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Evolution of the banks of thermokarst lakes in Central Yakutia (Central Siberia) due to retrogressive thaw slump activity controlled by insolation

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ABSTRACT

As observed in most regions in the Arctic, the thawing of ice-rich permafrost (thermokarst) has been developing in Central Yakutia. However, the relationship between thermokarst development and climate variations is not well understood in this region, in particular the development rate of thaw slumps. The objective of this paper is to understand the current development of thermokarst by studying the evolution of the banks of thermokarst lakes. We studied retrogressive thaw slumps and highly degraded ice-wedge polygons (baydjarakhs), indicative of thermokarst, using high resolution satellite images taken in 2011–2013 and conducting field studies. The retrogressive thaw slump activity results in the formation of thermocirque with a minimum and maximum average headwall retreat of 0.5 and 3.16 $m \cdot yr^{-1}$ respectively. The thermocirques and the baydjarakhs are statistically more concentrated on the south- to southwest-facing banks of thermokarst lakes. Moreover, the rate of headwall retreat of the thermocirques is the most important on the south-facing banks of the lakes. These observations indicate a control of the current permafrost thaw on the banks of thermokarst lakes by insolation. In the context of recent air temperature increase in Central Yakutia, the rate of thermocirque development may increase in the future.

1. Introduction

Permafrost that contains a high ice-content exceeding that of soil pores is referred to as ice-rich (ACIA, 2006; French, 2007). Late-Pleistocene ice-rich permafrost is found in Northern Canada, Alaska, as well as Northern, Central and Eastern Siberia (French and Shur, 2010; Kanevskiy et al., 2011). Ice-rich permafrost is commonly composed of more than 40% volume of ground ice in the form of segregated ice and massive ice-wedges (ACGR, 1988; French and Shur, 2010). Ice-rich permafrost is sensitive to climate change and was extensively thawed during the early Holocene climatic optimum forming numerous thermokarst lakes (Romanovskii et al., 2000; Kaufman et al., 2004; Wanner et al., 2008). The thermokarst denotes the processes and landforms associated with ablation of ground ice and subsequent subsidence of the ground (Popov, 1956; ACGR, 1988; French, 2007).

Recent mean annual air temperature increases in arctic and subarctic regions have been significantly greater than global averages (Serreze et al., 2000; Johannessen et al., 2004; Skachkov, 2010). The frequency and magnitude of terrain disturbances associated with thawing permafrost (thermokarst) are thus increasing in these regions (Osterkamp, 2005; Jorgenson et al., 2006; Lantuit and Pollard, 2008; Lantz and Kokelj, 2008). As climatic simulations predict that the Arctic will experience one of the quickest warming on the planet, thermokarst processes should spread and intensify (ACIA, 2006). Thermokarst is a substantial risk for buildings and infrastructures because of the high volume of ground ice in these regions (Lunardini, 1996; Nelson et al., 2001). Permafrost thaw on lake banks can significantly alter lakes and streams by bringing suspended sediments and solute concentration (Lamoureux and Lafrenière, 2009; Kokelj et al., 2013). A better understanding of the distribution and rate of current thermokarst development is therefore of importance for inferring future changes in the arctic and subarctic regions.

The Central Yakutia, located in Central Siberia, displays an ice-rich permafrost and a strong continental climate favoring thermokarst formation (Fig. 1a) (Soloviev, 1973a; Romanovskii et al., 2000). As the mean annual air temperature at Yakutsk had increased by 3 °C between 1966 and 2009 (Skachkov, 2010) and thermokarst processes seem to develop rapidly at different study sites in Central Yakutia since the early 1990s (Iijima et al., 2010; Fedorov et al., 2014), this ice-rich

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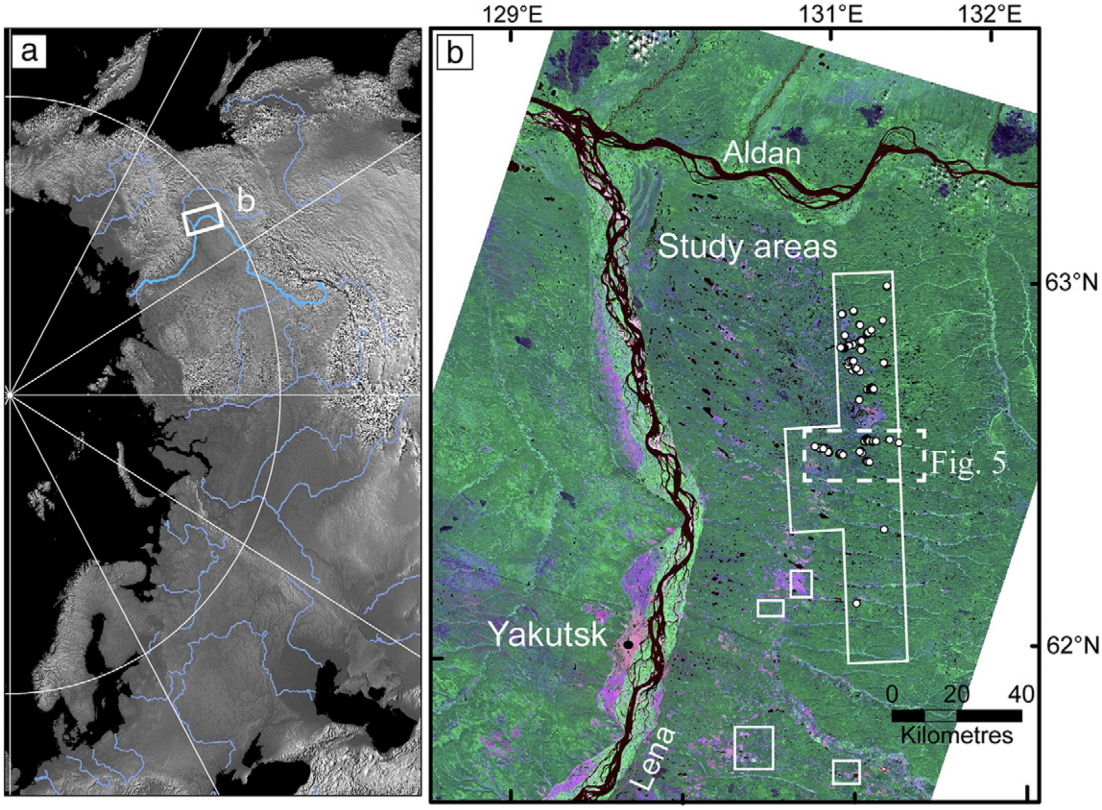

Fig. 1. Localization of the study areas in Central Yakutia. (a) Shaded-relief map of Siberia. (b) Distribution of retrogressive thaw slumps along the banks of thermokarst lakes (white dots). White rectangles represent the footprints of the high resolution satellites images used. Landsat ETM+ image as background.

permafrost is highly vulnerable and prone to extensive degradation. Along the banks of thermokarst lakes, the thawing of permafrost forms two different thermokarst landforms: retrogressive thaw slumps and highly degraded ice-wedge polygons (baydjarakhs). Deep permafrost thawing induces retrogressive thaw slumping and the formation of amphitheatrical hollows referred to as "thermocirque" (Fig. 2a) (Czudek and Demek, 1970). While retrogressive thaw slump are intensively studied in some arctic regions, their evolution in Central Yakutia has not been investigated recently (Czudek and Demek, 1970). Moreover, localized melting of ice-wedges forms highly-degraded conical polygons with wide troughs referred to as "baydjarakhs" (Fig. 2b) (Popov, 1956; Soloviev, 1973a). While it was assumed that the baydjarakhs only form on south-facing slopes due to insolation (Czudek and Demek, 1970), this assumption has not been demonstrated systematically and statistically.

Here we study the bank degradation of thermokarst lakes in Central Yakutia due to permafrost thaw. The analysis of the evolution of retrogressive thaw slumps and polygonal baydjarakhs provides a better understanding of the current thermokarst dynamic in this region. We used (i) field surveys and (ii) high resolution (50 cm) satellite images taken between 2010 and 2013, with the aim of: (i) characterizing the morphology and geographical distribution of thermokarst lake banks; (ii) estimating the annual rate of thermocirque development; and (iii) understanding the processes and origin of the slump development.

2. Study site

The Central Yakutia (Sakha Republic in the Russian Federation) located within the continuous permafrost zone is the lowland plain stretching along the Lena, Aldan and Vilyuy rivers and the Verkhoyansk Range (Fig. 1a; Bogatova and Bugrimova, 1981). The climate is continental (mean temperature −10 °C), characterized by a distinct seasonal variation (mean temperature +20 °C in July and −40 °C in January) and low precipitation of 250 mm per year, mainly occurring during the warm season (June–August) (Skachkov, 2010). The potential evaporation per year is however up to four times the precipitation in summer, and up to ten times during dry years (Gavrilova, 1973; Fedorov et al., 2014).

The central Yakutian lowlands are covered by Quaternary sediments consisting predominantly of silty clays and sandy silts of fluvial, lacustrine or loessic origin (Soloviev, 1973b; Péwé et al., 1977). Numerous fluvial terraces have developed along the Lena and Aldan rivers and their tributaries during the Pleistocene (Soloviev, 1973b). The permafrost in this region has a thickness of 400 to 700 m, with a maximum of 1500 m observed on the Siberian Plateau in the upstream of the Markha River, associated with an active-layer of 0.5–2 m (Ivanov, 1984; Romanovsky et al., 2007). The mean temperature of the permafrost at 10–20 m deep ranges from −2 °C to −4 °C (Soloviev, 1973b; Ivanov, 1984). In some parts of Central Yakutia, the upper part of the permafrost consists of ice-rich sediments, which are up to 20–30 m thick and called the "Yedoma ice-complex" (Czudek and Demek, 1970; Soloviev, 1973b). They contain ~70–80% of ice by volume and are characterized by massive syngenetic ice-wedges (≥10 m thick), as seen on the headwall of a thermocirque in Fig. 2a (Soloviev, 1959; Ivanov, 1984). This permafrost is syngenetic and made up of Quaternary sediments forming terraces of various origins (Soloviev, 1973b; Péwé et al., 1977). Syngenetic permafrost is defined as permafrost that formed more or less simultaneously with the deposition of the surrounding soil material (ACGR, 1988). The study area intersects the ice-rich Tyungulu and Abalakh terraces of the Lena River that contain ~70–80% of ice by volume (Soloviev, 1959; Dylik, 1964). These terraces can reach 40–60 m in thickness and are made of alluvial sandy loam containing up to 40–50% of ice by volume, and also show massive syngenetic ice-wedges (Katasonov and Ivanov, 1973; Soloviev, 1973b; Ivanov, 1984). A significant part (up to 40%) of the land surface in the