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ANALYSIS OF CHANGES IN THE NUMBER OF THERMOKARST LAKES IN PERMAFROST OF WESTERN SIBERIA ON THE BASIS OF SATELLITE IMAGES

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Changes in the number of thermokarst lakes in the territory of Western Siberian permafrost were investigated using multi-temporal satellite images in the period of 1973–2013. Over 30 test sites located in different permafrost zones were selected. From several hundred to several thousand thermokarst lakes were determined at each test site. The total number of formed lakes has been demonstrated significantly to exceed the number of disappeared lakes (by about 20 times). With the increasing geographical latitude, the number of disappeared lakes during the period of research decreases on average, and the number of newly formed lakes increases significantly.

Thermokarst lakes, global warming, multi-temporal satellite images, permafrost, Western Siberia

INTRODUCTION

The increase in the average annual temperature of the Earth surface observed over the recent three-four decades has resulted in the degradation of the permafrost terrains of Northern Eurasia. Thermokarst lake terrains have proven to be most sensitive to the temperature fluctuations in the permafrost territory [*Kirpotin et al., 2009; Kravtsova and Bystrova, 2009*]. Due to melting of permafrost, thermokarst lakes emerge and develop over relatively short periods (several decades) and can easily disappear, turning into dishes of dried lakes. However, the life time of several ancient thermokarst lakes may vary from several hundred to several thousand years [*Hinkel et al., 2003*].

Currently formation of thermokarst water bodies and depressions caused by permafrost degradation has been observed over the last 50 years in Alaska, Canada, and Europe [*Zuidhoff and Kolstrup, 2000; Luoto and Seppala, 2003; Riordan et al., 2006*]. As shown in [*Kirpotin et al., 2008a; Bryksina et al., 2011*], permafrost melting under conditions of climate warming results in acceleration of the thermokarst processes and in changes in the area of lakes in the permafrost zone of Western Siberia. However, neither the above studies nor other publications have dealt with the issues of change in the number of lakes in the permafrost zone.

The goal of this study was remote sensing-based research of the changes in the number of thermokarst lakes in Western Siberia depending on geocryological zoning of its territory on the basis of analysis of data on the number of disappeared and newly formed lakes over 40 years of studies (1973–2013).

CRITERIA FOR SELECTING TEST SITES AND THE DETAILS OF INTERPRETATION OF *LANDSAT* THERMOKARST LAKE IMAGES

The changes in the number of the thermokarst lakes were studied by examining multi-temporal *Landsat* satellite images. 33 test sites (TS) were selected in Western Siberia for studies. In choosing a TS, the complicacy of determining the thermokarst nature of the lakes by satellite images had to be taken into account. It is known [*Viktorov, 2006*] that lacustrine thermokarst terrains get formed on undulating plains with characteristic tundra vegetation and lake spots, usually round-shaped and randomly scattered in the territory.

In accordance with [*Viktorov, 2006*], formation of thermokarst lakes takes place under the impact of several factors, the main ones of which are the presence of permafrost rocks (accumulation of the critical yield of water) and the flat terrain. Therefore, most researchers of the lacustrine thermokarst plains proceed from the assumption that lakes of the thermokarst origin are mostly situated in the areas of ice-rich permafrost zones. For example, in the studies of V.I. Kravtsova et al. [*Kravtsova, 2009; Kravtsova and Bystrova, 2009; Kravtsova and Tarasenko, 2010*] containing analysis of geomorphological and climatic data, the entire permafrost zone of Western Siberia is classified as a territory with ubiquitous distribution of thermokarst lakes. Therefore, the lakes discussed in this study on the basis of satellite images are viewed as thermokarst lakes.

The test sites were selected considering the specific features of zonal-geocryological differentiation of territories [*Atlas..., 1984*]. In each permafrost subzone, several TS were selected, which allowed inves-

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tigation of the fluctuations in the number of the thermokarst lakes, depending on geocryological zoning of the territory. Fig. 1 demonstrates a schematic map of the permafrost zones of Western Siberia. The selected TS can be seen to be distributed in the territories under study rather uniformly. TS distribution by subzones is shown in Table 1. 13 test sites are located in the continuous permafrost subzone, 12 test sites are in the discontinuous permafrost zone, and 8 sites are in the insular subzone.

134 *Landsat* cloudless multi-temporal satellite images were used in remote studies, obtained for the territory of Western Siberia surveyed. All the images were selected from the generally accessible archives Global Land Cover Facility and refer to the 1T treatment level, including radiometric and geometric correction, using digital terrain models. The *Landsat* images included into the collection have gridding in the UTM projection. The satellite images used refer to the period of 1973–2013, with 90 % taken in the second half of the summer seasons (mostly in July–August), when the ice cover of the lakes preventing their identification in automated interpretation of the images fully disappears.

Treatment and decoding of satellite images were conducted using the software of modern ENVI 4.7 and ArcGIS 9.3 geographic information systems (GIS). On each test site, from several hundred to several thousand lakes were identified with GIS tools. The total number of the lakes studied on 33 test sites of Western Siberia equaled more than 50,000.

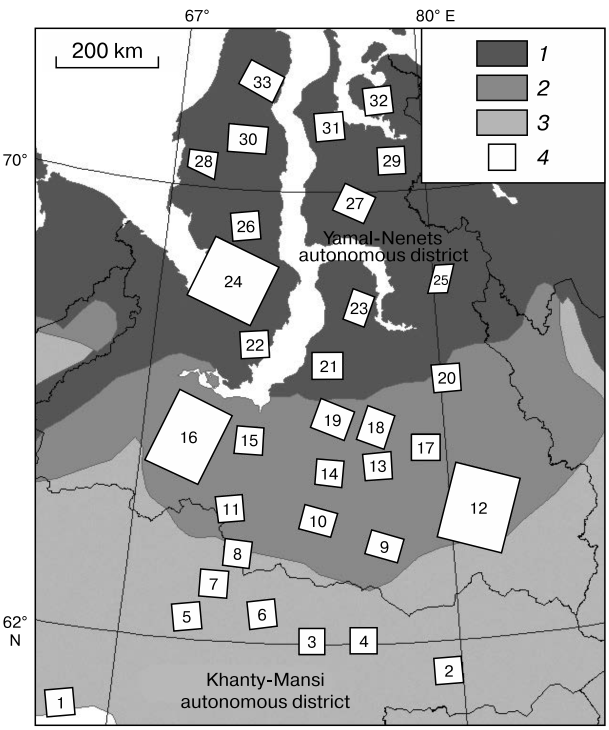

Fig. 1. A schematic map of permafrost zones in Western Siberia with test site boundaries.

Permafrost: *1* – continuous, *2* – discontinuous, *3* – insular; *4* – test sites.

Table 1. **Distribution of test sites by permafrost subzones**

Permafrost subzone	TS number	TS numbers
Continuous	13	21–33
Discontinuous	12	9–20
Insular	8	1–8

To ensure terrain uniformity of TS territories in forming thermokarst lakes samples, the mutual locations of the selected areas and of the landscape zones in the territories selected were compared, using a landscape map of Western Siberia [*Atlas..., 1971*]. The results of this comparison are shown in Table 2. The location of the sites within the determined landscape zones may serve as a basis for uniformity of the lake samples by certain permafrost zones, which is an important factor for interpreting the results of remote survey of changes in the number of the thermokarst lakes.

Resulting from decoding multi-temporal satellite images, digital maps were obtained, reflecting the location of the lakes on each test site for a given year of survey. The thermokarst lakes disappeared and newly formed in the period of survey were identified by comparing the initial and final maps on each test site. To make initial maps, the *Landsat-1* (1973), *Landsat-2* (1981), *Landsat-4* (1983, 1988), and *Landsat-5* (1984, 1987) images were used, whereas the maps for the ending year of the survey were formed based on the *Landsat-8* images for 2013. The *Landsat-1* images of 1973 were used to make the initial maps on 16 test sites, and for the remaining TS the *Landsat* images dated by the years of 1981–1988 were used. The use of the *Landsat-8* images taken in 2013 allows changes (reduction or increase) in the number of the thermokarst lakes to be evaluated for a rather long period of time (from 25 to 40 years on different TS).

As it follows from the above, by comparing the initial and final maps of the lakes location on each test site, both the thermokarst lakes which disappeared during the period of survey and the newly formed lakes were identified. Then, using the ArcGIS 9.3 system, the centers of the disappeared and newly formed lakes were identified, convenient for their location mapping.

Table 2. **Distribution of test sites by landscape zones**

Landscape zone (subzone)	TS number	TS numbers
Arctic tundra	3	31–33
Subarctic tundra	10	21–30
Forest tundra	6	15–20
Northern taiga	11	4–14
Middle taiga	3	1–3

THE SURVEY RESULTS AND THEIR ANALYSIS

The schematic map of the location of the disappeared lakes in the territory of Western Siberia in question is shown in Fig. 2. As seen from Fig. 2, the number of the disappeared lakes varies in different subzones, with the greatest lake density observed in the discontinuous permafrost zone. Remote sensing shows that the total number of the disappeared lakes in the territories of 33 test sites representing the permafrost zone of Western Siberia during the period of survey was 391, the total area of the aquatic surface of these lakes was 14,826 hectares, and the average area of a disappeared lake was 37.9 hectares.

Consider changes in the number of the disappeared lakes depending on the geographic latitude of their location in the territory under study. Shown in Fig. 3, *a* is the dependence of the number of the disappeared lakes (N_1) on the latitude of their location and on the permafrost zoning. The points in the diagram shown as triangles, squares, and rhombuses, depending on their location in different permafrost subzones, demonstrate the number of the disappeared lakes on each test site. As seen from Fig. 3, *a*, the number of the disappeared lakes on average diminishes as the geographic latitude increases. It is much less in the continuous permafrost subzone than in the discontinuous permafrost, i.e., the greatest reduction in the number of lakes in the permafrost zone of Western Siberia is primarily observed in the discontinuous permafrost subzone.

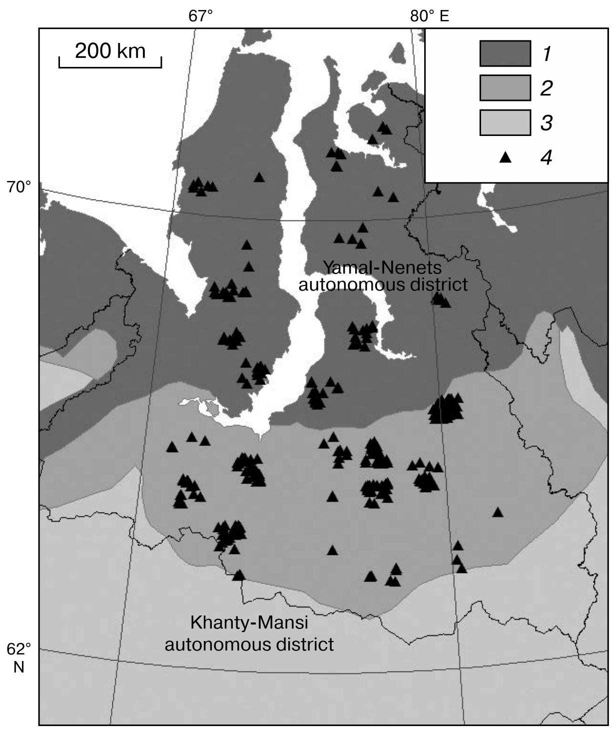

Fig. 2. A schematic map of the location of disappeared lakes in different permafrost subzones in Western Siberia.

Permafrost: *1* – continuous, *2* – discontinuous, *3* – insular; *4* – khasyreys (shrinking ponds).

Analysis of the changes in the number and area of the newly formed lakes in the territory in question has shown the number of these lakes in the indicated period in the permafrost zone of Western Siberia to be 7,751, while the total area of their water surface was 13,649 hectares. Hence, the average area of the newly formed lakes is 1.76 hectares, which is 22 times less than the average area of the disappeared lakes.

Fig. 3, *b* shows dependence of the number of the newly formed lakes in the period of survey (N_2) on the geographical latitude of the location of the test sites. As in Fig. 3, *a*, each point in the diagram shows the number of the newly formed lakes on a certain TS. It can be seen from Fig. 3, *b* that the number of the newly formed lakes on average significantly increases as the geographical latitude increases, while formation of new lakes manifests itself primarily in the continuous permafrost zone. A conclusion can be made from the analysis of the curves in Fig. 3, *a*, *b* that formation of new lakes mainly occurs in the continuous permafrost subzone, while disappearance of the lakes mainly occurs in the discontinuous permafrost subzone.

This conclusion is quantitatively corroborated by the results of comparative analysis of the changes in the average numbers of disappeared and newly formed lakes in different permafrost subzones. The average values shown in Table 3 were calculated as mean arithmetic values from the number of the lakes identified on all the test sites located in the subzones in question. Table 3 contains data on the range of variance in the number of disappeared and newly formed lakes in the territory of the permafrost subzones in question, as well as data on the total area of all the test sites and the total number of lakes in each subzone.

As it follows from Table 3, the average number of the disappeared lakes in the discontinuous permafrost subzone exceeds the corresponding number for the continuous permafrost subzone more than twice. In accordance with Table 3, the average number of the newly formed lakes in the continuous permafrost subzone doubles the number of the formed lakes in the discontinuous permafrost subzone. Hence, acceleration of the thermokarst processes in the permafrost zone of Western Siberia due to climate warming causes more intense formation of new lakes in the continuous permafrost subzone than in the discontinuous permafrost subzone, and more intense reduction in the number of the thermokarst lakes is observed in the discontinuous permafrost subzone, compared to the continuous permafrost subzone.

As shown in [*Dneprovskaya et al., 2009; Kravtsova and Bystrova, 2009; Polishchuk and Polishchuk,*

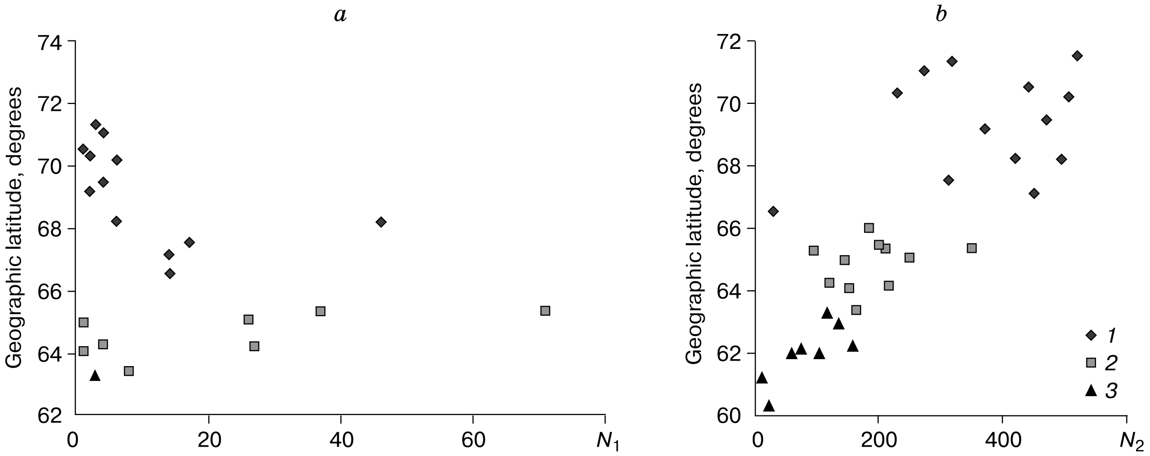

Fig. 3. Dependences of the number of disappeared lakes N_1 (*a*) and of newly formed lakes N_2 (*b*) on geographic latitude.

Permafrost: *1* – continuous, *2* – discontinuous, *3* – insular.

2014; Polishchuk et al., 2014], reduction in the total area of the thermokarst lakes is an important feature of the discontinuous permafrost zone of Western Siberia, which in [*Dneprovskaya et al., 2009*] is explained by the rise in the average air temperature. The study of the interconnection between the changes in the lake areas and the climatic characteristics in the territory of the West-Siberian permafrost zone on the basis of regressive analysis in [*Polishchuk and Polishchuk, 2013*] confirms that the rise in the average air temperature is accompanied by reduction of the areas of the thermokarst lakes.

As disappearance of a lake (formation of a khasyrey (shrinking pond) replacing a thermokarst lake) is the finishing stage in the process of lake surface area reduction, the causes of reduction in the number of lakes are the same as those which bring about the reduction in the lake sizes. The thermokarst researchers on Alaska [*Hinkel et al., 2003; Riordan et al., 2006*] indicate soil desiccation caused by permafrost rock melting due to climate warming and reduction in the annual precipitation rate as possible causes of the lake area reduction in the discontinuous permafrost zone.

According to [*Dneprovskaya and Polishchuk, 2007*], as the average annual air temperature rose approximately by 1 °C, the change in the amount of atomspheric precipitation in the permafrost zone of Western Siberia over the three recent decades did not exceed 1–2 %. Therefore, in the territory of the permafrost zone of Western Siberia soil desiccation resulting in lake drainage should be considered the most probable cause of reduction in the lake sizes.

One of the possible mechanisms of water drainage from a thermokarst lake due to soil desiccation caused by a rise in the soil temperature is described in [*Kirpotin et al., 2008b*]. As a rule, large lakes are older and have a lower level of the water surface than the comparatively young lakes. This creates conditions for water drainage from small lakes to larger lakes by way of soil desiccation during soil thawing. Under conditions of global warming, the permafrost thawing depth increases in the warm seasons, thus accelerating thermoerosional water drainage from the lakes and resulting both in reduction of the lake areas and in disappearance of some of them.

Comparative analysis of the above data on the number of the disappeared and newly formed lakes and their total areas in the entire permafrost zone of Western Siberia indicates another important pattern: with the total areas of the disappeared (14,826 hectares) and newly formed lakes (13,649 hectares) lakes, the number of the newly formed lakes is approximately 18 times greater than the number of the disap-

Table 3. **Changes in the number of disappeared (DL) and newly formed lakes (NLF) in different permafrost subzones (1973–2013)**

Permafrost subzone	Number of DL		Number of NFL		Total area of sites, km^2	Total number of lakes
	average	range	average	range		
Continuous	9.9	1–46	371.4	30–520	50 014	23 916
Discontinuous	22.4	1–71	186.4	95–350	64 010	18 441
Insular	–	–	85.8	12–158	20 452	7677

peared lakes. Hence, new thermokarst lakes are much smaller in size than the preceding ones. One can suppose then that the observed acceleration of the thermokarst processes caused by climate warming will be accompanied by significant growth in the number of small thermokarst lakes in the permafrost zone of Western Siberia.

In accordance with the experimental data of [*Audry et al., 2011; Pokrovsky et al., 2011*], the small thermokarst lakes of Western Siberia are plentiful natural sources of greenhouse gases, in particular, of carbon dioxide and methane. Therefore, the predominant growth in the number of small thermokarst lakes discovered in our study will contribute to the increase in the accumulation of greenhouse gases in the air.

CONCLUSION

The study presents the results of studying the poorly known change patterns in the number of thermokarst lakes. It has been shown that over the recent three-four decades, two different processes have been observed in the permafrost zone of Western Siberia: disappearance of thermokarst lakes and formation of new lakes.

Combined analysis of data on the total areas and the number of the disappeared and newly formed lakes in the West-Siberian permafrost zone has shown that with almost equal values of the total areas of the disappeared and newly formed lakes, the number of new lakes approximately 18 times exceeds the number of the disappeared lakes. Hence, the newly formed thermokarst lakes should have much smaller sizes than the disappearing lakes. Indeed, the average value of the area of the new lakes is 22 times less than that of the disappeared lakes. Therefore, one can suppose that the observed acceleration of the thermokarst processes due to global climate warming will be accompanied by significant growth of the newly formed small thermokarst lakes in the permafrost zone of Western Siberia.

The study of the changes in the number of the lakes depending on the geographical latitude shows that, as the latitude increases, the number of the disappeared lakes decreases on average, while the number of the newly formed lakes increases. It follows from the analysis of changes in the number of the lakes by permafrost subzones that formation of new lakes mostly takes place in the continuous permafrost subzone, while disappearance of the lakes mainly manifests itself in the discontinuous permafrost subzone.

Therefore, disappearance of lakes is the most characteristic process for the discontinuous permafrost subzone of Western Siberia. The possible causes of this process have been named. Lake disappearance is the finishing stage of the process of lake water area reduction; hence, the causes of the reduction in the number of lakes and in the lake sizes are the same. Soil desiccation caused by permafrost rock melting due to climate warming is named as one of the possible causes of the reduction of the lake areas in the discontinuous permafrost zone in the majority of the studies dealing with the thermokarst processes, in particular, those conducted in Alaska [*Hinkel et al., 2003; Riordan et al., 2006*]. Therefore the authors consider soil desiccation resulting in lake drainage to be the most likely cause of the disappearance of thermokarst lakes in the discontinuous permafrost subzone. Under conditions of climate warming, the thawing depth of permafrost soils increases in the warm seasons, which accelerates the thermoerosional water drainage from the lakes and results in the reduction of the water area in the lakes and in the disappearance of a number of lakes.

Acceleration of the thermokarst processes caused by climate warming and noted by many researchers results in more intense formation of new lakes, which is, according to the results obtained, the most characteristic process for the continuous permafrost subzone of Western Siberia. As follows from the above, the newly formed thermokarst lakes are usually small in size. According to the experimental data by [*Audry et al., 2011; Pokrovsky et al., 2011*], small thermokarst lakes Western Siberia are plentiful natural sources of methane. Therefore, one can assume increase in the methane emission into the air, as the number of small thermokarst lakes increases in the permafrost zone, which will contribute to intensification of the greenhouse effect.

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