A Structural Time Series Temperature Reconstruction in Dendroclimatology

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Abstract Structural time series modelling was applied to the problem of reconstruction of maximum temperatures from three regional *Phyllocladus aspleniifolius* tree-ring data sets from Tasmania, Australia. The resulting maximum temperature reconstructions span the past 190 years. Although the tree-ring chronologies cover the period 1156-1994 reconstructions over this extended time frame were not possible due to software limitations beyond the control of this study. Reconstructions reveal increased amplitude in all three time series in the twentieth as compared to the nineteeth century. Consistency between reconstructions also decreases in the twentieth century. Such changes are suggestive of differences in atmospheric circulation patterns of the two centuries. At a general level similarities between the *Phyllocladus aspleniifolius* and much publicised *Lagarostrobos franklinii* reconstructions are apparent. However, some significant differences exist between the two, and are most likely attributable to biological differences between species and to the higher elevation of *Lagarostrobos franklinii* tree-ring sites.

INTRODUCTION

The island state of Tasmania is home to a number of long lived endemic conifers, including *Lagarostrobos franklinii* (Huon Pine), and *Phyllocladus aspleniifolius* (Celerytop Pine). The distribution of the former is limited to areas of the west and southwest of the state which are protected from fire. It has yielded one of the longest proxy climate records in the Southern Hemisphere [Cook 1996]. However, significant climatic differences may arise between the east and west of the state in years of strengthened meridional flow and weakened zonal flow, and vice versa. The shorter-lived *P. aspleniifolius* possesses a state-wide distribution, and has previously been assessed as having dendroclimatic potential [Ogden 1978, Dunwiddie and LaMarche 1980, Campbell 1980, LaMarche and Pittock 1982]. Therefore this species has the potential to offer a spatial complement to the already impressive temporal record of *L. franklinii*. Figure 1 shows sites of *P. aspleniifolius* used in this study.

Cook *et al.* [1992], and Buckley [1997] have shown *L. franklinii* ring widths explain up to 46% or warm season mean temperature variation through the most popularly used principal components regression technique. [Fritts 1976]. Similar success was not achieved with *P. aspleniifolius*; only 11-15% of climatic variance was explained by ring widths.

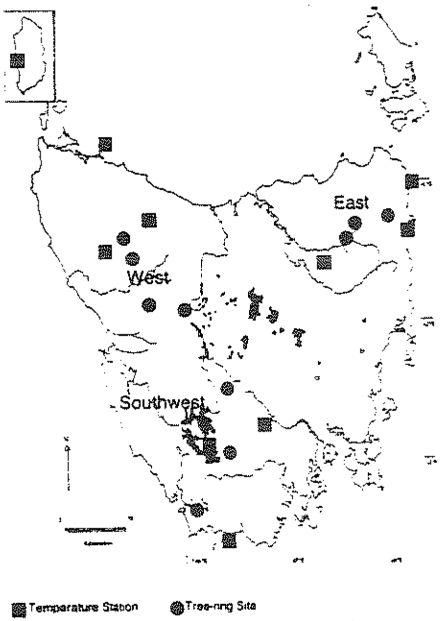

Figure 1. Location of Tasmanian tree-ring sampling sites and meteorological stations

Evidence of a nonlinear temperature response of *P. aspleniifolius* (Allen, in prep.) renders a strictly linear approach to temperature reconstruction from this species inappropriate. A plausible hypothesis for this response is that observed increases in temperature over the twentieth century have altered the temperature/photosynthesis relationship [see Read and Busby 1988]. The purpose of this paper is to investigate the potential utility of a structural time series approach to climate reconstruction; and to compare results with the *L. franklinii* reconstruction.

Structural time series (STS) techniques have been widely used in econometric studies [e.g. Mocan and Topyan 1993, McDonald and Hurn 1995] and offer one method through which nonlinearities and frequency domain features may be routinely incorporated into a model.

The fundamental idea behind STS is that a series can be expressed in terms of its basic features. These may be described as trend (μ), cyclical (ψ), seasonal (γ), irregular (ε), explanatory components (δx), and may or may not be present in a particular time series. Mathematically, this is expressed as:

$$y_t = \mu_t + \gamma_t + \delta x_t + \psi_t + \varepsilon_t \qquad [1]$$

The irregular component is assumed to be normally and independently distributed with a mean of 0, and a standard deviation of σ.

The estimation of structural time series parameters proceeds through the Kalman filter, a recursive procedure which computes the optimal estimator at a given time with all available information which is contained in previous observations [Harvey 1989]. It was first introduced to dendrochronology by Visser and Molenaar [1986] in an investigation of time dependent response of trees to climate. The recursive Kalman filter equations can be considered in three phases: predicting, updating and smoothing [van Deusen 1989]. Their derivation is given in Harvey [1989]. The key to implementation of the Kalman filter is to cast the model in State Space Form. The two basic equations comprising this form are known as the *measurement* and *transition* equations. The measurement equation is a statement of relations between the unobservable state variables and the observations while the transition equation serves as a description of the evolution of the characteristics of a physical process [Watson and Engle 1983]. Following Harvey and Durbin [1986], these are respectively:

$$y_t = Z_t\alpha_t + \varepsilon_t \qquad [2]$$

$$\alpha_{t+1} = T_t\alpha_{t-1} + R_t\eta_t \qquad [3]$$

where $E(\varepsilon_t) = 0$, and $Var(\varepsilon_t) = H_t$; $E(\eta_t) = 0$, and $Var(\eta_t) = Q_t$. Here, y_t are temperature indices. α_t, the state vector, links the observations with the measurement equation. Ideally, its length should be minimised. The initial state vector has mean a_0 and variance P_0. Elements of state and error matrices are known as hyperparameters and influence the stochastic behaviour of components. Z_t, H_t, T_t, R_t, and Q_t, are known as system matrices. Z_t is an N x m matrix, T an m x m matrix, R_t an m x g matrix, and ε_t an N x 1 vector. The error terms, ε_t and η_t are assumed to be uncorrelated with each other and the initial state, thus implying independence of transition and measurement equations.

It should be noted that there is not necessarily a unique solution to a problem when using the structural time series approach. Models are formulated on the basis of *a priori* information, goodness of fit and predictive power.

METHODOLOGY

Samples collected in the field included both increment cores and discs. Due to frequent wedging observed in *Phyllocladus*, three core samples were obtained from each tree cored. For each disc, three radii (where practical) were dated and measured. Cross-dating between sampled from one individual was first achieved, followed by cross-dating with other individuals at the same site. Cross-dating procedures basically followed Stokes and Smiley [1968], with computerised assistance. A 128-year 50% cut off spline was used to remove the growth trend from samples, the pooled autocorrelation estimated and then re-incorporated into the chronology with the aim of maximising the climatic signal contained by the ring width series.

Three regions were delineated as East, West and Southwest. Subsequent analysis proceeded on this regional basis.

Maximum temperature index series are average standard deviates for a number of selected stations across each region [after Meko

1981]. The optimal climatic window upon which to base reconstructions can be defined as the period in which climate is most important to tree growth. This window contains several consecutive months of significant, or near significant, correlations between ring width and the temperature index. An initial 20 month window (September of the previous growing season to April at the end of the current growth season) was tested for all regions, with the following windows being selected as optimal: East coast, December-April of the previous growing season; West coast, November to March of the previous growing season; and Southwest, November to March of the previous growing season. The regional seasonalised variables were constructed by averaging across relevant months for each region. Therefore, reconstructed variables are standard deviations of temperature for the growing season as defined above.

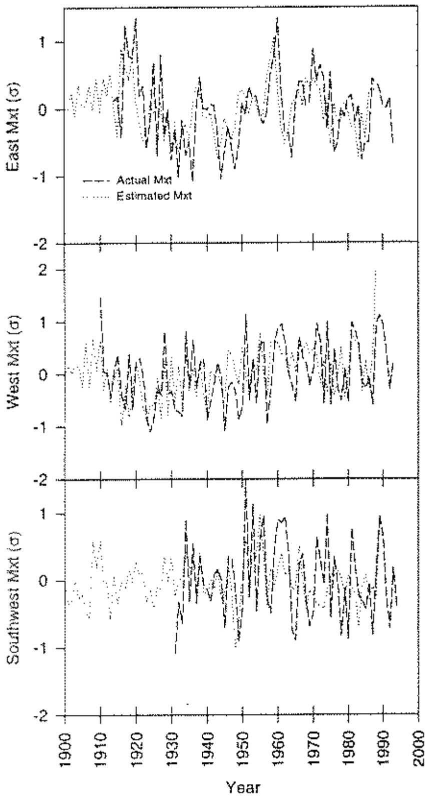

Figure 2a-c: Regional actual and estimated maximum temperature

Each region was modelled separately using the program STAMP^{TM}, with climate as the dependent variable, and the principal components of the regional tree-ring chronologies as the independent variables. The only significant spectral peaks (at .05), of 2 and 13.3 years, occurred in the Southwest data and led to the inclusion of a cyclical term in the Southwest model. Correlograms of regional temperature showed high negative first order autocorrelation, and therefore, an AR(1) term was also included in regional models. Explanatory variables (PCs) not significant at .1 were eliminated from the model in the interests of parsimony.

RESULTS

The structural time series models were:

East

$mxt\_1 = level + AR(1) + PC1 + PC3 + \varepsilon$

West

$mxt\_1 = level + AR(1) + PC1 + PC3 + \varepsilon$

Southwest

$mxt\_1 = level + AR(1) + \psi 1 + PC1 + PC2 + \varepsilon$

where mxt_1 is maximum temperature of the prior season, level is a trend line without stochastic slope, AR(1) the autoregressive order one component, PC1-PC3 are the principal components for each region, and *e* the irregular component.

Plots of STS estimated and actual temperatures are shown in Figures 2a-c. The strongest STS models were produced for the East and Southwest. It is noticeable that visibly better fits were obtained in the first parts of the time period for West and Southwest. Post-1960 the relationships deteriorate.

As seen in Table 1 STS models for all regions of the state perform better than the PC regression models, in terms of their R^2 and Akaike Information Criterion (AICs) However, despite considerably improved predictive power, the relationship between temperature and ring width remains relatively weak.

East and West reconstructions show increasing temperatures after a period of depressed temperatures in the early twentieth century, in agreement with meteorological

	East	West	SW
R^2 [PCR]	0.138	0.117	0.149
R^2 [STS]	0.307	0.279	0.315
AIC [PCR]	-7.13	-6.06	-5.81
AIC [STS]	-36.59	-38.98	-19.13

Table 1: Goodness of fit statistics for PC regression (PCR) and STS models. AIC has been calculated as the AIC corrected for bias: AIC = N*log(MSE) + 2p + 2{(p+1)(p+2)/(N-p-2)}, where N is the number of observations, and p the number of model parameters.

records (Figure 2,3). The heightened differences between East and West reconstructions around 1915-20 are also observable in climate data although that of the late 1970s - early 1980s is not.

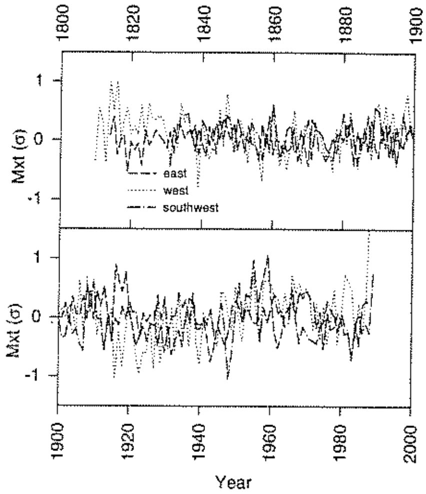

Figure 3: Regional *P. aspleniifolius* reconstructions of maxium temperature

Figure 4 illustrates numerous instances, including 1850, 1899 and 1908, when the sign of departure from the mean is opposite for the higher elevation *L. franklinii* and lower elevation *P. aspleniifolius*. Strict statistical comparison of the two reconstructions was not possible due to differing climate windows (January-April for *L. franklinii*).

DISCUSSION

The dramatic improvement in STS regional models over models based on principal component regression suggest that structural time series may represent a valid alternative methodology for climate reconstruction if a number of limitations and theoretical issues can be resolved. The particular prospects and problems surrounding the use of STS in dendroclimatology fall into two broad classes: those issues concerning software applicability and workability and those concerning the methodology itself.

Essentially, STAMP™ has been designed for econometric applications, and some limitations apparent in dendroclimatic applications stem from this. An important limitation for dendroclimatology is the inability of the program to generate 'forecasts' of more than 100 values. Because the use of STS models requires highly specialised software, few applications have been developed. Of those that have been in the field of dendrochronology, very few handle explanatory variables, critical for dendroclimatology. These programs are currently being reviewed and updated in order that explanatory variables may be included [pers. comm. J. Gove, US Forest Service 1997].

The most fundamental methodological problem with STS is its unsuitability to currently used calibration/verification schemes in dendroclimatology. As Gordon and deLuc [1981] point out, successful application of a calibrated model to an independent data set is imperative before any interpretation of a model can be made. Because the Kalman filter uses all prior information in updating the estimator, the use of a temporally independent verification period, as used by Cook *et al.* [1992], is inappropriate because information is lost, potentially resulting in large differences in estimates. So while internal statistics may suggest a good STS model fit, it is not strictly possible to test the STS model on a temporally independent data set.

Despite the fact that STS models have improved the estimates available from chronologies, explained variance in the models remains relatively low, suggesting that climate reconstruction from *P. aspleniifolius* may be neither viable nor reliable. However, bearing in mind the calibration/verification issue, some tentative evidence for the integrity of the reconstruction may be drawn from a comparison of the East and Southwest reconstructions over the past 180 years. The two series move closely together (Figure 3) for the nineteenth century with an apparent change in their relationship immediately prior to the turn of the century. A change in cross-dating of tree-ring series of the Southwest and East regions is also discernible at this time (Allen, unpub. data). Prior to the turn of the century, back to at least 1550 AD, cross-dating can be readily established, but becomes poor over the period 1890-1920. Lamb and Johnson [1961] and Cook *et al.* [1996] describe alternating periods of strong and weak westerly circulation. The period from approximately 1800 to the late 1920s is suggested as one of enhanced zonal flow with the period since the late 1920s described as one of enhanced meridional flow, with a southward displacement of the sub-tropical high pressure belt, resulting in substantially drier and warmer conditions across the state. Temperature data shows a clearly evident upward trend for west and east regions only, implying that the effect of enhanced meridional flow is less evident for the southwest than for the rest of the state. This is one mechanism through which the Southwest and East reconstructions might be expected to differ over this time interval.

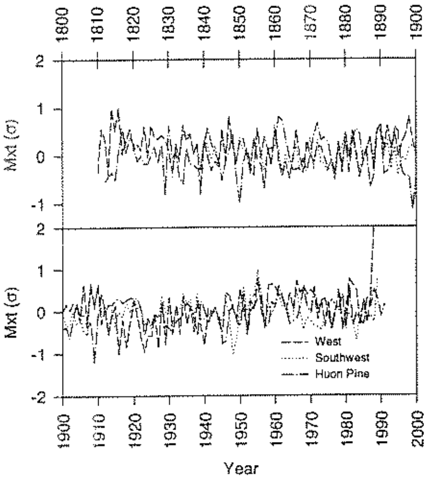

Figure 4: West Coast and southwest *P. aspleniifolius* maximum temperature reconstructions and principal component regression reconstruction of maximum temperature from *L. franklinii.*

With regard to the years of pronounced low growth for *L. franklinii*, historical records reveal that the summers of both 1898 and 1908 were particularly cold at higher elevations [Buckley 1997], but meteorological records for lower elevations do not concur. *P. aspleniifolius* lies at these lower elevations. That the general trend of the reconstructions are similar implies that the ring widths of *P. aspleniifolius* do contain useful climatic information. Differences at high frequencies however, prohibit successful cross-dating and are likely to be biological in origin.

CONCLUSIONS

Temperature reconstructions from *P. aspleniifolius* show some skill with the upward temperature trend being successfully reconstructed. Comparison with *L. franklinii* indicates broad agreement between reconstructions with regard to trend, but high frequency differences prohibiting cross-dating of species are likely to be due to biological factors. Differences between the East and Southwest reconstructions over the past 180 years may be indicative of previously described changes in the general atmospheric circulation over the past two centuries.

Although the issue of calibration/ verification is fundamentally problematical, STS reconstructions show dendroclimatological potential deserve further investigation, with attention being focussed on possible verification schemes and appropriate software.

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