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Past and recent changes in air and permafrost temperatures in eastern Siberia

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Abstract

Air and ground temperatures measured in Eastern Siberia has been compiled and analyzed. The analysis of mean annual air temperatures measured at 52 meteorological stations within and near the East-Siberian transect during the period from 1956 through 1990 demonstrates a significant and statistically significant (at 0.05 level) positive trend ranging from 0.065 to 0.59 °C/10 yr. A statistically significant (at 0.05 level) positive trend was also observed in mean annual ground temperatures for the same period. The permafrost temperature reflects changes in air temperature on a decadal time scale much better than on an interannual time scale. Generally, positive trends in mean annual ground temperatures are slightly smaller in comparison with trends in mean annual air temperatures, except for several sites where the discordance between the air and ground temperatures can be explained by the winter snow dynamics. The average trend for the entire region was 0.26 °C/10 yr for ground temperatures at 1.6 m depth and 0.29 °C/10 yr for the air temperatures. The most significant trends in mean annual air and ground temperatures were in the southern part of the transect, between 55° and 65° N. Numerical modeling of ground temperatures has been performed for Yakutsk and Tiksi for the last 70 yr. Comparing the results of these calculations with a similar time series obtained for Fairbanks and Barrow in Alaska shows that similar variations of ground temperatures took place at the same time periods in Yakutsk and Fairbanks, and in Tiksi and Barrow. The decadal and longer time scale fluctuations in permafrost temperatures were pronounced in both regions. The magnitudes of these fluctuations were on the order of a few degrees centigrade. The fluctuations of mean annual ground temperatures were coordinated in Fairbanks and Yakutsk, and in Barrow and Tiksi. However, the magnitude and timing of these fluctuations were slightly different for each of the sites.

Keywords: permafrost; East Siberia; climate warming; numerical modeling

1. Introduction

Substantial climate warming has occurred during the 20th century and especially during the last 30 yr of the century (IPCC, 2001a,b). It was also observed that over the past century temperatures have increased even more in the Arctic and sub-Arctic. The average near-surface air temperature increased in the Arctic by approximately 0.09 °C/decade, which is an almost twice-larger increase if compared to the entire Northern Hemisphere (ACIA, 2005). However, this increase has not been spatially or

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temporally uniform. Two regions in the Northern Hemisphere, the western part of the North America and Siberia were the most affected by the recent warming (Jones and Moberg, 2003; NEESPI, 2004; Groisman et al., 2006; http://www.ncdc.noaa.gov/gcag/gcag.html).

Increased atmospheric concentrations of greenhouse gases are very likely to have a larger effect on climate warming in the Arctic and sub-Arctic than in mid and low latitude areas in the future (Kattsov et al., 2005). IPCC climate models project a 3.5 and 2.5 °C increase in the global mean surface air temperatures by the end of the 21st century compared to the present climate for the A2 and B2 emission scenarios respectively (IPCC, 2001c). By 2071–2090 and using B2 emission scenario, five designated in the Arctic Impact Assessment (ACIA) studies global coupled atmosphere–ocean general circulation models project on an average more than 5°C increase in mean annual air temperature in the Central Arctic, and up to 5 °C warming in the Canadian Archipelago and Russian Arctic (Kattsov et al., 2005).

A recent increase (last 30 to 40 yr) in air temperatures has been reported for many regions in the Arctic and sub-Arctic (Serreze et al., 2000; Jones and Moberg, 2003; Hinzman et al., 2005). This increase, which was the most pronounced in Alaska, north-west Canada, and in western and eastern Siberia (Hansen et al., 1999), produced a subsequent increase in permafrost temperatures recorded at many monitoring stations within the Arctic (Osterkamp and Romanovsky, 1999; Isaksen et al., 2001; Oberman and Mazhitova, 2001; Romanovsky and Osterkamp, 2001; Pavlov and Moskalenko, 2002; Romanovsky et al., 2002; Chudinova et al., 2003; Clow and Urban, 2003; Harris and Haeberli, 2003; Osterkamp, 2003; Sharkhuu, 2003; Smith et al., 2005). However, the increase in permafrost temperatures was not uniform in space and time (e.g. Chudinova et al., 2003). Hence, in analyzing changes in permafrost temperatures a regional approach is needed. Also, the availability of the ground and permafrost temperature data is very different for different regions in the circumpolar North.

As a part of a National Science Foundation (NSF)/OPP (Office of Polar Program)/ARCSS (Arctic System Science) sponsored ATLAS (Arctic Transitions in the Land–Atmosphere System) project, we collected data on regional air and near-surface permafrost temperatures in the continuous permafrost zone of East Siberia spanning

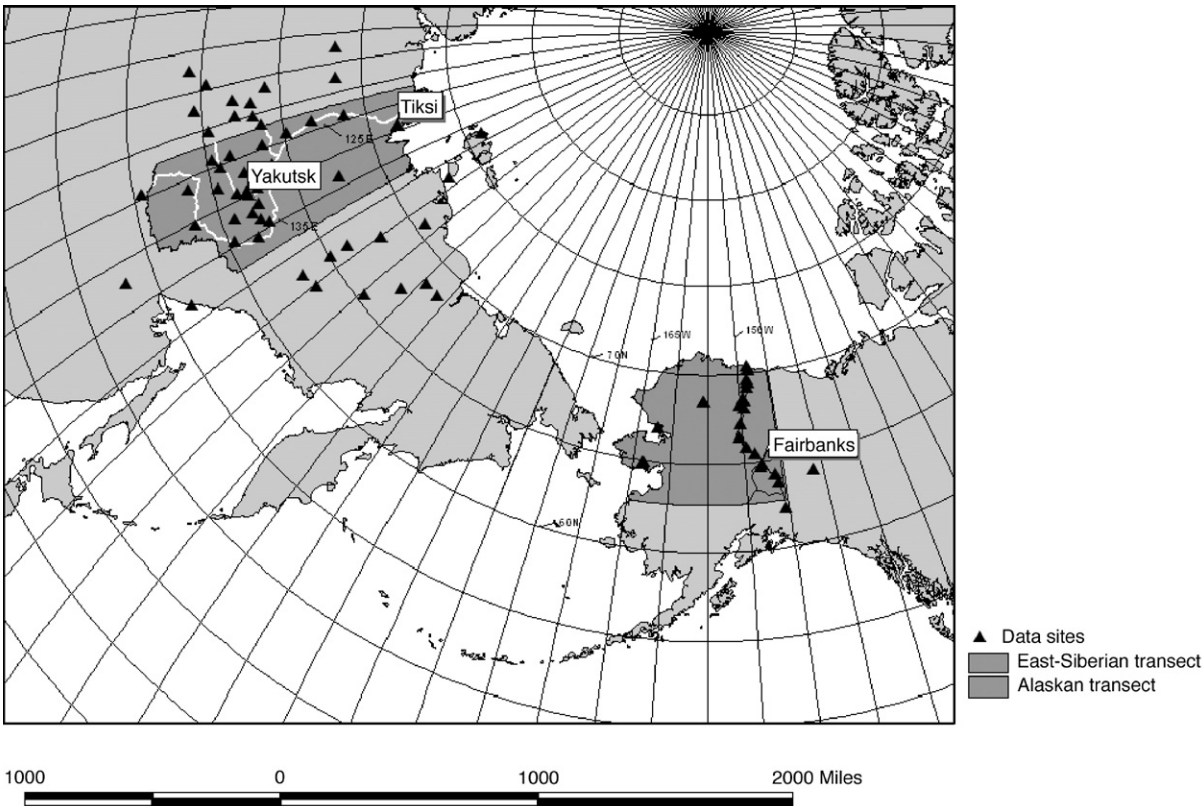

Fig. 1. Location of the East Siberian and the Alaskan transects of the IGBP project.

a time interval between 1950s and 1990s with monthly and, for some sites, daily time resolution. These data were collected at a number of meteorological stations in this region and at several specialized permafrost observatories. The major goal of this paper is to provide an analysis of spatial and temporal variability of the ground and permafrost temperatures during the last half of the 20th century from the central part of East Siberia, the region that could be designated as one of the "hot spots" of permafrost warming in the Northern Hemisphere. Both, the data from the meteorological stations and from the specialized permafrost observatories were used. To investigate the possible causes of the recent permafrost warming we compared the observed changes in ground temperatures with the air temperature records for the same area. To extend our knowledge about the ground and permafrost temperature dynamics for the time period not covered by the ground temperature measurements we applied a numerical modeling technique that was successfully used in Alaska (Romanovsky and Osterkamp, 1996, 1997; Romanovsky et al., 2002). This allowed placing recent permafrost warming in a longer-term perspective. Finally, the active layer and permafrost temperature regime in the central part of East Siberia were compared with similar data and modeling results from Alaska, another "hot spot" of the recent climate and permafrost warming.

2. Data description

The Tiksi–Yakutsk East Siberian transect, designated as the Far East Siberian transect in the International Geopshere–Biosphere Program (IGBP) Northern Eurasia Study project (IGBP-NES) (IGBP, 1996; McGuire et al., 2002), is centered on the 135° meridian, and was set as a collaborative effort of IGBP-NES with the GAME project of the WCRP (Fig. 1). This transect is bounded by the Arctic Ocean in the north, 60° N latitude in the south, and

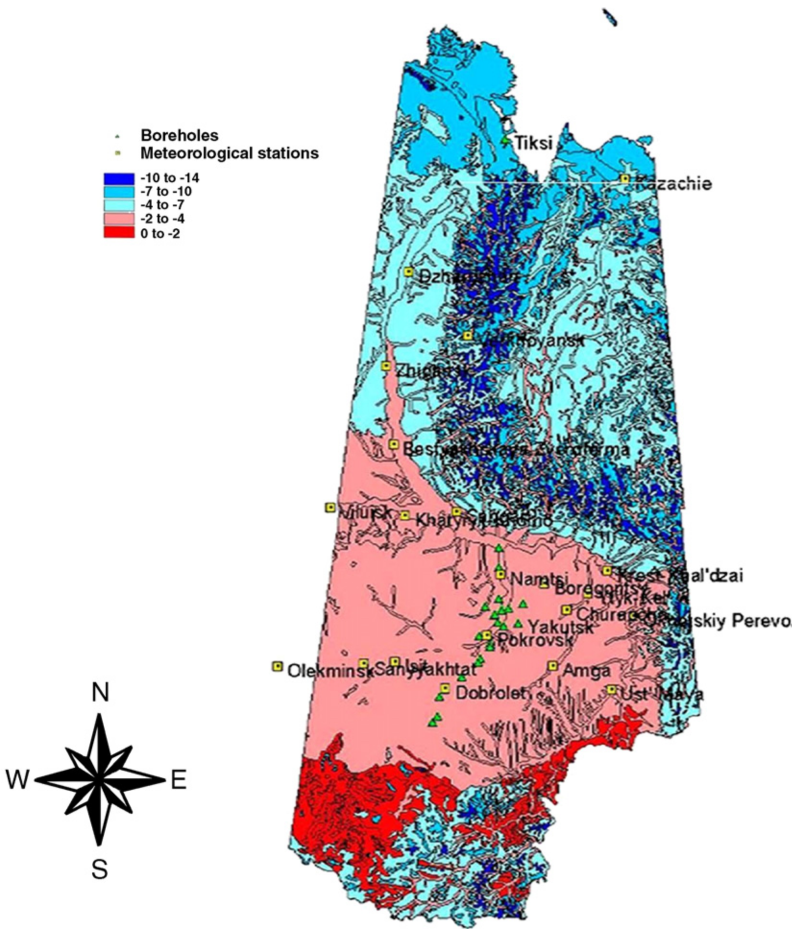

Fig. 2. Permafrost temperature map (modified from (Fedorov et al., 1989)) and location of the meteorological stations (yellow squares) and permafrost boreholes (green triangles) within the IGBP-NES East Siberian transect.

Table 1
Trends in mean annual air and ground (1.6 m) temperatures within the East-Siberian Transect

Station	Latitude (°)	Longitude (°)	Period of obtained data (yr)	Period used in this analysis (yr)	Trend in air temperatures (°C/10 yr)	Trend in ground (1.6 m depth) temperatures (°C/10 yr)
Kotelni	76.00	137.90	1933–2000	1956–1990	0.104	–
Tiksi	71.59	128.92	1956–1995	1956–1990	0.182	–
Dzhardzhan	68.73	124.00	1937–1992	1956–1990	0.130	−0.093
Bestyakhskaya Zveroferma	65.18	124.07	1959–1992	1959–1990	0.196	0.197
Sangar	63.97	127.47	1936–1994	1956–1990	0.224	0.054
Hatrik-Homo	63.57	124.50	1957–1991	1957–1990	0.255	–
Verkhneviluysk	63.27	120.19	1958–1990	1958–1990	0.509	0.710
Krest-Khal'dzhai	62.82	134.43	1960–1992	1960–1990	0.477	−0.186
Namtsy	62.73	129.67	1964–1994	1964–1990	0.590	0.312
Borogontsy	62.57	131.62	1959–1989	1959–1989	0.121	0.240
Ytyk-Kel'	62.37	133.55	1957–1994	1957–1990	0.173	0.613
Yakutsk	62.10	129.80	1882–1996	1956–1990	0.360	–
Churapcha	62.02	132.36	1936–1992	1956–1990	0.428	0.606
Okhotskiy Perevoz	61.87	135.50	1938–1992	1956–1990	0.200	−0.051
Tongulakh	61.55	124.33	1955–1990	1956–1990	0.517	0.650
Pokrovsk	61.48	129.15	1957–1994	1957–1990	0.190	–
Amga	60.90	131.98	1936–1994	1956–1990	0.294	−0.211
Isit'	60.82	125.32	1936–1994	1956–1990	0.362	0.155
Olekminsk	60.40	120.42	1882–1995	1956–1990	0.065	–
Ust'-Maya	60.38	134.45	1897–1992	1956–1990	0.344	0.147
Dobrolet	60.37	127.50	1959–1992	1959–1990	0.340	0.159
Saniyakhtat	60.35	124.04	1959–1994	1959–1990	−0.035*	0.063
Tommot	58.58	126.16	1957–1990	1957–1990	0.408	0.440
Uchur	58.44	130.37	1957–1990	1957–1990	0.329	0.780
Nagorny	55.58	124.53	1955–1990	1956–1990	0.356	–

by the 122° and 138° meridians (an area approximately the size of Alaska). The entire transect is located within the Sakha (Yakutia) Republic, Russian Federation. More information on environmental conditions (including permafrost and active layer characteristics) along this transect can be found in (Sazonova et al., 2004).

As a part of the mentioned above NSF project, new data for the 52 meteorological stations within the continuous permafrost zone in east Siberia were obtained. Originally, this dataset was compiled and digitized by our collaborators on this project from the Permafrost Institute in Yakutsk (group leader V. T. Balobaev) and at the Institute of Physicochemical and Biological Problems in Soil Science, Russian Academy of Sciences (group leader D. A. Gilichinsky). The published monthly meteorological regional reports (Klimatologicheskii spravochnik SSSR, 1961–1992) were used for this purpose. The data include monthly averaged air temperature, snow cover depth and ground temperature at several depths (0.05 m down to 3.2 m). The ground temperature data are available for only 31 out of 52 stations. The period of measurements ranges between 110 and 50 yr for the air temperatures and between 40 and 20 yr for ground temperatures.

Only 28 of these stations are situated within or nearby the East-Siberian transect (Fig. 2). Most of the stations, within or outside of the transect, have operated for more than 40 yr. For our further analysis we used data for the period from 1956 to 1990 and only those 25 stations that were not re-allocated during this period (Table 1). Average mean annual temperatures vary within the transect area from lower than −16 °C in the Verkhoyansk region to −8 °C near the southern limits of the transect. Permafrost temperatures at the depth of zero annual amplitude vary between −14 °C and 0 °C (Fig. 2). The data include daily (for a limited number of stations), monthly, and annual values of air temperatures and precipitation, 10-day mean depths of snow cover, snow density, and water equivalent, and the number of days with snow cover for each month. At some stations, the bare ground surface temperatures during the summer and winter were also collected. In addition to this, 21 stations within the transect have several shallow boreholes (0.1 to 3.2 m deep) where daily temperature measurements were performed. However, only monthly averaged temperatures were available. High inertia mercury thermometers were used for the ground temperature measurements. Such thermometers provide an accuracy of about ±0.1 °C. Generally, the accuracy and quality of measurements varied depending on the year of collection, but the measurement technique and equipment have remained the same for the last 25 yr of available data. All available data on air and ground temperatures and on snow cover characteristics from these 25 meteorological stations were incorporated into the GIS (Geographic Information System) "East Siberian Transect", which was developed at the University of Alaska Fairbanks (Romanovsky et al., 2001). These data are also on file at the NSF/ARCSS Data Center.

3. Analysis of measured temperatures

All available air and ground temperature series were used to calculate mean annual temperatures for each station. Although the temperature in shallow boreholes was measured at several depths, for our analysis we chose to focus on a depth of 1.6 m, which provides the longest and the most continuous records.

To assess the long-term trends in air and ground temperatures for the period 1956–1990, the linear regression was used. Calculated trends in air and ground temperatures at 1.6 m depth for all stations were compiled and converted into an ArcView format. Then the interpolation has been performed to obtain a regional picture of variations in temperature changes within the East-Siberian transect. We used software ArcView for creating a map of temperature changes and temperature trends. For the interpolation, Inverse Distance Weighted interpolator within the Surface Analyst application was used. This method generates values to each cell in the output grid theme by weighting the values of each data point by the distance between that point and the cell being analyzed and then averaging the values. All points (stations) were taken into account during interpolation.

As a result, two maps of trends in air and ground temperatures for the period 1956–1990 were created (Fig. 3). These maps are a valuable source of information about regional variations in air and ground temperatures within the East-Siberian transect for this period. All stations, except for one, demonstrate a statistically significant (at 0.05 level) positive trend in air temperature within a range from 0.065 to 0.59 °C/10 yr (Table 1). The only negative trend at the Saniyakhtat station (marked by asterisk in Table 1) is not statistically significant. The data shown in Fig. 3 are in a good agreement with published surface air temperature trend estimations for the entire Northern Hemisphere (Chapman and Walsh, 1993; Serreze et al., 2000). At the same time, because of their better spatial resolution, these data show that, for this region, the most significant trends tend to occur in the lower latitudes (between 55° and 65° North), rather than in the Arctic and High Arctic. Ground temperature trends generally follow the trends in air temperatures (Table 1 and Fig. 3) also with more pronounced warming

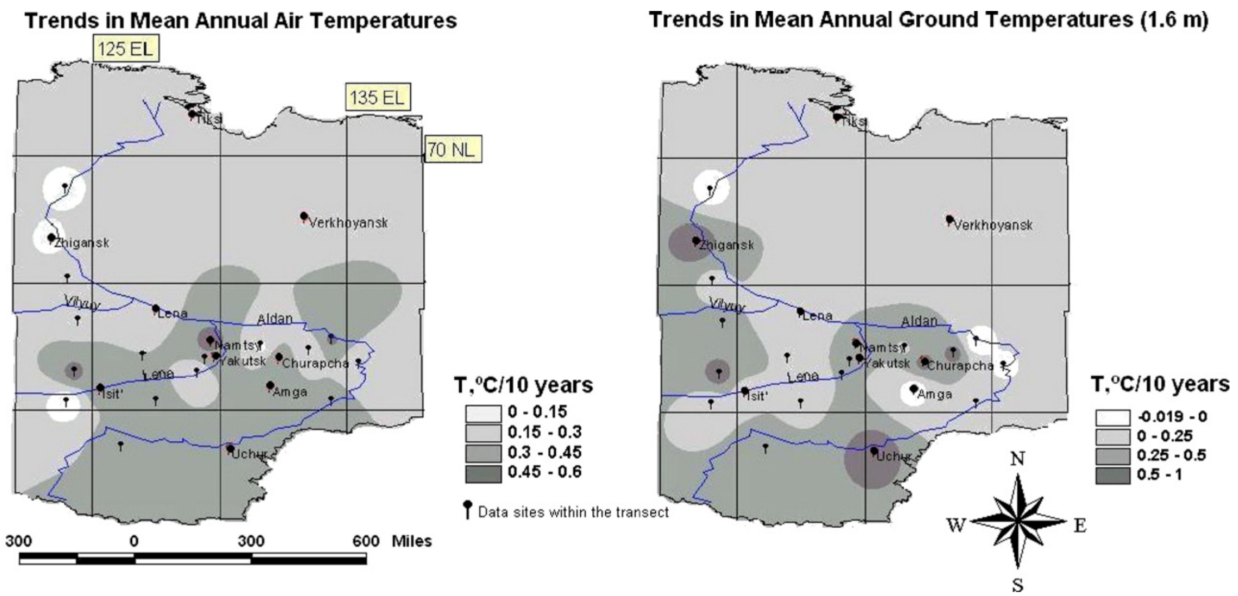

Fig. 3. Interpolated trends in mean annual air (left) and ground at 1.6 m depth (right) temperatures for the period between 1956 and 1990 along the East-Siberian transect.

in the lower latitudes. Unlike the air temperatures, the ground temperatures were warming more rapidly in the western and central parts of the transect. Also, four sites show small but statistically significant (at 0.05 level) negative trends in ground temperatures (Table 1). The trend values vary between −0.19 °C and 0.78 °C/10 yr. The average trend for the entire region is 0.26 °C/10 yr, which is very similar to the average trend in the air temperatures (0.29 °C/10 yr).

The differences in the direction of trends in air temperatures and ground temperatures at 1.6 m depth, though not typical, show the possibility of a complex reaction of the active layer and permafrost temperature regime to the air temperature changes at some particular sites. Thus, there are four sites within transect where the air temperatures experienced a positive trend while the ground temperatures were cooling (sites Dzharzhan, Krest-Khal'dzhai, Okhotskiy Perevoz and Amga, Table 1, Fig. 4). On the other hand, at some sites such as Zhigansk, Ytyk-Kel' and Uchur the ground temperature trends significantly exceeded the rate of the air temperature warming (Table 1). The major sources of these discrepancies are the local climatic (precipitation, wind) and ground surface (ground vegetation and snow cover dynamics) conditions. Changes in these conditions may significantly alter the local response of permafrost to the air temperature

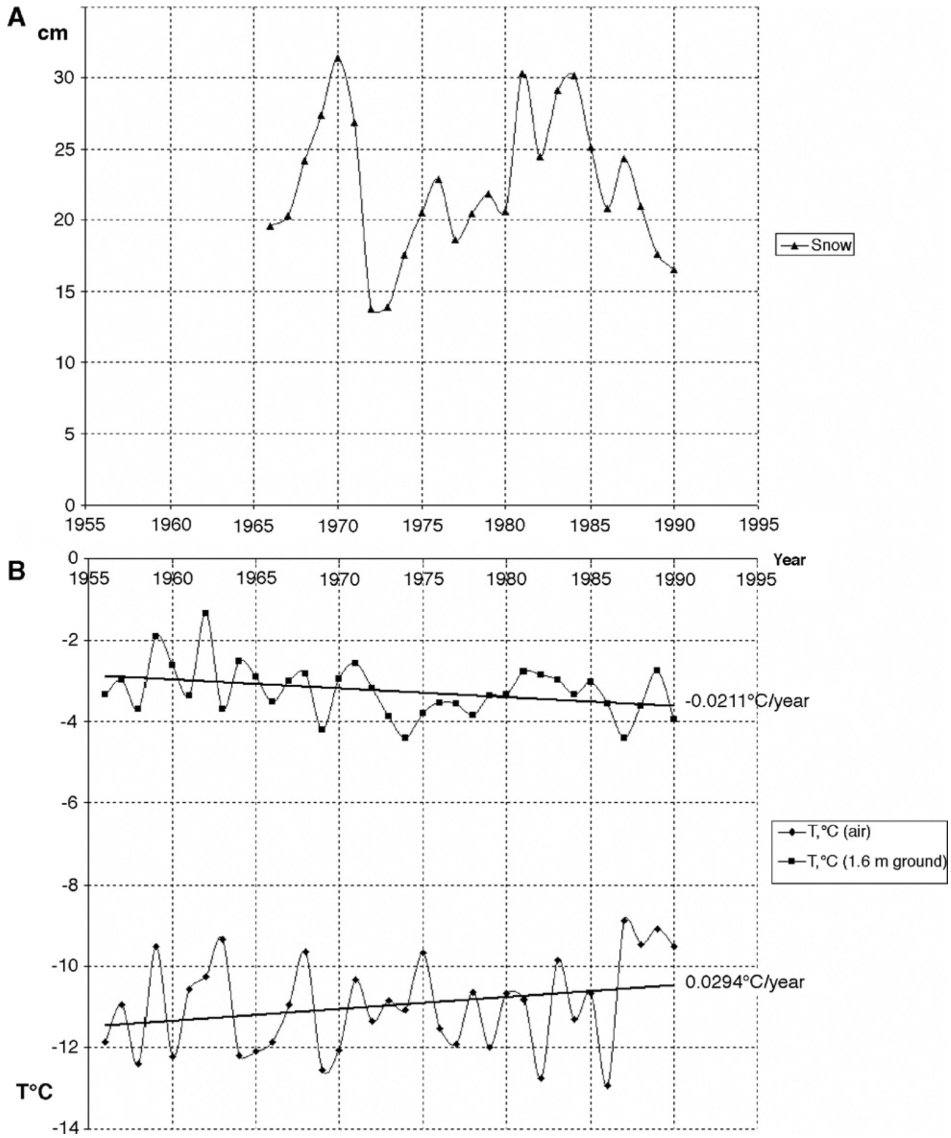

Fig. 4. Mean winter snow depth (A) and mean annual air and ground (1.6 m) temperatures (B) in Amga, one of the stations where ground temperatures were cooling during 1956–1990.

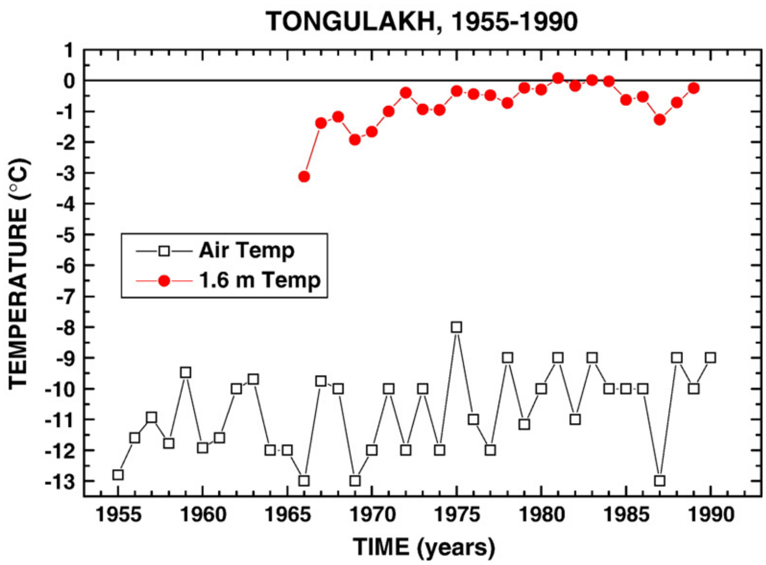

Fig. 5. Mean annual air (open squares) and ground (1.6 m depth) temperatures at the Tongulakh station (61.55 N°, 124.33 W°).

variations (Smith and Riseborough, 1996; Zhang et al., 2001). Fig. 4 also illustrates the potential danger of a simple trend analysis because the results depend strongly on the length of the analyzed time series. This figure clearly shows that the air temperature at the Amga station was generally on a decrease during the most of the 1956–1990 period (Fig. 4B, lower graph). However, the last 4 yr (1987 through 1990) were all above average. This warming event was responsible for the overall positive trend in the air temperatures. At the same time, this event did not produce any significant warming in the ground temperatures at 1.6 m depth (Fig. 4B, upper graph) because of the relatively shallow snow during these last 4 yr (Fig. 4A). Without this last-four-years increase, the overall trend in the ground temperatures at 1.6 m depth is still negative.

Significant and persistent increases in the ground temperatures during several decades late in the 20th century brought permafrost to the edge of degradation in several regions of the East Siberian transect (Fedorov, 1996; Federov and Konstantinov, 2003; Gavriliev and Efremov, 2003). Fig. 5 shows an example of this process for the site Tongulakh (61.55 N°, 124.33 W°). Permafrost is still stable at this site, but any further warming in the air temperatures and/or increase in snow cover will start the long-term process of permafrost degradation.

4. Numerical modeling of the past temperature dynamics

Most of the measured data covered only the period of significant positive trends in both air and ground temperatures. However, it is well known that this period was preceded by 20 to 30 yr of cooling in high latitudes of the Northern Hemisphere (Eisched et al., 1995; Serreze et al., 2000; ACIA, 2005). To place the active layer and near-surface permafrost temperatures measured during the last 20 to 40 yr into a longer-term prospective, numerical modeling of the permafrost temperature regime for the last 70 yr at several sites with intensive measurement datasets within the East Siberian transect was performed.

Numerical models used in these studies were described in (Romanovsky et al., 1997). Site-specific calibration of the models was accomplished using annually measured temperature profiles at the Yakutsk Permafrost Institute experimental site and at the Tiksi Permafrost observatory also operated by the Yakutsk permafrost Institute. The daily mean temperatures measured at these stations at the ground surface and at several depths in the first 3 m of soil were also used for calibration. Daily air temperatures and every 10 days snow cover thicknesses measured at the Yakutsk and Tiksi meteorological stations were used to complete the model calibration and to extend the calculations back in time. The lower boundary of the calculation domain was set at 125 m with a constant geothermal heat flux at that depth. Drilling records were used to determine the lithology and the initial thermal properties of the soils in the thawed and frozen states. The thermal properties (including unfrozen water content curves) were refined using a trial and error method (Osterkamp and Romanovsky, 1997; Romanovsky and Osterkamp, 2000). Results of calculations of the mean annual temperatures in the active layer and near-surface

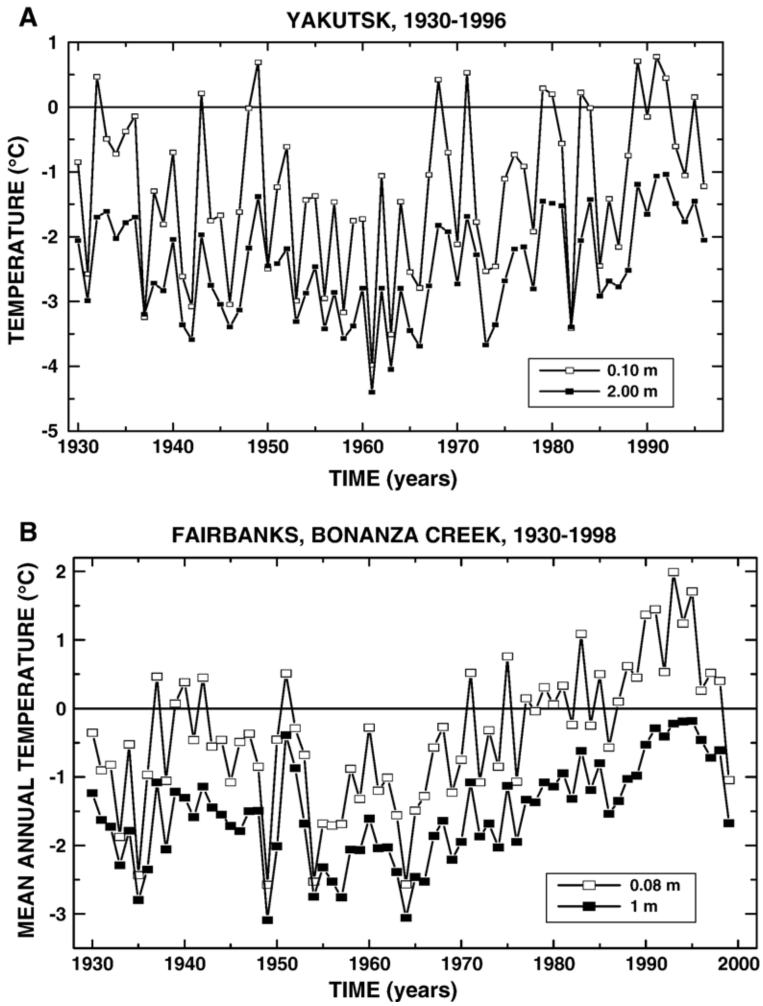

Fig. 6. Calculated mean annual temperatures in the active layer and near-surface permafrost in Yakutsk, East Siberia (A) and Fairbanks, Alaska (B).

permafrost at the Yakutsk Permafrost Institute experimental site are shown in Fig. 6A.

Calculation results show that during 1930–1996, there were several intervals with warmer soil temperatures in 1930s, late 1940s, late 1960s, late 1970s–early 1980s, and especially in late 1980s–early 1990s. Generally, the temperatures were decreasing from 1930s to early 1960s, and since then they were increasing (2 °C average increase between 1960 and 1996). These long-term fluctuations in permafrost temperature (with period of 60 to 70 yr) can be easily recognized from the set of calculated mean annual permafrost temperature profiles shown in Fig. 7. These profiles reflect long-term cooling, which started in late 1920s and progressed through 1960s. The decrease in permafrost temperatures was about 2.5 to 3 °C at the permafrost table and about 1 °C at the 15 m depth. During the period from 1960 to 1996, the permafrost temperatures rebounded to the initial temperature profile of 1929 and slightly exceeded it. For these calculations we didn't have a measured initial temperature profile. First, we assumed that the permafrost temperatures in 1929 were somewhat colder than at present. However, after 67 yr of the model's run, we finished up with colder than measured in 1996 temperature profile. Only after the postulation that the initial (1929) temperature profile was very similar to the present-day one, we were able to obtain the present-day temperature profile (filled circles in Fig. 7) that was reasonably close to the measured one in 1996 (filled squares in the same figure).

Measured ground temperature data from our GIS "East Siberian Transect" provide an opportunity to test the results of our numerical reconstructions of the active layer and upper permafrost temperature dynamics for the Yakutsk site. The comparison of these calculations with measured ground temperatures at the Churapcha

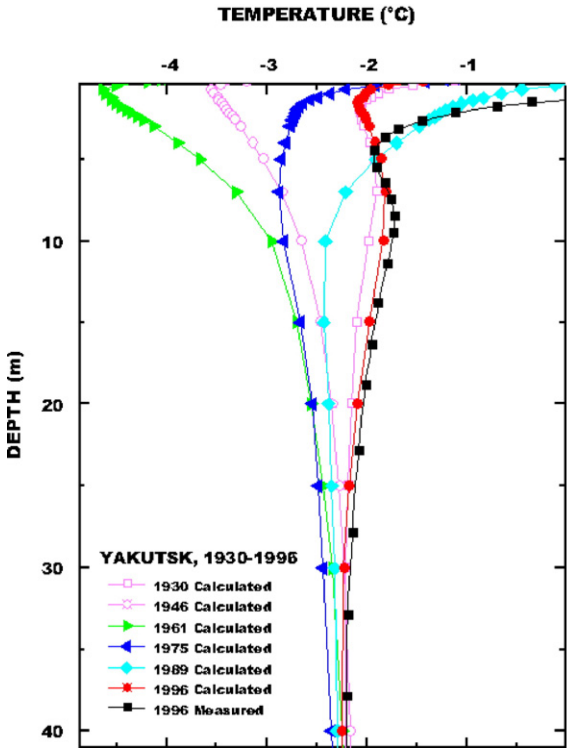

Fig. 7. Calculated mean annual and measured temperature profiles at the Yakutsk Permafrost Institute experimental station.

site (100 km east of Yakutsk) shows a good agreement (Fig. 8). The statistically significant (at 0.05 level) correlation coefficient between measured at Churapcha and calculated at Yakutsk temperatures at 1.6 m depth for the period 1958–1994 was 0.88.

Similar calculations of the past temperature regimes were made for several sites along the Alaskan transect (Romanovsky and Osterkamp, 1996, 1997; Osterkamp and Romanovsky, 1999; Romanovsky et al., 2002). One of the reconstructions was made for 1929–1998 for a Fairbanks site (Fig. 6B). The calculations show that the ground temperatures during the 1940s were warmer than the 1930s, 1950s and 1960s, but that the mean annual temperatures in the active layer and near-surface permafrost were not as warm as in the 1990s. During the 1980s and most of the 1990s, the mean annual ground surface temperatures at this site were above 0 °C. Permafrost remains stable and survives only because of the insulating effect of the organic mat at the ground surface and the related thermal offset in the active layer. The Yakutsk and Fairbanks temperature time series show significant and somewhat surprising similarities (Fig. 6). However, there is some lag in the soil temperature variations at the Fairbanks site compared to Yakutsk.

To compare the active layer and permafrost temperature dynamics in sub-Arctic (Yakutsk and Fairbanks) with the Arctic sites, similar calculations were performed for the Siberian site Tiksi (71.59 N, 128.92 E) and an Alaskan site at Barrow (71.18 N, 156.47 W). Model calibration was performed for the Tiksi site using daily air and ground temperature data from the Tiksi permafrost observatory operated by the Yakustk Permafrost Institute. Monthly air temperatures and every 10 days snow cover thicknesses measured at the Tiksi meteorological station were used to complete the model calibration and to extend the calculations back in time. Calibrated model used for calculations at the Barrow site was described in (Romanovsky and Osterkamp, 2000). At Barrow, the mean annual ground and permafrost surface temperatures have a range of more than 5 °C from about −7 °C to −13 °C (Fig. 9B). The ground temperatures were warmer for the late 1920s and 1940s than for the 1980s and 1990s (Romanovsky and Osterkamp, 2001). However, in 1998, the ground temperatures at Barrow were the highest for the entire period of calculations (1923–1998). The mean annual air and ground temperature variations at the Tiksi site in the Siberian Arctic show generally similar patterns. The warmest time was during the mid and late 1930s when

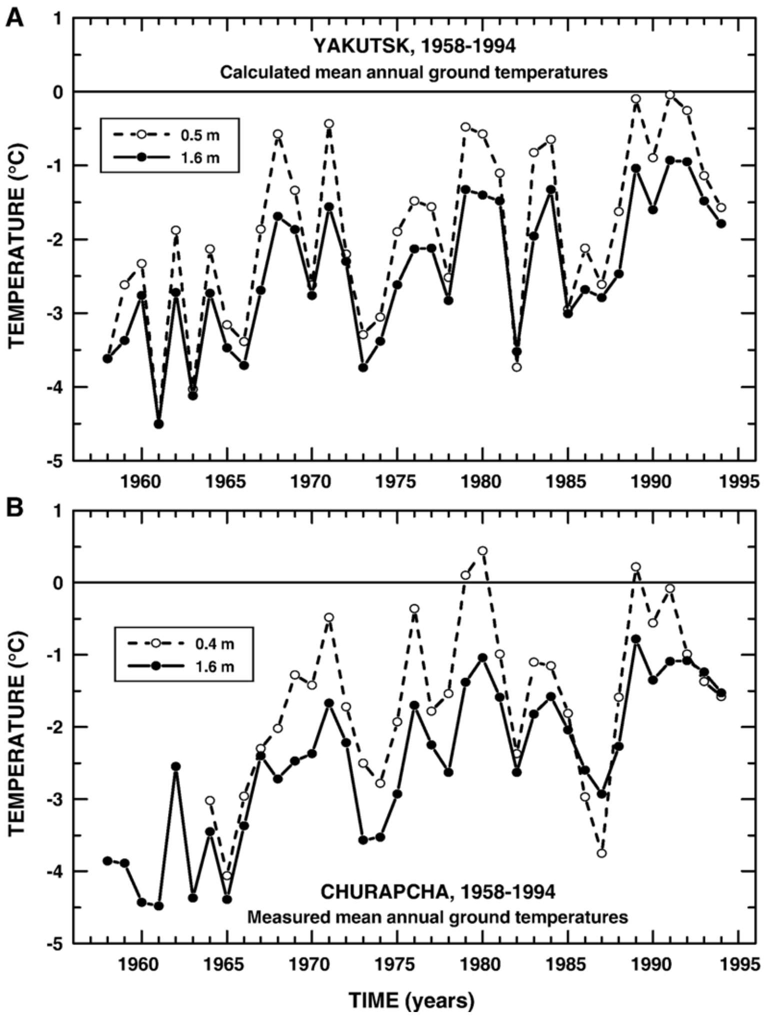

Fig. 8. The comparison of calculated mean annual ground temperatures at the Yakutsk Permafrost Institute experimental site (A) with measured temperatures at the Churapcha meteorological station (B).

the mean annual temperatures in the near-surface permafrost (1 to 3 m depth) were between −8 °C and −9 °C. For the rest of the time these temperatures were generally below −10 °C and only in early 1990s they warmed up to −9.5 ° and −9 °C (Fig. 9A).

5. Discussion

Data from the East Siberian transect, both for air and ground temperatures, show significant warming trends during the 1956–1990 period. The rate of this warming is very similar to the rate of climate warming in the Arctic predicted for the 21st century by most of the atmospheric Global Circulation Models (ACIA, 2005). However, the spatial patterns of this warming noticeably differ from these modeled predictions. Instead of increasing with latitude as predicted for 21st century by the models, the data show that the largest warming trends during 1956–1990 in both air and ground temperatures at 1.6 m depth were observed in the East Siberian sub-Arctic (55° N to 65° N). The rate of temperature increase here is almost twice than at the higher latitudes (Fig. 3, Table 1). As can be seen from the comparison between Figs. 6A and 9A, the latest increase in temperatures in lower latitudes started in the beginning of the 1960s, whereas in the higher latitudes the turning point from the mid-century cooling to the latest warming came in the mid 1970s. The same spatial and temporal patterns of the latest warming are typical for Alaska (Figs. 6B and 9B). According to Przybylak (2000), this is rather typical situation for the entire circumpolar North. In West Siberia however, the trends

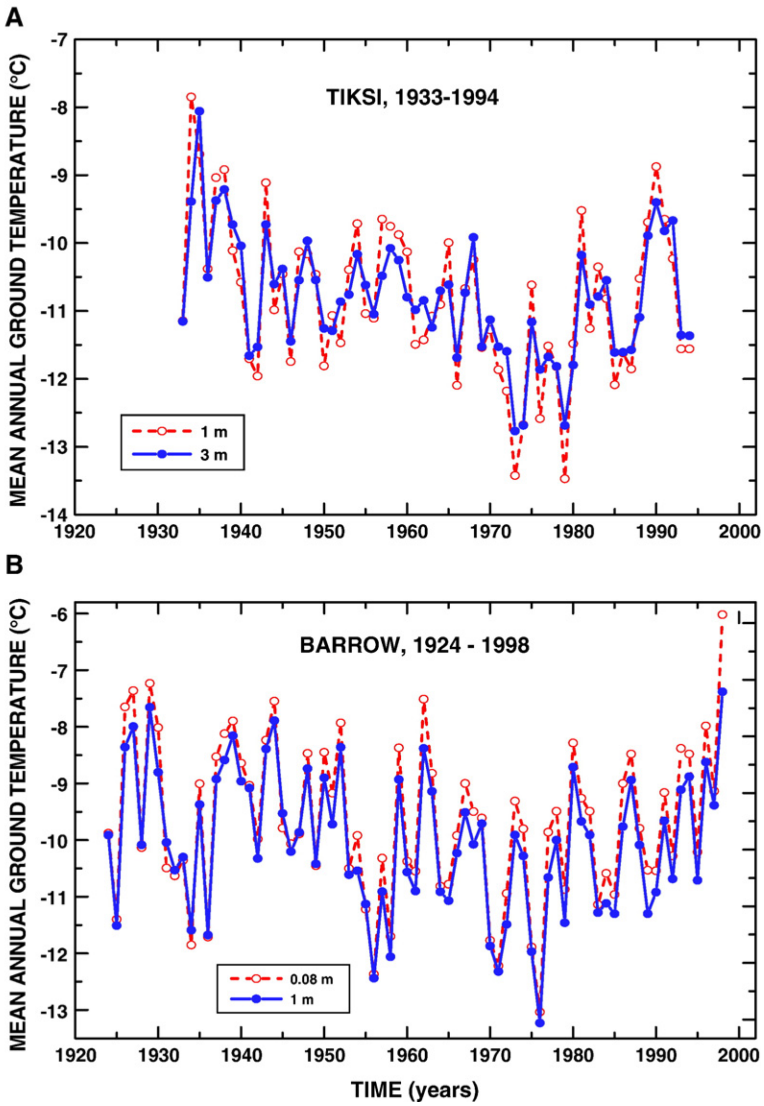

Fig. 9. Calculated mean annual temperatures in the active layer and near-surface permafrost in Tiksi, East Siberia (A) and Barrow, Alaska (B).

in the latest warming are very similar for all the latitudes (Pavlov, 2000).

Generally, the increase in ground temperatures within the East Siberian transect is in concert with the warming air temperatures. However, there are several sites where these two variables are in conflict. At four sites, the ground temperatures at 1.6 m depth were decreasing in 1956–1990, while the air temperatures had a positive trend for the same period (Table 1). More detailed analysis of the air temperature, ground temperature at 1.6 m depth, and snow cover dynamics at the Amga site (Fig. 4) shows that the ground temperatures correlate more strongly with the snow cover thicknesses than with the air temperatures (correlation coefficients are 0.45 and 0.005 respectively). Mean winter snow thickness decreased by 10% on average during 1965–1990 (from 0.24 m to 0.22 m). Because of the relatively shallow snow at this site (it's winter average thickness varied between 0.13 m and 0.31 m during this period), the sensitivity of the ground temperatures to the variations in the snow thickness is very significant.

At some sites, the ground temperatures were increasing much faster than the air temperatures (Zhigansk, Ytyk-Kel' and Uchur, Table 1). Again, probably the most reasonable explanation is the positive trend in the snow cover thickness. For example, at the Zhigansk site, the major increase in permafrost temperatures occurred during 1965–1980. The winter maximum snow cover

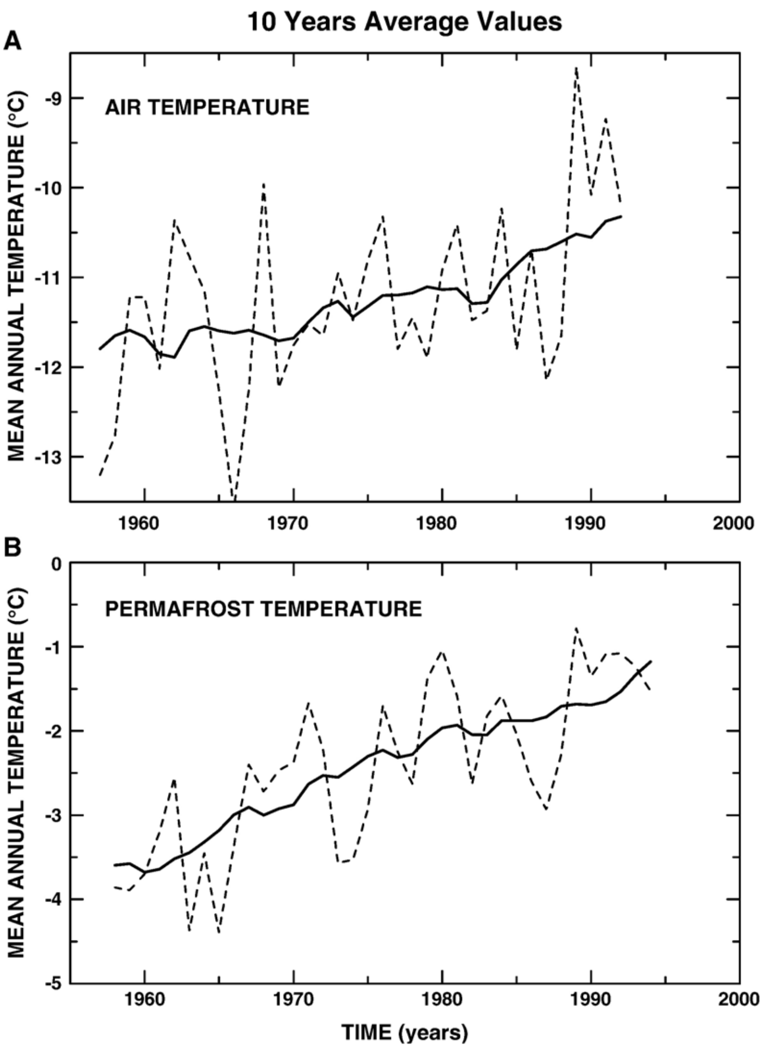

Fig. 10. Measured mean annual air (A) and ground (1.6 m depth) (B) temperatures (dashed line) and their 10-yr running average values (solid line) at the Churapcha meteorological station, East Siberia.

thickness for the same period increased from 0.3 m to 0.6 m. There also could be some other reasons for the rapid permafrost temperature change at these sites. They can relate to changes in the surface conditions (such as vegetation and moisture regime) or even to surface disturbances at the meteorological stations. Unfortunately, we do not have enough information to evaluate these other possibilities.

East Siberian air temperature and ground temperature (at 1.6 m depth) data were used to test a common but lately often scrutinized postulation that the permafrost temperatures are a reasonably good indicator of climate change. Comparisons between mean annual air and ground temperatures at 1.6 m depth at the Churapcha station (Figs. 10 and 11) show that on interannual time scale, these two parameters vary differently. A correlation coefficient between these two variables is 0.49 for the entire 1957–1992 time period. This coefficient will be even smaller for any shorter time interval. At the same time, the 10-yr running means (Fig. 10, solid line) show much better and statistically significant (at 0.05 level) correlation (correlation coefficient is 0.87). The longer averaging intervals increase this correlation even more (Fig. 12). Hence, these data suggest that the permafrost temperature reflects changes in air temperature on a decadal time scale much better than the interannual air temperature variations. The prime cause of a poor correlation between the permafrost and air temperatures on an interannual time scale is a significant interannual variability in the snow cover depth and duration. The much better correlation on a decadal time scale could be explained by the absence of any

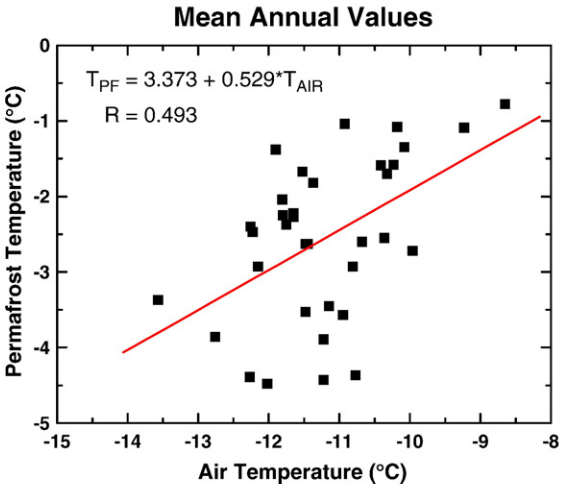

Fig. 11. The correlation between mean annual ground (1.6 m depth) and air temperatures at the Churapcha meteorological station.

significant long-term trends in the snow depth for the last 60 yr within the area of East Siberian transect with an exception for the Zhigansk station (Ye et al., 1998; Ye, 2001). It is more difficult to predict how close the changes in permafrost temperature will follow the air temperature variation on a longer time scale (century to millennia) because significant changes in the snow cover accumulation and in the surface vegetation are very possible on such a long time scale.

Better correlation between air temperatures and ground temperatures at 1.6 m depth can be achieved by averaging measured time series not only in time but also in space. Correlation coefficients based on mean annual temperatures from the sites within the East Siberian transect vary between 0.005 (Amga site) and 0.58 (Tongulakh). Simple averaging of correlation coefficients over all stations is 0.24. However, when we averaged all measurements of the mean annual air temperatures obtained at each station within the transect for each year and then did the same averaging for the permafrost temperatures, the statistically significant (at 0.05 level) correlation coefficient between these spatially averaged air and permafrost temperatures was 0.51 for the period 1956–1990. Hence, the spatial averaging over the entire region has a similar effect as the temporal averaging for any single site. As was mentioned earlier, the average trend for the entire region was 0.26 °C/10 yr for ground temperatures at 1.6 m depth and 0.29 °C/10 yr for the air temperatures.

6. Conclusions

The analysis of mean annual air temperatures measured at 52 sites within the East-Siberian transect during the period of 1956–1990 demonstrates a significant positive trend ranging from 0.065 to 0.59 °C/10 yr. A positive trend was also observed in mean annual ground temperatures at 1.6 m depth for the same period. The most significant trends in mean annual air and ground temperatures were in the southern part of the transect, between 55° and 65° NL. Generally positive statistically significant (at 0.05 level) trends in mean annual ground temperatures are slightly smaller in comparison with statistically significant (at 0.05 level) trends in mean annual air temperatures, except for several sites where the discordance between the air and ground temperatures can be explained by winter snow dynamics.

Statistical analysis of mean annual ground and air temperatures shows that these temperatures are correlated. Further analysis proved that the correlation between mean annual air and ground temperatures is improving when these two temperatures are averaged in time and/or in space.

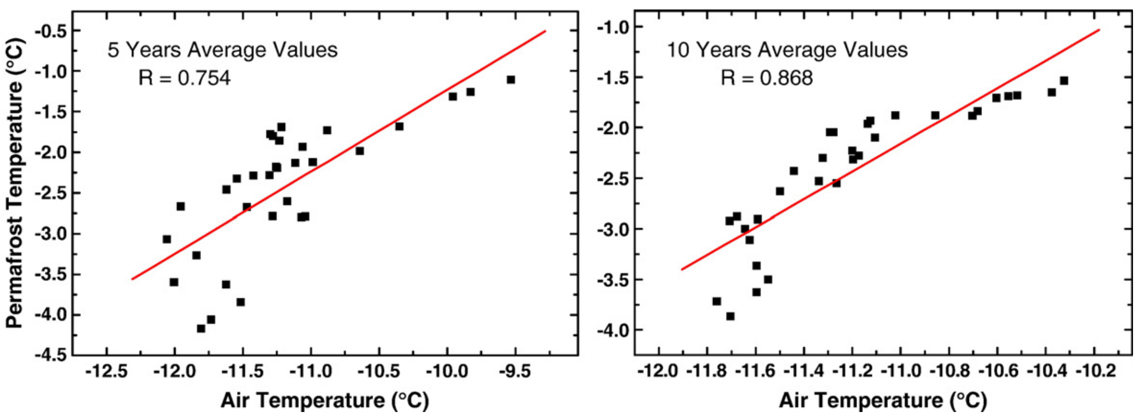

Fig. 12. The correlation between averaged ground (1.6 m depth) and air temperatures at the Churapcha meteorological station.

The numerical modeling of the ground temperatures at 4 sites (2 in Alaska and 2 in East-Siberia) for the 20th century shows that the decadal and longer time scale fluctuations in permafrost temperatures were pronounced in both regions. The magnitudes of these fluctuations were on the order of a few degrees centigrade. The fluctuations of mean annual ground temperatures were coordinated in Fairbanks and Yakutsk, and in Barrow and Tiksi. The magnitude and timing of these fluctuations were slightly different for each of the sites.

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