SCIENTIFIC JOURNAL
EARTH'S CRYOSPHERE

Earth`s Cryosphere, 2016, vol. XX, No. 1, pp. 75–81 **http://earthcryosphere.ru/**

METHODS OF PERMAFROST STUDIES

VARIATIONS IN SIZE AND NUMBER OF THERMOKARST LAKES IN DIFFERENT PERMAFROST REGIONS: SPACEBORNE EVIDENCE

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Changes in size and number of thermokarst (thaw) lakes are estimated by comparing Landsat images shot at different times during the current warming since the 1970s, with regard to spatial resolution difference between the MSS (*Multispectral Scanner*) and TM (*Thematic Mapper*) scanning systems. Observations at thirty nine test sites covering nearly 300,000 lakes in six permafrost areas of Russia (North of European Russia, West Siberia, East Siberia and Far East, Central Yakutia, and Transbaikalia) reveal weak contradictory trends in 1970 through 2000: Some lakes became 2.9 % smaller while others grew 1.2 % larger. Simultaneous shrinking of many lakes results from their drainage by rivers while lake growth is due to fluvial input, cyclical precipitation changes (Central Yakutia), anthropogenic loads (West Siberia), and rapid karst formation in ice-rich permafrost (Yamal and Yana-Indigirka plain). The dynamics of sizes and number of thaw lakes is controlled by interplay of different factors and cannot be a proxy of climate warming impact on permafrost.

Thaw lakes, karst, permafrost, climate warming, satellite images

INTRODUCTION

Dynamics of thermokarst (thaw) lakes attracts attention of scientists and engineers as a possible proxy of permafrost state under climate warming. Variations in area and number of thaw lakes in regions of continuous and discontinuous permafrost in Eurasia and Alaska have been largely investigated since the 2000s. Observations reveal significant and contradictory trends since the 1950s–1970s attributed to active karst formation as a result of climate warming. The trends are, namely, up to 50 % shrinking of lakes in discontinuous permafrost of Alaska [*Fitzgerald and Riordan, 2003; Riordan et al., 2006*] and up to 12 % greater shrinking in West Siberian continuous permafrost [*Smith et al., 2005; Kirpotin et al., 2008; Bryksina et al., 2009*], but two-fold expansion of lake area in Central Yakutia [*Kravtsova and Bystrova, 2009*]. Note that data from the same territories (specifically, from West Siberia) often disagree [*Kirpotin et al., 2008; Kravtsova and Tarasenko, 2010*], possibly, because of difference in survey techniques.

Therefore, it is urgent to develop unified remote sensing methods for monitoring the dynamics of thaw lakes which would provide reliable results from different permafrost regions with regard to their geographic specificity and karst controls. Thus it will become clear whether this dynamics can be diagnostic of permafrost state during climate warming.

DATA AND APPROACHES

Variations in number and sizes of thaw lakes are commonly studied using Landsat scenes. They are advantageous over other satellite images as the surveys have been run continuously since the 1970s by identical systems providing data which are easy to compare. However, these images have had different low resolutions (80 m in the *Multispectral Scanner* (MSS) and 30 m in *Thematic Mapper* (TM) and *Enhanced Thematic Mapper Plus* (ETM+) systems) at different observation periods.

Checking against ultrahigh-resolution (0.5–2.5 m) *WorldView-1*, *IRS-P5* (Cartosat), and SPOT-5 images shows that the deciphering coverage in Landsat images exceeds 90 % only for thaw lakes larger than 0.5 ha in ETM+(TM)/Landsat scenes and larger than 3 ha in MSS/Landsat data. This is important to know when counting lakes. The surface area estimates can be <10 % accurate only for lakes larger than 10 ha in ETM+(TM)/Landsat and 40 ha for MSS/Landsat images. Therefore, small lakes deciphered to less than 90 % have to be culled out, and errors in lake size estimates have to be taken into account. The comparison of multitemporal Landsat images that differ in resolution requires bringing them to the same resolution level by excluding the lakes undetectable by weaker scanning systems [*Tarasenko, 2013*]. Small lakes imaged in different ways at different positions relative to the pixel grid are likewise excluded from comparison of images shot at different times though to the same resolution. The limit lake sizes at which this comparison remains valid, estimated from synchronously shot Landsat images, are 0.4 ha for ETM+ (TM)/Landsat and 2 ha for MSS/Landsat data. As the lakes below these sizes are excluded, the number of lakes in different images becomes comparable [*Rodionova, 2014*].

It is unreasonable to estimate the total area of all lakes because the sizes of small lakes, which are predominant in most of regions, are estimated to a low accuracy. One should rather estimate changes in the area of individual lakes with regard to one-sigma errors (changes exceeding 1.64σ).

The lake size changes are quantified parallel with mapping the dynamics of thaw lakes to visualize the detected changes and analyze their spatial patterns.

CHOICE OF STUDY AREAS

Understanding the patterns of lake size fluctuations in different permafrost and landscape conditions requires observations of a large spatial coverage. The reported study was performed in six northern areas of Russia chosen according to the locations of thaw lakes, with reference to a specially compiled preliminary map based on *GoogleEarth* imagery (Fig. 1) [*Kravtsova, 2009*]. The choice was made proceeding from the fact that lakes in the permafrost zone, especially in the areas of ice-rich rocks, are mainly of karst origin or experienced karst effects in the past. Therefore, we considered all lakes in the region, irrespective of their genesis.

Karst commonly forms in ice-rich permafrost within coastal plains of northern seas. Karst lakes are especially widespread and quite large in the West Siberian plain and in the Yana-Indigirka and Kolyma plains of northern East Siberia. There are quite many thaw lakes also in the north of European Russia, in Central Yakutia, and in the northern Russian Far East (Anadyr plain); some lakes also exist locally along river valleys in different permafrost areas, including Transbaikalia.

On the other hand, the choice depended on the current climate warming patterns. Much karst was produced by thawing of Pleistocene sediments during the Holocene climate optimum. At present, karst may form as seasonal or perennial thaw reaches greater depths. However, its relation with current warming hypothesized by some authors [*Smith et al., 2005; Bryksina et al., 2009*] is debatable. When choosing study areas, we took into account increasing mean annual air and ground warming trends and geocryological risks mapped by *Malkova and Pavlov* [*2012*]. Air warming is the highest in southern West Siberia, Central Yakutia, and the Anadyr plain and the lowest in northern Central and East Siberia and in the Yugor Peninsula; the geocryological risks are the highest in northern West Siberia, northern European Russia, and Chukotka and low in the Lena delta, northern Yakutia, and partly in southern Yakutia [*Malkova and Pavlov, 2012*].

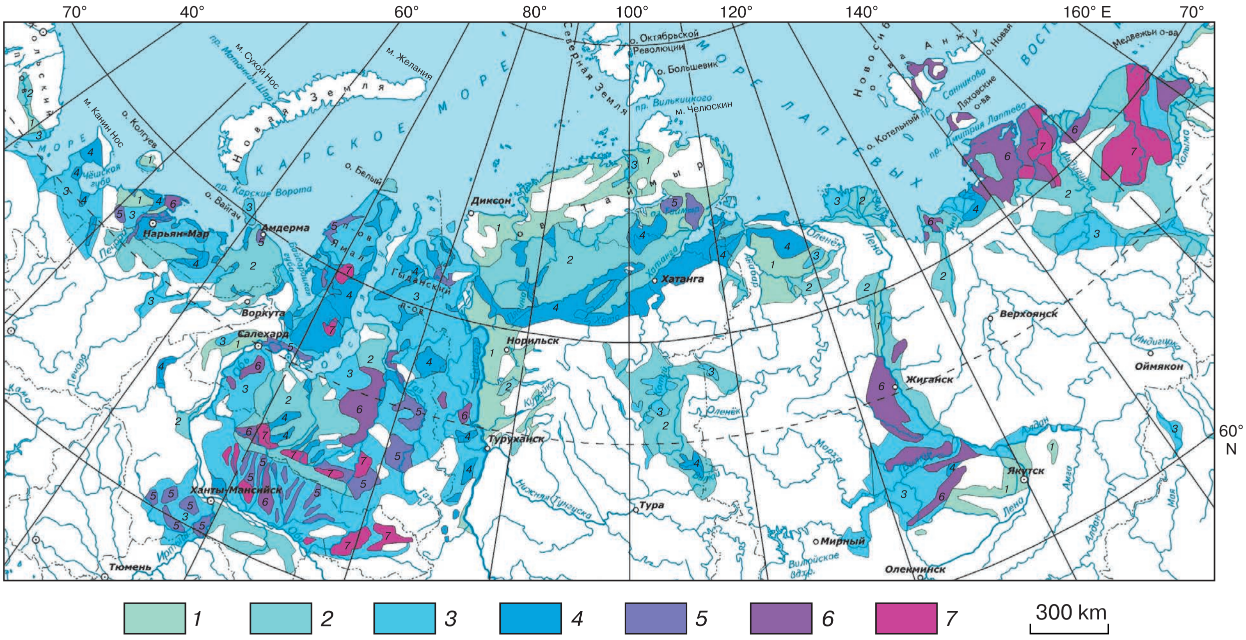

Fig. 1. Location map of thaw lakes in Russia.

Prevailing lake sizes or their combinations: *1* – small; *2* – medium; *3* – small + medium; *4* – small + large; *5* – small + very large; *6* – medium + large; *7* – medium + very large. Lake diameters (in km): 0.1–0.5 (small), 0.5–1.5 (medium), 1.5–3.0 (large), and 3–6 (very large).

Reference was also made to previous results showing the processes to vary between and within regions, with uneven and sometimes contradictory trends. For instance, lakes in the zone of continuous permafrost in West Siberia were reported either to expand [*Smith et al., 2005; Kirpotin et al., 2008; Bryksina et al., 2009*] or to shrink [*Kravtsova and Bystrova, 2009; Kravtsova and Tarasenko, 2010*].

Finally, the following study areas were chosen: northern European Russia; West Siberia; northern East Siberia; northern Russian Far East; Central Yakutia; and Transbaikalian lowlands (Fig. 2).

Studies were performed at thirty nine 20 × 30 km reference sites in each of the six areas, and covered about 300,000 lakes.

MATERIALS AND METHODS

Long-term lake size dynamics was analyzed in pairs of Landsat images shot within each reference site, on two dates: MSS (resolution 80 m, operated since 1972) or TM (resolution 30 m, since 1982) scenes were compared with the present TM or ETM+ systems (resolution 30 m), depending on data availability.

As mentioned above, many small lakes, which were beyond the resolution of MSS images and were smaller than the threshold sizes for TM images had to be excluded from calculations. The limit sizes were 2 ha for images of different resolutions (MSS and TM) and 0.4 ha for those of the same resolution (TM images shot on different dates). Excluding the small lakes did not change much the surface area totals estimated for each site consisting mainly of large lakes.

We compared the deciphered images with lakes larger than the chosen limit sizes, selected the lakes that changed in area (decreased or increased) for more than one-sigma error, and excluded those in which the changes were most likely due to calculation errors. Visual comparison of the scenes was facilitated by identifying the style of variations typical of each reference site.

RESULTS

The results for each reference site included the number of lakes, which decreased or increased in size, and the magnitude of changes in square km. The respective maps looked like the one in Fig. 3 for West Siberia, with twenty reference sites. Altogether, fifty six 1:100,000 maps of thaw lake dynamics were compiled (see some fragments in Fig. 4) to understand the causes of changes with reference to hydrological, meteorological, geobotanic, tectonic, geocryological, and other data.

For convenient comparison of results from the reference sites, all parameter values were normalized to the site area and plotted as in Figs. 5 and 6, for different parts of the permafrost zone. There are both increasing and decreasing lakes within each site (Fig. 5), but the decreasing trend is more prominent. The decrease and increase in area, on average for 39 sites in six areas, are, respectively –2.9 % and +1.2 %; the respective values for the number of lakes are –0.5 % and +0.3 % (Tables 1 and 2).

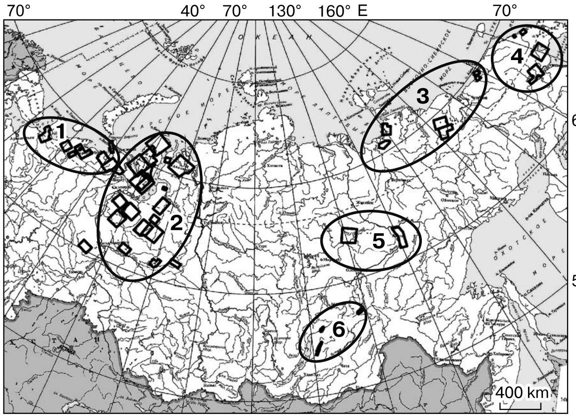

Fig. 2. Study areas and reference sites (boxes).

1 – northern European Russia, **2** – West Siberia, **3** – northern east Siberia, **4** –northern Far East, **5** – Central Yakutia, **6** – Transbaikalian lowlands.

The amount of shrinking was the greatest in West Siberia, in northern East Siberia within the Kolyma plain and in the Anadyr plain of the northern Far East (Fig. 6), mainly as a result of drainage by rivers and vegetation. No direct influence of climate warming on these processes was revealed, but accelerated erosion (including thermal erosion) may have caused some implicit effect.

The growth of lakes, both in area and in number, was generally much smaller than the reduction, except for Central Yakutia and the Yana-Indigirka plain, as well as some local areas within sporadic permafrost in West Siberia and Transbaikalia (Figs. 5 and 6). Local increase in lake areas, though inferior to the decrease, was also observed in the Yamal and Gydan peninsulas (West Siberia), in a zone of continuous permafrost. The lake growth in different areas has different causes, not necessarily related to climate warming.

In many cases (Pechora delta in northern European Russia; Yana delta in the Yana-Indigirka plain; Alazei valley in the Kolyma plain; lowlands in Transbaikalia), lakes grow due to increased water flow and budget in streams that connect the lakes and provide their recharge. Especially large growth of lakes in Central Yakutia correlated with cycles of high precipitation.

Lakes in the Yana-Indigirka plain, as well as in northern West Siberia (locally in Yamal and Gydan), in zones of continuous ice-rich permafrost, expand in narrow bands along their margins. The growth may

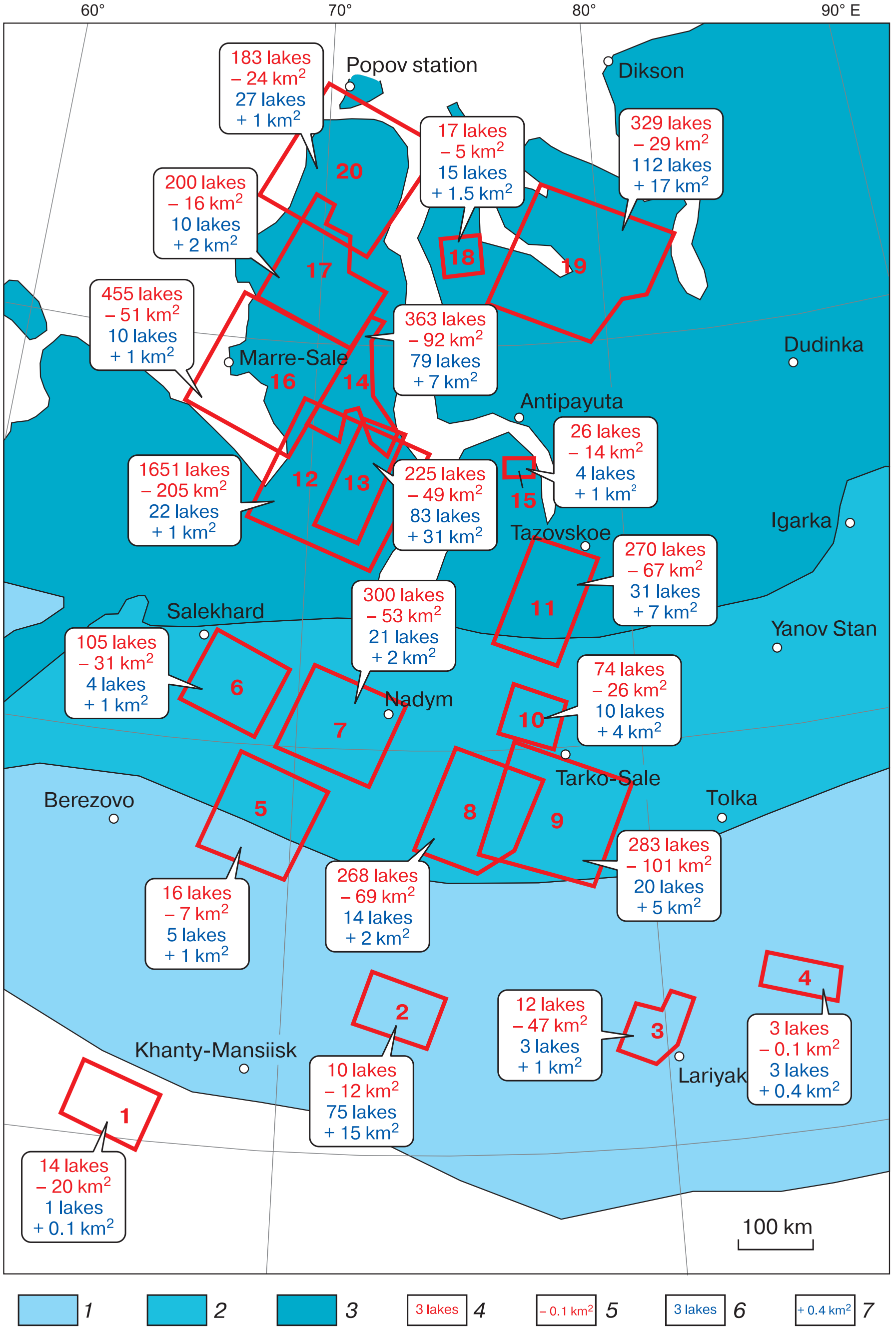

Fig. 3. Lake size changes within reference sites 1–20 (West Siberia).

1–3 – sporadic (*1*), discontinuous (*2*), and continuous (*3*) permafrost; *4*, *5* – number of shrunk lakes (*4*) and magnitude of change (*5*); *6*, *7* – number of expanded lakes (*6*) and magnitude of change (*7*).

result from thermal erosion, this being the only case where accelerated karst formation may have bearing on lake expansion.

The dynamics of lake areas in zones of petroleum production (southern West Siberia) is largely controlled by anthropogenic impacts. They are, namely, man-made changes to the drainage network (by excavations or filling) and to groundwater table (by injection of industrial waters and direct soil warming from utility structures).

Thus, most of thaw lakes in the permafrost zone of northern Russia are shrinking, mainly being drained by rivers and vegetated. The growth of lakes, which is significant in few areas and locally occurring in almost

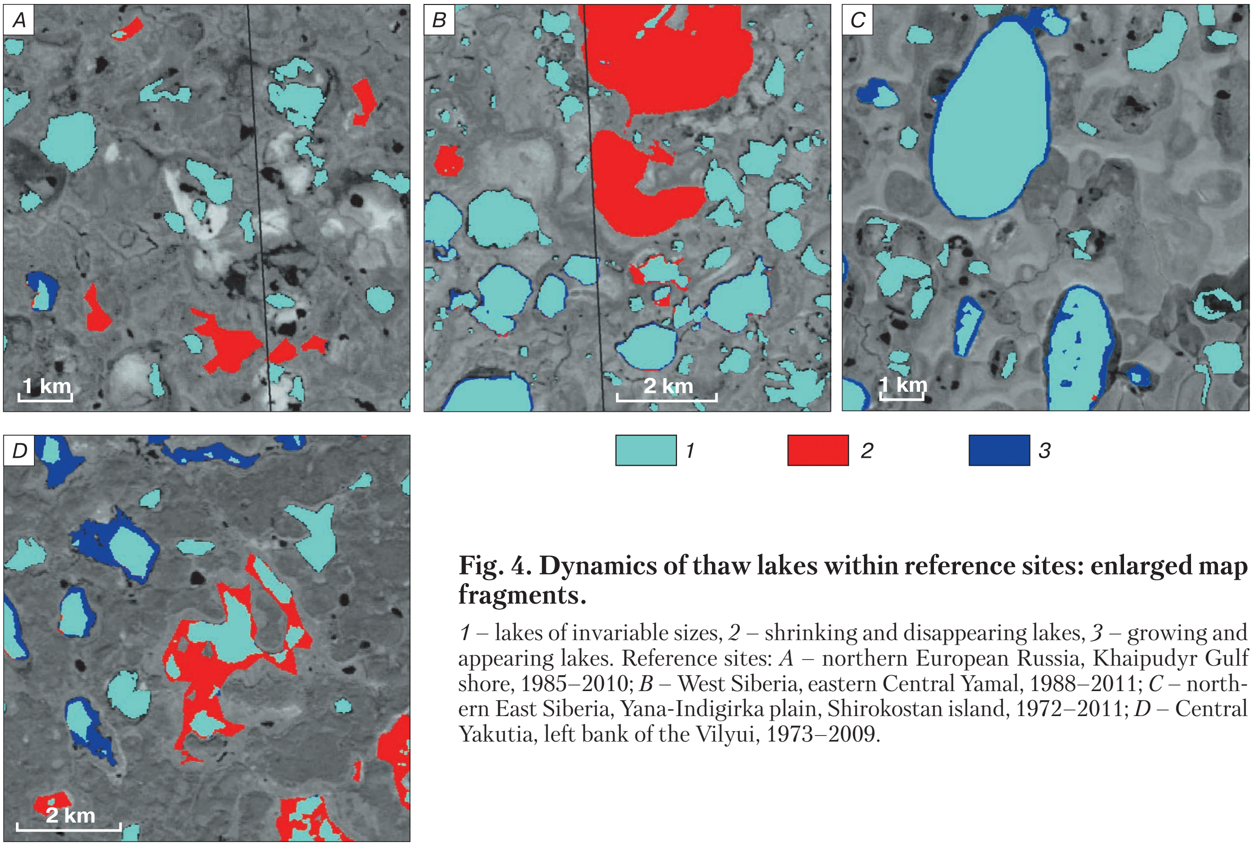

Fig. 4. Dynamics of thaw lakes within reference sites: enlarged map fragments.

1 – lakes of invariable sizes, *2* – shrinking and disappearing lakes, *3* – growing and appearing lakes. Reference sites: *A* – northern European Russia, Khaipudyr Gulf shore, 1985–2010; *B* – West Siberia, eastern Central Yamal, 1988–2011; *C* – northern East Siberia, Yana-Indigirka plain, Shirokostan island, 1972–2011; *D* – Central Yakutia, left bank of the Vilyui, 1973–2009.

all areas we studied, has several controls. They are, namely, flow budget of streams, meteoric moisture, karst activity in ice-rich permafrost, as well as human impacts.

Detailed studies of variations in sizes and number of thaw lakes in the northern Yana-Indigirka lowlands revealed also some neotectonic effects: uplift was favorable for drainage and shrinking (drying), while subsidence favored moisture accumulation and lake growth along narrow fringes, as well as increase in lake number.

Our results disagree with those of *Smith et al.* [*2005*] *and Bryksina et al.* [*2009*] who report lake growth in the zone of continuous permafrost in West Siberia and attribute it to current climate warming. We observed some increase in lake area as well, but

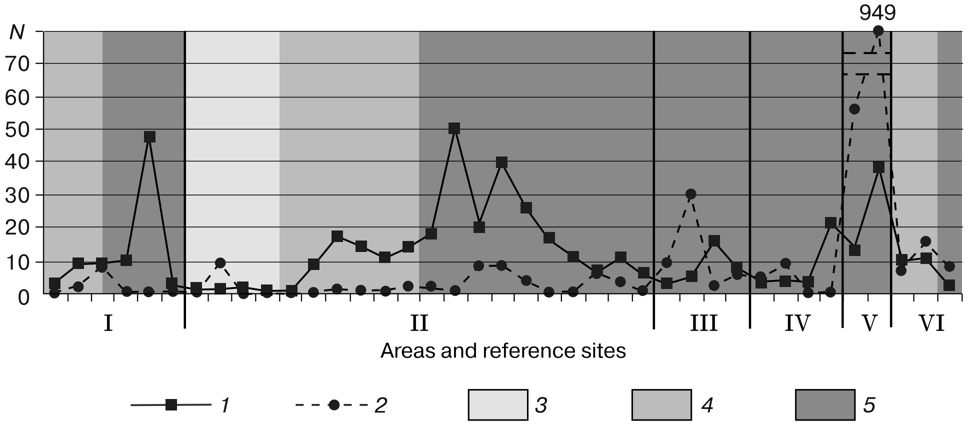

Fig. 5. Number of lakes that changed size, per 1000 km^2 (N) within reference sites:

1 – number of shrinking lakes; *2* – number of growing lakes. Each point shows results for a reference site; *3*–*5* – sporadic (*3*), discontinuous (*4*), and continuous (*5*) permafrost. Roman numerals stand for study areas: northern European Russia (I), West Siberia (II), northern east Siberia (III), northern Far East (IV), Central Yakutia(V), and Transbaikalian lowlands (VI).

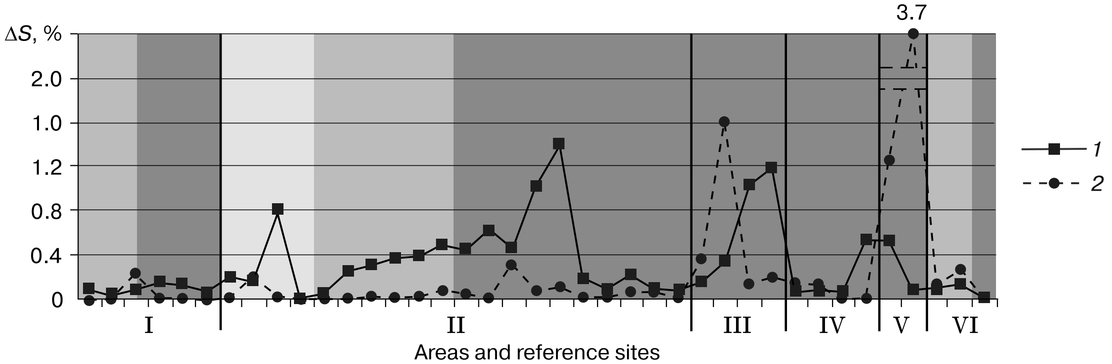

Fig. 6. Amounts of shrinking (*1*) and growth (*2*) of lake sizes relative to the surface areas of reference sites (ΔS).

Each point shows results for a reference site. Other symbols as in Fig. 5.

Table 1. **Variations of thaw lake sizes in different permafrost regions, from 1970s to 2000s**

Study area	S, km^2	ΔS, km^2	
		decrease	increase
Northern European Russia	3536	69.3 (−1.9)	29.1 (+0.8)
West Siberia	27 623	918.1 (−3.2)	101.0 (+0.3)
Northern East Siberia and Far East	18 779	416 (−2.2)	173.5 (+0.9)
Central Yakutia	1209	120.6 (−11.8)	309.0 (+30)
Transbaikalian lowlands	147	4.3 (−3.0)	6.5 (+4.5)
Russia as a whole	51 294	1528 (−2.9)	619 (+1.2)

Note. S is total area of analyzed lakes, on first shooting date; ΔS is lake size change (numerals in parentheses are magnitudes of change in percent of lake area on the first shooting date).

Table 2. **Variations in thaw lake number in different permafrost regions, from 1970s to 2000s**

Study area	N	ΔN	
		decrease	increase
Northern European Russia	42 173	341 (−0.8)	20 (+0.05)
West Siberia	230 162	870 (−0.4)	114 (+0.05)
Northern East Siberia and Far East	22 789	173 (−0.8)	44 (+0.2)
Central Yakutia	5058	60 (−1.2)	768 (+15)
Transbaikalian lowlands	1345	12 (−0.9)	31 (+2.3)
Russia as a whole	303 500	1456 (−0.5)	977 (+0.3)

Note. N is total number of analyzed lakes, on first shooting date; ΔN is lake number change (numerals in parentheses are change magnitudes in percent of lake number on the first shooting date).

shrinking obviously prevails (shrunk lakes are 4.5 times more numerous than the increased ones, and the amount of area reduction is 3.5 greater than that of expansion). Thus, expansion of lakes in this region under the effect of current warming is out of the question.

It is impossible to discriminate climate forcing of lake dynamics among the intricately interplaying hydrological, meterological, tectonic, and anthropogenic factors.

CONCLUSIONS

1. Thermokarst (thaw) lakes in the permafrost zone of Russia change in size and number through time, either increasing or decreasing.

2. The decreasing trend generally predominated in the period from the 1970s–1980s to the 2000s. In total, lakes from 39 reference sites decreased for −2.9 % in size and for −0.5 % in number and increased for +1.2 % and +0.3 %, respectively, but the specific values and patterns varied from site to site.

3. The variations in size and number of thaw lakes result from interplay of multiple controls: hydrology, precipitation, tectonics, and anthropogenic loads, in addition to climate warming, which could trigger permafrost thawing and karst formation. These agents are, specifically,

(a) water budget of streams that connect lakes and either drain or fill them, along with erosion in the lake vicinities, which creates either discharge or recharge sources. Correspondingly, the lakes shrink or grow and undergo size variations at annual cycles;

(b) atmospheric precipitation, often varying periodically. The dry and wet cycles correspond to decreasing or increasing trends in lake dynamics, respectively, which change annually depending on the duration of the cycles;

(c) human impacts, especially in areas of petroleum production and pipelines, which interfere with the drainage patterns and cause ground warming from engineering structures. Development can either increase or decrease the lake area but most often favors their growth;

(d) uplift and subsidence which favor drainage and shrinking of lakes or their recharge and growth, respectively.

4. Shrinking of many lakes observed simultaneously over the permafrost regions is mainly due to water budget decrease and vegetation, as well as to anthropogenic impacts in some cases, while lake growth has several causes, including those associated with the above factors. They are, namely: (i) accelerated karst formation in zones of ice-rich permafrost which causes lake growth within narrow fringes around them (in the Yana-Indigirka plain, in the Arctic coast, and in the Yamal and Gydan peninsulas); (ii) hydrological factors especially active in river valleys within the Kolyma and Transbaikalian lowlands and in deltas (the Yana and Pechora rivers); (iii) atmospheric precipitation, which influences especially the budget of lakes in Central Yakutia; (iv) petroleum development, especially in the Middle Ob plain and southern West Siberia.

5. It is impossible to discriminate climate forcing of lake size dynamics in the interplay of hydrological, meteorological, tectonic, and anthropogenic factors.

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Received March 2, 2015