SECULAR TRENDS IN HIGH NORTHERN LATITUDE TEMPERATURE RECONSTRUCTIONS BASED ON TREE RINGS

ROSANNE D. D'ARRIGO and GORDON C. JACOBY
Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, New York 10964, U.S.A.

Abstract. Boreal tree-ring records from high latitude North America, Scandinavia and Russia provide baseline data reflecting long-term trends in Arctic annual temperature. Reconstructions from 1682–1968 indicate the latter part and termination of the Little Ice Age and that the northern regions are now warmer by comparison. The resulting high-resolution, extended temperature time series allows examination of underlying causes of climatic change not possible using only the instrumental record. The recent recorded data for the Arctic show recovery from the cooling in the 1950's–1960's. The overall evaluation confirms that the high northern latitudes are now in an anomalously warm state relative to the past three centuries.

Introduction

Global climatic change can be identified by documenting sets of extremes that indicate a shift outside the bounds of natural variation or by establishing trends that are unusual and related to changing causative factors. Previous studies have established the importance of high northern latitudes in the global temperature regime (Kelly *et al.*, 1982; Jones and Kelly, 1983; Lachenbruch and Marshall, 1986; Walsh and Chapman, 1990). In these regions few meteorological records extend back for even the past 100 years, and these cannot represent the full range of climate variability.

Longer records based on tree-ring data can determine past centuries of temperature trends for this area and their relationship to Northern Hemisphere climate as a whole. Parsimonious standardization to preserve as much climatic information as possible in the tree-ring data yields time series with annual and also longer-term climatic response. The secular trends in resultant data sets and reconstructions of temperature are crucial for recognizing and quantifying possible global change.

Studies have demonstrated the ability of tree growth at northern sites to reflect fluctuations in temperature (e.g. Jacoby *et al.*, 1985; Payette *et al.*, 1985; Briffa *et al.*, 1988 and 1992; Graybill and Shiyatov, 1992). Recent 300-year reconstructions of Arctic and Northern Hemisphere annual temperature departures were based solely on eleven temperature-sensitive ring-width chronologies from the North American boreal treeline (Jacoby and D'Arrigo, 1989). Partly because of the limited geographic representation, these reconstructions need to be confirmed by new analyses. In this paper we present a revised and improved version of the Jacoby and D'Arrigo (1989) Arctic temperature reconstruction which has ex-

Climatic Change **25:** 163–177, 1993.

panded geographical coverage. Previously, the tree-ring sites extended over more than 90° of longitude across northern North America. Herein this coverage has been improved to include one newly developed site from eastern Canada as well as tree-ring-width data from northern Scandinavia (K. Briffa, pers. comm.) and Russia (Shiyatov, 1986; Graybill and Shiyatov, 1992) which have recently become available (Table I–II, Figure 1). Temperature fluctuations from these regions are important to larger-scale climatic trends (Kelly *et al.*, 1982; Jones and Kelly, 1983), and inclusion of the tree-ring data from these additional sites improves the previous reconstruction of Arctic temperatures, as discussed below.

Although early observers realized that tree-ring widths from high-latitude trees correlate with summer surface air temperatures (e.g. Giddings, 1943; Hustich, 1956), more recent studies have indicated that this is really an oversimplification (Garfinkel and Brubaker, 1980; Jacoby and Cook, 1981; Jacoby and Ulan, 1982;

TABLE I: Site information of northern tree-ring chronologies used to reconstruct Arctic temperatures. As shown in Figure 1. PIGL = *Picea glauca*, LRL = *Larix laricina*, THO = *Thuja occidentalis*, PISY = *Pinus sylvestris*, SRS = Siberian spruce, LRS = Siberian larch. NWT = Northwest Territories, MB = Manitoba, QB = Quebec, LB = Labrador, NWY = Norway, SWD = Sweden, FNL = Finland, RUS = Russia

Site	Location	Lat. (N)	Long.	Elev. (M)	Spp.	Years
North American Chronologies		(W)				
1. 412	Alaska	67 56	162 18	126	PIGL	1515–1977
2. Arrig.	Alaska	67 27	154 03	732	PIGL	1586–1975
3. Sheenjek	Alaska	68 38	143 43	808	PIGL	1580–1979
4. TTHH	Yukon	65 00	138 20	914	PIGL	1459–1975
5. Mack Mt.	NWT	65 00	127 50	1370	PIGL	1626–1983
6. Copperm.	NWT	67 14	115 55	215	PIGL	1428–1977
7. Hornby	NWT	64 02	103 52	160	PIGL	1491–1983
8. Churchill	MB	58 43	094 04	80	PIGL	1650–1988
9. Cape	QB	56 10	076 33	90	PIGL	1663–1982
10. Ft. Chimo	QB	58 22	068 23	46	LRL	1650–1974
11. Gaspe	QB	48 35	065 55	305	THO	1404–1982
12. S. W. Pond	LB	56 31	061 55	150	PIGL	1602–1988
Scandinavian Chronologies		(E)				
13. Lofoten	NWY	68 29	016 02	200	PISY	1485–1978
14. Pyhatunturi	FNL	67 00	027 15	260	PISY	1655–1983
15. Sompio	FNL	68 45	027 15	325	PISY	1560–1983
16. Morgammaras	FNL	68 45	026 30	300	PISY	1536–1983
17. Suojanpera	FNL	6919	028 08	140	PISY	1532–1983
Russian Chronologies		(E)				
18. Urals 6–8	RUS	64 42	059 57	298	LRS	1673–1970
19. Urals 9–10	RUS	64 42	059 57	289	SRS	1681–1969
20. Polar Urals	RUS	66 45–65 15	065 15–066 05	150–300	LRS	961–1969

TABLE II: List of tree-ring chronologies included in temperature reconstruction. Shown are the loadings of the first, second and fourth eigenvectors for each chronology, and the simple correlations ('*r*') of the chronologies with Arctic (Zone 1) annual temperature departures for 1880–1969

Site	1st E.V.	2nd E.V.	4th E.V.	Correlation
North American Chronologies				
1. 412	+0.23	+0.20	+0.05	+0.6228
2. Arrigetch	+0.26	−0.29	+0.07	+0.4506
3. Sheenjek	+0.17	−0.09	+0.55	+0.4558
4. TTHH	+0.29	+0.08	+0.16	+0.7082
5. Mack Mt.	+0.27	−0.13	+0.19	+0.4977
6. CuMine	+0.26	−0.05	+0.09	+0.5065
7. Hornby	+0.09	+0.40	+0.08	+0.2651
8. Churchill	+0.24	−0.27	−0.08	+0.3707
9. Cape	+0.16	−0.42	−0.05	+0.1086
10. Ft. Chimo	+0.14	−0.17	+0.26	+0.3506
11. Gaspe	+0.26	−0.11	+0.08	+0.5348
12. S. W. Pond	+0.23	−0.03	+0.03	+0.4959
Scandinavian Chronologies				
13. Lofoten	+0.06	+0.48	+0.27	+0.4256
14. Pyhatunturi	+0.24	+0.06	−0.27	+0.4363
15- Sompio	+0.26	+0.17	−0.21	+0.4969
16. Morgammaras	+0.27	+0.18	−0.03	+0.5672
17. Suojanpera	+0.25	+0.29	−0.07	+0.6368
Russian Chronologies				
18. Urals 6–8	+0.22	−0.05	−0.28	+0.3413
19. Urals 9–10	+0.16	+0.07	−0.36	+0.3188
20. Polar Urals	+0.22	+0.08	−0.35	+0.4701

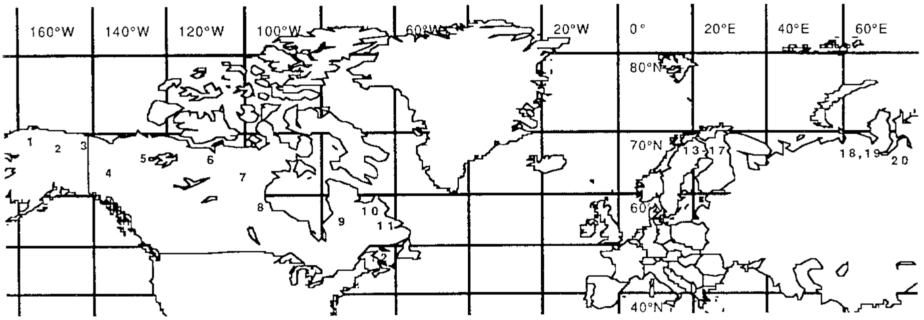

Fig. 1. Site locations of the boreal tree-ring width chronologies. The numbers are as in Table I–II.

Jacoby and D'Arrigo, 1989). One reason that the tree-growth summer temperature relationship can be considered simplistic is that the trees used in northern tree-ring studies are primarily evergreen conifers, for which photosynthesis can take place over a much longer season than the relatively short summer period of actual cambial-cell division. In temperate and subarctic regions, photosynthesis continues down to temperatures near freezing, and these photosynthates are stored and used in the summer radial growth season (Kramer and Kozlowski, 1979, pp. 196–199). The combined influences of fall and spring photosynthesis and milder winters can impart a temperature response beyond the summer season of cambial cell division and radial growth (e.g. Fritts, 1976; Kramer and Kozlowski, 1979; Garfinkel and Brubaker, 1980; Jacoby and Cook, 1981; Jacoby and Ulan, 1982; and from correlations between certain tree-ring chronologies and monthly temperatures for the cooler seasons). Thus tree physiology considerations as well as regression and other analyses indicate that ring-width variations at selected sites are responses to, and thus recorders of, thermal information beyond the summer season of radial growth (Jacoby and D'Arrigo, 1991).

Almost all of these sites are near the northern and/or elevational tree line. As shown by Bryson (1966) the position of the northern tree line lies close to the juncture of air masses converging from the polar regions and from more temperate regions to the south. The northern limits of tree growth and the growth rates of individual trees are strongly influenced by thermal effects of the varying air masses sweeping across the northern boreal forests and the forest-tundra ecotone. The temperatures at a site will thus correspond to regional variations as changing air masses pass through the site locations. Thus variations in regional and corresponding site temperatures strongly influence tree growth.

In sampling the sites used herein we and other dendroclimatologists sought out sites where the trees are growing near the limits of survival due to thermal conditions, yet where there is little evidence of disturbance by other factors. In attempting to relate the growth variations of these thermally-stressed trees to temperature, we realize that the mean temperature from a weather station is inadequate to represent a tree's full thermal environment (Tranquillini, 1979, pp. 6–7). Individual tree sites may be warmer or cooler relative to surrounding terrain depending on topography, exposure and other physiographic factors. Another caveat is that individual instrumental climatic stations in far northern regions can be remote from the selected sites of interest. Also, many are in valley locations with frequent inversions whereas the tree sampling sites are usually on slopes or hills. Regionalized temperatures remove local station noise and bias, thus often giving a better representation of temperature variations.

Similar trends have been observed in chronologies from widely-separated regions (Figure 2). This similarity of trends strongly indicates that although microsite factors are the direct cause of the growth variations, the sites and trees are responding to regional variations. These results lend further support to the feasibility of climate-tree growth linkages over large distances.

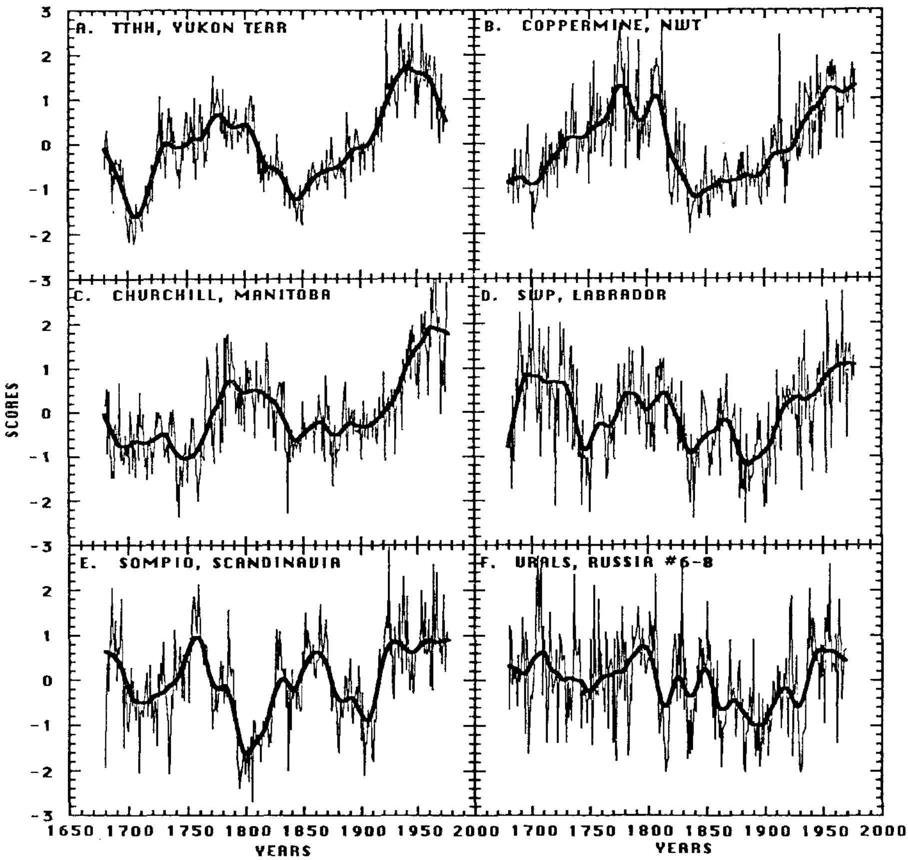

Fig. 2. Plots of six of the twenty chronologies used to reconstruct Arctic temperatures. These chronologies represent western (A & B), central (C) and eastern Canada (D) as well as Scandinavia (E) and Russia (F).

Data and Methodology

Two improvements in the North American boreal ring-width data set are a modified chronology for Churchill, Manitoba and a new time series from Labrador (Table I–II, Figure 1). The Churchill chronology was improved by incorporating data from Scott *et al.* (1988) which contain more low-frequency climatic information than the previously-used chronology. The somewhat sparse coverage in easternmost Canada is supplemented by the new Labrador chronology. Of the resulting 12 series from North America, ten are of white spruce (*Picea glauca* [Moench] Voss), one is eastern larch (*Larix laricina* [DuRoi] K. Koch) from Fort Chimo, Quebec and the other is northern white cedar from the Gaspe, Quebec (*Thuja occidentalis* L.).

Five boreal tree-ring width chronologies from Scandinavia have been added to the North American data set (Table I–II, Figures 1 and 2). They are largely a subset of a ring-width and density data compilation used to reconstruct late summer temperatures for Fennoscandinavia back to 1700 (Briffa *et al.*, 1988) and even earlier (Briffa *et al.*, 1990 and 1992). All are scots pine (*Pinus sylvestris* L.). Similar to the individual time series developed for northern North America (Jacoby and D'Arrigo, 1989), we standardized the raw ring-width data from Scandinavia using only negative-exponential or straight-line curve fits to develop ring-width indices for each core for each year. The negative-exponential curve is biologically justified when there is an age trend in ring widths (Fritts, 1976). This standardization approach differs from that used by Briffa *et al.* (1988) for their reconstruction of Fennoscandinavian late summer temperatures (based in part on the same samples), in which a 60-year low-pass Gaussian filter was used to preserve variance at primarily high and medium frequencies. A more recent version of the Briffa *et al.* (1988) reconstruction (Briffa *et al.* 1992; Briffa and Schweingruber, 1992) used smoothing splines (Cook and Peters, 1981) in order to retain more low-frequency information. The chronologies selected for use in the present study all demonstrated high percentages of explained variance in the first eigenvector in principal components analysis of the individual ring-width indices (Cook, 1985), indicating a common, broad-frequency (presumably climatic) signal within the trees at each site.

The Russian data consist of three time series from the northern Ural Mountains (Table I–II, Figures 1 and 2). Two of the series are ring-width chronologies published by Shiyatov (1986), located near 64°42′ N, 59°57′ E. One is siberian larch (*Larix sibirica*) and one is siberian spruce (*Picea obovata*). The third series is a reconstruction of gridded (65° N–70° E) summer (June–July) temperature based on siberian larch tree-ring data from extreme northern Russia near the Kara Sea, extending from 66°45′–65°15′ N and 65°15′–66°05′ E (Graybill and Shiyatov, 1992). The Kara Sea region is believed to be particularly sensitive to large-scale climate variation (Kelly *et al.*, 1982). In these three cases we did not have the raw ring-width data and thus used the available chronologies or reconstructed values. The three tree-ring time series were standardized using the corridor method (Shiyatov *et al.*, 1989), which preserves a broad range of frequencies. The third series, a reconstructed summer-temperature series, is merely the chronology rescaled by a single coefficient and a constant term (Graybill and Shiyatov, 1992). Therefore it is equivalent to the chronology itself. As discussed in Jacoby and D'Arrigo (1989), the deciduous larch (represented here by two from Russia and one of the North American chronologies) may not integrate annual temperature conditions as well as the evergreen species. However Graybill and Shiyatov (1992) do show some positive correlations with non-growing season temperatures, although they note that they do not have an explanation for this. The entire northern data set comprises a network of 20 chronologies with a common period of nearly 300 years, from 1681–1969 (Table I–II, Figure 1).

The instrumental temperature data set used here is that of Hansen and Lebedeff (1987 and 1988), which consists of 80 equal-area temperature boxes for the globe. See Hansen and Lebedeff (1987) for a full description of the derivation of their global data set. This temperature data set was also employed in Jacoby and D'Arrigo (1989). The chronologies selected for this study all showed positive correlations in a preliminary screening with the Arctic (Zone 1, 64–90° N) annual temperature departures for the common period from 1880–1969 (Table II). For comparison the temperature data of the Climatic Research Unit (CRU), University of East Anglia, were also used to reconstruct Arctic temperatures (e.g. Jones, 1988). The results were very similar and are not shown here.

The method used to reconstruct temperature is multiple linear regression analysis (Fritts *et al.*, 1990) in which a set of predictor variable(s) based on the tree-ring data is used to estimate, in a regression equation, the predictand variable(s), in this case the annual temperature departures of Hansen and Lebedeff (1987) for the Arctic.

Prior to regression analysis, PCA was performed on the 20-chronology data set in order to reduce the number of predictors into a smaller number of orthogonal or uncorrelated time series (Fritts *et al.*, 1990). The PCA was based on the interval from 1880–1969, the period of overlap with the temperature data. The first 4 eigenvectors, explaining 70.5% of the overall variance within the tree-ring data, had eigenvalues more than one and were retained for further evaluation.

Leads and lags of tree growth in their relation to climate are appropriately used in dendroclimatic reconstructions (see Fritts (1976) and Jacoby and D'Arrigo (1989) for more detailed discussions of this subject). The four sets of eigenvector scores for the previous ($t-1$), current (t) and following ($t+1$) years of growth were tested as candidate predictors of the Arctic instrumental temperature departures. The first, second and fourth components and associated lagged variables showed significant correlations with the temperature data over the interval from 1880–1968 (at the 0.05 level, using a one-tailed t-test) and were retained as potential predictors in the regression analyses. Shown in Table II are the 1st (44.3% of the overall variance), 2nd (12.1%) and 4th (6.7%) sets of eigenvector loadings for the 20 chronologies. All the chronologies show positive loadings in eigenvector one, indicating a common signal among the boreal tree-ring data from northern North America and northern Europe. The second and fourth eigenvectors show contrasting patterns between the chronologies from these two regions. This is typical of the PCA process (e.g. Kutzbach and Guetter, 1980).

Results and Discussion

Several combinations of the eigenvector scores and lagged variables were compared to the Arctic temperature data in regression modeling. The best results were obtained using the first and second sets of principal component scores at lags t and $t+1$, and the fourth eigenvector at lag t for a total of five predictors. In Jacoby and D'Arrigo (1989), the predictors were the 1st component at lags t and $t+1$ and the second at lag t. The Arctic temperature reconstruction based on the 20 chronologies is shown in Figure 3A. The ar^2 (variance explained, adjusted for degrees of freedom) for the full reconstruction is 66% (Table IIIA). For the early calibration

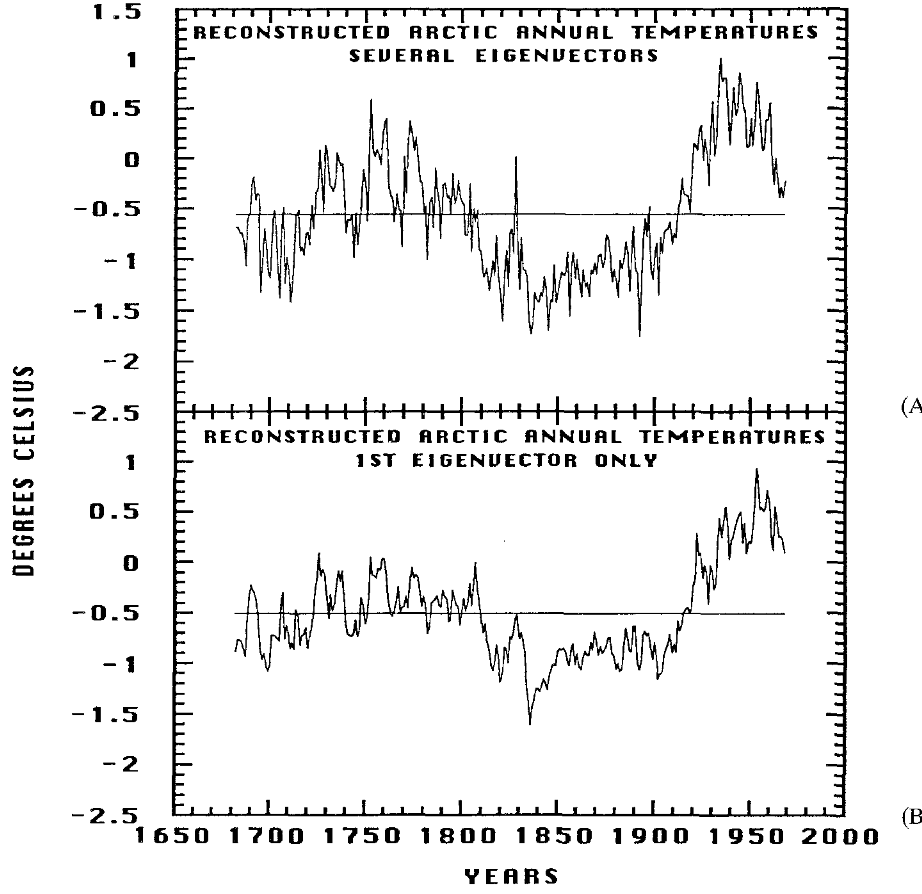

Fig. 3. (A) Arctic annual temperature reconstructions for 20 chronologies using several eigenvectors. (B) As in (A) but using eigenvector one only.

period (1880–1940) the ar^2 is 0.63, the RE is 0.77 and the Spearman coefficient is 0.61. For the later period of calibration (1941–1968) the values are 0.35, the 0.73 and 0.77, respectively. Any RE value above 0 indicates predictive skill in the estimated values (Gordon and Leduc, 1981). Both Spearman coefficients are significant above the 0.001 level. The results from Table IIIA are improved over the previous Arctic model of Jacoby and D'Arrigo (1989) (Table IIIC), except that the ar^2 for the early and late calibration periods are slightly lower. Figure 3B and Table IIIB show an alternative version of the reconstruction in which only the first eigenvector at lags t and $t+1$ was used. This was done in order to determine if the trends obtained from the first eigenvector alone, which represents the dominant mode of tree growth among the chronologies, differed from that of the full reconstruction. A comparison of Figures 3A and B shows that the trends are very similar. However, the statistics are much improved in the model using several eigenvectors

TABLE III: Calibration-verification statistics for Arctic temperature reconstruction models. Based on annual temperature data of Hansen and Lebedeff (1987). (A) = Model based on North American (12 chronologies), Scandinavian (5 chronologies) and Russian (3 chronologies) data; (B) = Model as in (A) but using eigenvector 1 only; (C) = Model from Jacoby and D'Arrigo, 1989. Predictor variables for (A) are: 1st and 2nd eigenvectors, lags t and $t+1$; 4th eigenvector, lag t. Predictor variables for (B) are: 1st eigenvector at lags t and $t+1$. Predictor variables for (C) are: 1st eigenvector, lags t and $t+1$; 2nd eigenvector, lag t. *** = significant above 0.001 level, n.s. = not significant

Calibr.	Verif.	r	r^2	ar^2	RE	S
(A) Arctic Model EV's 1, 2, 4						
1880–1969	–	0.82	0.68	0.66	–	–
1880–1940	1941–1968	0.81	0.66	0.63	0.77	0.61***
1941–1968	1880–1940	0.68	0.47	0.35	0.73	0.77***
(B) Arctic Model EV 1						
1880–1969	–	0.74	0.54	0.53	–	–
1880–1940	1941–1968	0.77	0.59	0.57	0.18	0.15 n.s.
1941–1968	1880–1940	0.37	0.14	0.07	0.66	0.67***
(C) Jacoby and D'Arrigo, 1989						
1880–1973	–	0.78	0.61	0.60	–	–
1880–1940	1941–1973	0.81	0.66	0.64	0.28	0.54***
1941–1973	1880–1940	0.68	0.46	0.41	0.39	0.67***

as predictors. We note here that Monte Carlo tests were performed as an additional evaluation of the validity of the reconstructions published in Jacoby and D'Arrigo (1989). Actual and estimated temperatures for the full calibration period for models A and B are shown in Figure 4.

The major low-frequency trends of the reconstructed Arctic annual temperature departures (Figure 3) are very similar to those obtained by Jacoby and D'Arrigo (1989). In both sets of models, there is a cooling in the late 1600's to early 1700's, a relative warming in the 1700's, an abrupt decline in temperature in the early 1800's and a gradual warming trend since the middle to late 1800's. These major trends resemble some of the individual North American chronologies (Figure 2) which have more common agreement with each other than the Scandinavian and Russian chronologies have with each other. The Scandinavian and Russian chronologies introduce other variations into the reconstruction, as described below.

A very brief warming in the middle 1820's to 1830's becomes more pronounced with the inclusion of the Scandinavian data. This warming episode was also noted by Briffa *et al.* (1988) in their reconstruction of late summer Fennoscandinavian temperatures, based partly on the same Scandinavian chronologies used here. This warming is also present in the annual box temperatures for northern Europe compiled by Hansen and Lebedeff (1987), and in individual records compiled by Jones and Bradley (1992). Although Scandinavian chronologies have a strong summer

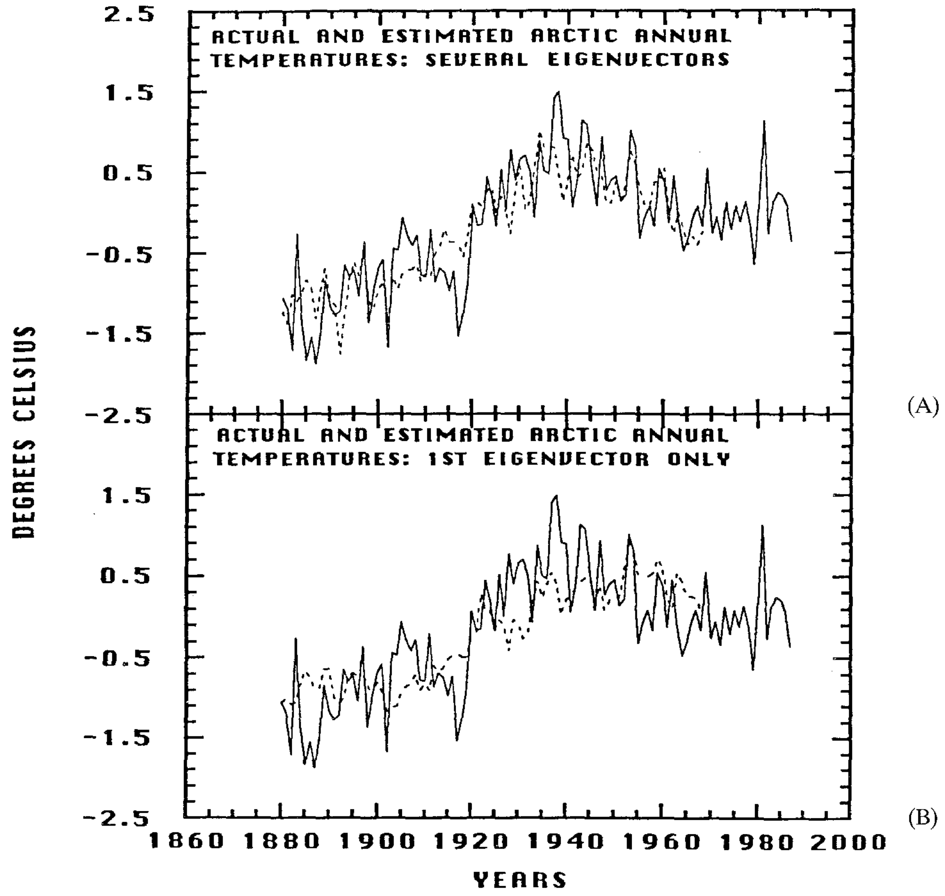

Fig. 4. Actual (solid line) and estimated (dashed line) annual Arctic (Zone 1) annual temperatures. (A) = Model using several eigenvectors; (B) = Model with eigenvector one only.

climatic signal as shown in several studies (e.g. Briffa *et al.*, 1988), we have also found strong correlations with non-growing season temperatures using long instrumental temperature records (e.g. for Oslo, Norway).

Another difference between the North American and Scandinavian records is a gradual increase in growth since the mid-late 1800's in the North American data as compared to a more abrupt, steplike growth increase around 1920 in the Scandinavian data. Although the 1920's warming influenced the entire Arctic, the warming in the eastern Arctic preceded that in northwestern Greenland and in the west (Kelly *et al.*, 1982).

The Graybill and Shiyatov (1992) reconstruction shows above average conditions in the 1700's, cooler temperatures in the 1800's (particularly 1800–1820) and warmer temperatures over the past century. These authors note that their calibration-verification statistics are weaker in the more recent, warmer interval, which is also the case (at least in terms of explained variance) for the results which we have found (Table III). For the early calibration period in our record (1880–1940) the mean of the temperature data is −0.438, increasing to 0.230 for the later period (1941–68). In a comparison of the first eigenvector scores with the temperature data divided into subsets above and below the mean, a correlation of 0.571 was found with warmer than average temperatures, increasing to 0.597 with those below average.

The correlations between the Scandinavian/Russian chronologies and the temperature data, their loadings in the first principal component (Table II), and some improvement in the calibration-verification statistics (Table III) all indicate that the new reconstruction is significantly improved as a result of the added coverage. Examination of the regression coefficients in terms of the original predictors or chronologies (Table IV) indicates that the added chronologies are significantly weighted in the regression, lending further proof to an improvement as well as confirmation of the Jacoby and D'Arrigo (1989) version.

A frequently raised question is whether recent increases in tree growth are due to CO_2 fertilization. We constantly check for this possibility by examining the residual variance in the tree-ring data after the regressions. In the data from these high-latitude, temperature-stressed trees, the variations of the residuals after modeling with temperature do not have any trend that suggests a CO_2 fertilization effect through 1968, or in the earlier study (Jacoby and D'Arrigo, 1989) through 1973. These findings obviously do not preclude a CO_2 effect in other trees from other locations.

We are in the process of updating our sample collections and processing them through the late 1980's and 1990's. Eleven of the twenty chronologies used here to reconstruct Arctic temperatures extend through at least 1982. The first principal component scores of these eleven time series indicate that the trees began to recover from the mid-century's cooling of high northern latitudes by the early 1980's (Figure 5). Of these eleven chronologies, three which extend through at least 1988 (Arrigetch, Gaspe and Saltwater Pond) continue to reflect some warmth over the past decade. In addition to warming trends detected in surface air temperatures from high northern latitudes (Hansen and Lebedeff, 1987), borehole temperature studies support surface warming over the past century across northern North America, including warmings of 2–4 °C at the permafrost surface in northern Alaska (Lachenbruch and Marshall, 1986), and of 1–2 °C for ground surface temperatures in central-eastern Canada (Jessop *et al.*, 1991).

Conclusions

An improved reconstruction of temperature variability for the Arctic has been presented, based on a tree-ring data set with significantly improved geographical coverage as compared to a previous study (Jacoby and D'Arrigo, 1989). It is encouraging that, with the inclusion of 8 chronologies from the climatically-sensitive

TABLE IV: Regression (beta) coefficients in terms of original screened predictors. Results are based on regression model output developed for eigenvector one only, which is the dominant mode of variation in the final reconstruction. The original chronologies were lagged for years t and $t + 1$. Two chronologies, Cape and Fort Chimo, did not exceed the 95% confidence limit and were not entered into this temperature regression model for eigenvector one. Starred beta values exceed two standard errors from zero. As can be seen, the Scandinavian and Russian chronologies do in fact contribute significantly, and thus improve upon, the original models based on only North American tree data

Site	Lag yr	Beta	STD ERR
North American Chronologies			
FourTwelve	t	0.0337*	0.0008
FourTwelve	$t + 1$	0.0335*	0.0008
Arrigetch	t	0.0278*	0.0005
Arrigetch	$t + 1$	0.0282*	0.0005
Sheenjek	t	0.0235*	0.0004
Sheenjek	$t + 1$	0.0224*	0.0003
TT-HH	t	0.0379*	0.0010
TT-HH	$t + 1$	0.0388*	0.0010
Mack Mt.	t	0.0322*	0.0007
Mack Mt.	$t + 1$	0.0326*	0.0007
Coppermine	t	0.0314*	0.0007
Coppermine	$t + 1$	0.0315*	0.0007
Hornby	t	0.0152*	0.0002
Hornby	$t + 1$	0.0136*	0.0001
Churchill	t	0.0310*	0.0007
Churchill	$t + 1$	0.0334*	0.0008
Gaspe	t	0.0328*	0.0007
Gaspe	$t + 1$	0.0323*	0.0007
S. W. Pond	t	0.0256*	0.0005
S. W. Pond	$t + 1$	0.0274*	0.0005
Scandinavian Chronologies			
Lofoten	t	0.0181*	0.0002
Lofoten	$t + 1$	0.0142*	0.0001
Pyhat.	t	0.0280*	0.0005
Pyhat.	$t + 1$	0.0278*	0.0005
Sompio	t	0.0297*	0.0006
Sompio	$t + 1$	0.0302*	0.0006
Mogram.	t	0.0316*	0.0007
Mogram.	$t + 1$	0.0314*	0.0007
Suojan.	t	0.0319*	0.0007
Suojan.	$t + 1$	0.0312*	0.0007
Russian Chronologies			
Urals 6–8	t	0.0235*	0.0004
Urals 6–8	$t + 1$	0.0240*	0.0004
Urals 9–10	t	0.0177*	0.0002
Urals 9–10	$t = 1$	0.0200*	0.0003
Polar Urals	t	0.0246*	0.0004
Polar Urals	$t + 1$	0.0239*	0.0004

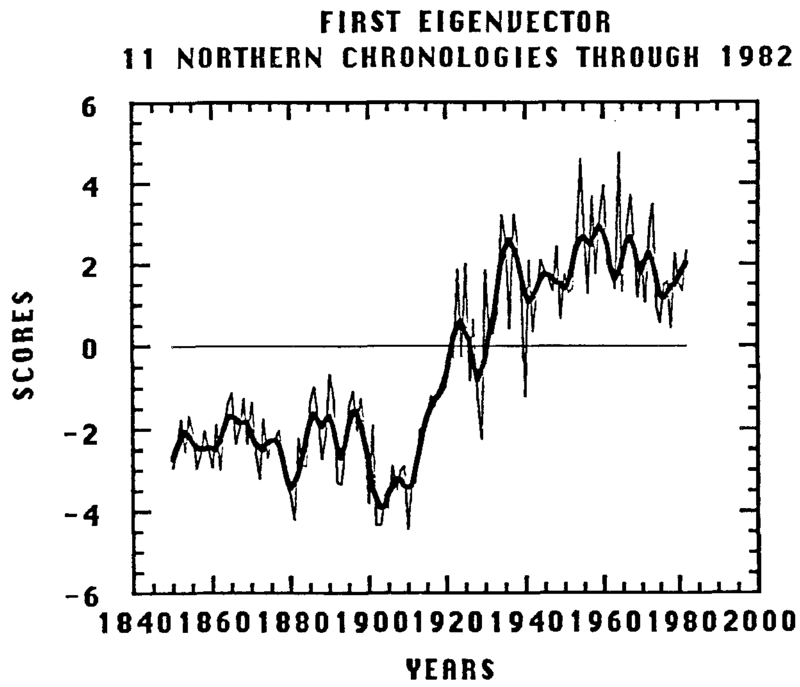

Fig. 5. First eigenvector of eleven chronologies used in Arctic reconstruction which extend through at least 1982 (shown here since 1850). These include: Arrigetch, Mack. Mt., Hornby, Churchill, Cape, Gaspe, S. W. Pond, Suojanpera, Morgammaras, Sompio and Pyhatunturi. The PCA period is 1880–1982.

areas of northern Scandinavia and Russia, the resulting trends are similar to those obtained using only the North American chronologies. We further note that there are striking similarities between our reconstructed trends and those reconstructed, inferred or developed for some other locales [e.g. for British Columbia (Luckman, 1989) and China (Zhang De-er, 1980)].

The warming of the Arctic and Northern Hemisphere since about 1965 is considered to be more spatially pervasive hemispherically than the earlier 20th century warming but with large spatial variations within latitude bands (Hansen and Lebedeff, 1987; Jones, 1988). The greatest recent warming has occurred in Alaska and the marginal ice zone from the Greenland Sea through north central Asia, with some cooling in Scandinavia and northeastern Canada. The overall secular trend of Arctic temperatures, considering both the reconstructions and zonally-averaged recorded temperature data, is a warmer period relative to the past three centuries. This trend may be partly ascribed to recovery from the Little Ice Age but also to a recent increase above that level. In future reconstruction efforts, there will be continued improvements in spatial coverage and the period of record will be updated through the late 1980's to early 1990's.

Acknowledgements

We thank K. Hunkins and D. Kent and anonymous reviewers for reviewing the manuscript and E. R. Cook for advice and technical assistance. We also thank J. Hansen and S. Lebedeff for use of their temperature data, and K. Briffa, H. Fritts, D. Graybill, S. Shiyatov and P. Scott for providing tree-ring data. This research was supported by Grants ATM89-15353, ATM87-16630, ATM85-15290 and ATM83-13789 of the Climate Dynamics Program of the National Science Foundation. The Saltwater Pond chronology was developed under Grant DPP-88-00749, Division of Polar Programs of the National Science Foundation. Lamont-Doherty Earth Observatory Contribution No. 5084.

References

Briffa, K. R., and Schweingruber, F. H.: 1992, 'Dendroclimatic Evidence of Northern and Central European Summer Temperatures', in Bradley, R. S. and Jones, P. D. (eds), *Climate since A.D. 1500*, Unwin Hyman, London & Boston.

Briffa, K. R., Jones, P. D., Pilcher, J. R., and Hughes, M. K.: 1988, 'Reconstructing Summer Temperatures in Northern Fennoscandinavia Back to A.D. 1700 Using Tree-Ring Data from Scots Pine', *Arctic Alpine Res.* **20**, 385–94.

Briffa, K. R., Bartholin, T. S., Eckstein, D., Jones, P. D., Karlen, W., Schweingruber, F. H., and Zetterberg, P.: 1990, 'A 1400-Year Tree-Ring Record of Summer Temperatures in Fennoscandia', *Nature* **346**, 434–39.

Briffa, K. R., Jones, P. D., Bartholin, T. S., Eckstein, D., Schweingruber, F. H., Karlen, W., Zetterberg, P., and Eronen, M.: 1992, 'Fennoscandian Summers from A.D. 500: Temperature Changes on Short and Long Time Scales', *Clim. Dynam.* **7**, 111–119.

Bryson, R. A.: 1966, 'Air Masses, Streamlines and the Boreal Forest', *Geogr. Bull.* **8**, 228–269.

Cook, E. R.: 1985, *A Time Series Analysis Approach to Tree-Ring Standardization*, Ph.D. thesis, Univ. of Arizona, Tucson.

Cook, E. R. and Peters, K.: 1981, 'The Smoothing Spline: A New Approach to Standardizing Forest Interior Ring-Width Series for Dendroclimatic Studies', *Tree-Ring Bull.* **41**, 45–53.

Fritts, H. C.: 1976, *Tree Rings and Climate*, Academic Press, N.Y.

Fritts, H. C., Guoit, J., Gordon, G. A., and Schweingruber, F.: 1990, in Cook, E. R. and Kairiukstis, L. A. (eds.), *Methods of Dendrochronology, Applications in the Environmental Sciences*, Kluwer Acad. Publ., Dordrecht, Chapter 4, pp. 163–217.

Garfinkel, H. L. and Brubaker, L. B.: 1980, 'Modern Climate-Tree Growth Relationships and Climatic Reconstruction in Sub-Arctic Alaska', *Nature* **286**, 872–874.

Giddings, J. L.: 1943, 'Some Climatic Aspects of Tree Growth in Alaska', *Tree-Ring Bull.* **4**, 26–32.

Gordon, G. A. and Leduc, S. K.: 1981, 'Verification Statistics for Regression Models', *Proc. Conf. on Probability and Statistics in Atmospheric Science*, Nov. 1981, Monterey, CA, pp. 129–33.

Graybill, D. A. and Shiyatov, S. G.: 1992, 'Dendroclimatic Evidence from the Northern Soviet Union', in Bradley, R. S. and Jones, P. D. (eds.), *Climate since A.D. 1500*, Routledge, New York.

Hansen, J. and Lebedeff, S.: 1987, 'Global Trends of Measured Surface Air Temperature', *J. Geophys. Res.* **92**, 345–372.

Hansen, J. and Lebedeff, S.: 1988, 'Global Surface Air Temperatures: Update through 1987', *Geophys. Res. Lett.* **15**, 323–326.

Hustich, I.: 1956, 'Correlation of Tree-Ring Chronologies of Alaska, Labrador and Northern Europe', *Acta Geograph.* **15**, 3–26.

Jacoby, G. C. and D'Arrigo, R.: 1989, 'Reconstructed Northern Hemisphere Annual Temperature Since 1671 Based on High-Latitude Tree-Ring Data from North America', *Clim. Change* **14**, 39–59.

Jacoby, G. C. and D'Arrigo, R. D.: 1991, 'Global Change and Thermal History as Recorded by Northern North American Tree-Ring Data', in Weller, G., Wilson, C. L., and Severin, B. A. B.

(eds.), *Proceedings of the Int'l Conferences on the Role of the Polar Regions in Global Change*, June 11–15, 1990, Univ. Alaska at Fairbanks, pp. 599–605.

Jacoby, G. C. and Cook, E. R.: 1981, 'Past Temperature Variations as Inferred from a 400-Year Tree-Ring Chronology from Yukon Territory, Canada', *Arctic Alpine Res.* **13**, 409–418.

Jacoby, G. C. and Ulan, L. D.: 1982, 'Reconstruction of Past Ice Conditions in a Hudson Bay Estuary Using Tree-Rings', *Nature* **298**, 637–639.

Jacoby, G. C., Cook, E. R., and Ulan, L. D.: 1985, 'Reconstructed Summer Degree Days in Central Alaska and Northwestern Canada Since 1524', *Quat. Res.* **23**, 18–26.

Jessop, A. M., Beltrami, H., and Mareschal, J. C.: 1991, 'Recent Warming in Eastern and Central Canada Inferred from Borehole Temperature Measurements', *Proceedings American Geophysical Union Fall Meeting*, Dec. 1991, San Francisco.

Jones, P. D.: 1988, 'Hemispheric Surface Air Temperature Variations: Recent Trends and an Update to 1987', *J. Clim.* **1**, 654–660.

Jones, P. D. and Bradley, R. S.: 1992, 'Climatic Variations in the Longest Instrumental Records', in Bradley, R. S. and Jones, P. D. (eds.), *Climate since A.D. 1500*, Routledge, New York, pp. 246–268.

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

Kelly, P. M., Jones, P. D., Sear, C. B., Cherry, B. S. G., and Tavakol, R. K.: 1982, 'Variations in Surface Air Temperatures: Part 2, Arctic Regions, 1881–1980', *Mon. Wea. Rev.* **110**, 71–83.

Kramer, P. J. and Kozlowski, T. T.: 1979, *Physiology of Woody Plants*, Academic Press, Orlando, FL, 811 pp.

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

Lachenbruch, A. H. and Marshall, B. V.: 1986, 'Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic', *Science* **234**, 689–696.

Luckman, B. H.: 1989, 'Global Change and the Record of the Past', *Geos* **18**, 1–8.

Payette, S., Filion, L., Gauthier, L., and Boutin, Y.: 1985, 'Secular Climate Change in Old-Growth Tree-Line Vegetation of Northern Quebec', *Nature* **315**, 135–138.

Scott, P. A., Fayle, D. C. F., Bentley, C. V., and Hansell, R. I. C.: 1988, 'Large-Scale Change in Atmospheric Circulation Interpreted from Patterns of Tree Growth at Churchill, Manitoba, Canada', *Arctic Alpine Res.* **20**, 199–211.

Shiyatov, S. G.: 1986, *Dendrochronology of the Upper Forest Boundary in the Urals*, Nauka, Moscow (in Russian).

Shiyatov, S. G., Fritts, H. C., and Lofgren, R. G.: 1989, 'Comparative Analysis of the Standardization Methods of Tree-Ring Chronologies', in Nobel, R. D., Martin, J. L., and Jensen, K. F. (eds.), *Air Pollution Effects on Vegetation Including Forest Ecosystems*, pp. 13–25, Proceedings of the Second U.S.-U.S.S.R. Symposium, U.S. Dept. of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Tranquillini, W.: 1979, *Physiological Ecology of the Alpine Timberline*, Springer-Verlag, New York.

Walsh, J. E. and Chapman, W. L.: 1990, 'Short-Term Climatic Variability of the Arctic', *J. Clim.* **3**, 237–250.

Zhang, D.: 1980, 'Winter Temperature Variation during the Last 500 Yrs in Southern China', *Kexue Tongbao* **25**, 497–500.

(Received 3 January, 1992; in revised form 1 June, 1993)