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

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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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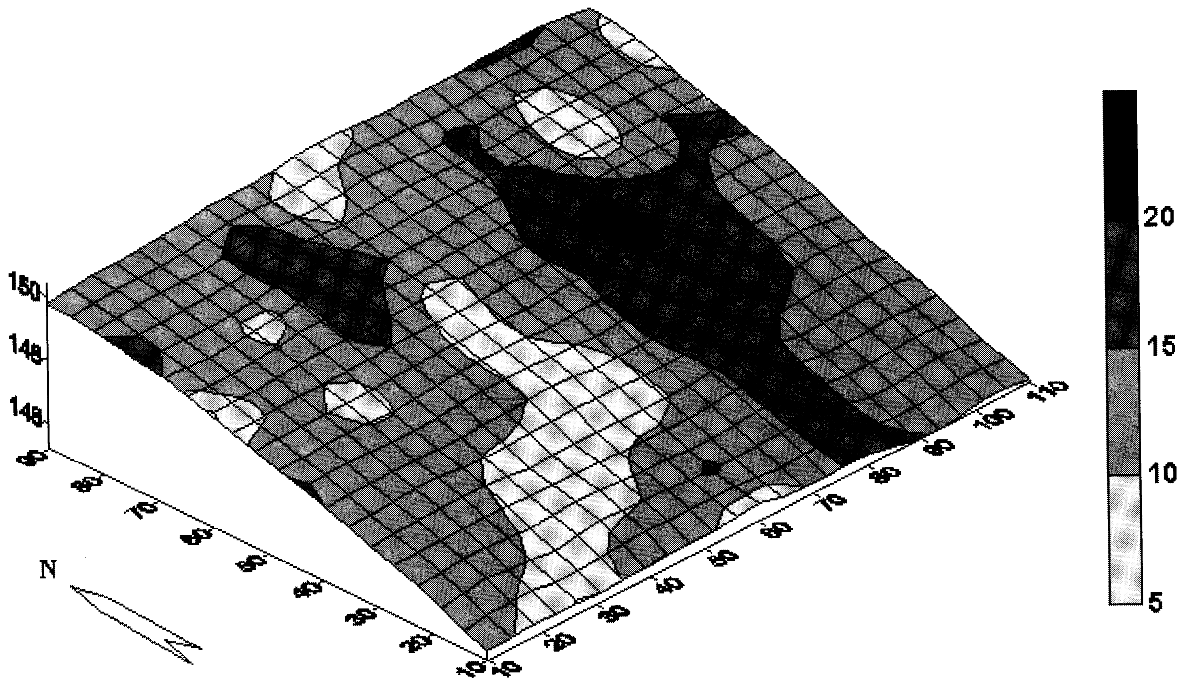

Figure 3 Terrain model of the Ayach-Yakha grid overlain with peat-layer thickness, cm; site-averaged thickness is 12 cm.

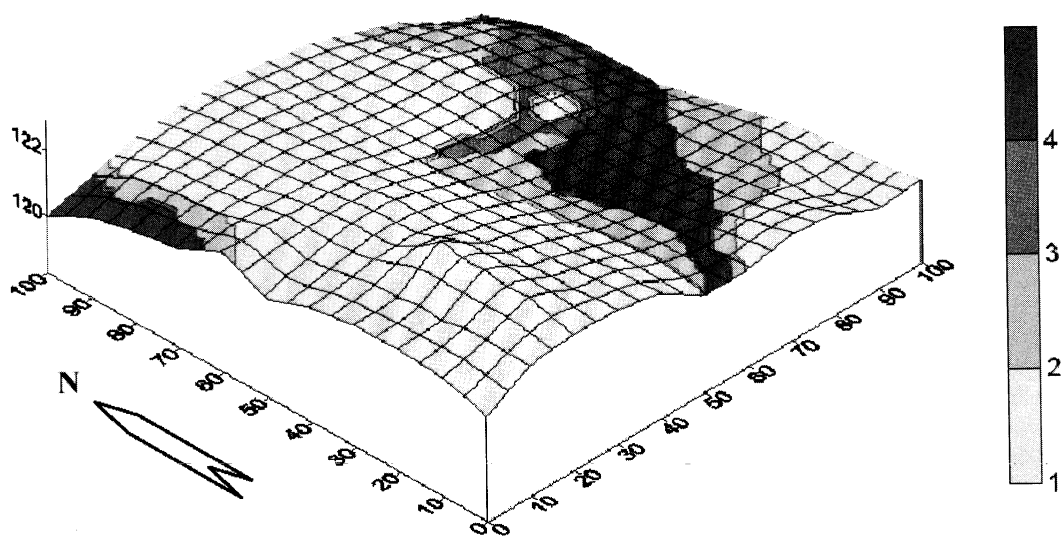

Figure 4 Terrain model of the Talnik grid overlain with vegetation classes. Shade legend: (1) lichens/mosses/shrubs/dwarf shrubs; (2) mosses (*Pleurosium*)/lichens/shrubs/dwarf shrubs; (3) mosses (*Polytrichum*)/lichens/shrubs/dwarf shrubs; (4) mosses/shrubs.

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

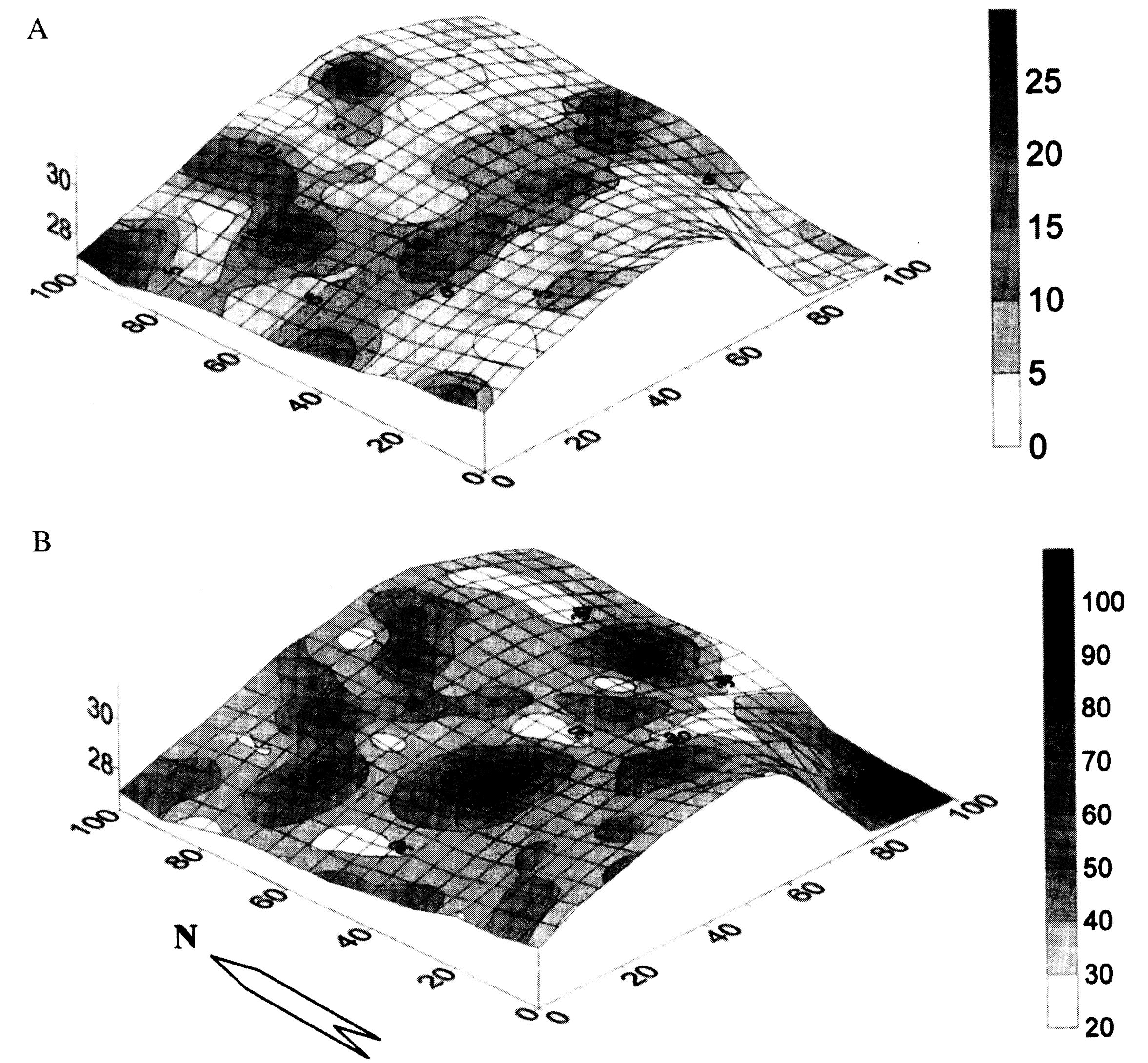

Figure 2 Terrain model of the Bolvansky grid and selected active-layer characteristics. (A): peat-layer thickness, cm; site-average value is 5 cm. (B): volumetric soil moisture at a depth of 20 cm; site-average value is 39.9%.

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).

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

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	+	+	+

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.

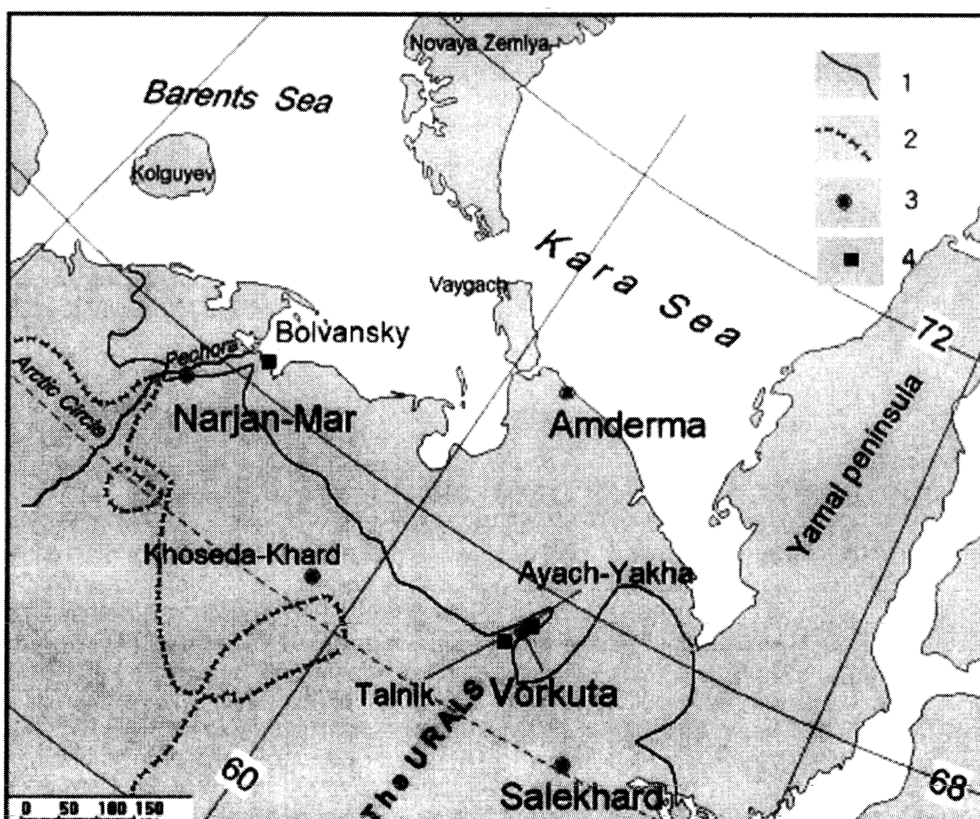

Figure 1 Location map of the European Russian CALM grids. Key: (1) boundary between continuous and discontinuous permafrost zone; (2) southern boundary of the cryolithozone; (3) weather stations cited in the paper and main towns; (4) CALM grids.

