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# Temporal variability in the strength of proxy-climate correlations

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**Abstract.** The strength of the correlation between annually resolved tree-ring carbon isotope indices and climate was explored using a moving window technique. Significant variations in the correlation with fixed-date monthly temperature were observed using a 15-year moving window. To investigate the influence of phenological changes upon this relationship, a 20-day moving window was applied to daily temperature data to define the period of optimal tree response. For oaks growing in east England, the strongest association began 87 days after initial bud burst, which corresponds to the opening of the second flush of leaves. These results demonstrate that daily climatic data may be used to calibrate proxy-climate relationships.

## Introduction

It is recognised that knowledge of the changes in hemispheric-scale climate conditions is an essential prerequisite to judging the significance of modern global warming (Briffa and Osborn, 1999). This requires proxy data covering several centuries, and ideally millennia, to securely pre-date any possible industrial effects in the Northern Hemisphere and atypical comparison with periods such as the 'Little Ice Age'. For the period before instrumental climate records, it is now a well-established practice to reconstruct climatic parameters using proxy variables. Of the many proxies covering the Holocene, absolutely dated tree rings provide the highest resolution data that cover the past 10,000 years (Pilcher *et al.*, 1984; Spurk *et al.*, 1998). The primary proxy data are usually standardised to minimize non-climatic variance, which may also remove some of the long-term climate signal (Briffa and Osborn, 1999) and then correlated with climatic variables over the same period. A transfer function (usually a linear regression) is then calculated from this relationship to enable unknown climate parameters to be predicted from proxy observation. The relationship is usually verified against independent data or climate data withheld from the training set (Briffa, 1995).

## Methods

We applied a moving window technique to determine the relationship between high-frequency carbon isotope indices from oaks growing at two sites in eastern England (52°50'N, 0°30'E) and temperature for the past 100 years. The high-frequency carbon stable isotope indices were calculated from the $\delta^{13}C$ values of latewood cellulose individually determined from five oaks (*Quercus robur*) growing at Sandringham Park and five oaks (*Quercus robur*) growing at Babingley Osier Carr. Cross-dating ensured absolute confidence in the integrity of dates. The isotope time-series were individually standardised by dividing with a 60-year Gaussian filter to remove the very low frequency variance. A 10-year high-pass Gaussian filter was applied to the standardised indices to define the high-frequency variance (Robertson *et al.*, 1997). Correlations were calculated between the carbon isotope indices and the corresponding monthly average temperature using a window of width 15 years. The procedure was repeated by progressively advancing the center at one-year increments to obtain a time-series of correlation coefficients. The choice of window width is somewhat arbitrary, and 15 years was chosen as a compromise between a very narrow window with a higher sampling error (which results in a low absolute threshold value of correlation being accorded statistical significance), and larger widths (which approximate the behaviour of the full data set). A LOWESS (locally weighted scatterplot smoothing) regression was applied to the resulting data.

## Results

The moving window technique demonstrates the sensitivity of correlations with fixed date temperature to changes in the timing of annual tree ring growth. Figures 1 and 2 show how the correlation between Sandringham and Babingley carbon isotope indices and mean July and mean August temperatures vary over the period 1895-1994, using a 15-year moving window. Each point on the graph marks the correlation calculated over a fifteen-year period, plotted at the median year (i.e., 1895-1909 is plotted at 1902). It is immediately obvious that there is considerable variation in correlation over the time period, and that this variation is of sufficient magnitude to render the correlations statistically significant for part of the period, and insignificant in others. For example, the 15-year correlation between the Sandringham carbon isotope index and mean July temperature

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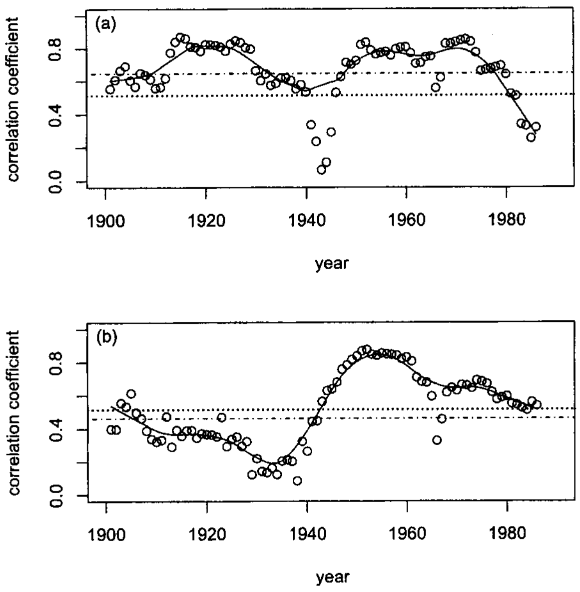

**Figure 1.** Moving 15-year correlation between Sandringham carbon isotope indices and a) mean July temperature and b) mean August temperature. The dotted line represents the 5% critical value for r (i.e. points with a correlation of greater magnitude indicate a significant correlation for that 15 year window). The dot-dashed line represents the overall correlation for the whole data set, and the solid line is a LOWESS regression through the data points.

varies between r=0.06 and 0.87 and it varies between r=0.08 and 0.87 with mean August temperatures. Similarly, the 15-year correlation between the Babingley carbon isotope index and July temperature varies from r=0.02 and 0.86 and it varies between r=0.00 and 0.63 with mean August temperature. At both sites, correlations less than 0.52 are significantly different from zero at $p=0.05$.

With the exception the early 1940s and the past few years, mean July temperature was significantly correlated with the carbon isotope index at Sandringham for most of the period of available data (figure 1). Thus the average correlation of 0.65, calculated across the entire period, reasonably reflects the more detailed picture obtained by using a moving average, although it does mask some variation in the strength of the relationship. In contrast, mean August temperature shows no significant correlation with the Sandringham carbon isotope index between median years 1907-1941, but is otherwise significantly correlated in most years. The overall average (r=0.46) therefore, underestimates the significance of mean August temperature on carbon isotope index for the period following 1941. At Babingley, mean July temperature was significantly correlated with the carbon isotope index, except for the years 1930-1959 (figure 2). The average correlation of 0.54, calculated across the entire period, reasonably reflects the values obtained from the moving window. With the exception of a few years, mean August temperature is not significantly correlated with the Babingley carbon isotope index. However, the overall correlation of 0.33 calculated over the entire period is significant at the 95% confidence interval owing to the larger number of observations.

## Discussion

Although uniform sensitivity to climate was sustained by white spruce growing in Alaska (Barber *et al.*, 2000), several studies (Briffa *et al.*, 1998a,b; Vaganov *et al.*, 1999) have found that the response of trees to climatic forcing has changed in recent years. Unlike trees growing at high northern latitudes, where tree growth is influenced primarily by a single dominant climatic parameter, the oaks from east England were growing under a temperate maritime climate with fewer extremes. At these sites, the principal controlling variable could switch between climatic variables, in response to whichever parameter is more limiting during the growing season. To investigate the changing climatic sensitivity of trees, all the factors influencing tree-growth should be considered (Briffa, 2000). These include physiological adaptations to enhanced atmospheric $CO_2$ concentrations (Farquhar and Sharkey, 1982; Kürschner *et al.*, 1996; Picon *et al.*, 1997) and changes in the length and timing of the growing season. The latter response is investigated further in this paper.

The lengthening of the growing season at high latitudes is supported by indirect evidence (Keeling *et al.*, 1996; Myneni, 1997) and by phenological observations (Walkovszky; 1998; Menzel and Fabian, 1999). In the British Isles, the unfolding of oak leaves has advanced by nearly three weeks since the 1950's (Sparks *et al.*, 1997; Sparks, personal communication, 2000). Although most studies report an earlier start to the growing season, it is more difficult to define the end (Worrall, 1999); resulting in conflicting results for either a delayed autumn (Menzel and Fabian, 1999) or advanced leaf fall, leading to a shorter growing season (Kramer, 1995).

As the correlation between monthly averaged temperature at fixed dates and carbon isotope indices has changed in the past 100 years (figures 1 and 2), the response to climatic forcing was investigated by applying a moving window to the daily central England temperature series (Parker *et al.*, 1992) to define the period of optimal association following bud burst. Although the response of carbon isotope indices to

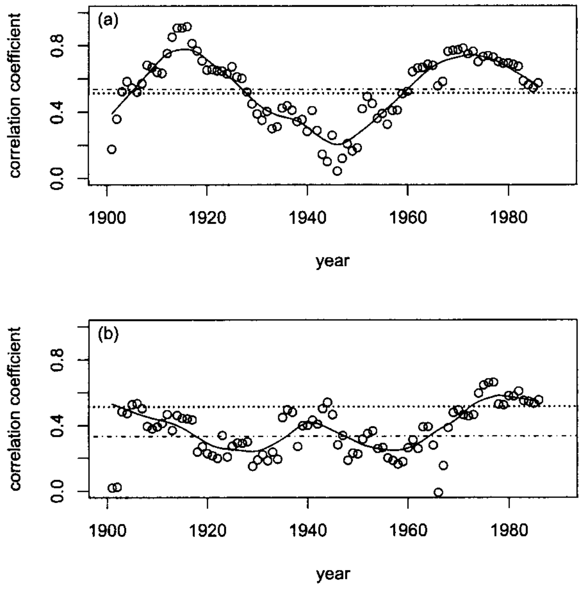

**Figure 2.** Moving 15-year correlation between Babingley carbon isotope indices and a) mean July temperature and b) mean August temperature. The dotted line represents the 5% critical value for r (i.e. points with a correlation of greater magnitude indicate a significant correlation for that 15 year window). The dot-dashed line represents the overall correlation for the whole data set, and the solid line is a LOWESS regression through the data points.

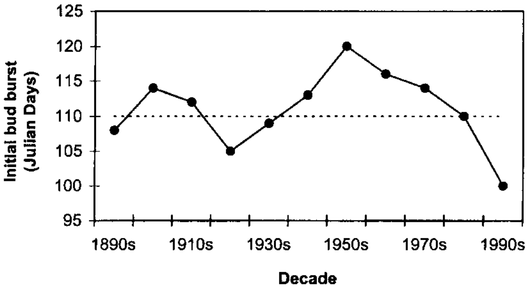

**Figure 3.** Decadal mean oak bud burst dates from the combined Marsham-Ashtead phenological record for the period 1890-1999 (Margary, 1926; Sparks and Carey, 1995; Sparks *et al.*, 1997; Sparks, personal communication, 2000). The dotted line represents the mean initial bud burst for the combined phenological series over this period (Julian Day 110).

relative humidity (or vapour pressure deficit) has been demonstrated to be optimal (Robertson *et al.*, 1997), daily data were unavailable. Oak bud burst data were obtained from the record kept by the Marsham family of Stratton Strawless in Norfolk, which covers the period 1736-1958 (Margary, 1926; Sparks and Carey, 1995; Sparks, personal communication, 2000) and observations from Ashtead, Surrey for the years 1947-1999 (Sparks *et al.*, 1997; Sparks, personal communication, 2000). The Ashtead data were used to extend the Marsham record from 1959-1994 by adding three days to the former to provide a continuous phenological record for east England (figure 3). This approach is supported by the close proximity of the sites (the two sites lie within 55 km of each other) and the observation that, although oaks may show considerable variation in bud burst dates, the relative trends are constant between years (Van Dongen *et al.*, 1997).

For the period with both phenological observations and carbon isotope indices, the correlation between the mean temperature for July/August (Julian days 182-243 in non-leap years) and carbon isotope values was $r=0.61$ ($p<0.01$; $n=91$) at Sandringham and $r=0.47$ ($p<0.01$, $n=91$) at Babingley. This strong association is supported by growth measurements (Hemming, personal communication, 1997). As this period is fixed relative to the calendar, it is generally assumed the factors that influence tree growth are relatively constant each year. However, the onset of tree growth changes in response to environmental factors, such as the accumulated winter temperature, which occur independent of the calendar date. At Sandringham, the optimal association was found for a period of 20 days beginning 88 days after initial bud burst ($r=0.60$; $p<0.01$; $n=91$) and at Babingley this was for a 20-day period beginning 86 days after the initial bud burst ($r=0.48$; $p<0.01$; $n=91$) (figure 4). The mean initial bud burst for the combined phenological series over the period 1895-1994 was Julian Day 113 and therefore, the mid-point of the 20-day period with the strongest association is Julian Day 210 or 29 July (in non-leap years). This period coincides with the second flush of leaves for mature oak trees. This 'Lammas' foliage, identified by its characteristic initial red-brown colour, has a higher tannin content than the first flush of leaves and is more resistant to insect attack. The leaves appear at late summer, during conditions favourable for photosynthesis. Therefore, the previously reported correlation with combined July/August climate data can be attributed to an approximate three-week period within these months that moves relative to the onset of initial bud burst.

However, the overall correlations with combined July/August climatic data are similar to those obtained using the moving-window as periods outside the window still influence the association, albeit to a lesser extent and, the use of bi-monthly data reduces the influence of irregular values. As both sites demonstrate a similar response to temperature, the influence of local disturbances may be excluded as a cause of this variability. These results demonstrate that mid-season growth parameters, such as carbon isotope indices, are influenced by changes in the timing of bud burst. However, phenological changes alone cannot account for the temporal variability in the proxy-climate correlations. If phenological changes continue at the same rate (Sparks *et al.*, 1997; Sparks, personal communication, 2000), additional approaches of calibration are required as fixed calendar dates may not be the best parameter against which to correlate isotopic time-series.

Although these results add further evidence to support the changing growing season for oaks in east England, they also demonstrate a potential problem when using tree-ring measurements as proxies for climatic reconstruction. This analysis shows that the magnitude of the relationship between the climatic parameters assumed to be controlling the proxy measurement can vary substantially over time. In terms of paleoclimatic reconstruction, this has a number of significant implications, which go far beyond the system of tree-ring proxy against climatic variable studied here. The correlation coefficient derived across the whole set of training data is effectively the average of a time-variant correlation, and may mask large variations in the strength of the relationship. The resulting transfer function is based on this average correlation and, when applied to proxy data, will reconstruct the climatic variable with differing efficiency across the time series,

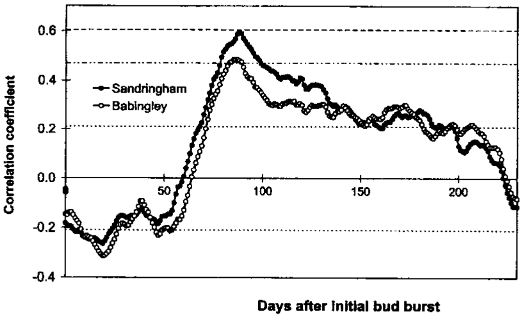

**Figure 4.** Moving mean 20-day correlation (start-point) between carbon isotope indices and daily central England temperature data after initial bud burst each year for the period 1895-1994. The dotted lines represent the 5% critical value for r (i.e. points with a correlation of greater magnitude indicate a significant correlation ($r=\pm0.21$, $p<0.05$, $n=91$)). The dashed line represents the overall correlation between the Sandringham carbon isotope index and the mean temperature for Julian days 182-243 (equivalent to July/August for non-leap years) for the period with both phenological observations and isotope values over the period 1895-1994. Similarly, the dot-dashed line represents the overall correlation between the Babingley carbon isotope index and the mean temperature for Julian days 182-243 (equivalent to July/August for non-leap years) for the period with both phenological observations and isotope values over the period 1895-1994.

depending on the strength of the relationship at a particular time. At times when the climate variable is strongly forcing the proxy, the reconstructed data will be good. At other times, when the correlation is low and some other variable has taken over the primary forcing role, the reconstructed data might be very poor.

The same problem can be expected in the interpretation of any climate proxy from any other source, if the proxy could respond to more than one climate variable. Paleoclimatologists therefore require some independent evidence to indicate when and over what time period such reconstructions are reliable. One approach might be to use multiple proxies in the hope that each will respond somewhat differently to climatic driving in order to help deconvolute such a complex signal. This is only likely to be successful if we have a fundamental understanding of the physical processes and biological system to develop the appropriate models (Schleser *et al.*, 1999). Until then, we need to recognise that climatic reconstruction from proxy data gives a time average of the relationship, and is therefore of variable reliability.

## Conclusions

Significant differences were observed in the temporal response of carbon isotope indices to temperature when explored using a moving window of 15 years. As the response to a single climate variable was not constant, this finding has important implications for paleoclimatic reconstruction. Bud burst data were used to define the optimal response period of tree-ring carbon isotope indices to temperature. For oak trees in east England, this corresponds to the 'Lammas' growth of foliage. The moving window technique overcomes some of the problem of using fixed date monthly data for climatic reconstruction and offers an approach that is particularly useful in light of recent phenological changes.

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