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A continuous multimillennial ring-width chronology in Yamal, northwestern Siberia

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Abstract: Remains of subfossil Siberian larch trees in the Holocene deposits of the Yamal Peninsula (Western Siberia) have been collected in order to develop a continuous, multimillennium tree-ring-width chronology. This work has produced a calendar-age dated 4000-year (2000 BC to AD 1996) series. From these data, summer-temperature variability in this region has been estimated on annual to multidecadal timescales. Radiocarbon dating of selected older material shows that the oldest subfossil wood is 9400 years old and the dates of the sampled material are generally distributed evenly through time. It will, therefore, be possible to develop a tree-ring chronology for more than nine millennia. An initial assessment of long-term fluctuations in Yamal summer warmth has been realized through the reconstruction of tree-line dynamics using a combination of dendrochronological (absolute) dated material and less precisely (radiocarbon) dated older subfossils.

Key words: Dendrochronology, tree rings, summer temperature, subfossil wood, larch, *Larix sibirica*, tree-line dynamics, Western Siberia, Holocene.

Introduction

The reconstruction and analysis of natural climatic changes at high latitudes throughout the whole Holocene is an important goal. However, there are very few long, precisely dated and high-resolution proxy climatic series for these regions. Tree rings as a proxy indicator of past environmental conditions are of special interest as they facilitate the reconstruction of climatic parameters with seasonal and annual resolution for many hundreds and even thousands of years. To develop multimillennial tree-ring chronologies it is necessary to find special regions that meet specific requirements: well-preserved remains of trees that are well distributed throughout the Holocene and that exhibit high sensitivity to climatic changes. It is shown here that one such area with potential for developing near-Holocene-length series is the Yamal Peninsula, just east of the northern Polar Ural Mountains in northwestern Siberia.

Background to dendrochronology in Yamal

Holocene deposits in the southern Yamal Peninsula contain a large amount of subfossil tree remains: tree trunks, roots and branches. This is the result of intensive accumulation and the good preservation of buried wood in the permafrost. The occurrence of this material in the present-day tundra zone of the Yamal Peninsula was described for the first time by Zhitkov (1913). Later, Tikhomirov (1941) showed that, on the evidence of remains of trees preserved in peat, during the warmest period of the Holocene, the northern tree-line reached the central region of the Yamal Peninsula (up to 70°N), whereas today the polar timberline passes through the southernmost part of the peninsula at a latitude of 67°30′N.

By 1964, attention had been drawn to the potential significance of Yamal subfossil wood for reconstructing climatic and other natural processes over many thousand years, as a result of fieldwork carried out within the valley of the Khadytayakha River in the southern part of the Yamal Peninsula (Shiyatov and Surkov, 1990).

The systematic collection of subfossil wood samples was begun, in 1982, in the basins of the Khadytayakha, Yadayakhodyyakha and Tanlovayakha rivers in southern Yamal in the region located between 67°00′ and 67°50′N and 68°30′ and 71°00′E (Figure 1). These rivers flow from the north to the south; hence, no driftwood can be brought from the adjacent southern territories. At the present time, the upper reaches of these rivers are devoid of trees; larch and spruce-birch-larch thin forests are located mainly in valley bottoms in the middle and lower reaches.

The most intensive work on constructing a supra-long chronology in Yamal has been carried out during the last six years. Some preliminary results were published in 1995 and 1996 (Hantemirov, 1995; Shiyatov *et al.*, 1996; Hantemirov and Surkov, 1996). The present article reviews the recent status of the work, partly undertaken as a contribution to the ADVANCE-10K programme, and incorporates a review of other recent articles (i.e., Hantemirov, 1999; Hantemirov and Shiyatov, 1999a; 1999b).

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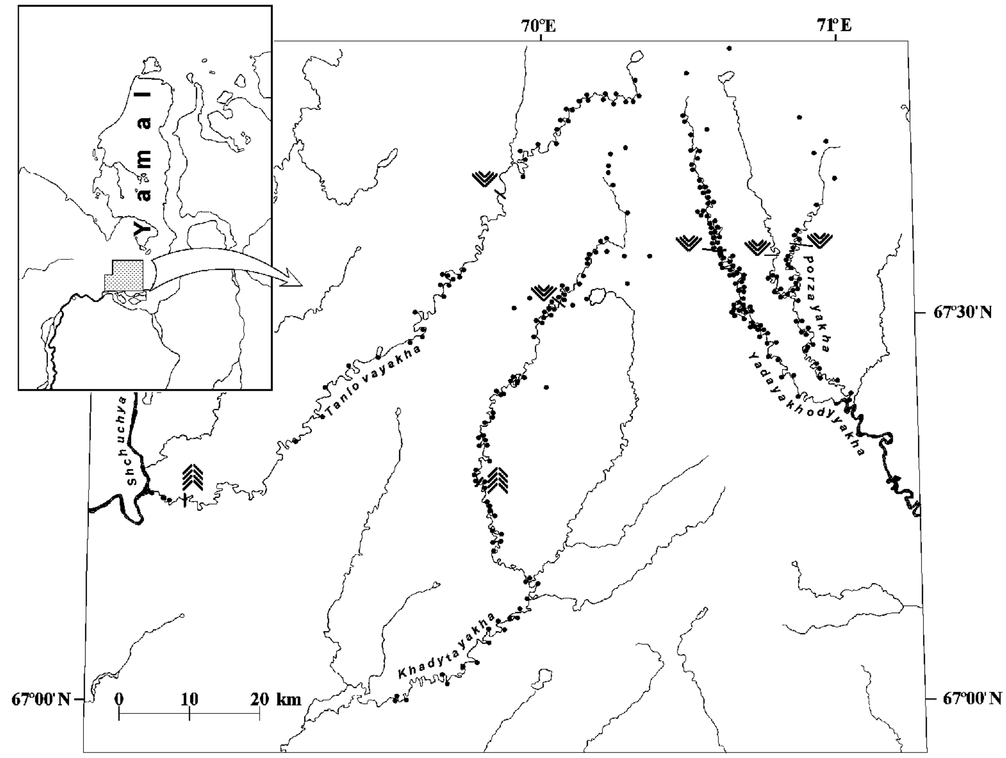

Figure 1 Subfossil wood sampling sites. Symbols show the present-day polar boundary of (upward-pointing arrows) spruce and (downward-pointing arrows) larch growth in river valleys.

Methods and materials

Subfossil sites

Remains of dead trees can be found lying on the surface and tend to be up to a maximum of 750 years old. Within the frame of this research, some 30 of these dead trees have been collected. There is also subfossil wood at the bottom of thermokarst lakes, but this source of material is much more difficult to collect and has not, as yet, been explored.

However, by far the most significant source of subfossil wood remains, often trunks in a near-complete state, with bark, roots and large branches, is the material found in alluvial deposits. In the southern part of the Yamal Peninsula very intensive lateral erosion of sandy riverbanks occurs, according to our observations up to 2–4 m per year. Living trees, growing along the river terraces, are undermined and often fall into the running water (Figure 2). This occurs mainly in spring and early summer, when water level and stream velocities are high.

Some fallen trees remain at the bottom of the river near to their growth sites. After a few years these trees are buried by sand and silt deposits. As the river channel is continually moving, these buried trees soon become incorporated within the permafrost layer. Subfossil wood lies usually up to 5–6 m below the surface and can be exposed by the river, perhaps after many hundreds or thousands of years, when the riverbed is deepened. The frequency of log deposits is variable. In the best case, 50–60 stems may be exposed within a distance of 200–400 m along the river (Figure 3). In total, 1945 samples have been collected from alluvial deposits at the time of writing.

The second important source of subfossil wood is peat deposits. In this area, there are a large number of mires that reach a depth of 2–3 m. The largest logs are usually found at the base of these peats, where they are exposed by the erosional activity of lakes and rivers. Large lakes, with dimensions of more than 1 km are very strongly affected by wave erosion, which is typical for regions with permafrost and where there are often strong winds during the summer months. Such wood remains are *in situ* because these trees probably grew in depressions and were subsequently engulfed by later peat formation. To date, 196 samples have been recovered from such peat deposits.

Materials

We travelled by helicopter to the upper reaches of the river to be sampled. Small boats were then used for locating and collecting cross-sections from wood exposed along the riverbanks. It was also possible, when going with the stream, to explore the nearest lakes.

The best-preserved material from an individual tree is usually found at the base of the trunk, near to the roots. However, many of these remains are radially cracked and it is necessary to tie cross-sections, cut from these trunks or roots, using aluminium wire before sawing. This wire is left in place afterwards as the sections are air-dried.

At present, a total of 2171 sawn wood samples has been collected: from trunks and some roots of subfossil larch (*Larix sibirica* Ldb.); and from spruce (*Picea obovata* Ldb.) and birch (*Betula tortuosa* Ldb.). By far the greatest proportion of these samples is made up of Siberian larch (95%) with most of the remainder being Siberian spruce (4%) and the rest mountain birch (1%). However, it has to be noted that sometimes it is very difficult to distinguish between larch and spruce on anatomical grounds. All of these samples are now stored at the Laboratory of Dendrochronology at the Institute of Plant and Animal Ecology, Ekaterinburg, Russia.

Most of the wood samples contain only 60–120 rings (Figure 4). The maximum number of counted rings in any subfossil sample is 501, and the average of all samples is 125 rings. Living larch and spruce trees in this region may have up to a maximum of 400 rings.

Radiocarbon dating

To provide some estimate of the possible length of the eventual chronology, 55 radiocarbon dates from 53 remains of subfossil trees (51 samples of larch and 2 of spruce) were determined.

Figure 2 Living larch and spruce trees falling into the Khadytayakha River. (Photograph: S.G. Shiyatov.)

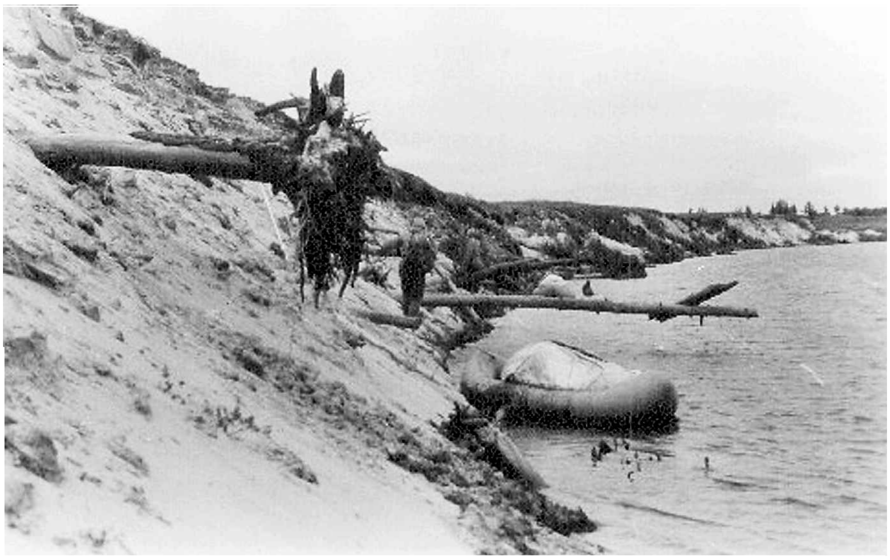

Figure 3 Subfossil wood of larch and spruce in alluvial deposits of the Yadayakhodyyakha River. The larch in the foreground died in 751 BC. (Photograph: S.G. Shiyatov.)

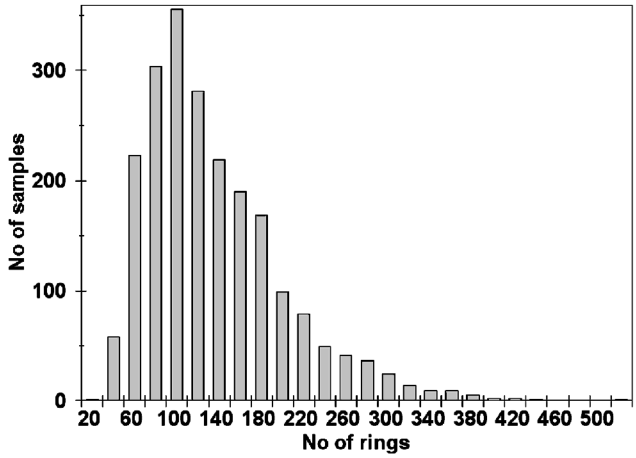

Figure 4 The distribution of the number of rings in the subfossil wood collection.

Radiocarbon analysis and data calibration were performed in the Laboratory of Historical Ecology of the Institute of Plant and Animal Ecology, Ekaterinburg (11 dates) and the Radiocarbon Laboratory of the Physical Institute of Bern University (44 dates). Two samples were dated in both laboratories. Comparison of these results showed an acceptable degree of similarity in the dates obtained. The results of the radiocarbon dating of subfossil wood from the Yamal Peninsula have been published earlier (Shiyatov and Erokhin, 1990; Shiyatov *et al.*, 1996; Hantemirov and Shiyatov, 1999a; 1999b).

These dates show that the absolute age of the oldest subfossil wood reaches 9200–9400 years. The dates are distributed more or less evenly through time (but see below). This provides strong evidence of the feasibility of developing a tree-ring chronology that is more than 9000 years long. Moreover, the radiocarbon dates provide a basis for distinguishing several main stages of tree vegetation development in the Yamal Peninsula in the Holocene (Hantemirov and Shiyatov, 1999a; Figure 5).

Using our own data and some additional data from other authors, it is possible to propose the following general scheme:

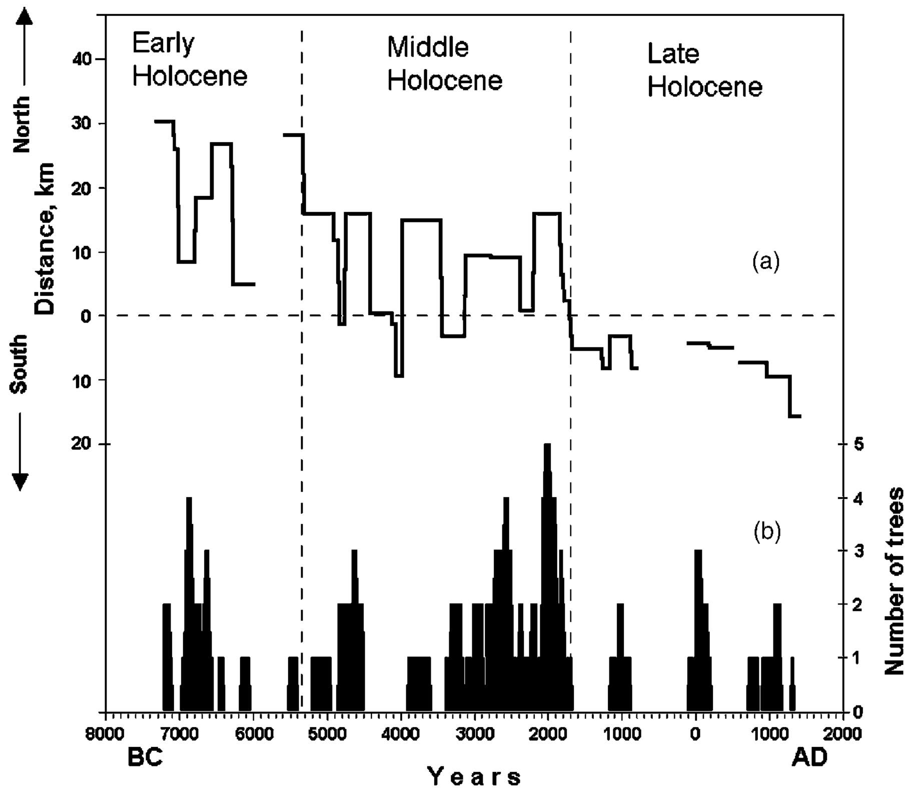

Figure 5 Fluctuations in the northern boundary of coniferous trees with respect to the current location of the northernmost clumps of larch in river valleys (a); and the temporal distribution of the numbers of radiocarbon dated samples (b). A proposed division of the Holocene in Yamal based on these data is also shown (from Hantemirov and Shiyatov, 1999a).

open larch forests were already growing in Yamal in the early Holocene, i.e., 9–10.5 thousand years ago. The most favourable period for tree growth lasted from 7200 to 6000 BC. Then, until 5600 BC, climatic conditions deteriorated somewhat; however, this did not result in any significant shift of the polar boundary to the south. Such a shift did occur later, at about 5400 BC. By that time, the overall density of forests in Yamal had also decreased considerably. Hence, this period may be considered one of transition to the next period of the Holocene. From 5400 to 1700 BC, the polar tree-line boundary was located at approximately 69°N. Trees survived in river valleys during unfavourable periods (4500–3900 and 3600–3400 BC) and expanded to interfluvial habitats during the more favourable times (5200–4500, 3900–3600 and 3400–1800 BC). Although the last period was probably one of the most favourable in the Holocene, the tree-line failed to return to the position it attained at 5400 BC.

A strong southward shift of the polar boundary of open forests and a significant decrease in stocking density occurred for the second time at approximately 1700 BC. This stage may be regarded as the end of the middle Holocene and the onset of the current stage of tree vegetation development in the Yamal Peninsula. Over the past 3700 years, forest-and-tundra communities were preserved mainly in river valleys located in the very south of the Yamal Peninsula. Relatively favourable conditions existed in 1200–900 BC, 100 BC–AD 200, and during the 'Mediaeval Optimum' (AD 700–1400).

Tree-ring chronology construction

The definition of tree rings on cross-sections of subfossil larch is reasonably good, though the clarity of rings can be improved by rubbing chalk powder into the wood vessels. Total ring-width measurements have been made along one radius of some 2170 samples, with an accuracy of 0.01 mm. Considering that, first, the climatic conditions within this area are very homogeneous and, second, that the sensitivity (a measure of interannual-timescale variability; Fritts, 1976) of the individual tree-ring series tends to be very high (mean sensitivity coefficients range from 0.3 to 0.6), the majority of the sample series can generally be dated using standard cross-dating techniques applied between samples. Series that cannot be confidently cross-dated are those that are generally too short (i.e., contain too few rings). The percentage of successfully cross-dated samples that contain more than 150 rings is about 80%. The number of dated series with less than 100 years is about 35%. Spruce chronologies also cross-date well with the larch data.

The main difficulty in cross-dating tree-ring series in this region is the occurrence of frequent 'missing' rings on measured radii. In some samples, generally those with relatively narrow rings, up to 5–10% of the rings are absent on the measured radius.

The first step in developing a multimillennial ring-width chronology is the production of several 200–400 year long 'floating chronologies' – groups of individual series firmly cross-dated relative to each other but only preliminarily anchored in time on the basis of radiocarbon dates. Construction of the absolutely dated chronology was started using tree rings of living trees growing in the southern part of the Yamal Peninsula, within the river valleys mentioned above. Initially, a 1250-year chronology from the Polar Ural mountains (Shiyatov, 1995) was used as a 'master' dating series as well. There is a high degree of similarity in the annual variability of radial tree growth between the Yamal and Polar Urals areas because of their proximity (about 200 km).

Later, the main problem was to establish positive overlap positions between the absolute (recent) series and the most recent 'floating' chronologies. Some periods proved to be difficult to bridge, notably between 350 and 450 BC, and especially 1250 and 1350 BC. For these time intervals, the chronologies should still be considered 'provisional' due to the relatively low sample replication.

However, at present we have some confidence in considering the chronology to span the 4000 years from 2000 BC to the present with high reliability. Within this period, data from 535 subfossil wood samples are incorporated: 513 of them collected from alluvial deposits and 22 on the surface. Figure 6 shows the sample distribution through time of the trees recovered from alluvial deposits.

A 'corridor-standardized' version of the Yamal chronology

In one approach to constructing a mean chronology, 224 individual series of subfossil larches were selected. These were the longest and most sensitive series, where sensitivity is measured by the magnitude of interannual variability. These data were supplemented by the addition of 17 ring-width series, from 200–400 year old living larches.

To remove the growth trend that can obscure climatic influences on tree growth, a procedure known as standardization (Fritts, 1976), the 'corridor method' was used, as described in detail in Shiyatov (1986). This incorporated some correction of the mean chronology to reduce the variance where this was artificially inflated due to low replication, here taken to be those time intervals with fewer than seven samples per year. This amounted to 605 years (15% of the total chronology length). Within these periods, a larger correction was made for periods represented by only three samples (97 years, 2.4%). Figure 7 shows the corrected corridor-standardized version of the absolute Yamal larch chronology. This emphasizes interannual to multidecadal timescales of variability.

Climatic reconstruction

The width of the annual growth rings in many tree species depends, among other things, on the width of one or more previous rings (manifest as statistically measurable autocorrelation). This is due to the degree of biological persistence that follows from extended physiological processes such as needle formation and longevity, and storage of materials (Fritts, 1976). Rather than using a lagged regression model, incorporating predictors from years prior to (and sometimes following) the predictand climate year (e.g., Briffa *et al.*, 1983), the chronology was instead statistically prewhitened and the residuals from a general autoregression model were used for estimating past climate variability. This means that the resulting reconstructions are representative of interannual to multidecadal timescales only and will not show century- to millennial-scale changes. These are explored later using the evidence of tree-line changes.

At high latitudes, interannual variability in ring width is known to correlate well with variations in summer temperature. To define the optimum season for this study, we correlated individual monthly mean temperature series with the prewhitened chronology. The temperature data used were observations from the Salekhard meteorological station located 150 km to the southwest of the research area. Correlations were calculated for the period AD 1883–1996.

The largest correlation coefficients show that ring width is increased in association with warm conditions during June and, more especially, during July, with correlation coefficients for June of 0.35 and for July of 0.63. An average of June and July mean temperatures was therefore selected as the predictand to be reconstructed using these tree-ring data.

The complete reconstruction is plotted in the form of temperature anomalies from the mean of the full reconstructed period (2000 BC–AD 1996) in Figure 8.

This long record shows that the amplitude of temperature variability within the range being reconstructed here has altered noticeably through time. Figure 9 summarizes the changes in interannual variability of summer temperatures over the last 4000 years in this region. There is no correlation between this variability and mean reconstructed temperatures over corresponding 50-year periods. Various periods can, therefore, be categorized according to their mean and variance, i.e., periods with similar mean temperature may be distinguished according to whether they exhibit high interannual variability or low variability, implying different potential impacts on people and ecosystems.

The separate frequencies of extreme cold and extreme warm summers are shown in Figure 10. High numbers of moderate ($<2\sigma$) negative extremes occur in the eighth and sixth centuries BC, and the first and thirteenth, fourteenth, sixteenth and eighteenth centuries AD. There are none in the third century BC. Most equivalent positive extremes occurred in the tenth, fifth and second centuries BC and in the seventeenth and eighteenth centuries AD. None occurred in the seventeenth and thirteenth centuries BC.

Before discussing relatively long-term variations in the

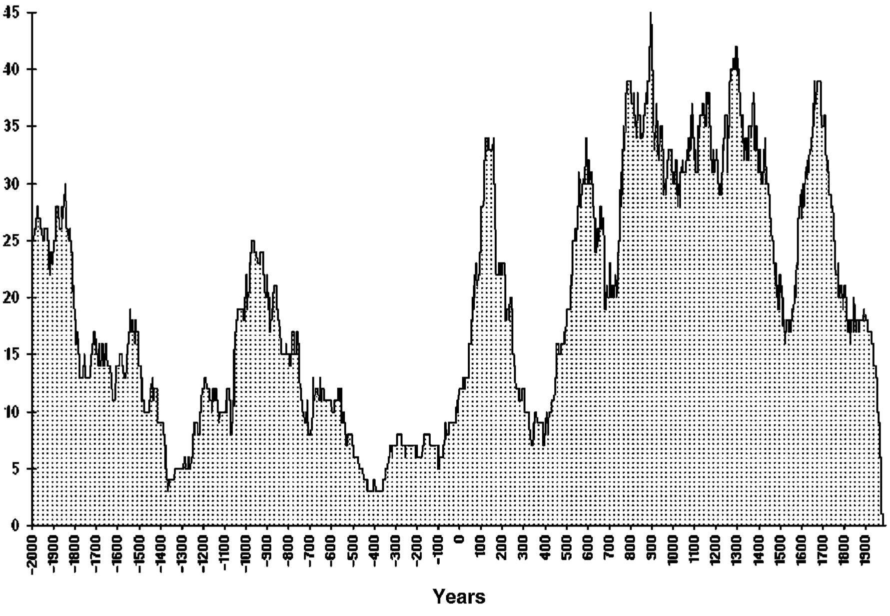

Figure 6 The temporal distribution of all subfossil trees used in the chronology.

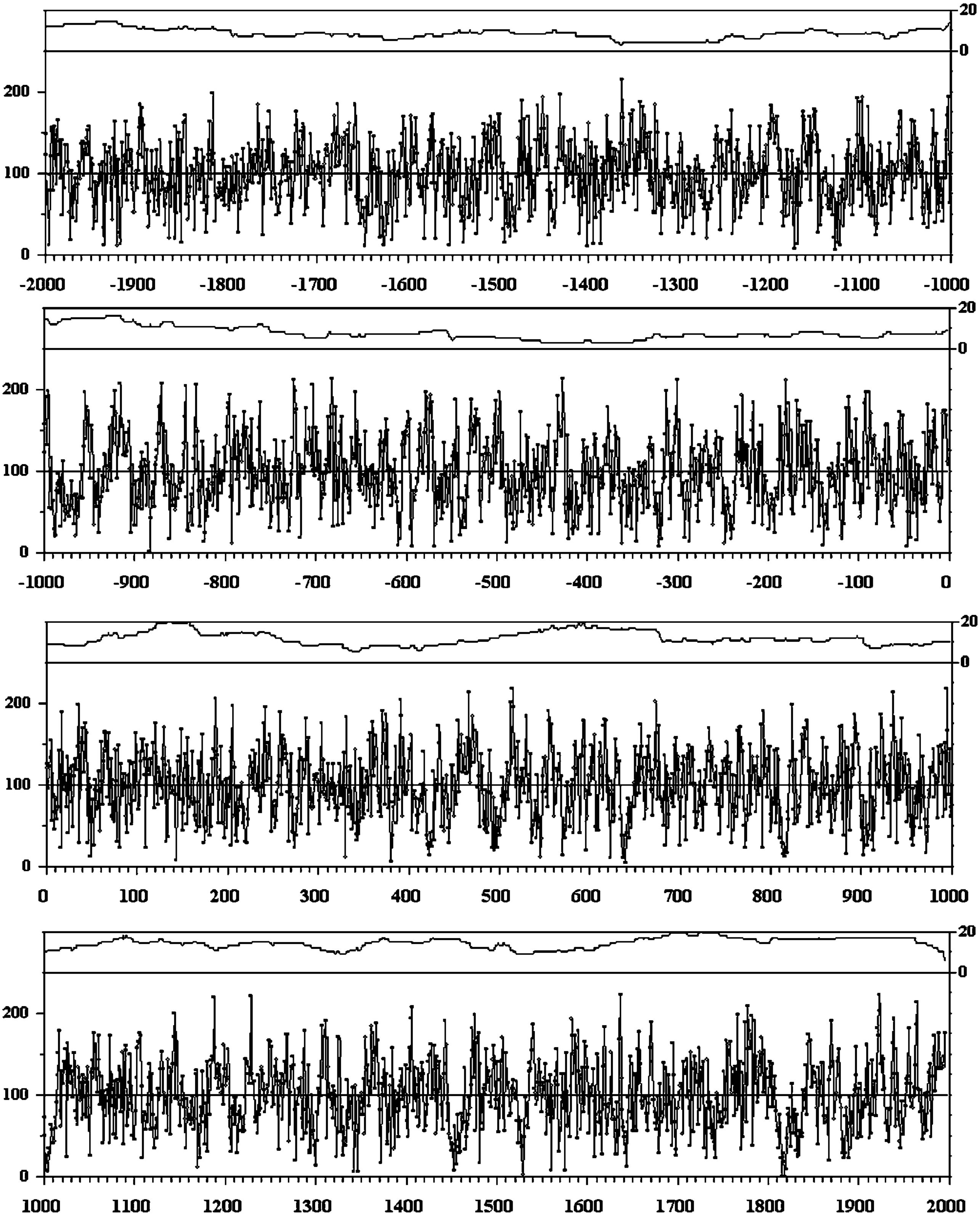

Figure 7 Corridor-standardized version of the absolute Yamal larch chronology. The units are arbitrary indices with an overall mean of 100. The histogram shown above each panel shows the number of samples incorporated at that time.

reconstructions (Figure 11), it is necessary to stress again that the majority of constituent tree-ring series forming the chronology range in length from about 100 to 300 years (on average 180 rings). This fact, and the method of standardization used here to remove non-climatic trends that are of equivalent length or longer than the series in question, mean that the calibrated reconstruction will not represent multicentennial or longer variations in temperature, despite the total length of chronology (e.g., Cook *et al.*, 1995). However, fluctuations of summer temperatures on annual, decadal and part-century timescales are discernible.

Having emphasized the effective band-pass nature of the reconstruction, it is apparent (Figure 11a) that many of the extreme decadal-timescale cold periods occurred within the last 1400 years. The most severe were AD 620–650, 800–830, 995–1015 (the most severe cooling), 1440–1470, and, finally, 1805–1840.

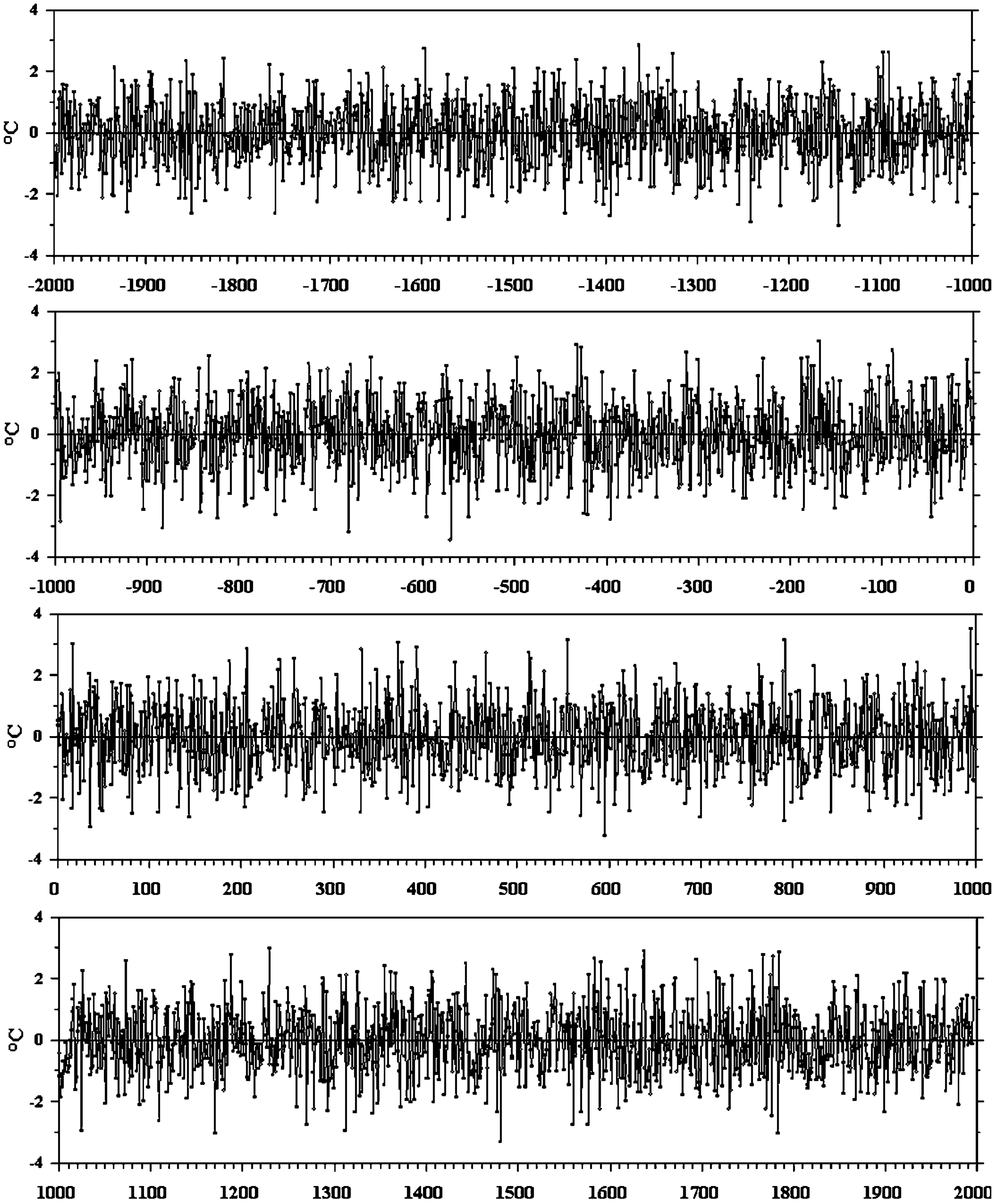

Figure 8 Reconstructed southern Yamal mean June–July temperature anomalies relative to mean of the full reconstructed series.

Many short warm periods occurred during the first half of the reconstruction, in 1210–1190, 530–500, and 440–425 BC.

Among the more notable longer (multidecadal) cool periods, the most severe occurred in the nineteenth century AD, while other, longer, cool periods included 500 to 280 BC (perhaps even to 190 BC), and AD 1600–1750. The latter may be a western Siberian manifestation of the so-called 'Little Ice Age'. The warmer periods include 1770–1660 and 1380–1320 BC and the second half of the eighteenth century AD. The long warm period that lasted from about 10 BC to AD 160 is also a remarkable feature of the reconstruction.

Recent warming is also clear, especially if it is judged to have commenced at the beginning of the nineteenth century. The low interannual variability and the minimum occurrence of cold

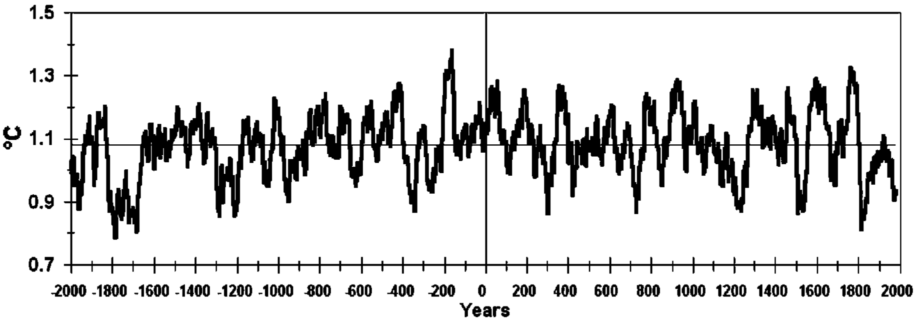

Figure 9 Standard deviations of summer temperatures in a moving 50-year window, indicating changes in the magnitude of interannual variability over the last 4000 years.

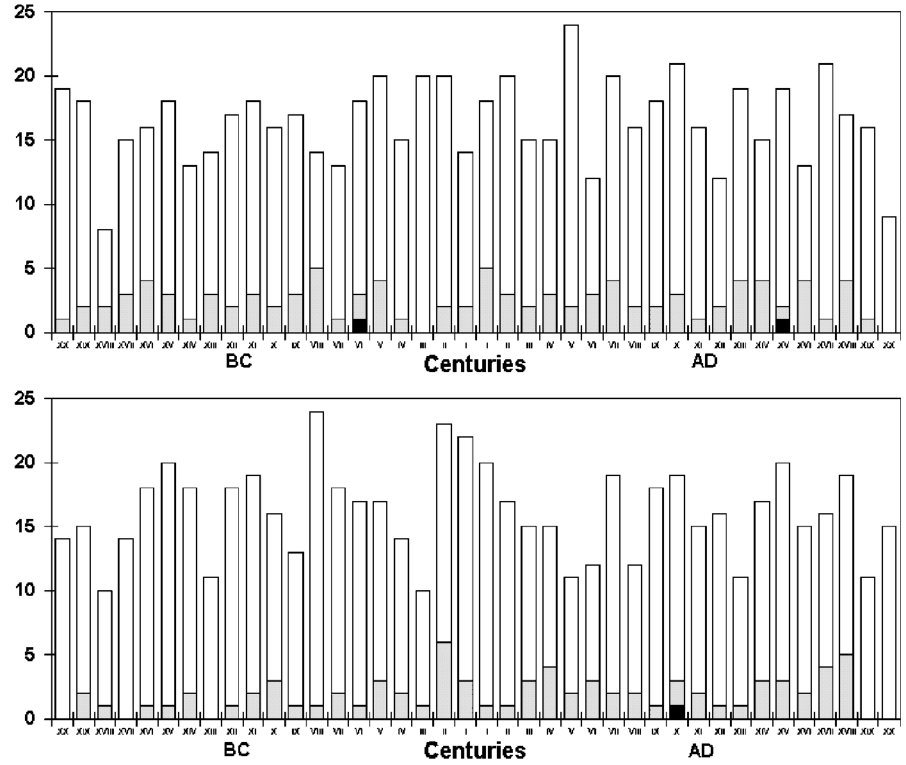

Figure 10 Negative (upper) and positive (lower) summer-temperature extremes. Extremes are defined as anomalies exceeding one standard deviation of the full reconstructed series: 1σ, 1.09°C, white histogram; 2σ (grey); and 3σ (black).

extremes during the twentieth century argue that the most recent decades of this long summer record represent one of the most favourable climate conditions for tree growth within the last four millennia.

Reconstruction of tree-line dynamics

To display century-to-millennium-scale climate variability, it is possible to construct a record of tree-line shifts, as the dynamics of polar and upper tree-lines reflect long-timescale climatic changes, though with some limitations (e.g., Payette and Lavoie, 1994).

Figure 12 shows a reconstruction of tree-line dynamics composited from evidence from the different river valleys in the Yamal Peninsula, expressed with respect to the present-day polar limits of larch. This long-timescale representation of summer conditions is based on the relative positions of more than 500 trees, each of which has been precisely dated by cross-dating their ring patterns. The data were treated separately for each valley system and tree position transformed into anomalies from their own present-day limit, and, because no river valley could, as yet, supply sufficient samples to cover the whole period, the data were then combined to form a single regional indication of tree-line shifts. This should be considered as a preliminary result because there is some subjectivity in the way the different valley data were expressed.

Shifts of tree-line during the last 3700 years were relatively small and less significant than those that occurred earlier, being confined to a total range of about 5 km centred on the latitude of the present-day limit. However, there was a dramatic southward shift of the tree-line that occurred abruptly in the middle of the seventeenth century BC. At that time the larch tree-line apparently retreated from a position at least 20 km north of the present-day location to one some 2–3 km north, within a space of only 50 years. From the presently available data, the full magnitude of this shift is impossible to estimate, because the samples available come from a restricted research area and other subfossil material might exist beyond the northern limit of this area. This major tree-line shift has been noted previously on the basis of radiocarbon dating (Figure 5) but it is dated much more exactly here on the evidence of precise dendrochronological cross-dating. This coincides with an abrupt and large cooling shown in the tree-ring temperature reconstruction after 1660 BC. This may have been a severe double cooling event (Figure 11a), the latter part of which

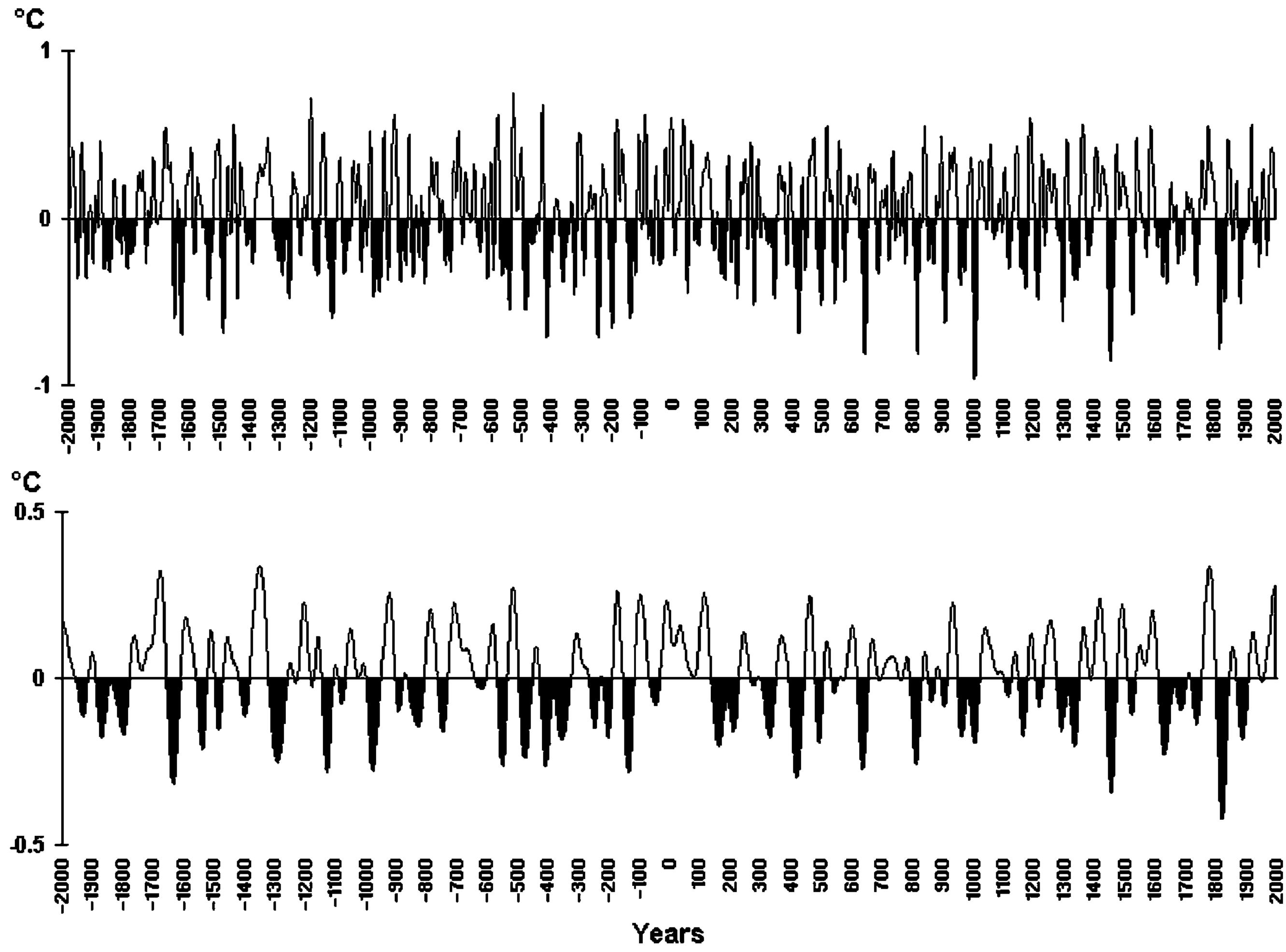

Figure 11 The reconstructed summer temperatures after filtering with different band-pass filters: 20-year low-pass values (upper) and 60-year low-pass values (lower).

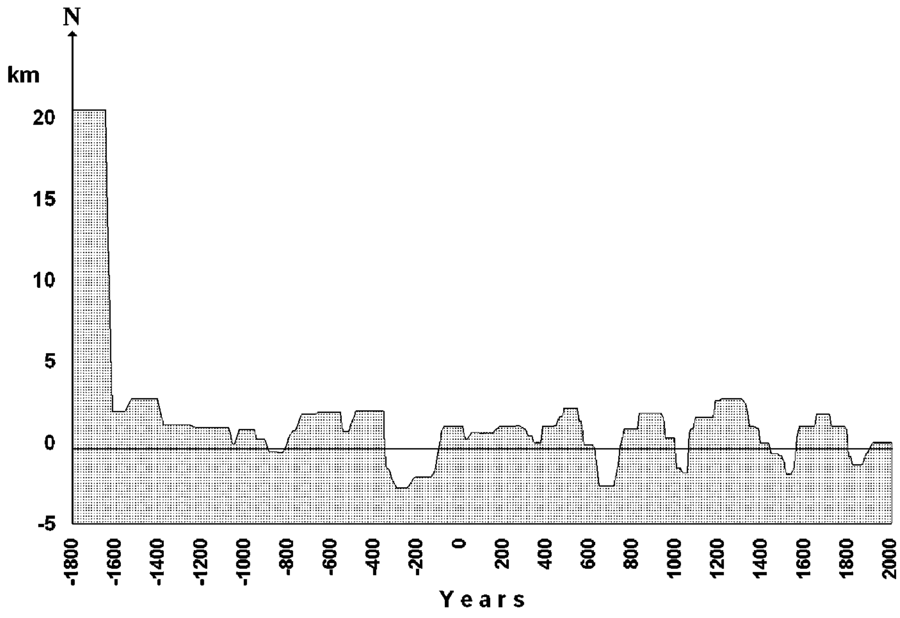

Figure 12 Regional reconstruction of polar tree-line dynamics on the Yamal Peninsula since 1800 BC. The zero line indicates the position of the recent polar timber-line.

may have been associated with the eruption of the Thera volcano around 1628 BC (Baillie, 1999; Grudd *et al.*, 2000).

During the last 3700 years, five periods of unfavourable climate are evident as minor southward tree-line shifts. The later four of these commenced at around AD 600, 950, 1450 and 1800, all coincident with the onset of severe cool periods as indicated in the temperature inferences based on the ring-width chronology in Figure 11b. The most persistent southward tree-line shift of the last three and a half millennia occurred at around 350 BC and lasted for 350 years. This does not correspond directly with a cold period in the tree-ring-based reconstruction, though it is preceded by a protracted cool phase stretching from about 500 to 300 BC. However, the temperature reconstruction does show warm conditions from 100 BC to AD 100 coincident with the rapid northward expansion of the tree-line at about 100 BC. The magnitude of the range shifts occurring after 3600 BC are generally within about 5 km. All of these recent changes are dwarfed by the very much larger shift that occurred abruptly in the middle of the seventeenth century BC. As regards periods of more recent northerly tree-line (such as from 100 BC to AD 500, 800–900, 1100–1300, 1600–1800), these imply periods of persistent warmth that are not reflected in the temperature reconstruction, at least in the version based on the processing approach used here. Combining the evidence of precisely dated tree-line shifts based on dendrochronology with the evidence from radiocarbon dating that also provides information about the density of forest samples (see also Figure 6), it is, however, possible to summarize the longer-timescale variation of summer temperature.

From 1800 to 1300 BC, though the tree-line was generally further to the north than today, the southerly migration indicates that a continuous deterioration of climatic conditions was under way. Then warming followed that lasted for the next four centuries. A further onset of worsening conditions began at 900 BC and continued to 100 BC, with the least favourable period occurring in the period 400–300 BC, coincident with the period of poor pine growth and the long-standing 'gap' that prevented the completion of the long Fennoscandian chronologies (see Grudd *et al.* and Eronen *et al.* in this issue). From the beginning of the first century BC to about the start of the sixth century AD, generally warm conditions prevailed. Then began a quasi 400-year oscillation of temperature, cooling occurring in about 550–700, 950–1100, 1350–1500 and 1700–1900. Warming occurred in the intermediate periods and during the twentieth century. The more northerly tree-line suggests that the most favourable conditions during the last two millennia apparently occurred at around AD 500 and during the period 1200–1300. It is interesting to note that the current position of the tree-line in Yamal is south of the position it has attained during most of the last three and a half millennia, and it may well be that it has not yet shifted fully in response to the warming of the last century.

Conclusion

The work we describe here marks significant progress in the development of a Holocene-length tree-ring chronology for the Yamal Peninsula. A large amount of well-preserved subfossil wood, with climate-sensitive ring widths, has provided the basis for a reliable reconstruction of high to medium frequencies of summer warmth. Radiocarbon dating of tree samples, and more precise dendrochronological dating of the same samples, has enabled a preliminary interpretation of tree-line shifts that represent longer-timescale temperature variations. The immediate task for the future is to extend the length of the chronology, while substantially increasing the sample depth throughout its whole length. Together with experimentation using new data-processing techniques, this will certainly provide longer and more accurate longer-timescale information directly interpretable from these data.

In addition to climate reconstruction, the multimillennia-length Yamal tree-ring chronology has great potential for contributing to other studies of the ecology, geology and archaeology of northern Siberia.

Acknowledgements

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