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Quantitative Holocene climatic reconstruction from Arctic Russia*

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Abstract

Vegetation changes reflected in fossil pollen spectra are a primary source of information about climate fluctuations in the past. A statistical-information (transfer function) method based on the correlation of recent pollen spectra with modern climate conditions has been used to reconstruct Holocene climatic changes from fossil pollen. Climatic variables used for the reconstructions are the mean annual, January, July temperatures and annual precipitation. Peat sections with pollen and ^{14}C data from the Arctic Russia were used for the reconstructions. The reconstructed climate fluctuations are similar to the climate changes obtained from many sites in the former USSR. A clear signal for Younger Dryas cooling, 11,000–10,000 yr BP and early Preboreal warming is apparent. The early Preboreal (10,000–9000 yr BP) was the warmest time for sites from modern coastal and island areas. The warm interval occurred in the Boreal period, about 8500 yr BP. According to the reconstructions the warmest time for non-coastal areas was the last half of Atlantic period, 6000–4500 yr BP. Other warm intervals were reconstructed about 3500 and 1000 yr BP. Reconstructions show that warming periods are primarily defined as times of increased summer temperatures, and cooling periods as time of decreased winter temperatures. The precipitation followed the temperatures: during the warming periods precipitation increased and during the cooling periods it decreased. Precipitation maximum, about 100 mm higher than present, are reconstructed for the warmest interval, 6000–4500 yr BP at all sites.

Introduction

Vegetation changes reflected in fossil pollen spectra are a primary source of information about climatic fluctuation in the past. Different mathematical (transfer function) methods have been used to reconstruct Holocene climatic changes from fossil pollen (e.g. Webb & Bryston, 1972; Bryson & Kutzbach, 1974; Klimanov, 1976, 1984; Sachs et al., 1977; Heusser et al., 1985; Guiot et al., 1993, and others).

We used a statistical-information method (transfer function) which is based on the correlation of recent pollen spectra with modern climate conditions. Linear equations link pollen percentages to modern climate (Klimanov, 1976, 1984). Our method is based on more than 800 surface pollen spectra taken from across the former USSR. Modern climate variables are from the Climatic Atlas of the USSR (1960). Climatic variables used for the reconstruction are mean annual (T_{yr}), January (T_I), and July (T_{VII}) temperatures and total annual precipitation. The main statistical error is ± 0.6 °C for T_{yr} and T_{VII}, ± 1.0 °C for T_I, and ± 25 mm for P.

Several sites with fossil pollen and radiocarbon data from the Russian Arctic were used for the climate

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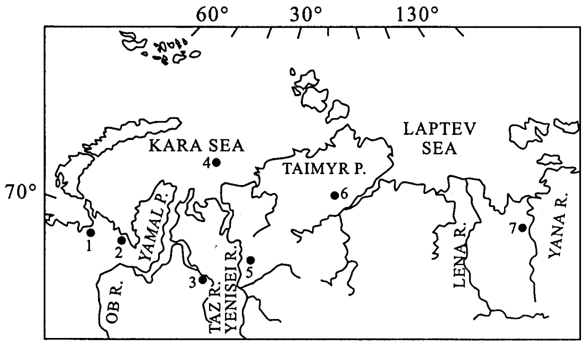

Figure 1. Map showing the location of the studied sites. 1. Khaipudurskaya Guba section; 2. Baidaratskaya Guba section; 3. Pur-Taz section; 4. Sverdrup Island section; 5. Yenisei section; 6. Taymyr sections; 7. Kazach'e section.

reconstruction (Figure 1). All sites used for the reconstructions are peat sections. Conventional radiocarbon dates on bulk sediments provide chronological control except for the Pur-Taz section, which is dated by AMS ^{14}C, dated. All radiocarbon dates used in the paper are uncalibrated. Most pollen diagrams have been already published and are cited, but two new high-resolution pollen diagrams for Pur-Taz and Yenisei sections are provided. The sampling interval gives a time resolution of about 100 yrs and varies slightly from site to site.

Study sites

The Khaipudurskaya Guba site

The site is located on the Yareikhoi highlands (68 °N, 60 °E) near the Khaipudurskaya Gulf of the Barents Sea in the modern shrub tundra zone (Figure 1). T_{VII} is about 10–11 °C, T_I is about –19 to –20 °C, T_{yr} is about –1 °C and P is 350–400 mm.

Basal peat from 5 m depth overlying lake sediment was radiocarbon dated to 6280 ± 600 yr BP (MGU-695). The pollen records reflects the climate changes for the last 6500 yr (Bolichovskaya et al., 1988; Velichko et al., 1997). The paleoclimate curves are presented in Figure 2.

According to this reconstruction, the time of greatest warmth and moisture throughout the investigated period was from about 6000 to 4500 yr BP. T_{VII} was up to 3–4 °C warmer, T_I was up to 2 °C warmer, T_{yr} was up to 2–3 °C warmer, and P was about 100 mm greater than today. The pollen percentages show that open spruce forest replaced the modern tundra at that time. Another warm period with open spruce forest occurred about 3500–4000 yr BP.

The Baidaratskaya Guba site

The site is located at 68 ° 51′N, 66 ° 54′E in the shrub-tundra zone, on the southeastern part of the Yugorsky Peninsula (Figure 1). T_{VII} is about 6–7 °C, and T_I is about –22 °C, P is about 250–300 mm.

Twelve radiocarbon dates were obtained from the section. The *Alnus fruticosa* wood from the top of the sandy-clay layer underlying the peat sequence on the 4.2 m depth was radiocarbon dated to 10,900 ± 120 yr BP (MGU-1362), indicating that this layer accumulated during the Allerød. The set of radiocarbon dates (8000 ± 125 yr BP (WAT–2924), 8210 ± 110 yr. BP (GIN-7862a), 8120 ± 90 yr BP (GIN-7862b), and 8090 ± 40 yr BP (GIN-7862c)) from the clay/peat transition layer shows that peat accumulation started about 8200 yr BP. The top of the peat section was radiocarbon dated to 4140 ± 70 yr BP (WAT-2895).

The pollen records reflect the vegetation and climate changes for the end of Late Pleistocene time and for 8200–4100 yr BP data (Andreev et al., 1998; Serebryanny et al., 1998). Reliable climate reconstructions are possible only for the Allerød and Holocene, because of the lack of radiocarbon dates for the Late Pleistocene sediments. The reconstructed paleoclimate curves are presented in Figure 3.

Reconstruction for the Allerød shows that climate was relatively warm. T_{VII} was up to 1.5–2 °C warmer than modern, T_I 1–2 °C lower, T_{yr} 1–1.5 °C lower, and P was about 75 mm greater than today. Open birch (*Betula pubescens*) forest with shrub alder (*Alnus fruticosa*) existed around the site. During the Younger Dryas accumulation stopped, probably because of a major hydrological change when lake was drained. No sediments accumulated between 10,900 and 8200 yr BP.

According to the reconstruction, several warm and rather moist period can be recognized in the Holocene, 8200–4100 yr BP ago (Figure 3). The warmest interval during that time was 6000–5500 yr BP. All temperatures were up to 2.5–3 °C warmer than modern, although P remained near modern. The open birch forest was gradually replaced by shrub birch tundra especially after a cooling dating to 4500 yr BP.

The Pur-Taz site

The site is located at 66 ° 42′N, 79 ° 44′E in the forest-tundra zone, between the Pur and Taz rivers (Figure 1).

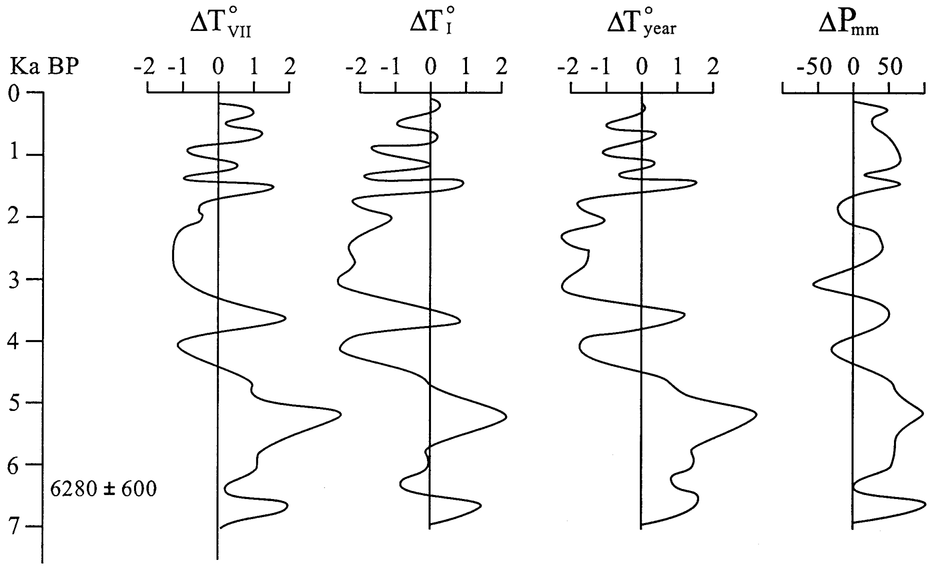

Figure 2. Paleoclimate curves from Khaipudurskaya Guba section pollen. All quantitative characteristics are quoted as deviations from the present values.

T_{VII} is from 12–14 °C, and T_I range from –26 to –28 °C, resulting in T_{yr} of –8 to –9 °C; annual precipitation is about 450 mm. The base of the peat section is AMS-dated to 9200 ± 60 yr BP (CAMS-2428) and the top to 4570 ± 60 yr BP (CAMS-24132). The macrofossil and pollen data (Figure 4) reflect the climate changes from 9200–4500 yr BP (Peteet et al., 1988). The paleoclimate curves are presented in Figure 5.

These paleovegetation data are the first high-resolution, AMS-dated records from Siberia used for

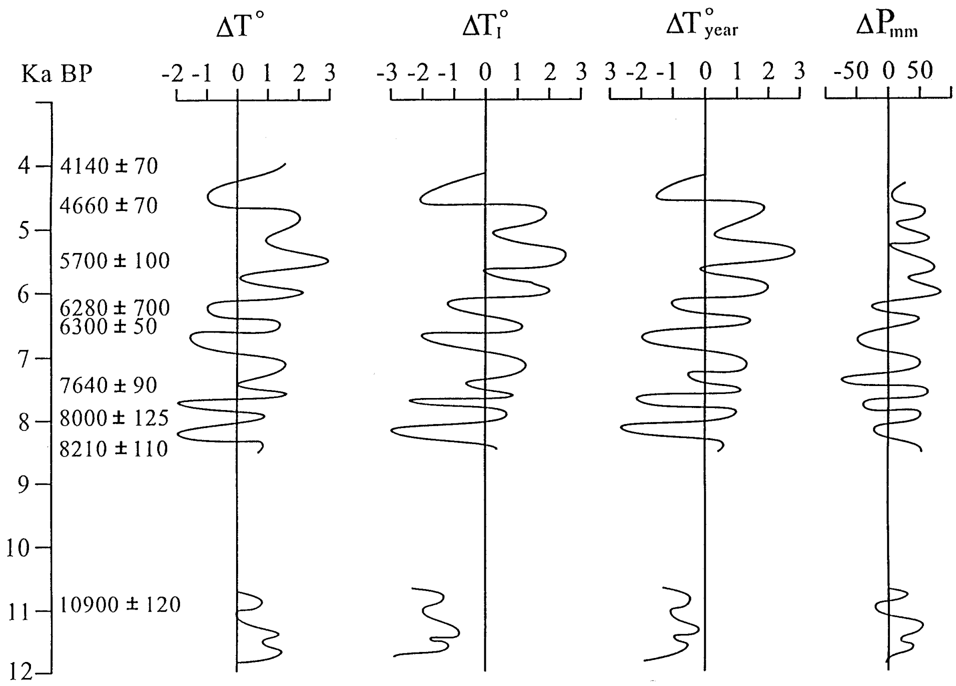

Figure 3. Paleoclimate curves from Baidaratskaya Guba section pollen.

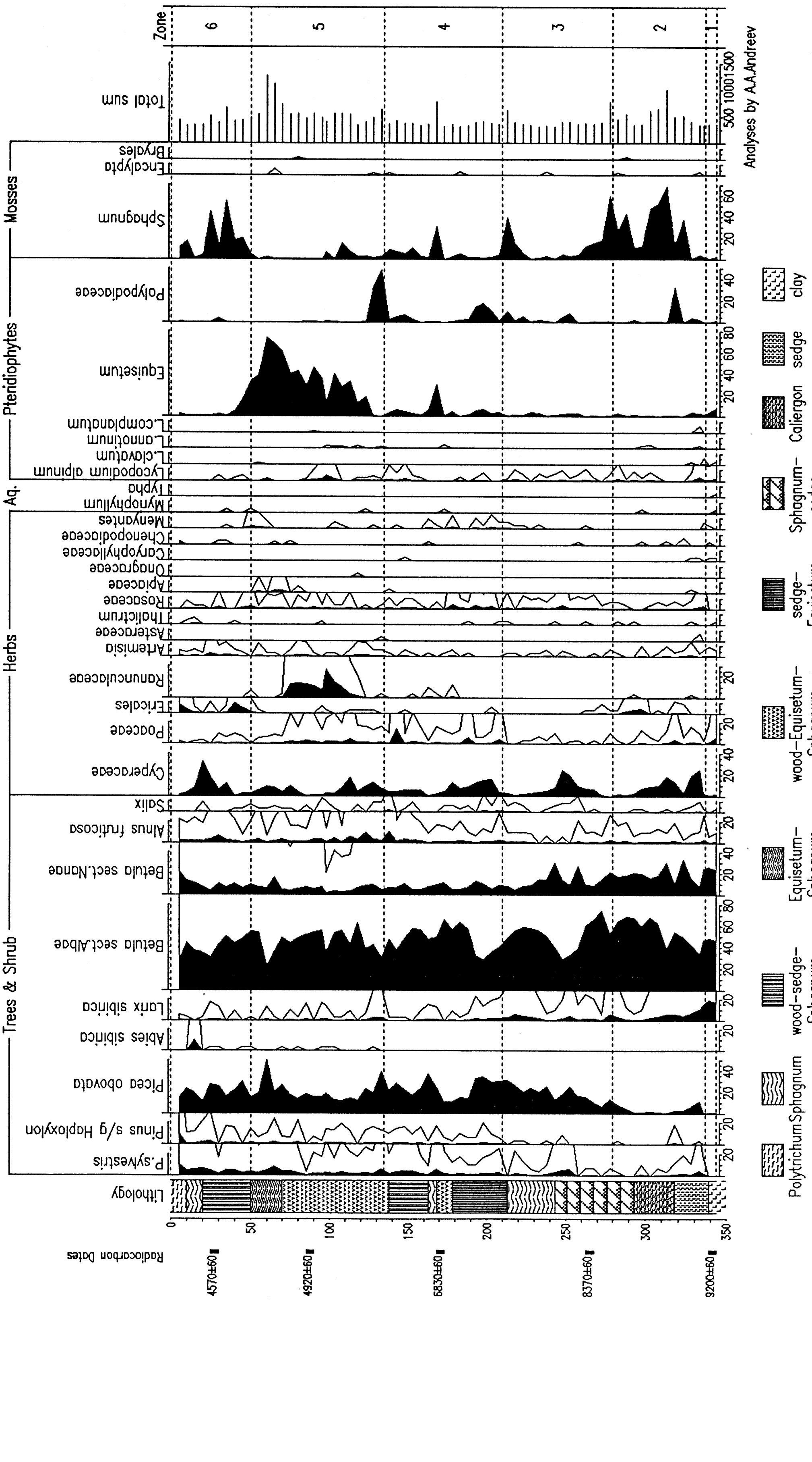

Figure 4. Pollen and spores diagram from Pur-Taz section.

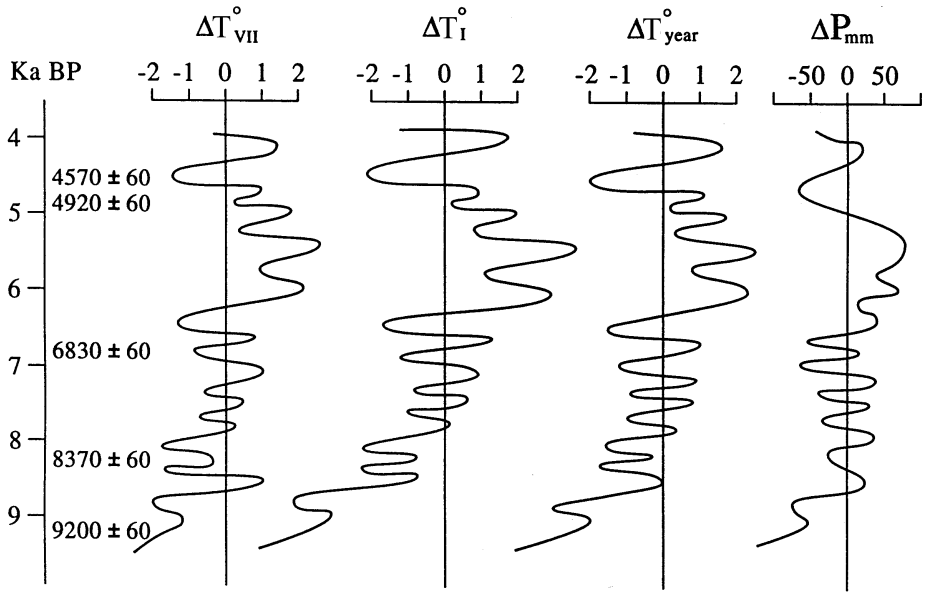

Figure 5. Paleoclimate curves for Pur-Taz section pollen.

paleoclimatic reconstruction and therefore we describe them with considerable detail. According to the reconstruction, the coldest time during the period from 9200–4500 yr BP was the end of Preboreal period, just prior to 9200 yr BP. T_{VII} was about 3 °C lower than modern, T_I 5 °C lower, T_{yr} °4 lower, and P was about 100 mm less than modern. The site was largely surrounded by larch forest during that time.

During the Boreal period, 9200–8000 yr BP, three warm oscillations are reconstructed. During the first and the last oscillations temperatures and precipitation were still lower than modern conditions. The first and third peaks of spruce pollen express these oscillations. The greatest, second oscillations was at about 8500 yr BP. T_{VII} was about 1 °C higher than modern, T_I 0.5 °C lower, T_{yr} was close to modern, and P was about 25 mm higher than modern. A second peak in *Picea* pollen reflects this warm and moist oscillation. The oldest radiocarbon dated spruce macrofossils from the north of West Siberia are dated to 8800–8400 yr BP (MacDonald et al., submitted) and support the warmings and northward movement of the spruce treeline.

At the Boreal/Atlantic transition, about 8300–8000 yr BP, a cooling took place. The T_{VII} was about 1.5–2 °C lower than modern, T_I 2.5 °C lower, T_{yr} 2 °C lower, and P was about 25 mm less than modern. Peaks in *Betula nana* and Cyperaceae pollen above a layer dated to 8370 yr BP express this cooling.

From 8000 to 6000 yr BP four brief warm periods are reconstructed. Temperatures and precipitation rose above modern conditions for each period. Spruce becomes dominant at the site, and many woody spruce remains along with spruce needles are preserved (Peteet et al., 1998).

A rather large cooling is reconstructed between 7000 and 6000 yr BP. According to previous chronological analyses and paleoclimatic reconstructions from other sites from the European part of Russia to the Far East (Andreev et al., 1989, 1993, 1995; Velichko et al., 1997 and others), there is a regional cooling event and it dates to about 6400 yr BP. The T_{VII} was about 1–1.5 °C lower than modern, T_I was and T_{yr} 1.5 °C lower, and P was about 50 mm less than modern. A rising increase in fungal sclerotia and *Rubus* sp. macrofossils between 7000 and 6000 yr BP, may reflect the overall drier conditions. The appearance of a few charcoal pieces reflecting the presence of fire on the landscape at that time.

The end of Atlantic period, 6000–4500 yr BP, was the warmest time during the interval investigated. All reconstructed temperatures and precipitation were higher than their modern values. Four relatively warmer peaks were identified during this time, the second of them (at about 5500 yr BP) was the greatest. T_{VII} was about 2.5 °C higher than modern, T_I 3–3.5 °C higher, T_{yr} 2.5–3 °C higher, and P was about 75 mm higher than modern. The peaks in *Picea* and *Alnus* pollen as well as the first appearance of *Albies* pollen express these warmings.

At the Atlantic/Subboreal transition, about 4500 yr BP, another cooling takes place. T_{VII} was about 1.5 °C lower than modern, T_I and T_{yr} 2–2.5 °C lower, P was about 50 mm less than modern. The increase in *Betula nana* and peak in Cyperaceae pollen generate this cooling.

The paleoclimatic reconstructions from pollen spectra at the top of the section show a warming in T_{VII} about 1.5 °C higher than modern, T_I 2 °C higher, T_{yr} 1.5–2 °C higher, and P was about 25 mm higher than modern. A peak in *Abies* pollen generates this warm episode.

The Sverdrup Island site

The site is located on the Sverdrup Island (74 ° 30′N, 79 ° 30′E), 110 km from the Kara Sea coast, in the modern Arctic desert zone (Figure 1) T_{VII} are about 2–3 °C, T_I is about –26 to –28 °C, T_{yr} is about –10 °C and P is 200–300 mm.

The basal peat from 0.80–0.85 m depth, overlying eolian sediments was radiocarbon dated to 11,640 ± 40 yr BP (GIN-7625). Layers in the overlying peat, at 0.55–0.65 and 0.35–0.45 m dated to 10,490 ± 380 yr BP (GIN-7626) and 9770 ± 280 yr BP (GIN-7627) respectively. The pollen data reflect vegetation changes from about 11,600–9700 yr BP (Andreev et al., 1997b; Serebryanny et al., 1998).

The records from the high Arctic areas often contain high percentages of long-distance pollen due to low pollen productivity of local vegetation (Krenke & Fedorova, 1961; Knaap, 1987; Bourgeois, 1990; Andreev et al., 1997a). Our paleoclimate reconstructions for the Sverdrup Island site illustrate well the limitations of the transfer-function method for high Arctic records, where long-distance pollen is a major component of the records. For example, reconstructed climate characteristics from the samples ^{14}C dated to the Allerød (11,600 yr BP) show that T_{VII} was about 8–10 °C, T_I –28 °C, and P was about 400 mm. Reconstruction from the sample ^{14}C dated to the Younger Dryas (10,500 yr BP) shows some cooling compared to the Allerød, however these temperatures were higher than today. T_{VII} was about 6–8 °C, T_I –28 to –30 °C, and the P was 300 mm. The reconstruction for the early Holocene shows a large warming about 10,000–9800 yr BP: T_{VII} was about 14–16 °C, T_I ranged from –20 to –23 °C, and P was 400–500 mm. Although, these reconstructions do show increasing temperatures and precipitation far too large, because of the significant amounts of long-distance, non-local pollen, they probably reflect a larger regional trend in temperatures and precipitation.

The Yenisei River site

The site is located along the Yenisei Rivere (68 ° 10′N, 87 ° 09′E) in the northern forest (Figure 1). T_{VII} is 13–14 °C, T_I is –22 to –24 °C, and P is about 450 mm. Seven radiocarbon ages were obtained from the 3.5-m deep section. The bottom peat produced an age of 5920 ± 70 yr BP (TO-49070), and the top peat (10–15 cm) produced an age of 1520 ± 70 yr BP (WAT-2894) (Andreev et al., submitted b). The pollen data (Figure 6) reflect climate changes from 6000–1500 yr BP. The paleoclimate curves are presented in Figure 7.

These data are the first high-resolution records from this part of Siberia, and are used here for the first time for paleoclimatic reconstructions. They reflect climatic changes for the second half of Holocene. This time interval is absent in the Pur-Taz section and hence we describe it in detail here.

According to the reconstructions, the end of the Atlantic period, from 6000–5500 yr BP, was the warmest interval during the section investigated which encompassed from 6000–1500 yr BP. T_{VII} was about 2 °C higher than modern, T_I and T_{yr} 2–3 °C higher, and P was about 75–100 mm higher than modern. A slight cooling is reconstructed between 5000 and 5500 yr BP. T_{VII} was about 1 °C higher than modern, T_I and T_{yr} were 1–2.5 °C higher than present-day, and P was about 50 mm more than modern. Another warm period occurred about 5000 yr BP. All temperatures were about 2 °C higher than modern, and P was about 50 mm higher than modern. Spruce forest grew around the site during this warm period. Peaks in *Picea* pollen reflect warmings while peaks in *Betula* pollen – coolings.

At the Atlantic/Subboreal transition, at about 4500 yr BP, a cooling is reconstructed. T_{VII} was close to the modern, T_I and T_{yr} were 1 °C below the present-day, and P was close to the modern. Several warmings are reconstructed for the Subboreal period, from 4500–2500 yr BP, the largest occurs about 3500 yr BP. All temperatures were about 2 °C higher than modern and P was about 50 mm higher than modern. A peak of *Picea* pollen generates this warming.

At the Subboreal-Subatlantic transition, at about 2500 yr BP, a cooling is reconstructed. All temperatures were 2 °C below modern and annual precipitation was 75 less than modern. Two subsequent warmings are reconstructed after 2500 yr BP; the largest occurred about 2000 yr BP. Temperatures were about 1–1.5 °C higher than modern and AP was about 50 mm higher than modern. In a cooling about 1500 yr BP, temperatures

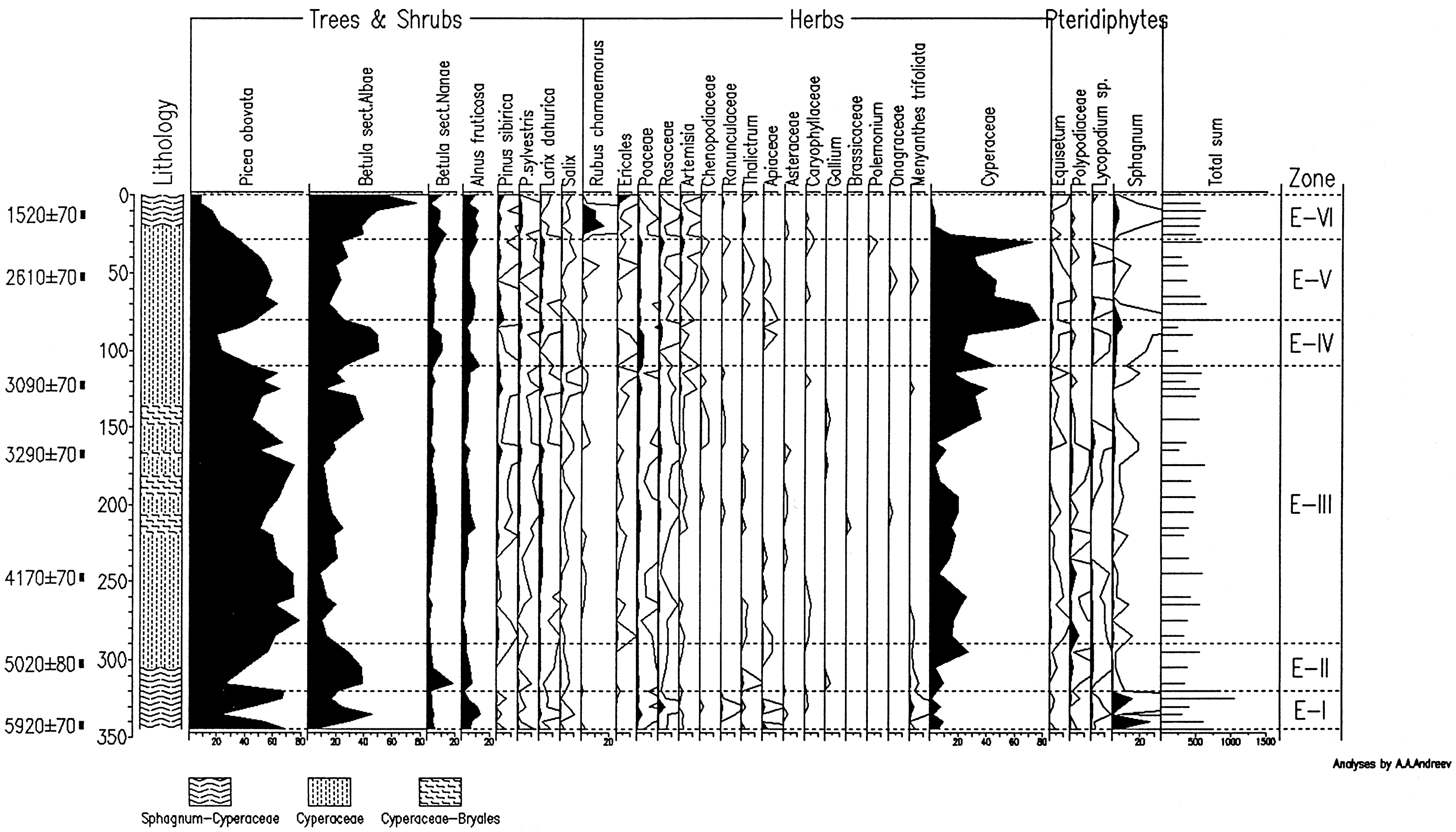

Figure 6. Pollen and spores from Yenisei section.

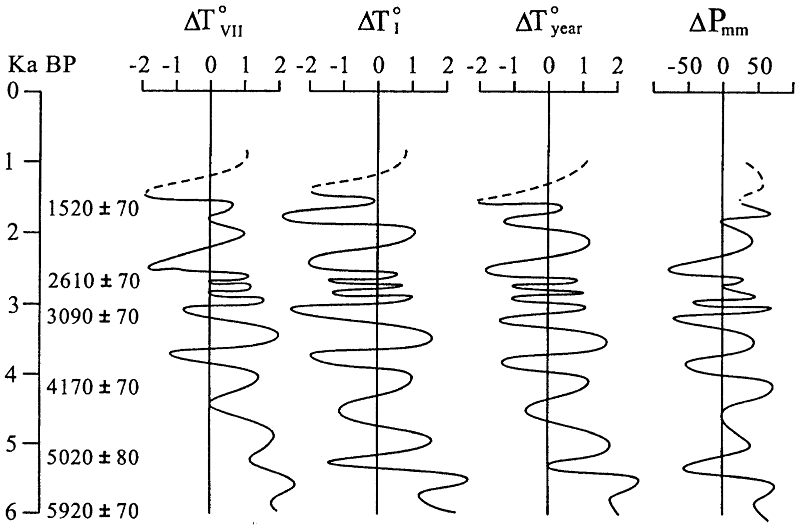

Figure 7. Paleoclimate curves from Yenisei section pollen.

were 2 °C below modern and P was 25 mm less than modern. The decline in *Picea* pollen and increase in *Betula* are primarily responsible for these climatic oscillations.

The pollen spectra from the top of the section is interrupted to show a warming with the temperatures about 1 °C higher than modern and P about 25–50 mm higher than modern. This may be a manifestation of a warming dating to 1000 yr BP, the so-called Medieval Warm Period of the 9th–14th centuries which was indicated in some areas of the globe (Hughes & Diaz, 1994). This warming is also recorded in other sites in Northern Eurasia (Klimanov & Elina, 1984; Klimanov & Serebryanaya, 1986; Shumova & Klimanov, 1986; Yakushko et al., 1988; Andreev et al., 1989, 1993, 1995).

The Taymyr sites

A number of sections are located in the central part of the Taymyr Peninsula: XX-44 on the B. Romanikha River (70 ° 46′N, 99 ° 08′E) with ^{14}C dates: 9200 ± 40 yr BP (GIN-679), 9000 ± 150 yr BP (GIN-680), 6120 ± 70 yr BP (GIN-682), 4420 ± 50 yr BP (GIN-681); I-96 on the Kalamissamo River (73 ° 48′N, 100 ° 40′E) with a ^{14}C date 8220 ± 120 yr BP (GIN-1198); BX-9 on the B. Balakhnya River (73 ° 12′N, 100 ° 50′E) with a ^{14}C date 8310 ± 70 yr BP (GIN-774); XX-13 on the Boganida River with a ^{14}C date 8600 ± 70 yr BP (GIN-665); A-318 with a ^{14}C date 10,860 ± 80 yr BP (GIN-685); G-119 on the Ladonnakh River (72 ° 00′N, 96 ° 20′E) with a ^{14}C date 5500 ± 100 yr BP (GIN-979). All sites are in the modern tundra and shrub tundra zones. T_{VII} in the area is about 4–6 °C, T_I –32 to –34 °C, P is about 250 mm.

Pollen data analyzed by Nikol'skaya (Nikol'skaya, 1980; Nikol'skaya & Cherkasova, 1982; Klimanov & Nikol'skaya, 1983) were used to generate the climatic changes since the Younger Dryas. The average paleoclimate curves based predominantly on reconstruction from XX-44 site are presented in Figure 8. According to these reconstructions, several warm and rather moist periods are recognized about 10,000, 8500, 6000–4500, 3500 and 1000 yr BP. The time of greatest warmth and moisture throughout the investigated period was about 8500 and from about 6000 yr BP to 4500 yr BP. T_{VII} were up to 3 °C higher, T_I 2 °C higher, and P was about 100 mm greater than today.

The Kazach'e (Samandon) site

This is located in the Yana River valley (70 ° 45′N, 136 ° 26′E, 3 km to the north of the Kazach'e settlement, in the forest-tundra zone (Figure 1). T_{VII} is about 11 °, T_I is –37 °, T_{yr} is –15 to –16 °, and P is about 200 mm.

Fifteen radiocarbon dates were obtained from the peat section (Andreev et al., submitted a). The *Larix* wood from the bottom (2.9–3.0 m) dates to 6970 ± 100 yr BP (GIN-5391), and the peat from 2.6–2.7 m dates to 5980 ± 100 yr BP (GIN-5390). However, we did not use the bottom radiocarbon date, because the wood could have been deposited before the peat accumulation begun. A possible hiatus and/or very slow peat accumulation is identified by ^{14}C dates 3990 ± 100 yr BP, (GIN-5386) from 1.2–1.3 m and 1530 ± 70 yr

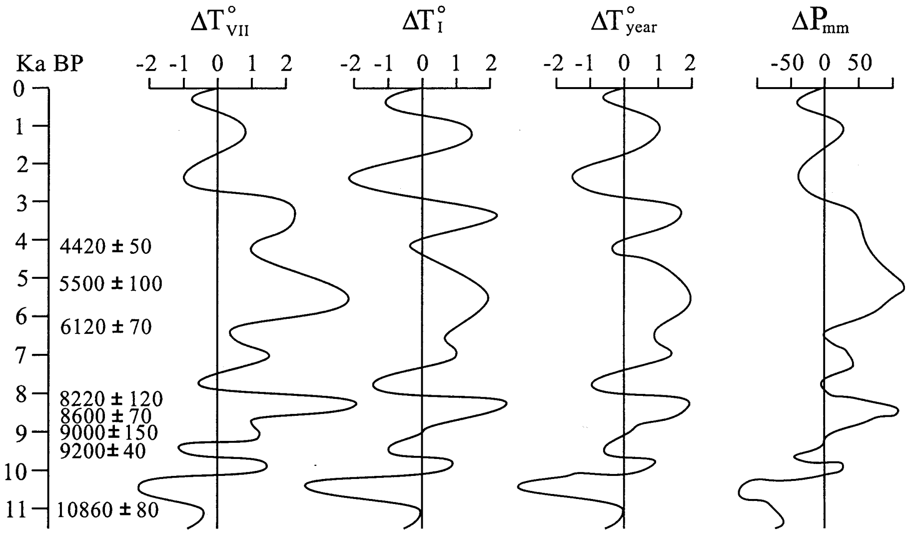

Figure 8. Average paleoclimate curves from Taymyr sections pollen.

BP (GIN-5385a) from 1.0–1.0 m, which makes climate reconstruction problematic for that time. Peat from the upper 0.2–0.3 m was dated to 480 ± 150 yr BP (GIN-5383a).

The pollen data reflect changes for the last 6400 yr BP (Andreev et al., 1995, submitted a; Velichko et al., 1997). The paleoclimate curves are presented in Figure 9. Several warm and moist periods are recognized in the reconstruction. The warmest time was between 6000–4500 yr BP. All temperatures were up to 2 °C warmer and P was about 75 mm greater than today.

Discussion and conclusions

Our reconstructions indicate that several climatic changes occurred in the Russian Arctic during the Holocene. All reconstructed climatic fluctuations are more or less correspondent with vegetation changes. Sometimes reconstructed climate fluctuations do not correspond well with significant changes in pollen spectra. The lack of correspondence may be due to the statistical-information technique used to derive climate fluctuations from pollen percentages of only trees and

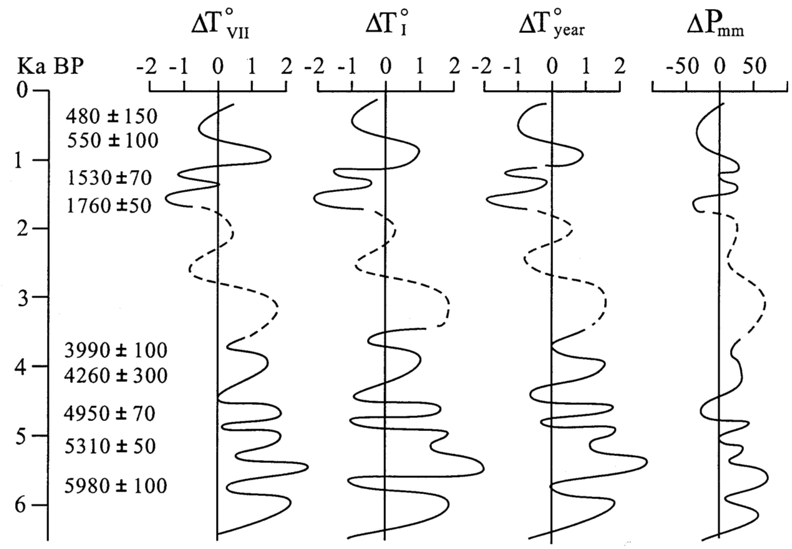

Figure 9. Paleoclimate curves from Kazach’e section pollen.

shrubs species as well as tree, herbs and spores percentages sum, the technique does not use the percentages of herbs and spores (Klimanov, 1976, 1984).

A Late Glacial cooling period reconstructed at the Sverdrup and Taymyr sites, does correspond with Younger Dryas. Clear evidence for early Holocene (10,000–9700 yr BP) warming is also apparent at the same sites. Many studies identify the early Holocene as the warmest time for what is presently the coastal and island areas in the Russian Arctic (Makeev & Ponomareva, 1988; Ukraintseva et al., 1991; Ukraintseva, 1992; Makeev et al., 1992; Andreev et al., 1997; Velichko et al., 1997; Serebryanny et al., 1998). The Arctic Ocean coastline was about 100–300 km further to the north during the early Preboreal, in comparison to today, which contributed to a warmer and more continental climate. The vegetation changes reflect this influence. In the later Holocene, climatic fluctuations were moderated by the stronger influence of the Arctic Ocean.

The middle of the Boreal period, at about 8500 yr BP, was reconstructed as another warm interval. It is recognized in many placed as the Boreal thermal maximum (Khotisnky, 1977, 1984; Andreev et al., 1989, 1993, 1995; Velichko et al., 1997).

According to many reconstructions maximum Holocene warmth occurred during the last half of Atlantic period, from 6000–4500 yr BP. Several climate fluctuations were reconstructed for this time; the second of them (at about 5500 yr BP) was the maximal for the Holocene.

In the middle of Subboreal period (Subboreal thermal maximum), at about 3500 yr BP, and the warming dated to 1000 yr BP (the so-called Medieval Warm Period) were reconstructed as other regionally significant warm periods. These two warm periods are also recognized in many placed in Northern Eurasia (Khotinsky, 1977, 1984; Klimanov & Elina, 1984; Klimanov & Serebryanaya, 1986; Shumova & Klimanov, 1986; Yakushko, 1988; Bezus'ko et al., 1988; Andreev et al., 1989, 1993, 1995; Velichko et al., 1997).

Our climate reconstructions show that the warming periods are defined primarily as times of higher summer temperatures, whereas the cool periods are defined as times of decreased winter temperatures. Annual precipitation trends follow the temperatures: during warm periods precipitation increased, and during the cooling periods precipitation decreased.

The reconstructed climate fluctuations are very similar to temperature and precipitation changes obtained from previously investigated sites in the former USSR (Khotinsky, 1977, 1984; Klimanov & Elina, 1984; Klimanov & Serebryanaya, 1986; Shumova & Klimanov, 1986; Yakushko et al., 1988; Bezus'ko et al., 1988; Andreev et al., 1989, 1993, 1995; Velichko et al., 1997 and others). A tendency for the climate to vary in consistent manner across Arctic Russia may reflect regional patterns of climate change during the Holocene. The patterns of Holocene climate change reconstructed here must be substantiated with additional data. For example, hiatuses in peat accumulation (e.g. Kazach'e site) need to be thoroughly identified in order to strengthen our age model. AMS ^{14}C dates from continuously accumulating lake sediment records would improve paleoclimate reconstructions. New high-resolution lake and peat sites throughout Arctic Russia and further evaluation of our transfer function technique could verify our climate reconstructions.

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