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400-year May–August precipitation reconstruction for Southern England using oxygen isotopes in tree rings

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ABSTRACT

Few long and well-dated summer precipitation reconstructions that extend beyond the longest records of instrumental measurements exist in Europe. Further understanding of the past trends in summer precipitation and the mechanisms driving that variability are necessary to improve the predictions of climate models. Tree rings are unique in their ability to provide high-resolution, absolutely dated climate signals for the study of palaeoclimatology. The physiological processes controlling oxygen isotope composition ($\delta^{18}O$) in wood are reasonably well understood highlighting its potential as a climate proxy in a variety of environments. Significant correlation between wood $\delta^{18}O$ and precipitation has been demonstrated worldwide reflecting both direct rainout processes and indirectly evaporative enrichment. We present an annually resolved reconstruction of precipitation based upon oxygen isotope variations in tree ring cellulose covering the most recent ~400 years for England. The May–August precipitation series, which was formed by combining reconstructed values based on oxygen isotope composition ($\delta^{18}O$) in tree ring cellulose of pedunculate oak (*Quercus robur*) (1613–1893) and instrumental data (1894–2003), indicates significant decadal and centennial precipitation variability culminating in dry conditions in the early-middle 17th century and the late 20th century. The analysis demonstrated statistically robust May–August precipitation signal in the $\delta^{18}O$ values of oak cellulose back to 1697, the first year of the oldest instrumental precipitation series in England.

1. Introduction

Climate models for the twenty-first century predict pronounced precipitation decreases in Europe in summer (Meehl et al., 2007). This together with increased incidence of heatwaves may lead to serious social and economic consequences (Schär et al., 2004). For England decreased summer precipitation has been detected particularly in the last three decades adversely affecting water resources and hence water availability (Jones et al., 1997). However, the driving mechanisms of European summer precipitation variability are not well understood and the models show less skill in the prediction of variability in comparison to the winter season (Zveryaev and Allan, 2010 and references therein). Therefore, further understanding of the past trends in summer precipitation and the mechanisms driving that variability are necessary to improve the predictions.

Few long and well-dated summer precipitation reconstructions that extend beyond the longest records of instrumental measurements exist in the northern hemisphere (IPCC et al., 2007). For central Europe the annually resolved estimates are based on tree ring-width data, which at temperate sites contain weaker climate signal and less well replicated records may be susceptible to some loss of low frequency variability due to applied detrending procedures for the removal of growth trends (Wilson et al., 2005; Büntgen et al., 2010). In comparison, the physiological controls on $\delta^{18}O$ in tree rings are reasonably well understood; thus the $\delta^{18}O$ record of tree rings has the potential to perform well in temperate sites, where growth is not dominated by a single factor (McCarroll and Loader, 2004). The added advantage is that no detrending procedures may be necessary thus preserving low frequency variability in the reconstructed climate signal (Young et al., 2010).

This paper presents an annually resolved May–August precipitation reconstruction for England developed from $\delta^{18}O$ measurements in tree ring cellulose of pedunculate oak (*Quercus robur*). The reconstruction allows the examination of the low- and high-frequency precipitation variability of the last ~400 years in southern England, which to the authors' knowledge, has not been

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possible before. The existence of the longest instrumental precipitation records across Europe provide an unusually long dataset against which to assess the validity of our precipitation reconstruction. Moreover, the long instrumental records allowed us to avoid the use of the 20th century data to calibrate the isotope/precipitation relationship. This period is characterised by significant anthropogenic effects, such as increasing atmospheric CO_2 levels and localised SO_2 pollution, which can influence isotopic discrimination within trees and interfere with isotope/climate relationships (Savard et al., 2004; McCarroll et al., 2008; Treydte et al., 2009; Rinne et al., 2010).

A potential problem in using tree ring parameters for climate reconstruction is the effect of non-climate changes (such as human interference) during the period of the reconstruction (Warren et al., 2001; Rinne et al., 2010). Such effects within a time series may remain unidentified in the absence of evidence that allow climate and non-climatic effects to be distinguished. Reconstructed climatic parameters will therefore be less reliable over this time period. From a detailed knowledge of the site management history, we identify the presence of such a non-climatic effect during the period of our precipitation reconstruction, and show how we removed it from the reconstructed record.

The basic principle in the utilisation of stable oxygen isotopes for palaeoenvironmental studies is that the isotopic composition of precipitation is related to air mass characteristics and trajectory including temperature and amount of precipitation (Dansgaard, 1964). The correlation between precipitation amount and isotopic depletion is the result of two factors. Firstly, cloud cooling leads to increasing precipitation and falling δ values of precipitation. Secondly, the tendency of the raindrops to become isotopically enriched as they fall to the ground owing to evaporation and exchange processes is most limited at high rates of precipitation (Darling and Talbot, 2003). A further indirect response is that of evaporative enrichment in the leaf that works to fractionate further the leaf water in favour of the heavier isotope. In this manner, hot, dry years preserve a record in the tree ring that not only reflects the source water (air-mass) characteristic but also the amount of rainout and evaporation in the leaf, in this manner whilst not representing a *direct* precipitation proxy stable oxygen isotopes may provide information on wet and dry years.

Epstein et al. (1977) suggested that the isotopic signal in plant material could be correlated with the soil (source) water, which reflects the isotopic signature of precipitation. No fractionation occurs during water uptake by terrestrial plants (Wershaw et al., 1966). However, when xylem water is transported to the leaves, modification of the isotope signal occurs. Evaporative effects and exchange with atmospheric water vapour lead to leaf water enrichment (loss of ^{16}O relative to ^{18}O), the degree of which depends upon vapour pressure deficit, which is inversely proportional to relative humidity (Dongmann et al., 1974; Saurer et al., 1998; Poussart et al., 2004). The evapotranspiration signal in $\delta^{18}O$ of leaf water is dampened by a Péclet effect (Flanagan et al., 1991; Barbour et al., 2000; Farquhar et al., 2007). The overall isotopic modification in the leaf is therefore generally related to relative humidity (Roden et al., 2000; Waterhouse et al., 2002) and hence this control can overprint to varying degrees the temperature signal arising from initial isotopic composition of the xylem water. However, this latter signal is partially restored in the trunk during cellulose synthesis from sucrose transported from the leaf, since an average of 42% of sucrose oxygen atoms are exchanged with xylem water during this process (Hill et al., 1995; Roden et al., 2000). In summary, $\delta^{18}O$ in tree ring cellulose is expected to be related in varying degrees to precipitation amount, temperature and relative humidity. The relative importance of the three parameters will depend upon species and site conditions, and each has been reported as exerting a controlling influence on cellulose $\delta^{18}O$ (see McCarroll and Loader, 2004 and references therein)). For precipitation amount and tree-ring $\delta^{18}O$ significant correlation has been demonstrated worldwide (e.g. Robertson et al., 2001; Weiguo et al., 2004; Treydte et al., 2006).

2. Material and methods

2.1. Regional setting

Pedunculate oak (*Q. robur*) was analysed from the Deer Park of the Woburn Abbey Estate 65 km northwest of London, England. The climate is humid maritime temperate, being dominated by southwesterly depressions from the Atlantic during the winter and experiencing a more continental climate influence from continental Europe during the summer. The total area of the Woburn Deer Park (51°59′N and 0°35′W) is 12 km^2 and is approximately 150 m above Mean Sea Level. The altitude variation across this open parkland is small. The vegetation consists of both old and newly planted pedunculate oak trees on a deer grazed pasture. The soils are poorly drained, seasonally waterlogged clayey and fine loamy over clayey soils $\leq$80 cm in depth (Rinne, 2008).

2.2. Tree ring data

This study formed part of a larger-scale research project and network study (ISONET) for which there was a common sampling strategy to ensure comparability of results across the consortium (Treydte et al., 2007; Loader et al., 2008). Samples for dendrochronology and isotopic measurement were collected at breast height using a 5 mm diameter increment borer. Two cores were taken from each tree and generally a total of eight cores were pooled at annual resolution to provide sufficient wood for isotopic analysis.

The oak samples were cross-dated as described in Rinne et al. (2010). The four oldest oaks, which were nearly 400 years of age, were selected for this study. Analysis of four trees is usually considered a minimum for representative reconstruction of environmental variability from stable isotopes in tree rings (Leavitt and Long, 1984; Robertson et al., 1997). The adequacy of the sample size for capturing inter-annual variability can be evaluated using the expressed population signal:

$$\mathrm{EPS}(t) = tr_{bt}/(tr_{bt} + (1 - r_{bt})) \tag{1}$$

where t is the number of trees and r_{bt} the mean between tree correlation. EPS $>$ 0.85 suggests adequate sample size.

As an exception to the general pooling protocol, two time periods with above average ring-width growth were used to examine inter-tree isotope variability. For these years only the two cores from each individual tree were pooled at annual resolution. The first period is 1812–1878, where 15 non-consecutive years with exceptionally high inter-tree differences in the amount of wood contributed for $\delta^{18}O$ analysis were selected (Fig. 3a). The purpose was to assess whether the pooling could have resulted in a significant loss in environmental signal in the $\delta^{18}O$ chronology through large changes in the relative contributions from each tree. The EPS value was calculated to evaluate the adequacy of the sample size.

The only other period enabling a study of inter-tree isotope variability is the beginning of the dataset during the most rapid period of "juvenile" growth: 1627–1646 (tree 1), 1617–1641 (tree 2), 1613 ($\delta^{18}O$)/1612 ($\delta^{13}C$)–1641 (tree 3) and 1627–1652 (tree 4) (Fig. 1). The separate isotope series were used to determine whether the individual tree $\delta^{18}O$ series were affected by a non-environmental