ACTIVE-LAYER MONITORING IN NORTHEAST RUSSIA: SPATIAL, SEASONAL, AND INTERANNUAL VARIABILITY[1]

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Abstract: This paper focuses on regional analysis of results from a program of active-layer monitoring at three active CALM (Circumpolar Active Layer Monitoring program) sites in northeast Russia. The length of the observation period varied between 3 and 9 years at different sites. Thaw depth was measured mechanically on 100 × 100 m grids with 1–4 replications at each grid node, 1–4 times per thawing season. Additional parameters, depending on site, were volumetric soil moisture, thickness of the organic layer, thickness of the moss cover, absolute elevation of nodes, surface disturbance and quality of microhabitats, and density of vegetation cover. There were no evident trends in end-of-season thaw depth at our sites in northeast Russia during the 1994–2002 period. Water tracks, surface disturbances, soil moisture, and organic soil horizon thickness are major controls over spatial variations of end-of-season thaw depth. The influence of different factors on the thawing process is seasonally specific. Temporal variation of thaw depths is strongly temperature dependent.

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INTRODUCTION

The contemporary permafrost regions occupy about 25% of the global land surface (Zhang et al., 1999, 2000), and at some locations permafrost extends into the lithosphere as much as 1500 m (Washburn, 1980). Physical, chemical, and biological processes are inhibited strongly by the low temperatures associated with permafrost. During the warm season, a thin layer of ground at the atmosphere/lithosphere boundary thaws, resulting in a drastic acceleration of these processes in the appropriately named *active layer*. The dynamics of seasonal thaw and the maximum thickness of the active layer both depend strongly on soil-temperature behavior, which is driven primarily by air temperature, albedo, the thermal properties of vegetative and soil cover, soil moisture, ground water mobility, snowpack thickness, and other related factors (e.g., Yershov, 1998). Particular combinations of these controls in different permafrost landscapes are highly variable, making it difficult to model the seasonal dynamics of near-surface thawing at local (Romanovsky and Osterkamp, 1995, 1997; Klene et al., 2001) or global scales (Anisimov and Nelson, 1996, 1997; Nelson et al., 2002). More complex difficulties result from climatic changes, which are becoming progressively obvious in the polar regions (Anisimov et al., 2001). At present, climatic changes vary considerably between different parts of the Arctic, resulting in both positive and negative feedbacks in interactions between permafrost, the active-layer, vegetation, and the atmosphere (Oechel et al., 1993, 2000; Hinkel and Nelson, 2003; Zamolodchikov and Karelin, 2001).

Beginning in the early 1990s, the relations and concerns expressed above served as the basis for a new international effort, the *Circumpolar Active Layer Monitoring* (CALM) project. The project's main goals are "to assess changes in the active-layer and to provide ground truth for regional and global models" (Brown et al., 2000, p. 168). In the Russian Northeast (Chukotka district) the CALM network presently includes three permanent sites. The prime objectives of this paper are to address the seasonal and long-term dynamics of permafrost thawing and the key factors controlling the spatial and temporal variability of active-layer thickness (ALT) in this region.

SITE DESCRIPTIONS

Cape Rogozhny

The Cape Rogozhny site (64°49' N, 176°50' E) was established in 1994 on the northern coast of Onemen Bay, on the Bering Sea (Fig. 1). Geomorphologically, the area consists of a low, undulating plain occupying elevations of 5–30 m a.s.l. The CALM site is located on a gentle (0–3°) southwest-facing hillslope. The predominant vegetation is mossy-hummock tundra, with hummocks formed by cottongrass (*Eriophorum vaginatum* L.). Hummocks are 15–20 cm high and 20–40 cm in diameter, and occupy 60–70% of the surface, the remaining area being comprised of inter-hummock depressions or troughs. Within the sample grid, the projective cover (cover density) of dwarf shrubs is 30–40%, green mosses occupy 20–30%, and fruticose lichens 5–10%. Frost cracks, ice wedges, and frost boils are well developed. Soils within the sample grid are Gleyic-Histic Cryosols with a poorly developed (usually less than 10 cm thick) organic layer, and are underlain by sandy clay with peat

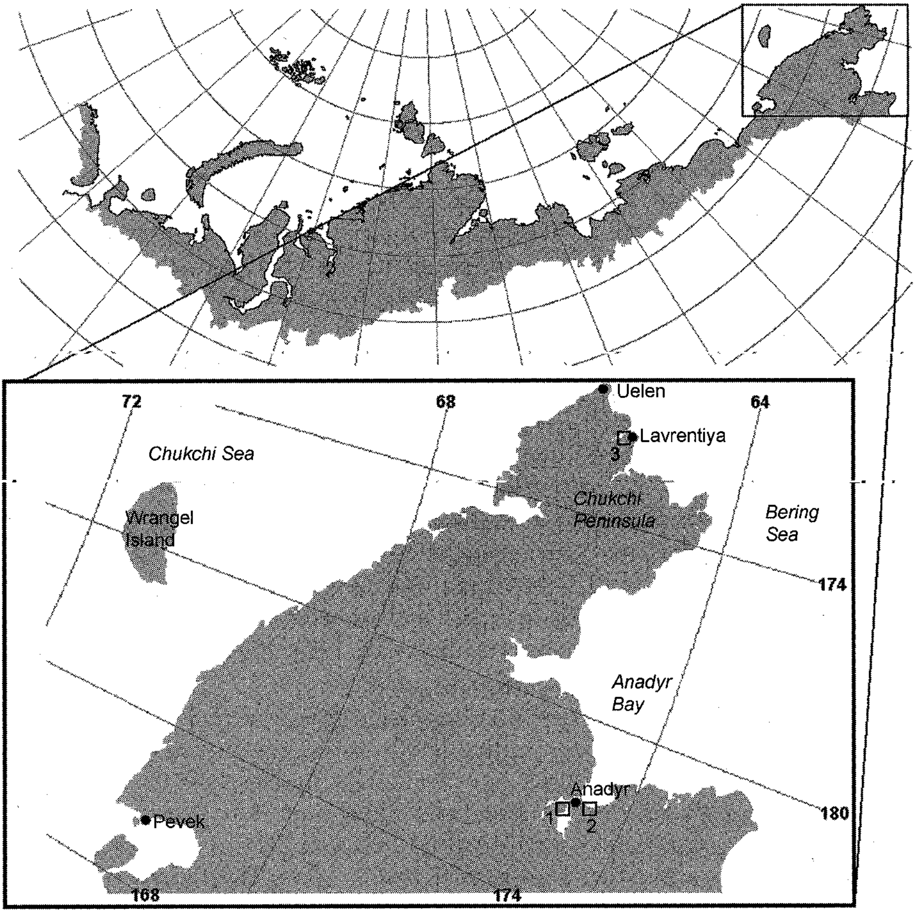

Fig. 1. CALM sites in Northeast Russia. Legend: 1 = Cape Rogozhny; 2 = Mount Dionisiya; 3 = Lavrentiya.

inclusions. Fine-grained sands of Late Pleistocene age up to 20 m thick are underlain by glacial till of Middle Pleistocene age.

Mount Dionisiya

Observations at the Mount Dionisiya site (64°34' N, 177°12' E) were initiated in 1996. The site is located 25 km south of Anadyr city at 140–145 m a.s.l., and is 35 km from the Cape Rogozhny site (Fig. 1). The surrounding flat and gently inclined periglacial terraces vary in texture from gravel to loam. The landscape is rich in water tracks and vegetation is variable, ranging from shrub tundra to dwarf shrub-sedge-mossy tundra and dwarf shrub-tussock-mossy tundra. The CALM grid is located on a slightly inclined (3°S and 2°W) proluvial-diluvial toeslope at 140–145 m a.s.l. The site comprises a network of slowly flowing water tracks (McNamara et al., 1999) with moist sedge-cottongrass plant communities and wet to mesic dwarf shrub–cottongrass tussock tundra occupying most of its area. Some peat hillocks, 1–4 m in diameter, 0.4–0.6 m high, and covered by dwarf shrubs and lichens, are present. Frost cracks and frost boils are also developed.

The Cape Rogozhny and Mount Dionisiya sites are located in the Nizhneanadyrskaya Lowland, within the continuous permafrost zone. Taliks are found only beneath Onemen Bay and large lakes. Permafrost thickness in the local area ranges between 100 and 300 m, with temperatures at the depth of 12 m between –3 and –5°% depending on site conditions (Kotov, 1995). Climatic conditions at the sites are well described by data from the nearest Anadyr weather station (64°47' N, 177°34' E). Mean annual air temperature is –7.7°%, and annual precipitation averages 312 mm. July is the warmest month (10.7°%), and January is the coldest (–22.8°%). On average, there are 221 days per year with snow cover at least 40 cm thick (Gidrometeoizdat, 1990).

Lavrentiya

The Lavrentiya site (Fig. 1) was initiated in 2000 near the settlement of Lavrentiya, on the Bering Strait coast (65°36' N, 171°03' W). The site's low, gently sloping (5–10°) ridges and hills, interspersed with stream valleys and small shallow lakes, are characteristic of post-glacial relief in this area. The distinguishing physiographic features are the low hilly relief formed through erosion of Mesozoic block structures by glacial, fluvial and marine processes. The CALM sample grid is located on a gentle mountain slope with northeast exposure (3°N and 1°E) at 70 m a.s.l. between a low massif and a marine terrace. Microrelief on the Gleyic-Histic Cryosol soils is poorly developed. The predominant plant communities are wet sedge *Salix* mossy tundra. At the peak of vegetative growth the projective cover on the CALM grid of *Salix* species averaged 32%, sedges 35%, other vascular species 6%, mosses (including *Sphagnum* spp.) 66%, and lichens 3%.

The local climate and atmospheric motion are highly seasonal and have a strong maritime influence. Strong offshore winds bring cool and cloudy weather and frequent fogs during the warm season. The oceanic climate has high humidity and a small range of diurnal and monthly air temperatures. The closest permanent weather station is at the settlement of Uelen (66°10' N, 169°50' W). Long-term observations at Uelen yield a mean annual air temperature of –7.8°C, and mean monthly temperatures of +5.3°C and –20.3°C for the warmest (July) and coldest (February) months, respectively (Gidrometeoizdat, 1990). In general, summer temperatures are considerably lower than in the Anadyr region, whereas winter air temperatures are higher, resulting in similar annual averages. Due to the severe climate conditions, the area is part of the continuous permafrost zone. Permafrost occurs throughout the area to depths of 200–400 m, and has average annual temperatures of –5 to –7°% at a depth of 12 m (Kotov, 1995).

METHODS

Field Procedures

The standard sampling design recommended under the CALM program (Brown et al., 2000) was applied, with minor modifications, at all CALM sites in northeast

Russia. Permanent 100 × 100 m grids were established, with 10 m intervals between grid nodes, and the nodes were marked with stakes. Thaw depth was determined at each grid node using a steel rod. During measurements both grids at the Cape Rogozhny and Mt. Dionisiya sites had one replication per node, and four replications per node at the Lavrentiya grid. The active layer was measured once each year at the end of the warm season at the Cape Rogozhny and Mt. Dionisiya sites, whereas the Lavrentiya grid was monitored throughout the warm season, with up to four complete plot measurements per warm season.

An additional set of parameters was monitored at the three sites in order to estimate the influence of different natural controls over the temporal and spatial variability of the active layer. At the Cape Rogozhny site we inventoried the surface characteristics of microhabitats, such as tundra, vehicle tracks, and frost boils. At Mt. Dionisiya the relative areas occupied by tundra vegetation, water tracks, and frost boils were determined, accompanied by grid leveling. The most comprehensive set of additional parameters was collected at the Lavrentiya grid, including qualitative characteristics of microhabitats, measurements of volumetric soil moisture, projective cover of vegetation, moss cover, and organic-layer thickness.

A topographic survey of grid nodes was performed using a Russian 2H-10KL optical leveling instrument. Volumetric soil moisture was estimated by real dielectric resistance in the topmost 7 cm of the soil organic horizon using a Vitel portable probe (Vitel Inc., 1994). Soil moisture measurements were replicated four times at each grid node during plot measurements. The moisture probe was calibrated gravimetrically by 185 volumetric soil samples taken from different ecosystems and organic/mineral horizons with variable volumetric moisture content. Regression analysis using these calibrations yielded a polynomial expression for the local soils:

$$SM = -2.47 + 2.80{*}E - 0.0432{*}\mathrm{E}^2 + 0.000279{*}\mathrm{E}^3,$$
$$R^2 = 0.947,\ SE = 7.3,\ n = 185, \qquad (1)$$

where SM is volumetric soil moisture (%) and E is a real dielectric constant.

The projective cover of plants was determined using a square (40 × 40 cm) portable census grid (sampling frame) divided into 100 4 × 4 cm squares. The sampling frame was centered on one of the CALM grid nodes for each cover census. The thickness of the moss layer was measured with a small ruler, using four replications within each sample. The thickness of the soil organic layer was estimated using a specially designed steel pipe 4 cm in diameter, 40 cm long, and a longitudinal cut 1 cm wide. The pipe was driven into the soil's mineral horizon. After the soil sample was removed, the thickness of the organic layer was measured with a ruler through the longitudinal cut in the pipe. The organic layer was identified visually by soil color and texture. These soil samples were taken once, 20–40 cm from each grid node.

The Cape Rogozhny and Mt. Dionisiya grids were equipped with temperature dataloggers measuring air and soil temperatures to a depth of 1 m. Although the Lavrentiya grid itself is is not equipped with a temperature logger, it is located only 400 m from a permanent micrometeorological tower with automatic air and soil temperature sensors at depths of 0, 5, and 10 cm.

In addition to observations made according to the CALM protocol (Nelson et al., 1996; Brown et al., 2000), several other geocryological and ecological surveys were conducted at the sites. Detailed descriptions of cryolithological structure and cryogenic processes were compiled for the Cape Rogozhny site (Kotov et al., 1998; Kotov, 2001). Mt. Dionisiya is one of the official sites of the International Tundra Experiment or ITEX (Molau and Molgaard, 1996; Henry, 1997; Arft et al., 1999), a program designed to examine variability in arctic and alpine plant species response to increased temperatures. The Lavrentiya site is the location of intensive and continuous year-round investigations of CO_2, water vapor fluxes, and energy balance using the eddy-covariance technique (Zamolodchikov et al., 2003).

Climate Data

Climatic factors were analyzed using long-term weather data from the Anadyr and Uelen stations. Two types of data sets were purchased from the All-Russia Research Institute of Hydrometeorological Information–World Data Center (RIHMI-WDC; www.meteo.ru). The first data set includes monthly data beginning with weather station initiation (1899 for Anadyr' and 1929 for Uelen) and extending through 1996. The second data set consists of daily data for 1994–2002. These data sets were used for descriptions of climatic trends and climate/active layer dependencies at the Cape Rogozhny and Mt. Dionisiya sites.

The third weather data set was recorded starting from July 2000 during eddy covariance measurements (Zamolodchikov et al., 2003) in the vicinity of the Lavrentiya CALM site. These data were used to analyze climate/active layer dependencies at the site. Comparative analysis of available diurnal weather data for Lavrentiya and Uelen (2000–2001) revealed a strong linear relationship ($y = 0.98x + 0.19$, $R^2 = 0.86$, $n = 309$), which made it justifable to use the Uelen daily records to supplement the Lavrentiya records for May and June of 2000.

Analytical Procedures

Analytical procedures included statistics, estimates of cryological ratios, and visual analysis of electronic maps of the grids. Basic statistical analysis (means, standard deviations, Pearson correlations) was performed using standard spreadsheet functions. Statistical hypothesis testing and regression analysis procedures were made using the STATISTICA data analysis software package (StatSoft, 2001). The significance level chosen for significance testing was 0.05. The standard error of the mean (SE) was estimated as:

$$SE = STD/n^{0.5}, \qquad (2)$$

where STD is a parameter's standard deviation, and n is the number of observations. The coefficient of variation (CV) was estimated as:

$$CV = M/STD, \qquad (3)$$

where M and STD represent the sample mean and standard deviation, respectively.

The relation between active-layer thickness and air temperature is a variant of the Stefan solution (Nelson and Outcalt, 1987; Brown et al., 2000), given by

$$Z = E\,DDT^{0.5}, \qquad (4)$$

where Z represents thaw depth, DDT is accumulated thawing degree days, and E is a site-specific "edaphic factor." In this paper, DDT was calculated in two different ways. For long-term analysis (1930–2000) this value was obtained by summing the product of the positive monthly averages over the thaw period (usually June–September) and the number of days in a given month. For examination of soil thaw within the grids, DDT was calculated by summing positive daily averages of temperature from the beginning of the thaw period through the date of thaw depth measurement. The daily data set provides an opportunity to compare both approaches for the 1994–2002 period. Monthly (DDT_m) and daily (DDT_d) based end-of-season values were in appropriate correspondence ($DDT_m = 0.879DDT_d + 91.1$, $R^2 = 0.970$, $n = 9$ for Anadyr and $DDT_m = 0.938DDT_d + 22.9$, $R^2 = 0.998$, $n = 9$ for Uelen). In other words, the monthly based approach allows adequate description of long-term interannual variability of DDT values.

Following Hinkel and Nelson (2003), a normalized index of variability (I_i) for the grid nodes is estimated by:

$$I_i = (Z_i - Z_{avg})/Z_{avg}, \tag{5}$$

where Z_{avg} is the average active layer thickness (ALT, cm) on a grid in a particular year and Z_i is the corresponding value for the ith-node. The interannual node variability (INV, %) is the absolute value of the difference between the maximum and the minimum I within the period of interest.

ALT and other parameters were mapped over the grid area using triangulation with a linear interpolation algorithm in the Surfer mapping package (Golden Software, 2002). The algorithm creates triangles by drawing lines between data points. The original points are connected in such a way that no triangle edges are intersected by other triangles. The result is a patchwork of triangular faces over the extent of the grid. The lower left corners of maps in this paper's figures correspond to the southwest corner of the CALM sampling grids.

RESULTS

Current Climatic Situation

Within the period of CALM observation at our sites (1994–2002), the annual averages of air temperature at the Anadyr' and Uelen weather stations are similar in absolute values (Fig. 2A) and interannual dynamics $R = 0.93$; $P < 0.01$). Besides the temperature increase observed in 1999–2002, the warmest period is 1995–1997. During the period of CALM observations there does not appear to have been a positive trend of mean annual air temperature.

The DDT parameter is an important climatic predictor of seasonal thawing (e.g., Nelson et al., 1997; Brown et al., 2000). For Anadyr' and Uelen (Fig. 2B), averages over the period of 1994–2002 (1003 and 483°C, respectively) differ significantly ($P < 0.01$). DDT values do not correlate significantly ($R = 0.53$, $P = 0.14$) and hence, despite the similar annual temperatures, the two locations differ in specific temperature conditions over the thawing period. Inspection of the temperature data shows that the difference is attributable to colder summers at the Uelen location.

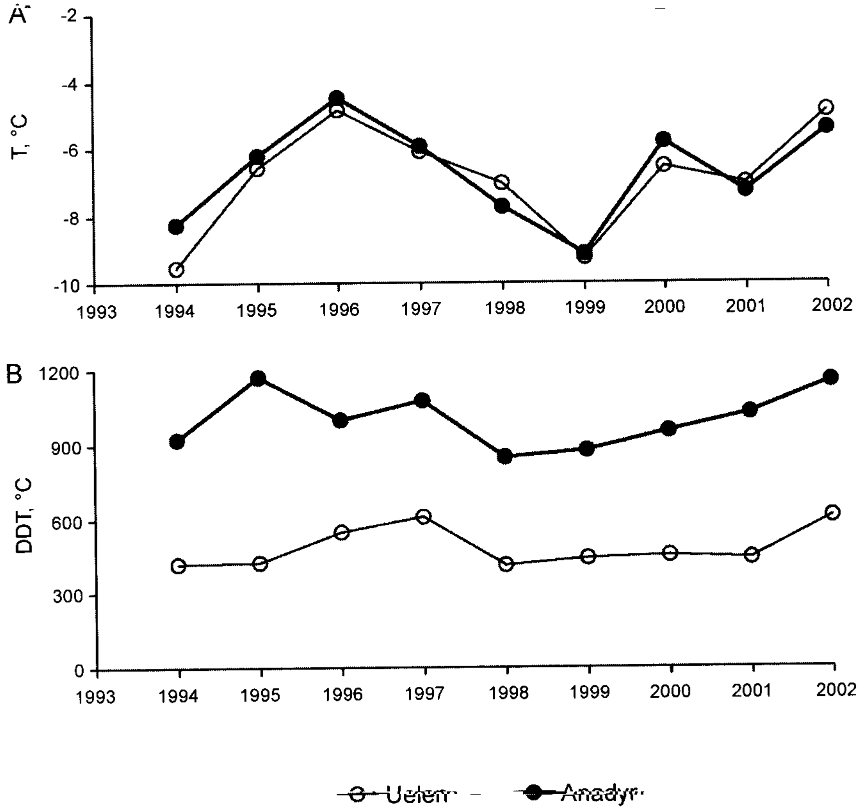

Fig. 2. Time series of (A) mean annual air temperature and (B) *DDT* at Uelen and Anadyr weather stations, 1994–2002.

This raises the question of whether climatic conditions during the period of CALM observations are typical, compared to previous decades of the 20th century. Analysis of decadal averages shows that the 1970s were the coldest in both areas, whereas the warmest were in the 1990s in Anadyr' and the 1930s in Uelen (Fig. 3A). The decade of the 1990s does not, therefore, appear to be anomalous in terms of average temperature.

A corresponding analysis of *DDT* values, however yields a different result (Fig. 3B). Both weather stations demonstrate the largest values of *DDT* in the 1990s. At Uelen, a positive decadal trend of *DDT* values is significant ($P = 0.02$), amounting to 13.5°C days per decade. At Anadyr' the increase is 11.3°C days per decade, although the trend is not statistically significant ($P = 0.11$). At the decadal scale we conclude that there has been a very modest warming trend during the thaw season.

Spatial Variability of ALT

The Cape Rogozhny grid exhibits very low spatial variability in active-layer thickness. The average annual range of ALT is 24 cm, which constitutes 56% of the average (44 cm) for the period of observations. Maps of ALT for this site show relatively great homogeneity unless an inordinately fine class-interval scheme is

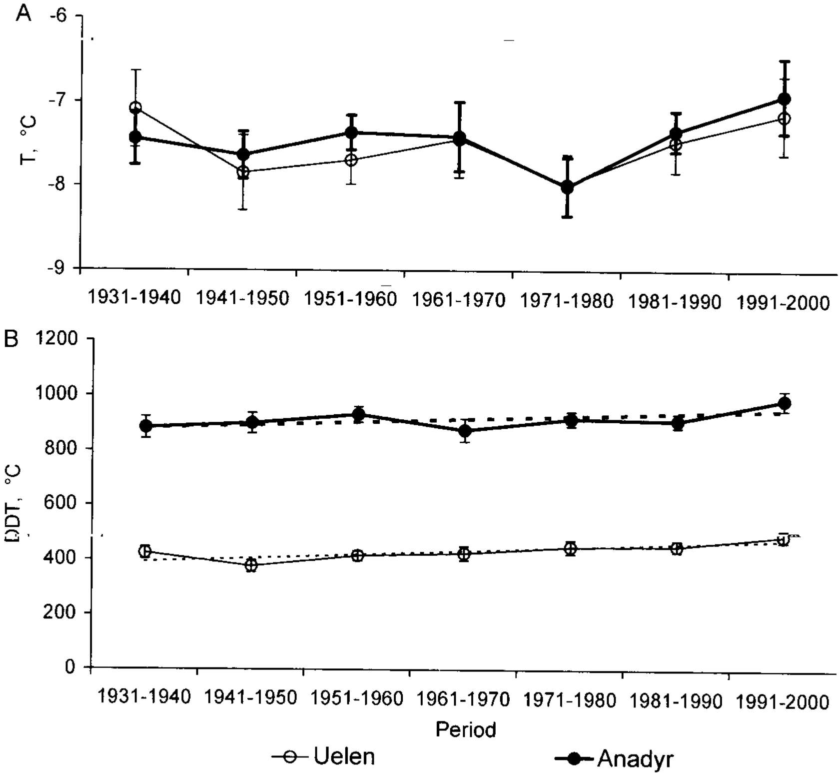

Fig. 3. Decadal averages of annual air temperatures (A) and *DDT* (B) at Uelen and Anadyr weather stations, 1931–2000. Data are means ± *SE* ($n = 10$).

selected (Fig. 4). The average annual coefficient of spatial variation (*CV*) is only 0.11. Interannual variation is, however, rather high (*INV* = 21%, 9 years of observations). Disturbances to the vegetative and soil cover are the most important factors responsible for the spatial variability observed at this site. Disturbances have both natural (frost boils) and anthropogenic (all-terrain vehicles) sources. Three nodes are affected by frost-boil activity and have an average ALT value of 50 cm. An old vehicle track persists on the grid (Fig. 4A) and is best observed on the map for 1997 (Fig. 4B). At least 24 grid nodes are influenced by the track and have an average ALT value of 45 cm. Although the vegetative cover on the track had largely recovered by the early 1990s, thaw depth remained slightly greater than in undisturbed tundra (43 cm). All differences between the average ALT values in all pairs of three landscape types are statistically significant ($P < 0.028$, *t*-test).

The Mt. Dionisiya site demonstrates relatively large spatial variability within the grid: the range of variation is 52 cm on average, or 108% of the average depth of thaw (49 cm) over seven years of observations. The spatial CV (0.21) is twice that of the Cape Rogozhny grid. The interannual variation of active-layer thickness is also considerable (*INV* = 31%).

Frost boils and patches of bare ground (average ALT = 73 cm) are characteristic of the site. An area of slowly flowing water tracks in the northwest corner of the grid

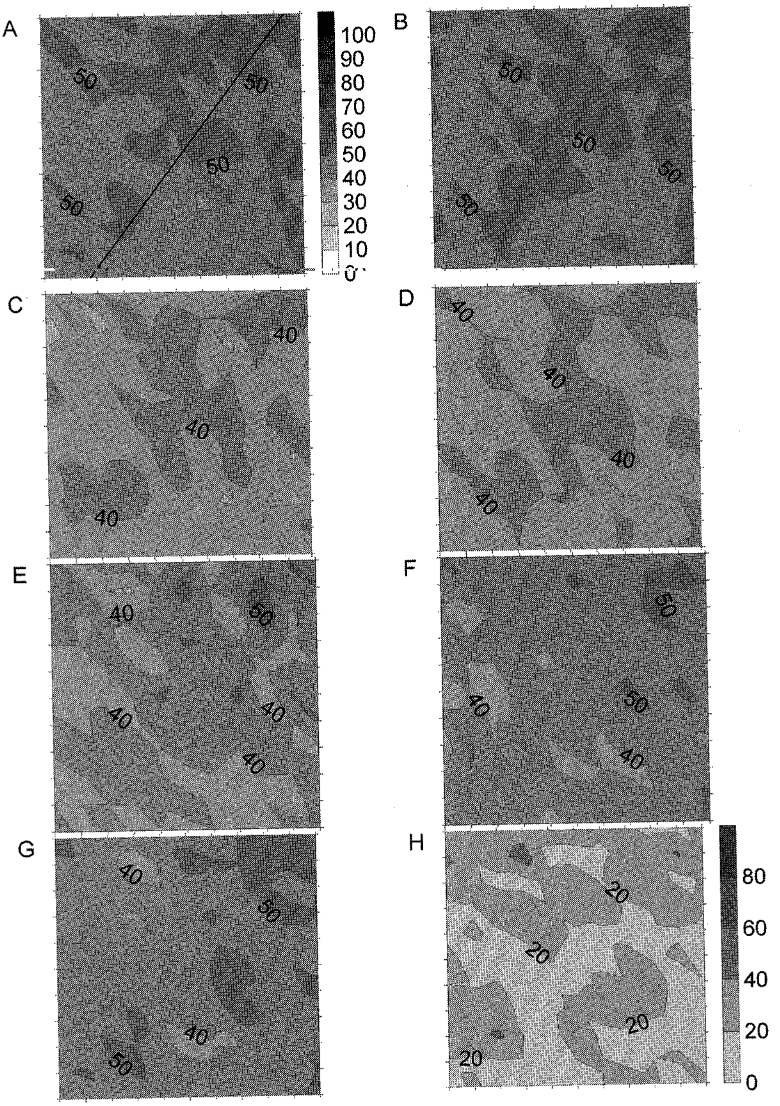

Fig. 4. Interannual node variability (INV) and thaw patterns at the Cape Rogozhny grid. Average thaw depth and INV values are given in brackets. A. September 11, 1996 (48.5 cm, S.D. 4.8 cm), line shows the all-terrain vehicle track. B. September 7, 1997 (49.7 cm, S.D. 5.1 cm). C. August 20, 1998 (37.8 cm, S.D. 5.4 cm). D. August 20, 1999 (38.0 cm, S.D. 4.8 cm). E. September 17, 2000 (41.9 cm, S.D. 5.6 cm). F. September 3, 2001 (44.1 cm, S.D. 4.7 cm). G. August 27, 2002 (46.5 cm, S.D. 5.0 cm). H. INV (21.6%, S.D. 8.3%).

(Fig. 5A) has an average active layer thickness of 61 cm ($n = 10$), while the remainder of the grid averages only 49 cm. Average ALT values between all three site landscapes are significantly different ($P < 0.035$, *t*-test).

Water tracks are associated with local depressions of mesorelief. In rainy years (1996–1999), when the accumulated precipitation sum exceeded 100 mm by the time

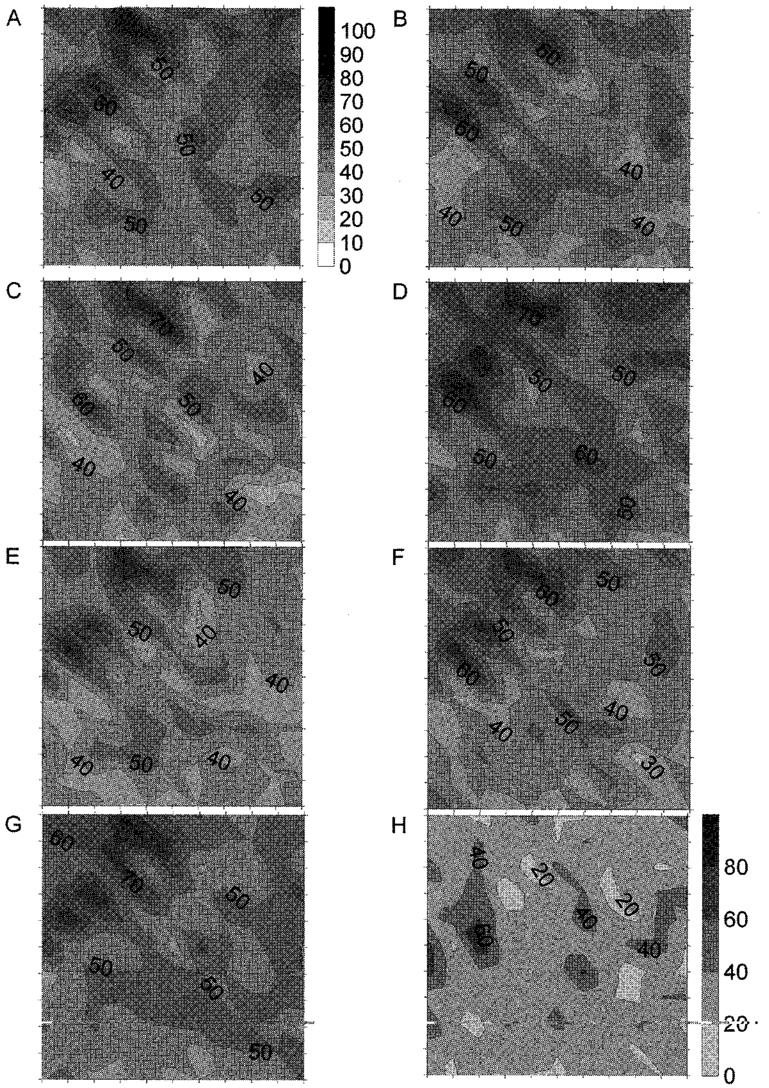

Fig. 5. Interannual-node variability (INV) and thaw patterns at the Mount Dionisiya grid. Average thaw depth and INV values are given in brackets. A. August 21, 1996 (50.3 cm, S.D. 9.9 cm), lines mark water tracks. B. August 10, 1997 (47.2 cm, S.D. 9.5 cm). C. September 27, 1998 (45.3 cm, S.D. 10.9 cm). D. October 7, 1999 (53.0 cm, S.D. 10.8 cm). E. August 9, 2000 (46.4 cm, S.D. 10.4 cm). F. August 21, 2001 (47.0 cm, S.D. 10.4 cm). G. September 15, 2002 (52.1 cm, S.D. 10.4 cm). H. INV (31.3%, S.D. 13.1%).

of ALT measurement, the coefficients of correlation between thaw depth and absolute elevation of the grid nodes vary in the range of 0.10–0.28, although these results do not always show statistical significance. In dry years (2000–2001) with low precipitation sums (less than 100 mm) there is a complete absence of correlation $R < 0.4$, $P > 0.7$).

ALT values at the Lavrentiya site are highly variable. The range of values averages 61 cm, or 102% of the average depth of thaw (60 cm) over three years of observation, necessitating a large number of isarithm intervals on the map of thaw depth (Figs. 6A, 6C, and 6E). In contrast with two other grids, however, the spatial distribution of thaw depths is similar in different years ($INV = 9\%$).

Data on the spatial distribution of volumetric moisture in the topmost soil layer were collected on the Lavrentiya grid (Figs. 6B, 6D, and 6F). Similar measurements were made by Miller et al. (1998) in northern Alaska. Within the grid, soil moisture varies over the range of 36–86%, and averages 68%. The spatial distribution and absolute values of soil moisture are similar in different years ($INV = 10\%$).

Data were also collected on the thickness of moss cover, thickness of the organic horizon (Fig 7B), and the absolute elevation of the grid nodes (Fig 7A). These data provide a source of information for statistical analysis of the various controls over ALT. Using a stepwise regression procedure, we determined that soil moisture (*SM*, %) and the thickness of the organic layer (*OD*, cm) are statistically significant ($P < 0.01$) predictors of ALT (*Z*, cm):

$$Z = 48.9 + 0.34 \cdot SM - 0.71 \cdot OD \cdot$$

$$R^2 = 0.336, SE = 9.7, n = 121. \tag{6}$$

Because this equation explains only 34% of the variation in active-layer thickness, it is clear that other controls are operating. The positive sign of the *SM* coefficient is a result of the relatively high thermal conductivity of wetter soils (Hinkel et al., 2001), as well as the convective effect of subsurface water movement. The negative sign of the *OD* coefficient is, of course, a consequence of the well-known insulating properties of the organic layer.

Seasonal Changes in the Active Layer

Seasonal changes of active-layer thickness and soil moisture were monitored at the Lavrentiya site two to four times per thaw season. Thaw occurs rapidly in the early part of the season (approx. 0.7 cm per day), and slows substantially by late summer (0.2 cm per day) after 230 Julian day, or mid-August (Fig. 8A). Figure 8B demonstrates that by the end of the season soil moisture in the uppermost layer provides a poor representation of average seasonal soil moisture conditions. This result is similar to that obtained by Miller et al. (1998) and indicates that soil moisture should be monitored over the course of the thaw season. Soil moisture values at the end of all three thawing seasons were similar (about 68%). In summer 2001 volumetric soil moisture averaged at 64%, and in summer 2002 at 53%.

Temperature is clearly the main control over seasonal changes of thaw depth. The correlation between seasonal thaw values and $DDT^{0.5}$ is very strong (Fig. 9), with a direct proportional relationship, well approximated by equation (4). According to seasonal data, the "edaphic" coefficient E for local landscapes has a value of 2.31.

The spatial distribution of thaw depth on the Lavrentiya grid is much more variable during the course of a single season ($INV = 34\%$, $n = 9$) than is the end-of-season distribution in different years ($INV = 10\%$, $n = 3$). Stated alternatively, the rates and patterns of seasonal thaw are dissimilar in different parts of the sample plot. Shiklomanov and Nelson (2002) and Hinkel and Nelson (2003) found that spatial

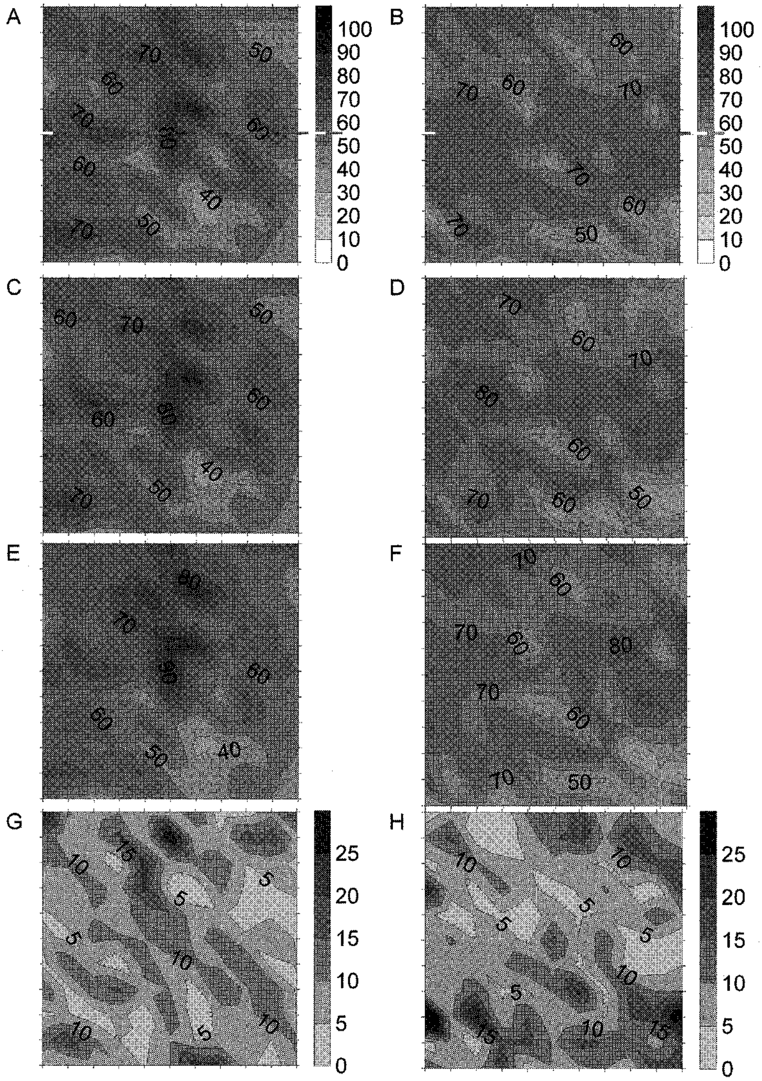

Fig. 6. Interannual node variability (INV), soil moisture and thaw patterns at the Lavrentiya grid. Averages and INV values are given in brackets. A. Thaw depth, September 29, 2000 (58.7 cm, S.D. 12.2 cm). B. Soil moisture, September 29, 2000 (67.9%, S.D. 10.3%). C. Thaw depth, September 25, 2001 (60.0 cm, S.D. 11.8 cm). D. Soil moisture, September 25, 2001 (67.1%, S.D. 10.5%). E. Thaw depth, September 29, 2002 (61.5 cm, S.D. 12.3 cm). F. Soil moisture, September 29, 2002 (67.7%, S.D. 10.9%). G. Thaw depth INV (8.9% cm, S.D. 5.7%). H. Soil moisture INV (9.6%, S.D. 6.8%).

patterns of thaw depth are reproduced from year to year, even if the magnitude of thaw depth differs substantially between years. A question therefore arises about the nature of seasonal patterns of particular controls over the spatial distribution of thaw depth within the grid. Figure 10 shows intra-seasonal correlations between thaw depth and soil moisture, most cover thickness, and the thickness of the soil organic

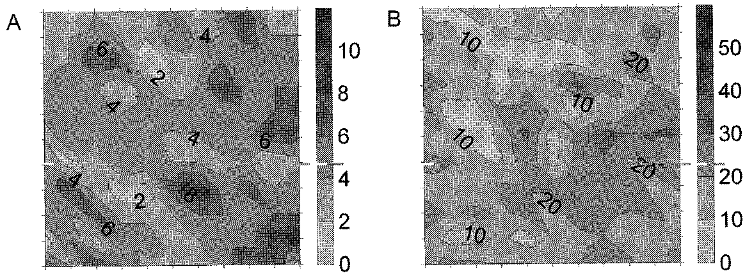

Fig. 7. Thickness of moss cover (A, 4.6 cm, S.D. 2.0 cm) and thickness of organic soil horizon (B, 17.0 cm, S.D. 8.3 cm) at Lavrentiya grid.

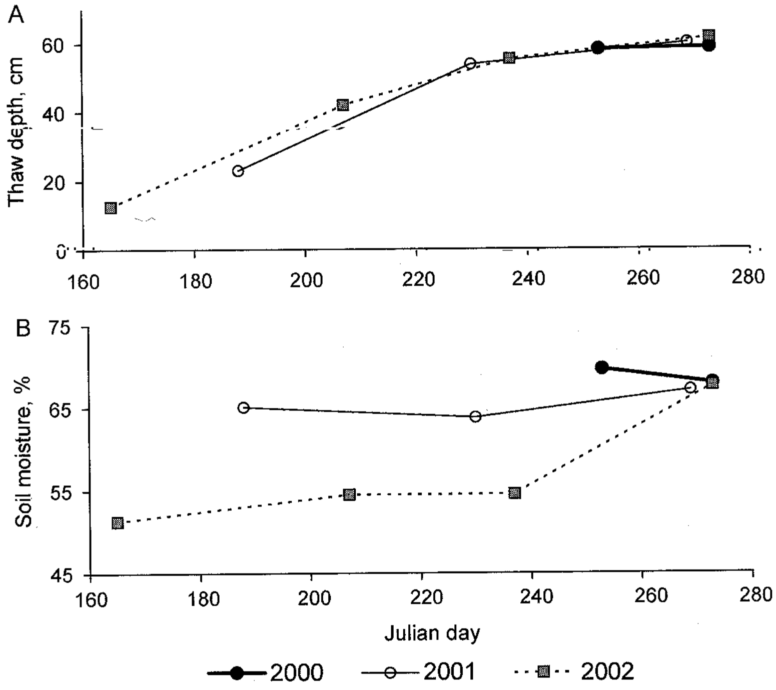

Fig. 8. Seasonal dynamics of (A) thaw depth and (B) volumetric soil moisture at the Lavrentiya grid.

layer. The significance of soil moisture and moss cover decreases over the course of a season. The influence of the organic horizon is minimal at the beginning and end of the thawing season, and maximized in the middle.

We used data obtained on different dates within a single thaw season in a stepwise regression, with thaw depth as the dependent variable and soil moisture, absolute elevation, moss-cover thickness, and organic-layer thickness as independent variables. For all intra-seasonal measurements in 2001 and for the grid measurement on June 13, 2002, these procedures yielded regression results similar to the end-of-season

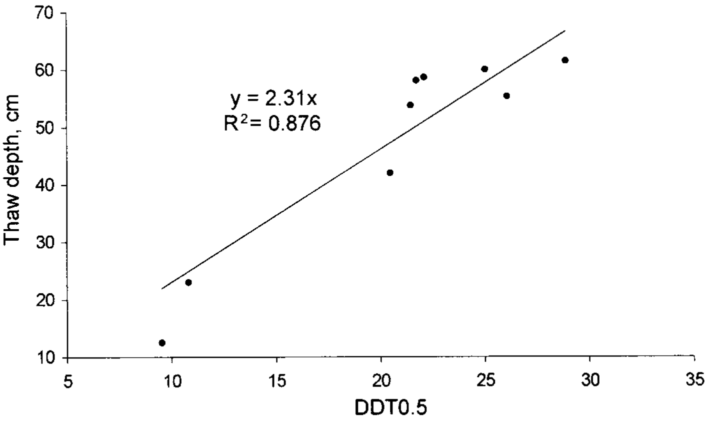

Fig. 9. Seasonal values of thaw depth vs. squared root of accumulated DDT_{air} at the Lavrentiya grid.

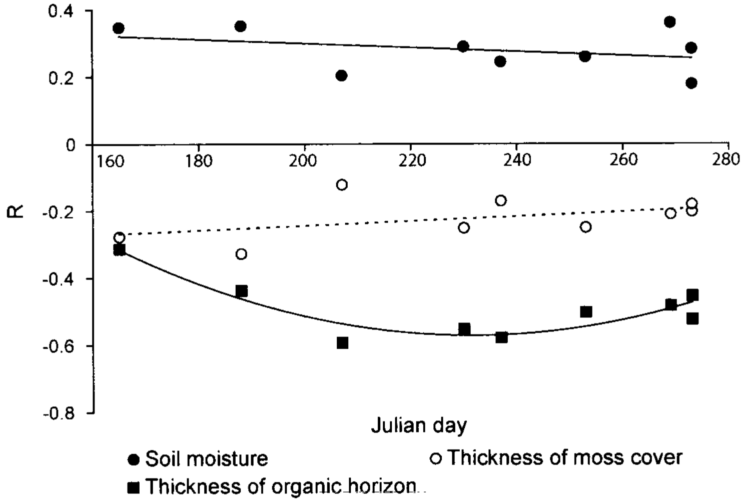

Fig. 10. Seasonal changes of correlation (R) between thaw depth and other factors (soil moisture at date of measurement, thickness of moss cover, and thickness of organic soil horizon). R coefficients with absolute value of 0.17 are statistically significant ($P = 0.05$).

average data analysis (Eq. 6). Soil moisture and the thickness of the organic horizon were found to be significant, with R^2 values in the range of 0.20–0.38. The three remaining grid measurements in 2002 revealed only organic layer thickness to be a significant control over thaw depth, with values of R^2 in the range 0.27–0.35.

Interannual Variability of End-of-Season Thaw Depth

End-of-season thaw depth at the Cape Rogozhny sample grid averaged 44 cm, with interannual variation in the range of 38 to 50 cm for the seven-year observation

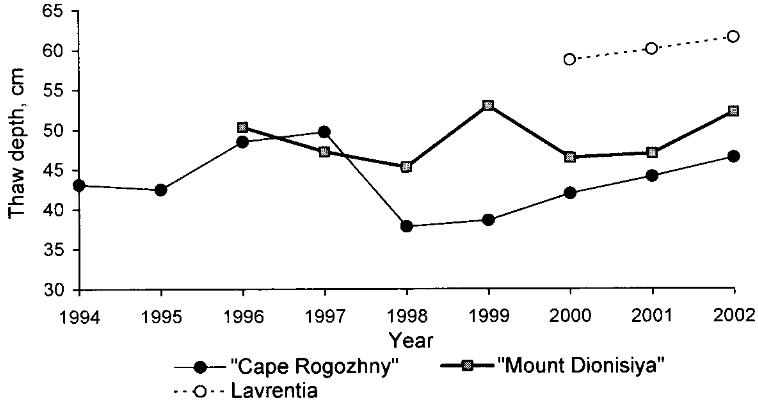

Fig. 11. Interannual dynamics of end-of-season thaw depth on CALM grids in Northeast Russia.

period (Fig. 11). Maximum seasonal thawing at the site was registered in 1996 and 1997 (48 and 50 cm, respectively). Active-layer thickness at the Mt. Dionisiya site ranged between 45 and 53 cm (49 cm average) for the five-year measurement period.

Unfortunately, not all data obtained at this site provide reliable end-of-season thawing estimates. In 1997 and 2000, observations were conducted during the period when thaw was still progressing, on 10 August and 9 August, respectively. In 1999, however, measurements were completed on 7 October, 22 days later than usual, and it is possible that some freezeback from the bottom of the active layer had occurred by this date (Mackay, 1977). The northernmost of our CALM sites (Lavrentiya) experiences the largest end-of-season thaw depth (60 cm), but also has large (59–61 cm) interannual variations.

All three Chukotka sample grids demonstrate moderate to strong linear relations between ALT and DDT^{05} (Fig. 12). At the Cape Rogozhny site $R^2 = 0.573$, 0.430 at Mt. Dionisiya, and 0.998 at the Lavrentiya site. These relations are close to direct proportion with zero intercept, following from Equation (3), only at the Cape Rogozhny grid. At the Mt. Dionisiya and Lavrentiya grids, linear trends with intercept inclusion are rather far from direct proportion. These results become more evident by comparison of two types of linear approximation for entire grids and landscape elements (Table 1). R^2 values in the case of approximation with zero intercept are close to zero for the Mt. Dionisya and Lavrentiya grids. The main landscape elements of the Mt. Dionisiya grid also have a poor level of the approximation, and only water tracks demonstrate non-zero R^2.

Estimates for site-specific edaphic factors (E) for the three sample grids are 1.44 at Cape Rogozhny, 1.66 at Mt. Dionisiya, and 2.35 at Lavrentiya. Landscape specific values of E vary substantially (from 1.59 in intact tundra to 2.50 in frost boils) at Mt. Dionisia grid, but to a relatively low extent (from 1.42 in intact tundra to 1.65 in frost boils) at the others.

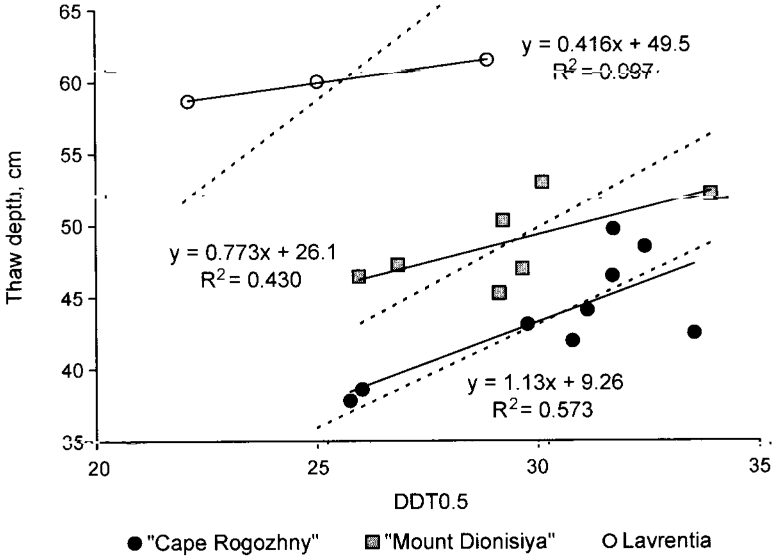

Fig. 12. End-of-season thaw depth vs. squared root of DDT_{air} in CALM grids in northeast Russia. Solid line marks linear trends including intercept; dashed line indicates trends with zero intercept.

TABLE 1

Approximation of Relations of End-of-Season Active Layer thickness (*ALT*, cm) and Square Root of Accumulated *DDT* (°C) Using Two Types of Linear Equations

Site	Landscape element	$ALT = E\ DDT^{0.5}$		$ALT = a\ DDT^{0.5} + b$		
		E	R^2	a	b	R^2
Cape Rogozhny (n = 9 years)	Whole grid	1.437	0.532	1.133	9.26	0.573
	Intact tundra	1.418	0.568	1.158	7.94	0.599
	Old vehicle tracks	1.485	0.376	1.046	13.41	0.457
	Frost boils	1.652	0.374	1.081	17.41	0.519
Mt. Dionisia (n = 7 years)	Whole grid	1.660	0.000	0.773	26.13	0.430
	Intact tundra	1.599	0.000	0.697	26.57	0.375
	Water tracks	2.072	0.424	1.607	13.69	0.463
	Frost boils	2.500	0.000	0.738	51.87	0.317
Lavrentiya (n = 3 years)	Whole grid	2.347	0.000	0.416	49.52	0.997

DISCUSSION

Interannual variations in the spatial distribution of thaw depth are probably due to microrelief features within the plots. The Cape Rogozhny and Mt. Dionisiya sites both have tussock (vegetation hummock) microrelief. This microrelief provides an additional source of thaw depth variation if measurement points are not exactly coincident from year to year. The high-frequency spatial variation of ALT associated with tundra tussocks precludes mapping of even small areas (Nelson et al., 1998a, 1998b, 1999) and results in significant interannual variation (Hinkel and Nelson, 2003). At the Lavrentiya site, the microrelief is not so well developed, and all node measurements have four replications, resulting in little interannual variation in the pattern of mapped ALT fields. The high interannual spatial variability of thaw depth at the Cape Rogozhny and Mt. Dionisiya sites should, therefore, be interpreted with caution.

Intra-seasonal changes in the controls over the spatial variability of thaw depth were determined for the Lavrentiya site. The influence of moss cover and soil moisture is greater at the beginning of seasonal thaw, and declines as the season progresses. The thinner the organic soil horizon at a particular location, the greater the thawing rate. This is the main source of within-season variation in thawing dynamics over the plot, and the source of high values of INV based on intra-seasonal data. Rates of thawing become less heterogeneous after the organic layer thaws.

Temperature is the most important determinant of interannual ALT variability. End-of-season thaw depth correlates strongly with $DDT^{0.5}$ at all the grids studied. Nevertheless, only at the Cape Rogozhny site is this relationship close to being a direct 1:1 relation, following from equation (3). At the Mt. Dionisiya and Lavrentiya grids an appropriate level of linear approximation is achieved only by inclusion of the positive intercept (26 and 50 cm correspondingly). This means that the active layer exhibits some compensation for summers with extremely large or small degree-day accumulations at the Mt. Dionisiya and Lavrentiya sites. Micrometeorological measurements at the Lavrentiya site (Zamolodchikov et al., 2003) help to elucidate this behavior.

The energy balance at the boundary between the atmosphere and soil surface is described by the following equation (Baldoucchi et al., 1988):

$$Rn = H + Le + G, \tag{7}$$

where Rn is net radiation, H is sensible heat flux, Le is latent heat flux, and G is ground heat flux. According to our unpublished data, Rn in the second half of the warm season was 1.5 times higher in 2002 than in 2000, and 1.2 times higher than in 2001. The corresponding ratios were 2.0, 1.3 for H, and 1.1, 1.0 for Le. This increase of net radiation resulted in a considerable increase in the sensible heat flux, but was not followed by a corresponding increase in the latent heat flux. This phenomenon is due to depletion of water in the topmost soil layer, as evidenced by a minimum in volumetric soil moisture during the 2002 season. Low soil moisture results in a decrease of the soil's thermal conductivity (Hinkel et al., 2001), which is apparent in our data through a low G flux rate in 2002 (0.9 of corresponding values in 2000 and 2001). G is ultimately the determinant of soil thawing, explaining why the smallest increase in ALT occurred during the warmest of the 2002 thaw season, in distinct contrast to 2000 and 2001. This situation also accounts for thaw depths becoming similar at the end of different thawing seasons (Fig. 8A).

The CALM grids in northeast Russia differ in the value of the "edaphic factor" E. It is at a maximum at the Lavrentiya site (2.35), and substantially smaller at Cape

Rogozhny (1.47) and Mt. Dionisiya (1.66). Thus, the northmost site (Lavrentiya) demonstrates the greatest thaw depths under the smallest $DDT^{0.5}$ values.

CONCLUSIONS

Spatial patterns of thaw depth differ at the various CALM sample grids in Northeast Russia. At Cape Rogozhny, the small range of spatial variability within the grid combines with large interannual variation. At Mt. Dionisiya, both types of variation are pronounced. At the Lavrentiya site, spatial variability within the grid is high but interannual variation is low. These differences are the result of site-specific factors (drainage lines, surface disturbance, soil moisture, and organic soil horizon thickness) controlling the spatial variability, and of local microrelief.

At Cape Rogozhny, the main source of spatial variation in thaw depth is disturbance of the surface cover. The disturbance is poorly expressed, and thaw depth over the plot varies only slightly. At Mt. Dionisiya, the main source of the relatively large spatial variation in ALT is related to the positions of water tracks. At the Lavrentiya site, the main factors responsible for spatial variation are soil moisture and organic-layer thickness, which are themselves highly variable within the plot. Other influences may not yet have been determined.

The Cape Rogozhny and Mt. Dionisiya sites both have sufficient record length (9 and 7 years, respectively) to determine whether a short-term trend of active-layer thickness is developing. Close examination of these series does not reveal any significant trend. This conclusion is consistent with the lack of pronounced climatic trends during this period. Analysis of air temperature over a longer period did, however, reveal evidence of a warming tendency in the summer period.

The CALM program uses relatively simple techniques to monitor the active layer, can be applied by different specialists in the polar regions, and will eventually provide a set of standardized, long-term data on the spatial and temporal variability of the active layer. We hope that the results reported here will prove useful for investigators modeling active layer behavior at local, regional, and circumpolar scales.

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