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Temperature variability over the past millennium inferred from Northwestern Alaska tree rings

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Abstract We describe a new tree-ring width data set of 14 white spruce chronologies for the Seward Peninsula (SP), Alaska, based on living and subfossil wood dating from 1358 to 2001 AD. A composite chronology derived from these data correlates positively and significantly with summer temperatures at Nome from 1910 to 1970, after which there is some loss of positive temperature response. There is inferred cooling during periods within the Little Ice Age (LIA) from the early to middle 1600s and late 1700s to middle 1800s; and warming from the middle 1600s to early 1700s. We also present a larger composite data set covering 978–2001 AD, utilizing the SP ring-width data in combination with archaeological wood measurements and other recent collections from northwestern Alaska. The Regional Curve Standardization (RCS) method was employed to maximize potential low-frequency information in this data set. The RCS chronology shows intervals of persistent above-average growth around the time of the Medieval Warm Period (MWP) early in the millennium, which are comparable to growth levels in recent centuries. There is a more sustained cold interval during the LIA inferred from the RCS record as compared to the SP ring-width series. The chronologies correlate significantly with Bering and Chukchi Sea sea surface temperatures and with the Pacific Decadal Oscillation index. These atmosphere–ocean linkages probably account for the differences between these records and large-scale reconstructions of Arctic and Northern Hemisphere temperatures based largely on continental interior proxy data.

1 Introduction

Alaska and the Arctic as a whole warmed considerably during the twentieth century (e.g. Chapman and Walsh 1993, IPCC 2001), with temperatures along the western Alaskan coast rising 1.41°C from 1965 to 1995 (Stone 1997). There is, however, only limited meteorological data available to evaluate climate changes for these remote northern regions. Proxy records covering the past ~1,000 years can provide a longer term context for analysis of recent anthropogenic warming effects. This context includes evaluation of natural climate conditions during the so-called Little Ice Age (LIA); a widespread cold period defined largely on glaciological evidence (~1450–1850 AD; Grove 1988) and the Medieval Warm Period (MWP; ~1000–1300 AD—Lamb 1965; Hughes and Diaz 1994; Bradley et al. 2003). Both are examples of relatively recent, extreme climate episodes that preceded major anthropogenic modification due to increasing greenhouse gases. Proxy data for northwestern Alaska and other land areas surrounding the North Pacific Ocean can also aid study of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) and other features of North Pacific climate over past centuries to millennia.

To improve coverage of paleoclimatic data for northwestern Alaska, we collected living and relict wood samples of white spruce (*Picea glauca* [Moench] Voss) from 14 sites on the Seward Peninsula (SP) in the summer of 2002. These sites are located at or just below elevational treeline in the Camp Haven area near the Tubutulik River on the southeastern SP (Table 1, Fig. 1). This area is characterized by well-drained limestone outcrops, interspersed with wide gravel pavements

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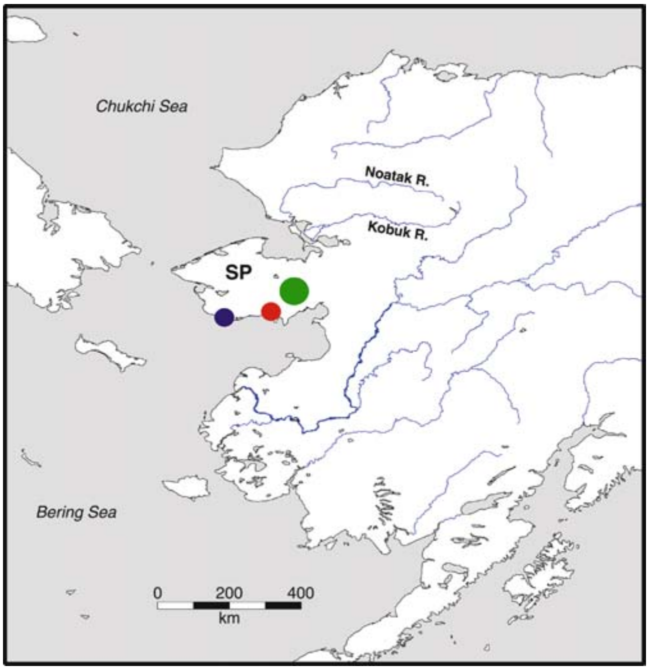


Fig. 1 Map of Seward Peninsula, Alaska and vicinity showing location (*green dot*) of 14 white spruce sites sampled in the late summer of 2002. Noatak and Kobuk rivers, where wood dwellings were sampled by Giddings (1941), are labeled. Nome (*blue dot*) and White Mts. (*red dot*) meteorological stations are also indicated

that minimize the occurrence of fire and allow the white spruce trees to live to advanced age (Juday 1985).

The SP is influenced by oceanic effects due to its proximity to the Bering and Chukchi Seas and the North Pacific Ocean. The climate is also impacted by the Aleutian Low and Siberian High pressure cells and their associated effects on temperature and precipitation. However, SP climate is also influenced by conditions in the continental interior, particularly on the eastern SP where the tree sites are located. The SP is wetter and more maritime than much of interior Alaska, with warmer winters and cooler summers. A longitudinal (western) limit to tree growth on the SP, located at approximately 163°40′–42′W, is probably a result of adverse summer conditions related to decreased solar insolation, fog and maritime effects. The Camp Haven study area is situated approximately 1° longitude to the east of the westernmost limit of erect trees (Table 1, Fig. 1).

We also describe a composite chronology generated by combining the new SP ring-width measurements with data obtained from the Alaskan collections of J. L. Giddings (e.g. 1941, 1948). In addition to his published data, some other Giddings samples were processed at the TRL-LDEO; and by Graumlich and King (1997). These ring-width data were derived primarily from archaeological wood (derived from old dwellings and other sources) of white spruce, originally collected by Giddings for northwestern Alaska. The locations from which this wood was collected cover a 24,000 km^2 region of the Noatak and Kobuk river basins (Fig. 1) and date as far back as 978 AD (Giddings 1941, 1948; Graumlich and King 1997). The Graumlich and King (1997) data also include some more recent collections extending up to 1992. The large sample size of this combined data set allows us to attempt to optimize low-frequency climate information for the past millennium using recent advances in detrending procedures (Briffa et al. 1992, 1996; Cook et al. 1995; Esper et al. 2003).

2 Tree-ring data and analysis

2.1 The SP ring-width composite chronology

Trees on the SP were sampled only in areas without evidence of major disturbance (e.g. fire). Care was taken in sampling to reach the pith in order to obtain maximum age. Although we did not record pith offset information for application of the regional curve standardization (RCS) method (see below), such information is considered to have at most a minimal impact on the final RCS chronology (Esper et al. 2003). The SP wood samples were cross-dated and processed using standard methods of tree-ring analysis (Fritts 1976; Cook and Kairiukstis 1990). There are strong within-site common signals between the ring-width series, with an

Table 1 Site and chronology information for SP tree-ring data

Site name	Site	Latitude (°N)	Longitude (°W)	Elevation	Years (M)
Almond Butter Lower	AL	65.188	162.206	168	1607–2001
Almond Butter	AB	65.187	162.210	213	1406–2001
Alpine View	AV	65.111	162.183	282	1542–2001
Burnt Over	BO	65.213	162.244	259	1621–2001
Bye Rosanne	BR	65.082	162.189	282	1575–2001
Death Valley	DV	65.193	162.268	239	1358–2001
Echo Slope	ES	65.098	162.150	229	1590–2001
Frost Valley	FV	65.089	162.154	229	1611–2001
Gordon's Cat	GC	65.208	162.206	168	1400–2001
Hey Bear	HB	65.219	162.217	213	1533–2001
Hey Bear Upper	HU	65.221	162.217	229	1383–2001
Mt. Molè	MM	65.077	162.177	229	1534–2001
Ptarmigan Hill	PH	65.069	162.233	244	1718–2001
Windy Ridge	WR	65.187	162.220	251	1556–2001

Table 2 First eigenvector loadings for 14 SP ring width chronologies for the 1718–2001 common period

1	AB	0.280
2	AL	0.211
3	AV	0.297
4	BO	0.208
5	BR	0.280
6	DV	0.291
7	ES	0.278
8	FV	0.273
9	GC	0.255
10	HB	0.273
11	HU	0.278
12	MM	0.268
13	PH	0.237
14	WR	0.292

overall mean inter-series correlation of $r = 0.59$ (using COFECHA; Holmes 1990). Across all sites (675 series from 355 trees) there is a series intercorrelation of $r = 0.56$ (STDEV = 0.09). Long-term biological trends (Fritts 1976) were removed from the ring-width series using Turbo ARSTAN (Cook 1985; E. Cook, personal communication). Conservative methods of detrending, using negative-exponential or straight-line curve fits, were employed in the standardization process in order to retain low-frequency information related to climate (e.g. Jacoby and D'Arrigo 1989). The so-called STANDARD chronology (Cook 1985) was employed for analysis. Some of the SP wood samples were processed for maximum latewood density and these results are described in D'Arrigo et al. (2004, and see Sect. 6).

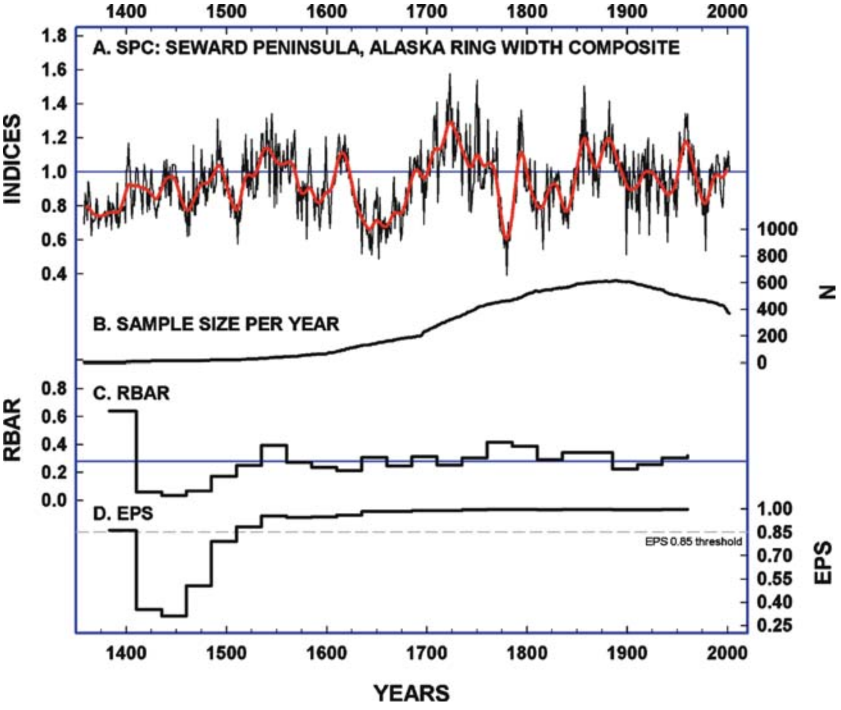
To evaluate coherence among the 14 resulting ring-width chronologies, principal component analysis (PCA) was performed over the 1718–2001 common period. The first eigenvector accounted for nearly 72% of the overall variance in the chronology data set. It shows common positive loadings, ranging from 0.208 to 0.297, among the chronologies (Table 2). Due to the coherent nature of these results, it was decided to combine the raw ring-width data from all sites in order to create a composite record for the SP (SPC). The resulting SPC chronology spans the period from 1358 to 2001 AD(Fig. 2a). Median segment length among all samples is 250 years, indicating that the tree-ring data can resolve low-frequency variations with a realizable limit of approximately 100–150 years (Cook et al. 1995).

The signal strength in the SPC chronology was evaluated over time using the calculated running series of average correlations (RBAR) and the expressed population signal or EPS statistic (Fig. 2c, d; Cook and Kairiukstis 1990). RBAR is the mean correlation coefficient among tree-ring series (Briffa 1995). We used a 50-year window with 25-year overlaps between adjacent windows. The mean RBAR is 0.277 and remains fairly stable after around 1515. It is more variable as sample size decreases prior to 1545; 20 in 1484 and 2 in 1358 (Fig. 2b). The EPS assesses the degree to which the chronology represents a hypothetical chronology based on an infinite number of cores (Briffa 1995). An arbitrary value of 0.85 is often considered to be acceptable for EPS (Wigley et al. 1984; Cook and Kairiukstis 1990). The EPS exceeds this value after around 1500.

2.2 The SP/Giddings ring-width composite chronology

Correlation analysis between the SPC chronology and the Graumlich (420 series) and Giddings (101 series) data was made to assess whether the common signal

Fig. 2 **a** SPC ring-width composite chronology extending from 1358 to 2001 AD. A 25-year smoothing spline (*red line*) has been superimposed on this record to emphasize multidecadal-scale fluctuations. **b** Changing sample size over time. **c** RBAR (with mean line) and **d** EPS (*dashed line* is 0.85 cutoff)



between the data sets was strong enough to warrant their pooling together to develop a longer and better replicated data set. The analysis, made over the 1710–1921 period (where EPS values in all chronologies are > 0.85), shows that the Graumlich and Giddings chronologies correlate with the SPC series with *r* values of 0.63 and 0.64 respectively. Therefore, despite the Noatak-Kobuk region being located ca. 300 km north-east, the Graumlich and Giddings data appear to co-vary reasonably with the SPC data and therefore could be readily merged into a single highly replicated chronology (1196 series) representing northwestern Alaska. Two versions of the chronology were developed. First, a traditional STANDARD chronology (Fig. 3a, SPG), detrended using negative-exponential or straight-line functions, was generated for direct comparison with the SPC series. Second, RCS (Mitchell 1967; Briffa et al. 1992, 1996; Cook et al. 1995; Esper et al. 2003) was evaluated to determine if this method might be useful for optimizing the low-frequency climatic information gleaned from the composite data set. This method of standardization (which often works best on data sets with large sample sizes such as found here) allows for the preservation of potential low-frequency variance in excess of the length of individual samples used in chronology development (Briffa et al. 1992; Esper et al. 2003). With a mean sample length (MSL) of 250 years, and periods where MSL is substantially lower than this value (Fig. 3e), it is likely that traditional detrending methods would remove potential low-frequency information at frequencies greater than the MSL (Cook et al. 1995).

As the composite tree-ring data set is a combination of many ring-width series, representing many different sampling sites and therefore ecologies, one single regional curve could not be used to detrend all the series. The full data set was therefore divided into four subsets. The archaeological data sampled by Giddings were treated as one separate group, while the SPC and Graumlich living tree data were combined and subdivided into three groups by growth trend type. The three latter groups were identified by finding the best

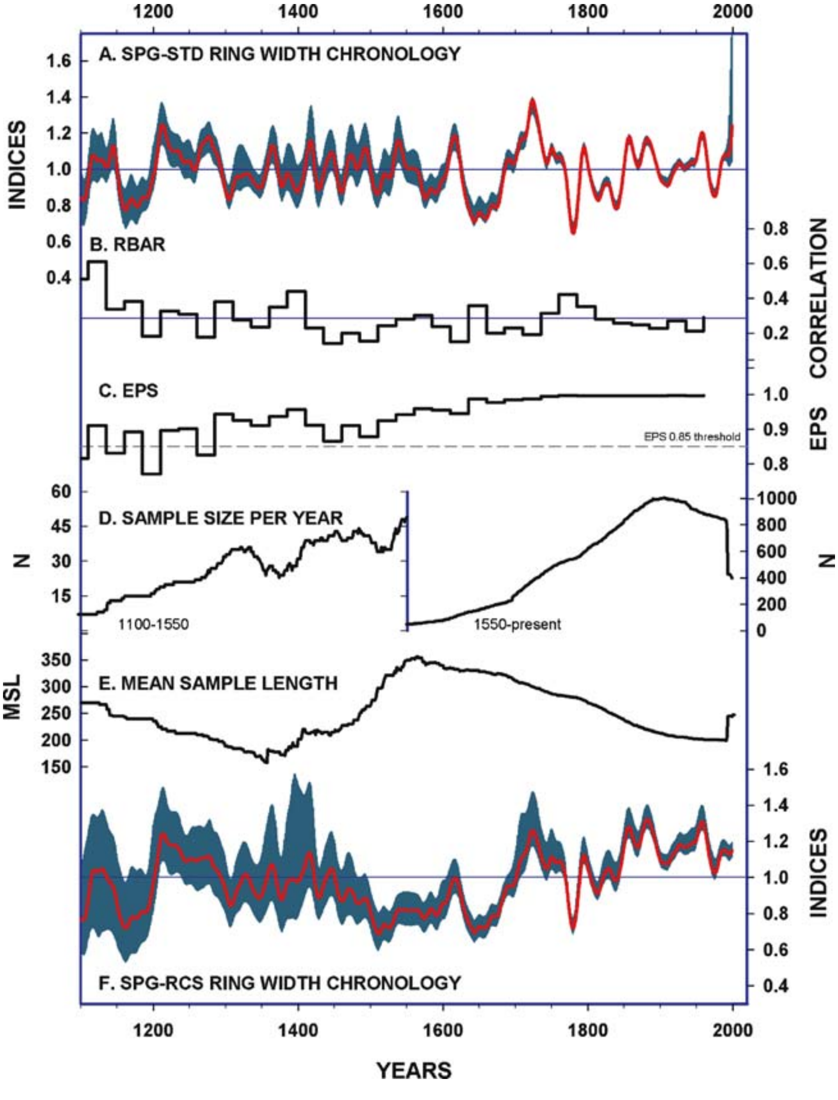


Fig. 3 **a** SPG-STD ring-width composite chronology, derived using traditional methods of standardization, based on merged SP and Giddings ring-width measurements. Record extends from 978 to 2001 AD but is truncated prior to 1100. We show a 25-year smoothing spline (*red line*) version of this record to emphasize multi-decadal-scale fluctuations with 95% confidence limits estimated using the bootstrap method (*blue shading*). **b** SPG-STD Rbar (with mean line). **c** SPG-STD EPS (*dashed line* is 0.85 cutoff). **d** Changing sample size over time. The *y*-axis for two periods (1100–1550 and 1550–present) have been optimized to clearly show replication for each period. **e** Mean sample length (MSL) of the SPG data set. **f** SPG-RCS chronology derived using regional curve standardization (RCS) method; other details (*spline*, confidence limits) as in **a**. Correlation of the SPG-RCS series with the SPC chronology over the overlapping period from 1358 to 1992 is $r = 0.68$

least-squares fit of each individual series with three different standardization options: negative exponential function, negative regression function or those series modeled either by a horizontal line or an increasing trend. For each of these four defined groups, individual mean cambial age-aligned curves were generated, smoothed by a spline function of 10% of the series length (Esper et al. 2003) and this smoothed curve was used to detrend the respective series in each group.

The resultant four RCS chronologies compare reasonably well (mean inter-series $r = 0.74$ (STDEV = 0.09) over the 1476–1941 period of common overlap (not shown), indicating that (1) no serious detrending bias has been introduced using the RCS method and (2) that the lack of pith offset information has not been significantly detrimental to the analysis. The final chronology (SPG-RCS), derived by averaging all the individual detrended series, is presented in Fig. 3f.

The EPS statistic (Fig. 3c) indicates that the SPG and SPG-RCS records, which extend from 978 to 2001 AD, are reliable over much of their length with stable, high values after around 1100 AD (the records are plotted since 1100—Fig. 3). Sample size increases from 2 in 980 to 21 in 1140 (Fig. 3d). It declines considerably after 1992, which is the last year of the Graumlich collections, but is still very strong over the past decade. These two chronologies thus provide well-replicated, long-term perspectives on tree growth for northwestern Alaska over much of the past millennium.

3 Results

In order to identify climate–growth relationships for white spruce on the southeastern SP, we computed simple correlations between the SPC chronology and monthly mean temperatures for Nome, the longest meteorological station available for comparison (Fig. 1). Time series of Nome summer (June–August) mean temperature and total precipitation for 1909–2001 are shown in Fig. 4a, b, respectively. There is a significant positive trend in summer temperature, and a less pronounced (not significant) overall negative trend in summer precipitation. It should be noted that the linear trend in the temperature series is driven by the 1976 upward shift in values which suggests a significant influence from the North Pacific. The correlations between the SPC chronology and Nome temperature and precipitation were calculated for a 19-month interval beginning in April of the previous growing season and ending in October of the current growing season in order to consider the impact of climatic conditions during and prior to ring formation on radial growth.

Figure 5 shows the results of correlation analysis comparing the Nome monthly mean temperatures and the SPC chronology for two time periods: 1910–1970 and 1971–2001. Positive correlations with summer (June–August) temperatures are evident for the earlier period from 1910 to 1970. The correlation with temperature in June is not significant, while correlations temperature in July and August are significant at the 0.10 and 0.01 levels, respectively. These relationships were not sufficiently strong to attempt a reconstruction.

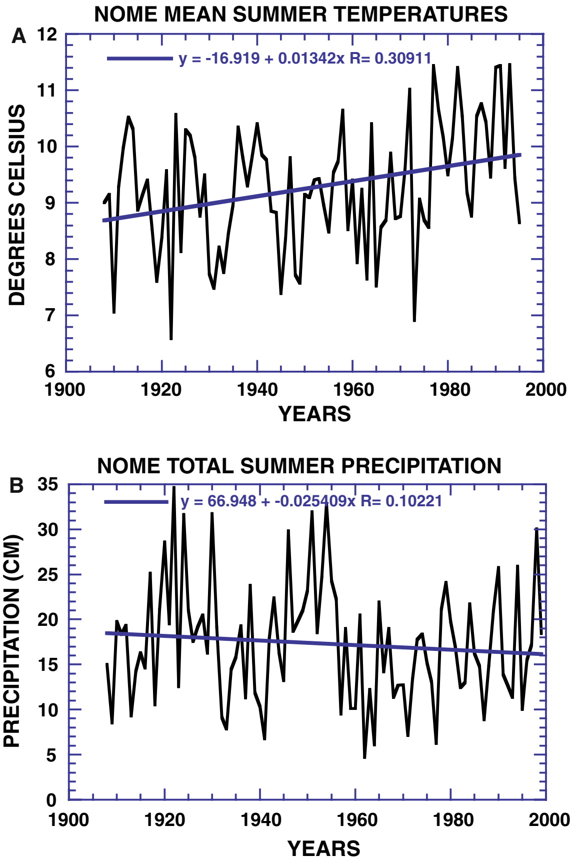


Fig. 4 Time series plots of Nome, Alaska summer mean temperature (**a**) and summer total precipitation (**b**) for period of record from 1909 to present. The Nome station data were extracted from the Global Historical Climatology Network (GHCN; Vose et al. 1992). Linear trend lines and equations are also shown. Temperature trend is significant ($P = 0.003$) while precipitation trend ($P = 0.330$) is not significant

We also compared the SPC series to a short temperature record for the village of White Mountain on the eastern SP (Fig. 1; 64°41′N; 163°24′W; 15 m.a.s.l.; 1922–1946; http://www.ngdc.noaa.gov/paleo/pubs/lloyd2002/lloyd2002.html). The climatic conditions at White Mountain are closer to those at the tree-ring sites than are conditions at the Nome station on the southern coast. Correlations for White Mountain summer (June–August) temperatures for this early period are 0.41, 0.56 and 0.41, respectively.

There is a significant (0.05 level) negative correlation with Nome temperature in current April. This negative association has been noted for other northern sites, and may result from the tendency for drought stress to occur when growth is initiated in an early spring while the ground is still frozen (Tranquillini 1979; Jacoby and Cook 1981; Juday 1985). There are also significant negative correlations with temperature in prior May

(0.10) and July (0.05). When only the post-1970s period is examined (1971–2001), the positive temperature signal is not significant for the summer months, although it is stronger for June (Fig. 5b). A negative association with temperature in spring is still evident, but in May rather than April (0.01). There is also a significant negative correlation with prior August temperatures (0.01).

Results for Nome precipitation (not shown) did not reveal any consistent pattern that might help explain the recent loss in positive temperature response. However, the meteorological trends in Fig. 4 indicate that summer temperatures at Nome have risen in recent decades without any significant overall rise in moisture availability, which would be expected to increase evapotranspiration and the likelihood of drought stress.

Next, we compared the SPC series to SSTs for the Bering and Chukchi Seas, obtained from the UK Hadley Centre HADISST data set (Fig. 6a). Averaged over the oceanic regions in the vicinity of the SP and Bering Strait from 60° to 67°N and 160° to 174°W, correlations are highest for summer (July–August) SST for 1900–1970 ($r = 0.40$; 0.001). Prior to 1900 there are considerable missing data. The relationship weakens after 1970, possibly reflecting the recent loss of positive temperature response mentioned previously.

Correlations between the SPC chronology and the monthly index of the PDO (Mantua et al. 1997; Mantua and Hare 2001) for 1901–1970 are almost consistently negative for the prior and current growth years (Fig. 6b). The strongest relationships are in prior December and current spring ($r = -.33$ for March and April, significant at the 0.01 level). This latter signal is potentially important with regard to North Pacific climate dynamics, since the most dominant PDO–temperature relationship in North America is found in the boreal spring season (Minobe 2000; Cayan et al. 2001). Unlike the negative relationship with the SPC chronology, the Nome temperature record shows a positive

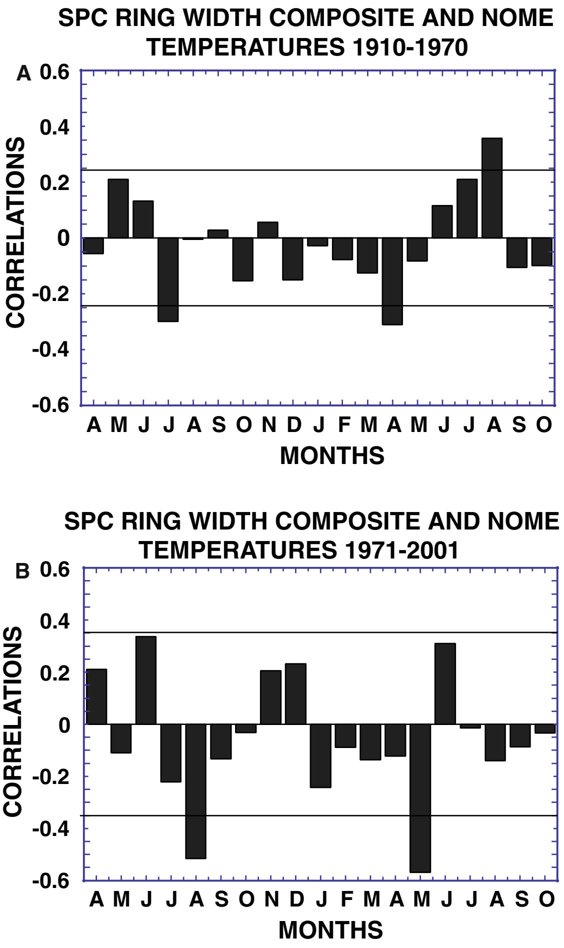


Fig. 5 Correlation of SPC chronology with Nome mean monthly temperatures from April of the prior year to October of the current growth year for two time intervals: (**a**) 1910–1970 and (**b**) 1971–2001. Horizontal lines indicate 95% levels of significance

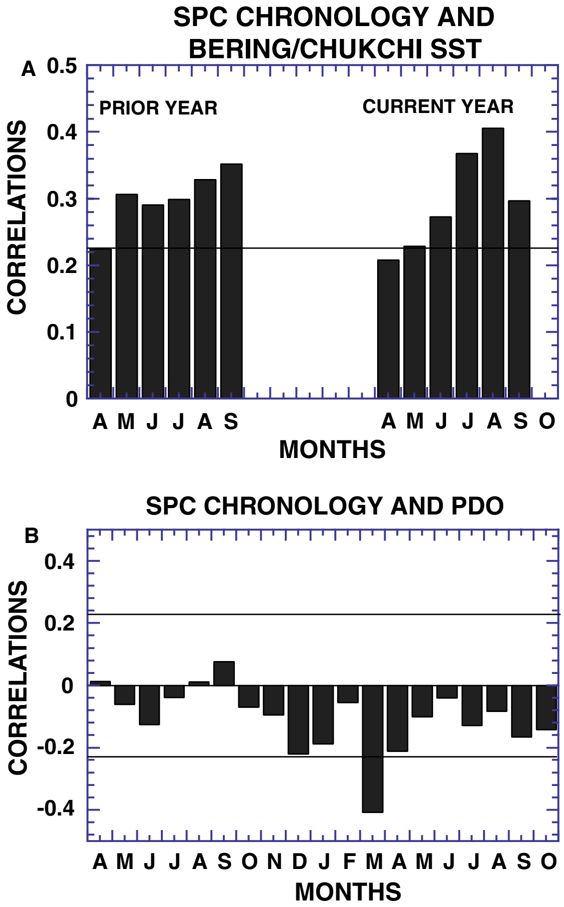


Fig. 6 Comparison of SPC chronology with large-scale monthly climate indices for 1901–1970. **a** Correlations with spatially averaged Bering-Chukchi SSTs (60°–67°N, 160°–174°W) for region surrounding Seward Peninsula, obtained from Hadley Centre SST (HADISST, vers. 1.1) data set. Comparison is for warm season months of prior and current growth years. Correlations not shown for colder months when there is considerable missing data. **b** Correlations with PDO index of Mantua et al. (1997) for prior and current growth year. Horizontal lines indicate 95% significance levels

correlation with the spring (March and April) PDO ($r = 0.39$ for 1909–1970, significant at the 0.01 level).

The spatial correlation map in Fig. 7a compares the SPC record with the SST field for the North Pacific (Kaplan et al. 1998) during boreal spring (March–May). This season showed the strongest relationships between SP tree growth and North Pacific SST in initial analyses. A large area of positive correlation is observed in the middle North Pacific Ocean, with negative correlations to the south and east, resembling an inverse spatial pattern to that observed for the spring PDO (Fig. 7b). This relationship suggests that the SP tree-ring data are capturing the large-scale spatial pattern of SSTs associated with the PDO, and that these data contain useful information about past climate variability over a considerable area of the North Pacific.

Based on the above analyses and our own observations, the SP trees appear to be primarily integrating temperature conditions, weighted towards the spring and summer months, in the region of northwestern Alaska and the surrounding oceans. The SPC record (Fig. 2a) indicates cold conditions in this region during the early to middle 1600s period within the LIA. There is a pronounced increase in growth, to the highest levels in the record, from the middle 1600s to early 1700s, indicating relative warmth. Cooling is inferred for the late 1700s to middle 1800s, with the most severe cold in the decade centered around 1780 AD. The index value in 1780 is 0.388, and the mean value for the 1775–1785 decade is 0.615 relative to the long-term mean of 1.0. This event (1780), the cause of which is unknown, is also seen in some of our tree-ring records from northern interior Alaska. Increased growth indicates warming from the middle to late 1800s, after which conditions are somewhat below average until the middle of the twentieth century. Following a brief growth increase in the 1950s, there is a decline, with some growth recovery in the 1990s.

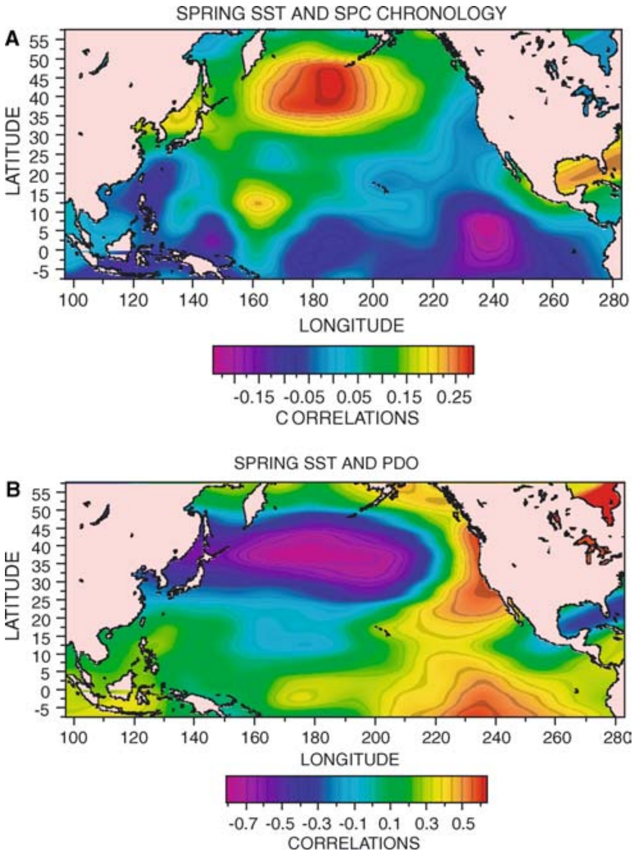


Fig. 7 Spatial correlation fields with SPC chronology and North Pacific SST based on Kaplan et al. (1998) data set for 1900–1991. **a** Spring (MAM) SST and SPC chronology. **b** MAM SST and spring PDO index. Note difference in scale between **a** and **b**

The SPG-RCS record clearly captures more low-frequency information than the traditionally derived SPG series (Fig. 3). When compared to the SPG record, the SPG-RCS record shows higher index values from ca. 1800 to the present which are comparable to the high index values around 1700 AD. There is also a notable period of low index values in the sixteenth century in the SPG-RCS record, not captured in the SPG series. These observations extend the inferred cool conditions early in the LIA from ca. 1450–1680 and suggest that conditions over the last few centuries were relatively warmer than what would be inferred from the SPC and SPG-STD series (Figs. 2 and 3).

Both the SPG-STD and SPG-RCS records (Fig. 3) indicate several intervals of persistent above-average growth that broadly coincide with the timing of the late MWP. These are more pronounced in the SPG-RCS record, with the greatest peak in growth during the early to middle 1200s and lesser peaks in the early to middle 1100s and the early 1400s. These intervals are punctuated by generally below-average values. Bootstrap 95% confidence limits (Efron 1987) expand in both records indicating lower confidence in this earlier period, although the RBAR and EPS indicate reliability back to around 1100 AD. For the SPG-STD series, growth during these early-millennium intervals is exceeded by a period of above-average growth centered around 1700 AD. In the SPG-RCS series, growth during these early intervals is comparable to that of several periods within the eighteenth to twentieth centuries. A cooling trend in the 1400s marks the transition into the LIA.

Multi-taper method (MTM) spectral analysis (Mann and Lees 1996) was used to evaluate the SPC and SPG-RCS records in the frequency domain (Fig. 8a). The results for the SPC series indicate the greatest variance at low frequencies, with significant peaks (>0.01 level) at 31–37 years and above 70 years. There are also significant peaks at 2–3 years. Spectral analysis of the SPG-RCS chronology shows a similar pattern, with dominant modes of variation at 28–34 years and above 60 years (Fig. 8b). The 28–34-year peak is in agreement with a similar mode of variation (25–36 years) identified in merged tree-ring records for the Gulf of Alaska region and Patagonia (Villalba et al. 2003). This latter mode is believed to represent an important climate forcing

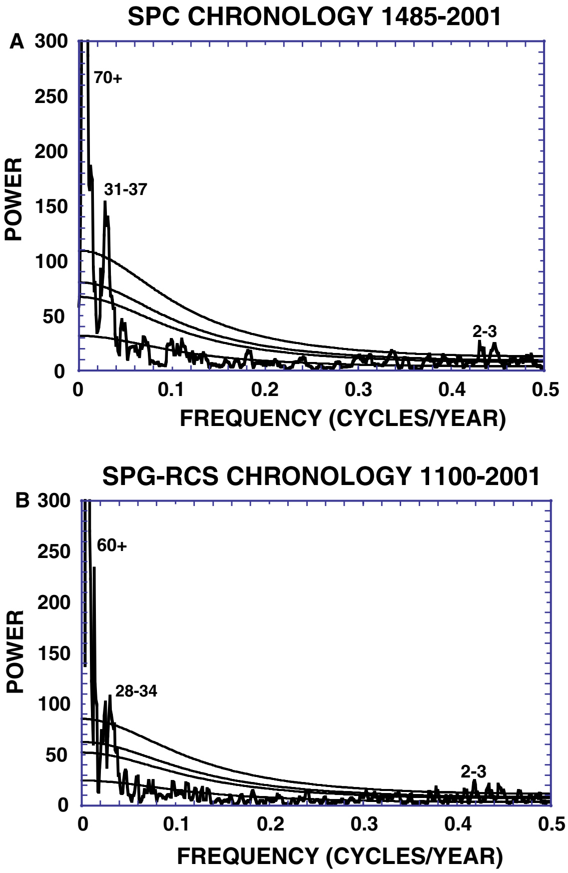


Fig. 8 Multi-taper method (MTM) spectral analysis (Mann and Lees 1996) of **a** SPC tree-ring chronology for 1485–2001 AD, and **b** SPG-RCS chronology for 1100–2001 AD, periods for which chronologies are considered most reliable based on RBAR and EPS. Null, 90, 95 and 99% levels of significance shown by *black lines*. Significant peaks are labeled

mechanism for the extratropical western Americas (Villalba et al. 2003).

4 Discussion and conclusion

We have described composite tree-ring width chronologies of white spruce for northwestern Alaska. These records fill a spatial gap in paleoclimatic data coverage for the western Arctic and North Pacific regions. Extending as far back as 978 AD, they supplement the very few paleo-temperature records for northern North America that cover the past 1,000 years (e.g. Luckman et al. 1997; Luckman and Wilson 2004 (in press)). Although correlations with local temperatures were not sufficiently strong to develop a reconstruction, our results demonstrate that these records reflect atmosphere–ocean climate conditions for the northwestern Alaskan region.

The growth increase during the broad-scale warming of the mid-twentieth century (e.g. IPCC 2001) is not unusual relative to other above-average periods in these records. Large-scale paleotemperature reconstructions for northern latitudes indicate a much more sustained and pronounced response to recent warming in the tree and reconstructed estimates (e.g. Overpeck et al. 1997; Jacoby et al. 1999; Mann et al. 1999; Esper et al. 2002). Consistent with this observation, there is only weak positive agreement between our northwestern Alaskan records and a reconstruction of Arctic temperatures based on circumpolar northern treeline series for 1600–1970 ($r = 0.11$ and $r = 0.19$ for the SPC and SPG-RCS chronologies, respectively: Jacoby et al. 1999; updated from Jacoby and D’Arrigo 1989; D’Arrigo and Jacoby 1993). We interpret this finding to indicate the importance of oceanic influences on SP and far northwestern Alaskan climate relative to the (primarily continental interior) northern records included in these large-scale temperature reconstructions. The chronologies presented herein thus provide information on past variations in atmosphere–ocean temperatures that is distinct from much of the data contained in the large-scale reconstructions. This information (particularly for the SPG-RCS record) includes evidence consistent with the occurrence of a MWP and a sustained LIA in northwestern Alaska and vicinity. The expanded confidence limits in the early part of the millennium illustrate the need for additional records to more adequately evaluate the occurrence of the MWP.

Maximum latewood density data for the SP was used in a related study to reconstruct warm season temperatures for Nome (D’Arrigo et al. 2004). The density parameter is complementary to ring width, and typically shows stronger correlations with year-to-year meteorological data than does ring width (e.g. D’Arrigo et al. 1992). However, despite often lower correlations between ring-width and local meteorological data, ring-width data can often reflect low-frequency climate trends better, as found herein. The Seward MXD record correlates with the SPC and SPG series at 0.24 and 0.25, respectively, for the period 1683–1970 used in the SP density study (D’Arrigo et al. 2004).

The SP ring-width data appear to have lost some positive response to temperature in recent decades. This result is consistent with the studies of Jacoby and D’Arrigo (1995), Barber et al. (2000), Lloyd and Fastie (2002) and Davi et al. (2003) for various regions of Alaska, where similar shifts in recent temperature response have been observed and were attributed to drought stress. Interestingly, Wilmking et al. (2004) have observed that the coherency of this shift in response varies along an east–west precipitation gradient in Alaska. Other factors, including changes in ozone levels, shifts in seasonality and timing of snowmelt, and changing response to maximum and minimum temperatures (Briffa et al. 1998; Vaganov et al. 1999; Wilson and Luckman 2002a, 2003) (or a combination of factors) may provide additional explanation for the shifts in growth response observed at some northern tree sites. The recent shifts in response of the SP and other northern tree-ring data will need to be taken into account in future studies.

The tree-ring series for northwestern Alaska are sensitive to North Pacific climate variability. The correlations between SP tree growth and Bering/Chukchi SSTs reflect the importance of maritime effects on the SP and vicinity (e.g. Overland et al. 2004). The negative relationship found between the SPC chronology and PDO contrasts with the positive response seen in tree-ring records elsewhere in western North America (e.g. Biondi et al. 2001; D'Arrigo et al. 2001; Gedalof and Smith 2001). This opposing sign of relationship between the tree-ring and temperature data and the PDO may be at least partly explainable by the negative response to spring temperatures in northern trees mentioned earlier, and by increasing susceptibility to drought stress.

The northwestern Alaska chronologies supplement a network of temperature-sensitive tree-ring series we have developed from sites around the North Pacific rim, including Alaska, Kamchatka, the Kurile Islands, and Hokkaido (Gostev et al. 1996; D'Arrigo et al. 1997; Wiles et al. 1998; Davi et al. 2002; Jacoby et al. 2004). Dendroclimatic reconstructions have been developed for several of these North Pacific rim sites (Gostev et al. 1996; Davi et al. 2002; Jacoby et al. 2004). These North Pacific records add useful information to existing data sets being used to model past changes in the PDO and other features of the North Pacific climate (e.g. Deser et al. 2004). These records can also contribute to analyses of trans-hemispheric modes of climate variation identified in instrumental data (e.g. Seager et al. 2003) and in tree-ring data for the western coasts of the two Americas (Villalba et al. 2003). An expanded analysis using the new tree-ring records for northwestern Alaska and other regions of the North Pacific will be the subject of future investigation.

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References

Barber V, Juday G, Finney B (2000) Reduced growth of Alaska white spruce in the twentieth century from temperature-induced drought stress. Nature 405:668–672

Biondi F, Gershunov A, Cayan D (2001) North Pacific decadal climate variability since 1661. J Climate 14:5–10

Bradley R, Hughes M, Diaz H (2003) Climate in medieval time. Science 302:404–405

Briffa K (1995) Interpreting high-resolution proxy climate data—the example of dendroclimatology. In: von Storch H, Navarra A (eds) Analysis of climate variability, applications of statistical techniques. Springer, Berlin Heidelberg New York, pp 77–94

Briffa K, Jones P, Bartholin T, Eckstein D, Schweingruber F, Karlen W, Zetterberg P, Eronen M (1992) Fennoscandian summers from AD 500: temperature changes on short and long time scales. Clim Dyn 7:111–119

Briffa K, Jones P, Schweingruber F, Karlen W, Shiyatov G (1996) Tree ring variables as proxy climate indicators: problems with low-frequency signals. In: Jones P, Bradley R, Jouzel J (eds) Climatic variations and forcing mechanisms of the last 2000 years. Springer, Berlin Heidelberg New York, pp 9–41

Briffa K, Schweingruber F, Jones P, Osborn T, Shiyatov S, Vaganov E (1998) Reduced sensitivity of recent tree growth to temperature at high northern latitudes. Nature 391:678–682

Cayan D, Kammerdiener A, Dettinger M, Caprio J and Ingraham W Jr (2001) Changes in the onset of spring in the western United States. Bull Amer Meteorol Soc 82:399–415

Chapman W, Walsh J (1993) Recent variations in sea ice and air temperature in high latitudes. Bull Amer Meteorol Soc 74:2–16

Cook E (1985) A time series analysis approach to tree-ring standardization. Ph.D. thesis, University of Arizona

Cook E, Kairiukstis L (1990) Methods of dendrochronology: applications in the environmental sciences. Kluwer, Dordrecht

Cook E, Briffa K, Meko D, Graybill D, Funkhouser G (1995) The 'segment length curse' in long tree-ring chronology development for paleoclimatic studies. The Holocene 5:229–237

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

D'Arrigo R, Jacoby G, Free R (1992) Tree-ring width and maximum latewood density at the North American treeline: parameters of climatic change. Can J For Res 22:1290–1296

D'Arrigo R, Yamaguchi D, Wiles G, Jacoby G, Osawa A, Lawrence D (1997) A Kashiwa oak (*Quercus dentata*) tree-ring width chronology from northern coastal Hokkaido, Japan. Can J For Res 27:613–617

D'Arrigo R, Villalba R, Wiles G (2001) Tree-ring estimates of Pacific decadal climate variability. Clim Dyn 18:219–224

D'Arrigo R, Mashig E, Frank D, Jacoby G, Wilson R (2004) Reconstructed warm season temperatures for Nome, Seward Peninsula, Alaska since AD 1389. Geophys Res Lett 31. DOI 10.10298.2004GLO19756

Davi N, D'Arrigo R, Jacoby G, Buckley B, Kobayashi O (2002) Warm-season annual temperature variability for Hokkaido, Japan reconstructed from tree-ring density data: AD 1557–1990. Clim Change 52:201–217

Davi N, Jacoby G, Wiles G (2003) Boreal temperature variability inferred from maximum latewood density and tree-ring width data, Wrangell Mt. region, Alaska. Quat Res 60:252–262

Deser C, Phillips A, Hurrell J (2004) Pacific interdecadal climate variability: linkages between the tropics and North Pacific during boreal winter since 1900. J Climate 17:3109–3124

Efron B (1987) Better bootstrap confidence intervals. J Amer Stat Assoc 82:171–185

Esper J, Cook E, Schweingruber F (2002) Low-frequency signals in long tree-ring chronologies and the reconstruction of past temperature variability. Science 295:2250–2253

Esper J, Cook ER, Krusic PJ, Peters K, Schweingruber FH (2003) Tests of the RCS method for reserving low-frequency variability in long tree-ring chronologies. Tree-Ring Res 59:81–98

Fritts H (1976) Tree rings and climate. Academic, New York

Gedalof Z, Smith D (2001) Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophys Res Lett 28:1515–1518

Giddings J (1941) Dendrochronology in northern Alaska. University of Arizona Bull. 12: University of Alaska Publication 4

Giddings J (1948) Chronology of the Kobuk-Kotzebue sites. Tree-Ring Bull 14:26–32

Gostev M, Wiles G, D'Arrigo R, Jacoby G, Khomentovsky P (1996) Early summer temperature since 1670 AD for Central Kamchatka reconstructed based on a Siberian larch tree-ring width chronology. Can J For Res 26:2048–2052

Graumlich L, King J (1997) Late Holocene climatic variation in northwestern Alaska as reconstructed from tree rings. A final report on cooperative research with the National Park Service

Grove J (1988) The Little Ice Age. Methuen, London

Holmes R (1990) Dendrochronology Program Library—User's Manual. University of Arizona, Tucson

Hughes M, Diaz H (1994) Was there a 'Medieval Warm Period'? Clim Change 26:109–142

IPCC (2001) Intergovernmental panel on climate change: 3rd assessment report. Climate Change 2001: impacts, adaptation and vulnerability

Jacoby G, Cook E (1981) Temperature variations as inferred from a 400-year tree-ring chronology from Yukon Territory, Canada. Arctic Alpine Res 13:409–418

Jacoby G, 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, D'Arrigo R (1995) Tree-ring width and density evidence of climatic and potential forest change in Alaska. Global Biogeochem Cycles 9:227–234

Jacoby G, D'Arrigo R, Juday G (1999) Tree-ring indicators of climate change at northern latitudes. World Resources Rev 11:21–29

Jacoby G, Solomina O, Frank D, Eremenko N, D'Arrigo R (2004) Kunashir (Kurile Islands) oak response to temperature and relation to the Pacific Decadal Oscillation (PDO). Palaeogeogr, Palaeoclimatol, Palaeoecol 209:303–311

Juday G (1985) Proposed Camp Haven Gap research natural area. BLM, unpublished report

Kaplan A, Cane M, Kushnir Y, Clement A, Blumenthal M, Rajagopalan B (1998) Analyses of global sea surface temperature 1856–1991. J Geophys Res 103:18567–18589

Lamb H (1965) The early Medieval warm epoch and its sequel. Palaeogeogr, Palaeoclimatol, Palaeoecol 1:13–37

Lloyd A, Fastie C (2002) Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. Clim Change 52:481–509

Luckman B, Wilson R (2004) Summer temperatures in the Canadian Rockies over the last millennium—a revised record. Clim Dyn (in press)

Luckman B, Briffa K, Jones P, Schweingruber F (1997) Tree-ring based reconstruction of summer temperatures at the Columbia Icefield, Alberta, Canada AD 1073–1983. The Holocene 7:375–389

Mann ME, Lees J (1996) Robust estimation of background noise and signal detection in climatic time series. Clim Change 33:409–445

Mann ME, Bradley R, Hughes M (1999) Northern hemisphere temperatures during the past millennium: inferences, uncertainties and limitations. Geophys Res Lett 26:759–762

Mantua N, Hare S (2001) The Pacific Decadal Oscillation. J Oceanogr 58:35–44

Mantua N, Hare S, Zhang Y, Wallace J, Francis R (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. Bull Amer Met Soc 78:1069–1079

Minobe S (2000) Spatio-temporal structure of the pentadecadal variability over the North Pacific. Prog Oceanogr 47:381–408

Mitchell V (1967) An investigation of certain aspects of tree growth rates in relation to climate in the central Canadian boreal forest. Technical report No. 33. University of Wisconsin, Department of Meteorology, Wisconsin, p 62

Overland J et al (2004) Seasonal and regional variation of pan-Arctic surface air temperature over the instrumental record. J Climate (in press)

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

Seager R, Harnik N, Kushnir Y, Robinson W, Miller J (2003) Mechanisms of hemispherically symmetric climate variability. J Climate 16:2960–2978

Stone R (1997) Variations in western Arctic temperatures in response to cloud radiative and synoptic scale influences. J Geophys Res 102:21769–21776

Tranquillini W (1979) The physiological ecology of the alpine timberline. Springer, New York

Vaganov E, Hughes M, Kirdyanov A, Schweingruber F, Silkin P (1999) Influence of snowfall and melt timing on tree growth in subarctic Eurasia. Nature 400:149–151

Villalba R, Boninsegna J, Stahle D, Luckman B, D'Arrigo R, Lara A (2003) Tree-ring records of long-term variability in tropical and high-latitude circulation modes of climate in the Americas. Geophysical Research Abstracts 5: 13942. European Geophysical Society, Nice, France, April 2003

Vose R, Schmoyer R, Steurer P, Peterson T, Heim R, Karl T, Eischeid J (1992) The global historical climatology network: long-term monthly temperature, precipitation, sea-level pressure, and station pressure data, ORNL/CDIAC-53, Environmental Science Division, Publication No. 3912

Wigley T, Briffa K, Jones P (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J Clim Appl Met 23:201–213

Wiles G, D'Arrigo R, Jacoby G (1998) Gulf of Alaska atmosphere-ocean variability over recent centuries inferred from coastal tree-ring records. Clim Change 38:289–306

Wilmking M, Juday G, Barber V, Zald H (2004) Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. Global Change Biol 10:1724–1736

Wilson R, Luckman B (2002) Tree-ring reconstruction of maximum and minimum temperatures and the diurnal temperature range in British Columbia, Canada. Dendrochronologia 20:1–12

Wilson R, Luckman B (2003) Dendroclimatic reconstruction of maximum summer temperatures from upper treeline sites in interior British Columbia, Canada. The Holocene 13:851–861