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Active-layer Spatial and Temporal Variability at European Russian Circumpolar-Active-Layer-Monitoring (CALM) sites

G. Mazhitova,[1]* *G. Malkova (Ananjeva),*[2] *O. Chestnykh*[3] *and D. Zamolodchikov*[3]

[1] Institute of Biology, Komi Science Centre, Russian Academy of Sciences, Syktyvkar, Russia
[2] Earth Cryosphere Institute, Siberian Division, Russian Academy of Sciences, Moscow, Russia
[3] Centre for Ecology and Productivity of Forests, Russian Academy of Sciences, Moscow, Russia

ABSTRACT

Three 100 × 100 m grids were established in European Russia in the framework of the Circumpolar-Active-Layer-Monitoring (CALM) project. Records range from 4 to 7 years in length. The grids are in mineral soils with mean annual permafrost temperature from −0.5 to −2.5°C. The sites are known to be sensitive to decadal-scale climatic changes. The grids differ in mean annual air temperature, but have similar thawing indices (DDT). Two grids with deeper annual thaw, separated by 400 km, reveal remarkable similarity in thaw depths, seasonal dynamics and interannual variability. All grids respond to thermal forcing rather consistently, although thaw increments caused by similar increases in DDT are smaller at the grid with the shallowest annual thaw. Stepwise multiple regression and other statistical analyses identified organic-layer thickness and some, but not all, topographic features as the variables having explanatory power with respect to thaw-depth variability. These and other variables examined do not, however, explain all the variability in the thaw depth. The effects of organic-layer thickness on thaw depth are shown to change during the warm season. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: permafrost; active-layer; monitoring; European Russian Arctic

INTRODUCTION

The Circumpolar-Active-Layer-Monitoring (CALM) programme is designed to observe the response of the active layer to climate change (Brown *et al.*, 2000). Three 100 × 100 m grids were established in the continuous and discontinuous permafrost zones of European Russia within the framework of this programme. Current (2002) records from these grids are from 4 to 7 years long, a period which is of insufficient duration to detect a climate warming signal, especially considering natural short-term climatic fluctuations. However, these records allow assessment of the active layer's sensitivity to thermal forcing, as well as analyses of its spatial patterns.

Records from weather stations in the region show synchronous air temperature fluctuations during the 20th century, with well-expressed half-century climatic cycles (Oberman and Kakunov, 2002). The warming phase of the most recent cycle gave way to cooling around 1995 (Pavlov, 2002; Oberman and Mazhitova, 2001). The region, especially its eastern section, is among the best studied in Russia with respect to permafrost. Records from comprehensive permafrost monitoring conducted by the Polyarnouralgeologia Company are 20 to 30 years long. These records show that the warm permafrost (−0.5 to −3.0°C) that is widespread in the region is sensitive to decadal-scale variations in mean annual air

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* Correspondence to: G. Mazhitova, Institute of Biology, 28 Kommunisticheskaya St, Syktyvkar, 167982, Russia.
E-mail: mazhitova@ib.komisc.ru

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temperature (MAAT) ranging within 3°C (Oberman and Mazhitova, 2001). However, direct measurements of active-layer dynamics, which would allow statistical assessment of variability within principal landscapes and suit modelling needs, have not yet been conducted. The three CALM sites in the region allow us to fill this knowledge gap to a certain extent.

This paper analyses data from those European Russian CALM sites, primarily with regard to the interannual and spatial variability of the active layer.

REGIONAL BACKGROUND

In the European Russian North there is a continuous permafrost zone between the Ural Mountains and the Pechora River Delta (Figure 1). Mean annual permafrost temperatures (MAPT) range from −1 to −5°C and permafrost thickness reaches 300–400 m. South of this zone, the discontinuous permafrost zone occurs with MAPT ranging from 0 to −2°C and permafrost thickness up to 100–200 m (Melnikov and Grechishchev, 2002; Oberman and Mazhitova, 2003). The first CALM grid in the region, Ayach-Yakha, was established in 1996. Two other grids, Talnik and Bolvansky, have operated since 1998 and 1999, respectively. The Bolvansky grid is located at the western limit of the continuous permafrost zone, whereas the Ayach-Yakha and Talnik grids represent the discontinuous permafrost zone (Figure 1). Given the range of permafrost conditions within the discontinuous zone, the choice of the two locations is satisfactory; they are close to the extremes of the thaw-depth range in loamy soils with anchored permafrost; i.e. where permafrost is annually reached by seasonal frost. Ayach-Yakha is close to the 'cold' extreme and Talnik to the 'warm' extreme.

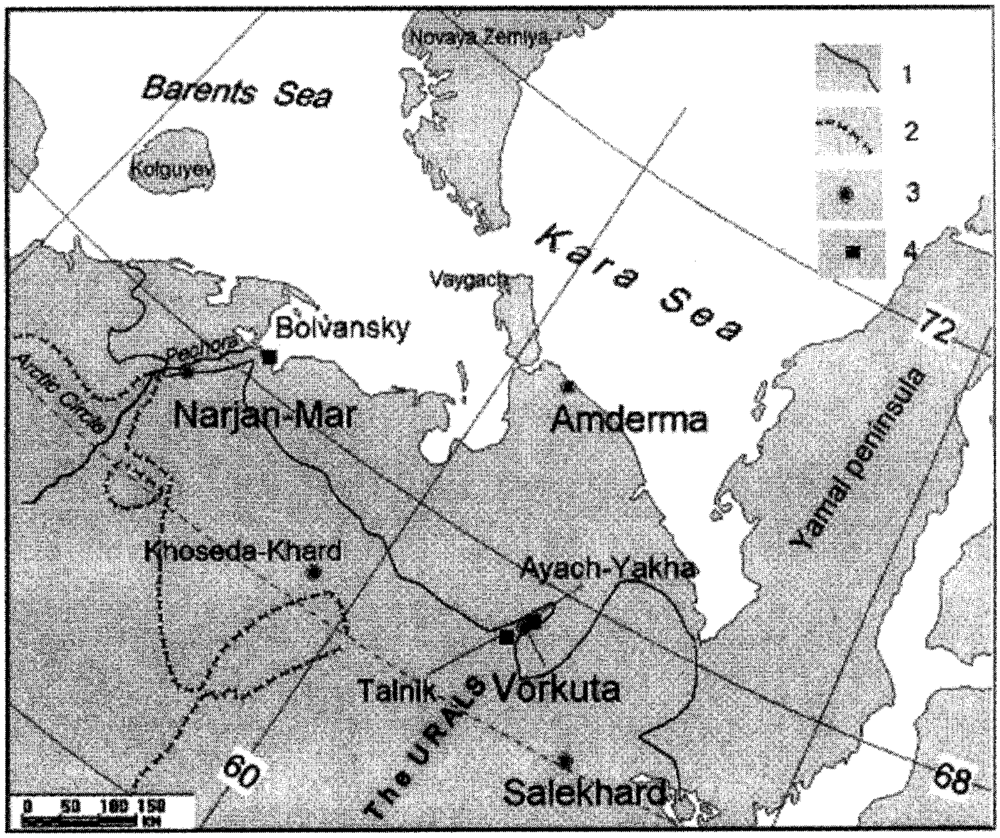


Figure 1 Location map of the European Russian CALM grids. Key: (1) boundary between continuous and discontinuous permafrost zone; (2) southern boundary of the cryolithozone; (3) weather stations cited in the paper and main towns; (4) CALM grids.

METHODS

Field Procedures

The European Russian CALM sites employ the standard systematic sampling design recommended under the CALM programme (Brown *et al.*, 2000). Permanent 100 × 100 m grids have been established, with 10 m intervals between grid nodes. The 121 nodes are marked with stakes. Thaw depths are determined through four replicated measurements at each grid node. Measurements are conducted annually at the end of the warm season with the use of a graduated steel rod.

Besides the standardized thaw depth measurements, efforts to assess controls over the spatial and temporal variability of the active layer have been undertaken at each site. Sets of these additional data are affected by accessibility and other site-specific characteristics, and thus differ for the three sites (Table 1).

Volumetric soil water content is measured at grid nodes by a portable Vitel Hydra® probe at Ayach-Yakha and Talnik. However, at Ayach-Yakha it is measured in the upper mineral soil horizon, whereas at Talnik in the upper soil layer, regardless of whether it is organic or mineral. Measurements are conducted annually at the end of thaw season and in some years also earlier in the season. Water measurements at grid nodes were conducted at Bolvansky only once, in August 1999, simultaneous with site establishment. Soil samples of a known volume were taken at each grid node from the depth of 20 cm, and water content was determined gravimetrically. Air, soil and upper permafrost temperatures are measured by miniature StowAway Onset® data loggers programmed for at least eight readings daily in summer and at least four readings daily in winter. Permafrost temperature at the depth of zero annual amplitude is measured in three deep boreholes at the Bolvansky site. Soil subsidence is determined at Ayach-Yakha for each grid node with the use of a 2H-10KL leveling instrument (Russia), which provides for 4 mm of possible elevation error per 1 km distance. Measurements were made in early or mid-September in 1999, 2000 and 2002. A benchmark of the national geodetic network located near the site was used as a base. Organic layer thickness was measured once near each grid node at Bolvansky and in four replications for most nodes at Ayach-Yakha. Small blocks of soil were taken with a knife and placed back into pits after conducting measurements to minimize disturbance. Soils of the grids were classified according to the World Reference Base for Soil Resources (1998). Vegetation classes used to map vegetation were defined arbitrarily for each site.

Analytical Procedures

Analytical procedures include generating maps using triangulation with a linear interpolation algorithm (Golden Software, 1999). The thawing index DDT (°C days) was calculated by summing average daily air temperature for the period beginning with positive daily averages and ending on the day of grid probing. The normalized index of variability (*Iv*), (Hinkel and Nelson, 2003), is given by:

$$I_v = (Z_i - Z_{avr})/Z_{avr}$$

where Z_{avr} is the averaged thaw depth for a particular year and Z_i is the node-specific value. Interannual node variability (INV, %) discussed in this paper is the absolute value of the difference between the maximum and the minimum *Iv* over the period of interest.

Table 1 Data available from European Russian CALM sites.

Data item	Bolvansky	Ayach-Yakha	Talnik
End-of-season thaw depths for each grid node	+	+	+
Seasonal thaw dynamics (for some years)	+	+	+
Maximum annual snow depths for each grid node	−	+	−
Soil water content (at least, at the end of warm seasons) for each grid node	+	+	+
Air temperature records from the site	−	+	+
Soil/upper permafrost temperature records	+	+	−
Permafrost temperature in deep boreholes	+	−	−
Soil subsidence values for each grid node	−	+	−
Organic layer thickness for each grid node	+	+	−
Vegetation map	+	+	+
Soil description	+	+	+

SITE DESCRIPTIONS

Bolvansky

The Bolvansky CALM site (68°17.3′N; 54°30.0′E) is located in the Pechora River Delta, on the northernmost extremity of Cape Bolvansky, which juts into the Pechora Inlet. The Bolvansky weather station operated on the Cape from 1935 to 1997. Long-term MAAT is −4.4°C and mean annual precipitation is 404 mm. The Cape is an undulating plain with numerous lake depressions and large flat-bottom valleys, some of them with permanent creeks. Elevations range from 20 to 35 m a.s.l. The surficial material is a boulder sandy loam of Quaternary age exceeding 100 m in thickness. Depressions are occupied by polygonal peatlands and fens with peat thickness ranging from 0.5 to 5 m. The area is geocryologically unstable due to its position at the western extremity of the continuous permafrost zone. Permafrost develops under convex and flat surfaces, whereas the permafrost table is deeper in valleys, both dry and drained by streams. Data from numerous boreholes show that open taliks occur under the Pechora valley and beneath many lakes (Ershov, 1988).

The Bolvansky grid contains 121 sampling nodes and occupies the top of a hill with gentle slopes. Dwarf shrub/lichen tundra with tundra circles (frost boils) occupies the site. The site contains three boreholes. Permafrost temperature at the depth of zero annual temperature amplitude (10 to 12 m) is −2.1°C in a borehole located in the central and highest point of the site. The temperature decreases from this point to the site margins down to −1.6 to −1.8°C, following the decrease in elevation. A closed talik occurs at the southeastern corner of the site, with its area fluctuating from year to year and covering from three to seven grid nodes. The range of elevations within the site is 5 m. Organic (peaty) soil layer thickness reaches 22 cm at some grid nodes, whereas the site average is only 5 cm (Figure 2A). Lower soil horizons are developed in gravelly sandy loam. Volumetric water content of the loam ranges mostly from 30 to 40%; generally, the thicker an organic layer, the higher the water content. The maximum soil water content was found in a boggy former lake depression at the southeastern corner of the site (Figure 2B).

Ayach-Yakha

The Ayach-Yakha CALM site (67°35.4′N; 64°09.9′E) is located near the town of Vorkuta, 400 km to the east of Bolvansky. MAAT at the Vorkuta weather station is −5.9°C and precipitation is 550 mm (1948–2002). In this area, adjacent to the Ural Mountains, the thickness of Quaternary deposits is shallower than at Bolvansky and does not exceed a few dozen metres. This is one of the reasons for discontinuous permafrost, in spite of a lower MAAT than in the Bolvansky area.

The Ayach-Yakha grid is located 13 km northeast of the town of Vorkuta on an undulating plain covered with silty loam of glacial-marine origin. The grid occupies a gentle (3°) southwest-facing slope with a creek flowing within 20 m of its lower border. The range of elevations within the site is 5 m. Schist bedrock is exposed in the creek valley. At the two lowest tiers of the grid the loamy deposit is about 120–150 cm thick over the bedrock. The originally square grid was converted into a rectangular array during the second year of observations, with 99 grid nodes measured. The first-year statistics have been recalculated accordingly. The reason for the deletion of the lowest tier was that the high stone content in soils made thaw measurements unreliable. At the modified grid, practically no stones occur, except for five grid nodes at the southwestern grid corner.

The MAPT at the depth of zero annual amplitude is not known. However, considering a large number of boreholes in the vicinity of Vorkuta, it can be assumed that it is between −1.5 and −2.0°C. Dwarf shrub/feather moss tundra with numerous frost boils occupies the site. Some dwarf birch and willow thickets are up to 50 cm high. Soil organic layer thickness ranges from 0 to 25 cm, with a site average of 12 cm (Figure 3).

Soils are gleyed and thixotropic, with cryoturbation best developed under and around frost boils. The soils are classified as Turbi-Histic (Gleyic) and Gleyi-Turbic Cryosols. Volumetric water content in the upper mineral soil layer ranged in 1999–2000 from 32 to 48% and exceeded the field capacity all the time. At several grid nodes ephemeral ponds developed in some years. Site-averaged snow thickness, measured in late April when it should be close to the annual maximum, varied in 1998–2002 from 30 to 47 cm, with the range from 9 to 67 cm across the grid. Snow density varied from 0.20 to 0.37 g/cm^3. The summer (thawing season) N-factor, the ratio of the thawing degree-day sum at the soil surface to that in the air (Carlson, 1952), is 0.86 for 1999–2002 if calculated using air temperatures measured at the site, and 0.87 if calculated with data from the Vorkuta weather station air temperature record.

Talnik

The Talnik CALM site (67°19.8′N; 63°44.0′E) is located 20 km south of the town of Vorkuta, near the

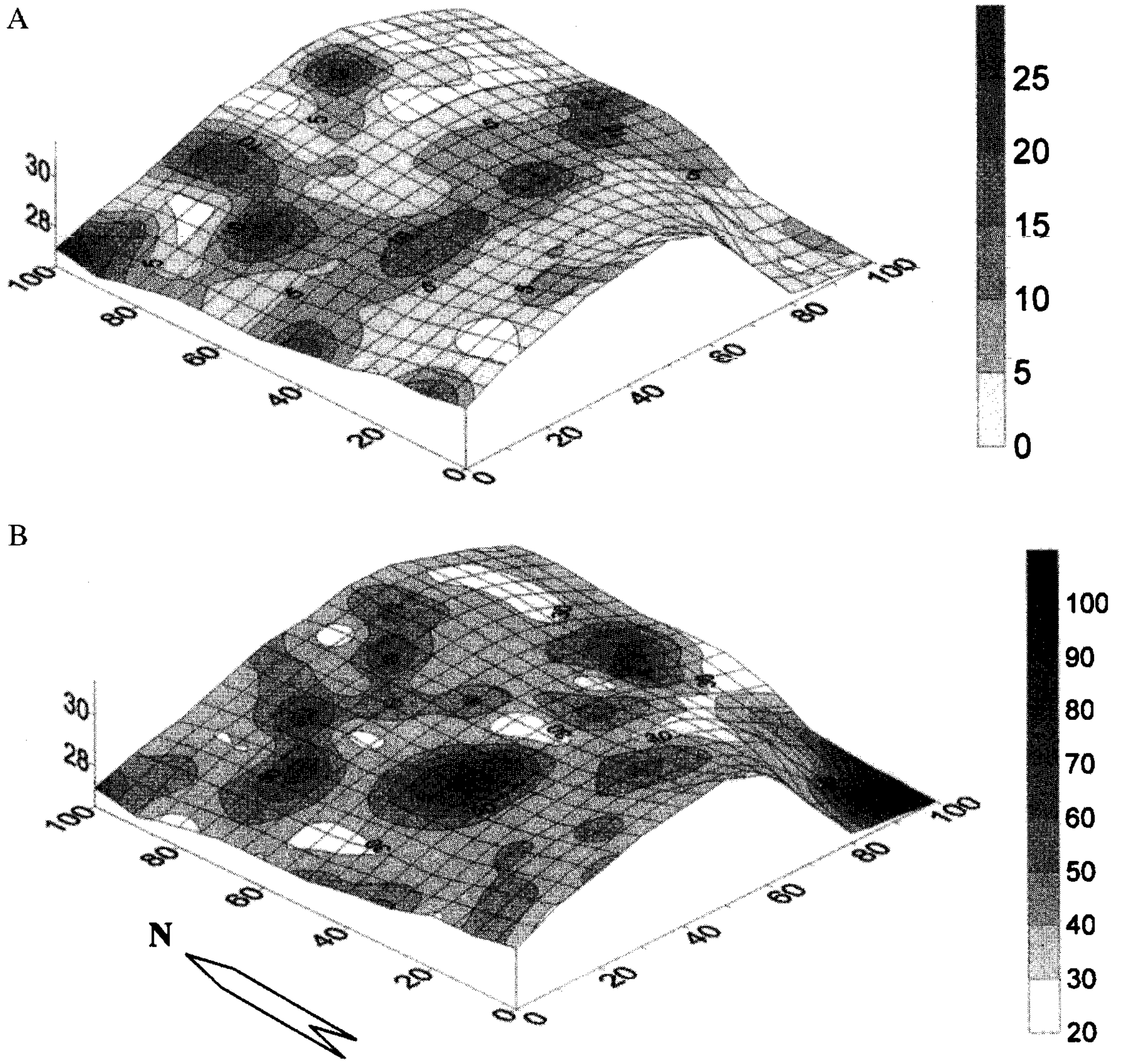


Figure 2 Terrain model of the Bolvansky grid and selected active-layer characteristics. (A): peat-layer thickness, cm; site-average value is 5 cm. (B): volumetric soil moisture at a depth of 20 cm; site-average value is 39.9%.

Talnik railway station. The distance from the Ayach-Yakha site is 40 km. The site is located on the same undulating glacial-marine plain as Ayach-Yakha and occupies a gentle northeast-facing slope. The range of elevations within the site is 4.7 m, with a distinct ridge and a depression/hollow each covering approximately one half of the site (Figure 4).

The MAPT is not known; however, it should not be less than −2.0°C according to the most recent permafrost map of the area (Oberman and Mazhitova, 2003). Fifty-seven per cent of the site is covered with a lichen/feather moss/tall shrub/dwarf shrub community, and the remainder is occupied by communities dominated by feather mosses and dwarf birch. Willows in depressions are up to 1.5 m high. Moss coverage is more than 70% in depressions, but less than 30% on a ridge. Soils are loamy Stagnic Cryosols and Stagni-Gelic Cambisols. The organic layer has not been surveyed across the entire site, but its thickness in three soil pits varied from 4 to 25 cm. Snow thickness reaches 200 cm in depressions, and ranges from 40 to 60 cm on the ridge. Detailed data on carbon fluxes and plant productivity patterns have been collected from the site (Zamolodchikov *et al.*, 1998, 2000; Zamolodchikov and Karelin, 2001).

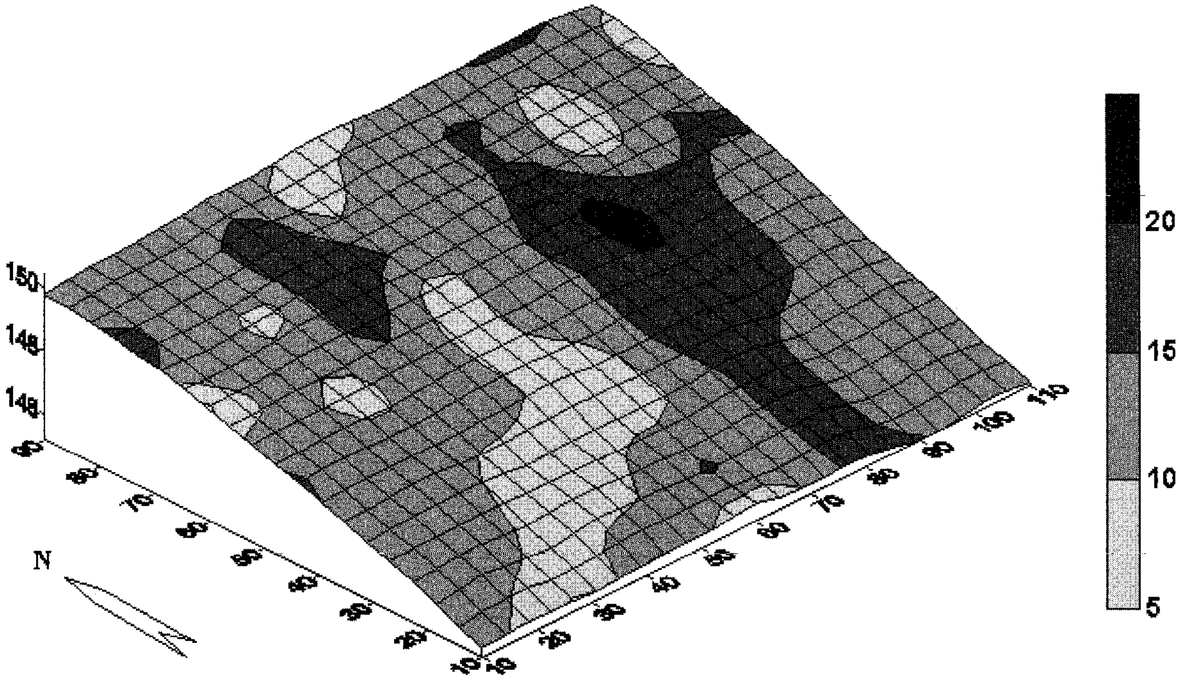


Figure 3 Terrain model of the Ayach-Yakha grid overlain with peat-layer thickness, cm; site-averaged thickness is 12 cm.

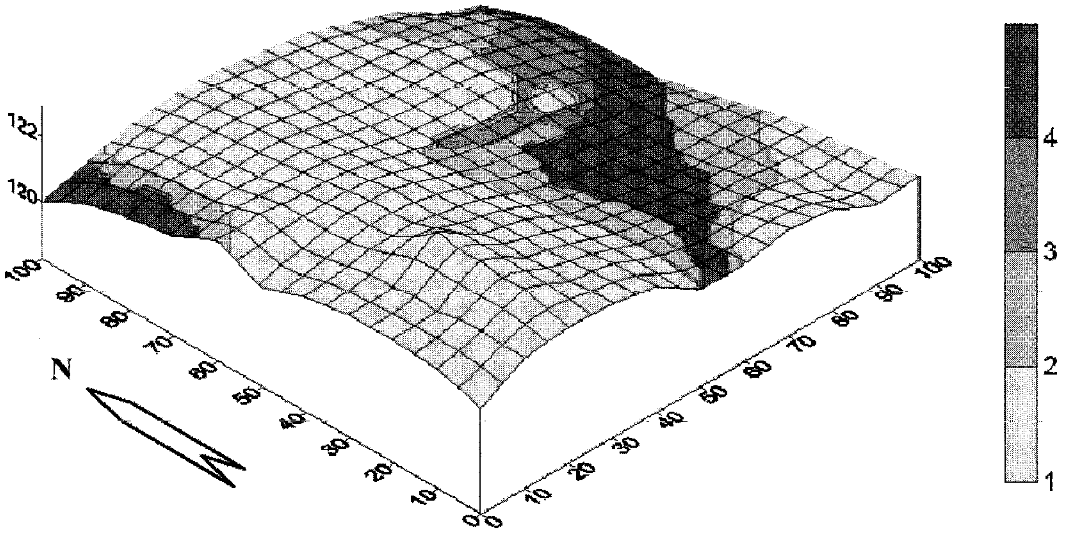


Figure 4 Terrain model of the Talnik grid overlain with vegetation classes. Shade legend: (1) lichens/mosses/shrubs/dwarf shrubs; (2) mosses (*Pleurosium*)/lichens/shrubs/dwarf shrubs; (3) mosses (*Polytrichum*)/lichens/shrubs/dwarf shrubs; (4) mosses/shrubs.

RESULTS

Bolvansky

Thaw-depth measurements were made at this site on varying dates: late August in 1999, early July and mid-September in 2000, mid-September in 2001, and late September in 2002. Thaw reaches its maximum depth in the second half of September, the last month with a positive mean month air temperature. Thaw depths vary greatly across the site owing to the heterogeneity of landscape components, primarily lithologic composition (organic-layer thickness) and vegetation. Figures 5A to 5D show observed thaw patterns.

In late August 1999, when the accumulated DDT reached 638°C days, site-averaged thaw depth was 61 cm and ranged from 21 to 98 cm. A talik on a shrubby slope in the southeast corner of the grid encompassed only three grid nodes. In early July 2000, with DDT at 448°C days, site-averaged thaw was 49 cm and ranged from 12 to 98 cm. Summer 2000 was extremely warm, DDT reached 1143°C days in mid-September, and site-average thaw was 106 cm, varying from 45 to 146 cm. The talik increased in area and encompassed seven grid nodes. Summer 2001 was warm and dry, with DDT totalling 1123°C days in mid-September. Water-saturated ground was found at 70–80 cm, versus 30–40 cm in the year 2000. However, both site-averaged and node-specific thaw depths were very similar to the 2000 values, with the same average of 106 cm. The talik area and shape changed little. Summer 2002 was rainy and cool, with DDT at the end of a warm season of 872°C days. Despite this, site-averaged thaw depth remained at the 2000–01 level (104 cm), with the range from 50 to 136 cm. The talik reduced in area to four grid nodes.

The INV calculated for 2000–02, i.e. the years for which maximum (September) thaw values are available, is shown in Figure 5F. It varies from 0.4% to 37% with the average 10%. This value is low compared to some other CALM grids (Hinkel and Nelson, 2003), although comparison is not strictly valid since the latter were calculated for 1000 m^2 grids.

Spatial thaw patterns at the site are controlled by landscape features. For the purpose of the paper, we distinguish between macro-, meso- and micro-topographic forms. Macro-topographic forms are those related to a whole 100 × 100 m grid. For example, a slightly convex slope on which the Ayach-Yakha grid is established (Figure 3), is considered a macro-topographic form. Meso-topographic forms are of several dozen metres in the largest dimension and may encompass several grid nodes. An example is a depression in the southeast corner of the Bolvansky grid encompassing six grid nodes. Micro-topographic forms are less than 10 m in the largest dimension and may form within one cell of a CALM grid. A good example is presented by slightly convex frost boils numerous in the three grids under discussion. The only obvious effect of surface meso-topography on thaw depth observed at Bolvansky is the closed talik at the southeast corner of the site; the corner represents the marginal shrubby part of a lake depression. Snow thickness is high in this depression, providing for the deep position of permafrost table. Across the rest of the grid, micro-topography, lithological composition of the active layer (peat layer absence/presence and thickness) and vegetation are more powerful controls than the meso-topography. The shallowest thaw is observed in poorly drained micro-depressions and micro-hollows, where a peat layer has developed and a cloudberry (*Rubus chamaemorus*)/dwarf shrub/moss/lichen community grows. The thaw is deeper in the areas with tundra circles (frost boils) lacking a peat layer. The site-maximum thaw values are observed under frost boils completely lacking vegetation or partly overgrown with dwarf shrub/lichen vegetation.

Except for the talik area, the main control over thaw depth at the site is an organic (peat) layer. The thicker this layer, the shallower thaw depths. Results of ranking the organic layer and average thaw depth for each class are shown in Table 2. To assess the statistical significance of the differences shown in this table, each pair of samples was compared for each data of observation. Preliminary graphs showed that distributions were close to normal. Considering different sample size, comparison of dispersions was conducted using the Fisher test (*F*-criterion). Only in August (14.08.99) did the three classes of peat thickness differ significantly (0.05 level) with regard to thaw depth. In July, grid nodes with a 0–3 cm thick peat layer demonstrated significant difference from nodes belonging to two other peat thickness classes, whereas the difference between the two other classes was non-significant. September data (columns 5 and 6 in Table 2) demonstrated the opposite result: the grid nodes with the thickest peat layer (11–21) differed significantly from the other two classes, whereas the difference between the latter classes was non-significant.

Thaw depths measured in July, August, mid- and late September can be correlated with DDT accumulated by each date in the same way it is applied to study the response of the end-of-season thaw depths to air temperature forcing (e.g. Nelson and Outcalt, 1987; Andersland and Ladanyi, 1994). Figure 6 shows that the increase in thaw depth during a warm season is well correlated with increasing amount of heat (R^2 of 0.9 or higher) both for the whole grid, and for separate peat-thickness classes.

Ayach-Yakha

Dates of end-of-season thaw depth measurements at this grid varied from September 2 to September 19. At the nearby Vorkuta weather station, September has positive mean month air temperatures during the whole period of record, since 1947. Mean May air

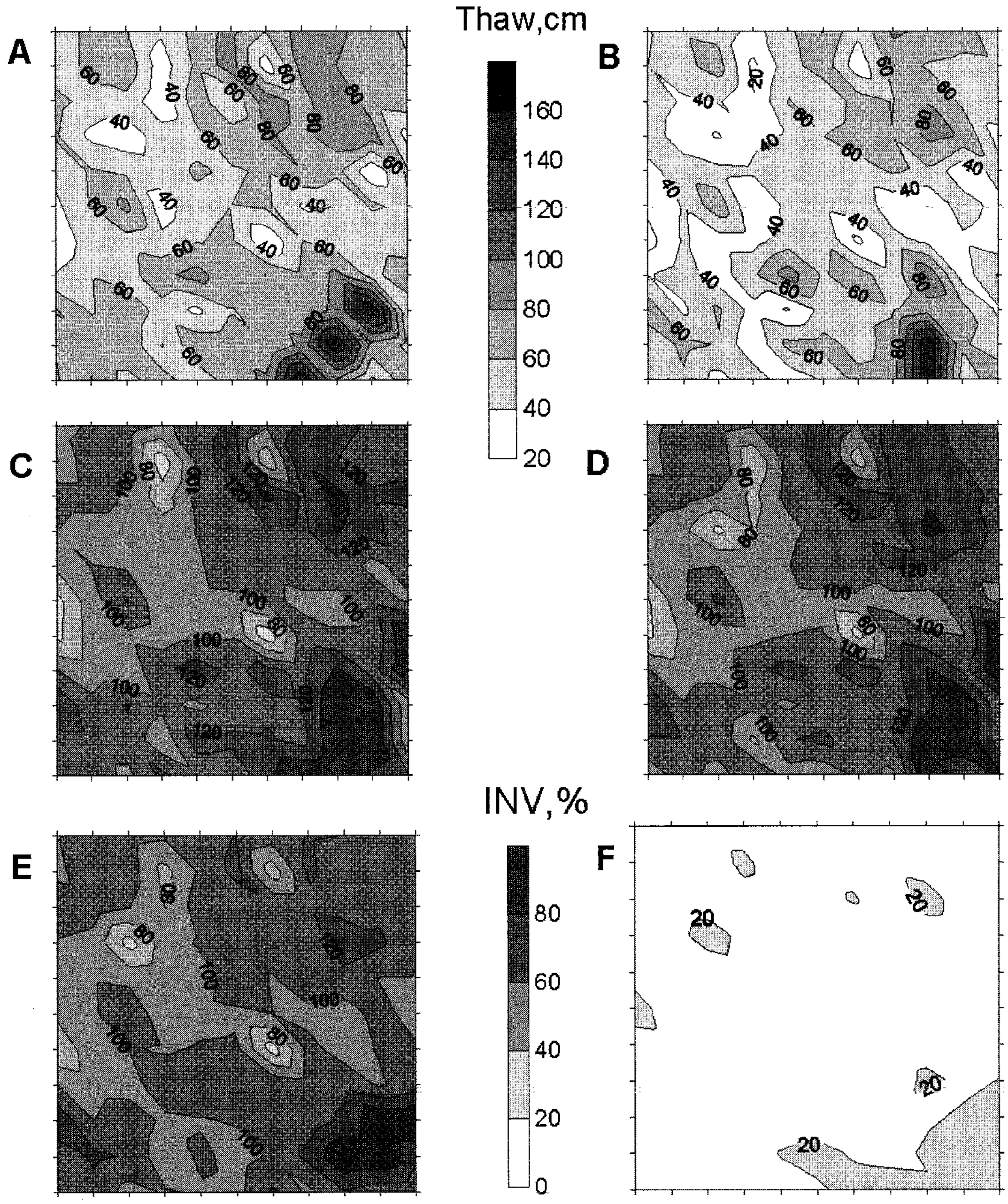


Figure 5 Thaw and interannual node variability patterns at the Bolvansky grid. Site-averaged thaw and INV values are given: A: August 14, 1999 (61 cm, SD 22.4 cm; B: July 12, 2000 (49 cm, SD 22.0 cm); C: September 19, 2000 (106 cm, SD 21.9 cm); D: September 10, 2001 (106 cm, SD 20.8 cm); E: September 21, 2002 (104 cm, SD 16.6 cm); F: INV (10%, SD 7.9%).

temperature can be positive or negative. Figure 7 shows observed end-of-season thaw patterns. DDT values by the date of grid probing were low in 1996–99 (809–998°C days), high in 2000–01 (1214 and 1137°C days), and low again in 2002 (829°C days). Full annual DDT values were a few per cent higher, except for the extremely warm year of 2000, when 10% of the full DDT was accumulated after the grid

Table 2 Relationships between thaw depth (h) and organic-layer thickness at the Bolvansky grid.

Peat-layer thickness, cm	Thaw depth, cm									
	14.08.99		12.07.00		19.09.00		10.09.01		21.09.02	
	h	St.Dev.	h	St.Dev.	h	St.Dev.	h	St.Dev.	h	St.Dev.
0–22 (n = 121)	61	22.4	49	22.0	106	21.9	106	20.8	104	16.6
0–3 (n = 63)	76	21.4	63	21.4	121	17.1	119	16.7	113	13.5
4–10 (n = 42)	54	12.7	42	13.3	101	15.1	101	16.1	102	12.5
11–22 (n = 16)	40	15.9	31	14.0	84	22.7	86	22.2	87	20.6

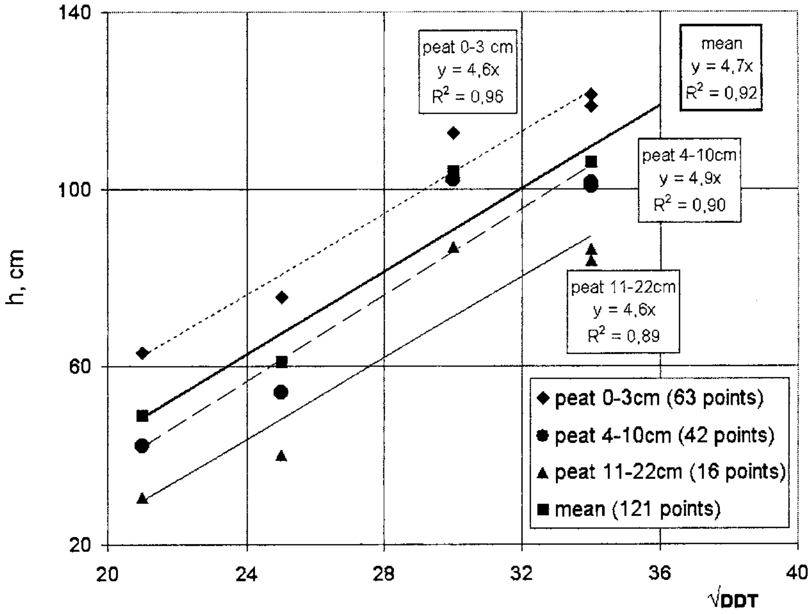
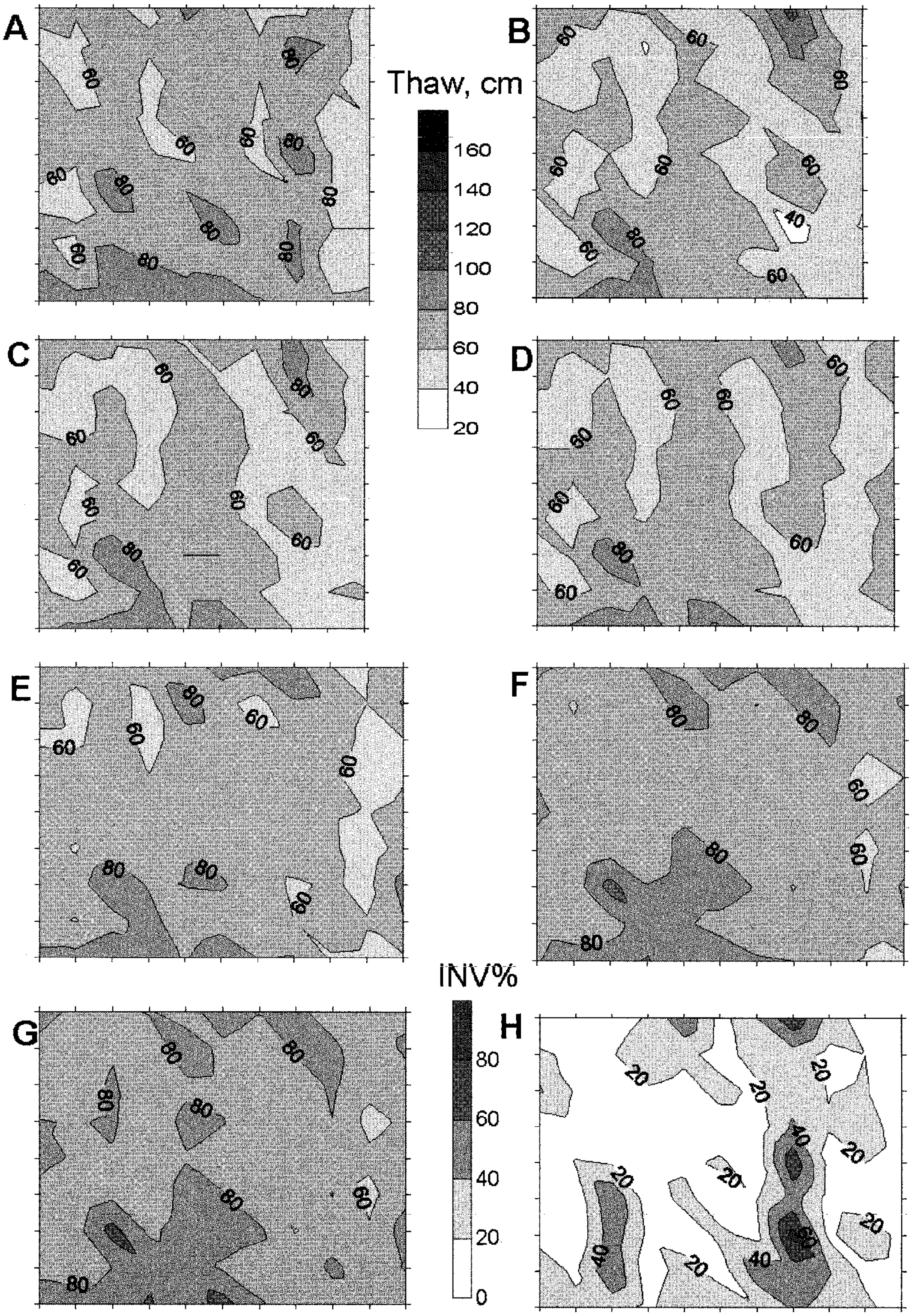


Figure 6 Seasonal thaw (h, cm) dynamics at the Bolvansky grid. Thaw depths were measured in August 1999, July and September 2000, September 2001 and September 2002.

probing on September 2. Site-averaged snow depth was largest in 1997–98 (47 cm) and smallest in 1999–2000 (30 cm). Liquid precipitation was smallest in 1997 and largest in 2002. In general, the two warmest summers of 2000 and 2001 were drier than the long-term average and were preceded by moderately cold winters with the snow shallower than the 1996–2002 site average. As Figure 7 shows, an after-effect of these two warmest summers on thaw depth was still observed after a relatively 'warm' winter 2001–02 and a cool summer 2002. Site-averaged INV is 23% with node-specific INV values ranging from 1 to 88%. The grid nodes with the highest INV values are located in a hollow crossing the site in its eastern part. Soil water content is rather dynamic in this hollow, with temporal ponds observed at some nodes. The lowest INV values are characteristic for the grid nodes located on the most convex portion of the grid (macro-slope shoulder).

The site-averaged surface subsidence totalled 13 cm from 1999 to 2002. In this period, average thaw depth at the site increased gradually from year to year. Subsidence varied across the site, ranging from 0 to 31 cm with most nodes experiencing subsidence of 10 to 20 cm. The large hollow crossing the site in its eastern part presented the most complicated pattern with slight heave in its upper part, where thaw depth at two nodes decreased during the period 1999–2002, and the highest values in the lower segment of the hollow, where thaw depths increased during the same period. In general, if the whole site is assessed, no significant correlation occurred between node-specific thaw depths and subsidence values. However, subsidence is well correlated with the node-specific


A
B
C
D
E
F
G
H
Thaw, cm
160
140
120
100
80
60
40
20
INV%
80
60
40
20
0

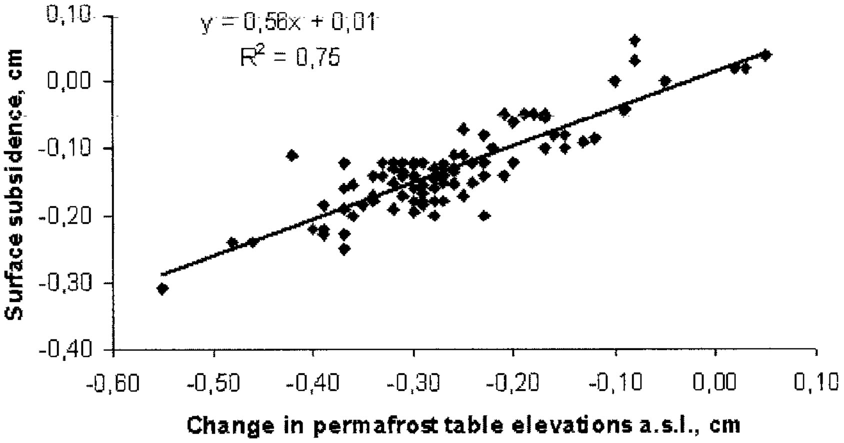


Figure 8 Correlation between surface subsidence and changes in the position of the permafrost table at Ayach-Yakha in 1999–2002.

amounts of the downward or upward movement of the permafrost table (Figure 8).

To identify the best predictors of spatial pattern of thaw, a multiple linear regression analysis was conducted for the year 2000, which experienced an extremely warm summer and 'set' a thaw depth level for the following 2 years. Thaw depth was considered a dependent variable, and six independent variables were included in the analysis: (1) vegetation height, (2) elevation, (3) deviation from the linear slope, (4) soil organic layer thickness, (5) annual maximum snow depth and (6) volumetric water content in the upper mineral soil horizon. Values of the variables were determined for most grid nodes.

Vegetation height was the only variable not represented quantitatively. Instead, two classes were considered: 'short vegetation' and 'tall vegetation.' Low dwarf shrub/moss vegetation forms the first class, whereas dwarf birch and willow thickets, both taller than 40 cm, form the second class. Node elevations were calculated above a conventional zero level set by the node with the lowest elevation a.s.l. Conventionally, this variable can be termed macro-topography. Deviations from a two-dimensional linear slope (the latter approximates the macro-slope on which the grid is located) represent the surface meso-topography expressed quantitatively. The annual maximum snow depth, as the analysis showed, was partly redundant with the variables representing macro- and meso-topography, although the degree of the redundancy was small. The site-averaged INV of the snow depth is 41%, which is rather high and indicates that snow pattern varies from year to year. Only the most distinct features of the pattern, (e.g. snow accumulation in the hollow) are reproduced consistently from year to year.

Initially, samples corresponding to the two vegetation classes were analysed separately. The results indicated that the effect of vegetation height on thaw depth was non-significant ($p < 0.05$). This allowed us to merge the two samples for further analysis. Stepwise multiple regression was applied, which showed that the 'best' (statistically significant at $p < 0.05$) predictors of the end-of-season thaw depth (AL, cm) were soil organic layer thickness (OL, cm) and node elevation (E, m). The form of the resulting equation is:

$$AL = 94.29 - 1.48\ OL - 1.66\ E$$

yielding an R^2 value of 0.34 with a standard error of 9.91.

At $p < 0.01$ the only significant variable is organic layer thickness. The equation explains only 34% of the thaw depth variability within the grid, from which 26% is attributed to the effect of organic layer thickness and 6% to the effect of elevation. The increments in R^2 due to other variables total 0.02 (2%).

Talnik

End-of season grid probing at this site was conducted in early October 1998, in mid-September in

Figure 7 Thaw and interannual node variability patterns at the Ayach-Yakha grid. Site-averaged thaw and INV values are given: A: September 2, 1996 (67 cm, SD 14 cm); B: September 19, 1997 (62 cm, SD 14 cm); C: September 12, 1998 (63 cm, SD 12 cm); D: September 11, 1999 (64 cm, SD 12 cm); E: September 2, 2000 (69 cm, SD 12 cm); F: September 7, 2001 (73 cm, SD 11 cm); G: September 13, 2002 (76 cm, SD 11 cm); H: INV (23%, SD 17%).

1999–2001, and in late September in 2002. Climatic characteristics of the period of observation are the same as those for Ayach-Yakha. Annual thaw patterns are shown in Figure 9. Two portions of the grid are clearly observed: a north-south trending ridge with a shallower thaw and a depression in the eastern part of the grid with much deeper thaw. Standard deviations of the site-averaged thaw depths are therefore high; for example, in 1998 the deviation totaled about 30% from the end-of-season mean. The standard deviation to mean ratio is even higher earlier in the warm season, constituting 40–50% in late June and July. The deepest end-of-season thaw was observed in the year 2000 after the extremely warm summer, and decreased slightly in the following 2 years. Thaw patterns reproduce rather consistently from year to year. INV is 16%, ranging from 2 to 81%, with the highest values observed in depressed, poorly-drained parts of the grid and the lowest values in a better drained ridge.

Seasonal thaw dynamics are well studied at this grid, where several probings were conducted throughout the thaw season in four of the five summers. At the beginning of the warm season, several loci appear with the most rapid thaw. With few exceptions they correspond to the deepest depressions or the highest ridges. By the end of July, especially the loci in depressions leave behind the rest of the grid with regard to thaw depths. The rate of thawing in these points decreases during the second half of the warm season, but they remain larger than the rest of the grid nodes. Figure 10A compares seasonal thaw dynamics in different years. The dynamics were rather similar in 2000–02, i.e. in the years with equally high values of end-of-season thaw (110–111 cm). However, in the cool summer of 1999, thaw depths were shallower throughout the season and the end-of-season value was only 91 cm. In late July (Julian days 200–210 on Figure 10), which may be considered the middle of the warm season, site-averaged thaw depth in 1999 comprised only 34% of the end-of-season value, whereas in 2000–02 it comprised 70 to 80% of the respective end-of-season values by that date.

Site-averaged volumetric moisture content in the upper (usually organic) soil layer ranged from 26 to 63%. Values were usually at a minimum (Figure 10B) in mid-summer (1999, 2000 and 2002). However, in the very dry warm season of 2001, they were lowest at the end of the season.

The spatial pattern of thaw at the site is controlled to a large degree by meso-topographic forms. These forms also control many other factors affecting thaw depth. Thaw is deepest in two large depressions/hollows in which ground water is likely to be flowing. These depressions have high water contents relative to other locations on the grid; this is especially visible in dry periods. Saturated moss cover and soil peat layer conduct heat better than the drier lichen/moss cover dominating the ridge in a central part of the site. Flowing ground water acts as an additional heat-transfer mechanism. Moreover, the depressions are covered with up to 2 m of snow in winter, compared to 40–60 cm on the ridge. Deep snow in the depressions allows dwarf birch and willow thickets to reach 1.5 m heights, explaining the relation between thaw depth and shrub coverage. The onset of thaw in depressions is usually delayed relative to that on the ridge due to the energy requirements involved in melting the large volume of snow (unpublished observations were made in 1996). This delay is later compensated by the higher thawing rates, as described above.

These discussions can be demonstrated by mean correlation coefficients (R) between end-of-season active layer depth and other factors. Thaw depth shows significant ($p < 0.05$) negative correlation with node elevations ($R = -0.45$), lichen coverage ($R = -0.43$) and low dwarf shrub coverage ($R = -0.51$), and significant positive correlations with tall shrub ($R = 0.48$), herb ($R = 0.37$) and moss ($R = 0.28$) coverages. As a rule, correlation with soil moisture content is also positive, although it is significant ($R = 0.28$) only when site-averaged volumetric moisture content is less than 45%, and non-significant ($R = 0.11$) when it exceeds 45%.

DISCUSSION

One of the three European Russian CALM grids is located in the continuous permafrost zone, whereas the others are in the discontinuous permafrost zone. In spite of this, MAAT is lower at the grids located in discontinuous permafrost experiencing more continental climate (−5.9°C at the Vorkuta weather station versus −4.4°C at the Bolvansky station). The difference is completely due to winter temperatures, whereas DDT values differ very little at the three grids. The reason is that DDT values in the region increase northwards regardless of continentality, with the exception of the Pechora valley, for which positive deviations are characteristic. Long-term DDT values are 972°C days at the Bolvansky weather station (1935–97), 1169°C days at the Naryan-Mar station (1927–99), and 1002°C days at the Vorkuta station (1947–2001) indicating similarity of the CALM sites in this respect. Climatic fluctuations, as registered by many weather stations, are synchronous over the

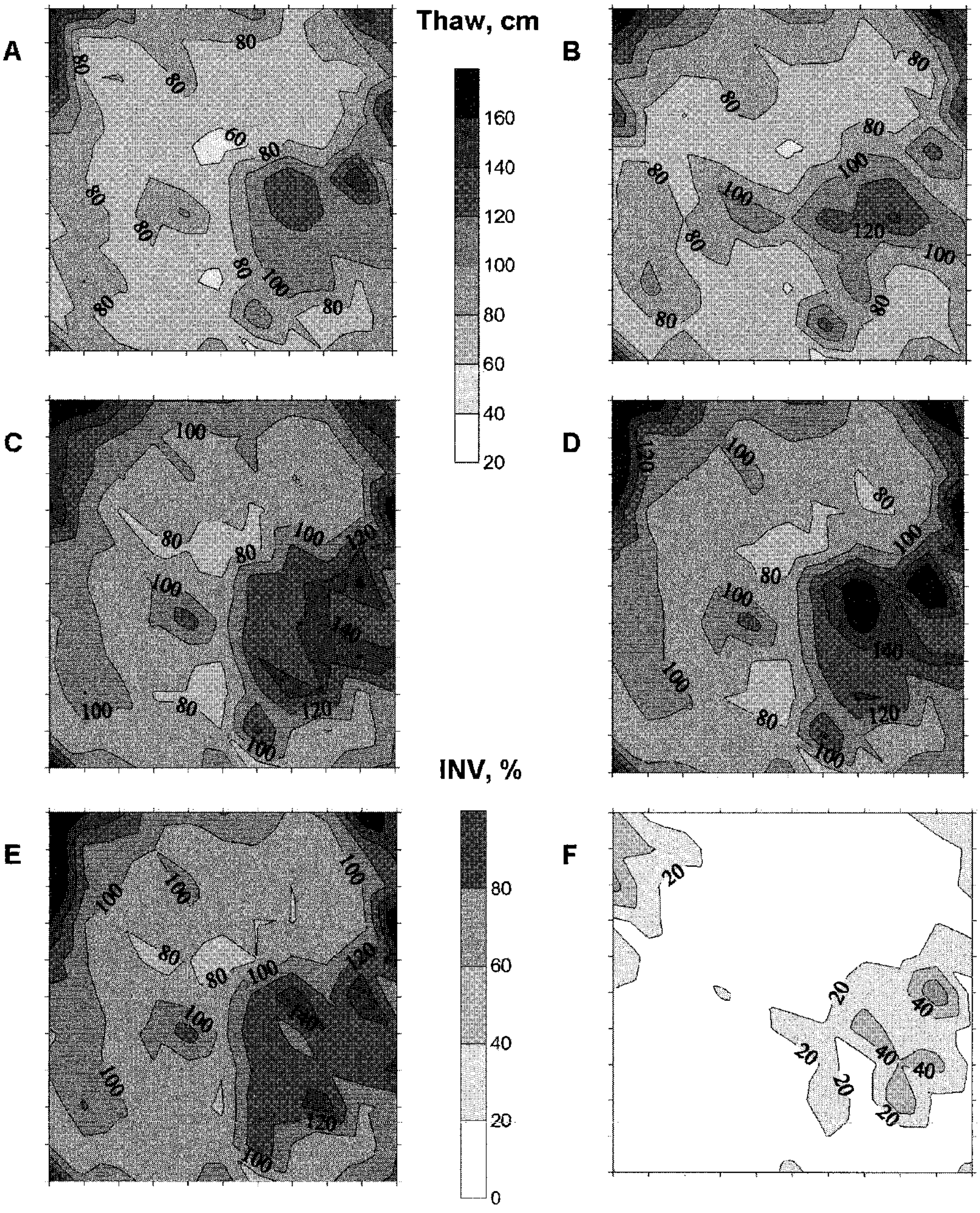


Figure 9 Thaw and interannual node variability patterns at the Talnik grid. Site-averaged thaw and INV values are given: A: October 1998 (89 cm, SD 25 cm); B: September 1999 (91 cm, SD 26 cm); C: September 2000 (111 cm, SD 28 cm); D: September 2001 (111 cm, SD 32 cm); E: September 2002 (110 cm, SD 29 cm); F: INV (16%, SD 14%).

European Russian North, including the warming of 1970–95 and the ongoing cooling. Thus, natural climatic fluctuations should affect thaw trends at the three CALM grids in a similar way.

General trends of interannual thaw dynamics are the same at the three sites (Figure 11). Two 'warmer' sites with deeper average thaw, Bolvansky and Talnik, reveal remarkable similarity of even absolute annual

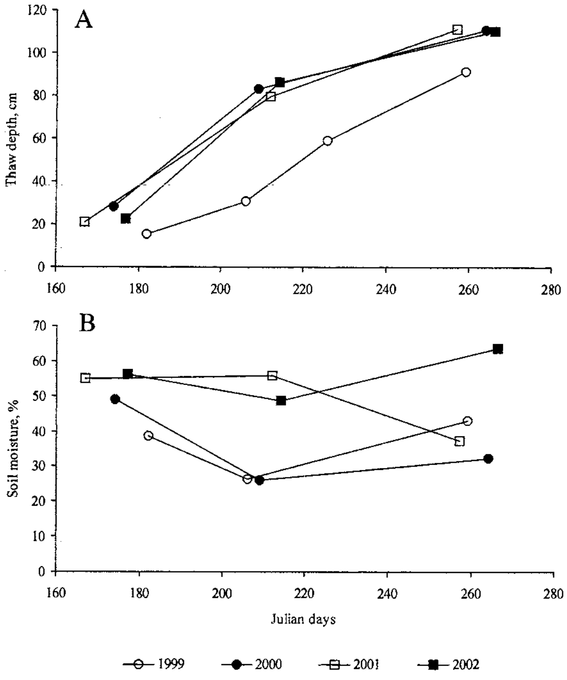


Figure 10 Seasonal dynamics of the site-averaged (A) thaw depth and (B) soil moisture at the Talnik CALM site.

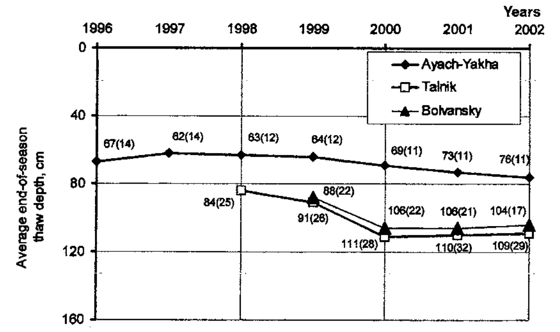


Figure 11 Interannual thaw variability at European Russian CALM grids. Site-averaged end-of-season thaw depths are given for each point with standard deviations shown in parentheses.

values of thaw, with the average thaw for the period of observation of 101 cm at both sites. The 'colder' site, Ayach-Yakha, demonstrates shallower average thaw (68 cm) for the period of observation; the curve showing interannual thaw dynamics at this site is less variable. The range of average annual thaw values in 1999–2002 constitutes 19% of the average thaw at Bolvansky and Talnik and 17% at Ayach-Yakha, in addition to the smaller absolute thaw values and the smoother character of the Ayach-Yakha curve.

Interannual thaw variability is caused by corresponding climatic variability, primarily by heat input during the warm season. The effects of winter severity are much smaller. For example, the winter of 1998–99 was extremely cold and resulted in the 1998 MAAT being the lowest for the entire period of observation in the Vorkuta and the Khoseda-Khard weather stations (the latter is located between the Bolvansky and the other two sites). However, none of the three grids responded to this winter; instead, thaw continued to gradually increase at the grids. Also, no clear effects of either winter or summer precipitation levels on thaw depths were revealed. The summer N-factor (ratio of DDT at the soil surface to that in the air) is 0.86–0.87 at Ayach-Yakha, which is in the middle of the range known for seven sites representing major physiographic divisions in northern Alaska (Klene *et al.*, 2001). Unfortunately, N-values are not available for Bolvansky and Talnik.

Figure 12 shows regressions of thaw depths by $DDT^{0.5}$ using a form of the Stefan solution (Andersland and Ladanyi, 1994). Not only end-of-season values, but also those obtained earlier in the warm season were used. The R^2 of each regression significantly differs from zero at $p = 0.01$. Differences in seasonal thaw dynamics at the three sites are obvious. Bolvansky and Talnik, which are rather similar with respect to landscape features, despite the large distance between them, demonstrate nearly identical regression lines. The Ayach-Yakha line has a much smaller slope. Thaw starts earlier at this site due to shallower snow and the southwestern aspect. At the end of June, average thaw depths are similar at the three sites and equal to 26 cm. Later, thaw depth increases much more rapidly at Bolvansky and Talnik than at Ayach-Yakha, which is caused by a combination of landscape features. The figure indicates that the same increases in DDT cause much smaller increases in thaw depths at the cold Ayach-Yakha site than at the two 'warmer' sites. These results allow us to forecast thaw depths at the three sites by a particular date within a warm period or an end-of-season value, based only on known DDT values accumulated by the corresponding date. Cross-validation of this model was performed for Ayach-Yakha and Talnik. It was not performed for Bolvansky because of the small sample size. Both Ayach-Yakha and Talnik data sets were divided into two subsets equal or about equal in size. The subdivision was made by two different ways, randomly and chronologically. In each pair of subsets, thaw depths for a testing subset were predicted based on the regression derived from a training subset. Standard error of estimate (*SE*) was determined for each subset based

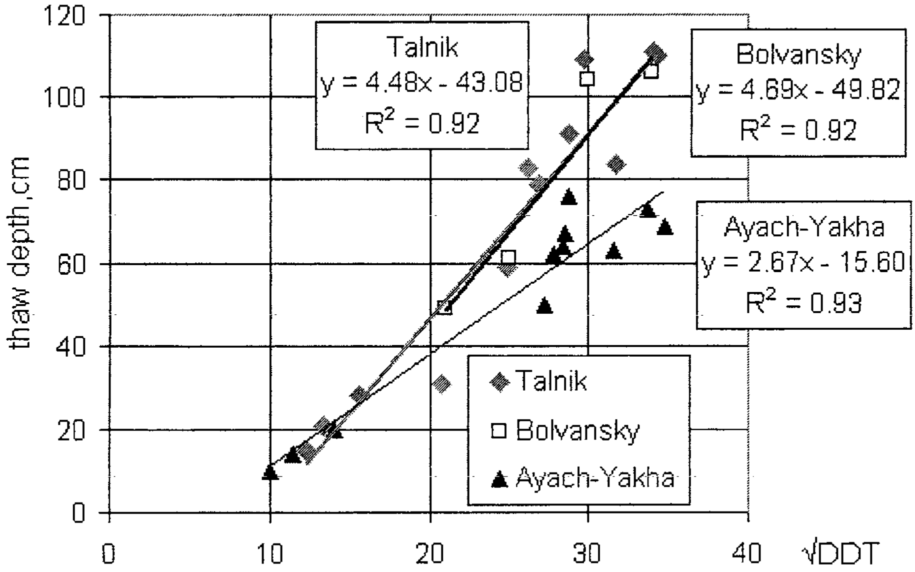


Figure 12 Thaw depth plotted against the square root of the thawing index at the three European Russian CALM sites.

on comparison with observed values. As the validation showed, in all examined cases *SE* of a subset did not depend on the subset used as a training or as a testing one (Fisher criterion, $p = 0.05$). This result demonstrates that the model performs satisfactorily.

Our data complement the results of one-dimensional (vertical) modelling conducted for two sites in the European Russian North under the PERUSA project (Mazhitova *et al.*, in press). The modelling showed that a 'warm' mineral site will react to global warming much faster than a 'cold' peaty site. Our results support the assumption that 'cold' mineral sites similar to those at Ayach-Yakha will demonstrate an intermediate level of reaction. The extremely warm summer of the year 2000 caused a characteristically large increase in thaw depth at Talnik and a smaller increase at Ayach-Yakha. An after-effect of this summer was observed at Ayach-Yakha in 2001 and 2002: thaw depth continued to increase gradually in these years. However, at the other two sites, thaw decreased slightly in 2001 and 2002 following a decrease in DDT in the air. This again demonstrates that the cold site is less responsive to air temperature forcing but, once an extreme year re-establishes a new thaw level, it is preserved for a longer time compared with two other sites. This is in agreement with the conclusion regarding Markovian behaviour of thaw depth at the Alaskan CALM grids (Nelson *et al.*, 1998; Hinkel and Nelson, 2003).

Lower site-averaged INV values at Bolvansky and Talnik (10 and 16%, respectively) indicate the more consistent and predictable response of these two sites to air temperature forcing. However, the Ayach-Yakha value (23%) is still low compared to some 1000 × 1000 m CALM grids (Hinkel and Nelson, 2003). At all three sites, high node-specific interannual variability is primarily related to highly dynamic soil water content, including pond formation in some years.

A discussion of thaw dynamics should also take into account surface subsidence, especially if the magnitude is large enough. At the loamy and moist Ayach-Yakha ice content in the upper layer of permafrost is probably high; cores taken from this layer at two grid nodes supports this assumption. Therefore, progressive downward retreat of the permafrost table caused surface subsidence totalling 13 cm in 3 years. This value cannot affect the conclusions we made above on the seasonal and interannual thaw dynamics. However, it is important that subsidence was highly variable over the site, and cannot be ignored when interpreting results at some particular grid nodes.

The range of thaw variability within the CALM sites may differ from that within the landscapes/physiographic divisions to which the sites belong. To assess how representative the sites are, a specially designed study should be conducted employing geostatistics, like that conducted for Alaska (Shiklomanov and Nelson, 2003). The coastal plain covered with glacial-marine deposits and represented by the Bolvansky grid contains, besides upland areas, numerous lake depressions. The piedmont plain, also covered with glacial-marine deposits and represented by the

Ayach-Yakha and Talnik grids, is to a greater degree dissected by streams so that landforms like hilltops, slopes of different aspects, and inter-hill depressions should be considered. The same landforms cause larger contrasts with respect to permafrost conditions in the discontinuous permafrost zone than in the continuous. The CALM grids mostly characterize dominant upland landforms within corresponding physiographic divisions. Therefore, although the sites do not characterize the entire range of variability within the divisions, they do reveal the primary controls on active-layer spatial variability.

The main control seems to be the macro- and meso-topography described in this paper: a lake depression with an underlying talik at Bolvansky, a large ridge and a depression/hollow at Talnik. Although Ayach-Yakha is more homogeneous with respect to major landscape features compared to the other sites, it has a windward slope aspect, i.e. a large topographic form causes permafrost at this grid due to snow redistribution. Macro- and meso-topography affect the thaw depth through various mechanisms, for example, depth to bedrock (Ayach-Yakha) or snow accumulations in depressions. Snow thickness, which is one of the main controls over permafrost distribution patterns at the regional scale (Oberman, 1998), may also affect thaw depth at a scale as detailed as that of CALM grids if the range of snow thickness within a site is large enough. Indeed, snow thickness affects thaw patterns at Bolvansky and Talnik, but not at Ayach-Yakha, where snow cover is uniformly thin over the site. Another important control is organic-layer thickness, which shows a negative linear correlation with thaw depths. Within the Ayach-Yakha grid, which is more homogeneous with regard to meso-topography, it becomes the main control. As data from the Bolvansky grid show, the effect of organic-layer thickness on thaw depth may change during a warm season. At Talnik, vegetation is highly differentiated within the site (again, due to meso-topography and snow), so that it also operates as a control. Within the homogeneous Ayach-Yakha, thaw variability is lower than at two other grids, and controls over it are most difficult to determine; six analysed variables were found to control only 34% of the variability. As the variables known to be the strongest controls over thaw patterns were included in the analysis, one can assume that most of residual variability is of a random nature.

CONCLUSIONS

In general, the CALM strategy proved effective in the north of European Russia. The response of the active layer to air temperature forcing is consistent and predictable in the examined landscapes, so that data from CALM grids allow modelling of the impact of air temperature. The grid design also reveals local controls over active layer depth. Variability within wider landscape units is, in our opinion, a problem which is not adequately addressed by CALM, and should therefore be analysed under a specially designed project. Prerequisites for such analyses are very good in European Russia, as the amount of permafrost data available from various sources is large compared to many other regions.

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