INTRODUCTION

The measurement data on the interannual variability in seasonal thaw depth began to accumulate from the onset of the geocryological science development. The early works addressing this problem have been reviewed by E.A. Vtyurina [1976]. The launch of the International Circumpolar scientific program on the active layer monitoring (Circumpolar Active Layer Monitoring program, CALM) gave a new impetus to the study of seasonal freeze-thaw depth (active layer, AL). However, the CALM sites are distributed very unevenly with most of them concentrated on the plains in the Arctic and subarctic zones, whereas inland plains, plateau, highland and mountains within the permafrost zone have been given a considerably lesser coverage to.

Despite the large amounts of field data available to date, there is no universally accepted views on the identification of key meteorological factors determining multi-year dynamics of the seasonally thawed layer thickness (ALT). Many researchers consider the thawing index to be this kind of driving factors for the Arctic and subarctic zones [Matveeva, 1976; Nixon and Taylor, 1998; Brown et al., 2000; Nixon, 2000; Hinkel et al., 2001; Leibman, 2001; Moskalenko et al., 2001; Nixon et al., 2003; Fedorov-Davydov et al., 2004; Tarnocai et al., 2004; Melnikov et al., 2005; Mazhitova and Kaverin, 2007; Nelson et al., 2008; Shiklomanov et al., 2008, 2012; Streletskiy et al., 2008].

Relying on the long-term monitoring the area along the Mackenzie river valley (Canada) with 1200 km long N–S transect the researchers have inferred that the influence of atmospheric temperatures on the thaw depth declines in the NS direction – from the Arctic to boreal zone [Nixon and Taylor, 1998; Nixon, 2000; Nixon et al., 2003; Tarnocai et al., 2004].

Thermal resources accumulated during the summer season do not have any significant impact on the ALT fluctuations in mountainous areas of the permafrost zone, which is substantiated by some research [Bla-gooobrazov, 1964; Harris, 2001]. Quite a number of authors have provided their research findings attesting to the winter weather conditions becoming essential for the thaw depth, since they stipulate the amount of heat accumulated in the soil layer by the beginning of the warm season [Bla-gooobrazov, 1964; Maksimova and Minaillow, 1971; Konstantinov et al., 2006, 2008; Viereck et al., 2008], which typifies mainly the inland areas of the permafrost zone. However, some papers consider the influence of the winter factors to be essential for soil thawing processes only with some specific types of the Arctic and subarctic landscapes [Bogatyrev, 1974; Fedorov-Davydov et al., 2004; Akerman and Johansson, 2008].

Almost all researchers acknowledge the impact of rain precipitations on soil thawing processes, which is analyzed in two aspects, both directly – through the heat carried to the soil by infiltration flow, and indirectly – through seasonal variations in ice content in the active layer, depending on the rain precipitations amount at the end of preceding warm season. Yet, there is still a paucity of research on these processes in natural conditions [Maksimova and Minaillow, 1974; Sryjabin et al., 1998; Leibman, 2001].

Some authors suggest that optimal conditions for seasonal thawing in the areas with different landscapes can be caused by various combinations of climatic factors, with multi-year highs resulting from the specific in each case constituent elements of climate [Maksimova and Minaillow, 1971]. Finally, there is a consensus of opinion among the researchers that the main difficulty establishing key meteorological factors affecting the interannual variability of thaw depth, stems mainly from the strong influence of zonal and regional differences and landscape specificity [Pavlov et al., 2004; Pavlov, 2008].
Interannual variability in thaw depth in Central Yakutia was first described in research work performed by M.K. Gavrilova [1966], thus proving it to be inconspicuous in the region. The same conclusion was made by A.V. Pavlov, a lead researcher on the thermal balance of permafrost landscapes carried out in the area back in the 1970s [Pavlov, 1975, 1980].

For the first time, this principle was embodied by A.I. Danilin in cryopedometer back in the 50-ies of the last century. Later on, others attempted to develop other designs of tube gauges [Richard and Brown, 1972; Mackay, 1973], which became widely applicable in geocryological investigations in Canada and Alaska Currently, CALM program has assigned the frost/thaw tubes, as one of the basic techniques, along with mechanical and geothermal surveying methods [Nelson et al., 2008; Shiklomanov et al., 2008, 2012].

Advantages and disadvantages of frost/thaw tubes have been well described in the geocryological literature [Leibman, 1998, 2001; Nixon and Taylor, 1998; Nixon, 2000; Nelson and Hinkel, 2003; Nixon et al., 2003; Turnocai et al., 2004; Konstantinov et al., 2006, 2008, 2012a,b; Konstantinov, 2009; Smith and Brown, 2009]. Using them would be most relevant in case of a wide distribution soils, with low moisture content, soils subjected to deep thawing, and highly saline soils. To complement the advantage of frost/thaw tubes, the principle of one place of the measuring point is strictly observed, which is especially important for a continuous monitoring. The use of water as the working fluid does not require prior calibration and provides virtually unlimited long-term stability.

Moreover, in the event of some discrepancy between the zero-degree isotherm position, defined with the tube and actual phase boundary (or upper limit of plastic frozen soil for clays) in the ground, due to the difference in freezing points for soil and water, this will not affect the reliability of resulting statistical parameters of time series observations, since the error is of systematic nature in this case. Given that at the beginning of each summer season, the entire column of water in the tube is in frozen condition, a possible expulsion of the measuring tube by frost heaving (up to a certain limit) is not supposed to affect the accuracy of measurements either.

Therefore, even if the levelling of the frost/thaw tube changes, the water inside it melts relative to the surface ground during warm season thawing, as much as the process is controlled by the heat amount accumulated at the end of winter season in the soil horizon and heat flow contributions in the summer. It’s only when the lower end of the measuring tube reaches the AL base level that the frost/thaw tube fails to measure thaw depth properly. Foreign researchers estimated the accuracy to be about ±2 cm in determina-
tions of thaw depths with frost/thaw tubes [Nixon and Taylor, 1998].

This is comparable to the accuracy of its determination by probing and appears much better than when measured with temperature sensors. The description of the frost/thaw tube design employed in our studies is described in detail by [Konstantinov et al., 2006, 2008, 2012a,b; Konstantinov, 2009]. Early in summer 2008, two sites were adequately furnished with a dense network of measuring tubes in the vicinity of Yakutsk. Since 2012, they have been included in the database program CALM and numbered R42 and R43.

RESULTS AND DISCUSSIONS

CALM R42 site. The site is located in the ridge-top of bar elevation on the Lena Rv. terrace II (Fig. 1, a). In plan, it represents a rectangle with sides of 50 and 30 m. The tubes are spaced every 5 m on seven lines, totaling 77 pieces within the site area (Fig. 2, a).

CALM R43 site. The site is located 35 km north west of Yakutsk in the interfluve area of the Lena and Kenkeme rivers (Fig. 1, b). The tubes are spaced every 10 m on six lines, totaling 36 pieces within the site area (Fig. 2, b).

Fig. 1. General view of R42 (a) R43 (b) sites.

Fig. 2. Location plan of frost/thaw tubes on CALM R42 (a) and R43 (b) sites.
Other experimental sites are comprised of 11 sites equipped with single frost/thaw tubes. On their basis, the observations have been carried out since 1998.

A brief description of all the experimental sites is provided in Table 1.

The winter season plays a decisive role in the formation of both thermal conditions in soils and the upper limit of permafrost, or perennially frozen rocks. To avoid the winter season falling into different observation years, in our research we chose to use not a calendar year, but one-year long period, as proposed by A.V. Pavlov [1965], beginning from October, 1, which has proven to correspond to an average date of the onset of stable freezing of soils in the vicinity of Yakutsk. Accordingly, average values for annual meteorological elements have been calculated for this period. For instance, in our study the designated observation year 2007/08 means the year from October, 1 2007 through September, 30 2008.

Fig. 3 shows diagrams of the main meteorological parameters, soil temperature and maximum thaw depths over the 16-year long period of observations. The data sourced from Yakutsk weather station, CALM sites and sites with single frost/thaw tubes. Averaged values of parameters from three sites in the denudation plain and eight sites in denudation-aggradation plain were used for the latter. The values averaged over each site were used for plotting thaw depth diagrams for all the CALM sites.

The studies were carried out in the setting of the warming surface atmosphere in the Central Yakutia at the turn of the 20th century. During the observation period the mean annual air temperature varied from –7.0...–9.8 ºC, which is on average 2.0–2.5 ºC higher than in the 70–80-ies of the last century. Fig. 3 shows that the correlation between the amount of summer air temperatures and maximum thaw depths at the experimental sites is weak. Only the 2003/04 minimum summer temperatures accounted for the lowest thaw depths.

In 2006/07 and 2012/13, when the summer temperature sums were close to average values over the observation period, the ALT markedly increased. According to the data from two CALM sites, the thaw line showed no response to the greatest values of the summer temperature sums in 2011/12. Some elucidations on the minor role of thawing index in the ALT interannual variability in the boreal zone can be found in the published literature.

M.K. Gavrilova [1981] concluded in her years-long research on the thermal balance in permafrost landscapes of central and south Yakutia, that the excess heat input to the Earth’s surface in the years with warmest summer seasons goes mainly to intensify the evaporation and turbulent heat transfer, while only its very small portion is allocated on the heat progression into the soil. The permafrost zone landscapes extending south of the tundra zone exhibiting insulating properties due to their vegetation and soil cover, are believed by many foreign researchers to greatly weaken the potential of thermal resources of the summer season to affect the ALT fluctuations [Nixon and Taylor, 1998; Nixon, 2000; Nixon et al., 2003; Tarnocai et al., 2004].

The analysis of the thaw depth dynamics throughout the entire review period, allowed to clearly identify its valley values in 2000/01 and 2003/04, and peaks in 2006/07 and 2012/13. The minimum thaw depths account for the years with little snow in

<table>
<thead>
<tr>
<th>Experimental site</th>
<th>Above mean sea level, m</th>
<th>Topography of site</th>
<th>Age and composition of the upper layer of sediments</th>
<th>Soils of active layer</th>
<th>Vegetation cover</th>
<th>Temperature of rocks*, ºC</th>
<th>Seasonal thaw depth, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>R42-site</td>
<td>101–102</td>
<td>Above-flood terrace II of the Lena Rv.</td>
<td>Quaternary sand loam, sands</td>
<td>Silty sand loam (dry unit weight 1000–1400 kg/m³; sand fractions 3–12 %, silty fr. – 79–92 %, clayey fr. – 5–9 %)</td>
<td>Mixed herbs-gra- mineous meadow</td>
<td>–1.5...–2.0</td>
<td>1.9–2.1</td>
</tr>
<tr>
<td>R43-site, sites with single frost/thaw tubes</td>
<td>210–220</td>
<td>Denudation-aggradation plain</td>
<td>Quaternary silty loam</td>
<td>Silty loam (dry unit weight 960–1700 kg/m³; sand fractions 19–47 %, silty fr. – 41–66 %, clayey fr. – 7–20 %)</td>
<td>Larch forests/vaccinium type</td>
<td>–2.5...–3.5</td>
<td>1.2–1.4</td>
</tr>
<tr>
<td>Sites with single frost/thaw tubes</td>
<td>220–230</td>
<td>Denudation plain</td>
<td>Neogene sand loam, sands</td>
<td>Fine-grained sand (dry unit weight 1100–1800 kg/m³; sand fractions 75–85 %, silty fr. – 8–11 %, clayey fr. – 6–15 %), sand loam (dry unit weight 1200–1750 kg/m³; sand fractions 61–67 %, silty fr. – 25–29 %, clayey fr. – 6–10 %)</td>
<td>Pine forests, pine-larch forests</td>
<td>–2.0...–3.5</td>
<td>1.9–2.2</td>
</tr>
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* Temperature of rocks at the depth of zero annual amplitudes.
winters and for the lowest mean annual ground temperatures. Some research results obtained earlier in the study area indicated a strong influence of the previous winter season on the thaw depth, mainly due to the interannual differences in the cooling degree of the soil layer [Konstantinov et al., 2006, 2008].

The first peak of thaw depth falls for the year with a maximum average annual soil temperature. August of 2005/06 was a record rainy month (monthly rainfall totaled 151 mm) in Yakutsk in the history of precipitation data of the Yakutsk meteorological station since 1891, with almost all the monthly amount of rain fallen in 4 days of the third decade of August. This brought about a partial flooding of the meadows, forested foothills of gentle slopes and upland areas of the interfluve tundra within the denudation and denudation-aggradational plains. Since the beginning of winter 2006/07, the soil layer wetted to an excess had been covered with fairly thick snow cover, which stipulated the abnormal duration of the AL freezing processes.

For example, the full freezing in some areas in the larch forests ended only in late March and early April, when the radiation balance of the earth's surface was a positive value. Due to a very weak cooling throughout the winter and early summer 2006/07, favorable conditions for deeper thawing thus were created in soil layers. Interestingly, the increased seasonal ice content in the active layer during the overwetted soils freezing in winter 2006/07 did not play any paramount role in restraining the deep progression of thawing. The data on extremely deep soil thawing in summer 2006/07 were obtained at the experimental sites with single tubes, so whether they were of microlocal nature may be justifiably questioned.

But there is another evidence of the deep thawing of soils in summer 2006/07, which consists in thermokarst subsidence of the surface in forests with undisturbed vegetation within denudation-accumulative plains with ice complex, that very summer. For example, in the area of native larch forest, the placement of CALM R43 site, a thermokarst subsidence occurred to a depth of 10–15 cm. The subsidence encompassed a 15–25 m wide forest strip on the border with the alas meadow, which was the most extensive flooded in late summer 2005/06.

Since the research commenced in this area, the thermokarst subsidence in the undisturbed forest landscapes has been documented only in summer of 2006/07. It stands to reason to assume that during this summer season the depth of soil thawing reached its maximum over 16 years of observations, at least within the bounds of the denudation-aggradational plains with ice complex. This occurred owing to a favorable coincidence of two meteorological factors preceding the onset of the warm season, namely, the surface flooding due to record high rainfall amount in late summer 2005/06, succeeded by snow-rich winter, which led ultimately to the abnormal conditions of the heat content of soils after winter season.

The second thawing maximum accounts for year 2012/13. An increase in the thaw depth was recorded in all 36 tubes at CALM R43 site. On average, it increased by 5 % on the site, as compared to previous years (Fig. 3). Since the thaw front advancement took place in the sixth year from the start of the observations, any possible man-made effects, like construction of site facilities in early summer 2007/08 (drilling and/or installation of measuring tubes) are excluded. The ALT increase was also recorded in 2012/13 in soils of different texture (sands, silty clay loam and sand loam) at all sites with single tubes within the limits of the denudation and denudation-aggradational plains (Fig. 3).

However, at CALM R42 site, located on the above flood-plain terrace II of the Lena River, no dynamics in the thaw depth has been documented, as compared to the previous years (Fig. 3). In summer 2012/13, apart from average amount of rainfall, all other meteorological elements were close to their long-term norm. Over the 16 years of observations three maxima in the summer rainfall precipitations accounted for the 2002/03, 2005/06 and 2012/13 summer seasons, with the thaw line advancement documented only in the latter. These differences may have been conditioned by the precipitation patterns in those years. So, a small amount of rainfall precipitated in May and June of 2002/03 and 2005/06, with their peak falling for July and August.

Only in summer 2012/13 large amount of precipitation fell evenly in the first three months of the season thaw – from May through July (Fig. 4). A un-
form pattern of rainfall events in summer is not typical for the climate of Central Yakutia. Relying on the Yakutsk weather station historical data over the last 100 years, in summer months 80% of rainfall precipitations is characterized by an uneven distribution with their bulk amount precipitating in the second half of the summer. Thus, a pronounced effect of rainfall on soil thawing is not considered common in this region, taking into account, in addition, that summers with heavy rainfalls are quite rare here.

The fact that soils at R42 and R43 sites reacted differently on rainfall precipitations in summer 2012/13 presents an interesting research result. The soils of both CALM sites are represented by silty sediments, however, with the ALT differing significantly (as in Table 1). The ALT measurements carried out in late summer showed that in the silty soils of the area the thaw depths were influenced by rainfalls in the areas with low active layer thickness (site R43), whereas no impact was documented in the areas with high ALT (site R42).

The analysis of data obtained at all the CALM sites shows very little interannual variability of the maximum thaw depths, which agrees well with a similar inference made in [Gavrilova, 1966; Pavlov, 1975]. The variability of average values for each site over 6 years of observations did not exceed 3% at R42 site, and 6% at R43 site.

CONCLUSIONS

1. The study area is characterized by a very small interannual variability of maximum thaw depth. Over 6 years of observations at CALM sites the variations in maximum thawing depth did not exceed, on average, 3–6% for each site.

2. The relationship between the summer air temperatures sum (thawing index) and the thaw depth has proven weak. However, the relation with latest interannual variability of mean annual soil temperatures, which is controlled mainly by the weather conditions of the winter period, tends to be more pronounced.

3. Given the abnormally high amount of heat accumulated in soil at the end of winter season during the period of observations on the denudation-aggradational plain, the thermokarst subsidence of the surface in the forests with undisturbed vegetation shortly followed the AL thawing peaks.

4. The thaw depths increased by 5% in soils with different texture (silty sand loam and silty clay loam) within the denudation and denudation-aggradational plains due to the impact of summer rainfalls. This took place in the summer season with a uniform pattern of heavy rainfalls during the summer, which was not observed in other rainy summers, where the rainfalls peak occurred in the second half of summer. Therefore, the rainfall precipitations affecting the thaw depths in the study area, depend not only on the amount but also the mode of precipitation events during the summer period.

5. The thaw line reacted differently to the same meteorological factors in different landscapes of the same area, as was ascertained by the observations. Thus, the rainfalls pattern and rainfall amount fallen during the same summer led to an increase in the AL thawing depth within the denudation and denudation-aggradational plains and had no effect on its variability in the area of above-floodplain terrace II of the Lena Rv.

The research result and findings presented here can not claim to have addressed the problem in full,
suggesting its further investigations. With the observations continued in the course of many years we can expect different reaction of the thawing depth on the same factors, even within the same landscape extent, given the diversity of variations resulted from the complex combinations of separate elements of the climate, varying from year to year.

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