Reconstruction of Summer Temperature for a Canadian High Arctic Site from Retrospective Analysis of the Dwarf Shrub, Cassiope tetragona

Authors: Rayback, Shelly A., and Henry, Gregory H. R.

Source: Arctic, Antarctic, and Alpine Research, 38(2) : 228-238

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2006)38[228:ROSTFA]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 38, No. 2, 2006, pp. 228–238

Reconstruction of Summer Temperature for a Canadian High Arctic Site from Retrospective Analysis of the Dwarf Shrub, *Cassiope tetragona*

Shelly A. Rayback† and*
Gregory H. R. Henry‡*

*Department of Geography, 1984 West Mall, University of British Columbia, Vancouver, BC, V6T 1Z2, Canada.
†Present address: Department of Geography, Old Mill Building #213, 94 University Place, University of Vermont, Burlington, VT 05405-0114, U.S.A.
srayback@uvm.edu
‡ghenry@geog.ubc.ca

Abstract

We used retrospective analysis of the widespread evergreen dwarf-shrub, *Cassiope tetragona*, to reconstruct average summer air temperature for Alexandra Fiord, Ellesmere Island, Canada. Retrospective analysis is a technique based on dendrochronological methods. In this study, chronologies are based on the morphological characteristics of the plant stems. Two growth and two reproduction chronologies, ranging from 80 to 118 years long, were developed from each of two populations at the High Arctic site. We used multiple regression models to develop a 100-year-long (1895–1994) reconstruction of July–September average air temperature that explained 45% of the climatic variance in the instrumental record. The reconstruction revealed an increase in summer temperature from ~1905 to the early 1960s, a cooling trend from the mid-1960 to the 1970s, and an increase in temperature after 1980. These historical temperature patterns correspond well with those from other climate proxies from sites on Ellesmere and Devon Islands. As well, the similarity between our model and an arctic-wide proxy temperature time series suggests that the *Cassiope*-based reconstruction contains a large-scale temperature signal. There is great potential for the development of proxy climate data using *Cassiope tetragona* from sites throughout the Arctic.

Introduction

High-resolution paleoclimatic records provide the necessary perspective to understand past climate variability and whether recent climatic observations are unusual within the context of long-term change. The need for proxy climate records from arctic sites is particularly pressing in light of the present discussion of the origins and mechanisms of current global climate change (IPCC, 2001; ACIA, 2004). General Circulation Models forecast the greatest temperature changes will occur in the Arctic within the next 100 yr (+4.0 – 7.5°C in summer; +2.5 – 14.0°C in winter) (IPCC, 2001; ACIA, 2004). The direct and indirect impacts of changing climate on arctic ecosystems, as well as the cascading effects on ecosystems and climate patterns at lower latitudes may be substantial (IPCC, 2001). However, our current understanding of past climate variability in the Arctic and the key role the high northern latitudes play in the global climate system remains incomplete.

In the Canadian High Arctic, weather stations (HAWS) operated by the Meteorological Service of Canada are few and widely scattered. Of the three fully operational HAWS, two are located on Ellesmere Island: one at Eureka (79°59′N, 85°59′W; 10 m a.s.l.) and the other at Alert (82°30′N, 62°20′W; 62 m a.s.l.). As the topography of Ellesmere Island is characterized by high mountain ranges, ice sheets, glaciers, and fiords, the climatic conditions at the HAWS are not representative of all sites on the island. As well, the short length of the HAWS meteorological records (late 1940s to present) limits investigations of climate variability over time spans equal to or longer than the record (Hardy and Bradley, 1997).

Fortunately, there are a good number of climate proxies developed from sites on Ellesmere Island and in the eastern Canadian Arctic. Available proxies include ice core records, and freshwater diatoms, pollen, and laminated sediments from lake sediment cores. Unfortunately, some of the proxies are spatially limited, which can present problems when climatic information is derived from one region and extrapolated over much larger and geographically diverse areas (Jones and Kelly, 1983). In addition, some proxies are temporally limited and until now, only ice cores and laminated lake sediments provided long-duration and high-resolution proxies for sites in the High Arctic. Finally, none of these proxy records are based directly on terrestrial components of arctic ecosystems.

In this study, we reconstruct past climate for a site in the Canadian High Arctic through retrospective analysis of the growth and reproduction in the evergreen dwarf-shrub, *Cassiope tetragona*. Retrospective analysis is based on the principles of dendrochronology, i.e., the study of the patterns of annual tree-ring widths (Fritts, 1976). Yet unlike tree-ring studies, *C. tetragona* chronologies are based on the morphological characteristics of the plant stems (Rayback and Henry, 2005). In previous studies that examined the response of *C. tetragona* to climate variables, the species' annual growth and reproduction responded positively to ambient growing season temperatures (May–September) (Callaghan et al., 1989; Havström et al., 1995; Johnstone and Henry, 1997). Unfortunately, the chronologies used in prior studies were neither cross-dated (a pattern matching technique), nor were they standardized when used to reconstruct past climate (Callaghan et al., 1989; Havström et al., 1993, 1995; Aanes et al., 2002). Furthermore, prior attempts at climate reconstruction were based on short chronologies of <36 yr, and the calibration and verification of climate models were not carried out (Havström et al., 1995; Johnstone and Henry, 1997). Our recent work suggests chronologies of 100+ yr can be reconstructed from live stems. Such chronologies, covering the late 19th and 20th centuries, are of particular interest given the range of climate conditions experienced in the Arctic since the end of the Little Ice Age (c. 1850) (Overpeck et al., 1997).

The main objectives of our study were: (1) to reconstruct summer climate conditions at Alexandra Fiord, Ellesmere Island, over the past 100+ yr; (2) to investigate the growth/reproduction–climate relationship; (3) to examine high- and medium-frequency variability in the climatic reconstruction; and (4) to compare our reconstruction to other climate proxies and instrumental data from the Canadian High Arctic.

1523-0430/06 $7.00

Methods

CASSIOPE TETRAGONA

Cassiope tetragona (L.) D. Don (Ericaceae) is a long-lived, evergreen, dwarf-shrub with a circumarctic distribution (Hultén, 1968), and is an important component of low shrub-heath, dwarf shrub-heath, and mixed heath communities (Bliss and Matveyeva, 1992). The species initially grows monopodially with upright stems (~10 cm). Later, the plant may develop into a loose prostrate mat of stems that radiates outward from a central root mass and can grow to cover an area of ~1 m^2 (Crawford, 1989; Havström et al., 1993). The plant may form clones when trailing stems produce adventitious shoots that later disintegrate, resulting in physically separate, but genetically identical individuals (Havström, 1995). Along each stem, two alternating sets of opposite leaves are produced, forming four distinct rows (Johnstone and Henry, 1997). Johnstone and Henry (1997) found the pattern in the positioning of leaf node scars in adjacent leaf rows was analogous to the wave-like pattern in leaf-lengths first described by Warming (1908), and later used by Callaghan et al. (1989) and Havström et al. (1993, 1995) to identify and date individual annual growth increments and to develop short chronologies (26 yr). As leaf scars remain visible along the length of a shoot for long time periods, Johnstone and Henry (1997) used the pattern to identify, measure, and date annual growth increments and to generate longer chronologies (26–36 yr).

STUDY AREA

Alexandra Fiord (78°53′N, 75°55′W) lies on the east coast of central Ellesmere Island (Figs. 1A, 1B). The lowland is a post-glacial outwash plain bound by upland plateaus (500–700 m a.s.l.), Twin Glacier, and the coastline of Alexandra Fiord. Closed to semi-closed vegetation occurs over 90% of the Alexandra Fiord lowland (Muc et al., 1989). Heath communities dominated by *C. tetragona* and *Dryas integrifolia* cover >50% of the area, occupying habitats such as fellfields, well-drained heath tundra, and snowbeds (Muc et al., 1989). The mean growing season (June–August) air temperature in the lowland is 3.2°C (mean annual temperature, –15.2°C), with summer precipitation of 10–60 mm (annual precipitation, 100–200 mm) (Labine, 1994; C. Labine, unpublished data). Further information on the climate of Alexandra Fiord is available in Labine (1994).

INSTRUMENTAL CLIMATE DATA

We used instrumental climate data from the Eureka HAWS located on the west coast of Ellesmere Island, 250 km northwest of Alexandra Fiord (Fig. 1B) (Meteorological Society of Canada, 1948–1998). Climate data have been recorded continuously at the station since May 1947. While the Eureka HAWS and Alexandra Fiord are not grouped into the same climate region (Maxwell, 1981), climate variables (e.g., air temperature, incoming shortwave, net radiation) recorded during the growing season correlated more strongly between Alexandra Fiord and the Eureka HAWS than with the HAWS at Alert, Ellesmere Island (Labine, 1994). The Eureka HAWS has the warmest summer climate conditions of any of the HAWS, making it a good counterpart to the thermal oasis of Alexandra Fiord (Maxwell, 1981; Edlund and Alt, 1989; Labine, 1994).

CHRONOLOGY DEVELOPMENT

In July 1998, we collected *C. tetragona* plants at two sites at Alexandra Fiord (hereafter referred to as Lowland [30 m. a.s.l.] and Bench [150 m. a.s.l.]) (Fig. 1C). Twelve to fifteen plants were collected from a visually homogenous area at each site and chosen for the longest stems possible. The plants were air-dried for a week and then stored.

In the laboratory, we selected five to nine stems per plant for measurement. We chose stems for their length and, when possible, for live green leaf buds and leaves at the tip of the shoot. Stems were straightened by placing them in a lukewarm bath for 15 min, and then they were inserted into 1-cm-diameter glass tubes to dry. We removed two adjacent rows of leaves along each stem by hand, being careful to leave in place any flower buds or flower peduncles.

Under a dissecting microscope (10× to 30× magnification), we measured the internode distances between leaf scars using a manually operated caliper system (designed by J. Svoboda, University of Toronto). The internode lengths were measured from the base to the tip of the shoot. We identified the annual growth increments (AGIs) by the wave-like patterns in internode lengths, with the terminus of annual growth delimited by the shortest internode length at the end of each wave-series (Johnstone and Henry, 1997). Annual production of leaves, flower buds, and flower peduncles were calculated by counting the total number of each variable found within the AGI.

Measurement series were visually cross-dated, a pattern matching technique which is used to assign calendar year dates to each AGI (Stokes and Smiley, 1968). We verified the visual cross dating by statistically comparing measured segments with the full chronology (COFECHA; Dendrochronology Program Library) (Holmes et al., 1986). Two to nine stems per plant were cross-dated, and 12 to 15 plants were used to create site chronologies. We also constructed chronologies for the annual production of leaves, flower buds, and flower peduncles, based on the number of variables per AGI.

We standardized all *C. tetragona* measured series using dendrochronological methods (Fritts, 1976; Cook and Briffa, 1990). Inspection of the individual series revealed a juvenile growth trend in which shorter AGIs characterized the first years of shoot elongation. In addition, because *C. tetragona* plants at Alexandra Fiord do not reproduce until ~10–15 years of age, we hypothesized that reproduction may also be influenced by a juvenile growth trend. To minimize the juvenile effect on growth and reproduction, all stem series were standardized and all flower bud and flower peduncle chronologies were truncated to begin at the first year of bud formation or flower production. The sample depth for all Lowland and Bench chronologies ranged from a minimum of 3 to 17 stems for the period of 1895–1915, to a maximum sample depth of 64 (Bench) and 76 (Lowland) stems later in the chronologies.

Based on the signal-to-noise ratio (SNR) and *a priori* information regarding the plant's growth and reproductive characteristics, chronologies for each site were standardized using flexible cubic splines (ARSTAN; Dendrochronology Program Library) (Wigley et al., 1984; Cook, 1985; Cook and Briffa, 1990). In our study, a smoothing spline was needed to maximize the inter-stem correlation without losing the climate signal entirely. Relatively small changes within the plant's architecture (e.g., inter-shoot shading, resource partitioning, apical dominance) (Johnstone and Henry 1997) could have as great an effect on plant growth as climate over the lifetime of the plant. Thus, intraplant effects had to be filtered as much as possible. We selected 20-year cubic splines for the growth chronologies, and 60- and 70-year cubic splines for the flower peduncle and flower bud chronologies, respectively. Following standardization, the annual indices from the individual stems were averaged using a biweight robust mean to produce master chronologies for each site (Cook and Briffa, 1990). In order to maintain what remained of the low frequency signal in the site chronologies, we retained the standardized chronologies for analysis.

CORRELATIONS AND RESPONSE FUNCTIONS

We investigated climate-growth and climate-reproduction relationships through correlation and response function analysis

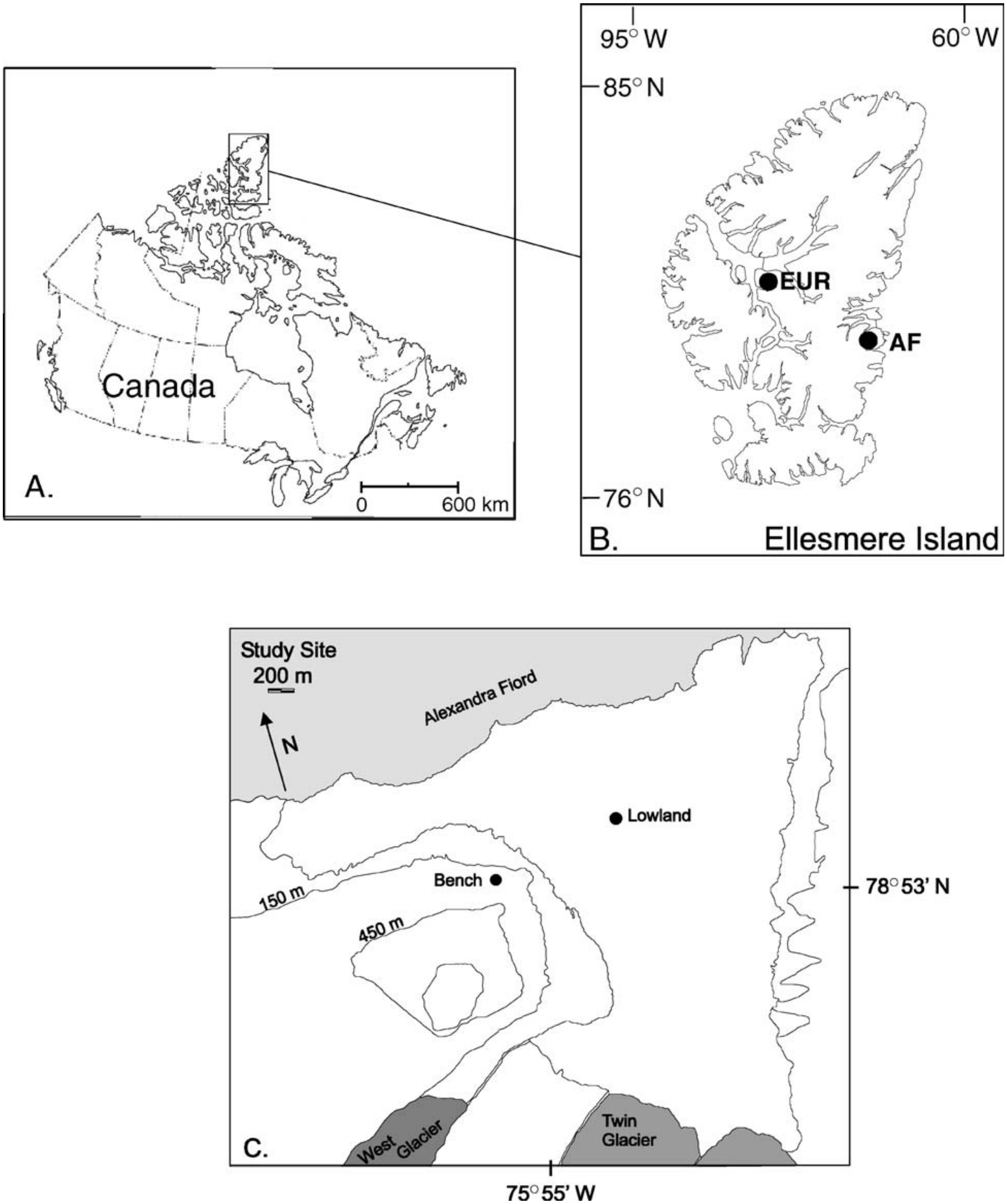

FIGURE 1. (A, B) Canada (Natural Resources Canada, 2005) and Ellesmere Island with the locations of Alexandra Fiord (AF) and the Eureka High Arctic Weather Station (EUR). (C) Alexandra Fiord and the locations of the Lowland and Bench sampling sites.

(PRECONK, v. 5.11; Fritts, 1999). In PRECONK, a response function analysis is run by regressing principal components of temperature and previous growth (reproduction) on the annual growth (reproduction) indices. We calculated correlation and response function coefficients between the Alexandra Fiord growth and reproduction chronologies and average monthly air temperature from the Eureka HAWS for the common period of 1948–1996. Correlation and response function coefficients were calculated for a 17-month period (previous May to current September) and 2 yr of previous growth (reproduction) were included in the models to account for lag effects.

TRANSFER FUNCTIONS

Following investigation of the correlation and response function coefficients, transfer function models predicting average summer air temperature from *C. tetragona* growth and reproduction indices were

TABLE 1

Non-standardized and standardized summary statistics of annual *Cassiope tetragona* plant performance from the Lowland and Bench sampling sites at Alexandra Fiord, Ellesmere Island. AGI = annual growth increment; Leaf = number of leaves; Bud = number of flower buds; Ped = number of flower peduncles.

	Lowland				Bench			
	AGI[a]	Leaf[b]	Bud[c]	Ped[c]	AGI[a]	Leaf[b]	Bud[c]	Ped[c]
(a) Non-standardized								
Chronology Length	1879–1996	1879–1996	1900–1996	1917–1996	1884–1996	1884–1996	1894–1996	1904–1996
Number of Years	118	118	97	80	113	113	103	93
Sample Size (plants)	15	15	15	15	13	13	13	12
# of Stems Measured	86	86	85	74	79	79	74	59
Mean	4.76	10.16	0.42	0.35	3.95	8.78	0.48	0.25
Standard Deviation	2.06	2.86	0.65	0.60	1.45	2.26	0.66	0.51
(b) Standardized								
Mean	0.98	0.99	0.75	0.82	0.99	0.99	0.60	0.56
Standard Deviation	0.11	0.08	0.39	0.41	0.09	0.06	0.67	0.58
Signal-to-Noise Ratio	0.14	0.11	0.07	0.35	0.66	0.37	0.11	0.20
Mean Sensitivity	0.12	0.08	0.57	0.63	0.09	0.07	0.80	0.81
Auto-correlation	−0.29	−0.28	0.27	0.02	−0.26	−0.18	0.39	0.22

[a] Annual growth increment estimates are measured in mm yr^{-1}.

[b] Annual leaf production estimates are for four leaf rows on a stem.

[c] Estimates for annual production of flower buds and peduncles are for 2 of 4 leaf rows on a stem.

Number of Stems per Plant: Lowland, 2–8 stems; Bench, 4–9 stems.

calibrated using stepwise multiple linear regression analysis (MGLH procedure; SYSTAT, v. 5.0, 1990–1992). We calibrated preliminary models predicting temperature for individual months of the growing season (May through September), and for different combinations of months (e.g., June–September) (Case and MacDonald, 1995). We included growth and reproduction indices from the two sites as potential predictors in the transfer function analyses. Both forward ($t+1$, $t+2$) and backward ($t-1$) lagged indices were added to capture persistence effects in the growth-reproduction-climate relationships (Jacoby and D'Arrigo, 1989). Chronologies for the annual production of flower peduncles were not included in the transfer function analysis because of their shorter length.

To demonstrate the temporal stability of the empirically derived equation linking *C. tetragona* growth and reproduction to temperature, we used the traditional data-splitting method of Fritts (1976). We split the full data set into an "early" period (1948–1980) and a "late" period (1964–1996) and then calibrated transfer functions for each period using stepwise regression. The calibration models developed for the "early" and "late" periods were then verified over the remaining one-third of the data set, 1981–1994 and 1948–1963, respectively. Verification statistics included Pearson's product-moment correlation coefficient (r), reduction of error statistic (RE), the coefficient of efficiency (CE), and the nonparametric sign test of first differences (Fritts, 1976; Briffa et al., 1988).

Results

CHRONOLOGY CHARACTERISTICS

The Lowland growth chronologies are the longest *C. tetragona* chronologies (1879–1996) yet developed for the Arctic (Table 1a). The growth chronologies from both sites were characterized by low SNR, mean sensitivity, standard deviation and first-order autocorrelation values (Table 1b). In contrast, the reproductive chronologies showed high mean sensitivity and standard deviation values, but low SNR and first-order autocorrelation (Table 1b).

GROWTH/REPRODUCTION–CLIMATE RELATIONSHIP

While many of the correlation and response function coefficients were not significantly different from zero ($P > 0.05$), the majority of the coefficients were positively associated with air temperature during the growing season months (May–September) (Figs. 2A, 2B). The Lowland growth variables were positively correlated ($P < 0.05$) with June average air temperature. At the Bench site, growth variables were significantly correlated with June (AGI) and September (AGI, leaves) average air temperature. There was also a significant response function relationship between annual production of leaves and August temperature. Growing season temperature in June, July, and September was positively correlated with flower peduncle production at both sites. At the Lowland site, flower bud production was positively related to July and September temperature, while at the Bench site it was positively associated with May, June, and July temperature.

There were significant correlation and response function relationships between the Lowland and Bench variables and average air temperature during the winter months (October–April) as well (Figs. 2A, 2B). At the Bench site, the response function coefficients for growth were positively associated with previous October (AGI) and January (leaves) temperatures, but negatively associated with February (AGI, leaves) temperatures. In addition, there were negative response function relationships between annual production of flower buds and previous November (Lowland) and December (Bench) temperatures.

The transfer function model predicting July–September average air temperature provided the best results for the period of 1948–1994 (adjusted $R^2 = 0.45$) (Tables 2, 3). Early (1948–1980) and late (1964–1996) calibration models accounted for 39% and 46% of the variance (adjusted R^2) in the temperature record, respectively (Table 2). For the late (1981–1994) and early (1948–1963) verification periods, Pearson' product-moment correlation coefficients (r = 0.59; r = 0.50) were significant, indicating that the model is able to estimate values not contained in the calibration period. The positive CE (0.10; 0.09) and RE (0.12; 0.22) values indicate that the model has some predictive skill. Although the level of significance cannot be tested, positive RE and CE values are generally accepted as an indication of successful

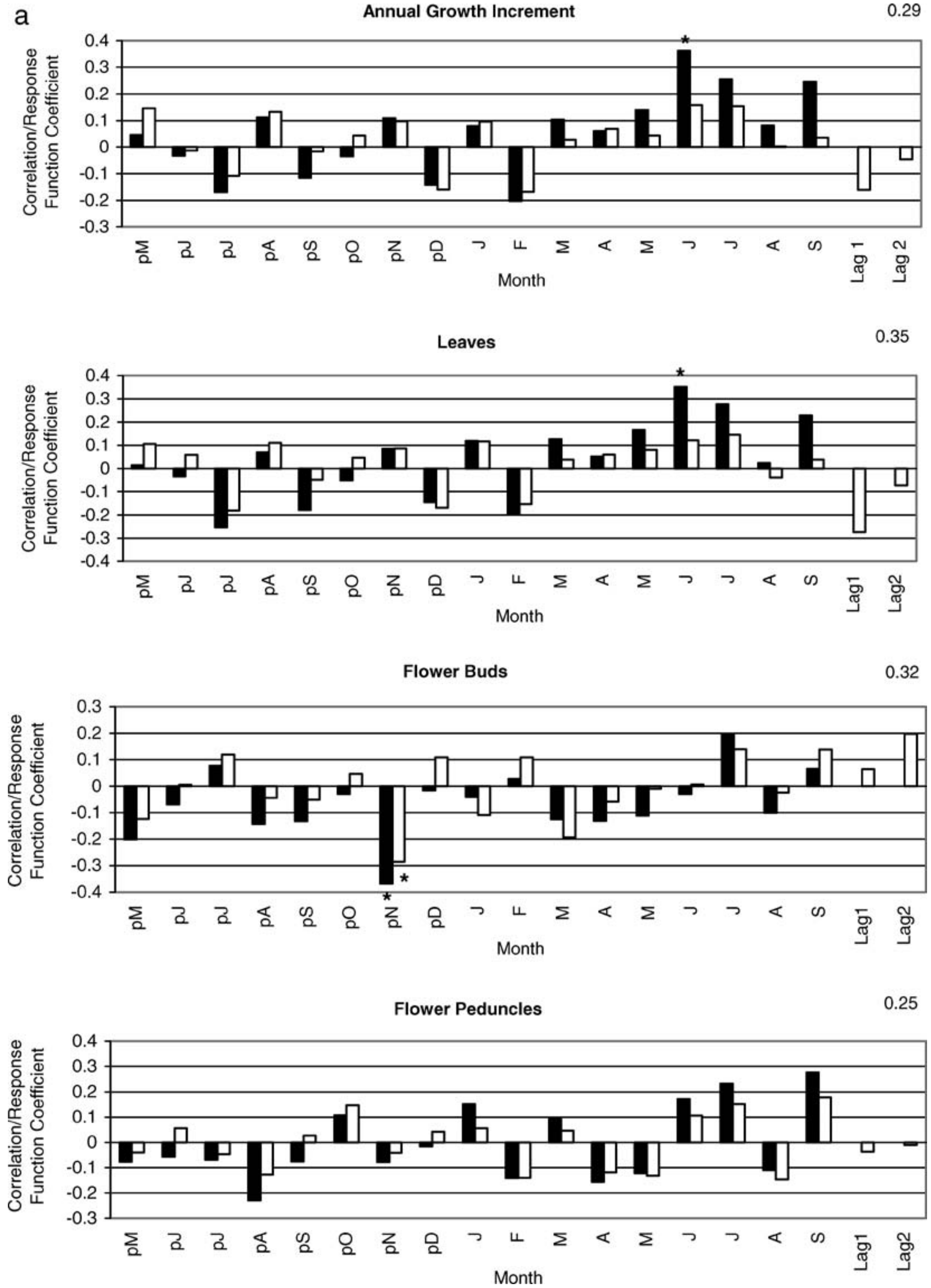

FIGURE 2. Response function and correlation coefficients for annual growth and reproduction chronologies and monthly temperature at the (A) Lowland and (B) Bench sites. Each pair of bars represents the correlation coefficient (solid bar) and the response function coefficient (hollow bar) for a given month. The time period covered begins in the previous May (pM) and continues to the current September (S). R^2 values (upper right) indicate the proportion of variance accounted for by the response function model, including temperature and prior growth. Lag 1 and Lag 2 are the 1 year and 2 year lag effects. *$P < 0.05$.

reconstruction of the climatic variable (Briffa et al., 1988). The sign tests for the verification periods were not significantly different from zero. Given that the early and late models passed three out of the four verification tests, the transfer function estimates of July–September average air temperature were considered time stable (Fritts, 1976; Fritts et al., 1979). Therefore, the full model calibrated over the 1948–1994 period was also considered time stable and was used to reconstruct summer air temperature. The full model met the assumptions of parametric statistics (Neter et al., 1996).

AVERAGE AIR TEMPERATURE RECONSTRUCTION

The 100-year-long reconstruction (1895–1994) of July–September average air temperature is the longest *C. tetragona*–based proxy

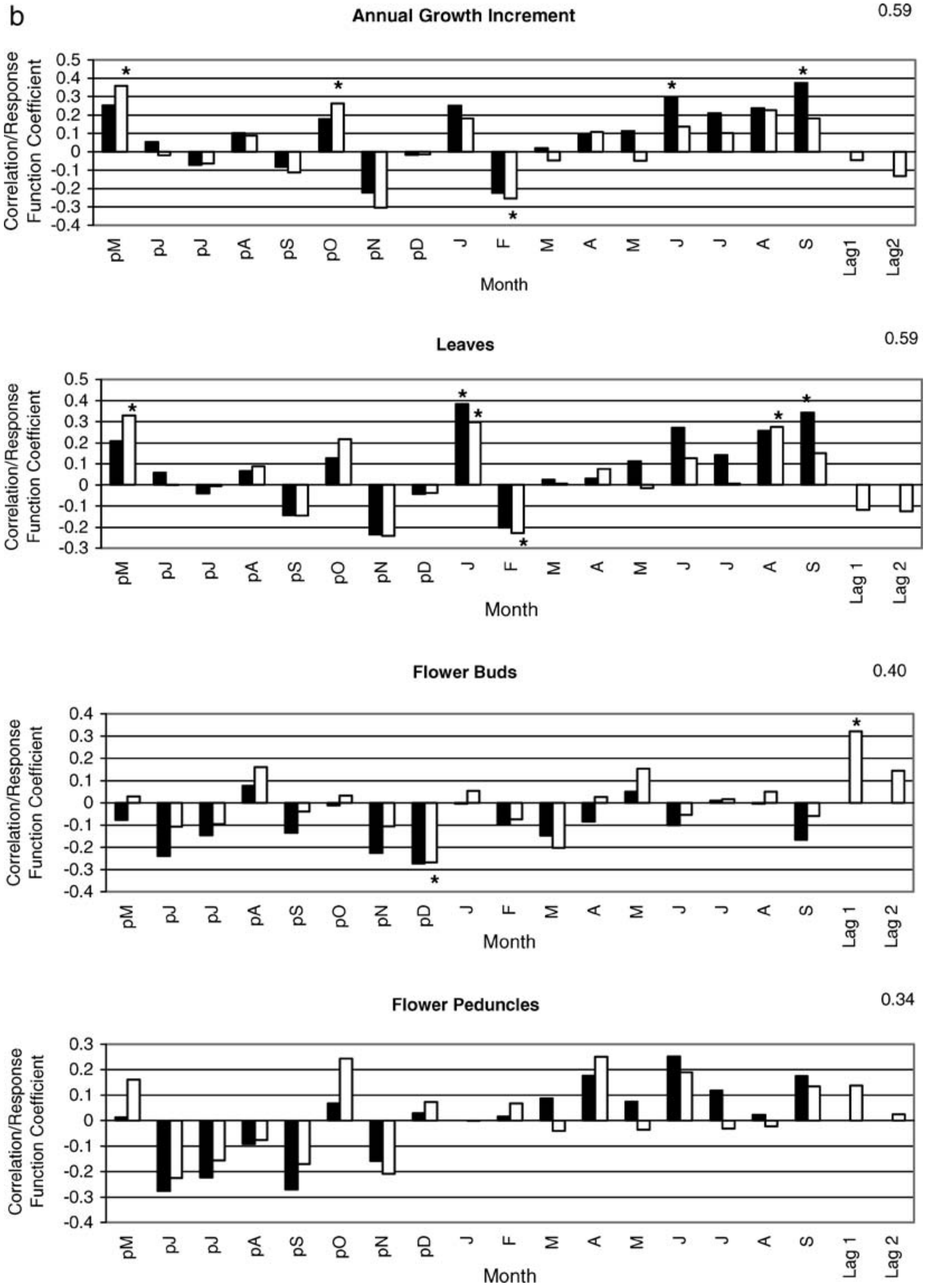

FIGURE 2. (Continued)

constructed for the Arctic (Fig. 3). The record was necessarily shortened by the shortest predictor chronology (Bench; number of flower buds, 1894–1996), and by lags and leads included in the full model. Overall, the reconstruction followed the observed data from the Eureka HAWS (1948–1994). However, the model underestimated the instrumentally recorded data in particularly warm or cold years (e.g., 1954, 1961, 1979, 1983), and occasionally smoothed over short periods of moderate inter-annual variability (e.g., 1971–1975). The first 15–20 yr of the air temperature model are characterized by high inter-annual variability (Fig. 3). Despite the early variability, the reconstruction revealed a sharp decrease in temperature at the turn of the century followed by an increase from ~1905–1910 to the early 1960s (Figs. 3, 4A). A cooling trend characterized the 1960s–1970s of the reconstruction until a shift occurred in the early 1980s when temperatures rose once again (Figs. 3, 4A).

Discussion

CHRONOLOGY CHARACTERISTICS

The mean and standard deviation values of the growth variables from both sites were similar to those reported in previous studies of

TABLE 2

Calibration and verification statistics for July–September average air temperature reconstruction. RE = reduction of error statistic (Fritts, 1976); CE = coefficient of efficiency (Briffa et al., 1988); Sign Test = nonparametric sign test of first differences (Fritts, 1976).

	Calibration							Verification					
Model	Period	n^a	X^b	x^c	R	R^2	R^2 adj	Period	n^a	r	RE	CE	Sign test
Early	1948–1980	33	24	6	0.71	0.51	0.39	1981–1994	14	0.59*	0.12	0.10	8/4 (hit/miss)
Late	1964–1994	31	24	5	0.74	0.55	0.46	1948–1963	16	0.50*	0.22	0.09	9/6 (hit/miss)
Full	1948–1994	47	24	7	0.73	0.53	0.45						

[a] Sample size.

[b] Initial number of candidate predictor variables in stepwise multiple regression.

[c] Final number of predictor variables retained in model.

* $P < 0.05$.

Cassiope tetragona at High Arctic sites (Nams and Freedman, 1987; Callaghan et al., 1989; Havström et al., 1993; 1995; Johnstone and Henry, 1997). In contrast, the mean number of flower peduncles produced per year at the Lowland and Bench sites was less (Havström et al., 1995; Johnstone and Henry, 1997). We hypothesize that potentially variable environmental conditions at Alexandra Fiord in the early 20th century may have suppressed flower bud development and flower production in mature plants and delayed it in juvenile ones. It is also possible that fragile flower buds and peduncles fell off the oldest stems. However, manually removed flower buds and peduncles normally leave visible and identifiable scars along the stem. The mean annual flower bud production values reported in our study are the first observations recorded for a period of greater than 1 yr (Nams, 1982).

The low SNR values for the growth and reproductive chronologies at both sites indicate a high amount of noise present in the chronologies. However, no other standardization method yielded higher SNR values. We hypothesize that the high level of intra- (not shown) and inter-plant variability is the result of the plant's architecture and associated microenvironmental conditions, within-plant resource partitioning (e.g., water, nutrients, photosynthates), and poorly understood community dynamics within arctic ecosystems (Rayback and Henry, 2005).

In general, high mean sensitivity and low first-order autocorrelation values for tree-ring series are indicative of high inter-annual variability and sensitivity to yearly climate conditions (Fritts and Shatz, 1975). Previous studies have shown that *C. tetragona* increases flower bud and peduncle production under short-term, favorable ambient growing season temperatures and under experimentally enhanced temperatures (Nams and Freedman, 1987; Johnstone, 1995; Johnstone and Henry, 1997). In contrast, *C. tetragona* exhibits a rather conservative growth response to short-term variations in growing season climate. The lower sensitivity may serve to stabilize the annual vegetative productivity of this species in the resource-poor arctic environment (Sørensen, 1941; Shaver and Kummerow, 1992). The mean sensitivity values were similar to those reported by Johnstone and Henry (1997). Low autocorrelation values indicate that *C. tetragona* growth is relatively uninfluenced by low-frequency climatic trends. However, standardization of the growth chronologies with flexible cubic splines may have removed more of the low-frequency climatic fluctuations than intended (Cook and Briffa, 1990).

TABLE 3

Regression equation details. Low = Lowland; Ben = Bench; AGI = annual growth increment for year *t*; AGI3 = annual growth increment for year $t - 1$; Leaf3 = number of leaves for year $t - 1$; Bud2 = number of flower buds for year $t + 2$; Bud3 = number of flower buds for year $t - 1$.

Predictor variables	Full model 1948–1994	Early calibration 1948–1980	Late calibration 1964–1994
Constant	−25.93**	−27.87**	−18.87**
Low AGI	6.60*	10.58*	5.50*
Low AGI3	−10.78	−21.72*	
Low Leaf3	26.55**	39.95**	9.04*
Low Bud2	−1.03**	−1.01*	
Ben AGI	4.72*		4.98*
Ben Bud2	0.66*	0.73	0.45
Ben Bud3	−0.73*	−0.66	−1.02**

* $P < 0.05$.

** $P < 0.01$.

GROWTH/REPRODUCTION-CLIMATE RELATIONSHIP

The positive influence of early growing season temperatures on the growth and the initiation of photosynthesis in *C. tetragona* and other arctic plants is well documented (Callaghan et al., 1989; Havström et al., 1995; Johnstone and Henry, 1997). In addition, warmer, early growing season temperatures initiate the elongation of flower peduncles and the subsequent formation of the flowers early in the summer (Nams, 1982; Johnstone, 1995). Flower buds are generally visible and swollen in the leaf axils by late June to mid-July (Nams, 1982; Johnstone, 1995). Temperature patterns at the end of the growing season may facilitate the translocation of nutrients in the plants for winter storage, as well as cue critical winter hardening that protects the plant tissues from injury due to intracellular freezing and desiccation (Chapin et al., 1980; Fritter and Hay, 2002). Warmer late summer temperatures also facilitate successful reproduction by allowing the further development of flower buds prior to over-wintering (Nams and Freedman, 1987; Johnstone, 1995). *Cassiope tetragona* pre-forms flower buds 1 yr prior to actual flowering (Sørensen, 1941). Lastly, data on the influence of winter temperature on arctic plants is scarce (Körner and Larcher, 1988). In this study, there were few significant correlation and response function coefficients for the winter months, and those coefficients that were significant may be the product of the arbitrary assignment of winter temperature into monthly increments that are not necessarily physiologically or ecologically based.

SUMMER TEMPERATURE RECONSTRUCTION

Interpretation of the first 15–20 yr of the summer temperature reconstruction is problematic. The high variability revealed in the early portion of the reconstruction may be a statistical artifact, the result of uncommon variance or noise increasing with decreasing sample size

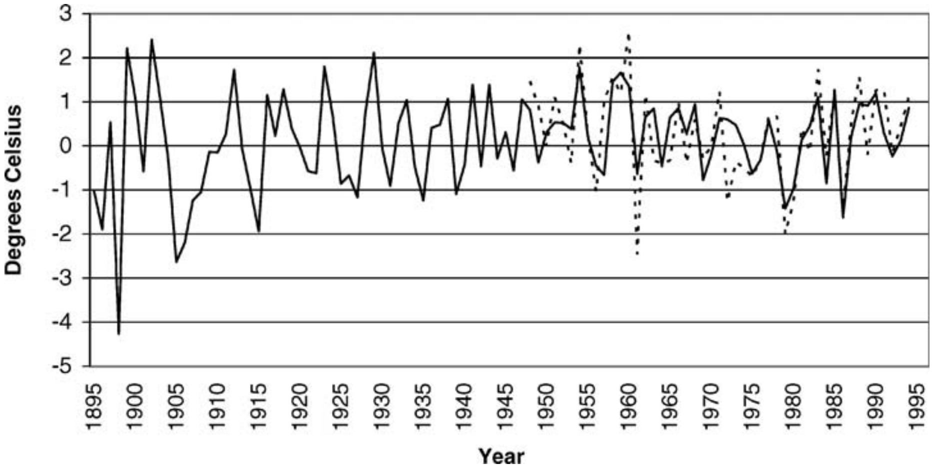

FIGURE 3. Observed (dotted line) and reconstructed (solid line) July–September average air temperature for Alexandra Fiord, Ellesmere Island. Reconstruction covers the period of 1895–1994.

early in the chronology (Fritts, 1976; Cook and Briffa, 1990). However, our reconstruction revealed a decrease in temperature at the turn of the century followed by an increase around 1905–1910. The temperature decline during this same period is also recognizable in the Arctic-wide, average summer air temperature series (Fig. 4B) (Overpeck et al., 1997), and as a decrease in lake varve thickness at Lake C2 and Lake C3, Ellesmere Island (Fig. 4C) (Lamoureux and Bradley, 1996; Lasca, 1997). Unfortunately, the short length of our model (100 yr) makes it impossible to determine how the decrease in temperature fits into the overall trend of increasing warmth in the early 20th century that is evident in other arctic proxies (e.g., Overpeck et al., 1997). Furthermore, we acknowledge that the use of flexible smoothing splines does reduce our ability to reconstruct longer-term climate trends.

Proxy evidence from Arctic Canada indicates that within the context of the late Holocene, summer temperatures during the last 100 yr were exceptionally high (Koerner and Fisher, 1990), and the period of 1931–1960 was warmer than 80% of the last 3000 yr (Lamoureux and Bradley, 1996). Beginning in ~1905–1910, our reconstruction showed an increase in summer temperature which continued into the early 1960s, reaching its peak between ~1945 and 1965. The Arctic-wide, average summer air temperature time-series (Fig. 4B) (Overpeck et al., 1997), and lake varve records from Lake C2, Lake C3, and Lake Tuborg, Ellesmere Island, also support warmer temperatures in the Canadian Arctic from ~1920 to 1965 (Figs. 4C, 4D) (Lamoureux and Bradley, 1996; Lasca, 1997; Smith et al., 2004) . In addition, ice core melt records from Ellesmere, Devon, and Axel Heiberg Islands provide evidence of a large increase in the amount of melting during the last 100 yr, particularly during the mid-1920s to 1930s and the 1950s to 1960s (Fig. 4E) (Koerner, 1977; Fisher and Koerner, 1983; Koerner and Fisher, 1990). Since 1920, anomalously high solar radiation and lower volcanic aerosol loading, along with exponentially increasing atmospheric trace gases may have influenced the warming trend across the Arctic (Overpeck et al., 1997, and references therein; Mann et al., 1998; Free and Robock, 1999; Lean and Rind, 1999).

Beginning in the mid-1960s and lasting throughout the 1970s, our reconstruction showed a decrease in summer temperature. A similar cooling trend characterizes the ice core melt records from the Devon Island Ice Cap (Fig. 4E) (Fisher and Koerner, 1994), and the sedimentary records from Lake C3 and Lake Tuborg, Ellesmere Island (Figs. 4C, 4D) (Lasca, 1997; Smith et al., 2004). The cooling trend is also pronounced in the Arctic-wide, average summer air temperature reconstruction (Fig. 4B) (Overpeck et al., 1997). Our model is further supported by instrumental climate records, which are marked by a decline in temperature after 1962–1963 (Meteorological Service of Canada, 1948–1998). Multiple factors may have influenced the mid-century cooling in the High Arctic, including a change in high-latitude atmospheric circulation after 1962 (Bradley and England, 1978; Kahl et al., 1993), an increase in arctic tropospheric aerosols caused by increased volcanism, and a leveling off of solar irradiance by the mid-20th century (Overpeck et al., 1997, and references therein).

Finally, our reconstruction revealed an increase in summer temperature at Alexandra Fiord since the early 1980s. Tree-ring records from the Low Arctic of North America show that trees began to recover from the mid-century cooling by the early 1980s (D'Arrigo and Jacoby, 1993). The upward trend in temperature is also evident in the Arctic-wide, average air temperature time-series (Fig. 4B) (Overpeck et al., 1997). The close correspondence between our model and the Arctic-wide time-series indicates that the *Cassiope*-based reconstruction contains a large-scale temperature signal. The temperature increase was also detected in the HAWS instrumental record; the 1990s is the warmest decade on record (Meteorological Service of Canada, 1948–1998). The observed warming of the last decade is likely caused by a combination of anthropogenic and natural forcing factors, changes in the predominant mode of atmospheric circulation, as well as climate feedback mechanisms (Mann et al., 1998; Thompson and Wallace, 1998; Serreze et al., 2000; Moritz et al., 2002).

Further work developing *C. tetragona* chronologies from sites located across broad latitudinal and longitudinal gradients in the Arctic will facilitate local-scale assessment of recent climate change, as well as highlight patterns of regional differences. In addition, longer *C. tetragona* chronologies that extend back to the end of the Little Ice Age will allow us to place the reconstructions within the longer-term perspective of other proxy data. By increasing the overall number of proxy data sets for Arctic Canada, we will improve our understanding of the spatial and temporal variability of northern climate and the arctic climate system.

Acknowledgments

We would like to thank the Polar Continental Shelf Project and the Royal Canadian Mounted Police for logistical support, the Meteorological Service of Canada (Environment Canada) for providing climate data from the Eureka High Arctic Weather Station, and the many contributors to the World Data Center for Paleoclimatology, Boulder, CO, U.S.A. We would also like to thank Connie A. Woodhouse, Keith R. Briffa, Marc Macias, and one anonymous reviewer for their comments and suggestions on previous versions of this manuscript. This study was supported by research grants from the Natural Sciences and Engineering Research Council of Canada and from ArcticNet Network of Centres of Excellence of Canada to G. H. R. Henry.

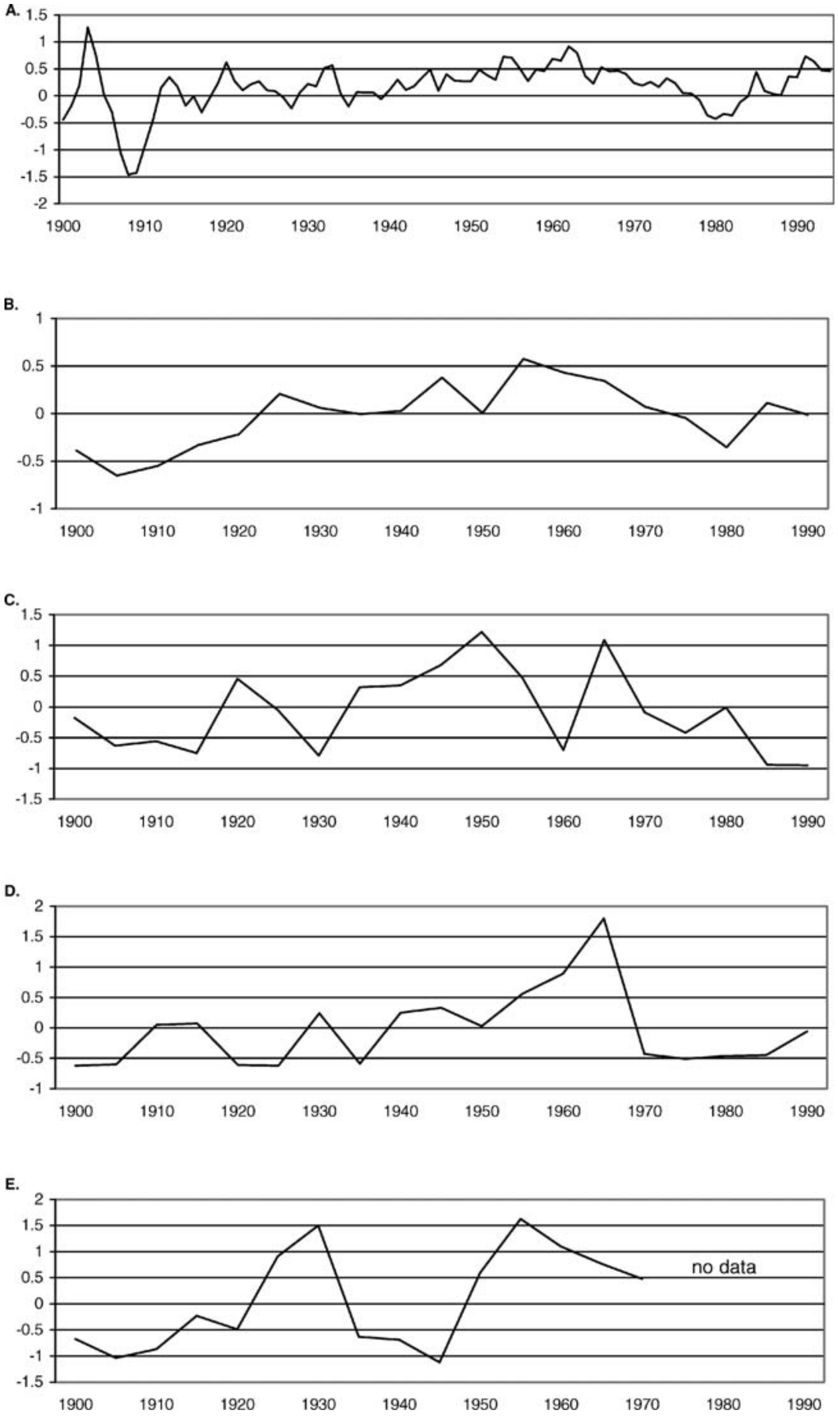

FIGURE 4. Comparison of standardized summer average air temperature proxy records from 1900–1995. (A) *Cassiope tetragona*–based July–September average air temperature reconstruction from Alexandra Fiord, Ellesmere Island, relative to the 1961–1990 mean from the Eureka HAWS, Ellesmere Island. The reconstruction is presented as a 5 year running mean. (B) Standardized, Arctic-wide, average summer air temperature (Overpeck et al., 1997); Lake varve thickness-based reconstructions from (C) Lake C3 (Lasca, 1997) and (D) Lake Tuborg (Smith et al., 2004), Ellesmere Island; (E) Devon Island summer percent ice melt record (Koerner, 1977; Koerner and Fisher, 1990). Lake varve and ice melt records are presented as standardized 5 year average time-series. Time-series (B–E) are plotted as σ units (Overpeck et al., 1997) and are archived at the World Data Center for Paleoclimatology, Boulder, CO, U.S.A. (http://www.ncdc.noaa.gov/paleo/recons.html).

References Cited

Aanes, R., Sæther, B., Smith, F. M., Cooper, E. J., Wookey, P. A., and Øritsland, N. A., 2002: The Arctic Oscillation predicts effects of climate change in two trophic levels in a High Arctic ecosystem. *Ecology Letters,* 5: 445–453.

ACIA, 2004: *Impact of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge, U.K.: Cambridge University Press (http://www.acia.uaf.edu).

Bliss, L. C., and Matveyeva, N. V., 1992: Circumpolar arctic vegetation. *In* Chapin, F. S., Jefferies, R. L., Reynolds, J. F., Shaver, G. R., and Svoboda, J. (eds.), *Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective*. San Diego: Academic Press, 59–90.

Bradley, R. S., and England, J. H., 1978: Recent climatic fluctuations of the Canadian High Arctic and their significance for glaciology. *Arctic and Alpine Research,* 10: 715–731.

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 and Alpine Research,* 20: 385–394.

Callaghan, T. V., Carlsson, B. A., and Tyler, N. J. C., 1989: Historical records of climate-related growth in *Cassiope tetragona* from the Arctic. *Journal of Ecology,* 77: 823–837.

Case, R. A., and MacDonald, G. M., 1995: A dendroclimatic reconstruction of annual precipitation on the western Canadian prairies since A.D. 1505 from *Pinus flexilis* James. *Quaternary Research,* 44: 267–275.

Chapin, F. S., III, Johnson, D. A., and McKendrick, J. D., 1980: Seasonal movement of nutrients in plants in differing growth forms in an Alaskan tundra ecosystem: implications for herbivory. *Journal of Ecology,* 68: 189–209.

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

Cook, E. R., and Briffa, K., 1990: Data analysis. *In* Cook, E. R., and Kariukstis, L. A. (eds.), *Methods of Dendrochronology: Applications in the Environmental Sciences.* Boston: Kluwer Academic, 97–162.

Crawford, R. M. M., 1989: *Studies in plant survival. Ecological case histories of plant adaptation to adversity.* Oxford: Blackwell, 296 pp.

D'Arrigo, R. D., and Jacoby, G. C., 1993: Secular trends in high northern latitude temperature reconstructions based on tree-rings. *Climate Change,* 25: 163–177.

Edlund, S. A., and Alt, B. T., 1989: Regional congruence of vegetation and summer climate patterns in the Queen Elizabeth Islands, Northwest Territories, Canada. *Arctic,* 42: 3–23.

Fisher, D. A., and Koerner, R. M., 1983: Ice core study: a climatic link between the past, present and future. *In* Harington, C. R. (ed.), *Climatic Changes in Canada, 3, Syllogeus.* 49. Ottawa: Museum of Natural Sciences, 50–67.

Fisher, D. A., and Koerner, R. M., 1994: Signal and noise in four ice-core records from the Agassiz Ice Cap, Ellesmere Island, Canada: details of the last millennium for stable isotopes, melt and solid conductivity. *The Holocene,* 4: 113–120.

Free, M., and Robock, A., 1999: Global warming in the context of the Little Ice Age. *Journal of Geophysical Research–Atmospheres,* 104: 19,057–19,070.

Fritter, A. H., and Hay, R. K. M., 2002: *Environmental Physiology of Plants.* New York: Academic Press.

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

Fritts, H. C., 1999: *PRECONK Version 5.11 User's Manual: Dendrochronological Modeling.* Tucson, Arizona: H. C. Fritts.

Fritts, H. C., and Shatz, D. J., 1975: Selecting and characterizing tree-ring chronologies for dendroclimatic analysis. *Tree Ring Bulletin,* 35: 31–40.

Fritts, H. C., Lofgren, G. R., and Gordon, G. A., 1979: Variations in climate since 1602 as reconstructed from tree rings. *Quaternary Research,* 12: 18–46.

Hardy, D. R., and Bradley, R. S., 1997: Climate change in Nunavut. *Geoscience Canada,* 23: 217–224.

Havström, M., 1995: *Arctic Plants and Climate Change—Experimental and Retrospective Studies of* Cassiope tetragona. Ph.D. thesis. Department of Systematic Botany, University of Göteborg, Sweden.

Havström, M., Callaghan, T. V., and Jonasson, S., 1993: Differential growth responses of *Cassiope tetragona*, an arctic dwarf-shrub, to environmental perturbations among three contrasting high- and subarctic sites. *Oikos,* 66: 389–402.

Havström, M., Callaghan, T. V., Jonasson, S., and Svoboda, J., 1995: Little Ice Age temperature estimated by growth and flowering differences between subfossil and extant shoots of *Cassiope tetragona*, an arctic heather. *Functional Ecology,* 9: 650–654.

Holmes, R. L., Adams, R. K., and Fritts, H. C., 1986: *Tree-ring chronologies of western North American: California, eastern Oregon, and northern Great Basin with procedures used on chronology development work including users manual for computer programs, COFECHA and ARSTAN.* Tucson, Arizona: Chronology Series VI, Laboratory of Tree-Ring Research, University of Arizona.

Hultén, E., 1968: *Flora of Alaska and Neighboring Territories.* Stanford, California: Stanford University Press.

IPCChange, 2001: *Intergovernmental Panel on Climate Change Third Assessment Report. Climate Change 2001: Impacts Adaptation and Vulnerability.* Cambridge, U.K.: Cambridge University Press.

Jacoby, G. C., and D'Arrigo, R. D., 1989: Reconstructed northern hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Climate Change,* 14: 39–59.

Johnstone, J. F., 1995: *Responses of* Cassiope tetragona, *a High Arctic evergreen dwarf-shrub, to variations in growing season temperature and growing season length at Alexandra Fiord, Ellesmere Island.* M.Sc. thesis. Department of Geography, University of British Columbia, Canada.

Johnstone, J. F., and Henry, G. H. R., 1997: Retrospective analysis of growth and reproduction in *Cassiope tetragona* and relations to climate in the Canadian High Arctic. *Arctic and Alpine Research,* 29: 459–469.

Jones, P. D., and Kelly, P. M., 1983. The spatial and temporal characteristics of northern hemisphere surface air temperature variations. *Journal of Climatology,* 3: 243–253.

Kahl, J. D., Charlevoix, D. J., Zaitseva, N. A., Schnell, R. C., and Serreze, M. C., 1993: Absence of evidence for greenhouse warming over the Arctic Ocean in the past 40 years. *Nature,* 361: 335–337.

Koerner, R. M., 1977: Devon Island ice cap: core stratigraphy and paleoclimate. *Science,* 196: 15–18.

Koerner, R. M., and Fisher, D. A., 1990: A record of Holocene summer climate from a Canadian high-arctic ice core. *Nature,* 343: 630–631.

Körner, Ch., and Larcher, W., 1988: Plant life in cold climates. *In* Long, S. P., and Woodward, F. I. (eds.), *Plants and Temperature.* Cambridge: Society for Experimental Biology, 25–57.

Labine, C., 1994: Meteorology and climatology of the Alexandra Fiord lowland. *In* Svoboda, J., and Freedman, B. (eds.), *Ecology of a Polar Oasis: Alexandra Fiord, Ellesmere Island, Canada.* Toronto: Captus Press, 23–39.

Lamoureux, S. F., and Bradley, R. S., 1996: A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. *Journal of Paleolimnology,* 16: 239–255.

Lasca, A. N., 1997. *Climate Change from Laminated Lake Sediments in the Canadian High Arctic.* B.A. thesis. Department of Geology, Bates College, Lewiston, Maine, U.S.A.

Lean, J., and Rind, D., 1999: Evaluating sun-climate relationships since the Little Ice Age. *Journal of Atmospheric and Solar-Terrestrial Physics,* 61: 25–36.

Mann, M. E., Bradley, R. S., and Hughes, M. K., 1998: Global-scale temperature patterns and climate forcing over the past six centuries. *Nature,* 392: 779–787.

Maxwell, J. B., 1981: Climatic regions of the Canadian Arctic Islands. *Arctic,* 34: 225–240.

Meteorological Society of Canada (Environment Canada), 1948–1998: National Climate Data and Information Archive (http://www.msc-smc.ec.gc.ca).

Moritz, R. E., Bitz, C. M., and Steig, E. J., 2002: Dynamics of recent climate change in the Arctic. *Science,* 297: 1497–1502.

Muc, M., Svoboda, J., and Freedman, B., 1989: Vascular plant communities of a polar oasis at Alexandra Fiord (79°N), Ellesmere Island, Canada. *Canadian Journal of Botany,* 67: 1126–1136.

Nams, M. L. N., 1982: *Ecology of* Cassiope tetragona *at a High Arctic lowland, Alexandra Fiord, Ellesmere Island, N.W.T.* M.Sc. thesis. Department of Biology, Dalhousie University, Canada.

Nams, M. L. N., and Freedman, B., 1987: Phenology and resource allocation in a High Arctic evergreen dwarf shrub, *Cassiope tetragona. Holarctic Ecology,* 10: 128–136.

Natural Resources Canada, 2005: The atlas of Canada: coastlines and boundaries of Canada map (http://www.atlas.gc.ca).

Neter, J., Kutner, M. H., Nachtsheim, C. J., and Wasserman, W., 1996: *Applied Linear Statistical Models.* Fourth edition. Toronto: Irwin.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R. S., Case, R., Douglas, M. S. V., Finney, B., Gajewski, K., Jacoby, G., Jenning, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., and Zielinski, G., 1997: Arctic environmental change of the last four centuries. *Science,* 278: 1251–1256.

Rayback, S. A., and Henry, G. H. R., 2005: Dendrochronological potential of the arctic dwarf-shrub, *Cassiope tetragona. Tree-Ring Research,* 61: 43–53.

Serreze, M. C., Walsh, J. E., Chapin, F. S., III, Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W. C., Morison, J., Zhang, T., and Barry, R. G., 2000: Observational evidence of recent change in northern high-latitude environment. *Climate Change,* 46: 159–207.

Shaver, G. R., and Kummerow, J., 1992: Phenology, resource allocation and growth of arctic vascular plants. *In* Chapin, F. S., III, Jefferies, R. L., Reynolds, J. F., Shaver, G. R., and Svoboda, J. (eds.), *Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective.* San Diego: Academic Press, 193–221.

Smith, S. V., Bradley, R. S., and Abbott, M. B., 2004: A 300 year record of environmental change from Lake Tuborg, Ellesmere Island, Nunavut, Canada. *Journal of Paleolimnology,* 32: 137–148.

Sørensen, T., 1941: *Temperature Relations and Phenology of the Northeast Greenland Flowering Plants.* Copenhagen: Commission for Scientific Research in Greenland.

Stokes, M. A., and Smiley, T. L., 1968: *An Introduction to Tree-Ring Dating.* Chicago: University of Chicago Press.

Thompson, D. W. J., and Wallace, J. M., 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters,* 25: 1297–1300.

Warming, E., 1908: *The Structure and Biology of Arctic Flowering Plants. I. Ericineae (Ericaceae, Pyrolaceae). I. Morphology and Biology.* Copenhagen: Commission for Scientific Research in Greenland.

Wigley, T. M., Briffa, K. R., and Jones, P. C., 1984: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology,* 23: 201–213.

Revised ms submitted July 2005