevitably result in an underestimation of the variability of past climate, the magnitude of the loss of variance being proportional to the amount of variance that remains unexplained by the correlation (e.g. McCarroll et al. 2011). This makes it difficult to examine the ability of a reconstruction to replicate the measured range of climate. Where a proxy/climate relationship can be shown to be strong and consistent through time the loss of variance can be removed by scaling the proxy data to have the same mean and variance as the climate data over their common period, albeit at the cost of an increase in mean squared error of the reconstruction (McCarroll et al. 2015).

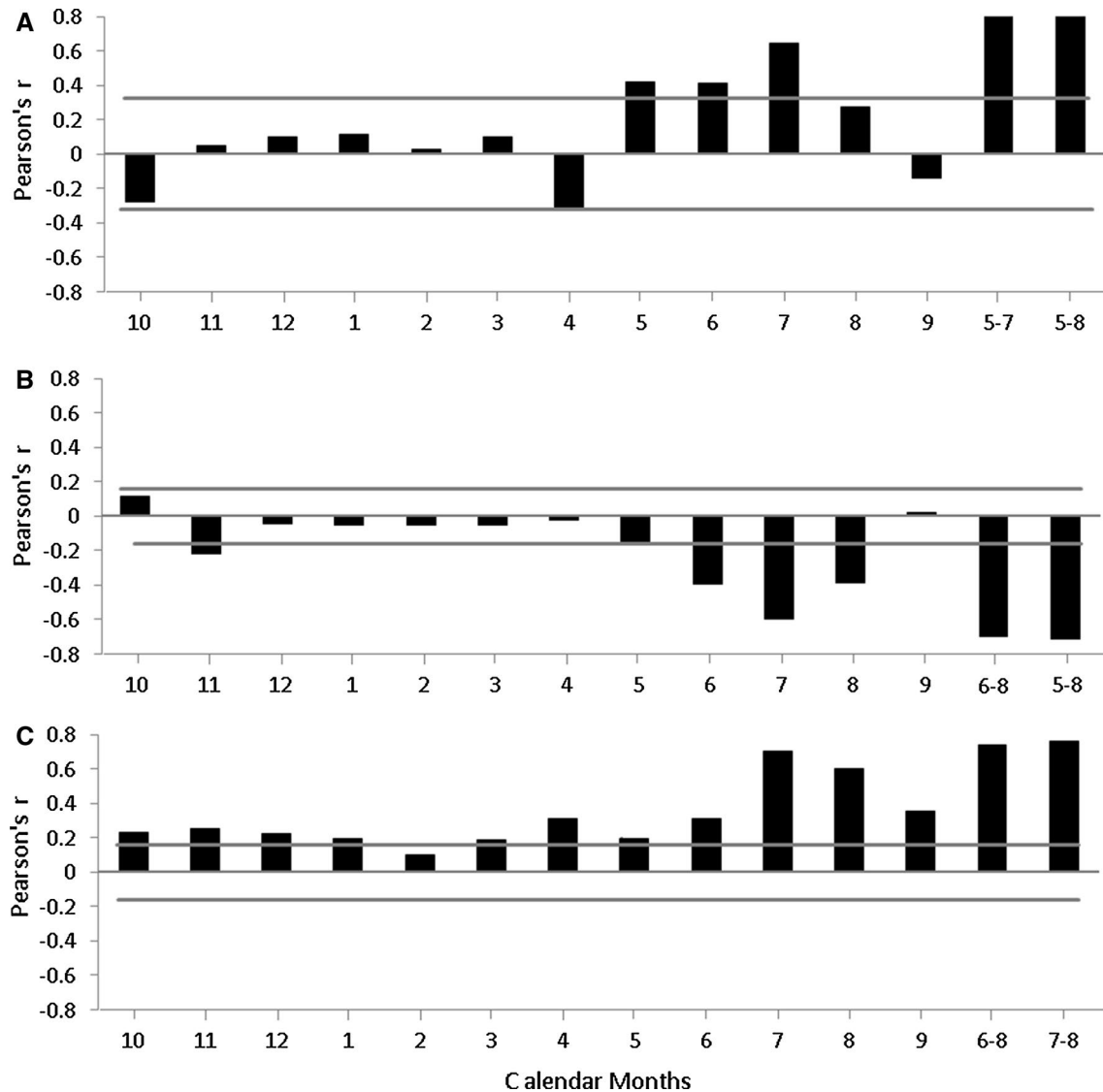
### 3 Results

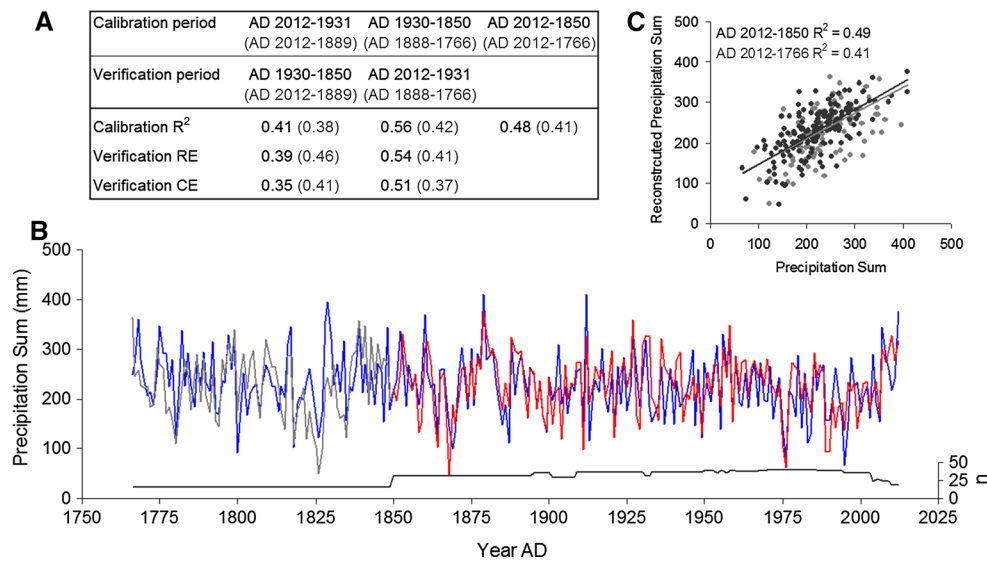
If our hypothesis is correct we would expect a strong relationship between our composite  $\delta^{18}\text{O}$  and the  $\delta^{18}\text{O}$  of summer precipitation. However, some studies have suggested that deep rooted trees (such as oak) may use precipitation from previous seasons and groundwater for summer growth, which would make reconstructing summer climate variables difficult (e.g. Robertson et al. 2001). We test this by comparing our mean oak  $\delta^{18}\text{O}$  chronology against the longest record of  $\delta^{18}\text{O}$  in precipitation available for the UK (Wallingford Oxfordshire) over the period for which data are currently available (AD 1982–2007) (Fig. 4a). There are positive significant correlations with May, June and July and a positive correlation (not significant) with August. When combined the highest correlation is for the May–August mean ( $r = 0.82$ ), which is also the highest combination of months for  $\delta^{18}\text{O}$  and precipitation (Fig. 4b). There are no significant correlations with any other months (Fig. 4a). The data presented in Fig. 4a suggest that the water used for oak growth at the sites sampled mainly comprises summer precipitation.

As hypothesised, there is a strong correlation between summer precipitation over the UK, as summarised by the England and Wales Precipitation (EWP) series (Wigley et al. 1984; Wigley and Jones 1987; Simpson and Jones 2012) and the  $\delta^{18}\text{O}$  of oak tree-rings. Each of the individual  $\delta^{18}\text{O}$  series has a significant negative correlation ( $p < 0.001$ ) with the summer (June–August) EWP ranging from  $r = -0.58$  (Allt Lan-las) to  $r = -0.33$  (Aviemore) (Table 1). Combining the individual site data into regional chronologies improves the correlations with summer EWP. Both the Wales and England composites correlate with the EWP at  $r = -0.60$  ( $p < 0.001$ ), and the Scotland

**Table 2** Matrix showing: top right *Pearson's product moment correlation coefficient* (*r*) between each individual carbon isotope series, composite carbon isotope series, summer (June–August) Englandand Wales precipitation (EWP) and summer (June–August) Central England Temperature (CET); bottom left, the period of overlap (*n*) in years between each series

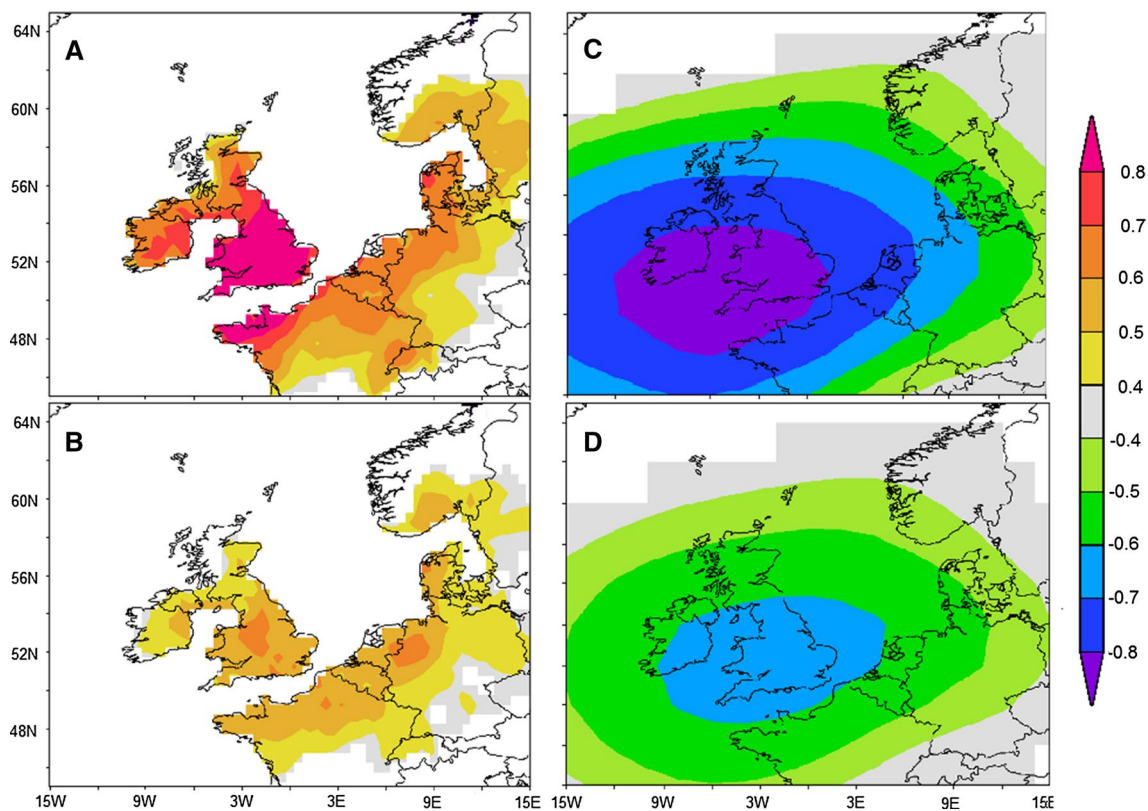
	Lanlas	Mapledurham	Aviemore	UK	EWP	CET
Lanlas		0.60	0.53	0.91	−0.54	0.67
Mapledurham	122		0.34	0.77	−0.49	0.61
Aviemore	102	98		0.79	−0.43	0.64
UK	161	161	102		−0.59	0.74
EWP	161	161	102	161		−0.55
CET	161	161	102	161	161	

**Fig. 4** Bar chart showing monthly correlations between: **a**  $\delta^{18}\text{O}$  measured in precipitation at Wallingford Oxfordshire and composite oak  $\delta^{18}\text{O}$  chronology over the period of available data (AD 1982–2007); **b** oak  $\delta^{18}\text{O}$  composite and England and Wales precipitation (EWP) from AD 1850–2012; and **c** oak  $\delta^{13}\text{C}$  composite and central England temperature (CET) from AD 1850–2010. Numbers on x axis represent sequential calendar months and combined months (e.g. 6–8,June–August). Horizontal grey bars represent 95 % confidence intervals. Combined months are for both the combination of sequential significant ( $p < 0.05$ ) months and for the combination of sequential months producing highest overall correlation. For temperature, as most months are significant we only show combined June–August and July–August, as the inclusion of any of the other significant months reduces the correlation coefficient



**Fig. 5** Composite figure showing calibration and verification of the oak  $\delta^{18}\text{O}$  composite reconstructing summer England and Wales precipitation (EWP) over two periods: period 1 (AD 1850–2012) of good replication; and period 2 (AD 1766–2012, covering the entire summer EWP), including the period of lower replication from AD 1766 to 1849. **a** Calibration and verifications statistics: period 1 (black

type) period 2 (grey type). **b** Inverted oak  $\delta^{18}\text{O}$  composite, AD 1850–2012 (red line), extended to AD 1766 (grey line), scaled to summer EWP (blue line). **c** A scatter plot of summer EWP against  $\delta^{18}\text{O}$  composite scaled to summer EWP (black dots), filled grey circles and caption show the period AD 1766–1849



**Fig. 6** Summer (JJA): England and Wales precipitation (EWP) (a) and EWP reconstructed from oak  $\delta^{18}\text{O}$  (b) spatially correlated against CRU TS3.10.01 gridded precipitation AD 1901–2009; EWP (c) and EWP reconstructed from oak  $\delta^{18}\text{O}$  (d) spatially correlated against 850mb air pressure from AD 1871 to 2009 using twentieth century

Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, CRU gridded data and NOAA air pressure data and accessed via Climate Explorer (van Oldenborgh et al. 2009; Trouet and van Oldenborgh 2013). All the above figures show only correlations with a significance of  $p < 0.01$



composite correlates at  $r = -0.48$  ( $p < 0.001$ ). The final UK composite correlates with the Summer (June–August) EWP at  $r = -0.70$  ( $p < 0.001$ ) (Fig. 4b), meaning that the EWP explains 49 % of the variability in the UK composite  $\delta^{18}\text{O}$  series, which is extremely high given that the common variability of summer precipitation across the UK is only around 50 % (Wigley et al. 1984). The highest overall correlation is found between the composite  $\delta^{18}\text{O}$  chronology and May–August EWP ( $r = -0.71$ ) (Fig. 4b), which encouragingly is the same combination of months as the  $\delta^{18}\text{O}$  chronology and isotopes in precipitation from Wallingford (Fig. 4a). The correlation is, however, only slightly lower for June–August EWP ( $r = -0.70$ ) and as the relationship with May EWP is not significant. June–August also has the advantage of defining a discrete meteorological season (summer), we therefore proceed using this period.

The calibration and verification statistics presented in Fig. 5a (RE, CE and  $R^2$ ), are all positive and high, suggesting that the data are suitable for palaeoclimatic reconstruction. The coherence of measured England and Wales precipitation is stronger during the nineteenth and early twentieth century (AD 1861–1915; PC1 = 55.2 %) than the later twentieth century (AD 1916–1970; PC1 = 45.4 %) (Wigley et al. 1984) and this is also reflected in our calibration results, with stronger values for the earlier part of the record.

Three of the series shown in Fig. 3 extend back beyond AD 1850 (Dinefwr, Lochwood and Woburn) and although overall sample depth is reduced by over half, from 31 to just 15 trees, a reasonable regional coverage is maintained, with one site from each of the three regions (Fig. 2). Although this much reduced composite series would not be expected to retain such a strong environmental signal, a split period calibration and verification exercise based on the full length of the EWP record, from AD 1766, yields calibration and verification figures that remain strongly positive (RE = 0.46 and 0.41; CE = 0.41 and 0.37, Fig. 5a) and over the full series length the correlation between summer rainfall and tree-ring  $\delta^{18}\text{O}$  remains strong ( $r = -0.64$ ,  $p < 0.001$ , Fig. 5c).

The UK composite  $\delta^{18}\text{O}$  series—inverted and scaled to June–August mean EWP over the period AD 1850–2012 (Fig. 5b)—displays both a strong visual and statistical match with the precipitation record. The match between scaled proxy and summer precipitation remains strong back to the inception of the EWP in AD 1766, despite the significant reduction in sample depth prior to AD 1850 (Fig. 5b). The number of times that the proxy series places a given year in the correct upper or lower quartile, as indicated by the precipitation series, gives some indication of the skill of the reconstruction and especially its ability to predict years with extreme values. Given that the probability of achieving such a match by pure chance is  $p = 0.25$  the success

rate of 48 out of 82 years is very strongly significant (*binomial sign test*,  $p < 0.0001$ ) (McCarroll et al. 2015).

The close relationship between British oak tree-ring  $\delta^{18}\text{O}$  and summer rainfall amount is confirmed by the pattern of correlation across space as well as over time. The pattern of correlation between the summer EWP series and gridded summer rainfall (CRU TS3) is very similar (Fig. 6a) to the pattern obtained using the composite isotope record (Fig. 6b). The strong link between summer precipitation across the UK and atmospheric circulation is confirmed by the strong temporal and spatial correlation with twentieth century reanalysis of 850 mb air pressure (Fig. 6c). A similar spatial pattern is found between the  $\delta^{18}\text{O}$  based reconstruction of summer EWP and 850 mb pressure confirming the link between oak  $\delta^{18}\text{O}$  and atmospheric circulation (Fig. 6d).

We compared our reconstruction of summer precipitation based upon oak tree  $\delta^{18}\text{O}$  with the precipitation reconstructions of Cooper et al. (2013) and Wilson et al. (2013) based upon oak ring widths. Over the period AD 1850–2009 the two ring-width-based (earlywood and latewood) reconstructions correlate strongly with each other ( $r = 0.60$ ,  $p < 0.001$ ) but only weakly with the isotope series ( $r = -0.23$  and  $-0.19$ ,  $p < 0.01$ ). Over the length of the EWP series, since AD 1766, the two ring-width series remain strongly correlated ( $r = 0.57$ ) but the correlations with the isotope series are not statistically significant ( $r = -0.10$  and  $-0.08$ ,  $p > 0.05$ ) (Fig. S1).

The  $\delta^{13}\text{C}$  composite chronology was compared with the summer central England temperature (CET) record. The correlations with monthly CET from AD 1850–2010 from the October of the previous year to September of the year of ring formation are shown in Fig. 4c. There are significant positive correlations ( $p < 0.05$ ) with every month except February, however as the data set is 160-years long even relatively low correlation co-efficient are significant ( $r = 0.16$ ). The highest correlations are confined to the major growing season months of July and August, and the highest overall correlation is with the mean of these two months ( $r = 0.76$ ,  $p < 0.001$ ). The correlation with mean June–August temperature is only slightly lower ( $r = 0.74$ ,  $p < 0.001$ ) and we use this combination of months to allow us to make a direct comparison with the  $\delta^{18}\text{O}$  record and the summer EWP. Verification statistics between the  $\delta^{13}\text{C}$  composite and summer CET (June–August) are all high and positive (RE = 0.66 and 0.56; CE = 0.53 and 0.38) suggesting that these data are suitable for reconstructing summer temperature. The  $\delta^{13}\text{C}$  composite scaled to summer (June–August) CET can be seen in Fig. S2. One of these three records Allt Lanlas (Fig. 2) has already been published as a record of summer temperature (Young et al. 2012b) and more detail and discussion of

the relationship between oak  $\delta^{13}\text{C}$  and temperature can be found there.

## 4 Discussion

Data from a previously published reconstruction of precipitation in the UK based upon oak tree  $\delta^{18}\text{O}$  are included in the data set presented here (Rinne et al. 2013). This 400-year reconstruction of May–August precipitation is based upon a rather small sample of 4-trees (Loader et al. 2013b), but despite this a strong relationship is found with May–August EWP, especially during the nineteenth century ( $r = 0.72$ ,  $p < 0.001$ , AD 1815–1893). The relationship with precipitation is however quite unstable and the correlation with recorded precipitation falls considerably during the twentieth century ( $r = 0.52$ ,  $p < 0.001$ , AD 1900–2003), possibly as a result of localised sulphate pollution (Rinne et al. 2013). The Rinne et al. (2013) reconstruction and the reconstruction presented here (Fig. 5) are numerically quite similar ( $r = 0.71$ ,  $p < 0.001$ , AD 1850–2003), however this is unsurprising as the Rinne et al. (2013) data are included in our reconstruction. The approach taken here of using a large and geographically disparate data set appears to circumvent the calibration instability found in the Rinne et al. (2013) data set (Fig. 5).

The results of the calibration and verification tests presented in Fig. 5 suggest that, even with a rather sparse and sub-optimal network of sites and limited replication, the relationship between oak tree-ring  $\delta^{18}\text{O}$  and summer rainfall is strong and also stable over the period for which England and Wales precipitation data are available. Such strong statistical relationships between tree-ring parameters, such as ring widths and relative density, and climate are usually restricted to very well replicated chronologies from high latitudes or altitudes, (e.g. McCarroll et al. 2013) where tree growth is strongly limited by a small number of environmental variables. There is, therefore, considerable potential for reconstructing past changes in summer precipitation using  $\delta^{18}\text{O}$  from British oak trees. A problem arises, however, when the reconstruction in Fig. 5b (based upon oak  $\delta^{18}\text{O}$ ) is compared to two long precipitation reconstructions that have recently been produced, based on the ring widths of British oak trees (Cooper et al. 2013; Wilson et al. 2013). Over the period of overlap these two ring-width based reconstructions are very different to the isotopic time-series presented here (Fig. S1).

The two precipitation reconstructions are based upon exceptionally well-replicated oak tree-ring width chronologies from East Anglia (Cooper et al. 2013) and south-central England (Wilson et al. 2013) and the data were compiled and analysed using sophisticated methods intended to avoid the loss of lower-frequency information. The two

ring-width based reconstructions despite being similar to one another ( $r = 0.60$ ,  $p < 0.001$ ) are so different from the  $\delta^{18}\text{O}$  based reconstruction (Fig. S1) that it appears unlikely that both can be interpreted as reliable indicators of past changes in the same climate parameter.

Since two well replicated, and apparently independent, reconstructions agree strongly with each other, but not with our isotope results, there is cause for further investigation. Both Cooper et al. (2013) and Wilson et al. (2013) interpret their data as measures of precipitation over a rather longer and not entirely overlapping time window (March to July) to that which we use to calibrate the isotope series (June–August), which may reflect, in part, that only latewood was used for stable isotope analysis. This is, however, not sufficient to explain the disagreement between the physical and chemical proxies, because even using the longer time window the EWP explains more than twice as much of the variance in the mean isotope series as in either of the ring-width series, and this holds over both the period AD 1850–2009 and the less well replicated period AD 1766–2009. However, the two ring-width chronologies are only independent in so far as they are not based on the same trees. Their coherence is to be expected, as it is well established that there are common environmental signals preserved within the ring-widths of British oak trees, which is why it is possible to cross-date oak tree-ring series and use them as a dendrochronological dating tool. The critical question is, therefore, whether the ring-width series more faithfully record changes in precipitation.

The ring-width reconstructions of Cooper et al. (2013) and Wilson et al. (2013) are not calibrated using local meteorological, or even exclusively British, rainfall data, but rather by carefully examining the spatial correlation footprint, over a combination of consecutive months, to identify which period and region achieves the highest significant correlation. The gridded precipitation data for this region and period are then used to calibrate the ring-width series. In both cases the region selected includes part of northern France. This method results in strong, significant and verifiable correlations with gridded precipitation data over the chosen time window (March–July) for the period for which gridded temperature data are available (AD 1901–2009). However, this procedure may, to some extent, compromise the independence of the ring-width and climate data and explain, why the strongest correlations are restricted to the recent period and why the ring-width data do not verify against long instrumental series of precipitation from the UK. The long rainfall records for Britain and surrounding regions demonstrate a strong spatial coherence and local data from across East Anglia and south-central England correlate very strongly with the EWP composite (Fig. 6a), so if the ring-width series are a reliable repository for past changes in precipitation it should be possible

to calibrate and verify them using either local records or the long EWP record. Both Cooper et al. (2013) and Wilson et al. (2013) compare their reconstructions to suitable long instrumental series and in both cases note that they fail to follow those series back in time. They postulate three hypotheses to explain the failure to verify their reconstructions beyond the period of the gridded precipitation calibration: (1) early instrumental precipitation series may be unreliable, (2) sulphate air pollution affects tree growth and (3) oak ring widths respond to some combination of climate factors rather than to precipitation alone and that this combination may vary over time.

The strong and consistent relationship between the oxygen isotope series and the EWP record suggests that the early instrumental data are reliable, which was also the conclusion of Wilson et al. (2013). It has been suggested that sulphate pollution can influence oak tree growth and potentially the isotopic signal in oak tree-rings (e.g. Rinne et al. 2010, 2013), but given the rural locations of most of the trees sampled for both ring-widths and isotopic measurements the second hypothesis also seems unlikely. The most likely reason for the marked difference between the whole ring width and (latewood) isotopic series is that the former is a measure of English oak tree growth, which encompasses a wide combination of environmental controls: rather than a single identifiable limiting factor. Due to the complex forcing combination on oak growth, the influence of precipitation, although no doubt present, is not expressed sufficiently strongly or consistently to allow it to be used in isolation as a strong and consistent record of past changes in precipitation. Stable oxygen isotopes in British oak tree-rings appear to be strongly controlled by changes in summer atmospheric circulation, which also controls the amount of summer rainfall, and by changes in air humidity, which are also linked to precipitation amount, although factors such as temperature are also likely to play a role in atmospheric humidity. We therefore suggest that  $\delta^{18}\text{O}$  of late-wood cellulose from British oak tree-rings provides the best currently available measure of past (pre-instrumental) summer rainfall.

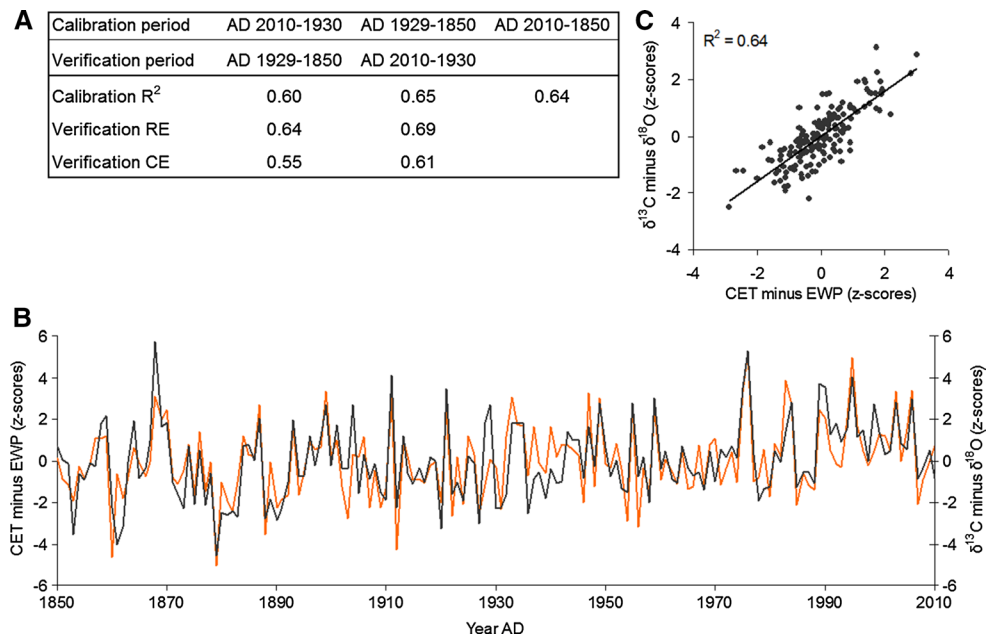
## 5 Reconstructing both temperature and precipitation

One of the major reasons for studying past changes in precipitation is to better understand and model the relationship between temperature and precipitation. It is important, therefore, that reconstructions of these two climate parameters are independent of one another. Unfortunately this is difficult to test, as temperature and precipitation do not vary independently. It is also unlikely that temperature and precipitation act independently on many natural archives, including

tree-ring widths, where both temperature and precipitation can influence growth (e.g. Cooper et al. 2013). British oak tree-rings, however, present us with an unusual opportunity because as well as using the oxygen isotope ratios to reconstruct summer precipitation, the stable carbon isotope ratios can be used to reconstruct past changes in summer temperature (e.g. Robertson et al. 1997; Loader et al. 2008; Treydte et al. 2009; Young et al. 2012b; Heinrich et al. 2013). Measuring both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  simultaneously on the same samples of tree-ring cellulose, which is now possible using highly efficient and cost effective pooling and measurement techniques (Young et al. 2011a; Woodley et al. 2012a, b) could potentially provide simultaneous reconstructions of summer temperature and precipitation for the UK and other areas with similar controls on tree-ring isotope fractionation. However, given that the samples produced by such a method would clearly not be independent, it is critically important to determine whether there is appropriate independence in the two climate signals. The alternative hypothesis being, as appears to be the case with some tree-ring width data, that the two isotope ratios might be influenced by some mixture of temperature and precipitation, so that the signals are conflated and the precipitation (oxygen) reconstruction is largely an inversion of the temperature (carbon) reconstruction. These competing hypotheses can be tested by using the measurements of the stable carbon isotope ratios ( $\delta^{13}\text{C}$ ) available from three of the sites (Allt Lan-las, Mapledurham and Aviemore). The  $\delta^{13}\text{C}$  composite from these sites is strong and reliable (for the period AD 1850–2010) indicator of the summer CET (Figs. 4c, S2).

Simply comparing the strength of the  $\delta^{13}\text{C}/\text{CET}$  and  $\delta^{18}\text{O}/\text{EWP}$  correlations is insufficient however, as the summer CET and EWP series are themselves strongly negatively correlated (AD 1850–2010,  $r = -0.55$ ,  $p < 0.001$ ). The critical test is whether the difference between carbon and oxygen chronologies reflects the difference between measured temperature and rainfall. Such a comparison requires all of the data to be z-scored over a common period, to remove the effect of different variance and units of measurement. The difference between the z-scored CET and EWP series correlates extremely strongly with the difference between the z-scored isotope series ( $r = 0.80$ ,  $p < 0.001$ ); the excellent fit between the two sets of differences can be seen in Fig. 7b, c. When standard tree-ring climate verification statistics are applied to this relationship the resulting RE, CE and  $R^2$  are all highly positive (Fig. 7a). These results suggest that a combination of carbon and oxygen isotope analyses from the same oak tree-rings can provide reconstructions of both summer temperature and summer precipitation and that the two signals are sufficiently independent to allow years or periods of divergence between temperature and precipitation to be recognised.

**Fig. 7** The differences between z-scored (to a mean of zero, standard deviation of one) June–August central England temperature and June–August England and Wales precipitation (orange) and oak  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (black), shown as a line graph in **b** and scatter plot in **c**. Verification statistics are shown in **a**



## 6 Conclusion

Wigley and Jones (1987) concluded that precipitation over the England and Wales region is primarily controlled by large scale atmospheric circulation. The combination of environmental factors which control oak tree  $\delta^{18}\text{O}$  in the UK and surrounding regions are likely to reflect such changes in atmospheric circulation ( $\delta^{18}\text{O}$  of source water and relative humidity) and therefore oak  $\delta^{18}\text{O}$  may be expected to reflect growing season (summer) hydro-climate. A combination of  $\delta^{18}\text{O}$  from oak tree-rings at eight locations across the (UK), with a mean sample depth of 34 trees, captures annual summer rainfall with a surprising degree of accuracy over the period AD 1850–2012 ( $r = -0.70$ ,  $p < 0.001$ ). This level of correlation compares favourably with climatic calibrations at tree line locations and represents one of the most highly-replicated oxygen isotope records produced to date. It also performs considerably better as a proxy for summer precipitation than two recently published reconstructions based upon very well-replicated oak tree-ring widths (Cooper et al. 2013; Wilson et al. 2013).

Oak is plentiful and often long-lived across the UK and material from archaeological collections spans the past millennium (e.g. Wilson et al. 2013). It should, therefore, be possible to reconstruct precipitation over this period using  $\delta^{18}\text{O}$  from oak tree-rings. The possibility of recovering an accurate measurement of both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  simultaneously, using recently developed methods that are both rapid and cost-effective (Young et al. 2011a; Woodley et al. 2012a; Loader et al. 2013a) raises the enticing prospect of reconstructing both summer temperature (Young et al.

2012b) and summer precipitation from the same isotopic analysis for the UK and northwest maritime Europe over the past millennium and potentially far beyond.

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**Conflict of interest** The authors declare that they have no conflict of interest.

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