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# Climate signal in tree-ring chronologies in a temperate climate: A multi-species approach

A.M. García-Suárez[a,b,c,*], C.J. Butler[a], M.G.L. Baillie[b]

[a]Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland, UK
[b]Palaeoecology Centre, Queens University, Belfast BT7 1NN, Northern Ireland, UK
[c]School of Geographical Sciences, Bristol University, Bristol BS8 1SS, England, UK

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## Abstract

Tree-rings can provide continuous yearly paleoclimatic records for regions or periods of time with no instrumental climate data. However, different species respond to different climate parameters with, for example, some sensitive to moisture and others to temperature. Here, we describe four common species growing in Northern Ireland and their suitability for climate reconstruction.

Our results suggest that beech and ash are the most sensitive to climate, with tree-ring widths more strongly influenced by precipitation and soil moisture in early summer than by temperature or sunshine. Oak is also sensitive to summer rainfall, whereas Scots pine is sensitive to maximum temperature and the soil temperature.

We find that the moisture-related parameters, rainfall and the Palmer Drought Severity Index (PDSI), and to a lesser extent, maximum and mean temperatures, can be reconstructed. Reconstructions of climate parameters with tree-rings as proxies may be relatively stable for some seasons such as May–July. We find that combinations of species are more successful in reconstructing climate than single species.

**Keywords:** Dendroclimatology; Climate proxies; Oak; Ash; Beech; Scots pine

## Introduction

The width of a tree-ring can be influenced by a variety of factors, some of which relate to the unique location of the tree, its age and management, and others to wider environmental factors such as temperature, rainfall and sunshine. Thus, the mean tree-ring chronology incorporates within it a climate signal specific to the environment in which the trees have grown. Species that show a clear climate signal usually live under limiting conditions. Examples include the following: temperature dependent conifers (e.g. Scots pine) in tree line boundaries in Scandinavia and Siberia, and drought dependant species (e.g. bristlecone pine) in western arid regions of the USA.

Around 20 years ago, dendroclimatic studies were discontinued using trees in the British Isles because it was believed that they were less sensitive to climate than those which live under more critical conditions. The limited usefulness of oak as a climate proxy had previously been demonstrated by Briffa (1984) and Pilcher and Baillie (1980a, b). Nevertheless, Hughes et al. (1982) showed that Scots pine in Scotland has a

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*Corresponding author at: Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland, UK. Tel.: +44 2837 522928; fax: +44 117 928 787.

*E-mail address:* amgs@arm.ac.uk (A.M. García-Suárez).

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temperature dependant growth at high elevations or in north facing slopes.

This work is focused on the relationship between tree-ring widths and climate under non-limiting conditions using multiple species and multivariate analysis. It tests the hypothesis that our understanding of the climate signal embedded in tree-ring patterns could be improved by using several species at the same time as well as by including the influence of a wide variety of meteorological parameters.

To reduce any geographical differences in the climate affecting the trees under study to a minimum, it is evidently preferable that the climate and tree-ring data refer to the same location. For this reason, we have used samples from trees grown very close to Armagh Observatory for which we have well calibrated and extensive meteorological series. We have assessed the strength of the climate signal embedded in the trees and have made some preliminary attempts at climate reconstruction.

Armagh Observatory is a climate reference station for Northern Ireland and has the longest series of meteorological records on the island of Ireland. Starting in 1795, these are also some of the longest from a single site anywhere in the British Isles. The careful standardisation of these meteorological series, in which we have been actively involved, underlies the calibration of the tree-ring/climate links we have found.

In our study, the effect of precipitation, sunshine hours, maximum and minimum temperatures, soil temperatures, cloud cover, PDSI, humidity and pressure have been explored on tree-ring widths of species common to Northern Ireland; oak (*Quercus robur* L.), Sessile Oak (*Quercus sessilis* Lhrh.), beech (*Fagus sylvatica* L.), ash (*Fraxinus excelsior* L.) and Scots pine (*Pinus sylvestris* L.). Dendroclimatic studies for species other than oak have not formerly been undertaken in Ireland.

## Data

### Tree-ring data

Partly due to its economic and social history, Ireland has reached the 21st century with almost none of its indigenous forests intact. This has clearly compromised the length of our studies to the extent that several of our tree-ring chronologies are shorter than some of the climate series. However, even with this limitation, a dendroclimatology study at Armagh gives us an opportunity to examine the possibility of using several species as climate proxies in Ireland.

Trees used in this study were selected from oak, beech, ash and Scots pine stands in the Observatory Estate or from public parks or private estates less than 10 km from the Observatory. All sites were at an altitude approximately the same as Armagh Observatory (60 m) and had a slope less than 10° to the horizontal. The individual tree-ring widths and the mean chronologies have been archived in the International Tree Ring Data Bank (NOAA).

In addition to these local chronologies, we also include in our study a subset of the wider Northern Ireland oak population extracted from the Tree-Ring Data Bank of Queen's University, Belfast; termed *NI oak*. This regional chronology is longer than the Armagh Observatory oak chronology and allows us to test whether the climate signal depends on the sample size. Our Northern Ireland regional oak chronology is composed of 47 trees of which 30 samples are from the QUB archive and the remainder from Armagh Observatory. The trees selected for our NI oak chronology were those from inland locations closest to Armagh Observatory (less than 25 miles) and at the same elevation.

Our NI Oak chronology commences in 1756 (well replicated from 1786). Previous to this there were several periods when the number of available oak samples is too small for climate studies. The longer Irish Oak chronology, published in 1984 (Pilcher et al., 1984), has several weak periods with a reduced number of trees, e.g. 1150–1400 AD and 1600–1750 AD (see also Baillie, 1982, 1995). These may reflect increased mortality rates due to climatic downturn – for instance, the Little Ice Age in the 17th and 18th centuries (Soon and Yaskell, 2004) – or an increased use of wood for fuel, charcoal production or building. In addition, at this time, forest clearance increased to meet the growing demands of farming (Aalen et al., 1997, p. 123; Mitchell, 1986, pp. 182–183). A decline in Scots pine populations in Fennoscandia in the 12th and 16th century has also been noted by Gunnarson and Linderholm (2002). As those trees in Fennoscandia grow at tree-line boundaries, this coincidence may be suggestive of a wider climatic cause.

### Climate data

The site of Armagh Observatory climate station (6° 39′.8 W, 54° 21′.2 N) is well exposed with minimal urban effects (Coughlin and Butler, 1998). The climate series include three independent temperature series (Butler et al., 2005), rainfall (Butler et al., 1998; García-Suárez et al., 2002), sunshine hours (Pallé and Butler, 2001), soil temperatures at 30 and 100 cm depth (García-Suárez et al., 2006), barometric pressure (Ansell et al., 2006), humidity (Butler and García-Suárez, 2009), cloud cover and wind speed and direction. The climate series have been standardised taking into account corrections for instrumental error, exposure and changes in the time of observation and are available at http://climate.arm.ac.uk and in the Armagh Observatory Climate Series (12 volumes).

Although the records of temperature and pressure commenced in 1795, there is a gap in the series that dates from 1825 to 1833. In temperature, this gap has been filled by data from two stations in Dublin following the procedure described in Butler et al. (2005). The Armagh temperature series are broadly in agreement with similar series from other parts of western Europe such as Central England, Uppsala and Stockholm (Butler et al., 2005). In general, there is an upward trend in the annual means but, seasonally, this trend is greater in autumn and winter (Butler et al., 2005). Soil temperatures at Armagh Observatory have increased twice as much as the mean air temperature over the past century (García-Suárez et al., 2006) whereas the sunshine totals and the PDSI series show a downward trend (Pallé and Butler, 2001; García-Suárez, 2005). The total annual rainfall series does not show a clear trend (Butler et al., 2007). However, we have found periods of reduced precipitation with respect to the mean of the series from the 1970s to the present and before the 1900s. At Armagh the rainfall is well distributed throughout the year, though spring months are drier and August–January wetter than average. Butler et al. (1998) found a significant decrease in summer rainfall from the 1960s whereas winter rainfall has increased from the beginning of the 20th century.

We have used a wide range of climatic parameters in this study, including: maximum and minimum temperatures (from 1844), mean temperatures (from 1795), sunshine hours (from 1886), rainfall (from 1838), humidity (from 1838), soil temperatures (from 1904), pressure (from 1850), plus derivative variables such as the monthly total number of days with rainfall above 5 mm, length of the growing season, etc. The PDSI which was taken from Dai et al. (2004), for longitude 6°15′W, and latitude 53°45′N, commences in 1871 for Ireland, but we have found the series reliable from 1885 after the introduction of the Stevenson Screen. Most previous dendroclimatology studies of this type have been concerned only with rainfall and mean air temperature (Briffa et al., 2002; Esper et al., 2005; Hughes et al., 1982; Fritts, 1976).

## Statistical methods

### Detrending

The extraction of climate signal from tree-rings is hampered by a variety of factors which arise from the complexity of tree growth. The most important is the change in growth-rate with age. Several methods have been developed to remove this age related growth trend from a series of ring width measurements (Fritts, 1976; Cook and Kairiukstis, 1990) but these standardisation methods can also remove long-timescale variance from the chronology (Cook et al., 1995) which inevitably will limit any dendroclimatic study and its interpretation.

Examples are as follows: (i) *A priori* defined mathematical models, such as a linear regression or negative exponential. These can be appropriate for young trees and conifers and are referred to here as *traditional methods* (Cook and Kairiukstis, 1990, Chapter 3; Fritts, 1976, Chapter 6). (ii) Filtering or smoothing the series, used *a posteriori*, which are more data adaptive methods and often more appropriate for disturbances such as competition. (iii) Detrending with an age-dependant biological growth curve, usually called a Regional Curve Standardisation (RCS). RCS curves are formed by averaging tree-ring width series which have been realigned according to the biological age, rather than calendar year. Where long-timescale variance is needed, RCS is currently considered to be the best method available because it can preserve low-frequency variance (Briffa et al., 1992; Esper et al., 2002, 2003). However, RCS relies on the availability of a large number of samples from comparable sites with a uniform distribution in time, including sub-fossil trees, which in our case is only possible for oak. As mentioned earlier, at present our samples of pine, ash and beech do not cover a sufficiently wide range of epochs to properly define an RCS.

### Empirical models and statistical tests

As the common species available in Northern Ireland have not grown close to their altitude or latitude limits, their radial growth-rates may be expected to depend on several climate variables simultaneously. Thus, to calibrate their growth–climate relationships, it is necessary to use empirical models. A *response function* relates the tree-ring widths (dependent variables) to a number of climate parameters (independent variables) in a multiple regression whereas when the tree-ring widths are the independent variables and the climate parameters are the dependent variables, the model is referred to as a *transfer function*. These empirical models allow us to determine which independent variables are important and the strength of the relationships. The functions are defined by the data in a calibration period and subsequently checked in an independent verification period. Fritts (1976, Chapters 6 and 7) and Cook and Kairiukstis, (1990, Chapter 4) have reviewed the use of response and transfer functions.

The methods and statistical tests that have been employed to assess the quality of these functions in both the calibration and verification periods are not unique to this study – they have been widely used in dendroclimatology (Fritts, 1976; Cook and Kairiukstis, 1990). One of these test parameters, the *variance explained*, VE, is defined as the square of the correlation coefficient ($R$) between the actual data and the values estimated by the model. We have also used the *sign-test*, the *t-student* test, the *reduction of error* (RE) and the *coefficient of efficiency* (CE) to measure the agreement between the actual and estimated series. If the values of VE, followed by the sign-test and student $t$-test, are significant and RE $>0$ and CE $>0$, the regression is judged to have passed the criteria in the calibration/verification periods and the regression model is considered useful (Fritts, 1976, Chapter 7). If the model is poor, single correlation coefficients between monthly climate variables and the tree-ring widths can still be significant and may be helpful to identify a relationship that can be used for climate reconstruction.

If trees in Northern Ireland were living under more limiting conditions, the number of climate variables relevant to the growth of each species would probably be reduced and multiple regressions may not have been necessary. Another useful method to determine climate–tree ring relationships is the use of pointer or signature years (Kelly et al., 1989, 2002). However, the study of signature years requires a larger number of mature samples than is available to us.

## Detrending tree-ring widths

In the first instance, we have used the methods referred to as 'traditional methods' to detrend our ash, oak, beech and Scots pine chronologies. These methods employ a regression curve which can be either linear, exponential or a spline (Cook and Peters, 1981). Taking into consideration the peculiarities of each species, that our aim is to reconstruct climate and to use those methods which provide the highest SNR and EPS[1,2] values, we have found it preferable to use different types of regression curve for each species. The oak and the beech chronologies have been detrended with a flexible spline with a length 75% of the length ($n$) of each of the series, the ash chronology with a fixed 60-year filter and the pine chronology with a double detrending method (a linear regression or negative exponential followed by a fixed 60-year spline). As a result of poor matching in some sections of the pine chronology, 30% of pine samples were rejected before detrending. Despite that, double detrending for pine was necessary to eliminate disturbances in growth. A lower cross-matching success rate for Scots pine than for oak has also been found in sub-fossil pine in Ireland by Pilcher et al. (1995). Fig. 1 shows the standardised chronologies for the four species. We note that there is significant correlation between the three deciduous species and between beech and pine which is confirmed by the correlation coefficients listed in Table 1.

Note that with the use of the above detrending methods, the climate reconstructions drawn from the tree-ring indices could result in the loss of climate information for intervals longer than 30–50 years. To test the dependence of the results on the detrending method, we used other high-frequency removal methods, such as Gaussian and first differences, which were the same for all chronologies. Also we used a preliminary RCS for oak (computed with Irish oaks all samples dating from 851 AD until 1991 AD for which information regarding the centre rings has been recorded; see García-Suárez, 2005). With those indices we carried out the same analysis of stability and transfer functions. Those chronologies are not shown but the climatic response drawn from the different indices is summarised here. The complete analysis has been described in García-Suárez (2005).

## Climate response

### Monthly climate response

Previous studies suggest that a cool summer has a negative effect on oak ring-width in Ireland (Briffa, 1984), whereas wet conditions throughout most of the year, particularly from May to July, have a positive effect (Pilcher and Baillie, 1980a) Briffa, 1984; Kelly et al., 2002). For beech and ash in the British Isles there are virtually none dendroclimatic studies to indicate which climate parameter is most relevant to growth and over which period. There have been studies, however, of Scots pine in Scotland by Hughes et al. (1982) and in Scandinavia by Gunnarson and Linderholm (2002), Briffa et al. (2002), Grudd et al. (2002) and Eronen et al. (2002).

For our study, we first need to establish the season during which trees respond most to climate, in other words, over which period the climate variables correlate best with the annual ring-widths. Traditionally, the periods running from July of the previous year to August of the current year (14 months) or from June of the previous year to September of the current year (16 months) have been used. In Table 2, we list those

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[1] The signal-to-noise ratio (SNR) is an expression of the strength of the observed common signal among the trees in a chronology. The Expressed Population Signal (EPS) quantifies how well a chronology based on a finite number of trees represents the hypothetical perfect or true chronology (Wigley et al., 1984).

[2] To ensure sufficient signal, we use the following sections of the chronologies: 1861–2001 for oak, 1813–2002 for beech, 1873–2002 for ash and finally, 1844–2002 for Scots pine.

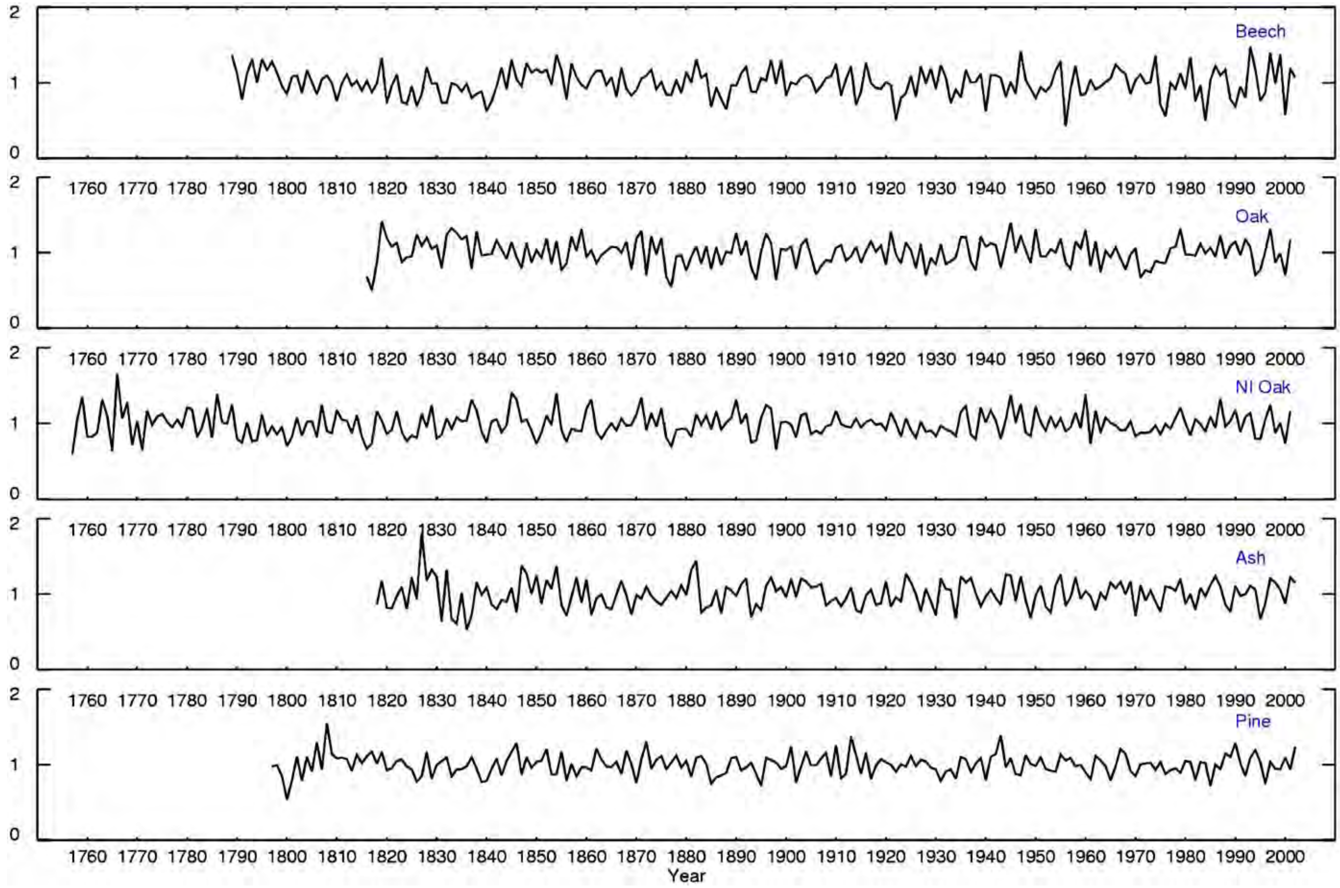

**Fig. 1.** Mean index chronologies for several species: (1) Beech. (2, 3) Oak chronologies, created by detrending with a flexible spline with a length 75% of the length (*n*) of each of the series. (4) Ash chronology, created by a fixed 60-year detrending. (5) Scots pine chronology, created by detrending with a double detrending method (a linear regression or negative exponential followed by a fixed 60-year spline).

**Table 1.** Correlation coefficients between the chronologies calculated for periods when EPS $>.85$.

| | Oak | Beech | Ash | Pine |
|---|---|---|---|---|
| Oak | 1.0 | – | – | – |
| Beech | $.21^{**}$ | 1.0 | – | – |
| Ash | $.29^{*}$ | $.35^{a}$ | 1.0 | – |
| Pine | NS | $.20^{a}$ | NS | 1.0 |

NS stands for non-significant.

$^{*}p<.01$.

$^{**}p<.05$.

months for which there is a significant correlation between the annual tree-ring-width and the respective climate parameters for that month. We considered months from April of the previous year (‘p’ indicates previous year) to November of the current year. Table 2 summarises when the different climate variables are important for growth and whether the correlation is positive or negative. We have correlated the ring-widths with the following climate parameters: monthly rainfall, mean, maximum and minimum temperature, sunshine, PDSI, soil temperature at 30 and 100 cm depths and monthly numbers of days with rainfall above 5 mm (*N* rain-days tot $\geq 5$ mm). Other variables, such as humidity, cloud cover and pressure, are not listed here although they show significant correlations (correlation coefficients for these variables and 3 others are shown in García-Suárez, 2005).

In Fig. 2, we show the monthly distribution of the correlation coefficients between the tree-ring chronologies and the mean monthly maximum temperature, rainfall, soil temperature at 100 cm depth and sunshine hours (see top). Asterisks, above some of the values, indicate coefficients significant at the 95% level. The period used is 1929–1977 and the coefficients run from previous October to current September.

From Fig. 2 and Table 2, we can deduce that the most important months for the selected species are usually May–July for the current year and October and November from the previous year, although the degree of influence depends on the species and on the climate variable in question (see the next section). In the extreme

**Table 2.** Months during which various climate parameters correlate significantly with the annual tree-ring width.

| **Chronologies** | Max *T* | **Rainfall** | **PDSI** |
|---|---|---|---|
| Beech | **pJul****, −pAug*, −May**, −Jun**, −Jul* | + pJul**, + pAug**, + **May****, + Jun*, + Jul* | + pSep* to + pOct*, + pNov**, + Apr** to + Jul** |
| Ash | −Jan*, −Feb*, −May*, −**Jun**** | + **May****, + **Jun**** | + Feb*, + Mar*, + **Apr**** **to** + **Jul****, + Aug** to + Sep$^{\sim}$ |
| Oak | + **May**$^{\sim}$ | **pOct***, −Jan*, + Jun* | + Jun*, + Jul* |
| Pine | −pAug*, + pDec*, + Jan**, + Mar** | −pNov* | – |
| **Chronologies** | ***N* rain-days tot ≥ 5 mm** | Min *T* | Air *T* |
| Beech | + pJul**, + pAug*, + pNov$^{\sim}$, + Apr$^{\sim}$, + **May****, + Jun$^{\sim}$, −Oct* | −pJul**, −pAug**, −Jul$^{\sim}$ | −pJul**, −pAug**, −Jul*, −Aug* |
| Ash | + pAug*, Jan*, + **May****, + Jun** | – | + pJul*, −Jan*, −Feb*, −Jun*, |
| Oak | + pOct*, + Jun**, + Jul* | −Jan* | – |
| Pine | −pNov* | + pDec*, + Jan**, + Mar*, + Aug* | + pDec**, + Jan*, + Feb$^{\sim}$ + Mar**, + Jul*, + Aug$^{\sim}$ |
| **Chronologies** | **Soil temp. at 30 cm** | **Soil temp. at 100 cm** | **Sunshine hours** |
| Beech | −pJul**, −pAug*, −May$^{\sim}$ | – | −pJul**, + pNov$^{\sim}$, −May*, −Jun**, + Sep$^{\sim}$, + Oct** |
| Ash | – | + **Mar**$^{\sim}$ | −pOct**, −May*, −**Jun**** |
| Oak | −pNov*, −pDec**, −Jan** | −pAug*, −pSep*, −pDec*, −Jan*, −Jul* | + pMay*, −Jun$^{\sim}$ |
| Pine | −pAug** to −pNov* | −pJun*, −pJul**, −pAug* to **pNov***, + Feb$^{\sim}$, + May$^{\sim}$, −Jun* | + Jan$^{\sim}$, + Jul** |

The coefficients have been calculated over period 1941–2001. The significances of the correlation coefficients are indicated as follows: $^{\sim}$ correlation is significant at 90% level; * significant at the 95% and ** significant at the 99% levels, respectively. The months in bold are the most stable as they consistently appear regardless of the period. The prefix *p* indicates the month of the previous calendar year. See also Fig. 2.

left panels of Fig. 2, we see that high maximum temperatures in May–July are prejudicial (negative coefficients) to growth in beech and ash, whereas higher temperatures in May are beneficial to oak. In the second from left panels, we see that the growth of beech, ash and oak are all favoured by higher rainfall in summer. From the third panels from the left, we see that growth-rates in all three of these species are reduced by higher soil temperatures over a significant part of the year.

## Stability of the relationships

The correspondence between tree-ring chronology and climate is often assumed to be stable with time. However, we found that sometimes the correlation coefficients and thus the tree-ring/climate links are changing in time, especially in non-summer seasons. Temporal stability implies that an association of the tree-ring widths with one or more climate parameters, which has occurred in the past, will still apply. This is usually tested by verification of the regression. We have noticed that some of those associations did not verify as well as expected. To explore this situation further we decided to test for possible change with time by simply calculating the correlation coefficients in 61-year sliding windows (see Figs. 3 and 4). The first 61-year window covered the period 1880–1940. Following windows were stepped 5 years to 1885–1945, 1890–1950, etc.[3]

Our study started with monthly climate data (not shown here) which, in some cases, such as for beech and ash produced more than 50 different significant monthly correlation coefficients. This made the analysis very difficult so it was decided to use seasonal variables instead. However, the monthly coefficients have been very useful to identify patterns in the tree's association to climate. Consecutive monthly variables with same sign of the correlation coefficient have been averaged (or totalled e.g. rainfall) into seasonal variables and shown in Figs. 3 and 4 for the periods: pMay–pJul (dashed line), pAug–pNov (dash–dot–dash; except for sunshine: pAug–pOct), pDec–Feb (dotted), Mar–Apr (long dashed), May–July (solid) and finally, Aug–Oct (dash–three dots–dashed). There were many seasonal climate variables involved, so we only show the curves for correlation coefficients significant at 95% in several of the periods. Figs. 3 and 4 illustrate the behaviour of the correlation coefficients for the following variables

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[3] There is a difference of 1 year (1905 instead of 1904) between the windows used for soil temperature and the other climate parameters because the records of soil temperature commenced in April 1904.

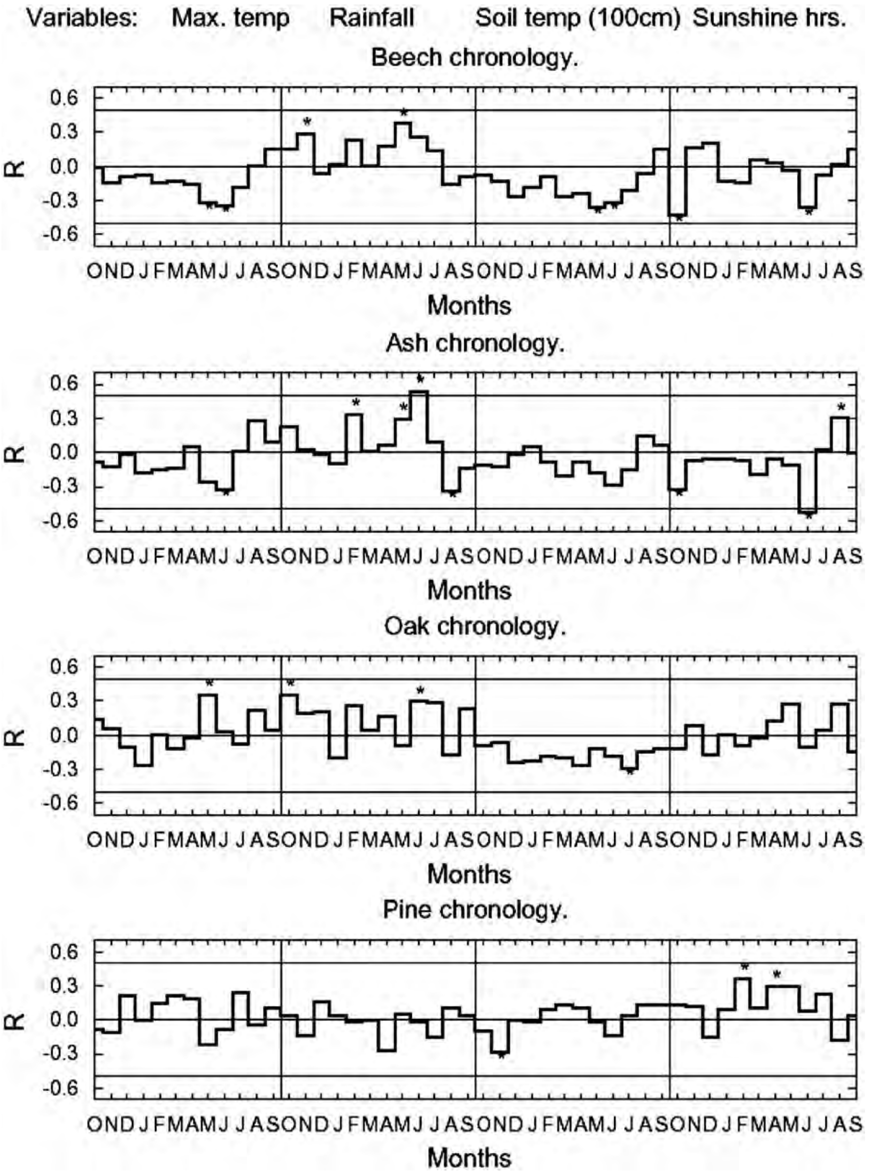

**Fig. 2.** Correlation coefficients between the mean monthly climate parameters and annual tree-ring widths for beech, ash, oak and pine in the period 1929–1977. The left panels are for maximum temperature, followed by rainfall, soil temperature (100 cm) and sunshine to the right. Asterisks indicate coefficients significant at 95% level.

(in descending order): (1) Maximum temperatures (top panel). (2,3) Soil temperatures at 30 cm and at 100 cm depth (second panel). (4,5) Rainfall and monthly total rain-day (5 mm) or Rday hereafter (third panel). (6) Pressure, (7) PDSI and (8) sunshine hours (fourth panel). Codes to facilitate identification with the relevant season and climate parameter are shown by the key in the right hand margin. Note the top item in the key corresponds to the variable with the highest correlation coefficient in the period 1941–2001, the next item to the second highest, etc.

For example, Fig. 3 (top) shows the correlation coefficient patterns for beech. The coefficient for mean maximum temperature in Aug–Oct of the current year (top on the key) is the only variable in this panel that shows a positive relationship to growth. The next seasonal variable (long dashed curve) shows the correlation coefficients obtained for the mean maximum temperature over the months March–April of the current year. The next curve corresponds to the pDec–Feb, followed by the coefficients for the pMay–July (dashed line) and pAug–pNov (dash–dot–dash) and finally, the coefficients corresponding to May–July (solid curve). Figs. 3 and 4 show the correlation coefficients over time for chronologies standardised using the ‘traditional methods’.

In general, we find that there is a clear division between positive and negative relationships for all species. The correlation coefficients for beech are rather less stable than for the other species with more curves

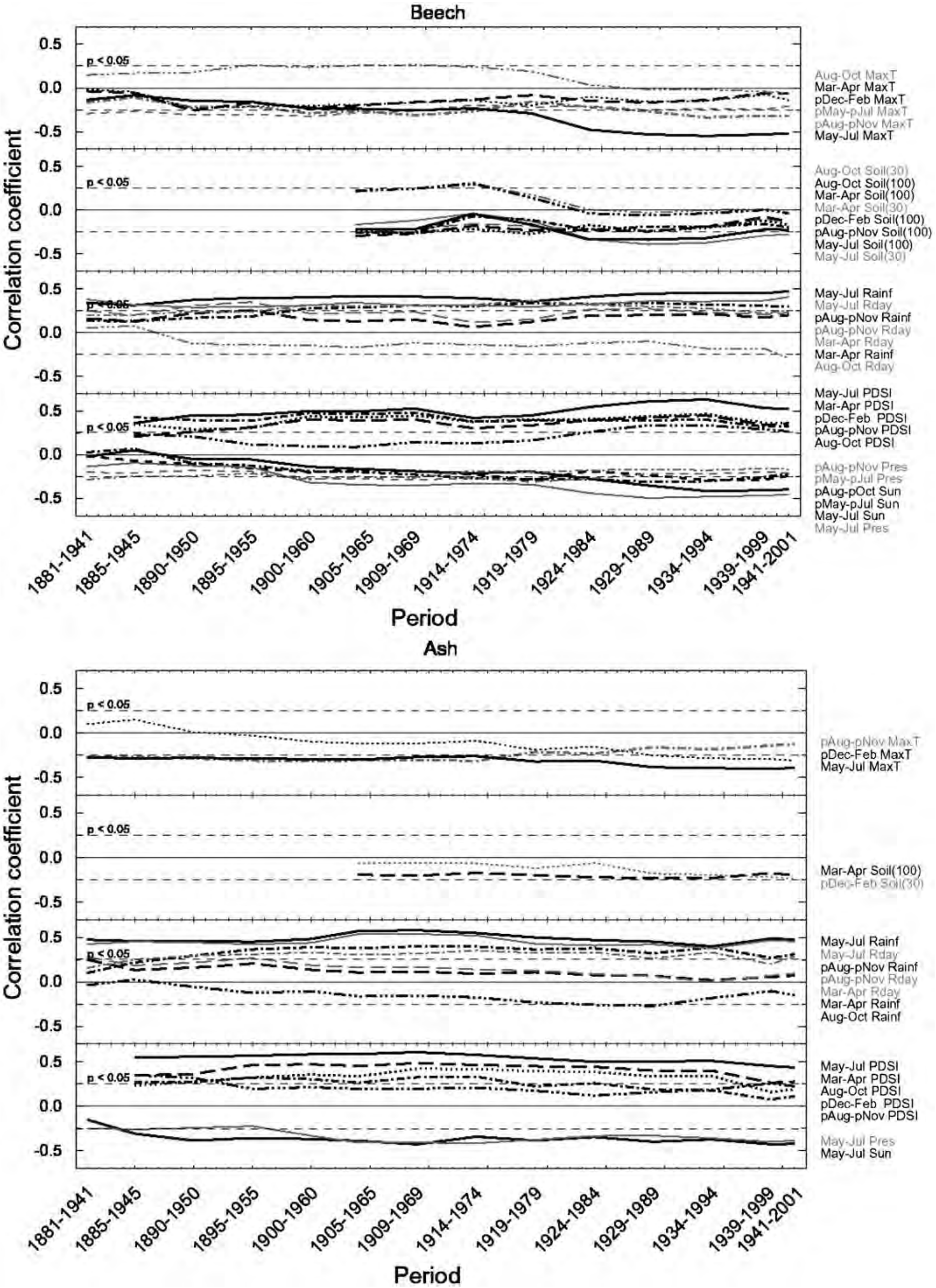

**Fig. 3.** Changes over time of correlation coefficients between seasonal climate variables and beech (top) and ash (bottom) indices (see text for further details).

included. However, together with ash, the beech coefficients are usually larger than for oak and pine, particularly those that are most stable (see also months shown in bold in Table 2). In addition we note the following:

(1) *Beech*: Stable and positive correlation coefficients are found for rainfall and the rain-day total in May–July and in pAug–pNov. PDSI coefficients are highly significant for May–July, Mar-Apr, pDec–Feb and pAug–pNov. In contrast, less stable curves are found for the maximum temperatures over May–July which behaves similarly to maximum temperature in Aug–Oct.

(2) *Ash*: Relatively stable curves are found for May–July and pAug–pNov rainfall and rain-day coefficients

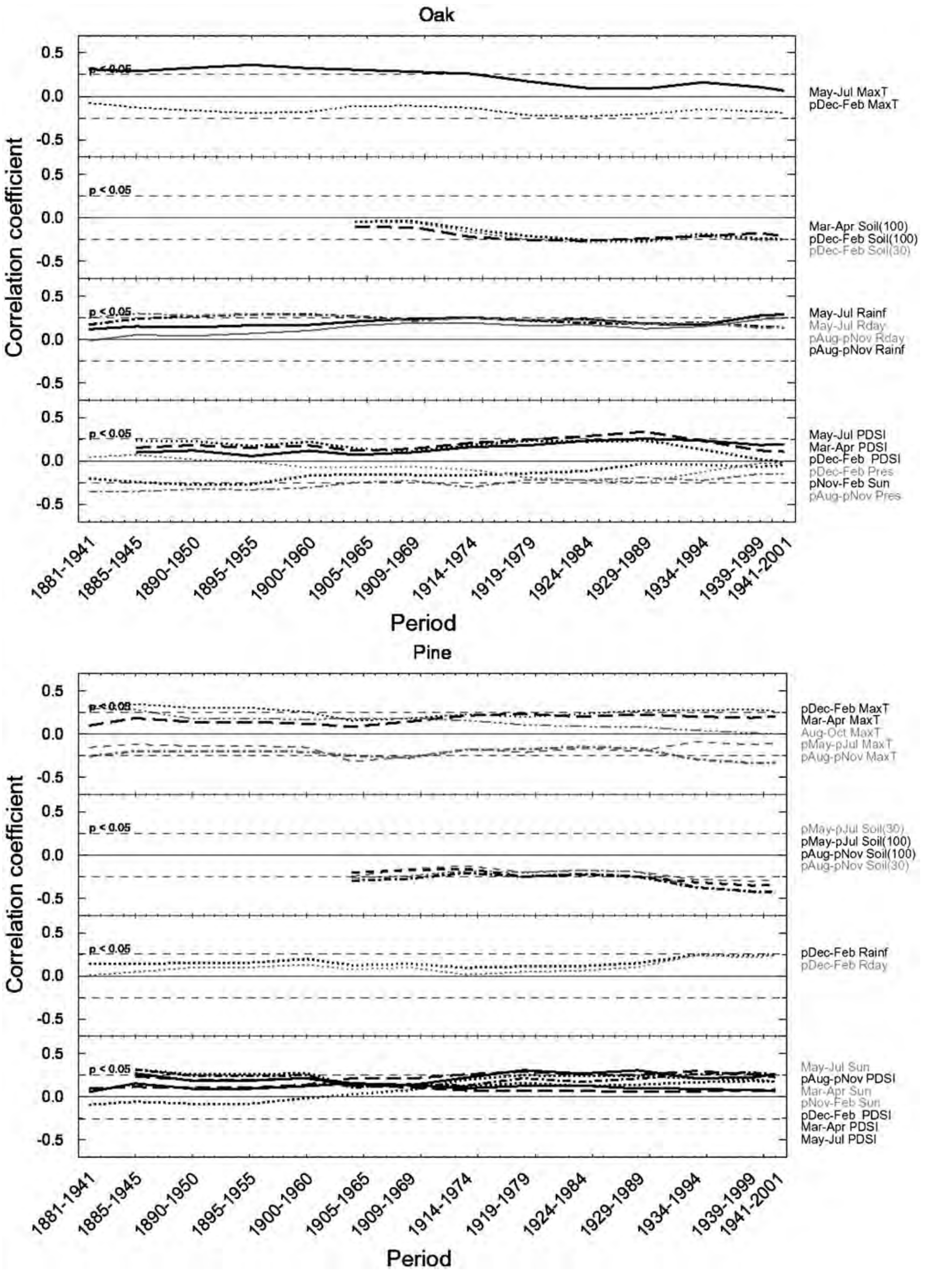

**Fig. 4.** Changes over time of correlation coefficients between seasonal climate variables and oak (top) and Scots pine (bottom) indices (see text for further details).

and similarly for PDSI in the seasons May–July, Mar–Apr, Aug–Oct. Stable but negative curves are found for May–July, pDec–Feb and pAug–pNov maximum temperature. None of the seasonal soil temperatures are consistently significant. The curves for May–July pressure and sunshine are significant and stable.

(3) *Oak*: None of the seasonal correlation coefficients are consistently significant at 95% for oak though pressure pAug–pNov almost qualifies. Also, the correlation coefficients between most climate variables and the tree ring-widths are smaller for oak than for beech and ash. However, the oak chronology does respond to some climate variables, e.g.

maximum temperature and PDSI May–July, rainfall and rain-day May–July and pAug–pNov and pressure pAug–pNov. For the NI oak chronology the correlation coefficients observed are similar to those computed for oak at Armagh Observatory except that the coefficients are enhanced with respect to the local chronology because of the larger sample size.

(4) *Pine*: The curves for pine are relatively flat and stable. However, in most cases the significance levels are low. Stable curves are found for maximum temperature pDec–Feb and Mar–Apr, PDSI pAug–pNov, sunshine May–July and Mar–Apr, soil temperature pMay–pJul (with 30 cm more significant than 100 cm). There are no stable coefficients for rainfall or rain-days and there is no stable link between the pine chronology and temperature in May–July (see also Table 2). A sensitivity to summer temperature is usually apparent in Scots pine grown at high latitude sites (Gunnarson and Linderholm, 2002; Briffa et al., 2002; Grudd et al., 2002; Eronen et al., 2002).

Despite the short gap used to separate the sliding windows, changes over time of the correlation coefficients between tree-ring widths and seasonal climate are evident in some cases. There are changes in significance and even dramatic changes in sign of some coefficients (e.g. in the coefficients in Aug–Oct or May–July for temperature with beech). Possible sources of these variations over time could be as follows:

(i) *Sample size variations*. The sample size for beech changed by six from 1880 to 1940, but between the periods 1914–1974 and 1924–1984 there is a difference of only one. The ash coefficients are more stable than the other species even though the sample size changes more for ash than for beech. We have tested the sample size effect for ash and beech by reducing the number of samples to those grown in 1880 (23 for beech and 10 samples for ash). We find that the correlation coefficients have the same general features as with the original samples, however, with a controlled sample size, all the coefficients have been reduced. This is due to the reduction of the signal to noise associated with the smaller sample size. Thus, instability in correspondence is not due to the introduction of new trees in the chronology.[4]

(ii) Previous studies have suggested that a tree's association to climate may change due to natural forcing because different climate variables can be important to growth in different periods. Baillie (1982) suggested that a change in climatic factors could have produced changes in the cross-correlation of several Irish oak chronologies from 1850 (using exactly the same trees). Oak at Armagh Observatory seems to have switched from summer temperature forcing (before mid-20th) to the current summer rainfall forcing (see Fig. 4i). Other authors have found similar loss/change of climate signal at other locations. Wilson et al. (2005), Briffa et al. (2002) and Vaganov et al. (1999) are only a few of the examples.

(iii) Another possible cause of instability in the correlation coefficients could be changing $CO_2$ levels in the atmosphere. Heath (1998) has drawn attention to the increased likelihood of $CO_2$-induced drought conditions with beech as $CO_2$ levels rise.

As for the possible dependence of the stability of the relationships on the detrending method, we find the same patterns using first differences indices or departures from Gaussian smoothed chronologies. There are some discrepancies such as enhancement/reduction of correlation coefficients but the most stable relationships show the same changes over time indicating that the choice of detrending method is not crucial (further details in García-Suárez, 2005). When using the preliminary RCS for oak, we found, however, some discrepancies in the coefficients meant that we have not used this oak chronology for reconstruction. This means we need to compute an RCS for oak using all epochs not only oak samples from the last millennium before using the RCS for detrending.

## Reconstructions

The correlations previously computed have indicated that reconstructions of rainfall, maximum temperature, PDSI and sunshine hours in summer and autumn seasons may be possible. Table 3 lists statistical parameters for the transfer functions for a number of climate parameters averaged over different seasons and using various combinations of species. Only the best-performing transfer functions, suitable for reconstruction, are included.

We find that the transfer functions with the largest VE are for PDSI and rainfall in May–July. With combinations of species including beech and ash, these transfer functions can explain up to 47% of the variance for PDSI and for rainfall in the calibration period and, up to 29% in the verification period. In respect of other spring/summer climate variables, transfer functions for maximum temperature in May–July can provide up to

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[4] In hindsight, it may have been preferable to adjust chronology variance for tree count as in Osborn et al. (1997) before testing stability over time, but as EPS is greater than .85 for all chronologies, we do not expect any changes in the results shown here.

**Table 3.** A summary of the quality of some of the best transfer functions of several seasonal climate variables using various combinations of species (see the section "Reconstruction for details").

| Variables | Species | Season | calibration period | Calibration | | | Verification | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *R* | Sign-test | Stud.-*t* | *R* | RE | CE | Sign-test | Stud.-*t* |
| Max temp. | Beech + Ash | May–July | 1941–2001 | .54$^{1}$ | 39/22$^{1}$ | 4.45$^{1}$ | .28$^{1}$ | + | – | 30/32 | 1.89$^{2}$ |
| | **Beech + Ash + Oak** | May–July | 1941–2001 | .59$^{1}$ | 44/17$^{1}$ | 3.61$^{1}$ | .36$^{1}$ | + | – | 33/28 | 1.86$^{2}$ |
| | Beech + Ash | Paug–pNov | 1941–2001 | .27$^{2}$ | 36/25$^{2}$ | 1.48 | .29$^{1}$ | + | – | 30/31 | 1.23 |
| | **Beech + Ash + Pine** | PAug–pNov | 1941–2001 | .45$^{1}$ | 45/16$^{1}$ | 1.53 | .35$^{1}$ | + | – | 32/29 | 1.77$^{2}$ |
| Air temp. | **Beech + Ash + Oak** | May–July | 1941–2001 | .41$^{1}$ | 39/22$^{1}$ | 2.37$^{1}$ | .30$^{1}$ | + | – | 28/33 | 1.96$^{2}$ |
| Rainfall | Beech + Ash | May–Jun | 1909–1969 | .69$^{1}$ | 46/15$^{1}$ | 4.96$^{1}$ | .57$^{1}$ | + | + | 38/23$^{2}$ | 3.70$^{1}$ |
| | Beech + Ash | May–July | 1909–1969 | .61$^{1}$ | 43/18$^{1}$ | 4.29$^{1}$ | .51$^{1}$ | + | + | 36/25 | 3.10$^{1}$ |
| | Beech + Ash | May–July | 1941–2001 | .56$^{1}$ | 40/21$^{1}$ | 3.57$^{1}$ | .53$^{1}$ | + | + | 40/21$^{1}$ | 2.79$^{1}$ |
| | Beech + Ash + Oak | May–July | 1909–1969 | .62$^{1}$ | 45/16$^{1}$ | 4.31$^{1}$ | .50$^{1}$ | + | + | 36/25 | 3.03$^{1}$ |
| | Beech + Ash + Oak | May–July | 1941–2001 | .58$^{1}$ | 42/19$^{1}$ | 3.22$^{1}$ | .49$^{1}$ | + | – | 43/18$^{1}$ | 1.37 |
| Pressure | Beech + Ash | May–July | 1941–2001 | .50$^{1}$ | 39/22$^{1}$ | 3.27$^{1}$ | .25$^{2}$ | + | – | 31/30 | 1.63$^{2}$ |
| Sunshine | Beech + Ash | May–July | 1944–2001 | .49$^{1}$ | 38/20$^{1}$ | 3.39$^{1}$ | .25$^{2}$ | + | – | 31/27 | 1.29 |
| | **All species** | May–July | 1944–2001 | .56$^{1}$ | 38/20$^{1}$ | 4.30$^{1}$ | .32$^{2}$ | + | – | 36/22$^{2}$ | .70 |
| PDSI | Ash | May–July | 1934–1992 | .51$^{1}$ | 41/18$^{1}$ | 2.49$^{1}$ | .49$^{1}$ | + | + | 36/22$^{2}$ | 2.88$^{1}$ |
| | **Beech + Ash** | May–July | 1934–1992 | .68$^{1}$ | 44/15$^{1}$ | 3.84$^{1}$ | .54$^{1}$ | + | + | 40/18$^{1}$ | 2.47$^{1}$ |
| | **All species** | PAug–pNov | 1934–1992 | .44$^{1}$ | 37/22$^{2}$ | 3.09$^{1}$ | .40$^{1}$ | + | + | 36/22$^{2}$ | 2.26$^{1}$ |
| | Beech | PDec–Feb | 1909–1967 | .46$^{1}$ | 40/19$^{1}$ | 2.59$^{1}$ | .28$^{1}$ | + | – | 39/20$^{1}$ | .07 |

35% of the VE and transfer functions for sunshine hours can be comparable. Reasonable levels of VE can also be found for some species and climate parameters in other seasons. For instance, the values of VE for the PDSI in pDec–Feb can be comparable or larger than for sunshine or pressure in summer. Note that the values of RE and CE are sometimes negative which diminishes our confidence in the regressions. We see that variables such as sunshine hours, pressure, maximum and mean air temperatures can be reconstructed though less accurately than moisture conditions (see Table 3).

From the above, we see that combinations of species usually improve the regression when two or more different species are used rather than single species. For example, we see in Table 4, that transfer functions for rainfall in May–July, show that compared with using only oak, a combination of ash, beech and oak, increases the VE by nearly a factor of five. In addition, a combination of species usually produces regressions that are more stable in time and that verify better than for single species. The models are particularly successful if they use beech and ash. The fact that the VE increases when all three deciduous species are included indicates that all three respond to rainfall variations, though differently. Rainfall reconstructions in seasons other than summer are not successful as they do not verify. Note that the numbers of predictors in the reconstructions can be equal to or less than 4 (number of species) which diminishes the danger of inflating the VE due to the ratio of number of predictors/observations.

Fig. 5 shows reconstructions of several of the more suitable climate variables together with the observed data (the transfer functions chosen are in bold in Table 3). Error bars which have been computed following Draper and Smith (1981, 31pp.) and Myers (1986, 32pp. and 84pp.) are shown in Fig. 5 at the extreme right hand side of each panel. Though, strictly speaking, error bars are variable with time, in fact they vary little from year to year as the variance $S^2$ is the dominant factor. Note that the observed data and the predictions are expressed as departures from the mean over the calibration period (enclosed within the dashed horizontal lines). The period studied is 1880–2001 split into calibration and verification periods.

We have obtained some successful reconstructions for maximum temperature, rainfall, sunshine and PDSI. These are as follows:

(1) *Temperature*: Temperature reconstructions are limited by the useful length of the ash and oak chronologies and by the possible changes over time of the sensitivity to temperature of beech. Although several mean air temperature reconstructions have been attempted, they usually explain less variance than the reconstructions for maximum temperature. Fig. 5 shows some attempts to reconstruct maximum temperature in May–July (panel iv). Panels v and vi

**Table 4.** The results of statistical tests on some examples of transfer functions for rainfall in May–July.

| Species | Period | Calibration | | | Verification | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *R* | Sign-test | Stud.-*t* | *R* | RE | CE | Sign-test | Stud.-*t* |
| Beech | 1941–2001 | $41^1$ | $44/17^1$ | $2.27^1$ | $.45^1$ | + | + | 34/24 | $1.97^2$ |
| Beech | 1941–2001 | $47^1$ | $39/22^1$ | $3.06^1$ | $.37^1$ | + | + | $42/19^1$ | 1.28 |
| Oak | 1909–1969 | $.29^1$ | 33/28 | $2.36^1$ | Not | Passed | | | |
| Oak | 1941–2001 | Not | Passed | | | | | | |
| Ash | 1909–1969 | $.58^1$ | $47/14^1$ | $2.88^1$ | $.41^1$ | + | – | 35/26 | $2.40^1$ |
| Ash | 1941–2001 | $.48^1$ | $39/22^1$ | $3.22^1$ | $.47^1$ | + | + | $38/23^2$ | $3.43^1$ |
| Beech + Ash | 1909–1969 | $.61^1$ | $43/18^1$ | $4.29^1$ | $.51^1$ | + | + | 36/25 | $3.10^1$ |
| Beech + Ash | 1941–2001 | $.56^1$ | $40/21^1$ | $3.57^1$ | $.53^1$ | + | + | $40/21^1$ | $2.79^1$ |
| Beech + Ash + Oak | 1909–1969 | $.62^1$ | $45/16^1$ | $4.31^1$ | $.50^1$ | + | + | 36/25 | $3.03^1$ |
| Beech + Ash + Oak | 1941–2001 | $.58^1$ | $42/19^1$ | $3.22^1$ | $.59^1$ | + | – | $43/18^1$ | 1.37 |

Note that '1' means significant at 99% level and '2' at 95%. For 'not passed' regressions see criteria in text.

show the reconstructions for maximum and mean air temperatures in pAug–pNov. Summer reconstructions are reasonably close to the observed data, except in the 1920s. The autumn reconstructions are weaker than for summer.

(2) *Rainfall*: Fig. 5 shows that rainfall has been more successfully reconstructed by our methods than almost any other climate parameter, with the possible exception of the PDSI. The reconstruction of May–June rainfall using beech and ash (Fig. 5, panel i) has reproduced much of the inter-annual and inter-decadal variation since the 1840s. Nevertheless, there are some periods (i.e. in the 1870s) when systematic differences occur.

(3) *Sunshine*: Panel (vii) in Fig. 5 shows an attempt to reconstruct sunshine for May–July. This reconstruction used a combination of all species for the calibration period 1941–1998. The reconstruction is reasonably good in the 1980s and 1990s and the 1940s, but it is poorer in the 1900s and 1930s.

(4) *PDSI*: Two PDSI reconstructions for the seasons May–July (panel ii) and pAug–pNov (panels iii) using combinations of ash and beech and all species, respectively, are shown in Fig. 5. The amplitude of the estimated year-to-year variations in the May–July PDSI reconstruction is comparable to the actual data. The decadal variability is also quite well reproduced and the verification is good. Note that there are some systematic differences in the 1920s and 1970s. The PDSI reconstruction is weaker for pAug–pNov than for summer.

To further illustrate the quality of the reconstructions we show, in Fig. 6, the departures from the mean of the observed data and the reconstructed data for two of the more successful reconstructions, namely for rainfall and PDSI in May–July.

## Discussion and conclusions

We have studied tree-ring climate links for four common species from Northern Ireland, namely: oak, beech, ash and pine. In order to eliminate geographical variation in climate, we have chosen trees grown very close to the longest running climate station in Ireland, Armagh Observatory. The pine and ash chronologies we have developed are the first, and the beech the longest, modern chronologies for these species from Ireland. However, these chronologies have been built only from living trees and despite our efforts they extend back only to the early 19th century.

While this study has given some useful insight into the use of tree-rings of common species simultaneously for climate reconstruction in a temperate climate, it may be some time before such reconstructions are possible for Ireland due to the current lack of long chronologies for species other than oak. It will be difficult to extend chronologies of beech and ash before 1800 due to the paucity of samples from that time. Nevertheless, a number of archaeological sites in Ireland have revealed specimens of ash several thousands of years old and it may eventually be possible to build an early ash chronology. Pine has its own problems as, although it was common prior to the second millennium BC, it subsequently died out and was not found again in Ireland until reintroduced in the 17th century.

In the following paragraphs, we summarise the key conclusions of this study:

(1) We have shown that oak, beech, ash and Scots pine respond differently to climate. The most relevant months for growth are usually May to July of the current year and October–November of the previous year. In addition, we have shown that the deciduous species in our selection, namely ash, oak and beech, are most affected by rainfall, PDSI and maximum

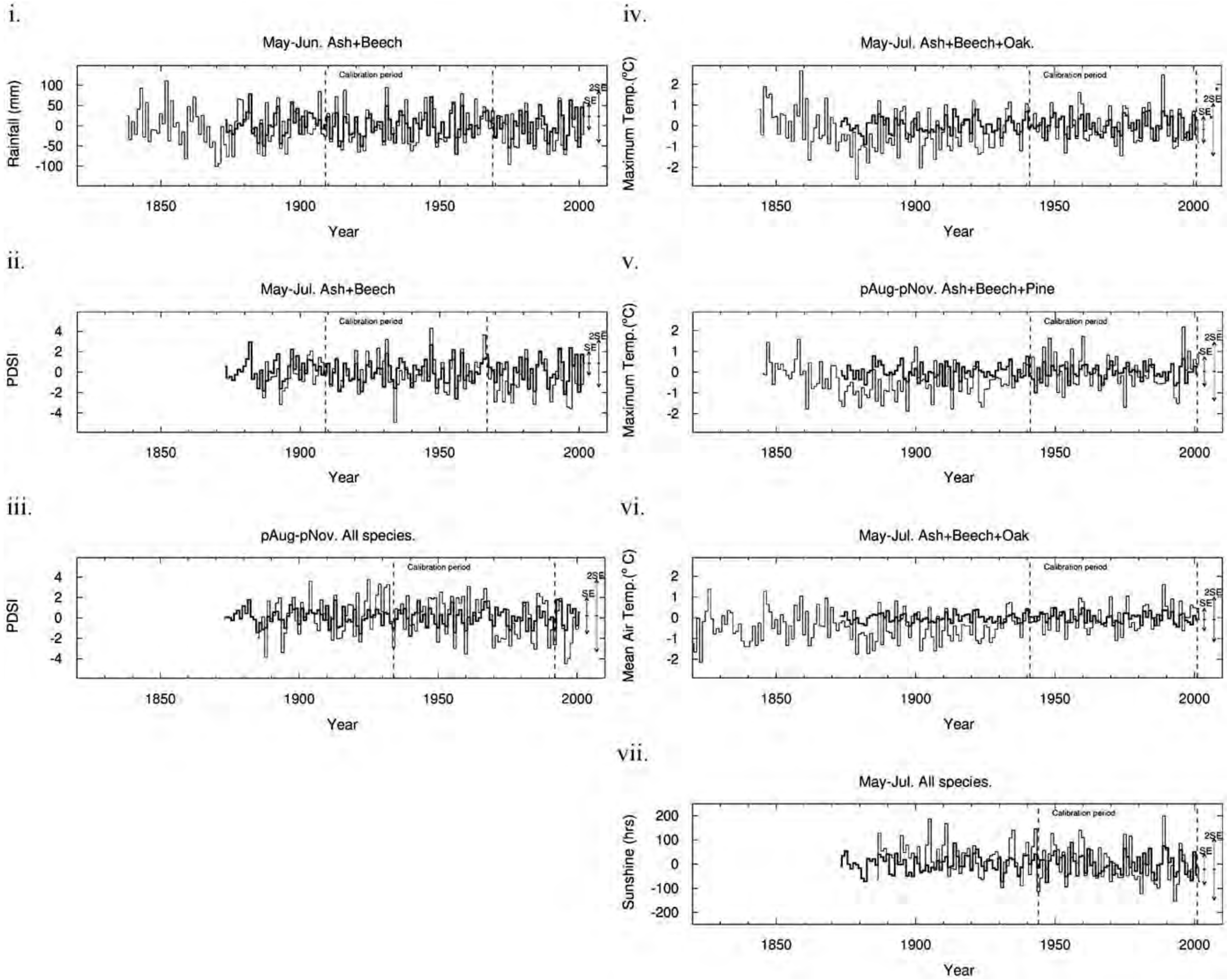

**Fig. 5.** Reconstructions of several climate variables (thick) and actual data (thin): (i) Rainfall in May–Jun using a combination of Ash + Beech. (ii) PDSI in May–July using a combination of Ash + Beech. (iii) PDSI in pAug–pNov using a combination of all species. (iv) Maximum temperature in May–July using a combination of Ash + Beech + Oak. (v) Maximum temperature in pAug–pNov using a combination of Ash + Beech + Pine. (vi) Mean air temperature in May–July using a combination of Ash + Beech + Oak. (vii) Sunshine in May–July using a combination of all species. The period of study is 1881–2001. Verification is performed on the remaining years of this period outside the calibration period.

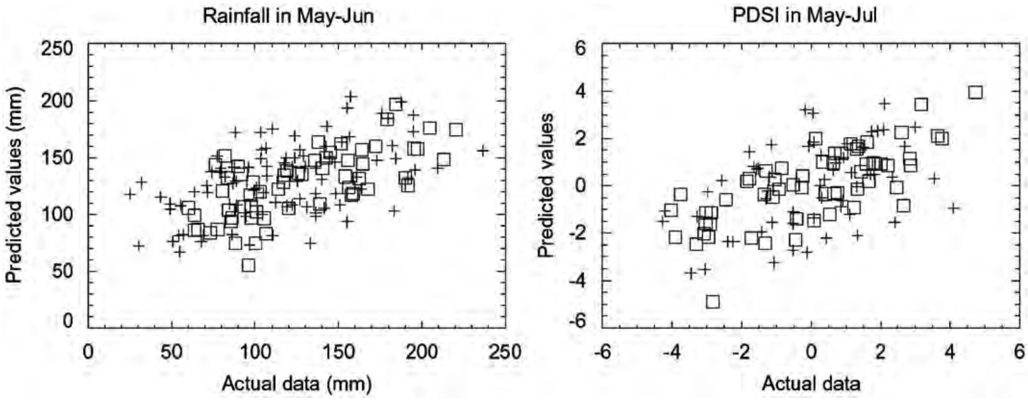

**Fig. 6.** Departures from the mean of observed data and estimates from the reconstructions for (i) rainfall in May–June ($R = .69$) and (ii) PDSI in May–July ($R = .71$). Open squares are for data in the calibration period, and crosses in the verification period.

temperature in late spring and early summer. In contrast, Scots pine responds to maximum temperature and the soil temperature in winter, autumn and spring. Unlike at other locations (i.e. in Scottish Highlands; Hughes et al., 1982), there is very little response to summer temperature showed by pine in Northern Ireland. It seems likely that the more benign climatic conditions in Armagh result in a longer growing season for pine with a consequent dilution of the effects of summer temperature.

(2) We have studied the temporal stability of tree-ring/climate links for each species. We find some evidence that changes over time occur, especially affecting non-summer seasons. The most stable associations are found for maximum temperature, rainfall and PDSI in May–July of the current year and the same parameters in autumn months of the previous year. The least stable link is usually for beech, particularly for sunshine and maximum temperature even in summer. While the reasons for the possible changes of the correlation coefficients with time are unclear, a time-dependent sensitivity could hamper climate reconstructions for previous centuries. We have suggested several possible reasons for the apparent temporal instability such as sample size variations, natural climate forcing or changing $CO_2$ levels.

(3) The variables best suited for reconstructions at Armagh Observatory are the late spring–early summer PDSI and rainfall. The VE in transfer functions with beech or ash are larger than for oak, and combined as predictors, ash and beech can explain more than 40% of the variance for summer rainfall and PDSI. PDSI reconstructions may be useful to study past moisture conditions. Other indices for drought conditions such as those suggested by Keyantash and Dracup (2002) should be investigated in the future.

(4) Reconstructions of the same parameters for late summer/autumn of the previous year (pAug–pNov) are also possible but annual reconstructions are significantly less reliable. The usefulness of the reconstructions is limited by the following: (i) Some of the transfer functions are poorly constrained reducing the possibilities of reconstruction (e.g. oak), (ii) Apparent instability in the relations to climate of species like beech. However, we have found that combinations of species are better able to reconstruct climate than single species. Particularly robust are the reconstructions that use ash and beech simultaneously as predictors.

(5) It is often suggested that the correlation coefficients between climate and the tree-rings depend of the methods of standardisation. Thus, different methods could affect the response and/or reconstructions, alter their stability, the VE and even the regression coefficients and the significant tests of the models. However, we have found relatively few differences in those parameters by using different standardisation methods (i.e. First differences and Gaussian), at least for the most stable seasons such as May–July. Though it is difficult to estimate the effects of detrending on the low-frequencies, the fact that we get similar results using different methods, lends credibility to the results. Further details of these tests are available in García-Suárez (2005).

(6) We have found that the Irish trees may be most useful to reconstruct moisture variations. However, in regional reconstructions, the rainfall and PDSI signal found in chronologies is often weaker than temperature (Briffa et al., 2002). This is possibly because rainfall and soil moisture variations are more localised than temperature and whereas the meteorological parameters we have used are representative of the place where the trees have grown, in other, regional studies local differences could occur. Wilson et al. (2005) have also shown that rainfall reconstructions using tree-ring data can be successful and robust at low-elevations in Europe.

The reconstructions shown here are conservative because, with only a percentage of the observed variation modelled and because by standardising the chronologies we, inevitably, may remove part of the low-frequency variability, the reconstructed data will necessarily have smaller amplitude than the true observed data. Extreme events such as very wet/dry years or years with extreme temperatures may be reproduced but with a less extreme character (e.g. rainfall in 1931 (see Fig. 5). When reconstructing past climate from tree-rings (e.g. the amplitude of the Little Ice Age or Medieval Warm Period), it is important to appreciate that these reconstructions are conservative as they only contain a part of the true climate signal.

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