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Thermokarst dynamics in Western Siberia: insights from dendrochronological research

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Abstract

Thermokarst dynamics and their underlying causes are investigated and reconstructed on the basis of Muzhy weather station records (Western Siberia) of air temperature, precipitation and snow cover, and a tree-ring chronology analysis of Siberian stone pine (*Pinus sibirica* Du Tour). The results indicate that the development of thermokarst over the last 50 years has depended primarily on increasing precipitation rather than increasing air temperature. Reconstruction of past thermokarst borderlines shows that the rate of thermokarst expansion in the second half of the 20th century increased to 7.4 cm/year, as compared to past rates ranging from 4 to 8.1 cm/year.

Keywords: Thermokarst; Precipitation; Air temperature; Tree-ring chronologies; Reconstruction

1. Introduction

The emergence and development of the cryolithozone are related indirectly to global climatic changes. Western Siberia has about 0.7 million km^2 of permafrost (Geocryology USSR, 1989) predominantly covered with boreal forests. Cryogenic processes within this huge area produce specific forms of relief such as thermokarst that dominates the landscape of Western Siberia. Thermal changes in the upper layer of the permafrost cause the genesis of thermokarst, which is related to seasonal and long-term processes of freeze–thaw (Foundations of geocryology (permafrost study), 1959; Pavlov, 1994; Osterkamp and Romanovsky, 1999; Osterkamp et al., 2000; Jorgenson et al., 2001). Changes in the conditions controlling freezing and thawing may be caused by natural and anthropogenic factors such as extremely high summer temperatures, fires, deforestation, etc. (Kachurin, 1961; Pavlov, 1996; Burn, 1998).

During the development of thermokarst bodies in the boreal zone, many trees were buried in thermokarst lakes and peatbogs (Vitt et al., 2000). Tree-ring analysis using living trees and buried wood makes it possible to reconstruct a history of thermokarst emergence and development (Payette and Delwaide, 2000). The dates of trees appearing or dying, as well as the annual width of tree rings, may demonstrate climatic changes and environmental transformations in ecosystems related to changes in air temperature, precipita-

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tion, and the dynamics of cryogenic processes. In the present study, we undertook to trace the development of a thermokarst depression during the last 100 years within an area in Western Siberia.

2. Area description, methods and material studied

Field material was collected in the thermokarst landscape of the northwestern section of Western Siberia (65°03′ N, 64°42′ E). The altitude of the test site is 22 m a.s.l. The thermokarst depression upon which the present study focuses is situated on a local watershed 700 m from the joint floodplain of the Ob and Synya rivers. The surface of the depression is 1.5–2.0 m lower than its surroundings. It is up to 3.5 m deep, waterlogged and colonised by bog mosses (*Sphagnum* spp.). This is a zone of discontinuous permafrost 150 km to the south of the northern limit of the boreal vegetation belt (Physical Geography Zonation of Tumenskaya Oblast, 1973). The thickness of the permafrost layer is 20–80 m, the depth of seasonal thawing (active layer) is 40–150 cm.

Many authors (Pavlov, 1998; Duchkov et al., 2000; Barashkova et al., 2000) have noted increasing temperatures over the last 20–30 years in Western Siberia. During the last 25–30 years the annual mean air temperature has increased from 0.5 to 1.5 °C, whereas the temperature of the upper permafrost layer has increased from 0.5 to 1.0 °C. In different regions, the increase ranges from 0.03 to 0.08 °C per annum with an average of 0.05 °C. The contemporary increase in soil temperature in this region ranges from 0.02 to 0.06 °C, with an average value of 0.047 ± 0.01 °C per annum (Duchkov et al., 2000). In the Yamal peninsula, the temperature of cryogenic soils has tended to increase by 0.03 °C per year at 10 m depth.

According to the Muzhy weather station records (30 km to the north of the study area), the average annual air temperature is −4.8 °C with a range from −22 °C in January to 15 °C in July. On average, the period with temperatures above 0 °C lasts for 135 days, with 67 days of temperatures higher than 10 °C. Annual precipitation ranges from 249 to 698 mm with an average long-term value of 475 mm, with 140 mm as snow (30%). The snow cover lasts for around 220 days. The maximum potential evaporation adds up to 494 mm; the deficiency of total evaporation is 59 mm and the total moisture deficit is 248 mm (Mezentsev and Karnatsevich, 1969).

Wood samples of Siberian stone pine (*Pinus sibirica* Du Tour)—cross sections and cores—were collected for dendrochronological analysis in three locations. The first one is situated on a steep (8–20°) frozen slope (the permafrost test site) near the thermokarst depression; 13 cross-sections were taken (Fig. 1). The majority of these trees incline towards the thermokarst depression. The second location is situated in the depression itself up to 6 m away from the frozen slope (the thermokarst depression test site); 15 cross-sections were taken. The majority of these trees had already died off and become partly submerged (Fig. 2). The third location, being a reference test site, is situated in a plain between neighbouring thermokarst depressions and location 1, approximately 100 m distant from the latter. This location is a flat local divide and also a permafrost area. None of the trees at this site have tilted trunks. Samples (10 wood cores) of living, non-inclined trees were taken from this location (two radii from each tree).

Cross-sections of wood were taken from the trunk base, whereas cores were taken 1.3 m above the trunk base. In the laboratory, the wood samples were prepared for tree-ring analysis according to conventional methods (Shiyatov, 1986). Measuring the width of tree rings was carried out along two radii using the TSAP system (Rinn, 1996). In each cross-section from the permafrost site, the first radius (R1) was taken strictly along the direction of tilt. General tilting for all the trees on the permafrost slope along the edge of the thermokarst depression is in the same direction. The second radius (R2) was always perpendicular to the first one. In the cross-sections from the thermokarst depression site, the first radius was taken as the longest one, and the second was measured perpendicular to the first. After measuring the tree-ring widths along each radius, all the tree-ring chronologies (TRCs) were cross-dated by sight as well as using the software package COFECHA (Holmes et al., 1986), for the purpose of detecting missing rings and trying to determine the life span dead trees. Periods of compression wood formation along R1 and R2 for TRCs from permafrost and thermokarst depression test sites can be related to the tree's inclination. A tree ring with compression wood accu-

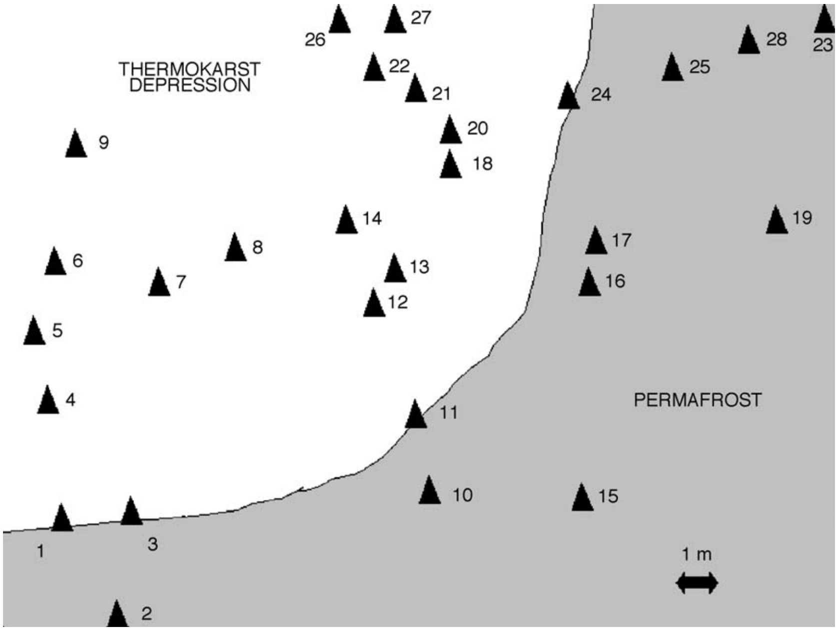

Fig. 1. Schematic map showing the location of trees within the thermokarst depression and on the adjacent permafrost slope (test sites); 1–28 are the tree numbers referred to in the text.

Fig. 2. Photograph of the thermokarst depression test site.

rately indicates the year when the tree began to tilt. The trees from the reference test site have no compression wood.

A procedure for constructing the generalized TRC was used for all the trees at the reference site. This generalized chronology has been used further for analysis of the response function of radial tree growth to the influence of the climatic factors (air temperature, precipitation, snow cover depth). We used for response function analysis the software package RESPONSE (Lough, 1983).

3. Results and discussion

The analysis of meteorological data available from the Muzhy weather station (1933–1990) showed a very slight increase in summer air temperatures (0.007 °C per annum, Fig. 3) accompanied by negative trends for the average temperature of the cold season (October–April) and average annual air temperature (− 0.02 and − 0.017 °C, respectively). This does not match the data mentioned above.

Increasing precipitation in summer (June–August) and in the cold season, as well as total precipitation and depth of snow cover (October–May) in open places is noteworthy. The increase in precipitation in summer adds up to 0.5 mm, in the cold season to 0.81 mm, the total annual precipitation to 1.42 mm and the depth of snow cover to 0.4 cm per annum (Fig. 4). Beginning in the late 1950s, precipitation has increased significantly. Average cold season precipitation from 1958 to 1988 was 152.3 mm but only 124.4 mm during the period 1933–1957. Total annual precipitation during these periods was 489.3 and 458.1 mm, respectively. Summer precipitation did not demonstrate such a great difference (199.1 and 195.8 mm). It should be noted that the depth of snow cover also changed beginning in the late 1950s. Thus, the average depth of snow cover from 1958 to 1985 was 54.4 cm as compared to 38.7 cm from 1933 to 1957. All the above data point to a significant increase in winter precipitation within the area under study. Our precipitation data show good similarity with the precipitation tendency for the Northern Hemisphere (Krenke et al., 1997; Vaganov et al., 1999; Zhang et al., 2000).

Table 1 presents positive anomalies in summer, winter and annual precipitation sums, maximum depth of snow cover and air temperature. It is worth noting that the highest number of anomalies relate to precipitation and snow cover depth and the frequency of anomalies increased from the late 1950s onwards. The following years were recorded as notably anomalous: 1956–1958 (majority of meteorological data); 1971 (all kinds of precipitation and snow cover depth); 1973 (cold season precipitation and snow cover depth-season of 1972/1973); 1978 (cold season and annual precipitation sums and snow cover depth) as well as 1982–1983 (precipitation and snow cover depth).

The Siberian stone pine stands within the investigated test sites are all of the same age class, namely they appeared during a period of less than 40 years (Fig. 5). This is not typical of Siberian stone pine stands. Usually Siberian stone pine stands have a different age structure, including trees with ages from 20 to 200 and more years all formed under a mature tree canopy. We assume the modern Siberian stone pine stand on the study area was established after a wild fire approximately 250 years ago. Charcoal remains at the upper active layer of the soil profile lend support to this working hypothesis.

No significant correlation has been revealed by response function analysis comparing ring-width dynamics to changes in air temperature, precipitation and snow cover depth within the reference site (Fig. 6). Nevertheless, a statistically insignificant but stable negative correlation is recorded between radial tree growth and snow cover depth, especially for the month of April. Perhaps deeper snow cover in April leads to later melting, which in turn affects the depth of the active soil layer as well as freeze–thaw processes (Moskalenko, 1998). This could delay the response of the root systems and retard physiological activity in spring. There are no relationships between tree mortality and meteorological conditions observed within the thermokarst depression site. Nevertheless, it should be noted that the majority of trees died off after the 1950s (Fig. 5).

The most interesting results came from analyzing the periods of compression wood formation in the trees on the permafrost and the thermokarst depression test sites. We did not record any compression wood in trees at the reference test site. The physiology of compression wood formation was described well by A.H. Westing (1965). Compression wood can be formed by the power of gravity when a tree stem

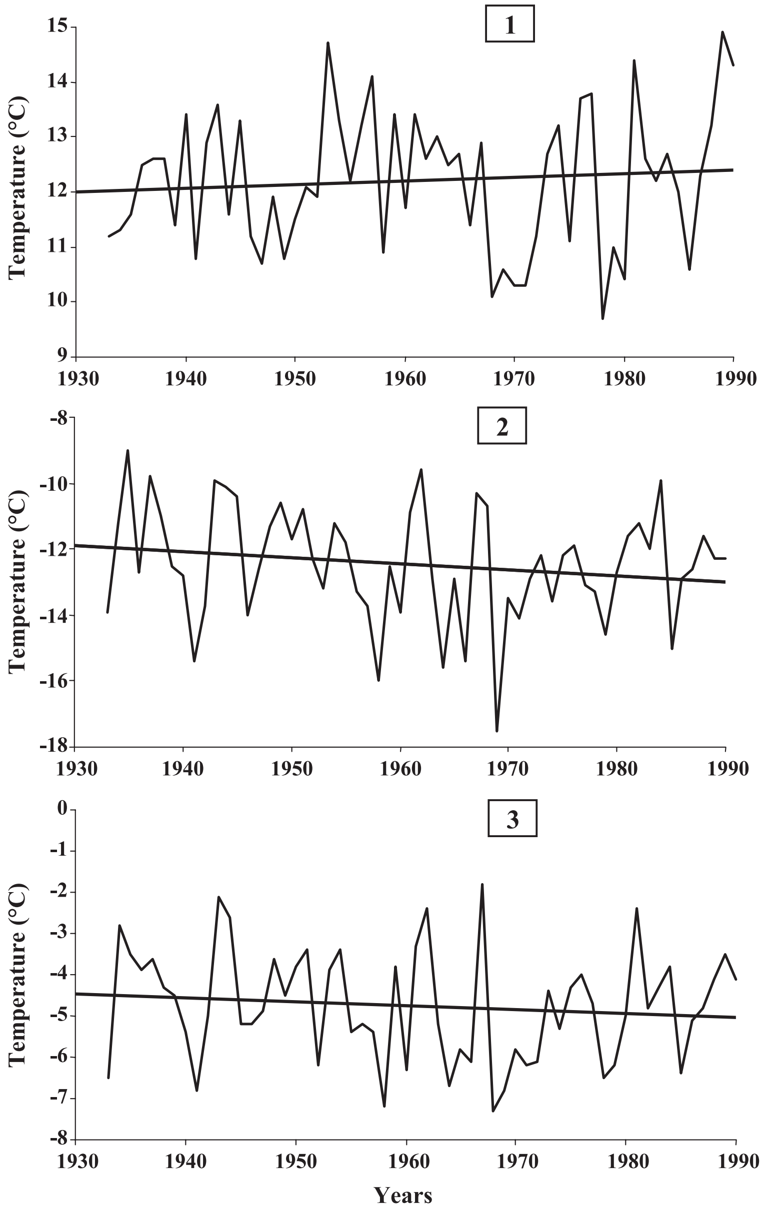

Fig. 3. The air temperature records at the Muzhy weather station and its long-term trends: 1—average summer temperature; 2—average temperature from October to April; 3—average annual temperature.

inclines from the vertical. Within the permafrost zone, solifluction, favoured by active snow melting and heavy precipitation, gives rise to a decrease in ground firmness on slopes between 3° and 15°, which can in turn cause trees to tilt and the formation of compression wood.

Fig. 7A shows the period of compression wood formation in the trees at the permafrost site. The development of compression wood formation beginning in the 1960's is obvious for all trees regardless of their position along the slope. Microsolifluctional processes were probably initiated during this period

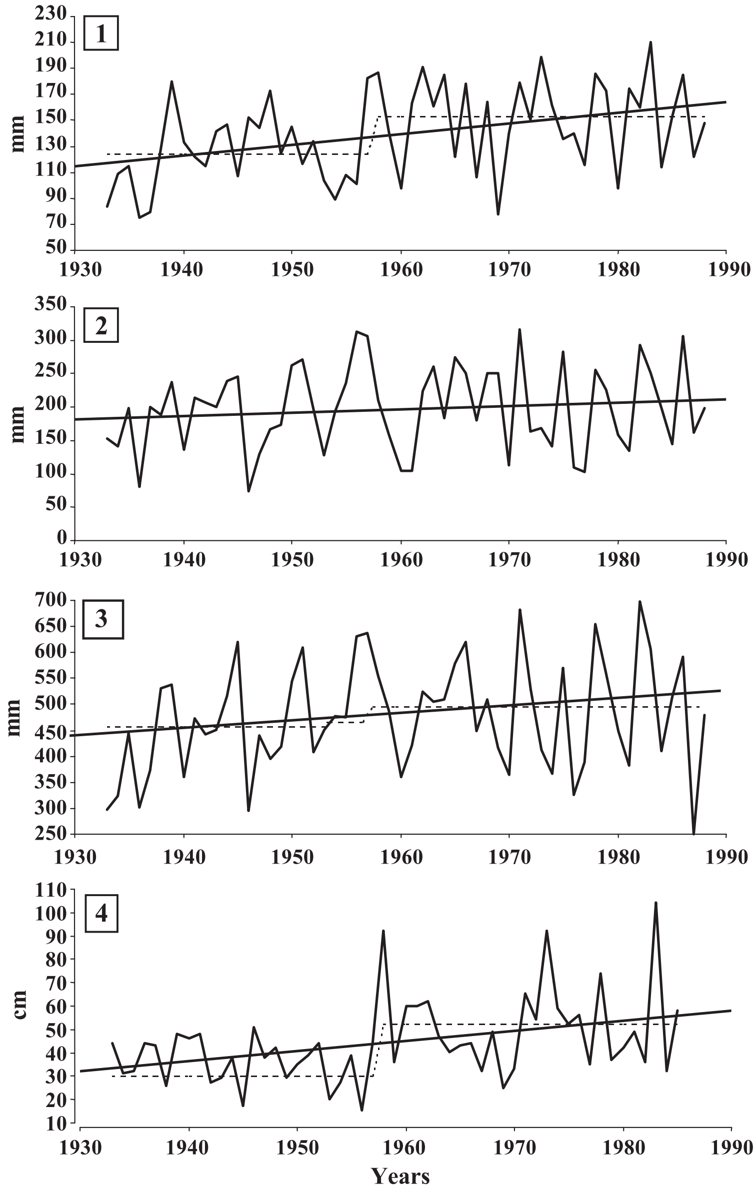

Fig. 4. The precipitation and maximum snow cover depth records at the Muzhy weather station and their long-term trends: 1—precipitation of cold season (October–April): 2—summer precipitation; 3—annual precipitation; 4—maximum depth of snow cover. Dotted lines show average long-term precipitation and snow cover depth for the periods of 1933–1957 and 1958–1990.

along the entire slope. This process started in 1945 (tree 24) continued in 1959 (tree 1), 1964 (tree 17) and 1966 (tree 3 and 28). The trees 25, 23, 11, 19, 2, 15, and 10 are attributed to the years 1971, 1975, 1975, 1979, 1983, 1987, 1997, respectively.

No general regularities in compression wood formation are shown in the trees within the thermokarst depression site (Fig. 7B). Temporal coincidence of compression wood formation can only be seen in individual neighbouring trees (4 and 5; 7 and 8) and

Table 1
Years with positive deviations over one standard deviation(s) for the records of the Muzhy weather station (precipitation 1932–1988, maximal snow cover 1932–1985, air temperature 1932–1990)

Deviation years	*Summer precipitation (s=62.94)*	*Winter precipitation (s=34.29)*	*Annual precipitation (s=106.8)*	*Snow cover (s=17.7)*	*Summer temperature (s=1.254)*	*Winter temperature (s=1.738)*	*Annual temperature (s=1.35)*
1934		+5.9					+0.6
1939							
1941						+1.2	
1943					+0.14		+1.3
1944							+0.8
1945			+37.8				
1950	+1.44						
1951	+10.4		+27.8				
1953					+1.24		
1956	+52.4		+48.8				
1957	+46.4	+7.9	+55.8		+0.64		
1958		+12.9		+29.7*		+1.8*	
1961							+0.1
1962		+16.9					+1.0
1964		+10.9				+1.4	
1965	+14.4						
1966		+3.9	+36.8			+1.2	
1967							+1.6*
1969						+3.3**	
1971	+55.4	+4.9	+101.0	+2.7			
1973		+24.9		+29.7*			
1975	+21.4						
1976					+0.24		
1977					+0.34		
1978		+11.9	+71.8	+11.7			
1979						+0.4	
1981		+0.9			+0.94		+1.0
1982			+116.0*				
1983	+31.4	+35.9*	+25.8	+41.7**			
1985	+46.4					+0.8	
1986		+10.9	+9.8				
1989	–	–	–	–	+1.44*		
1990	–	–	–	–	+0.84		

*, >2s; **, >3s; –, no data.
Shaded lines are for years with strong numerous anomalous meteorological elements.

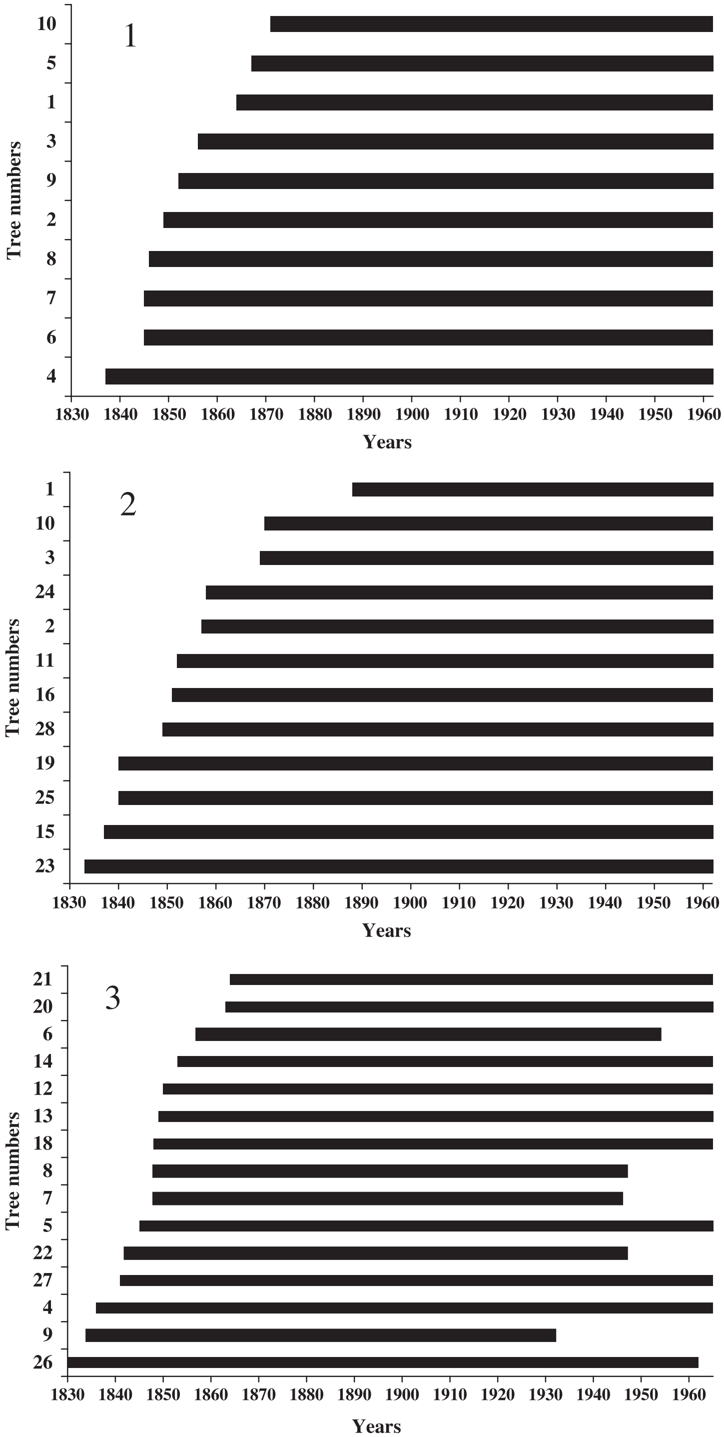

Fig. 5. Age structure of the trees at the reference test site (1), at the permafrost test site (2) and at the thermokarst depression test site (3).

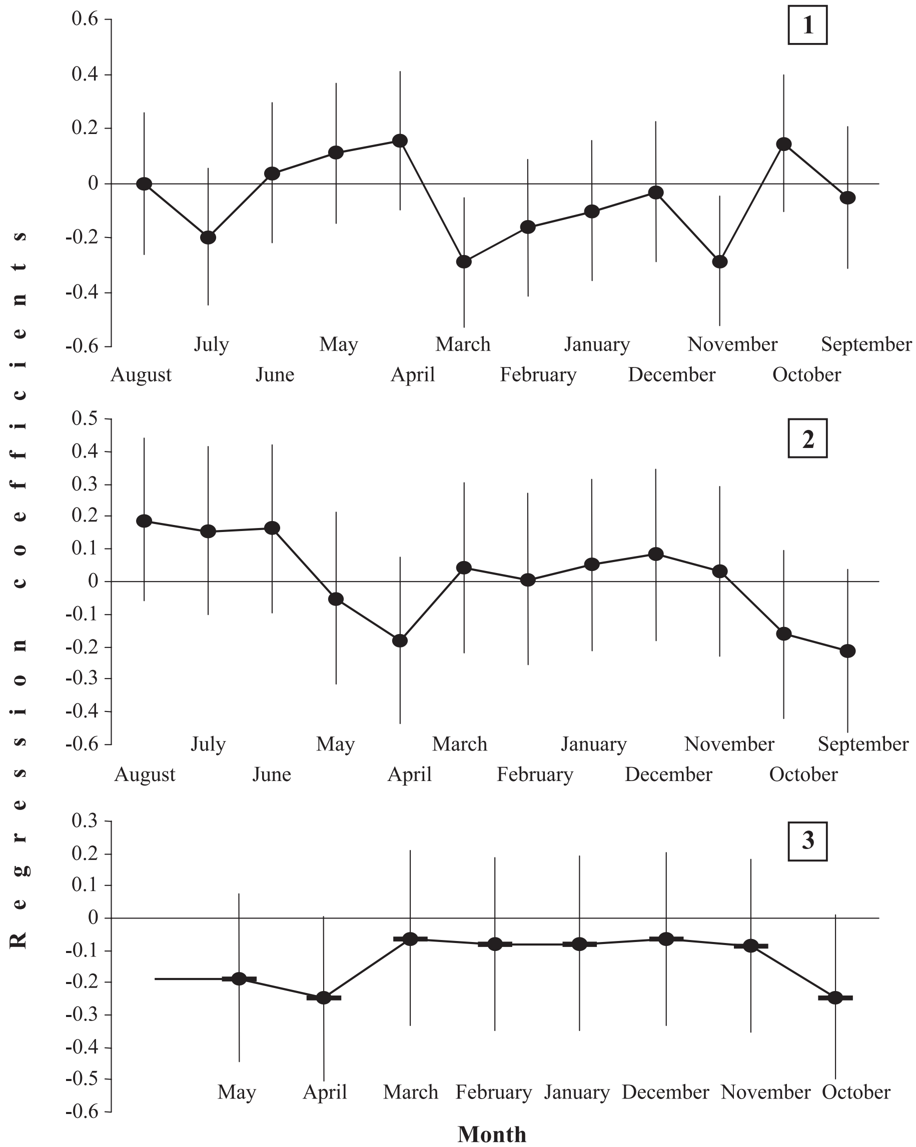

Fig. 6. The response function of radial tree growth at the reference test site for air temperature (1), precipitation (2), and snow cover depth (3). For temperature and precipitation, the period under consideration lasts from August of the current growing season back to September of the previous growing season, and for snow cover, from May of the current year back to October of the previous year.

in trees equidistant from the rim and dislocated along the same line (trees 22 and 26). The most active compression wood formation took place in the trees 4, 5, 6, 9 beginning in the late 1870s of the 19th century whereas the compression wood in the trees 22 and 26 started in the early 20th century. Trees 7 and 8 were affected in the 1930s, trees 4, 12, 13, 18, 20, 21 in the 1940s and 1950s. Coincidence of the periods of intense compression wood formation after 1950 with increasing precipitation suggests the cause of compression wood formation in the trees at the permafrost site was microsolifluctional processes conditioned, in the first place, by heavy winter and summer precipitation.

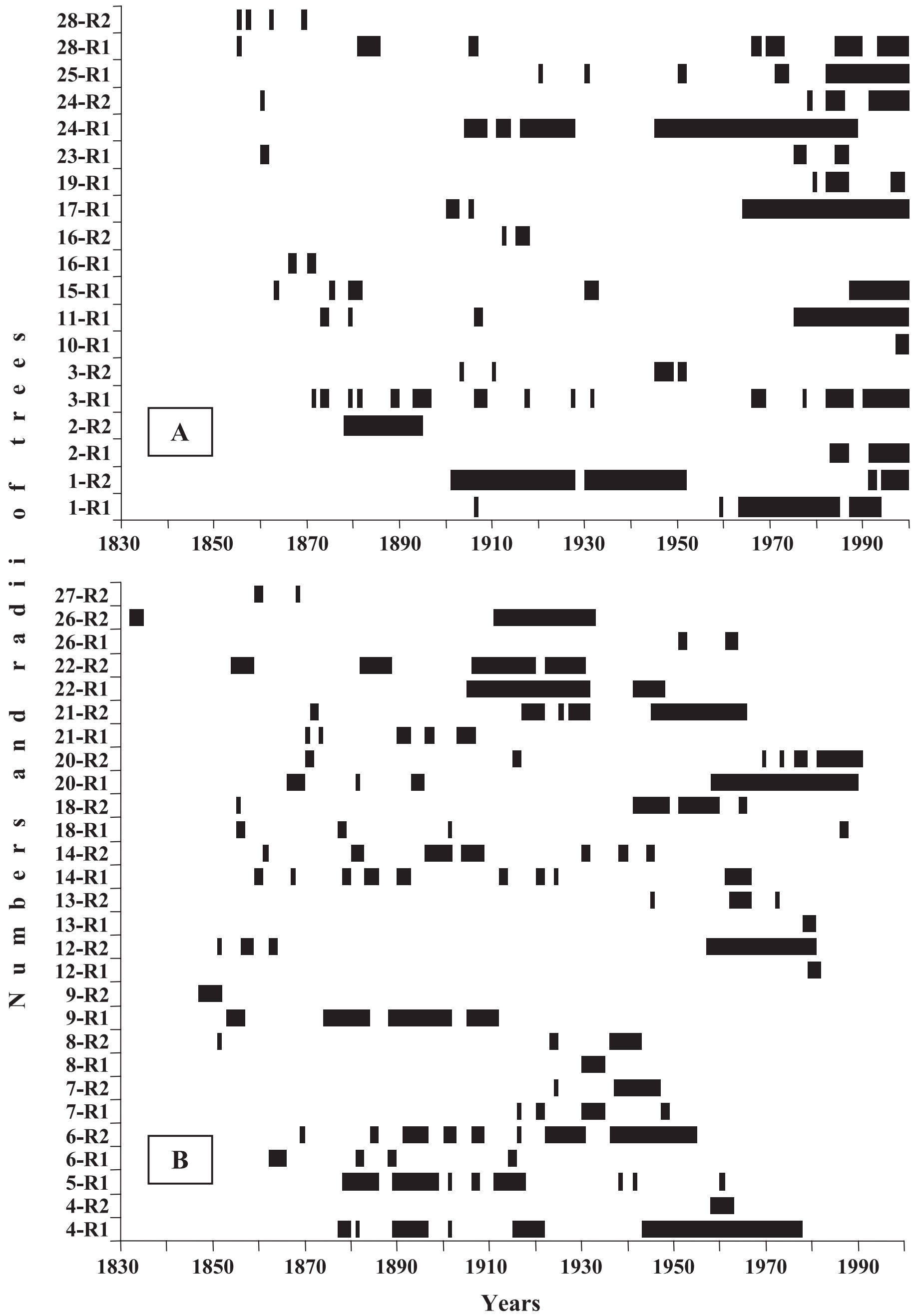

Fig. 7. The years of compression wood formation in all the trees along the radii R1 and R2 on the permafrost site (A) and at the thermokarst depression site (B).

A reconstruction of past thermokarst borderlines has been carried out by using graphs of the dynamics of radial increment along two radii (R1 and R2) in each tree at the thermokarst depression site while taking into account the years of compression wood formation. When comparing TRCs along two radii it

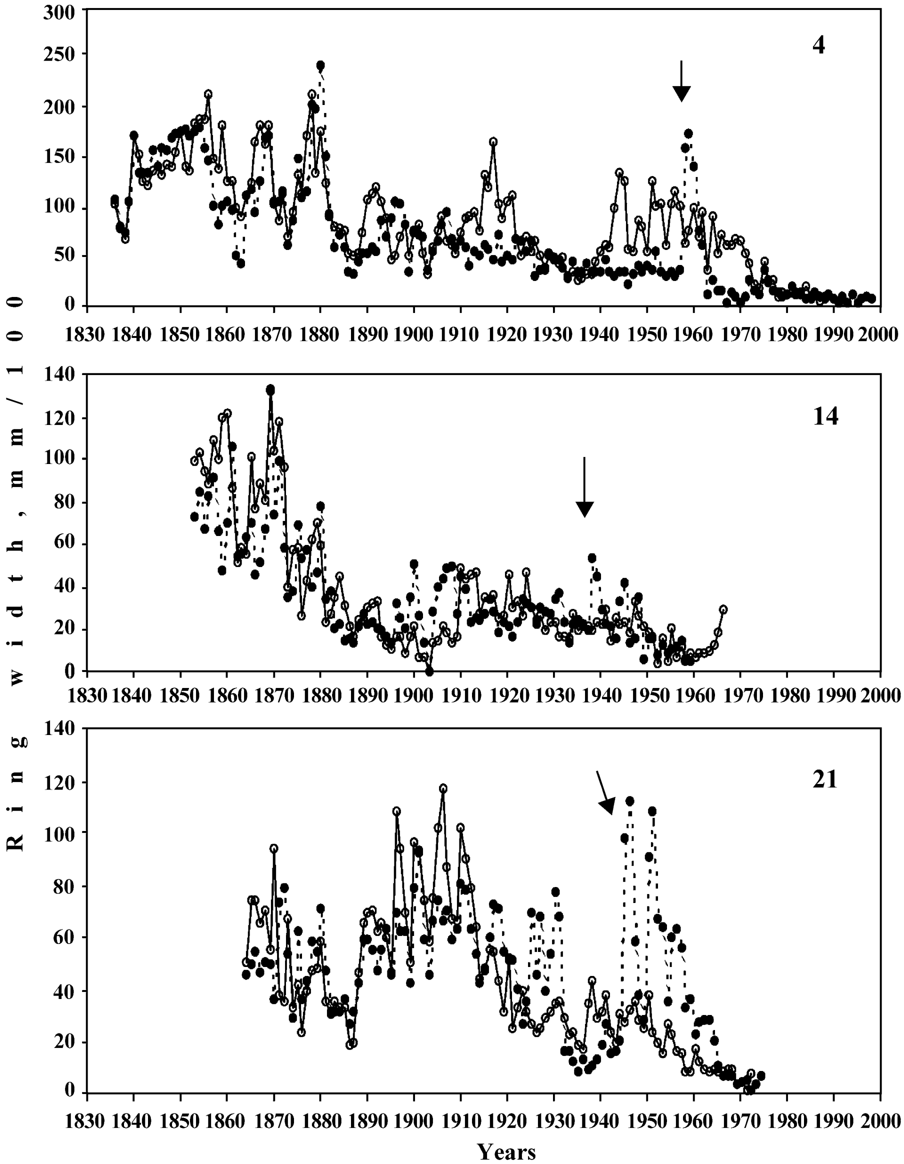

Fig. 8. Examples of tree-ring chronologies along two radii (R1—solid line; R2—dotted line) for trees 4, 14, 21 from the thermokarst depression site; arrows indicate the years when trees have occurred on the thermokarst borderline.

was noticed that in those years when the thermokarst borderline reached the basal part of a tree, the stem began to incline and form compression wood (Fig. 8). This happened as a result of the root system slipping down into a thermokarst depression causing the roots to lose the firm support of the permafrost. Fig. 9 shows thermokarst borderlines in 1930 and 1958 reconstructed using this approach, as well as the dates when each tree was on the borderline.

The rate of thermokarst expansion may be calculated from the dates of its known positions and the distance of each tree from the contemporary thermokarst borderline. Thus, tree 9 was on the thermokarst borderline in 1902; tree 6 in 1922; tree 5 in 1938; tree 4 in 1958. The actual distance from

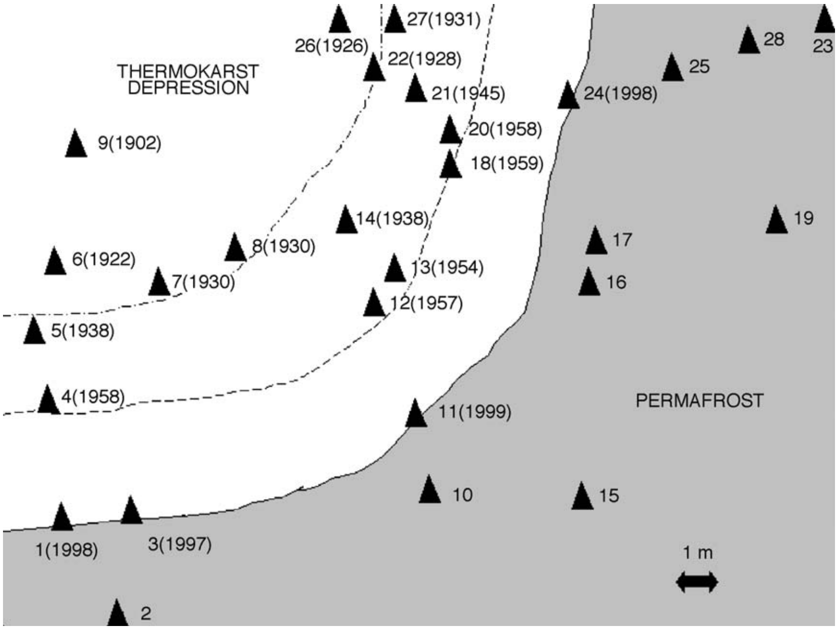

Fig. 9. The reconstruction of thermokarst borderlines (dotted lines) in 1930 and 1958. In parentheses—the years when each tree stood on the thermokarst borderline are shown.

these trees to the modern borderline is 6, 5.2, 3.9, and 3.1 m respectively. Thus the average rates of thermokarst expansion (distance/time in years) are 6.1, 6.4, 6.3, and 7.4 cm/year, respectively. The calculated thermokarst expansion rate in the area between trees 9 and 6 adds up to 4.0 cm per year; between trees 6 and 5, − 8.1 cm/year; between trees 5 and 4, − 4.0 cm/year. It is shown that the thermokarst expansion rate increased noticeably after 1958 (7.4 cm/year). The maximum value of 8.1 cm/year occurred between 1922 and 1938. This period is known to encompass some of the warmest decades of the 20th century, thereby causing a high rate of thermokarst development (Jones and Briffa, 1992, 1993).

As shown above, the number of years with heavy precipitation (in winter as well as in summer) began to increase in the late 1950's. It is well known that snow cover is one of the principal factors influencing the soil temperature regime. The average annual soil temperature depends on the specific winter conditions: the accumulated sub-zero temperatures, the depth of snow cover, as well as specific features of its accumulation throughout the season (Pavlov, 1975; Zhang et al., 1996; Skryabin et al., 1999). Correlation between summer precipitation and the dynamics of the seasonally thawed layer is also well known; the greater the precipitation, the deeper the seasonally thawed layer (Pavlov, 1996). Probably increased precipitation accelerated solifluctional processes, with excessive water being accumulated in the thermokarst depression due to the fact that water input exceeds potential evaporation in this region. This imbalance would have caused a rise in water level in the thermokarst depression, leading to an increase in the height of the thermoabrasion base along its slopes. In turn the thermoabrasion caused intensification of solifluctional processes on bordering slopes and facilitated expansion of the thermokarst body. Similar viewpoints concerning thermokarst development have been proposed for other regions (Payette and Delwaide, 2000).

4. Conclusions

We did not find evidence for a significant increase in air temperature in our study area, nor any noticeable influence of temperature on either tree radial growth or the development of the thermokarst depression over the last 100 years. However, we can confirm an increase in total precipitation and snow cover since the 1950s. We show that the expansion of the thermokarst depression under study that occurred during the last 50 years was caused by an increase in precipitation rather than in air temperature. However, we do not categorically identify precipitation as the sole factor in thermokarst development. Most probably, the trigger for thermokarst development may be dependent on a specific sequence of climatic changes in the region and the primary forcing variable may change from one meteorological element to another. In our study area, the trigger probably took place during the late 1920s and 1930s when high air temperatures probably caused the highest rate of thermokarst expansion (8.1 cm/year).

Since the age structure of the Siberian stone pine stand is homogenous, we assume that the modern stand was established after a wild fire about 250 years ago. Also, we assume the wild fire could be one of the causes for the origin and development of the studied thermokarst depression in the middle of the 18th century.

The method of tree-ring analysis adopted for geocryological studies made it possible to provide spatial-temporal reconstruction of the thermokarst region and explain the causes of recent expansion. This method achieves high temporal resolution and is accurate to within a year. Furthermore, it suggests the possibility of providing long-term reconstructions (up to a thousand years) using buried and fossil wood. In the future it should therefore be possible to reconstruct thermokarst dynamics in this area throughout the past millennium and, possibly, to make inferences concerning the responsible climatic forcings.

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References

Barashkova, N.K., Zadde, G.O., Kabanov, M.V., Servast'aynov, V.V., 2000. Modern tendencies of climatic changes in southern West Siberia. Geography and Natural Resource 3, 77–82 (in Russian).

Burn, C.R., 1998. The response (1958–1997) of permafrost and near-surface ground temperatures to forest fire, Takhini River valley, southern Yukon territory. Canadian Journal of Earth Sciences 35 (2), 184–199.

Duchkov, A.D., Sokolova, A.V., Pavlov, A.V., 2000. Estimation of modern changes in air and soil temperature in West Siberia. Earth Cryosphere IV (1), 52–59 (in Russian, resume in English).

Foundations of geocryology (permafrost study), 1959. Academy of Sciences Press, Moscow (in Russian).

Geocryology USSR. West Siberia Nedra, Moscow. In Russian.

Holmes, R.L., Adams, R.K., Fritts, H.C., 1986. Tree-ring chronologies of western North America: California Eastern Oregon and northern Great Basin with procedures used in chronology department work including users manuals for computer programs COFECHA and ARSTAN. Chronology Series, vol. VI. Laboratory of Tree-Ring Research University of Arizona, Tucson, Arizona.

Jones, P.D., Briffa, K.R., 1992. Global surface air temperature variations during the twentieth century: Part 1. Spatial, temporal and seasonal details. Holocene 2 (2), 165–179.

Jones, P.D., Briffa, K.R., 1993. Global surface air temperature variations during the twentieth century: Part 2. Implications for large-scale high-frequency palaeoclimatic studies. Holocene 3 (1), 77–88.

Jorgenson, M.T., Racine, C.H., Walters, J.C., Osterkamp, T.E., 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change 48 (4), 551–579.

Kachurin, S.P., 1961. Thermokarst on the USSR Terrain. Academy of Sciences Press, Moscow. In Russian.

Krenke, A.N., Kitaev, L.M., Turkov, D.V., 1997. Snow cover change and it climatic role. Earth Cryosphere I (1), 39–46 (in Russian, resume in English).

Lough, J.M., 1983. Program RESPONSE. Manual Tree-Ring Laboratory, Arizona Univ. Press, Tucson.

Mezentsev, V.S., Karnatsevich, I.B., 1969. Moisture Condition of the West Siberia Plain. Gidrometeoizdat, Leningrad. In Russian.

Moskalenko, N.G., 1998. Investigation of seasonal thaw of peatlands in the West Siberian cryolithozone. Earth Cryosphere II (1), 32–35 (in Russian, resume in English).

Osterkamp, T.E., Romanovsky, V.E., 1999. Evidence for warming and thawing of discontinuous permafrost of Alaska. Permafrost and Periglacial Processes 10 (1), 17–34.

Osterkamp, T.E., Viereck, L., Shur, Y., Jorgenson, M.T., Racine, C., Doyle, A., Boone, R.D., 2000. Observations of thermokarst and its impact on boreal forest in Alaska. Arctic, Antarctic, and Alpine Research 32 (3), 303–315.

Pavlov, A.V., 1975. Heat Exchange Between Soil and Atmosphere in Northern and Temperate Latitudes of the USSR. Yakutsk book publishing house, Yakutsk, in Russian.

Pavlov, A.V., 1994. Current changes of climate and permafrost in the Arctic and Sub-Arctic of Russia. Permafrost and Periglacial Processes 5 (2), 101–110.

Pavlov, A.V., 1996. Permafrost-climatic monitoring of Russia: analysis of field data and forecast. Polar Geography and Geology 20, 44–64.

Pavlov, A.V., 1998. Role of P.I. Mel'nikov in formation and development in Russian geocryological studies (1991–1995). Earth Cryosphere 4, 32–41 (in Russian, resume in English).

Payette, S., Delwaide, A., 2000. Recent permafrost dynamics in a subarctic floodplain associated with changing water levels Quebec, Canada. Arctic, Antarctic, and Alpine Research 32 (3), 316–323.

Physical Geography Zonation of Tumenskaya Oblast, 1973. Moscow University, Moscow. In Russian.

Rinn, F., 1996. TSAP (Time Series Analysis and Presentation) Version 3.0. Reference Manual. Rinntech, Heidelberg, Germany.

Skryabin, P.N., Skachkov, Yu.V., Varlamov, S.P., 1999. Climate warming and thermal state of ground in central Yakutia. Earth Cryosphere III (3), 32–40 (in Russian, resume in English).

Shiyatov, S.G., 1986. Dendrochronology of upper timberline in the Ural. Nauka, Moskow. In Russian.

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

Vitt, D.H., Halsey, L.A., Zoltai, S.C., 2000. The changing landscape of Canada's western boreal forest: the current dynamics of permafrost. Canadian Journal of Forest Research 30 (2), 283–287.

Westing, A.H., 1965. Formation and function of compression wood in gymnosperms. The Botanical Review 31, 381–480.

Zhang, T., Osterkamp, T.E., Stamnes, K., 1996. Influence of the depth hoar layer of the seasonal snow cover on the ground thermal regime. Water Resources Research 2 (7), 2075–2086.

Zhang, X.B., Vincent, L.A., Hogg, W.D., Niitsoo, W.D., 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38 (3), 395–429.