Thermokarst lake monitoring on the Bykovsky Peninsula using high-resolution remote sensing data

Theresa Henning [1]
Frank Günther [2]
Alexander Kizyakov [3]
Guido Grosse [2,4]

[1] *Technische Universität Dresden, Faculty of Environmental Science, Institute of Geography, 01069 Dresden, Germany, theresa-henning@web.de*
[2] *Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, 14473 Potsdam, Germany*
[3] *Lomonosov Moscow State University, Faculty of Geography, Department of Cryolithology and Glaciology, 119991 Moscow, Russia*
[4] *University of Potsdam, Institute for Earth and Environmental Sciences, 14476 Potsdam, Germany*

Abstract

Thermokarst lakes are a characteristic element of arctic permafrost regions and an indicator for their rapid landscape changes. Assessing their dynamics contributes to the understanding of driving processes of change, to the evaluation of impacts on landscape characteristics as well as to the estimation of the impact on the permafrost-related carbon budget. Monitoring thermokarst lake dynamics on the Bykovsky Peninsula, consisting of ice-rich Yedoma deposits, using high-resolution remote sensing imagery from 1951 to 2016, revealed a long-term tendency towards lake drainage. Approximately 17 % of the 1951 lake area was lost due to coastal erosion or the development of drainage networks. In parallel, coastal erosion driven land loss amounts to 2.3% of the peninsula. We find process interconnections between coastal erosion and lake change, as well as lake change dependency on land elevation in a developed alas-yedoma thermokarst relief.

Keywords: thermokarst, lake dynamics, yedoma, East Siberia, remote sensing

Introduction

Arctic permafrost landscapes are in equilibrium with environmental and climatic parameters. Changes in these external factors result in dynamic and rapid changes, highlighting the landscape's vulnerability. The observed increase of both, air temperatures and seasonal duration particularly affects permafrost regions with a large amount of ground ice. Degradation of ice-rich permafrost deposits, such as Yedoma Ice Complex , initiates thermokarst and subsequent lake formation. At the same time, progressing ice-wedge degradation creates pathways for lake seepage and ultimately may lead to lake drainage. Therefore, thermokarst lakes are one of the most characteristic features of permafrost regions, indicating the thaw of perennially frozen ground and portraying the expeditious alteration of permafrost lowland landscapes (Jones et al., 2011). Investigating their long-term dynamics is important for understanding the underlying driving processes, for evaluating impacts on geomorphology, hydrology, ecosystem change as well as for estimating the potential release of climate-relevant organic carbon, previously frozen in permafrost soils (Grosse et al., 2013).

As thermokarst lakes are abundant in Arctic lowlands with ice-rich yedoma permafrost, the Bykovsky Peninsula in the north of East Siberia currently exhibits more than 300 lakes larger than 1000 m² water bodies on a land surface area of 163 km².

The objective of our study is to create a time series of high resolution orthorectified imagery and to map thermokarst lakes on the Bykovsky Peninsula in four time steps, spanning an observation period of 64 years. Based on historical aerial photography and modern satellite imagery, we here report first results from detailed lake mapping that was carried out for monitoring lake expansion and lake drainage over time using the first and last dataset from 1951 and 2015, respectively. Furthermore, tendencies of drainage or expansion with respect to elevation and potential mechanisms for lake expansion and drainage were investigated.

Methods

Baseline datasets that were used comprise historical aerial photographs from 1951 that feature ahigh level of detail, as well as high resolution satellite images from

2015 (WorldView-1, WorldView-2, and RapidEye). WorldView data at 50 cm resolution consisted of two panchromatic stereo pairs that were used for digital elevation model extraction at 1 m resolution. Ground control points collected in the field and subsequent orthorectification of WorldView imagery provided a highly consistent georeferencing basis for other datasets. RapidEye data has been georeferenced and resampled to 5 m resolution. Air photo bundle block adjustment was done according to Günther et al. (2015) and air photos were resampled to 0.9 m ground resolution. After terrain correction of single air photos and mosaicking to a map geometry, lake and shoreline mapping was done manually in panchromatic imagery and automatically based on RapidEye's near-infrared band using a threshold based approach. Finally vector datasets were incorporated into GIS to measure lake area changes and coastal erosion magnitudes.

Results and discussion

Preliminary results of thermokarst lake changes over the 1951 to 2015 period revealed a net lake shrinkage tendency (Tab. 1).

Table 1. Thermokarst lake changes on the Bykovsky Peninsula from 1951 to 2015

	1951	2015
Lake quantity	577	816
Lake surface area [km²]	19.76	16.44
Land-lake-ratio [%]	11.87	10.11

In 1951, lake area was 1975.6 ha, while it decreased to 1644.4 ha until 2015. Considering the land loss of Bykovsky over the same time from 166.5 to 162.7 km² (without lagoon areas), this corresponds to an overall decrease of the peninsula's lake limnicity from 11.9 to 10.1 %. In contrast to the general lake area decrease, when focusing only lakes that are present in both datasets, the number of lakes has increased. This can be attributed to the fact that i.e. the drainage of a large lake may leave behind several smaller residual lakes. While drained large lakes were mostly located in lower elevation lake basins close to the coast, a considerably higher number of medium-size lakes drained through thermo-erosion valleys on yedoma uplands.

The initial assessment of thermokarst lake change rates focused on lakes that exist in both datasets. At this stage, we did not differentiate between growing and shrinking lakes.

Following these first order estimations, a net lake area decrease of $3.31 * 10^6$ m² was observed, corresponding to 5.2 ha lake area lost per year. Similar to lake change, coastal erosion was also investigated based on the net change area between two states of the coastline for the entire peninsula. Accordingly, mean total retreat across the entire coastline was 42.7 m, corresponding to an average rate over 64 years of 0.68 m/yr. This rate is somewhat higher than the mean erosion rate over the 1951-2007 time period found by Lantuit et al. (2011). This reflects considerably higher rates that emerged during the recent past with several all-time sea ice minima and very warm summers (Günther et al. 2015).

Conclusions

Our findings suggest that thermokarst lakes on the Bykovsky Peninsula are subject to high dynamics. Numerous lakes drained due to coastal erosion or the development of drainage networks, portraying the proneness of arctic coastal tundra lowlands to disturbances and changing environmental conditions. By monitoring thermokarst lakes on Bykovsky, a long-term tendency towards drainage was identified and this trend cannot be considered separately, but is rather the result of the interrelation of endogeneous and exogeneous forcings such as ice-wedge degradation and coastal erosion, both of which fostering accelerated permafrost degradation.

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