COMBINING RING WIDTH, DENSITY AND STABLE CARBON ISOTOPE PROXIES TO ENHANCE THE CLIMATE SIGNAL IN TREE-RINGS: AN EXAMPLE FROM THE SOUTHERN FRENCH ALPS

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Abstract. At present the most powerful tree-ring based climate reconstructions use high numbers of growth proxy series (ring width and density) to produce spatially smoothed estimates, such as average Northern Hemisphere summer temperatures. These single parameter reconstructions might be supplemented with regional climate reconstructions capable of capturing variability in more than one climate variable without lower replication compromising statistical quality, if multiple tree ring proxies were used. *Pinus sylvestris* and *Pinus uncinata* latewood density, width and δ^{13}C series are presented from two sites in the French subalpine zone, east of Briançon. Where two proxies have the same dominant climate control their combination enhances that signal. Where proxies differ in dominant controlling climate variable, combining series allows access to bi-variable calibrations. Using this approach, multi-proxy reconstructions of both temperature and precipitation would better reflect complex synoptic variability in climate on spatially useful scales.

1. Introduction

Trees form an exceptional physical archive of information on past climate and, where the climate is seasonal, annually incremental growth in sensitive trees ensures that information, stored in the chemical and physical variations within wood, can be assigned to a specific year. The vast majority of tree-ring climate reconstructions are based on variations in either ring width or wood density. However, in recent years another useful climate proxy, originally developed in the 1970's (e.g. Wilson and Grinsted, 1977) but only fully quantified in the late 1980's (see Farquhar et al., 1989), has come into focus. The photosynthetic products which make up wood contain a marker for climate in the ^{13}C/^{12}C signature of each ring. Stable carbon isotope ratios (δ^{13}C) have successfully been added to the suite of dendroclimatic proxies, with good results from many studies linking δ^{13}C variability to climate (see McCarroll and Loader, 2004; and references therein). Trees take in CO_2 via leaf stomata, through which water is also lost via transpiration. Several physical and biochemical processes within the leaf favor the assimilation of ^{12}C rich CO_2 (Farquhar et al., 1989). However, when internal CO_2 concentration drops due to stomatal action, or high photosynthetic assimilation rates, a greater proportion of ^{13}C moves through the pathway to be stored in carbohydrate. Once carbon is locked

Climatic Change (2006) 78: 363–379
DOI: 10.1007/s10584-006-9097-3

into lignin and cellulose it does not transfer between rings, so that a discreet record of δ^{13}C is preserved, essentially giving a measure of past fluctuations in internal concentration of CO_2 (McCarroll and Loader, 2004).

At cool, moist high latitude sites, the δ^{13}C signal in tree rings tends to be dominated by those variables that control assimilation rate; principally summer irradiance and temperature (McCarroll and Pawellek, 2001). At xeric sites the climatic signal in δ^{13}C tends to be dominated by stomatal conductance, thus δ^{13}C records variations in air humidity and those variables that control soil moisture status (Gagen et al., 2004).

As with all proxy data, tree-ring series are noisy. Climate information must be distilled from time series which contain the effects of forest dynamics, tree growth rates and local ecology, if derived from growth proxy series, and anthropogenic changes in the isotopic ratios of atmospheric CO_2, and possibly some age related trends, if derived from δ^{13}C. Consequently, only a proportion of the signal in any series is related to climate and, in some cases, common signal strength can be low, resulting in weak correlations when averaged tree-ring data are compared with instrumental climate data. This weakness is carried into reconstructions when transfer functions, using inverse calibration, are used to estimate the climate variables from the proxy series. Inverse calibration inevitably biases estimates towards the mean, thus underestimating the magnitude and frequency of past climate extremes (Birks, 1995; Robertson et al., 1999). The severity of this bias is inversely proportional to the strength of the initial proxy:climate correlation. The strongest, and least biased, tree-ring climate reconstructions will therefore be based on the highest calibration correlations. In a pilot study using trees from Finland, McCarroll et al. (2003) demonstrate that a powerful way of increasing the strength of calibration correlations is to combine different types of tree-ring proxy series. Perhaps more powerful is the potential to produce reconstructions which contain information on both temperature and precipitation variability by combining proxies which respond to different climatic factors, as has been carried out using ring-width proxies from colocated but elevationally-distinct chronology sites (e.g. Salzer and Kipfmueller, 2005). Multi proxy dendroclimatology may give access to bi-variable signals at the same site, which would potentially allow reconstructions of complex variations in regional synoptic climatology from a single population of trees.

We investigate whether, by combining more than one proxy series from the same population of trees, calibration statistics are improved and the potential for developing bi-variable reconstructions is enhanced. Using latewood width, density and δ^{13}C, two questions are addressed:

1. can estimates of a single climate variable common to two proxies be improved by combining their respective estimates, and;
2. can bi-variable reconstructions be developed by coupling two proxies; one which responds most strongly to temperature and one to precipitation.

2. Background

The climate of Western Europe is generally dominated by the action of the Atlantic. Decadal scale variability, as controlled by the North Atlantic Oscillation (NAO) influences both temperature and precipitation variability over the region, predominantly in winter (Beniston and Jungo, 2002). However, the NAO shows temporally unstable positive correlations with temperature and negative with precipitation over the Alpine region, suggesting that other atmospheric circulation modes can also dominate (Casty et al., 2005). This is particularly notable through periods such as the Little Ice Age, where proxy records suggest that instability manifested in decadal to multi-decadal phases of cool/wet and warm/dry conditions (Tessier, 1986). Whilst NAO forcing dominates in winter, the synoptic situation in summer is more complex. The traditional description would revolve around increased influence of locally driven systems, with a background of weak pressure gradients (Casty et al., 2005). However, low frequency ‘events’ increasingly cause dramatic changes in typical conditions, such as in the Europe-wide heat wave of summer 2003. The region can best be understood as a transitional zone where the influence of air masses with both continental and maritime origins can be felt.

The field sites for this study are located within the Briançonnais region of the French Hautes Alps. The climate of the area is defined by high insolation (3064 h/year) and low annual precipitation (900 mm). Mean annual temperature at Briançon is 7.7 °C. Average maximum daytime temperature through the summer (June–August) is 22 °C (1961–2002), within this period July has been the hottest month (average 24 °C). Average summer precipitation is 162 mm (1967–2002) with a minimum of 78 mm in 1967 and a maximum of 350 mm in 1992. January is the coldest month and July the driest and hottest (Meteo France station Briançon).

Ring width and wood density series from long-lived subalpine treeline species in the Alps contain useful climate information. Stable carbon isotope series respond to summer precipitation in the drier southern Alps (Gagen et al., 2005; Treydte et al., 2002). Growth proxy series, in the wider western Alps, tend to be controlled by summer temperatures (Rolland et al., 2000; Keller et al., 1997; Edouard et al., 1999; Petitcolas and Rolland, 1996; Tessier, 1986; Fauquette and Talon, 1995), although response can be site and species dependent (e.g. Rigling et al., 2002). These differing responses of δ^{13}C and growth proxy series to climate can potentially be exploited through multi-proxy dendroclimatology.

In the Hautes Alps, ring width series from young trees, or from heavily forested sites, often contain little common climatic information, considerably less than those from tree-line ecotones (e.g. Edouard et al., 1999). This site-dependant signal strength is easily overcome when compiling series from living trees. However, appropriate site selection criteria cannot be used when extending tree-ring records back in time. Sampling sub-fossil wood from shallow lakes over a wide area, or using archeological building materials, does not allow for pre-selection of site conditions. Stable carbon isotope series appear to be less site-sensitive and δ^{13}C series from heavily forested locations archive climate information as strongly as those from ‘marginal’ tree-line sites (Gagen et al., 2005). This has also been found in $\delta^{13}C$ series from pine trees in the Swiss Alps (Treydte et al., 2002) and northern Fennoscandia (McCarroll and Pawellek, 1998), although insensitivity to site conditions is probably limited to those locations where soil moisture conditions are similar (Saurer et al., 1997).

3. Materials and Methods

3.1. SAMPLING

Two study sites were located above Montgenèvre, east of Briançon (Figure 1), at the sub-alpine tree line. Sampling was carried out at an upper site at 2200 m (*Pinus uncinata)* and a lower site at 1800 m (*Pinus sylvestris*). Fourteen trees from each site were sampled for ring width and densitometric analysis by removing a 4 mm core from two sides of the trunk (see Fritts, 1976; for standard dendroclimatology methods). All samples were securely dated against regional master chronologies (Edouard et al., 1999). Six trees in total were analysed for $\delta^{13}C$; two from the lower site and four from the upper. Between-tree coherence of the $\delta^{13}C$ series and signal strength was such that fewer trees were needed to construct a high quality $\delta^{13}C$ time series (average between tree correlation using trees from both sites is $r = 0.62$) and sampling location was not a significant source of difference between mean tree $\delta^{13}C$ (Gagen et al., 2005).

Tree-ring width (total, earlywood and latewood) and wood density (maximum, minimum, average earlywood and average latewood) measurements were obtained using standard dendrochronological techniques (Fritts, 1976; Cook and Kairiukstis, 1990) with width measured to 0.001 mm precision. Density measurements were obtained using standard X-ray densitometry techniques (Schweingruber, 1988). Samples taken for $\delta^{13}C$ measurement were processed to holocellulose using Soxhlet extraction for the removal of resins and waxes (Hoper et al., 1998) followed by bleaching for lignin removal (Loader et al., 1997). Individual holocellulose samples were prepared using an offline combustion and cryogenic distillation system followed by analysis on a VG Micromass 602C dual inlet isotope ratio mass spectrometer (precision $\pm 0.05‰$). Isotope ratios are expressed using the conventional δ (delta) notation (McCarroll and Loader, 2004). In the following analysis only latewood variables (latewood width, maximum density and latewood $\delta^{13}C$) are presented, as these series were most coherent and most strongly related to climate (Gagen et al., 2005).

The $\delta^{13}C$ series were corrected for the anthropogenic increase in isotopically light atmospheric CO_2 (Friedli et al., 1986) by subtraction from an atmospheric $\delta^{13}C$ CO_2 curve (e.g. Saurer et al., 1997; McCarroll and Pawellek, 2001). Ring width and density series contain non-climatic information related to site ecology and forest dynamics, ring width additionally contains a trend related to tree age that

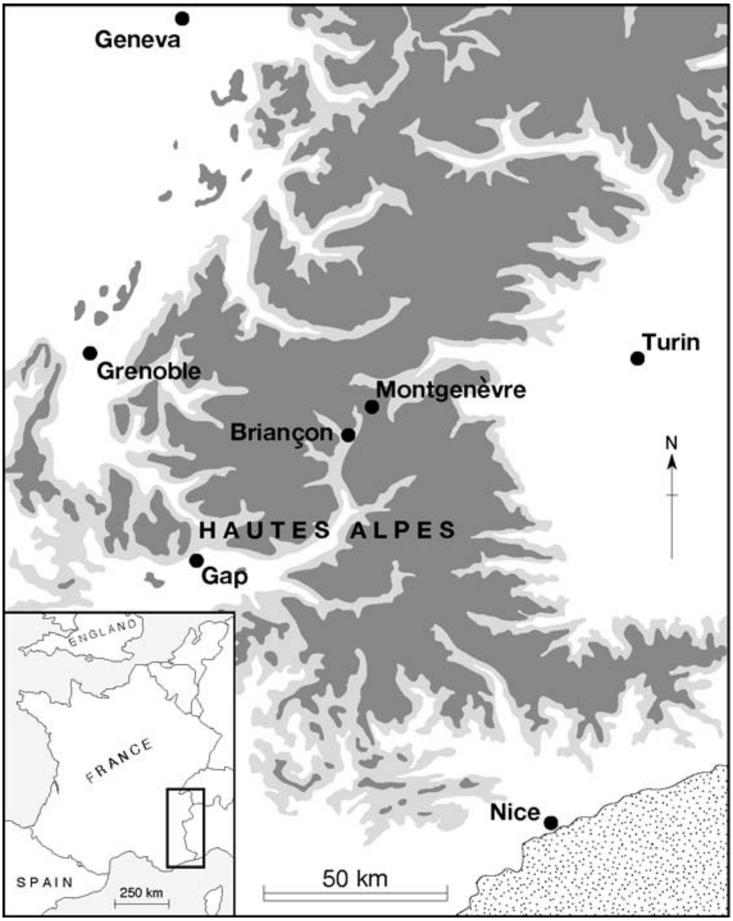

Figure 1. Location of field sites and meteorological station.

must be removed from the series; a process known as 'standardization'. All series were standardized as conservatively as possible, within the constraints of minimum series length, using the tree ring software program ARSTAN (Cook, 1985). The early part of each chronology was cut at the point at which Expressed Population Signal indicated an unacceptably low sample depth (at EPS < 0.85, Wigley et al., 1984) (Figure 2). Width series were standardized using a smoothing spline with a 50% cutoff frequency at 50% of series length, $\delta^{13}C$ series were corrected for changes in atmospheric CO_2 and linear detrended to remove juvenile changes in $\delta^{13}C$. Latewood density series were standardized by linear detrending.

Mean monthly maximum and minimum temperatures (1967–1995) and monthly precipitation totals (1961–1995), used for climate calibration, were obtained from a Meteo France station at Briançon, 14 km from the field site. A longer climate data series (1895–1980) from the Meteo France station at Gap, approx. 150 km from the field sites, was also used for verification. Climate data were tested for homogeneity

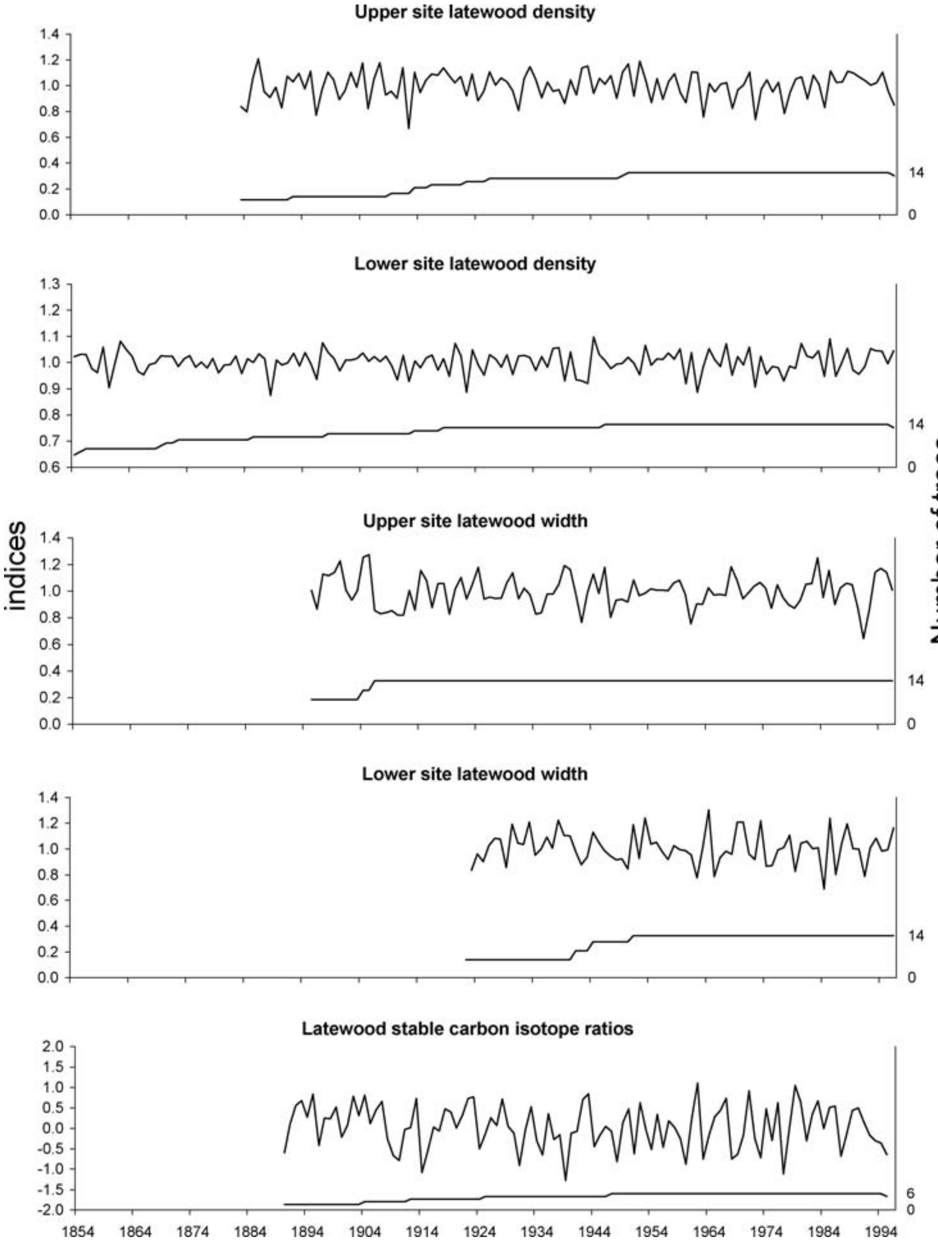

Figure 2. Latewood width, density and stable carbon isotope chronologies. Each chronology was cut at the point at which Expressed Population Signal indicated an unacceptably low sample depth. Width series were standardized using a smoothing spline with a 50% cutoff frequency at 50% of series length, δ^{13}C series were corrected for changes in atmospheric CO_2 and linear detrended for age related effects. Latewood density series were standardized by linear detrending.

TABLE I

Expressed population signal; upper, lower and combined ring width, density and δ^{13}C series. Figures in brackets show number of trees in each series

	Upper site	Lower site	Combined
Width	0.92 (14)	0.88 (14)	0.87 (28)
Density	0.95 (14)	0.81 (14)	0.73 (28)
δ^{13}C	0.88 (4)	0.80 (2)	0.90 (6)

using seasonal precipitation totals and by verifying correlations between adjacent stations. In the short overlap period between the two station records the Gap temperature series (June–August) correlates with the Briançon series at $r = 0.78$ ($n = 14$) and precipitation at $r = 0.73$ ($n = 20$). The lower correlation between the precipitation series is a reflection of the high degree of spatial variability in precipitation in mountain regions. The Gap temperature series was adjusted for altitudinal differences between the two stations.

3.2. CHRONOLOGIES

There is a difference in tree growth response to climate at the two study sites, seen when the upper and lower site proxy series are averaged. When Expressed Population Signal, an alternative to analysis of variance based on correlation coefficients (Wigley et al., 1984; Briffa and Jones, 1990), is calculated on combined-site means (Table I), the effect is to raise the EPS for the δ^{13}C series but to lower it for the two growth proxy series; this effect is discussed elsewhere (Gagen et al., 2005). Various studies have indicated that average trends in δ^{13}C are fairly insensitive to site conditions such as slope and aspect (Leavitt, 2002) and even to species (Hemming et al., 1998). It is noteworthy that the EPS value of 0.9 for the combined site δ^{13}C series is very high even though it is based on only six trees.

4. Results

Climate-proxy relationships were investigated using simple linear correlations with monthly precipitation and maximum temperature variables (Briançon station data) (Figure 3). Site to site differences in signal coherence, revealed by EPS scores, translate into different responses to climate in the width and density series, but not in δ^{13}C. Three time series are used in the following climate calibrations: mean latewood density and mean latewood width from *Pinus uncinata* at the upper site and a single combined-site latewood δ^{13}C series.

Only calibration correlations significant at $p \leq 0.01$ are considered to be a reliable indicator of strong climate forcing. Latewood width is correlated with

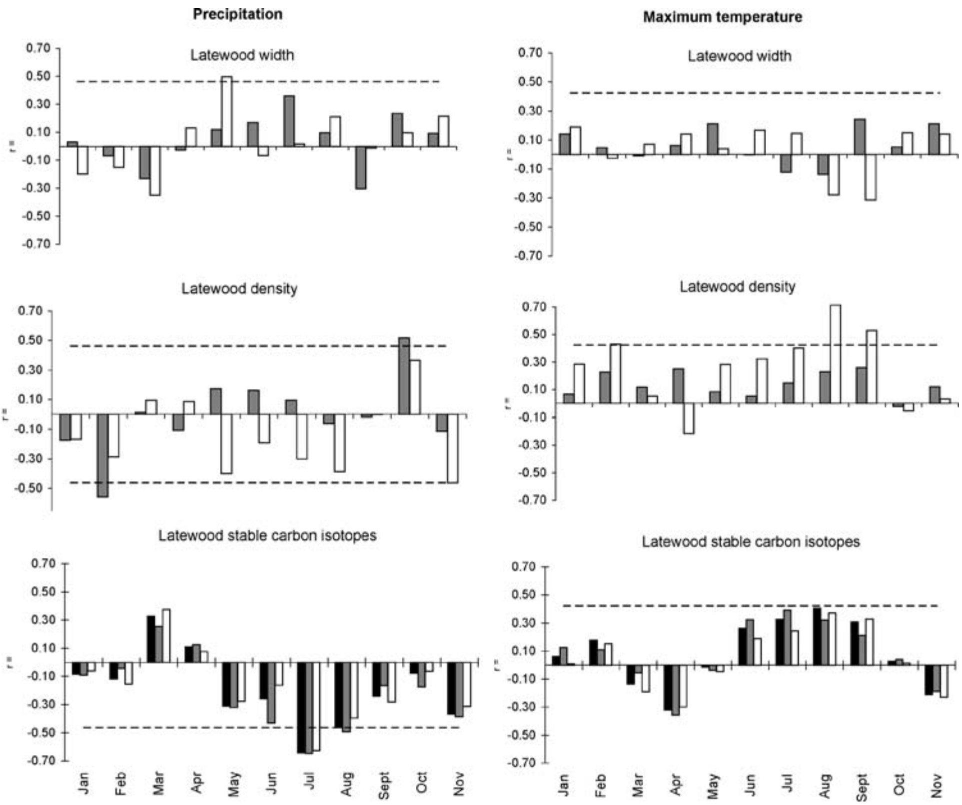

Figure 3. Simple linear correlations between all proxies and mean monthly maximum temperature (1961–1996) and precipitation (1996–1967) of the current year (Jan-November only). Dark grey shows lower site series, white upper site series, black combined upper and lower sites (stable carbon isotopes only). Significance levels ($P < 0.01$) are indicated.

May precipitation, latewood density with August and September temperature. The climate signal within the $\delta^{13}C$ series is dominated by late summer with strongly significant correlations with July and August precipitation and a weaker but significant ($p \leq 0.02$) correlation with August temperature. In all cases correlations with both precipitation and maximum temperature indicate that hot, dry summers cause stress for these trees, resulting in strong stomatal regulation of water loss and the subsequent production of ^{13}C-rich cellulose in narrow, dense latewood bands. Multivariate analysis (bootstrapped orthogonal regression after extraction of principal components) using the Briançon climate data series, supports the findings from simple linear correlations (Table II).

On the basis of the multiple regression analyses, composite climate variables of the appropriate part of the growing season were constructed and simple correlation coefficients calculated again (Table II). The strongest correlations reveal latewood width to be primarily controlled by growth season precipitation, latewood density by growth season temperature and latewood $\delta^{13}C$ by late summer precipitation.

TABLE II

Multivariate analysis results (bootstrapped orthogonal regression after extraction of principal components) of proxy climate relationships using Briançon climate data. The final two columns give the simple linear correlation value between each proxy and the strongest controlling composite climate variable using first Briançon and then Gap climate data

Proxy	$R =$	Verification $R =$	Standard deviation (correlation)	Standard deviation (verification)	Climatic variables included ($P < 0.05$)	Strongest correlation	Briançon ($n = 29$) $r =$	Gap ($n = 100$) $r =$
Latewood width (upper site)	0.44	0.36	0.05	0.09	Max. Temp. May Precipitation May and August	Total precipitation: May–Sept.	0.71	0.30
Maximum Latewood density (upper site)	0.69	0.64	0.04	0.08	Max. Temp Aug. and Sept. Precipitation July and Aug.	Mean maximum temperature: May–Sept.	0.75	0.58
$\delta^{13}C$ (combined)	0.78	0.71	0.05	0.10	Precipitation July and Aug.	Total precipitation: July–August	0.72	0.26

Combining months in this way raises the strongest calibration correlation coefficients to $r \geq 0.71$ because the monthly grouped, single variables are a more appropriate means to describe the 'true' climatic forcing for each proxy. A calibration significance level of $r = 0.71$ (corresponding to 50% variance explained) has been proposed as a useful indicator of suitability for palaeoclimate reconstruction (McCarroll and Pawellek, 2001; McCarroll et al., 2003).

Simple moving linear correlations were also calculated between each proxy and the appropriate composite climate variable using the longer instrumental climate data series from Gap. Whilst the correlations between all three series and the Gap data are weaker than with the Briançon series (particularly with regard to correlations with precipitation), due to the increased distance from the field sites and the lower altitude of the Gap station, the longer series verifies the stability of the forcings, over a longer calibration period (Table II).

4.1. COMBINING PROXIES

McCarroll et al. (2003) established that, where two proxies have the same dominant control, that signal may be enhanced by their combination. Improvements to the calibration are strongest when the two proxies share primary forcing variables but have different secondary controls, such that combining their estimates cancels out some of the noise. Two proxy estimates of a shared climate parameter can be averaged and weighted by respective percentage of variance explained, to obtain a weighted estimate.

There is potential for improving the proxy estimates of precipitation at Briançon by combining width and $\delta^{13}C$ derived estimates. Both proxies are moderately well correlated with May to September precipitation (1967–1996), such that combining their estimates raises the effective correlation to $r = 0.75$ (Figure 4). This estimate is now equal to that which can be gained for July and August precipitation using just the $\delta^{13}C$ series. Combining the proxies would thus allow an additional precipitation variable to be reconstructed.

The location of the southern French Alps on several climatic boundaries imparts considerable synoptic variability into the climate. This variability is particularly apparent in summer where warm/wet and cool/dry years are recorded, in addition to those which are warm/dry and cool/wet. Average summer maximum temperature and precipitation (June–August) are only weakly correlated ($r = -0.44$); 1991 is the hottest summer (1967–1996) but only the 8th driest, 1985 is the second hottest summer in the period, but was slightly wetter than average, whilst the wettest summer on record, 1992, was of average temperature. In this context, a reconstruction of growth season precipitation would be considerably more useful were it coupled to an equally robust estimate of temperature, given that warm summers cannot be assumed to have been dry. A bi-variable reconstruction would enable a more robust investigation of synoptic variability in the past.

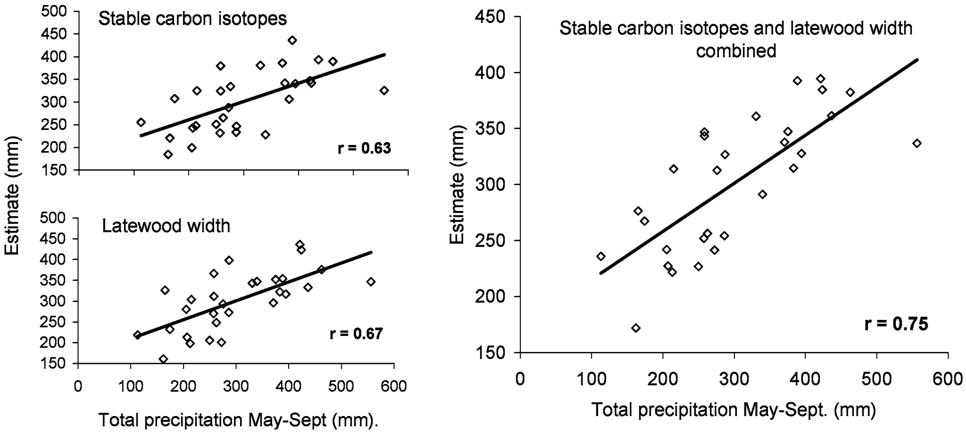

Figure 4. Combining latewood width and δ^{13}C improves the estimate of total growth season precipitation.

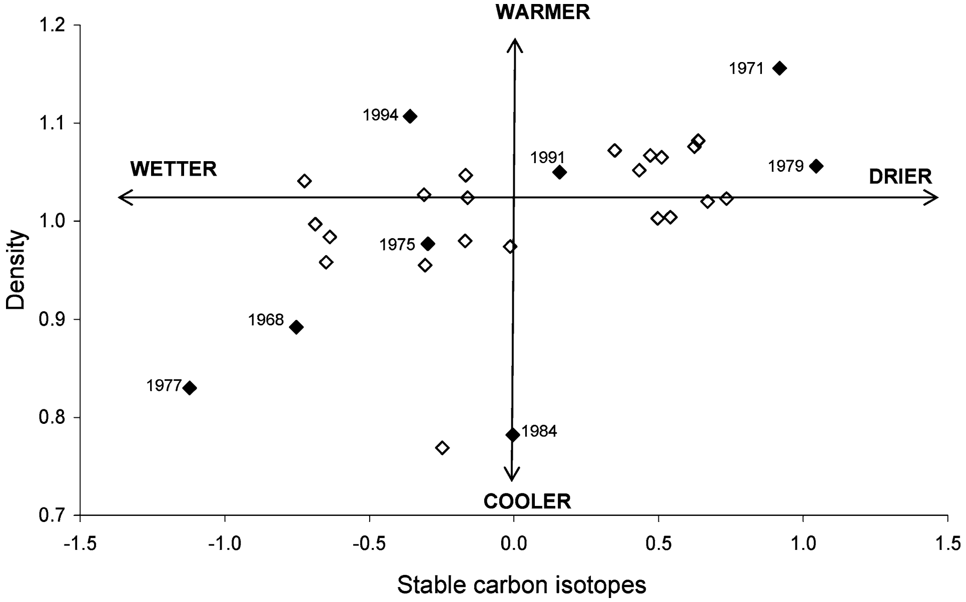

Figure 5. Latewood density provides a proxy for summer temperature, and latewood δ^{13}C a proxy for summer moisture stress, so when one is regressed on the other they provide a bi-variable estimate of summer climate.

In the regression of δ^{13}C on density ($r = 0.56$), the highest and lowest values in each series correspond to warm/dry and cool/wet conditions respectively, with less extreme values along each axis corresponding to more average conditions (Figure 5). The observations from the regression can be grouped into four quadrats by dividing the two data sets in half. The most extreme observations in each quadrat

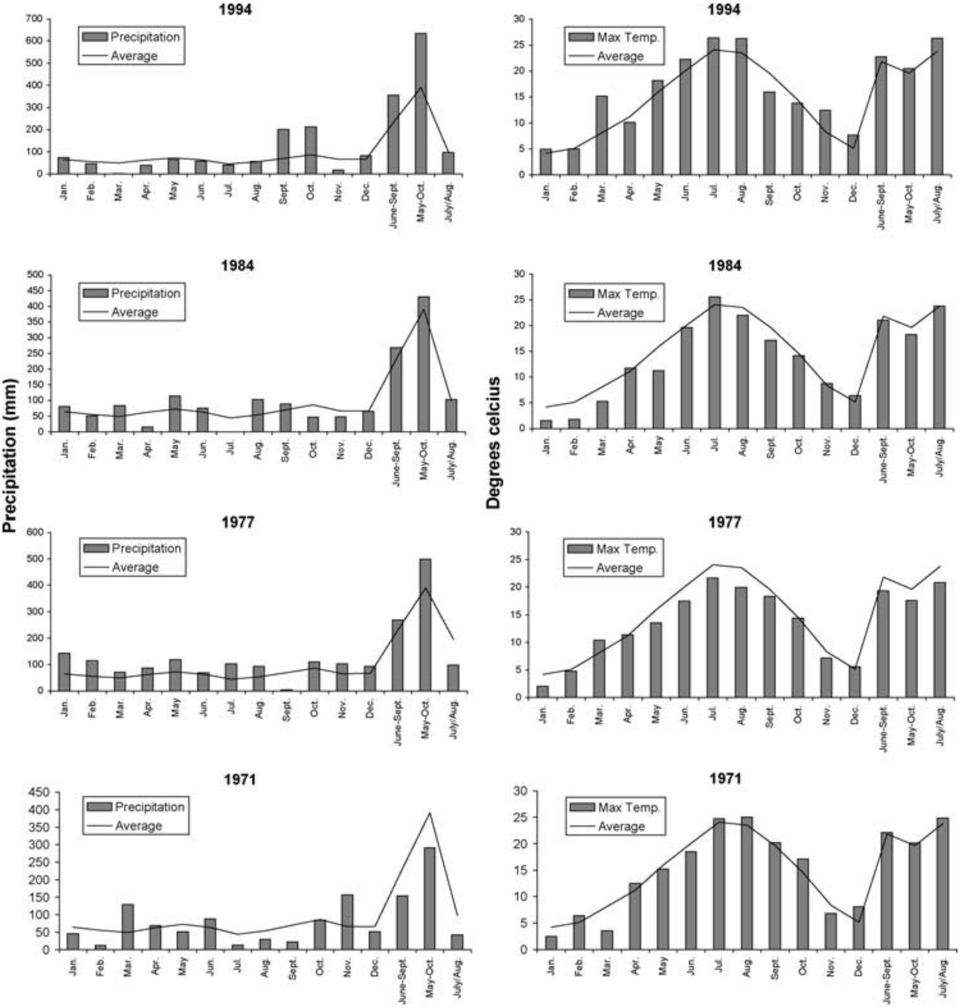

Figure 6. Climate of 1994, 1984, 1977 and 1971 compared to average conditions at Briançon.

should correspond to ‘signature’ conditions according to the association between ‘high’ and ‘low’ values for each proxy. Figure 6 gives the climate charts for four of the observations, identified in Figure 5 as the extremes in each quadrat (1977, 1984, 1971 and 1994). The model accurately predicts the warm/dry and cool/ wet years but the situation is more complicated with regard to the more unusual synoptic situations. Summer 1984 falls just within the category of cool/dry, suggesting the summer would have been cool but not particularly dry. This year was cooler than average, resulting in a low density latewood band, and July saw only 0.5% of average rainfall, but August 192%. As the growing season can continue into November at this locality, late August rainfall would replenish soil moisture enough to be of use to the trees and this is reflected in a low δ^{13}C value. In 1994, a high latewood density value occurs as a result of slightly above average summer temperatures, with a low δ^{13}C value forced by a June–Sept precipitation total 153% of average.

This simple model allows qualitative definitions of cool/warm, wet/dry to be coupled together and also allows individual years to be compared. In the ‘cool/wet’ quadrat; June to August 1968 (141 mm, 19.90 °C) was cooler and wetter than 1975 (99 mm, 21 °C), but not as cool and wet as the summer of 1977 (196 mm, 19.30 °C). In the ‘hot/dry’ quadrat; June to September 1991, 1979 and 1971 were of average temperature (23.78 °C, 22.12 °C and 22.10 °C respectively) but, 259 mm of rainfall fell in 1991, 153 mm in 1971 and128 mm in 1979. However, 1971 is predicted to be the hottest summer of these three years and is not. The anomalously high density value is probably caused by an exceptionally warm October in 1971 (average maximum temperature 17 °C, 1967–1995 average 14 °C). It is known that so-called ‘Indian summers’ can prolong the growth season in this area (Gagen et al., 2005) and that a particularly warm autumn will produce a dense latewood band (Edouard et al., 1999).

The ability to couple an estimate of temperature to one for precipitation for a given year, using multi-proxy methods within a single archive; lends considerable strength to the palaeoclimate potential of tree rings. The years which have been correctly identified in the above model are not simply those years in which the weather was unusual, a comparative estimate of summer climate can be given for all observations.

5. Conclusions

Taking $r \geq 0.71$ as a minimum acceptable calibration correlation, Table III summarizes those climatic parameters that might be reconstructed from the Montgenènvre series using a combination of single and combined proxies. Where two proxies have the same dominant climate control their combination enhances that signal and combining can be used to increase calibration correlation coefficients.

Where proxies have different controlling climate variables, combining series allows access to bi-variable calibrations. In this example the regression between

TABLE III

Climate parameters which might be reconstructed (calibration $r \geq 0.71$) using single and combined proxy series

Climate variable	Proxy	Simple linear correlation coefficient ($r =$)
Total July–August precipitation	δ^{13}C	0.72
May–September precipitation	Width and δ^{13}C	0.75
Mean maximum temperature May–September	Density	0.71

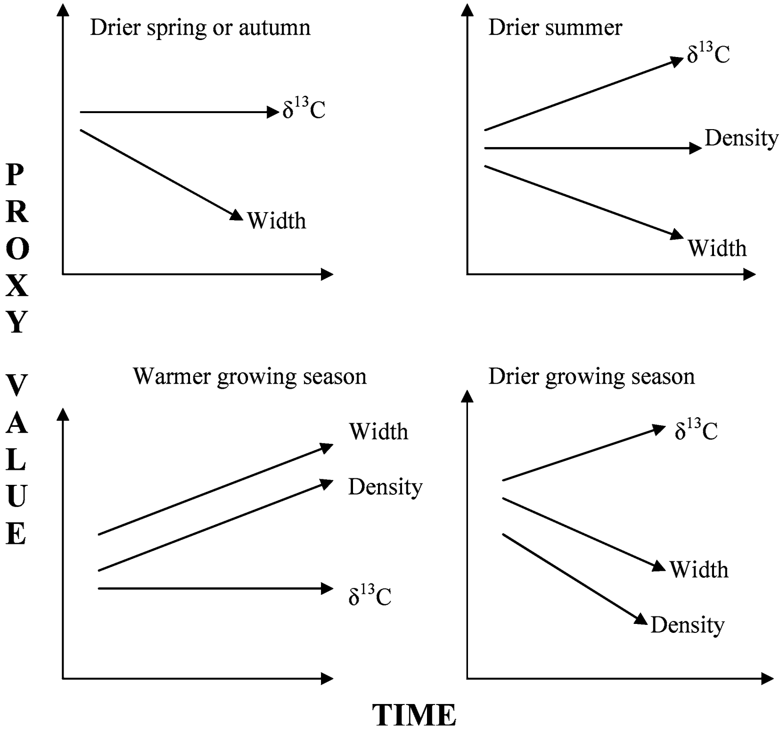

Figure 7. A possible extension of the multiproxy approach might allow covariance in different proxies to be resolved to seasonally specific climatic changes. For example, a change in spring or autumn precipitation would be detectable here by a response in latewood width (sensitive to growth season precipitation) with no response seen in latewood δ^{13}C (sensitive only to summer precipitation).

latewood density and δ^{13}C reveals a method by which to couple estimates of summer precipitation and summer temperature. The association between hot/cool and dry/moist is not strong enough to assume that a reconstruction of just one of the variables would allow inference of the other. The accuracy of two independent estimates of different climate variables, should always be higher than a single proxy estimate of one variable used to infer variability in another.

Seasonal changes might also be resolved by looking at the time stability of correlations between proxies. Where one proxy is sensitive to summer precipitation and another to precipitation of the entire growth season, for example, a change in spring precipitation will be visible in the correlation between the two proxies (Figure 7). As δ^{13}C and latewood width respond to the climate of different parts of the growth season, it is possible that if, for example, spring timing changed, affecting the climatic forcing of tree growth but not δ^{13}C, this should be visible in changes to the correlation between the two.

The greatest potential for multi proxy dendroclimatology lies in the development of reconstructions which offer coupled estimates of more than one climate parameter and are thus better able to reflect the complex synoptic variability of true climate. In terms of the regional climatology of the Alps, bi-variable reconstructions for the last 1000 years would increase our predictive skill will respect to future climate change. It has been suggested that extreme summer events, such as the 2003 heat wave, might become more frequent under future climate change scenarios, where European climate variability could potentially increase by 100% (Schär, 2004). Fully quantified records of summers which were exceptionally hot and dry would enable a more accurate assessment of the degree to which the 2003 event was unusual. There is considerable merit to expanding multi-proxy tree ring records from the Alps back through time using sub-fossil materials from lakes, to develop bi-variable reconstructions of growth season climate. Used in combination, tree-ring proxies have greater palaeoclimatic potential than when used singly

Acknowledgements

This work was conducted as part of the EU-funded projects FOREST (ENV4-CT95-0063) and PINE (EVK2-CT-2002-00136). We would like to thank all of our friends in both projects for their support and enthusiasm. Krystyna Flynn is thanked for assistance with sample preparation. Iain Robertson and Neil Loader are thanked for many useful suggestions.

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(Received 28 April 2004; accepted 8 November 2005)