The Holocene 9,5 (1999) pp. 629–634

Twentieth-century summer warmth in northern Yakutia in a 600-year context

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Received 28 July 1998; revised manuscript accepted 24 February 1999

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Abstract: We report unusual twentieth-century early-summer warmth recorded by larch tree-rings at the northern tree-line in far northeastern Eurasia (Yakutia). The tree-ring series are strongly replicated and well suited to the detection of fluctuations on interannual to century timescales. They are strongly correlated with local instrumental temperature data. Mean early-summer temperature in the twentieth century significantly exceeds that of any period of the same length since AD 1400. A century-scale trend, which commences in the mid-nineteenth century, is superimposed on interannual and decadal fluctuations, for example a marked cooling since 1978. While many of the 20 coolest early summers in the reconstruction occur within a few years after major explosive volcanic eruptions from low-latitude volcanoes, several of the 20 warmest early summers followed major explosive eruptions from high-latitude volcanoes.

Key words: Summer temperature, volcanic activity, dendrochronology, larch, *Larix cajanderi*, ring width, Yakutia.

Introduction

Long, high-resolution, natural records of climate permit an appraisal of twentieth-century climate in a historical context (Bradley *et al.*, 1996; Mann *et al.*, 1998). This perspective is important to an improved understanding of natural climate variability, as well as to the development of strategies for detecting anthropogenic climate change (Houghton *et al.*, 1996). Hence there is a pressing need for climate records that extend back before the Industrial Revolution in order to assess the nature and causes of natural climatic variability on interannual to century timescales (Hughes and Diaz, 1994). Few such records longer than 400 years exist outside western North America (Hughes, 1994), but a start has been made in some other regions, notably northern Eurasia (Briffa *et al.*, 1992; 1995; Graybill and Shiyatov, 1992). Bradley (1996) has attempted to identify optimum sites for global palaeotemperature reconstructions, using a 1000-year simulation from the GFDL coupled ocean-atmosphere general circulation model (Manabe *et al.*, 1991). He examined the contribution of 28 locations from which proxy data might be derived. Yakutia featured in the best 10 at both interannual and decadal timescales. This is also the Arctic land region that is most distant from other millennial or near-millennial annual resolution natural climate archives.

The tree-ring material

It has already been established that the annual rings of trees from northern Siberia contain excellent records of summer temperature in both their ring widths and maximum latewood density (Briffa *et al.*, 1995; Graybill and Shiyatov, 1992; Vaganov *et al.*, 1996). We have established a regional chronology (mean series of detrended ring widths) of *Larix cajenderi* Mayr. from the region around the settlement of Chokurdak in the Indigurka coastal lowlands of northern Yakutia. Material was collected from seven locations in the region bounded by latitudes 69°07′29″ and 70°32′23″ north and longitudes 143°56′18″ and 150°16′13″ east. It comprises cores from living trees, cross-sections from some living trees, and cross-sections cut from subfossil wood found in exposed river beds (the fieldwork was conducted in late summer when flow was lowest). All samples were crossdated (Stokes and Smiley, 1968) and ring widths measured to 0.01 mm. Mean ring width ranged from 0.20 to 0.36 mm, and percentage of missing rings from 0.27% to 0.90%, indicating slow grown trees sensitive to environmental variability. A composite regional chronology was produced, as the seven individual site chronologies (Hughes, Touchan, Funkhouser, Vaganov and Shiyatov, unpublished data) were highly correlated (mean correlation 0.66, n = 355). The regional chronology (Figure 1A) contained only samples with at

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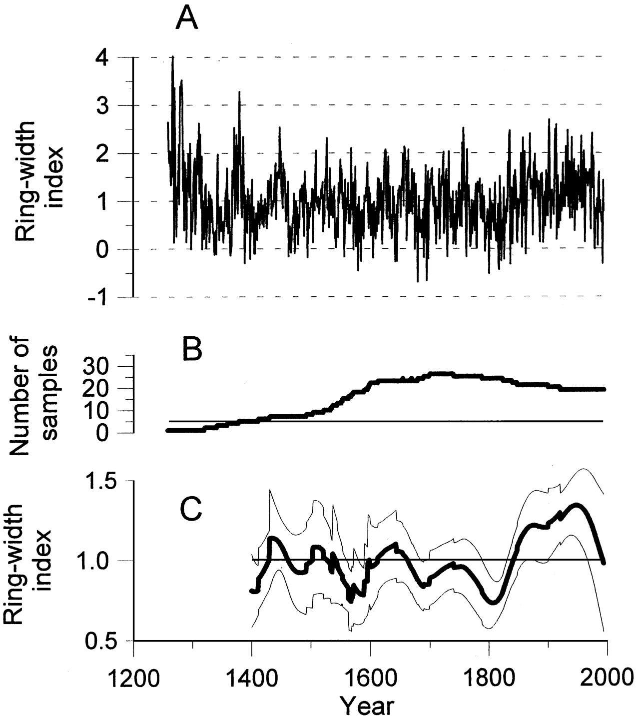

Figure 1 (A) The northern Yakutia larch regional tree-ring width chronology from AD 1400 to 1994. This is the mean of detrended time series of the widths of dendrochronologically dated tree rings from 34 samples, all with more than 300 annual rings. (B) Sample depth for the chronology. The heavy line shows the number of samples in the chronology in each year, the fine horizontal line indicates five samples, the level at which the chronology captures 85% of the variance common between samples at maximum replication (Wigley *et al.*, 1984). (C) The chronology produced by first fitting a spline with a 90% variance reduction function at 60 years to each sample's measurements and then taking their mean, is shown as the heavy line. The lighter lines are the 95% confidence limits for each year's value of this chronology.

least 300 annual rings, standardized by either a straight line or a negative exponential curve. That is, a line was fit to the time series of ring widths, and an index derived by dividing the observed ring width for a year by the calculated value. The reason for the use of these detrending methods was to minimize the removal of multidecadal to century scale fluctuations, while dealing with the age trend found in many tree-ring series. The standardized (detrended) individual samples were combined into a regional composite chronology using a biweight averaging procedure (Cook, 1985). The application of the 300-year minimum sample length reduced the number of available series from 78 to 34, but was deemed necessary in order to remove short series that could limit the capacity of the chronology to capture decadal up to centennial scale variability (Cook *et al.*, 1995). Of the samples that passed this test, 17 were shorter than 400 years, 15 between 400 and 500, and two more than 500 years long. Of the 34 series used, eight were detrended and standardized using a horizontal line through the mean, seven a straight line with negative slope, and 19 using negative exponential curves. Subsample Signal Strength (Wigley *et al.*, 1984) reached 0.85 in the mid-fourteenth century (Figure 1B). Sample depth varies along the chronology, and must affect the reliability with which environmental fluctuations in various frequency bands are recorded. Sheppard (1991) has developed a simple method for examining this effect. For example, in order to help assess whether variations of 60 years and longer shown by the chronology are consistent between the series making up the chronology, each individual core index series is smoothed using a spline that passes 90% of variance at 60 years and longer. Hence a distribution of smoothed index values is derived for each year, and confidence limits may be calculated for the chronology of 60-years and greater variation (Figure 1C). The only clearly significant fluctuation above the mean at 60 years and longer was the high growth centred on the mid-twentieth century. A low-growth period was identified for the period around the turn of the nineteenth century, and there were significant low-growth episodes at 60 years and longer at three earlier times. There was a similarly significant high growth period at 120 years and longer, also in the twentieth century (not shown).

Climate signal

There are strong correlations (Figure 2) between the composite regional ring-width chronology, and early-summer temperatures at Chokurdak (Razuvayev *et al.*, 1993). Although temperatures appear to be high enough for growth from the second pentad of June through mid-September on average, significant correlations between ring-width indices and pentad mean temperatures are not found after early July. The total number of tracheids produced and the mean radial diameter of earlywood tracheids determine most of the ring width in species with thin latewood such as *Larix*. Tracheids are the vertically aligned elements that make up most of the volume of conifer wood. The correlations (Figure 2) suggest that the role of temperature in determining one or both of these variables ends by mid-July. Early summer was defined as 6 June through 17 July on the basis of the strength of correlation between the tree-ring chronology and multiday temperature means for periods expanding out from late June. Our calculations of regression between the tree-ring series and mean surface temperature at Chokurdak used the period AD 1945 to 1989. This last year was determined simply by the availability of instrumental temperature records, whereas the starting year was chosen because of the incidence of missing data problems before 1945. Calibration R^2 was 0.62 ($F = 71.2$, $p < 0.0001$) and $R^2_{prediction}$ 0.60. $R^2_{prediction}$ is used in cross-validation, giving 'some indication of the predictive capability of the regression model' (Montgomery and Peck, 1992). In cases such as this, where R^2 and $R^2_{prediction}$ are similar, it is unlikely that there is significant overestimation of the skill of the model.

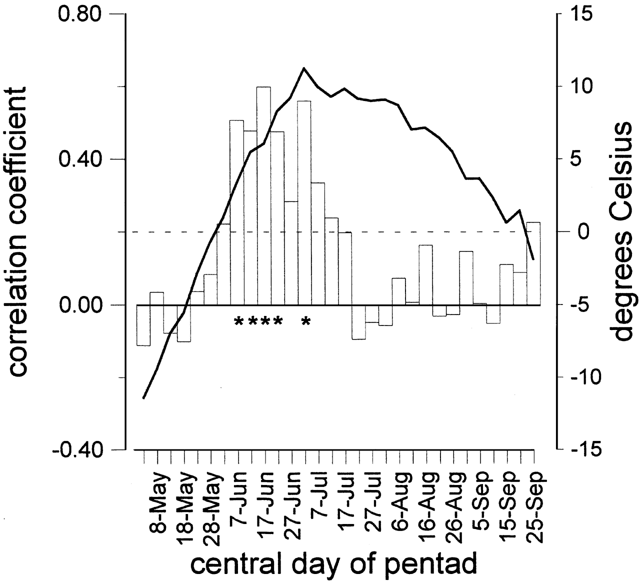

Figure 2 The continuous line shows pentad mean temperatures at Chokurdak, Yakutia, for the period 1945 through 1989 (right axis), with 0° Celsius shown as the broken line. The bar diagram shows correlations between each pentad's mean temperature and the Yakutia larch ring-width index chronology for the same years (left axis). Correlations were significant ($p < 0.001$) for pentads marked with asterisks.

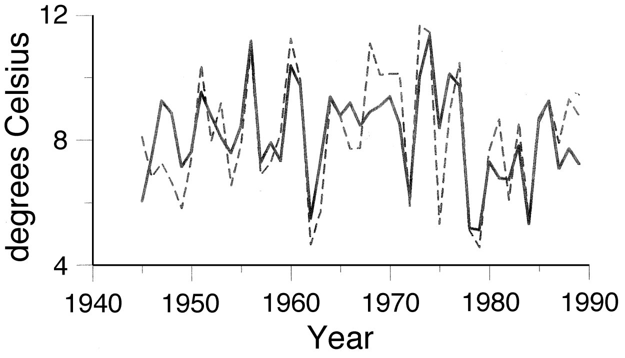

Figure 3 Actual (broken line) and reconstructed early summer (6 June through 17 July) temperature at Chokurdak, Yakutia.

Table 1 Correlation with Chokurdak mean temperature, 1945–1989

Month or season	Versus tree-ring chronology	Versus 6 June to 17 July instrumental
June	**0.74**	**0.87**
July	0.38	**0.61**
June/July	**0.70**	**0.91**
June/July/August	**0.56**	**0.80**
May through September	*0.40*	**0.68**
Prior October to current September	0.23	0.38
Calendar year	0.17	0.36

bold $p < 0.001$, *italic* $p < 0.01$, underline $p < 0.05$.

If the single outlier year 1975 is censored, calibration R^2 rises to 0.66 (F = 83.6, $p < 0.0001$). Figure 3 shows that, at least since 1945, the chronology also reflects multiyear trends in summer temperature. Correlations with monthly and seasonal mean temperatures at Chokurdak (Table 1) indicate that the chronology contains useful information on summer conditions beyond the optimal window of 6 June through 17 July, but no useful information outside the period May through September, at least on interannual timescales. Correlations with available gridded June/July mean temperatures (Jones *et al.*, 1999) in this region of the Arctic (Figure 4) are statistically significant ($p < 0.05$) for a range of approximately 1000 km.

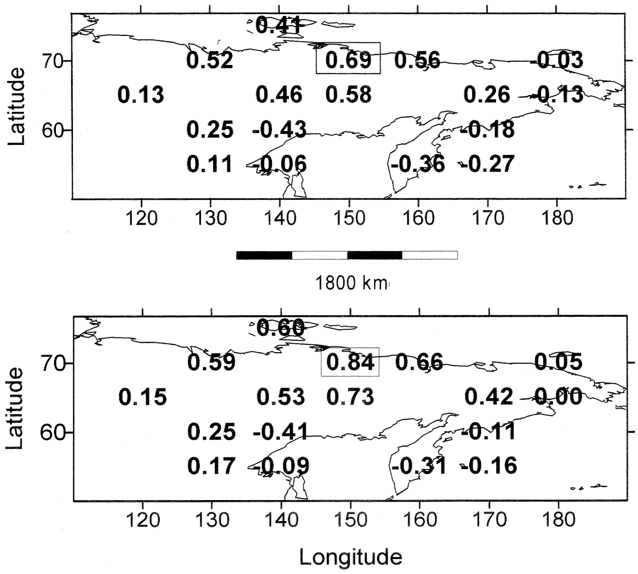

Figure 4 The upper panel shows the correlation coefficient between the Yakutia larch ring-width index chronology and mean June/July temperature at all gridpoints (5° latitude by 10° longitude) for which sufficient data were available for the period 1951–1989. The lower panel shows correlation coefficients between the 6 June through 17 July mean temperature at the Chokurdak station and the same mean June/July temperature data as in the upper panel. The coefficients enclosed in a box are those for the 70° north, 150° east gridpoint, very close to the Chokurdak station.

Briffa *et al.* (1998b) report a reduction in sensitivity of tree growth to summer temperature at high northern latitudes since the middle of the twentieth century. Their work was based on analysis of an extensive network of tree-ring chronologies. They found this effect to be stronger for maximum latewood density than for ring width. Given the limited length of the available meteorological records in our study region, we are not able to assess our data directly for this effect. Examination of Briffa *et al.*'s (1998b) Figure 1(b) indicates that this reduction in sensitivity is absent or minimal in the Indigurka coastal lowlands. We compared our reconstruction with June temperatures from Verhojansk, the nearest significantly longer station to Chokurdak, some 668 km to the southwest. The two series had a correlation coefficient of 0.45

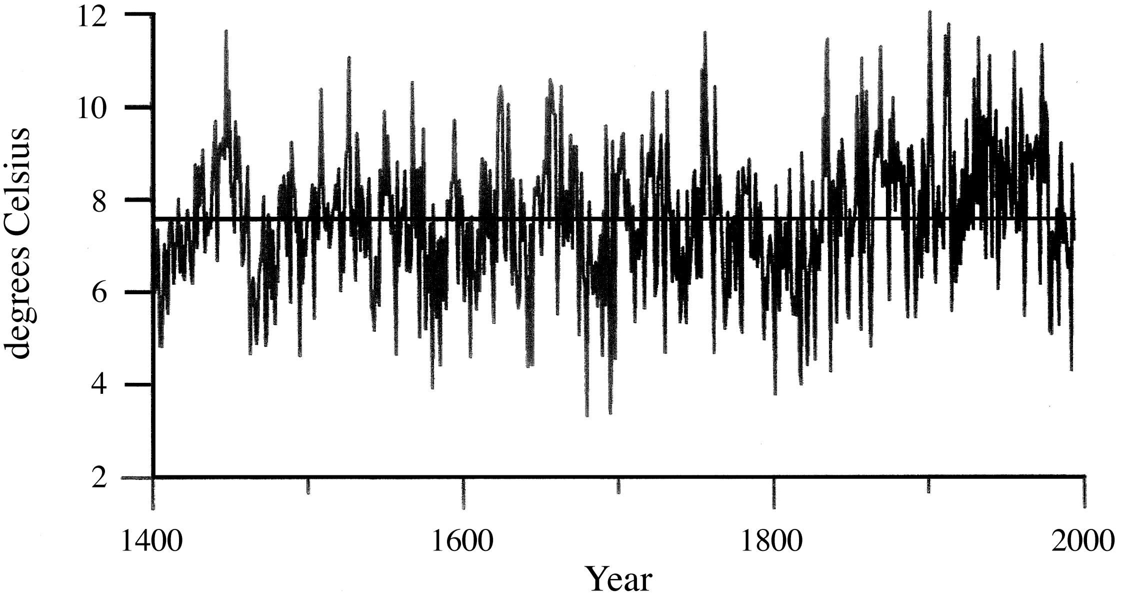

Figure 5 Early summer (6 June through 17 July) temperature at Chokurdak, Yakutia, reconstructed from larch tree rings. Horizontal line is twentieth-century mean.

($p < 0.001$) for 1907–1989, and 0.51 ($p < 0.001$) for 1945–1989. It should be noted that there are serious problems of missing data at Verhojansk, and that there have been a number of changes in observation procedures at this station (Razuvayev *et al.*, 1993). In the absence of clear evidence to the contrary, we do not consider the reduction in sensitivity problem to be significant for this study. If we are mistaken in this, the effect would be to strengthen the main conclusions of this paper, since we would be underestimating the strength of the temperature-ring width correlation, and the extent to which the twentieth century has been warmer than preceding centuries.

The reconstruction of early-summer temperature

The regression model was applied to the regional composite chronology to produce a time-series of reconstructed summer temperatures (6 June through 17 July) from AD 1400 to 1994 (Figure 5). The reconstruction we discuss begins at AD 1400 even though the chronology extended back to AD 1259, because the number of series contributing to the chronology before AD 1400 was judged to be insufficient (Figure 1B). Figure 5 shows that the twentieth century has warmer early-summer temperatures than the whole period since AD 1400. Only one of the twenty coldest summers in the reconstruction is in the twentieth century (1992), but eight of the twenty warmest summers are (Table 2). Of the ten coldest reconstructed summers, six follow within two years of a major volcanic eruption listed in Bradley and Jones (1992). Of those that do not (1580, 1642, 1695 and 1837) 1642 does follow the 1641 eruption of Parker in the Philippines (Briffa *et al.*, 1998a) and two (1695 and 1837), fall within 30 months after a major eruption. All but 1992 follow peaks in Robock's (1981) dust veil index and his (Robock and Free, 1996) Ice-core Volcano Index by not more than four years. It is likely that, were the Robock series updated, 1991 or 1992 would be one of the higher peaks,

Table 2 Extreme years of the Yakutia summer temperature reconstruction

Year	Mn Temp°C	Eruption[1]	Volcano	VEI	Latitude of volcano
20 coldest early summers					
1680	3.31	1680	Tongkoko, Sulawesi	5(?)[2]	1.5N
1695	3.37	–	–	–	–
1801	3.78	1800w[3]	St Helens, WA	5	46.2N
1580	3.93	–	–	–	–
1818	3.99	1815s	Tambora, Lesser Sunda Is	7	8.3S
1837	4.27	1835w	Cosiguina, Nicaragua	5	13.0N
1992	4.29	1991u	Pinatubo, Philippines	6	15.1N
1817	4.31	1815s	Tambora, Lesser Sunda Is	7	8.3S
1642	4.38	1641w	Parker, Philippines	6	6.1N
1822	4.41	–	–	–	–
1585	4.42	–	–	–	–
1645	4.43	1641w	Parker, Philippines	6	6.1N
1827	4.52	–	–	–	–
1643	4.53	1641w	Parker, Philippines	6	6.1N
1698	4.56	–	–	–	–
1605	4.60	–	–	–	–
1690	4.62	–	–	–	–
1495	4.62	–	–	–	–
1557	4.66	–	–	–	–
1463	4.67	–	–	–	–
20 warmest early summers					
1902	12.03	–	–	–	–
1914	11.77	1912u	Novarupta (Katmai), AK	6	58.3N
1448	11.63	–	–	–	–
1757	11.59	–	–	–	–
1912	11.51	1912u	Novarupta (Katmai), AK	6	58.3N
1933	11.47	1932s	Cerro Azul (Quizapu), Chile	5(+)	35.7S
1836	11.44	1835w	Cosiguina, Nicaragua	5	13.0N
1974	11.31	–	–	–	–
1870	11.28	–	–	–	–
1835	11.18	1835w	Cosiguina, Nicaragua	5	13.0N
1956	11.15	1956s	Bezymianny, Kamchatka	5	56.0N
1940	11.08	–	–	–	–
1527	11.05	–	–	–	–
1858	11.04	1854w	Sheveluch, Kamchatka	5	56.7N
1755	10.78	–	–	–	–
1930	10.58	–	–	–	–
1657	10.57	–	–	–	–
1568	10.51	–	–	–	–
1664	10.43	1663u	Usu, Japan	5	42.5N
1625	10.43	–	–	–	–

[1] Details of eruptions were taken from Table 1 in Briffa *et al.* (1998b), which was based on Simkin and Siebert (1994).
[2] ? indicates uncertainty about VEI; + indicates upper third of grade.
[3] Season of eruption: w – Dec–Feb; s – Mar–May; u – Jun–Aug.

representing the effects of the eruption of Mt Pinatubo in 1991. By reference to the modified catalog of Simkin and Siebert (1994) reported by Briffa *et al.* (1998a), we can assign only four of the twenty coldest summers to periods of not more than two years after major volcanic eruptions dated to the year (mean VEI 5.7, n = 7) (Table 2). It should be noted that one of these cold summers followed the eruption of Parker in 1641. A major volcanic eruption had a volcanic explosivity index (VEI) of 5 or greater, and 31 such eruptions were listed by Briffa *et al.* (1998a).

None of the coldest 20-year or 50-year periods are in the twentieth century, although the fifth-coldest 90-year period covers the first 26 years of this century (Table 3). The coldest 90-year period ended in 1828, the coldest 50-year period in 1827, and the second coldest 20-year period in 1817. As well as examining the coincidence of the coolest summers with major volcanic eruptions, we examined the timing of the warmest summers relative to such eruptions. Somewhat surprisingly, seven of the warmest early summers followed within two years of major eruptions (mean VEI = 5.7, n = 4) (Table 2). Interestingly, only two of these seven warm summers (1835 and 1836) were associated with a low-latitude eruption (Cosiguina in 1835), unlike the coolest summers, where three of the four following within two years of major eruptions involved volcanoes at low latitude, as were six of the seven within three years. Cosiguina was also associated with one of the cooler summers (1837). We found no evidence to support the suggestion that these reconstructed warm summers represented a rebound in tree growth from volcano-induced cold conditions. Useful information on the climate effects of volcanic eruptions may not be limited to years with unusually cool summers, but may also be extracted from reconstructed unusually warm summers. This possibility requires further testing in other northern regions, as has already been done for the association between volcanic eruptions and cold summers in northern regions (Briffa *et al.*, 1998a). The warmest 90- and 50-year periods ended in 1976, while the warmest 20-year period ended in 1456 (Table 3). The sudden drop in summer temperatures in 1978 is recorded by trees and the instrumental record (Figure 3). This feature is also seen in the larch-based reconstructions from the northern and southern reaches of the Kolyma drainage basin (Johansen, 1995; Earle *et al.,* 1994), as are some other decadal scale features, notable cool conditions in the first two decades of the nineteenth century, and warmth in the mid-twentieth century. Summer temperature is shown to be the primary determinant of tree-ring index in both these studies, which are based on single-site chronologies reaching back to 1631 and 1545 respectively.

Table 3 Extreme periods

	Temperature °C		Temperature °C
Coldest 20-years		**Warmest 20-years**	
1 1462–1481	6.28	1 1437–1456	8.85
2 1798–1817	6.30	2 1924–1943	8.77
3 1678–1697	6.30	3 1957–1976	8.75
4 1569–1588	6.60	4 1865–1884	8.73
5 1401–1421	6.62	5 1894–1913	8.56
6 1734–1753	6.85	6 1654–1673	8.48
7 1631–1650	6.85	7 1611–1630	8.13
8 1600–1619	6.92	8 1507–1526	8.09
9 1760–1779	6.97	9 1928–1846	8.04
10 1527–1546	7.16	10 1747–1766	8.02
Coldest 50-years		**Warmest 50-years**	
1 1778–1827	6.68	1 1927–1976	8.66
2 1457–1506	6.98	2 1864–1913	8.39
3 1571–1620	7.01	3 1411–1461	7.91
4 1668–1717	7.15	4 1622–1671	7.89
5 1728–1777	7.33	5 1504–1553	7.73
Coldest 90-years		**Warmest 90-years**	
1 1739–1828	6.97	1 1887–1976	8.38
2 1555–1644	7.19	2 1587–1676	7.63
3 1457–1547	7.25	3 1438–1528	7.62
4 1649–1738	7.56	4 1796–1885	7.53
5 1836–1925	8.01	5 1696–1785	7.52

The twentieth century in a 600-year context

In the Yakutia reconstruction (Figure 5) the mean early-summer temperature for 1900–1994 was 8.2°C compared to 7.6°C for 1400 to 1899, and the t-test probability of the means being drawn from the same population is less than 0.0001, in spite of the dramatic decline in temperatures since 1978 (mean for 1978–1994 is reconstructed as 6.9°C). The mean early summer temperature of the warmest 90-year period (1887–1976) was compared with that of the second and third warmest periods (1587–1676 and 1438–1527). In the case of both comparisons, the probability of both means being from the same population is less than 0.002. Similarly, the probability of the 1887–1976 mean (8.3°C) being drawn from the same population as the 1400–1886 mean (7.6°C) is less than 0.0001. The reconstructed summer temperature series contains multidecadal and century timescale variations, for example the predominantly cold periods in the late fifteenth, sixteenth, seventeenth centuries, eighteenth and early nineteenth centuries, and the predominantly warm periods in the mid-fifteenth, mid-seventeenth and eighteenth centuries, and in the period since the mid-nineteenth century. Of these features, higher temperatures in the twentieth century are shared with other tree-ring records at high northern latitudes, (Briffa *et al.,* 1995; Jacoby and D'Arrigo, 1991) and at high-elevation sites in continental interiors (e.g., LaMarche, 1974; Jacoby *et al.,* 1996). The development of all of these records was characterized by strenuous attempts to conserve multidecadal to century scale climate signal. The most closely comparable is the Polar Urals summer temperature reconstruction (Briffa *et al.,* 1995), as it is based on the tree-rings of larch near the northern tree-line. The unusual nature of the sustained high summer temperatures of the early and mid-twentieth century in these two widely separated regions of far northern Eurasia is clear. To that extent, our results support Briffa *et al.*'s (1995) conclusion of 'unprecedented recent warmth'. Where our results differ is in the warming commencing several decades earlier. Much of the warming in northern Yakutia had already taken place by the late nineteenth century. Given the distance between the two regions, and the differing influences on their climate, a difference is not too surprising. These differences indicate that broad similarities in climate variability during the twentieth century may not be reliable indicators of parallel behaviour in preceding centuries. Thus no record from a single location should be considered representative of multidecadal to century scale climate variability in the Arctic. Rather, our results demonstrate the need for a denser network of annual resolution climate records for the last thousand years. Such a network would provide invaluable background if twentieth-century climate is to be put in the context of pre-industrial climate variability, and for the design of strategies for the detection of anthropogenic climate change.

Acknowledgements

This work was supported by NSF grant ATM9413327. Thanks are due to Isai Eger and Anatoly Boychenko for field assistance, and to the Institute of Biology, RAS, Yakutsk, for general logistical support. The cooperation of the local authorities in Chokurdak, Sacca Republic, Russian Federation, is gratefully acknowledged. Henry Diaz made helpful comments on an earlier draft.

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