Permafrost regions vulnerable to thaw: A Landsat, GeoEye, and DEM-based analysis of Yedoma relief in the Kolyma Lowland, East Siberia

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Background

The Yedoma deposits are widespread on the lowlands of North-East Siberia, Alaska and Yukon territories. This sediments formed in late Pleistocene and are mostly silty ice rich deposits with large polygonal ice wedges (Shirrmeister et al., 2013) and buried well-preserved organic matter (Strauss et al., 2013). Climate warming in the end of Pleistocene contrubuted to the activation of thermokarst processes and thawing Yedoma deposits, which were most active in early Holocene (Kaplina, 2009). The remnants of the Yedoma deposits due to the high ice content are vulnerable in the modern warming climate. The dynamic of thermokarst lakes can indicate the reaction of the Yedoma landscapes to the climate changes.

Key questions:

1.What is the distribution of the Yedoma deposits area and how strong it was affected by thermokarst in Holocene?
2.What was the regularities of the thermokarst development?
3. What is the modern trend of the thermokarst lake area changes?
4. What is the difference between conditions of early Holocene and modern time for the thermokarst development?

Study region

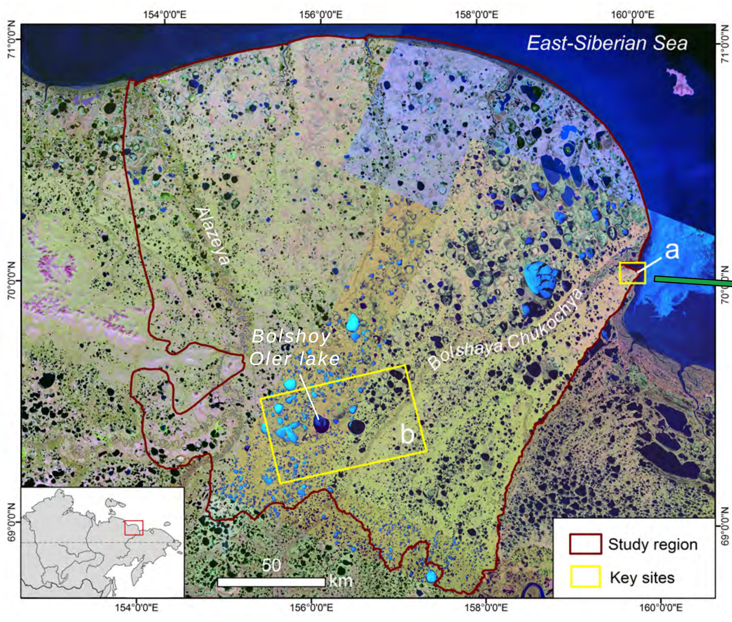


Fig.1.The study region - Kolyma lowland tundra. Mosaic from Landsat images.The key sites: a - cape Maly Chukochy; b - Oler.

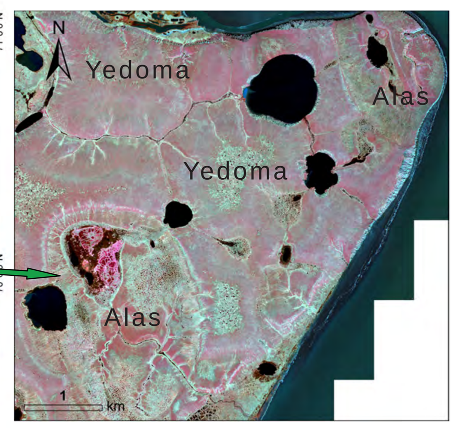


Fig.2. GeoEye image for the cape Maly Chukochy - region of field research.

Main landforms (fig.2):
Yedoma - positife relief forms, formed by late Pleistocene Yedoma deposits;
Alases - thermokarst-lake depressions formed due to Yedoma thawing in Holocene.

- Kolyma lowland tundra occupy about 45000 km^2 area and is located within the continios permafrost zone.
- Maximum heights are 70-90 m in the southern part gradually decreasing towards seashore.
- The mean annual air temperature is -15^{o}C... -13.5^{o}C. Mean annual temperature of permafrost varies from -11^{o}C to -7^{o}C. For the period 1979-2009 in the Yedoma deposits the mean temperature is increased by 0.05^{o}C per year (Kholodov et al., 2012).
- Depths of active layer vary from 20 to 70 sm depending of landscape conditions.

Methodology

Mapping of Yedoma deposits

The existing maps due to their small scale can't show the actual area of Yedoma deposits which are significantly reworked by thermokarst (fig.3).

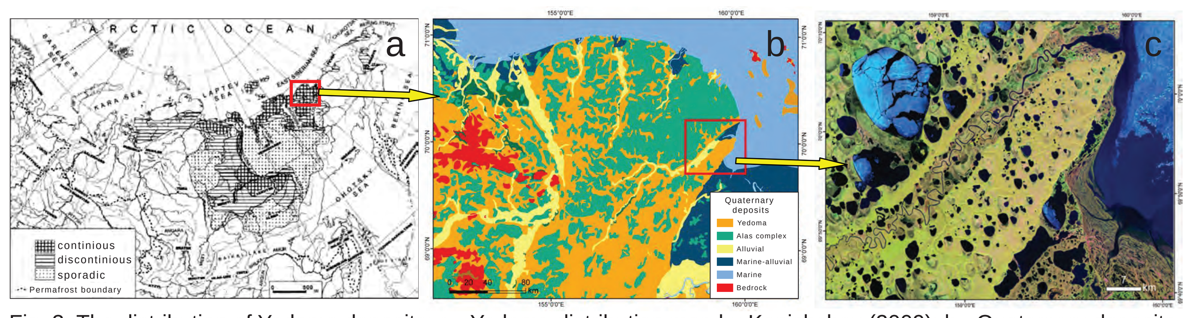


Fig. 3. The distribution of Yedoma deposits: a - Yedoma distribution map by Konishchev (2009); b - Quaternary deposits map of 1:1000000 scale (State Geological map...,2000); c - Landsat image.

For the mapping Quaternary deposits the Landsat images were used (fig.4). Allocation of deposits were done concidering the following characteristics:
1). spectral properties of satellite image;
2). morphology;
3). absolute heights from topomap of 1:200000 scale;
4). the boudaries of the Quaternary deposits from geological map of 1:1000000 scale.

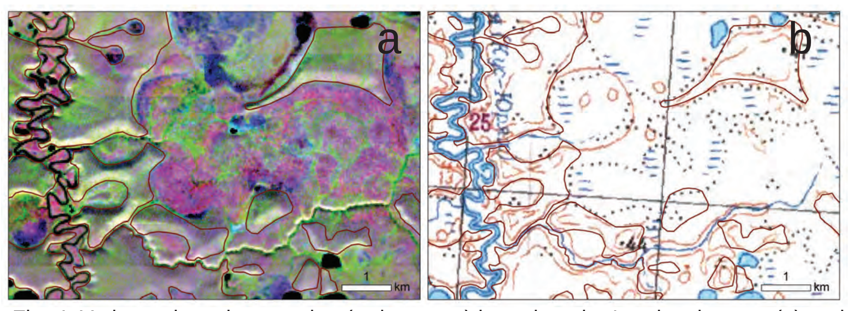


Fig. 4. Yedoma deposits mapping (red contour) based on the Landsat images (a) and topomap of 1:200000 scale (b).

The regularities of thermokarst development were revealed by DEM-analysis.

Allocating of the thermokarst lake area for Kolyma lowland tundra

Thermokarst lakes area coverage was quantified based on seven Landsat 8 images for the time period 2013-2014 from August till September. Atmospheric correction of each image was done for radiometric normalization across the dataset. An increase in ground resolution of the 30m multi-spectral data was achieved through resolution merge with the panchromatic channel to 15m pixel size. Subsequent mosaicking, classification and raster to vector conversion was done.

Modern thermokarst lake changes

1). The analysis of thermokarst lake changes were done for the key site Oler with the area of 2804 km^2 (fig.2) based on comparison of CORONA (21.07.1965) and Landsat (24.08.2014) images.
2). For the lake Bolshoy Oler the comparison of time series of Landsat images from 1999 to 2015 were done.
3). The aerial photography with resolution of 0,8 m (30.06.1972) and GeoEye images (26.09.2009 and 13.07.2013) with the resolution of 0,5 m for the detecting ponds changes of the bogged Yedoma surface were used.
4). The analysis of the summer air temperatures and precipitations of the weather stations Andrushkino and Chersky were done.

Results

Yedoma deposits distribution and thermokarst development in Holocene

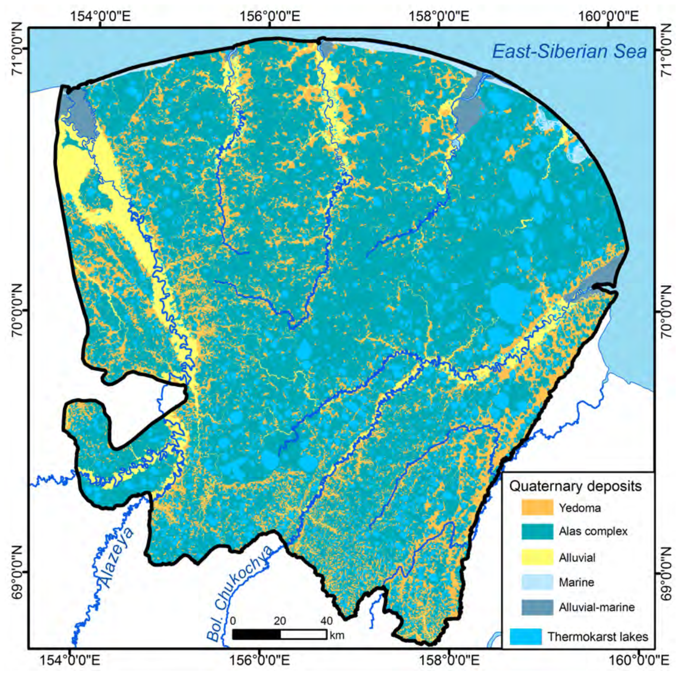


Fig. 5. Quaternary deposits map constructed by Landsat images.

The Yedoma deposits preserved on the 16% of the study region area and about 80% of the initial Yedoma plain was reworked by thermokarst in early Holocene.

Qaternary deposits area

Quaternary deposits	Area, km^2 (%)
Yedoma	6923 (16)
Alas complex	32175 (72)
Alluvial	4151 (9)
Alluvial-marine	680 (2)
Marine	476 (1)
All area	44406 (100)

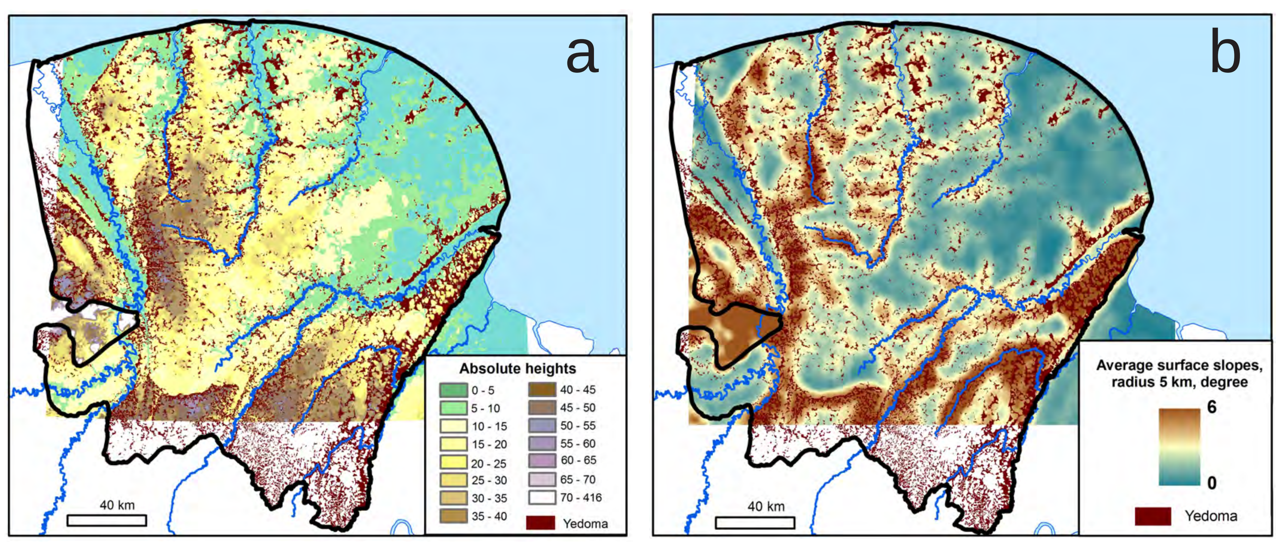


Fig. 6. The Yedoma deposits distribution in comparison with DEM (a) and average surface slopes map (b).

The analysis of the Yedoma distribution in comparison with DEM shows that mostly Yedoma preserved on the relative elevated areas with the highest value of average surface slopes. The thermokarst developed on the relative lowest flat areas of the study region.

Modern thermokast lake dynamic

Thermokarst lake changes for the key site Oler from 1965 tp 2014

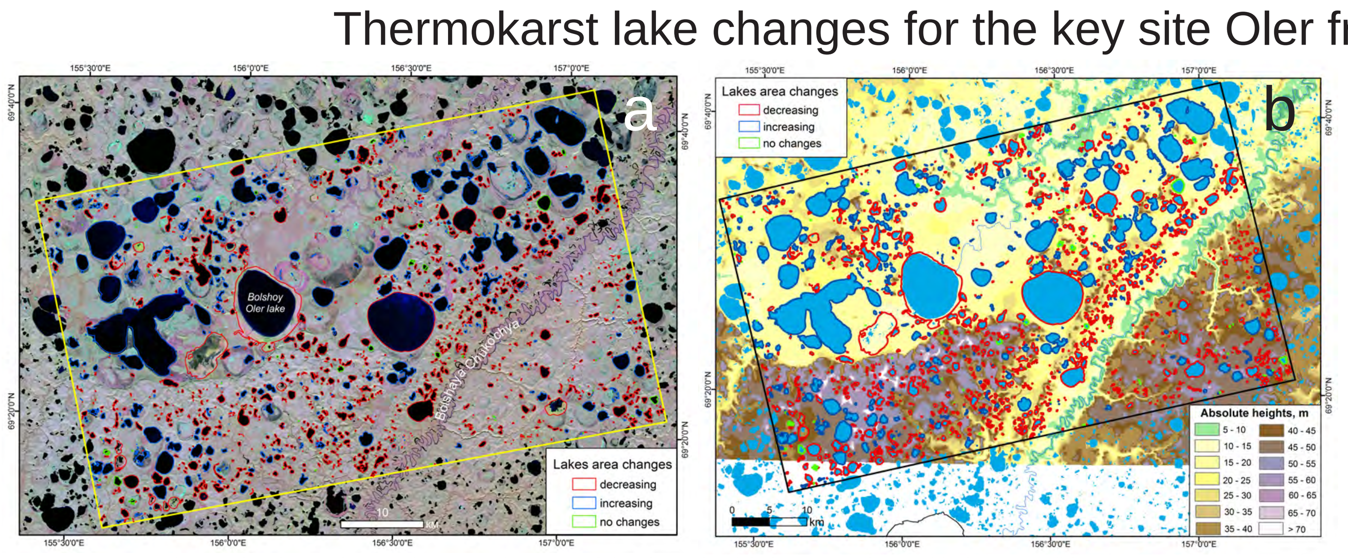
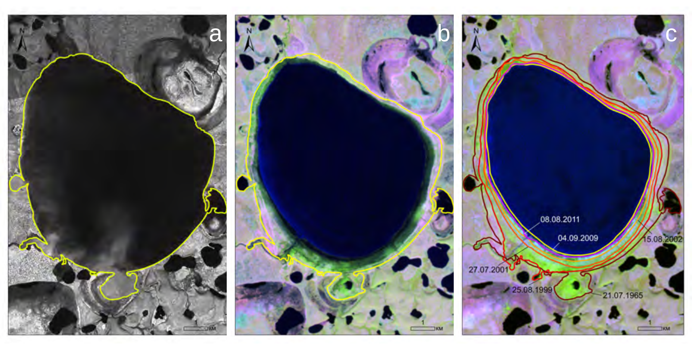


Fig. 7. The thermokarst lake area changes of the Oler site (a), in comparison with the DEM (b).

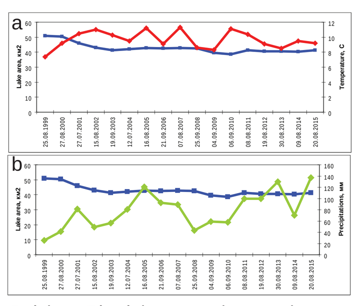
The changes of the thermokarst lakes for the Oler site

Image data	21.07.1965	26.08.2014	Changes
All lakes			
Area, km^2 (relative to the 1965, %)	589 (100)	549 (93)	-40 (-7)
Limnicity, %	21	19,5	-1,5
Lakes number	1626	1559	-66
Decreasing lakes			
Area, km^2 (relative to the 1965, %)	286 (100)	231 (81)	-55 (-19)
Ratio of the decreasing lakes area to the all area, %	48,5	42,3	-6,2
Lakes number	1147	1052	-95
Increasing lakes			
Area, km^2 (relative to the 1965, %)	294 (100)	309 (105)	+15 (+5)
Ratio of the decreasing lakes area to the all area, %	49,8	56,2	+6,4
Lakes number	408	452	+29

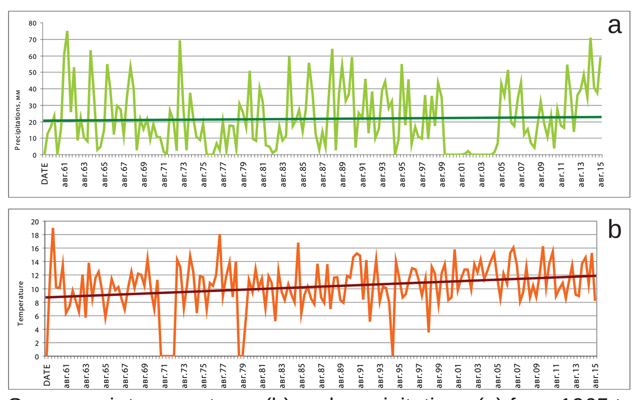
Dynamic of the Bolshoy Oler lake area



Bolshoy Oler lake area dynamic: a - CORONA (1965); b - Landsat (2015); c - most significant changes of lake area from 1999 to 2015 revealed from Landsat.

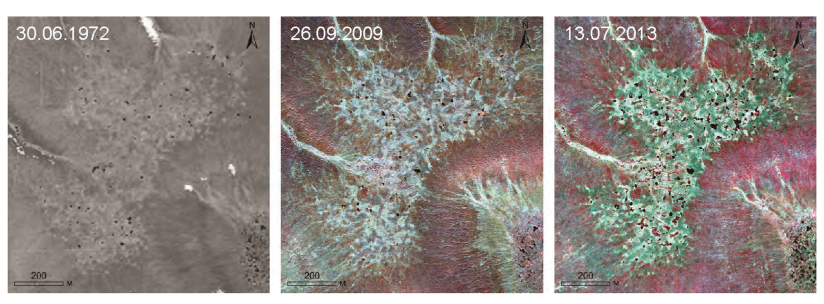


Bolshoy Oler lake area changes in comparison with summer air temperature (a) and precipitations (b) of the weather station Andrushkino.



Summer air temperatures (b) and precipitations (a) from 1965 to 2015 of the weather station Chersky.

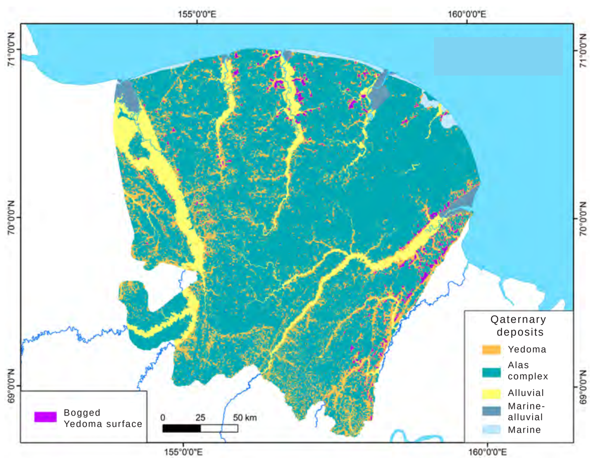
Ponds dynamic on the cape Maly Chukochy



Ponds dynamic of the bogged Yedoma surface for the site cape Maly Chukochy: the comparison of the aerial photo and GeoEye images.

Summer air temperatures and precipitations for the years of the aerial photo and GeoEye images data, weather station Chersky.

Year	Air temperature, °C	Precipitations, mm
June, 1972	No data	0,4
July, 1972	No data	26,6
August, 1972	No data	20,3
		Sum 47,3
June, 2009	8,7	4,4
July, 2009	10,4	18,3
August, 2009	8,8	32,1
	Average value 9,3	Sum 54,8
June, 2013	11,1	14
July, 2013	13,4	36,3
August, 2013	9,1	39,5
	Average value 11,2	Sum 89,8



Distribution of the bogged Yedoma surface allocated with using Landsat images.

Conclusions

Analysis of Yedoma distribution shows that about 80% of the initial Yedoma plains was reworked by thermokarst processes in Holocene. Modern relief was formed by 10000-11000 years BP (Kaplina, 2009) in the climate conditions with summer temperatures higher on 5^{o}C then modern (Lozhkin et al., 1975). The Yedoma preserved on the areas with less favorable conditions for thermokarst.

Most part of thermokarts lakes formed in early Holocene was drained. The modern thermokarst lakes exist in alas depressions and limnicity of the study area is about 13%. Only a few initial thermokarst lakes located within the Yedoma deposits were revealed.

Analysis of meteodata shows increasing trend of summer air temperatures and precipitations. In modern climate conditions the general trend of decreasing thermokarst lake area were observed. The decreasing occurs for small, meduim and some large lakes in the elevated sites and the increasing is more typical for the large lakes in the relative lowest relief position. Analysis of the Oler Bolshoy lake dynamic in comparison with meteodata doesn't show the correlation. For the bogged Yedoma surface which cover the 10 % of the all Yedoma area the increasing of ponds area were revealed. This sites can be good object for monitoring to indicate the reaction of the Yedoma landscapes to the modern climate changes.

The Landsat images can be used for the study of Yedoma deposits distribution and thermokarst development in Holocene and this is necessary basis for the analysis of the modern thermokarst lake dynamic.

Acknowledgements

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