AN ESTIMATE OF AVERAGE ANNUAL TEMPERATURE VARIATIONS FOR NORTH AMERICA, 1602 TO 1961

H. C. FRITTS and J. M. LOUGH
Laboratory of Tree Ring Research, University of Arizona, Tucson, AZ 85721, U.S.A.

Abstract. Annual surface temperature variations, 1602 to 1961, averaged over 77 United States and southwestern Canadian stations, are reconstructed from 65 arid-site tree-ring chronologies of western North America. Annual sea-level pressure reconstructions averaged over the North Pacific sector including North America and eastern Asia are inversely related to the temperature variations. Both the instrumental and reconstructed North American temperature averages are well correlated with Northern Hemisphere average temperatures during the early 20th-century warming but the correlation diminishes after the mid-1940s. The 1918 to 1947 interval is reconstructed to have been the warmest and 1877 to 1906 the coolest. The correlations between the temperature record and other high resolution temperature series from the Northern Hemisphere are generally insignificant. However, significant correlations are noted for certain 30-yr time periods. North American temperatures appear to have been out of phase with temperatures in Europe during the late 18th and early 19th centuries. Significant variations in the 30-yr mean temperatures are noted in several of the North American series. The warming early in the 20th century is the most marked followed by warming from 1717 to 1723 and from 1850 to 1866. Significant cooling occurs from 1810 to 1821 and from 1659 to 1669.

1. Introduction

Knowledge of climate prior to the mid-19th century, when few instrumental records are available (Lamb, 1972; 1977), is based on a variety of proxy records (substitutes for instrumental measurements) such as tree rings, pollen assemblages, ice cores and historical documents (Kutzbach, 1975; Barry *et al.*, 1979). However, these proxy data are imperfect records of climate, because they may contain systematic biases and random errors unrelated to climate (NAS, 1975). It is, therefore, necessary to consider the information that is common among as many of these independent records as possible to obtain the most meaningful and complete understanding of climate history.

When one attempts to understand the sequence of continental-wide or larger-scale changes in climate such as those for the Northern Hemisphere, it is best to include information from all parts of the area under consideration. This is necessary because complex spatial patterns of change can occur, as have been noted over the past 100 years (van Loon and Williams, 1976a, b; Barnett, 1978; Jones *et al.*, 1982; Jones and Kelly, 1983) and over longer time scales (Williams and Wigley, 1983).

The apparently naive idea that all 'valid' proxy records of recent temperature changes should show a Little Ice Age followed by the early 20th-century warming trend is perhaps an unfortunate consequence of the abundance of early instrumental data concentrated in Europe (Lamb and Johnson, 1966; Manley, 1974; Lamb, 1977). These early records often have been the primary, if not the only, source of information used to deduce past

Climatic Change 7 (1985), 203–224. 0165–0009/85.15.

hemispheric-wide temperature changes. (e.g. Miles and Gildersleeves, 1978). We are now aware that these European records represent a too-limited geographical area to portray adequately the temperature variations for the entire Northern Hemisphere.

Attempts to construct large-scale regional temperature averages before the mid-19th century date back to Köppen (1873). More recently, Groveman and Landsberg (1979) took a bold step in estimating the Northern Hemisphere temperature series of Borzenkova *et al.* (1976) back to 1549 using a mixture of early instrumental data and some proxy climate indicators, e.g. Alaskan and Scandinavian tree-ring widths. Although these authors provide statistical confidence limits for their regressions, the spatial distribution of their estimator data varies so much through time that any differences in climatic patterns, such as those noted by Jones and his co-workers, are likely to distort the reconstructions to unacceptable limits.

From 1579 to 1705, for example, only three or four estimators are used but these are drawn from Europe, Japan and Alaska. The number of estimators increases after 1705, but the majority are from the European sector. Between 1797 and 1825, *all* the estimators lie between 10° W and 50° E longitude. In addition to the problems created by this temporal inhomogeneity, the tree-ring chronology that Groveman and Landsberg use to represent the North American Arctic appears to be inadequately dated and replicated, and is not standardized. The use of one poor quality proxy record of this kind in such a small number of estimators can only compromise the reliability of the final reconstruction. Nevertheless, this work is a valuable landmark for it attempts to include a wider data source than used previously to estimate the hemispheric-wide temperature variations.

High quality tree-ring records sensitive to climatic variations are now becoming available throughout temperate and subpolar areas of the world (Hughes *et al.*, 1982). Such tree-ring chronologies can provide climatic information on time scales as short as one season to as long as a century. However, the reliability of such dendroclimatic data is maintained only by sampling high quality tree-ring materials, dating and processing them carefully, and subjecting only the best materials to rigorous dendroclimatic analysis (Fritts, 1976; Hughes *et al.*, 1982). Most tree-ring studies have focused on local areas or watersheds. In this study a grid of 65 North American tree-ring chronologies from semi-arid sites was used to reconstruct spatial variations of temperature and pressure over a large sector of North America and the North Pacific (see Blasing and Fritts, 1976; Fritts *et al.*, 1979). Similar approaches are now being used to reconstruct climate in other areas of the world (e.g. Hughes *et al.*, 1982; Briffa *et al.*, 1983).

We present estimates of annual surface air temperature for North America obtained by averaging reconstructions made for 77 different stations throughout the United States and southwestern Canada which were calibrated with the tree-ring record (Fritts, 1976; Fritts *et al.*, 1979). Related estimates of annual sea-level pressure were also obtained by averaging reconstructions made at 96 grid points for the North American and North Pacific sectors. All grid-point and station estimates (Figure 1) were obtained for the period 1602–1961.

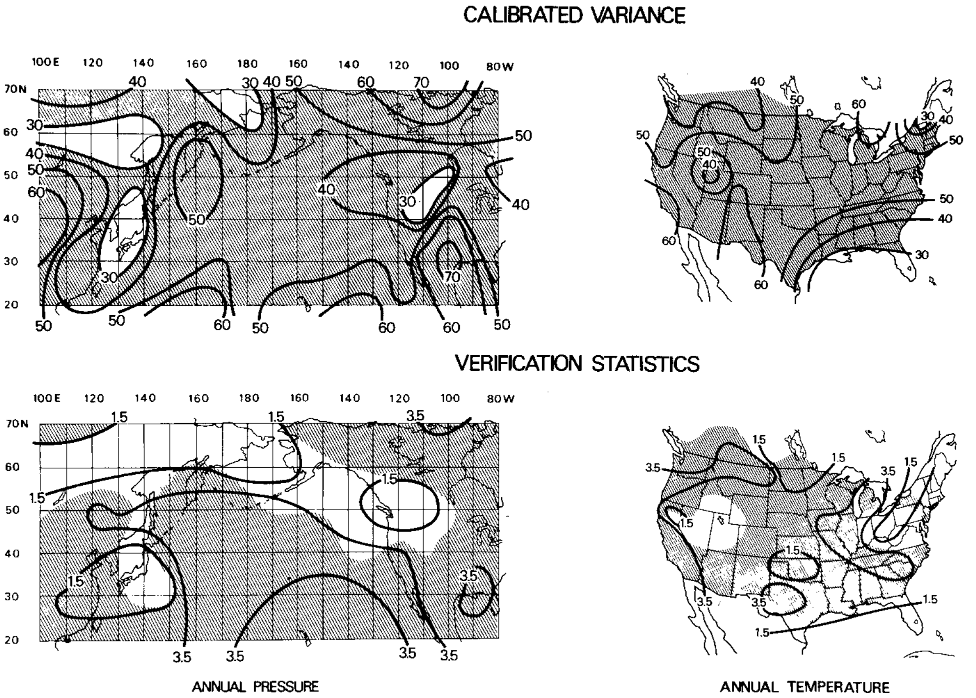

Fig. 1. Calibrated variance and verification statistics for annual temperature and annual sea-level pressure. (For the verification statistics, the contours refer to the number of verification tests passed, out of a total of five, and the shading to areas of positive reduction of error statistics.)

2. Data

In this section we will first describe the tree-ring (predictor) and climate (predictand) data sets. This is followed by a description of the calibration and verification procedures and finally the effects of spatial and temporal averaging on the characteristics of the reconstructions.

2.1. Tree-Ring and Climatic Data

Special collecting, measuring, and analyzing techniques have been designed to help separate and remove the nonclimatic variations from the climatic information in tree-ring-width data (Fritts, 1976; Hughes *et al.*, 1982). Such techniques were applied in the selection of 65 high quality arid-site western North American tree-ring chronologies. The chronologies were selected on the basis of the greatest number of trees sampled, the statistical characteristics of the data, the longest records, and the spatial distribution of the sampled tree sites (Fritts and Shatz, 1975). All chronologies in the 65-site array spanned the period from 1600 to 1963 but were best replicated after 1700, and had a geographical coverage extending from the North Pacific coastal states to the Black Hills of South Dakota and from the Canadian Rockies to Durango, Mexico (Fritts and Shatz, 1975).

Kutzbach and Guetter (1980) used climatic grids of varying densities and size to estimate climate over different regions. The density of our chronology grid is seven sites per million square kilometers (Cropper and Fritts, 1982), which is nearly three times the 'high density' network of 2.5 sites per million square kilometers, considered by Kutzbach and Guetter to be adequate for evaluating spatial sampling problems. They used high-density grids of instrumental data confined to restricted longitudinal sectors such as western North America to estimate climatic information over a wider area such as the entire North American continent and found that the results were sometimes comparable in quality to those obtained from lower-density grids spread over the entire region they were estimating.

We had noted that the large-scale atmospheric circulation features over the North Pacific and North America which influence the growth of the trees tend to move from west to east (Bryson and Hare, 1974) and influence surface temperature and precipitation in regions well beyond the area of the tree-ring grid. The results of Kutzbach and Guetter support these observations and help to justify our use of the 65 tree-ring chronologies to reconstruct climatic variations beyond the boundaries of the tree-ring grid which is confined to western North America and southwestern Canada.

The tree-ring predictors consisted of two sets of the first 15 principal components (PCs) of the 65 chronologies: the first, with, and the second, without, first-order autocorrelations removed. These accounted for 69 and 67%, respectively, of the total tree-ring variance over the period 1600 to 1963. Two sets of climatic predictand data were selected. The first included the larger principal components of seasonal surface temperature at 77 stations in the United States and southwestern Canada over the period 1901 to 1961 and the second, the larger principal components of seasonal sea-level pressure at 96 grid points between 100° E and 80° W/20 to 70° N over the period 1899 to 1961. (The grid points are located at 10° latitude intervals and 10° longitude intervals between 20 and 50° N and 20° intervals at 60 and 70° N.) The series were curtailed in 1961, as the tree-ring array is complete only through 1963. The 1962 and 1963 values were used to reconstruct climate through lagging relationships.

2.2. *Calibration and Verification*

Calibration models of different structure, in which the numbers of PCs of climate and growth and the leads or lags considered with the PCs of tree growth varied, were developed. A model included one or two pairs of the 15 tree-ring PC sets with and without autocorrelation removed for a lead of one year preceding climate to a lag of one year following climate (Fritts *et al.*, 1979). Several models were considered in an attempt to assess which autoregressive and moving-average (lag and leading) relationships gave the best reconstructed relationships as well as the most reasonable model structure in terms of the climate/tree-growth system (Fritts *et al.*, 1979). Stepwise canonical regression, modified from Blasing (1978) (also see Fritts *et al.*, 1979; Lofgren and Hunt, 1982), was used to calibrate principal components of growth with principal components of climate. This stepwise analysis reduced the large number of predictor principal components (15 or 30) to a smaller number of from one to seven canonical variates. A transfer function was obtained and applied to the three-ring principal components to reconstruct seasonal temperatures at each station and sea-level pressure at each grid point back to 1602.

The instrumental record of temperature prior to 1901 (the independent data) was used to verify each reconstruction (Gordon, 1982). In winter, for example, 54 stations had seven or more years of data prior to 1901, the number of years which we considered to be the minimum needed for statistical testing. Eight stations had more than 30 yr of independent observations. The amount of independent data available for the other seasons varied only slightly from these numbers.

Insufficient independent data were available prior to 1899 for comparable verification of the sea-level pressure models so a split calibration/verification technique was used. The data from 1901–1960 were divided into six different 10-yr subperiods. A given model was calibrated six times over the remaining 52 yr and reconstructions were obtained for the ten independent years of each subperiod. The six 10-yr subperiods were later combined to obtain a continuous 60-yr series of independent estimates which then were tested against the instrumental record (Gordon, 1982). In addition, the calibration and verification tests were applied to the principal components of sea-level pressure rather than the gridded data because the latter might be expected to include a high amount of spatial correlation (Livezey and Chen, 1983) and would complicate the interpretation.

Objective statistical tests to verify that the reconstructions are reliable can be made with data independent of the calibration period used to develop the transfer function. Only models with a sufficient number (two or more out of a total of five tests made at each grid point) of verification tests performing consistently better than expected by chance (at the 95% confidence level) and with positive reduction of errors were retained for further study. A number of different models passed the verification tests. Those with the best statistics were considered to have the best reconstructions and a number of models with different structure were selected. The same verification statistics, as well as the calibration statistics, were used to rank and select those models which gave the optimum reconstructions. The collective statistics for the selected series were well above the 95% confidence level.

In the case of pressure, those model structures with the best calibration and verification statistics were recalibrated using the instrumental data over the entire calibration period to obtain the final transfer function and reconstructions. This procedure verified the general *form* of the model for pressure but not the actual sea-level pressure reconstructions (Gordon, 1982).

The estimates from the two or three models with the best calibration and verification statistics were averaged for each variable and season. The increase in reliability of the final averaged series was measured by comparing the calibration and verification statistics derived from the combined reconstruction to the average of the statistics derived from the individual models. The combination almost always reduced more error than any of the statistics of the individual sets and the combination statistics were always higher than the average of statistics for the individual sets.

2.3. Averaging Procedures

The combined reconstructions for the seasons as well as the instrumental record were merged into annual estimates (December through November). The calibration and verification statistics were recalculated using the annual reconstructions and instrumental values. It is interesting to note here that our attempts to calibrate the tree-ring data directly with *annual* climatic data failed because no more than one or two canonical variates usually were significant.

One biological explanation for this result is that the factors limiting to growth varied according to the season considered. Low temperatures, for example, might be limiting in winter while high temperatures, if associated with drought, might be limiting in summer. This positive association between ring width and climate in winter would counteract the negative association in summer so that the statistical relationship with annually averaged temperatures would be too weak to give significant calibration and verification statistics. However, when seasonal data rather than annual data were calibrated, the inverse response to temperatures in summer would be converted to a temperature estimate that could be averaged with the estimates from other seasons to obtain a more reliable annual reconstruction. This procedure resulted in a marked improvement in both the calibration and verification statistics which became progressively better from the original seasonal calibrations to the combined models, to the annual estimates (Table I).

As an example of the improvement at different levels of averaging, the best performing models for seasonal temperature and seasonal sea-level pressure had calibrated variances averaged over all seasons and stations in the reconstructed grid of 30.1% and 28.6%, respec-

TABLE I: Selected statistics of association with instrumental data for combined seasons and the annual reconstructions.
RE = reduction of error.

Season	Variable	Calibration	Verification		
		Variance % in common	% Tests Significant	% RE > 0	Pooled RE
Winter	Temperature	41.6	38	57	−0.090
	Pressure	37.6	42	27	−0.153
Spring	Temperature	43.7	28	40	−0.036
	Pressure	40.2	32	40	0.017
Summer	Temperature	42.1	19	49	−0.011
	Pressure	27.9	20	27	−0.022
Autumn	Temperature	17.6	26	91	0.051
	Pressure	36.2	36	33	−0.084
Annual	Temperature	47.7	50	75	0.127
	Pressure	48.4	44	60	0.167

tively. The reconstructions from the best two or three models within seasons were averaged and the square of the correlation coefficient between the average estimate and the instrumental record calculated. Averaged for the four seasons these statistics indicated a variance in common of 36.2% and 35.5%, respectively. When the seasonal estimates were averaged to form annual values, the variance in common rose to 47.7% and 48.4%, respectively. Except for the percent reduction of error for autumn temperature, the statistics for all annual combinations were higher than those for the seasonal data.

The percentage variance calibrated in these annual values varied among the stations or grid points (Figure 1). For annual temperature, between 28% and 66% of the station variance was calibrated and for annual sea-level pressure between 24% and 76% of the grid-point variance was calibrated. The reduction of error pooled over all stations or grid points was 0.127 for annual temperature and 0.167 for annual pressure with 75% and 60% of the stations and grid points, respectively, having reduction of errors greater than zero, values which indicate some skill in the estimates (Figure 1 and Table I). The number of other verification tests that passed significance testing averaged 50% and 44%, respectively.

As might be expected, the temperature reconstructions were weakest around the periphery of the grid and in the eastern United States (Figure 1) which were the areas furthest removed from the tree sites. Although some groups of temperature stations located at sizable distances downwind from (east of) the tree sites had significant statistics, the relationship generally weakened with increasing separation distance and especially with increasing proximity to the maritime influences of the Atlantic Ocean and Gulf of Mexico. Large areas over the central portions of the pressure grid which were upwind from (west of) the tree sites had more than two significant verification tests pass or had positive reduction of error statistics. These, as well as a variety of other results (Gordon *et al.* in press; Lough, 1983; 1984), repeatedly demonstrate that the final chosen models performed adequately over the independent as well as the dependent period, and their averaged results appear to contain meaningful information on past variations in climate over a wide spatial grid.

The errors of the reconstructions were further reduced by combining several grid points or station estimates into regional averages or by smoothing the data temporally by using an 8-yr, 50% low-pass digital filter to enhance the low frequencies (LaMarche and Fritts, 1972; Fritts, 1976). This result may reflect the fact that only the larger principal components of tree growth and climate were used in the canonical analysis, so that the large-scale regional patterns of climate were calibrated at the expense of precision at the individual grid points or stations.

In this paper we take advantage of the reliability of the large-scale patterns by examining the grid and half-grid averages. We also utilize the data smoothed by filters or averaged over 30-yr periods to take advantage of the greater precision at low frequencies. The seasonal estimates appear to be badly perturbated by extremes of climate and by growth in prior years (reflected in the autoregressive-moving-average tree-response system); however, they can provide useful information about past climate if the largest-scale phenomena or lowest-frequency variations are considered (Gordon *et al.*, in press).

3. Analysis and Climatic Results

We now examine some of the features of the estimated climate, 1602 to 1961. We then compare our estimate to the Northern Hemispheric average temperatures, 1881 to 1961 and finally to other long independent temperature or proxy temperature series.

3.1. The Time Series

The annual reconstructed values for all stations and grid points were averaged to obtain large-scale temperature and sea-level pressure estimates (Figure 2). These data are plotted as departures from the 1901 to 1970 mean of the instrumental record. The square of the correlation coefficients between the averaged instrumental record and the averaged estimates shown in Figure 2 indicate that 62.4% and 71.4% of the variance is common for North American temperature and Western Hemispheric sea-level pressure over the calibration period. It should be noted here that these values using the overall mean are substantially higher than the average of the correlation squared of 47.7% and 48.4% obtained using the individual station or grid-point annual data referred to earlier.

Figure 2 also shows plots of the temperature estimates divided into a group of 42 stations which are generally west of 10.2° W longitude, thus near the tree sites, and 35 stations which are to the east and at least 300 km distant from the tree sites. These two plots sometimes vary from the average of all 77 stations indicating a seesaw pattern in the reconstructed temperature between the eastern and western half of the continent. Such a pattern has been shown to be a common mode of variation in the instrumental record (Diaz and Fulbright, 1981) and appears to be related to changes in the location and amplitude of the atmospheric long-wave troughs and ridges in the vicinity of North America.

The warming of the early 20th-century is apparent from the plots of the filtered data for all three temperature series. When the 77-station grid is examined only one period in the first decade of the 19th century is reconstructed to be warmer than the maximum filtered value in the 1930s. When the western series is considered there are eight periods that had higher reconstructed temperatures than the 1930 maximum filtered value. The eastern series exhibits only one warm period, reconstructed in the 1620s, with higher reconstructed temperature than the 1930 maximum filtered value. Using the 30-yr mean values, the warmest reconstructed 30-yr period over the whole United States and southwestern Canada is 1918 to 1947. For the eastern United States it is 1925 to 1954 and for the western United States, 1637 to 1666. The coldest 30-yr mean periods are 1877 to 1906 over the entire area, 1666 to 1695 for the eastern half and 1898 to 1927 for the western half of the grid. The latter overlaps the early 20th century warming illustrating the fact that the western half of the country sometimes was reconstructed to be quite different from the eastern half. It is apparent from this brief examination that the relative timing of extreme reconstructed warm and cold periods appears to vary markedly depending upon the stations and time periods included in the averaging.

The filtered reconstructed pressure series averaged over the half hemisphere, also shown in Figure 2, varies inversely with the temperature record. Previous studies (Diaz and

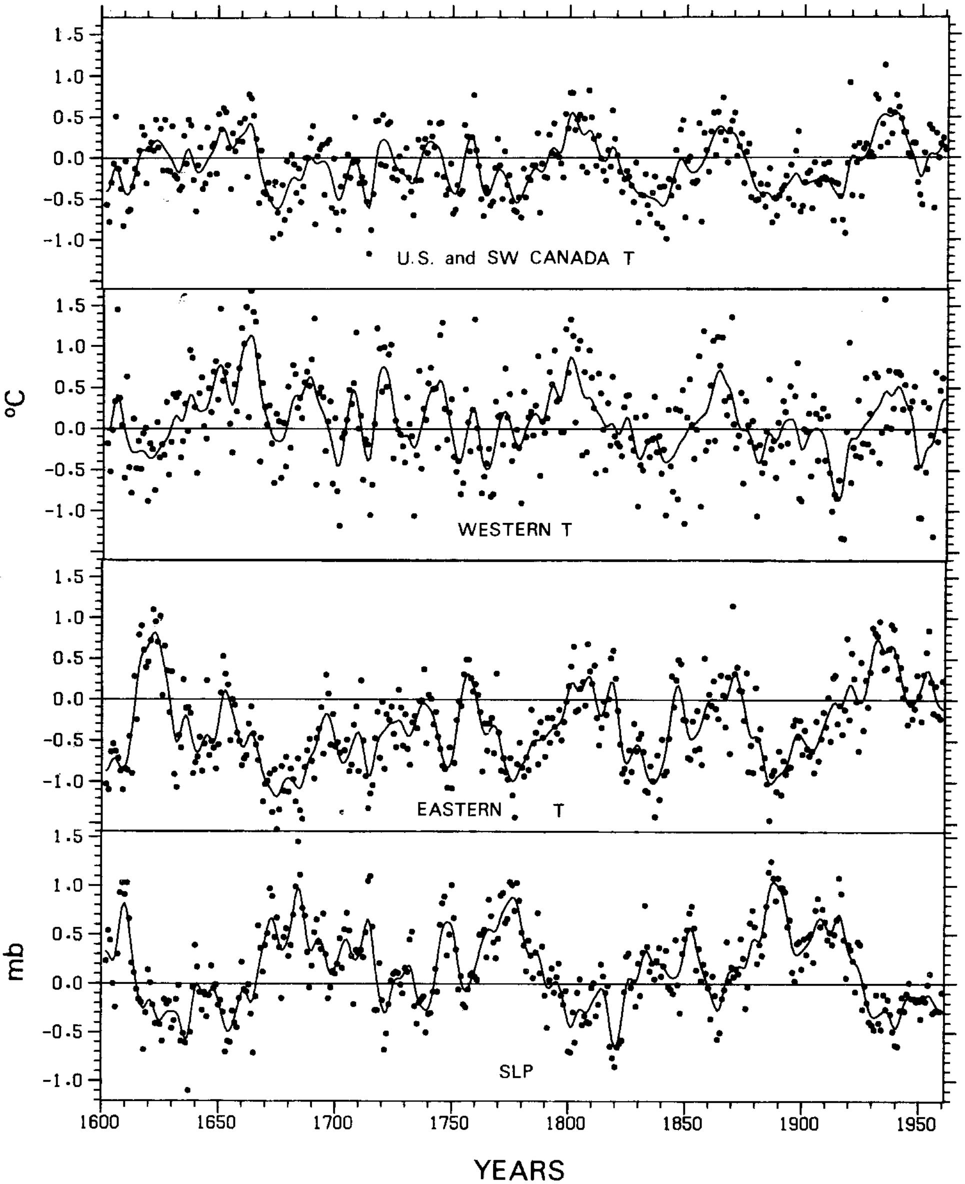

Fig. 2. Average annual reconstruction representing temperatures for 77 stations in the United States and southwestern Canada; temperatures for 42 stations in the western United States and southwestern Canada; temperatures for 35 stations in the eastern United States and sea-level pressure at 96 grid points (symbols represent original data and the line, values smoothed with the digital filter passing 50% at 8 years).

Namias, 1983; Erickson, 1983) have also noted linkages between large areal averages of sea-level pressure or mid-tropospheric heights and surface climate variations. The annual average pressure over North America and the North Pacific tends to be below the 20th-century average when United States temperatures are above the 20th-century average and vice versa. This relationship is apparent in both the instrumental and reconstructed records. The correlations between the two variables using the instrumental and reconstructed (in parentheses) data are: –0.61 (–0.72) for 1901 to 1960, –0.45 (–0.70) for 1901 to 1930 and –0.52 (–0.65) for 1931 to 1960 (all values are significant at the 95% confidence level). The slightly higher correlations for the reconstructed sea-level pressure than for the instrumental data could be due in part to the common origin and, in part, to the greater proportion of low-frequency variance in the reconstructions. The stability of the correlations of both the instrumental and reconstructed data between the two 30-yr periods (1901 to 1930 and 1931 to 1960) would suggest that the inhomogeneities reported by Trenberth and Paolino (1980) to be present in the early part of the sea-level pressure data set do not appear to alter markedly the correlation between the reconstructed and instrumental data sets of pressure and temperature.

The correlation between reconstructed pressure and temperature over the whole reconstructed period is –0.62, (significant at the 99% confidence level allowing for first order autocorrelation in the two series). The correlation is also strongest with average eastern United States temperatures ($r = -0.56$) compared to average western temperatures ($r = -0.36$), which is consistent with the findings of Diaz and Namias (1983). The correlations for all 30-yr subperiods range between –0.86 and –0.05 (and are significant at the 95% confidence level for 88.2% of the subperiods tested, allowing for first-order autocorrelation in the time series). It is clear that the pressure-temperature linkage is a consistent feature of these reconstructions, though the physical basis for this possible linkage still remains to be established.

3.2. Comparison with Average Northern Hemisphere Temperatures

In this section we compare our reconstructions of North American climatic conditions to the hemispheric-wide temperature variations presented by Jones *et al.* (1982). This type of comparison is important because the temperature data used to derive the hemispheric-averaged values have been shown by van Loon and Williams (1976a, b) and Jones and Kelly (1983) to exhibit complex and somewhat divergent regional trends. The comparisons discussed below were made first with the instrumental data and then the reconstructed data. The results were very similar, and we present only those for the reconstructed time series.

The correlations between the four time series shown in Figure 2 and the annual instrumental temperature average presented by Jones *et al.* (1982) are given in Table II for the whole period 1881 to 1960. Each of the average series is significantly correlated (at least at the 95% confidence level allowing for first-order autocorrelation in the time series) with Northern Hemisphere temperature variations, the strongest linkage being with the average sea-level pressure series (which may, implicitly, contain information about temperatures over a wider area than North America). Western United States temperatures seem less closely tied to the hemispheric average than those for the eastern United States.

A more informative picture of the association between our temperature estimates and Northern Hemispheric temperatures is given in Figure 3 which shows the correlation co-

TABLE II: Correlation between the average annual instrumental Northern Hemisphere temperature record (Jones *et al.*, 1982) and three reconstructed temperature and one reconstructed sea-level pressure series derived from western North American tree rings, 1881 to 1960 (* and ** indicate significance at the 95 and 99% confidence levels, allowing for first-order autocorrelation of the series).

	r
United States and southwestern Canada	0.62**
Eastern United States	0.72**
Western United States	0.28*
Average SLP	−0.77**

efficients for overlapping 30-yr subperiods. (The first correlation covers the years 1881 to 1910, the second 1882 to 1911 and so on to the last period 1932 to 1961.) From these plots we can identify two features: (a) eastern United States temperature and the average pressure series are most consistently significantly related to the hemispheric average and (b) all series show a decline in the magnitude of the correlation when data after 1947 are included in the 30-yr subperiod. The timing of this decline nearly coincides with the change in the character of Northern Hemisphere atmospheric circulation of the early-to-mid 1950s noted by several authors (e.g. Kutzbach, 1970; Diaz and Quayle, 1980; Balling and Lawson, 1982). Our results (Figure 3) also agree with the conclusion of Jones and Kelly (1983) that the early 20th-century warming was more coherent spatially than the subsequent cooling.

3.3. Comparison with Independent Temperature Series

We compare our reconstructions to various data sets reported to reflect temperatures at a given location (Table III). The first two entries in Table III include four tree-ring chronologies from sites at high altitudes or at northern latitudes in North America. The ring widths of trees on such sites have been shown to be directly responsive primarily to warm season temperatures. This contrasts with the tree rings used to form our reconstructions which are from lower altitude and middle-latitude arid sites (Fritts and Shatz, 1975) and contain information on temperature and precipitation in all seasons of the year (Fritts, 1974). The next entry in the table represents a 'hemispheric temperature estimate' (Groveman and Landsberg, 1979) derived from a variety of instrumental data and proxy sources from different localities. The last entry is Manley's (1974) temperature record for central England. Plots of four of the most relevant independent series are presented in Figure 4 along with a plot of our estimated mean temperature for the United States and southwestern Canada.

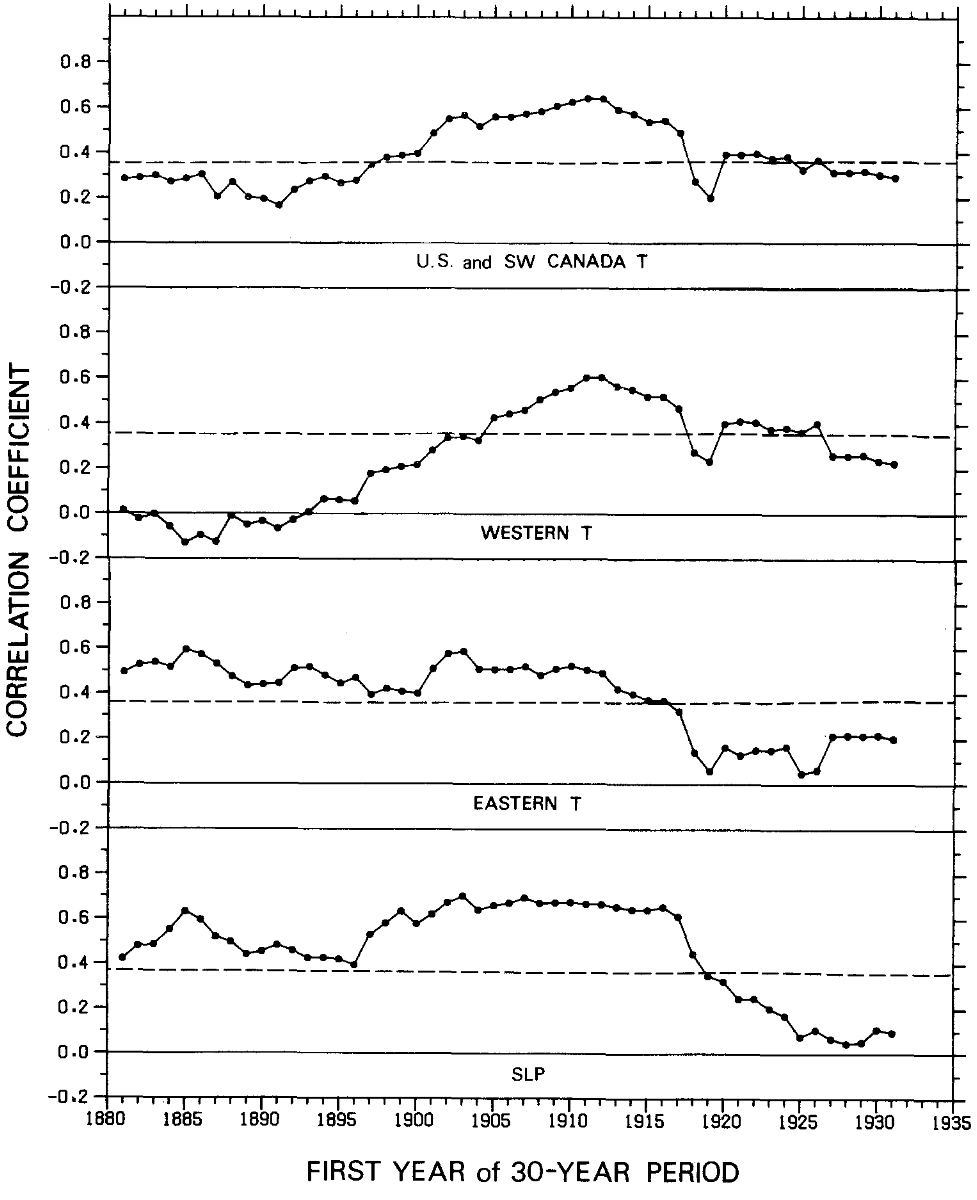

Fig. 3. Correlation coefficients, for 30-yr overlapping periods between average annual Northern Hemisphere surface temperatures (Jones *et al.*, 1982) and average annual values of 77 United States and Southwestern Canada temperature stations; 42 western United States and southwestern Canada temperature stations; 35 eastern United States temperature stations and 96 sea-level pressure grid points (dotted line represents 95% confidence level).

3.3.1. Correlations

The correlations of these series with our estimated temperature series before and after treatment with the low-pass filter were calculated and tested for significance after ac-

TABLE III: Independent temperature records used for comparison.

Source	Data	Region	Period
Jacoby and Cook, 1981	Ring-width index sensitive to summer degree days.	Yukon, Canada	1550–1975
LaMarche and Stockton, 1974	Ring-width index-sensitive to summer temperature.	Campito Mtn., Ca Sheep Mtn., Ca Almagre Mtn., Co	1170–1970 470–1970 560–1968
Groveman and Landsberg, 1979	Annual temperature	Northern Hemisphere	1549–1880
Manley, 1974	Annual temperature.	Central England	1659–1974

counting for autocorrelation (Table IV). During the period 1901 to 1960, significant positive associations are found between the unfiltered United States and southwestern Canada temperature estimate and the Yukon Territory, Sheep Mountain and Groveman and Landsberg's series. Examination of the filtered and residual series correlation suggests that this agreement is due to matching long-term trends and not to matching year-to-year variations.

However, over the entire independent period, 1602 to 1900, the only significant correlation is a negative one with the residual of the Sheep Mountain series. Our temperature estimates do not, therefore, appear to be linked in any consistent way to the other temperature and proxy temperature series examined. We also examined both the associations between the instrumental and reconstructed summer (JA) temperatures for the United States and southwestern Canada and the four tree-ring series. Apart from the Yukon territory series over the period 1901 to 1960, the relationships were much weaker than found with the annual temperature data. This may be partly attributed to the lower reliability of our summer temperature estimates when compared to the reliability of these annual values. In addition, Jones and Kelly (1983) present evidence that the variations of late spring and summer temperatures are more strongly correlated with the annual average temperature variation (at least of the Northern Hemisphere) than are temperature variations in other seasons. We, therefore, chose to use our annually averaged series which appear to be more reliable than the summer estimates, throughout the remainder of the study.

Correlation coefficients were also calculated for all common overlapping 30-yr subperiods (the same technique as described in Section 3.2). We note that due to the number of tests performed, the probability of obtaining significant correlations will be increased. It would, therefore, be unwise to consider the following discussion to be more than suggestive of particular relationships. The intervals of significant agreement or disagreement are shown in Table V. It is apparent from these results that the associations between our

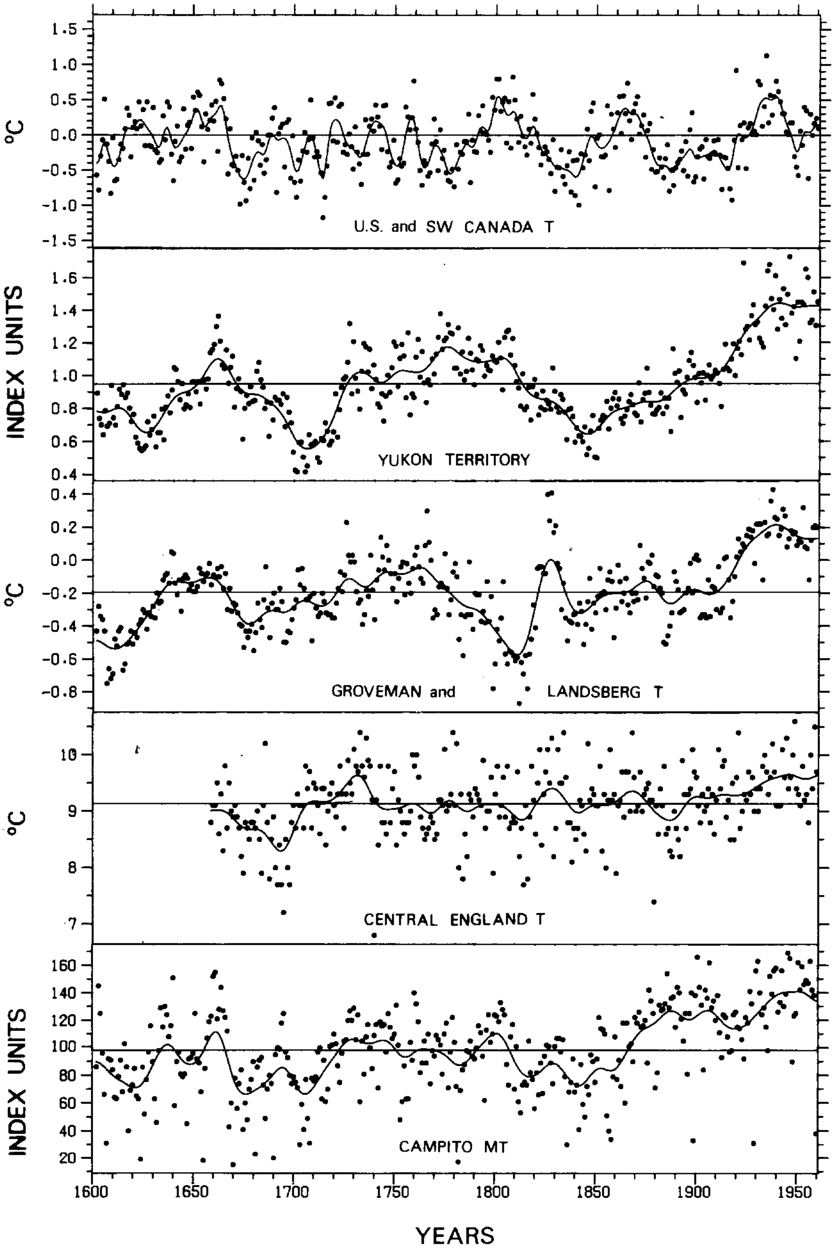

Fig. 4. Temperature reconstructions averaged over 77 United States and southwestern Canada stations; Jacoby and Cook's (1981) tree-ring chronology for the Yukon, Canada; Groveman and Landsberg's (1979) Northern Hemisphere temperature estimate; Manley's (1974) central England temperature series; and LaMarche and Stockton's (1974) tree-ring chronology for Campito Mountain, California (notation is the same as in Figure 1).

TABLE IV: Correlation of reconstructed temperature averaged for the United States and southwestern Canada with other independent temperature estimates. The filtered results were treated with a 13-term digital filter passing 50% variance at eight years or more (Fritts 1976).
(* and ** indicate significance at the 95 and 99% confidence levels, respectively, allowing for first-order autocorrelation in the unfiltered series. For the filtered series the degrees of freedom were approximated as the number of years divided by the number of filter weights.)

	1602–1900			1901–1960		
	Unfiltered	Filtered	Residual	Unfiltered	Filtered	Residual
Yukon T	0.11	0.17	0.04	0.45*	0.74	0.01
Campito M	0.07	0.18	–0.09	0.25	0.34	0.25*
Sheep M	0.11	0.27	–0.16**	0.30*	0.48	0.17
Almagre	0.02	0.06	–0.09	–0.01	–0.03	–0.08
Groveman and L	–0.06	–0.07	–0.02	0.56**	0.80	0.20
Manley T	0.05	0.15	–0.02	0.11	0.40	–0.04

temperature reconstructions and the different series vary considerably in magnitude and direction over time (Table V). A brief rise and fall in the United States and southwestern Canada temperature estimates (Figure 4) is positively and significantly correlated with similar trends in the inferred Yukon temperatures for data at midpoints within the 30-yr period with dates ranging from 1663 to 1675. (Midpoints are given so this period actually includes 15 years of data on each end spanning the interval 1648 to 1689.) Data at the midpoints in the periods 1803 to 1830, 1849 to 1863, and 1916 to 1930 are also shown to be positively and significantly correlated. The data at midpoints 1748 to 1756 are significantly inversely correlated showing strong disagreement. Two overlapping 30-yr periods, one centered in 1708 and the other in 1732 show significant correlations, the former, positive and the latter, negative.

The correlations of our data with Groveman and Landsberg's (1979) series are positive and significant only for data at midpoints 1656 to 1680 and 1915 to 1940. The latter occurs when the instrumental record of Borzenkova *et al.* (1976) is used in the Groveman and Landsberg's series. Significant negative correlation can be noted for data at midpoints 1776 to 1793 and 1813 to 1825 indicating marked disagreement. These are periods when the majority of Groveman and Landsberg's estimators are drawn from the European/North Atlantic sector of the hemisphere.

The Manley central England temperature series is inversely and significantly correlated for data at midpoints 1732 to 1735, 1743 and 1783. These apparent inverse correlations with our estimates of North American temperatures could represent a real opposite tem-

TABLE V: Midpoints of 30-yr intervals of significant agreement or disagreement (at the 95% confidence level, allowing for first-order autocorrelation of the series) between average United States and southwest Canada temperatures and the four independent temperature estimates shown in Figure 4 as indicated by significant correlations between 30-yr nonoverlapping periods (sign indicates positive or negative correlation).

Yukon T	Groveman and L	Manley T	Campito M
1663 to 1675 +	1656 to 1680 +	1732 to 1735 –	1656 to 1675 +
1708 +	1776 to 1795 –	1743 –	1790 to 1815 +
1732 –	1813 to 1825 –	1783 –	1872 to 1883 –
1784 to 1756 –	1915 to 1940 +	1873 to 1882 +	1925 to 1936 +
1803 to 1830 +			1910s to mid 1940s
1849 to 1863 +			
1916 ro 1930 +			

perature relationship between the two sectors though we recognize that the result could also be a random occurrence. The data for 1873 to 1882 are directly and significantly correlated.

The Campito Mountain series which is at high altitudes but within the area that was averaged to form our temperature estimate is positively and significantly correlated with the North American estimate for midpoint values 1656 to 1675, 1790 to 1815 and 1925 to 1936. The data for 1872 to 1885 are significantly inversely correlated.

The trends in temperature shown by all three temperature series from North America appear similar during the 1650s through 1680s, 1790s through 1830s and from 1910 to the mid-1940s. The Campito Mountain series exhibits a significant inverse relationship in the 1860s and 1870s, a time when the average reconstructed temperature in the West was varying in the opposite direction to that in the East. Thus the lack of agreement with this series during that time period could represent a real climatic opposition.

While it is a temptation to make generalizations, too few data sets have been analyzed to conclude anything more than that periods of significant agreement and disagreement occur both spatially and temporally. It is clear that the data sets examined here should not be used individually as indices of temperature variations over wider areas. The data support the findings cited earlier that the spatial and temporal differences in temperature trends over different areas within the Northern Hemisphere during the last 100 yr may also have been present for the three previous centuries.

It is apparent that all of the North American temperature series presented here, especially those in the western half of the region, differ from those in the European sector in many time periods. Such differences would be expected to result from shifts in the amplitude, intensity or position of the atmospheric long-wave troughs and ridges. However, the specific pattern and timing of these discrepancies in the temperature variations between the two sectors of the hemisphere need to be defined more precisely by the development, study, and analysis of other independent large-scale temperature estimates from North America as well as from other localities around the world.

3.3.2. Significant Differences in 30-year Means

As a first attempt at identifying whether there are any more-systematic variations present, we calculated 30-yr running means for each of the temperature series. Differences between adjacent nonoverlapping means in the period between 1602 and 1960 (1659–1960 in the case of central England temperatures) were tested for significance using a *t*-test at the 95% confidence level (Mitchell *et al.*, 1966). A possible climatic variation was considered to have occurred between adjacent 30-yr periods whenever a significant *t*-value reached a maximum (positive or negative) value.

The method using a *t*-test of either sign for a 30-yr period is particularly useful for identifying synchronous times of change in proxy records that are not well correlated with one another if the poor correlation is due to weak and persistent signals of different climatic parameters along with strong noise components. Wendland and Bryson (1974) used a similar approach to identify the major periods of marked climatic change during the Holocene. We recognize the possibility that nonclimatic variations such as nonstationarity or disturbances could be responsible for some of the inferred changes, but if the changes occur in a number of records this possibility is minimized. The results must be tested with additional data before this possibility can be completely excluded.

Our average reconstructed temperature series for the United States and southwestern Canada shows nine marked and significant differences between adjacent 30-yr mean values (Table VI). Regardless of the sign, the greatest difference was noted about 1918, followed by the differences in diminishing order of magnitude at 1821, 1791, 1877, 1667, 1850, 1717, 1761, and 1637. All of the highest ranking differences occur after 1790 with the exception of the 1667 change. The marked warming indicated by the 1918 difference is found within 20 yr of that date in all but the Almagre Mountain series, where a downward trend is indicated. The second-ranking difference corresponding to a cooling beginning in 1821 is also found in all the North American series within the same decade. Groveman and Landsberg's series shows a positive difference beginning with 1821, but the central England record shows no significant differences for this period.

The third-ranking difference (1791) does not appear elsewhere except possibly in Sheep Mountain and Almagre Mountain 11 to 15 yr earlier. The Groveman and Landsberg series shows a significant change in the opposite direction. The fourth-ranking difference shown as a cooling in 1877 could be considered to appear in the Groveman and Landsberg series seven years later. The sixth-ranking change indicating warming beginning in 1850 appears to lag in the high altitude tree-ring chronologies and in the Groveman and Landsberg series from six to 16 yr. The fifth-ranking difference at 1667 is accompanied by similar changes at Campito Mountain, Almagre Mountain and in Groveman and Landsberg's series. Other marked episodes in the different North American records are (a) warming centered about the mid-1630s and (b) warming centered between 1717 and 1723. The coincidence of these times of variation suggests that there have been as many as seven marked changes in the mean climate on the 30-yr time scale, involving several sites found in North America, over the 360-yr period considered here.

Of course as stated earlier, more high resolution proxy records from other parts of the

TABLE VI: First year following a marked variation of the mean as determined by the most significant (at the 95% confidence level) difference between nonoverlapping 30-yr means for reconstructed average annual United States and southwest Canada temperatures and six independent temperature records (sign indicates direction of change).

Decade	U.S. + S.W. Canada	Yukon T	Campito M	Sheep M	Almagre M	Groveman + L	Manley T
1630	1637 +	1637 +	1634 +	1636 +		1632 +	–
1640							–
1650				1651 +	1659 –		–
1660	1667 –		1668 –			1669 –	–
1670							–
1680		1685 –		1686 –	1689 +		–
1690							
1700							1702 +
1710	1717 +		1718 +				
1720		1723 +		1722 +		1721 +	
1730							
1740					1744 –		1740 –
1750			1753 –	1753 –	1759 +		
1760	1761 –	1768 +					
1770				1779 +	1774 +		
1780						1782 –	
1790	1791 +						
1800							
1810		1811 –	1813 –	1810 –	1818 –		
1820	1821 –					1821 +	
1830							
1840							
1850	1850 +			1859 +	1856 +		
1860			1866 +			1861 +	
1870	1877 –						
1880						1884 –	
1890							
1900				1900 +	1901 –		
1910	1918 +						
1920		1923 +				1920 +	
1930			1930 +				1932 +

Northern Hemisphere need to be tested in order to examine how well these dates represent major changes in other regions. If they do, then the reasons for these major swings in climate, several of which are within the so-called Little Ice Age, will need to be considered further. We note that any marked agreement or disagreement, if it exists, with the central England temperatures is not evident using this method.

4. Discussion and Conclusions

An estimate of temperature variation for the United States and southwestern Canada derived from western North American tree-ring series has been presented. Comparison of this estimated temperature series with the Northern Hemisphere temperature record since 1881 shows that estimated North American temperatures were closely in phase with the hemispheric average during the early-20th-century warming but that the relationship weakened beginning in 1947 when hemispheric temperatures started to decline. (Similar relationships were apparent in the instrumental time series of United States and southwestern Canada temperatures.) While it would be unwise to consider the series to represent anything more than North American conditions, no other proxy series of similar spatial coverage and time resolution for the particular time period has yet been produced. Thus this reconstructed record provides a regionally averaged estimate which, along with data from other parts of the Northern Hemisphere, can reveal how North American temperatures have varied from those in Europe and differ from what has been reported as the hemisphere temperature averages. Recognizing such differences may help us to establish the past hemispheric-wide temperature variations more precisely than has been possible before.

The comparisons of this temperature series with other independent temperature series shows that high-frequency (year-to-year) fluctuations of the different series are uncorrelated (Table IV). Over a few short subperiods within the 360-yr interval, significant associations can occur, but the strength and *direction* of the relationship may vary. Thus, for example, North American temperature variations appeared to have been out-of-phase with the European record for a variety of time periods especially during the late 18th and early 19th centuries. Significant variations (changes) in the 30-yr means occur in a number of the different North American series, with the greatest warming noted early in the 20th century. The next most important warming (apparent in several of the series) occurred between 1717 and 1723, followed by one between 1850 and 1866. Blasing and Fritts (1975), Garfinkel and Brubaker (1980), and Cropper (1982) also note wide-spread warming inferred from increased tree growth in Alaska and the Yukon during the 1850–1866 time period. The most marked cooling appeared to occur between 1810 and 1821 and the next most marked cooling occurred between 1659 and 1669. Blasing and Fritts (1975), Cropper and Fritts (1981), and Cropper (1982) also report declining growth and inferred declining temperatures in Alaska and the Yukon during this time period.

The results presented here also demonstrate that considerable differences can occur in the direction and magnitude of climatic variations represented by proxy records from different regions (*c.f.* Jones and Kelly, 1983; Williams and Wigley, 1983). Detailed comparison and documentation of the differences and similarities of independent proxy series is essential to the development of a realistic and comprehensive history of climate variations over space. As more high-quality proxy series become available from different parts of the Northern Hemisphere, we will have more confidence in the reliability of the overall mean temperature record for the hemisphere including better understanding of the possible spatial variations that contributed to the mean value. Such a record should provide some information on the dynamics of climatic variation and change and suggest the possible types of variation to expect in the next few decades. However, the available grid of sites and the geographic distribution of proxy records of past temperature changes still appear too limited to make generalizations about hemispheric-wide temperature variations much before 1880. More information is needed particularly from central Canada and the eastern half of North America, as well as from other parts of the world.

Acknowledgements

The important and substantial contributions of T. J. Blasing, G. R. Lofgren, and G. A. Gordon to the development of the dendroclimatic reconstructions are gratefully acknowledged. This research was supported by research grants GA-26581; ATM-75-17034; ATM-75-22378; ATM-77-19216; and ATM-8115754 from the Climate Dynamics Program of the National Science Foundation.

References

Balling, R. C. and Lawson, M. P.: 1982, 'Twentieth Century Changes in Winter Climatic Regions', *Clim. Change* **4**, 57–69.

Barnett, T. P.: 1978, 'Estimating Variability of Surface Air Temperature in the Northern Hemisphere', *Mon. Wea. Rev.* **106**, 1353–67.

Barry, R., Fritts, H. C., Imborie, J., Mitchell, J. M., and Savin, S. M.: 1979, 'Paleoclimatic Research: Status and Opportunities', in A. D. Hecht (ed.), *Quat. Res.* **12**, 6–17.

Blasing, T. J.: 1978, 'Time Series and Multivariate Analysis in Paleoclimatology', in H. H. Shugart, Jr. (ed.), *Time Series and Ecological Processes*, SIAM-SIMS Conference Series, No. 5, Society for Industrial and Applied Mathematics, Philadelphia, pp. 212–26.

Blasing, T. J. and Fritts, H. C.: 1975, 'Past Climate of Alaska and Northwestern Canada as Reconstructed from Tree Rings', in *Climate of the Arctic* (Proc. 24th Alaskan Science Conf., August, 1973). Gunter Weller and Sue Ann Bowling (eds.), Geophysical Institute, University of Alaska, Fairbanks, pp. 48–58.

Blasing, T. J. and Fritts, H. C.: 1976, 'Reconstructing Past Climatic Anomalies in the North Pacific and Western North America from Tree Ring Data', *Quat. Res.* **6**, 563–80.

Borzenkova, I. I., Vinnikov, K. Ya., Spirina, L. P., and Stekhnovskii, D. I.: 1976, 'Change in the Air Temperature of the Northern Hemisphere for the Periods 1881–1975', *Met. i. Gidr.* **7**, 27–35 (in Russian).

Briffa, K. R., Jones, P. D., Wigley, T. M. L., Pilcher, J. R., and Baillie, M. G. L.: 1983, 'Climate Reconstruction from Tree Rings: Part 1, Basic Methodology and Preliminary Results for England', *J. of Climatology* **3**, 233–42.

Bryson, R. A. and Hare, F. K.: 1974, *Climates of North America, World Survey of Climatology*, Vol. 11. Elsevier, Amsterdam.

Cropper, J. P.: 1982, 'Climate Reconstructions (1801–1938) Inferred from Tree-Ring Width Chronologies of the North American Arctic', *Arctic and Alpine Res.* **14**, 223–41.

Cropper, J. P. and Fritts, H. C.: 1981, 'Tree-ring Width Chronologies from the North American Arctic', *Arctic and Alpine Res.* **13**, 245–60.

Cropper, J. P. and Fritts, H. C.: 1982, 'Density of Tree-ring Grids in Western North America', *Tree-Ring Bul.* **42**, 3–9.

Diaz, H. F. and Fulbright, D. C.: 1981, 'Eigenvector Analysis of Seasonal Temperature, Precipitation and Synoptic-Scale System Frequency over the Contiguous United States, Part I. Winter', *Mon. Wea. Rev.* **109**, 1267–84.

Diaz, H. F. and Namias, J.: 1983, 'Associations between Anomalies of Temperature and Precipitation in the United States and Western Northern Hemisphere 700 mb Height Profiles', *J. of Climate and Applied Met.* **22**, 352–63.

Diaz, H. F. and Quayle, R. G.: 1980, 'The Climate of the United States Since 1895: Spatial and Temporal Changes', *Mon. Wea. Rev.* **108**, 249–66.

Erickson, C. O.: 1983, 'Hemispheric Anomalies of 700 mb height and Sea Level Pressure Related to Mean Summer Temperatures over the United States', *Mon. Wea. Rev.* **111**, 545–61.

Fritts, H. C.: 1974, 'Relationships of Ring Widths in Arid-site Conifers to Variations in Monthly Temperature and Precipitation', *Ecol. Mon.* **44(4)**, 411–40.

Fritts, H. C.: 1976, *Tree Rings and Climate*, Academic Press, New York and London.

Fritts, H. C. and Shatz, D. J.: 1975, 'Selecting and Characterizing Tree-Ring Chronologies for Dendroclimatic Analysis', *Tree-Ring Bul.* **35**, 31–40.

Fritts H. C., Lofgren, G. R., and Gordon, G. A.: 1979, 'Variations in Climate Since 1602 as Reconstructed from Tree Rings', *Quat. Res.* **12**, 18–46.

Garfinkel, H. L. and Brubaker, L. B.: 1980, 'Modern Climate-tree-growth Relationships and Climate Reconstructions in Subarctic Alaska', *Nature* **286**, 872–4.

Gordon G. A.: 1982, 'Verification of Dendroclimatic Reconstructions', in M. K. Hughes, P. M. Kelly, J. R. Pilcher, and V. C. LaMarche, Jr. (eds.), *Climate from Tree Rings*, Cambridge University Press, Cambridge, pp. 58–61.

Gordon, G. A., Lough, J. M., Fritts, H. C., and Kelly P. M.: in press, 'Comparison of Sea-Level Pressure Reconstructions from Western North American Tree Rings with a Proxy Record of Winter Severity in Japan', *J. Clim. and Appl. Met.* (accepted).

Groveman, B. S. and Landsberg, H. E.: 1979, 'Simulated Northern Hemisphere Temperature Departures 1579–1880', *Geophys. Res. Letters* **6**, 767–9.

Hughes, M. K., Kelly, P. M., Pilcher, J. R., and LaMarche, V. C., Jr. (eds.): 1982, *Climate from Tree Rings*, Cambridge University Press, Cambridge.

Jacoby, G. C. and Cook, E. R.: 1981, 'Past Temperature Variations Inferred from a 400-yr Tree-ring Chronology from Yukon Territory, Canada', *Arc. and Alp. Res.* **13**, 409–18.

Jones, P. D. and Kelly, P. M.: 1983, 'The Spatial and Temporal Characteristics of Northern Hemisphere Surface Air Temperature Variations', *J. of Climatology* **3**, 243–52.

Jones, P. D., Wigley, T. M. L., and Kelly, P. M.: 1982, 'Variations in Surface Air Temperatures: Part 1, Northern Hemisphere', 1881–1980, *Mon. Wea. Rev.* **110**, 59–70.

Koppen, W.: 1873, 'Ueber mehrjarige Perioden der Witterung', *Zeit.für Met.* **8**, 257–67.

Kutzbach, J. E.: 1970, 'Large-scale Features of Monthly Northern Hemisphere Maps of Sea Level Pressure', *Mon. Wea. Rev.* **98**, 708–16.

Kutzbach, J. E.: 1975, Diagnostic Studies of Past Climate', in *The Physical Basis of Climate and Climate Modelling*, GARP Publication Series No. 16, ICSU/WMO, WMO, Geneva, pp. 119–26.

Kutzbach, J. E. and Guetter, P. J.: 1980, 'On the Design of Paleoenvironmental Data Networks for Estimating Large-Scale Patterns of Climate', *Quat. Res.* **14**, 169–87.

LaMarche, V. C., Jr. and Fritts, H. C.: 1972, 'Tree-Rings and Sunspot Numbers', *Tree-Ring Bul.* **32**, 19–33.

LaMarche, V. C., Jr. and Stockton, C. W.: 1974, 'Chronologies from Temperature-Sensitive Bristlecone Pines at Upper Treeline in Western United States', *Tree-Ring Bul.* **34**, 21–45.

Lamb, H. H.: 1972, *Climate: Present, Past and Future. I. Fundamentals and Climate Now*, Methuen, London.

Lamb, H. H.: 1977, *Climate: Present, Past and Future. II. Climatic History and the Future*, Methuen, London.

Lamb, H. H. and Johnson, A. I.: 1966, 'Secular Variations of the Atmospheric Circulation since 1750', *Geophys. Memoirs* **110**, Meteorological Office, London.

Livezey, R. E. and Chen, W. Y.: 1983, 'Statistical Field Significance and Its Determination by Monte Carlo Techniques', *Mon. Wea. Rev.* **111**, 46–59.

Lofgren, G. R. and Hunt, J. H.: 1982, 'Transfer Functions', in M. K. Hughes, P. M. Kelly, J. R. Pilcher, and V. C. LaMarche, Jr. (eds.), *Climate from Tree Rings*, Cambridge University Press, Cambridge, pp. 50–6.

Lough, J. M.: 1983, *The Southern Oscillation and North American Climate, 1602 to 1962*, Technical Note No. 24, Laboratory of Tree-Ring Research, U. of AZ., Tucson, Az.

Lough, J. M.: 1984, 'The Documentary Record of Drought and Flood in China: A Comparison with Dendroclimatic Reconstructions from Western North America', Technical Note No. 31, Laboratory of Tree-Ring Research, U. of Az, Tucson.

Manley, G.: 1974, 'Central England Temperatures: Monthly Means from 1659 to 1973', *Quart. J. Roy. Met. Soc.* **100**, 389–405.

Miles, M. K. and Gildersleeves, P. B.: 1978, 'A Statistical Study of the Likely Influence of some Causative Factors on the Temperature Changes since 1665', *Met. Mag.* **107**, 193–204.

Mitchell, J. M., Dzerdzeevskii, B., Flohn, H., Hofmeyer, W. L., Lamb, H. H., Rao, K. N., and Wallen, C. C.: 1966, Climatic Change, WMO Technical Note No. 79, WMO, Geneva.

National Academy of Sciences: 1975, *Understanding Climatic Change*, National Academy Press, Washington, D. C.

Trenberth, K. E. and Paolino, D. A.: 1980, 'The Northern Hemisphere Sea-Level Pressure Data Set: Trends, Errors and Discontinuities', *Mon. Wea. Rev.* **108**, 855–72.

van Loon, H. and Williams, J.: 1976a, 'The Connection between Trends of Mean Temperature and Circulation at the Surface: Part I. Winter', *Mon. Wea. Rev.* **104**, 365–80.

van Loon, H. and Williams, J.: 1976b, 'The Connection between Trends of Mean Temperature and Circulation at the Surface: Part II. Summer', *Mon. Wea. Rev.* **104**, 1003–11.

Wendland, W. M. and Bryson, R. A.: 1974, 'Dating Climatic Episodes of the Holocene', *Quat. Res.* **4**, 9–24.

Williams, L. D. and Wigley, T. M. L.: 1983, 'A Comparison of Evidence for Late Holocene Summer Temperature Variations in the Northern Hemisphere', *Quat. Res.* **20**, 286–307.

(Received 29 December, 1983; in revised form 4 September, 1984)