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Evolution of thermokarst in East Siberian ice-rich permafrost: A case study

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ABSTRACT

Thermokarst lakes and basins are major components of ice-rich permafrost landscapes in East Siberian coastal lowlands and are regarded as indicators of regional climatic changes. We investigate the temporal and spatial dynamics of a 7.5 km^2, partly drained thermokarst basin (alas) using field investigations, remote sensing, Geographic Information Systems (GIS), and sediment analyses. The evolution of the thermokarst basin proceeded in two phases. The first phase started at the Pleistocene/Holocene transition (13 to 12 ka BP) with the initiation of a primary thermokarst lake on the Ice Complex surface. The lake expanded and persisted throughout the early Holocene before it drained abruptly about 5.7 ka BP, thereby creating a >20 m deep alas with residual lakes. The second phase (5.7 ka BP to present) is characterized by alternating stages of lower and higher thermokarst intensity within the alas that were mainly controlled by local hydrological and relief conditions and accompanied by permafrost aggradation and degradation. It included diverse concurrent processes like lake expansion and stepwise drainage, polygonal ice-wedge growth, and the formation of drainage channels and a pingo, which occurred in different parts of the alas. This more dynamic thermokarst evolution resulted in a complex modern thermokarst landscape. However, on the regional scale, the changes during the second evolutionary phase after drainage of the initial thermokarst lakes were less intense than the early Holocene extensive thermokarst development in East Siberian coastal lowlands as a result of a significant regional change to warmer and wetter climate conditions.

1. Introduction

Thermokarst lakes and basins are ubiquitous landforms in arctic lowlands. Current research has a particular focus on thermokarst processes in ice-rich permafrost deposits in Siberia and the North American Arctic, because these deposits are highly vulnerable to degradation under a warming climate. The high content of excess ice accounts for their high thawing potential, and the large amount of organic matter (OM), which has been stored in permafrost deposits for several thousand years, has a high potential for the release of greenhouse gases (Jorgenson et al., 2006; Walter et al., 2007; Schuur et al., 2009; Grosse et al., 2011; van Huissteden et al., 2011). These late Pleistocene fine-grained, ice-rich deposits are often referred to as "Yedoma" or "Ice Complex" (hereafter "IC"; Schirrmeister et al., 2011a, 2013). Thermokarst in East Siberian ice-rich permafrost massively developed at the transition from Pleistocene to Holocene, but after the Boreal period (9–7.5 ka BP), the thermokarst landscapes appeared as they do today and have experienced only minor changes since then (Romanovskii et al., 2004; Kaplina, 2009). Parallel to this concept of unidirectional thermokarst evolution, including initiation, expansion, drainage, and cessation of thermokarst activity leading to stable modern thermokarst landscapes, thermokarst has been regarded as a highly dynamic process, and the concept of a thaw lake cycle which has been repeated several times during the Holocene has been proposed (e.g. Hopkins, 1949; Tomirdiaro, 1965; Billings and Peterson, 1980; Hinkel et al., 2003). This concept describes secondary thermokarst activity in drained basins after sufficient ice aggradation, but substantial evidence is lacking that several complete thaw lake cycles have occurred in arctic tundra landscapes during the Holocene (French, 2007; Jorgenson and Shur, 2007). Many recent studies, which investigate changes in thermokarst lake area by means of multitemporal remote sensing, reveal ongoing thermokarst dynamics during the last decades. For different Siberian regions in the continuous permafrost zone, thermokarst area has been increasing (Smith et al., 2005; Walter et al., 2006; Kravtsova and Bystrova, 2009) or decreasing due to lake drainage (Kravtsova and Bystrova, 2009; Günther et al., 2010), but there are also areas where no changes occured (Kravtsova and Bystrova, 2009). These studies differentiate the settings in which these lake area changes take place, but there are great differences between the potential and impact of developing thermokarst in undisturbed ice-rich late-Pleistocene deposits and that in older-generation thermokarst basins (Morgenstern et al., 2011; Kessler et al., 2012). Such drained or partly drained thermokarst

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basins occurring in Siberian ice-rich permafrost are termed "alasses" (Soloviev, 1962; van Everdingen, 2005).

Several studies have been conducted regarding the general stratigraphy of Yedoma-type IC deposits in the Laptev Sea region (e.g., Wetterich et al., 2008; Schirrmeister et al., 2011a,b), the onset of thermokarst (Kaplina and Lozhkin, 1979; Tumskoy, 2002), recent changes of thermokarst lake area (Günther, 2009; Kravtsova and Bystrova, 2009; Günther et al., 2010), and the potential of future thermokarst evolution (Morgenstern et al., 2011). However, there is a gap in our knowledge about how these permafrost degradation landforms have developed during the Holocene, i.e. whether they experienced several cycles of drainage, permafrost aggradation, and thermokarst formation, or not. As a first step to answer these questions, this paper provides an exemplary study of a thermokarst landform, which is representative for thermokarst in ice-rich permafrost of the northeast Siberian coastal lowlands. Our investigations aim at the detailed characterization of the temporal and spatial dynamics of thermokarst in ice-rich permafrost. Field investigations of a partly drained thermokarst lake basin (alas) in IC deposits with three large lakes are combined with remote sensing, Geographic Information Systems (GIS), and sediment analyses to distinguish different stages of thermokarst dynamics. The specific objectives are to: 1) characterize the modern thermokarst landscape based on morphological and surface properties, 2) discriminate different phases of thermokarst development, and 3) reconstruct the landscape dynamics of the exemplary alas due to permafrost degradation and aggradation during the Holocene.

2. Study site and regional setting

The investigated alas is situated on Kurungnakh Island in the south-central Lena River Delta, Siberia (72°19′N; 126°12′E) (Fig. 1), in the continuous permafrost and subarctic tundra zone. Kurungnakh Island belongs to the third main terrace of the Lena Delta (Grigoriev, 1993), which is distributed in the southern delta as erosional remnants of a late-Pleistocene accumulation plain in the foreland of the Chekanovsky

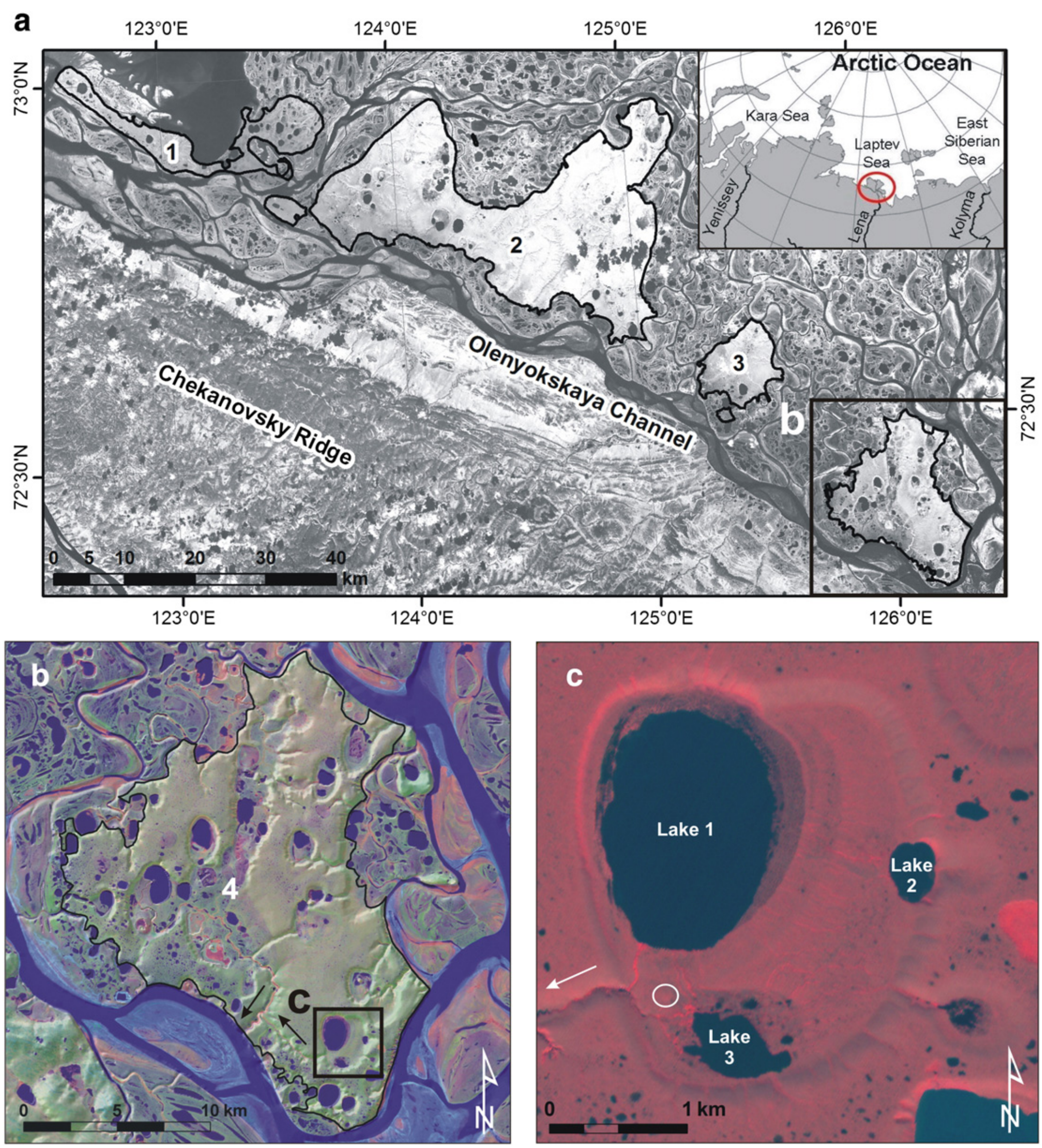

Fig. 1. Location of the study area. (a) Ice Complex (IC) remnants (black outlines) in the southwestern Lena River Delta forming the third terrace. 1—Ebe-Basyn Island, 2—Khardang Island, 3—Dzhangylakh Island (Landsat-7 ETM + mosaic, band 4). (b) Kurungnakh Island. Black outline marks the IC extent; arrows indicate the flow direction of the thermo-erosional valley draining the investigated alas. 4—Alas valley formed by coalescence of several alasses (Landsat-7 ETM+, RGB 4-5-3, over DEM shaded relief derived from topographic maps). (c) Investigated thermokarst depression with three large thermokarst lakes. White circle indicates a small pingo; white arrow shows the flow direction of the draining thermo-erosional valley (ALOS AVNIR-2, RGB 4-3-2, acquisition date: 18 August 2006).