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Interannual variations in the hydrothermal regime around a thermokarst lake in Beiluhe, Qinghai-Tibet Plateau

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ABSTRACT

Thermokarst is a term associated with the thaw of ice-rich permafrost and the resulting formation of irregular depressions in the landscape from thaw settlement. Thermokarst lakes may subsequently develop from ponds formed in depressions. These lakes commonly have collapsing shorelines, and the development of thermokarst terrain and associated thermal erosion may significantly influence the stability of infrastructure and the hydrothermal conditions of the surrounding permafrost. In this study, we examined interannual variations in the hydrothermal regime of a thermokarst lake in Beiluhe Basin based on field data measured in 2006–2013. The timing and nature of lake ice growth and melt were recorded. We observed considerable seasonal differences in lake water level (~0.5 m) and differences in water level between the lake and the water table in the surrounding ground (over 1.0 m). The nearly-saturated ground at the lakeshore (~35% in maximum volumetric water content) highlights the seepage effect from the lake to the surrounding ground. The vertical temperature profile from +2 m (air) to −2 m (lake bottom) and to 60 m depth in the ground was measured. The annual mean air temperature, lake-surface temperature, and annual mean lake-bottom temperature in 2010–2011 were approximately −3.6, 0.4, and >5 °C, respectively. The thermal offsets between the air and the lake surface and between the lake surface and lake bottom were 3 and 7 °C, respectively. The annual mean lake-bottom temperatures ranged from 2.3 to 6.9 °C at water depths from 1.2 to 2.1 m. The asymmetry of the bathymetry has resulted in distinct thermal regimes beneath the lake bottom in different locations. A through-talik was present at the deepest side of the lake, but some permafrost extended laterally beneath the lake bottom at the shallower side, forming an hourglass shape in cross section at one end. Lateral thermal erosion along the lakeshore was linked to the lake-bottom temperature and lake depth. Variation in permafrost table depth from the lake center to the lakeshore was greater on the east side near deeper water (≥2 m) than at the west side where water was shallower (≤70 cm). The results from this study have highlighted the hydrothermal relations between thermokarst lake development and permafrost conditions.

1. Introduction

The Qinghai-Tibet Plateau (QTP) is largely underlain by permafrost, with an areal extent of ~1.05×10^6 km^2 (Ran et al., 2012). Permafrost on QTP is characteristically thin, warm, and ice-rich, making it sensitive to thermal disturbance. In 1954 Qinghai-Tibet Highway (QTH) was built, and in the early 2000s Qinghai-Tibet Railway (QTR) was constructed, both traversing the plateau to Lhasa (Zhang et al., 2008). The climate on QTP is changing rapidly with recent increases in air and ground temperatures and precipitation (Liu and Chen, 2000; Wu and Zhang, 2008; Lin et al., 2015a). The combined influences of increasing human activities and persistent climatic warming have together accelerated the degradation of permafrost (Wang and Mi, 1993; Zhu et al., 1995; Nan et al., 2003; Jin et al., 2008) and increased thermokarst activity (Lin et al., 2010; Niu et al., 2011).

The term *thermokarst* was first introduced by M. M. Yermolayev in 1932 and is now widely adopted in geology and geomorphology (Czudek and Demek, 1970). Thermokarst terrain results from the melt of ice in permafrost and the associated thaw settlement of the ground surface, which forms irregular depressions on the landscape (Jorgenson et al., 2006). Thermokarst lakes may subsequently form if water accumulates in these depressions, and their formation often further degrades permafrost. Thermokarst terrain is a common feature of permafrost regions and is widespread in northern Canada (Sannel and Kuhry, 2011), Russia (Veremeeva and Gubin, 2009), and Alaska (Jorgenson et al., 2008). In China, numerous thermokarst lakes are distributed along QTR and QTH (Niu et al., 2011). Observations of a 2514

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km^2 part of Beiluhe Basin on QTP indicated that the number of thermokarst lakes increased by about 534 between 1969 and 2010 (from 761 in 1969 to 1295 in 2010). This represented an increase in lake surface area of about 4.1 km^2 (from 32.4 km^2 in 1969 to 36.5 km^2 in 2010). The increase in area was mostly accounted for by the initiation of about 400 small lakes (Luo et al., 2015).

The development of thermokarst lakes, an indicator of permafrost warming, has a significant effect on local surface water budgets and ecosystems by modifying micro- and macroscale topography (Johansson et al., 2006). Thermokarst lake development may also have implications for nearby infrastructure integrity as permafrost may degrade by lateral thermal erosion. As a result, the study of thermokarst processes presently receives significant international attention in the permafrost literature and requires an increasingly multidisciplinary approach to capture the associated processes and changes in environmental conditions.

On QTP, thermokarst lake area, geometry, and lake-bottom temperature have been reported by Niu et al. (2011). Lin et al. (2010, 2011) also examined the thermal regime, lateral erosion, and interannual variations in the hydrothermal regime at the thermokarst lake under investigation in this study. However, some topics related to thermokarst lakes, such as the nature of the ground/lake water balance and mechanisms of thermal erosion are still not fully understood. Here we present new information from this thermokarst lake, including: (i) periodic processes in ice growth and melt, (ii) water movement between the lake and surrounding ground, and (iii) the thermal offset between the air, lake-surface, and lake-bottom temperatures. These findings expand on the previous results, supplement the report on the thermal regime at the opposite (shallower) side of the lake by Lin et al. (2010), and contribute to a better understanding of relations between thermokarst processes, climate, and permafrost conditions in high elevation and mountainous regions.

2. Regional conditions, northern QTP

The QTP lies in western China where elevation exceeds 4000 m asl (Fig. 1). The plateau has a continental climate, characterized by long, cold winters and short, warm summers (Lin et al., 2015a). The mean annual air temperature (MAAT) in permafrost regions of QTP is below −4 °C, with minimum and maximum air temperatures of about −30 and 25 °C in January and July, respectively (Jin et al., 2008). The potential evaporation is 1300 to 1500 mm (Wu and Zhang, 2008), far exceeding the mean annual precipitation of 50 to 400 mm. Precipitation mainly occurs in May to September.

The QTP is a windy environment. Wind speeds are greatest in winter (January–March) and lowest in late summer (August–September). Mean annual ground temperatures (MAGTs) of permafrost in most high plains or valleys on QTP are above −1.5 °C, and permafrost thickness is <70 m (Zhou et al., 2000). At higher elevations, the MAGT is lower than −1.5 °C, and permafrost thickness may exceed 130 m (Lin et al., 2015a).

3. Study area and lakes, Beiluhe Basin

Beiluhe Basin is located in central QTP at elevations of 4500 to 4600 m asl (Fig. 1). The terrain is undulating, covered with sparse vegetation or fine to gravelly surface sands. However, vegetation cover is more developed around thermokarst lakes (Lin et al., 2010). At the Beiluhe weather station, the annual mean air temperatures were between −4.1 and −2.9 °C from 2005 to 2010, with an average value of −3.5 °C over this period. From 2004 to 2014 the annual mean precipitation ranged between 229 and 467 mm (average: 353 mm), while the annual mean potential evaporation was ~1588 to 1626 mm (average: 1613 mm). The Beiluhe Basin is within the continuous permafrost zone and the ground is ice-rich at 30–50% volumetric ice content. Drill cores obtained from the area indicate that the soil profile is composed of 1.5 m of fine sand containing some clay overlying massive icy permafrost 2–3 m thick. Mudstone and sandstone underlie the ice-rich permafrost. The mean annual ground temperature ranges from −1.8 to −0.5 °C and the active-layer thickness is 1.8–3.0 m. Permafrost is ~ 20–80 m thick and exhibits a geothermal gradient of 1.5×10^{-2} to 4.0×10^{-2} °C/m (Lin et al., 2010).

There are over 1200 lakes with areas >1000 m^2 in the Beiluhe Basin (Luo et al., 2015). The largest lake is >60,000 m^2, and the mean size is

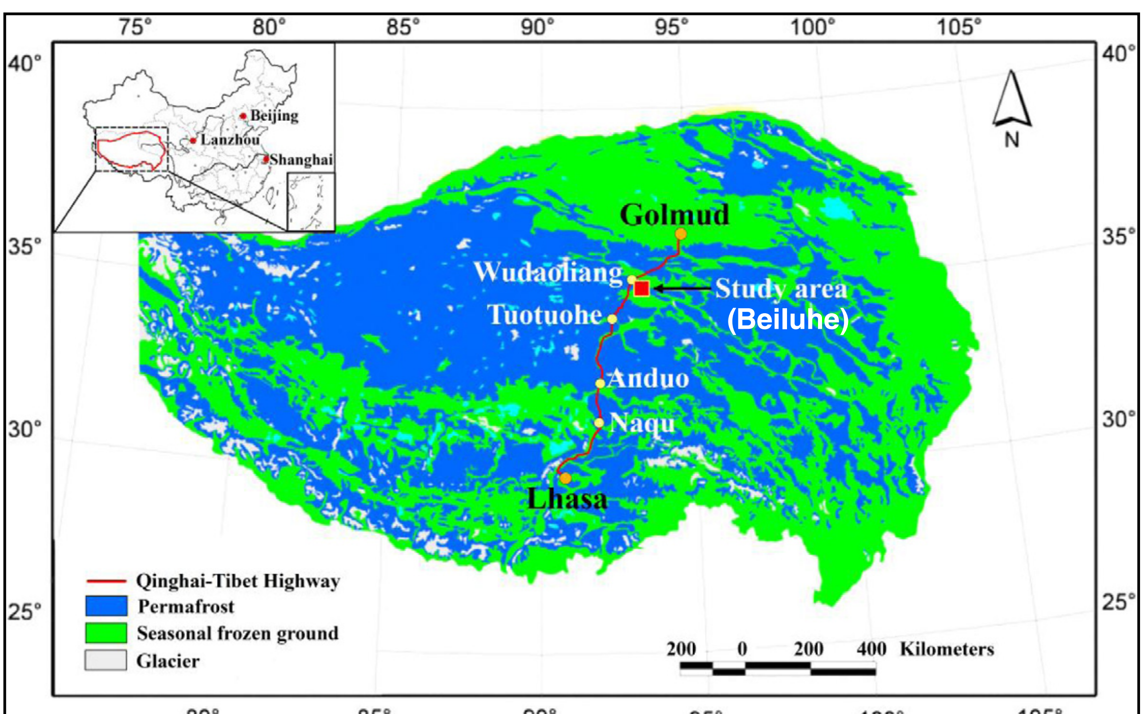

Fig. 1. Location of the study area in the continuous permafrost of Qinghai-Tibet Plateau (after Lin et al., 2016, Fig. 1).