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Effects of local factors and climate on permafrost conditions and distribution in Beiluhe basin, Qinghai-Tibet Plateau, China

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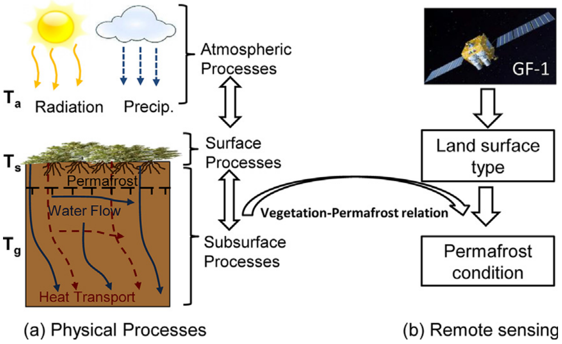
HIGHLIGHTS

- First report on spatial permafrost conditions in Beiluhe basin, Qinghai-Tibet Plateau.
- Spatial variations in permafrost conditions and recent ground thermal evolution have been synthetically descripted.
- Relations between local environment factors and permafrost were detailed revealed.
- First use of the GF-1 data to interpret vegetation and soils and infer permafrost distribution.

GRAPHICAL ABSTRACT



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ABSTRACT

Beiluhe basin is underlain by warm and ice-rich permafrost, and covered by vegetation and soils characteristic of the Qinghai-Tibet Plateau. A field monitoring network was established to investigate permafrost conditions and to assess potential impacts of local factors and climate change. This paper describes the spatial variations in permafrost conditions from instrumented boreholes, controlling environmental factors, and recent thermal evolution of permafrost in the basin. The study area was divided into 10 ecotypes using satellite imagery based classification. The field investigations and cluster analysis of ground temperatures indicated that permafrost underlies most of the ground in swamp meadow, undisturbed alpine meadow, degrading alpine meadow, and desert alpine grassland, but is absent in other cover types. Permafrost-ecotope relations examined over a 2-year (2014–2016) period indicated that: (i) ground surface temperatures varied largely among ecotopes; (ii) annual mean ground temperatures ranged from −1.5 to 0 °C in permafrost, indicating sensitive permafrost conditions; (iii) active-layer thicknesses ranged from 1.4 m to 3.4 m; (iv) ground ice content at the top of permafrost is high, but the active-layer soil is relatively dry. Long-term climate warming has driven thermal changes to permafrost, but ground surface characteristics and soil moisture content strongly influence the ground thermal state. These factors control local-scale spatial variations in permafrost conditions. The warm permafrost in the basin is commonly in thermal disequilibrium, and is sensitive to future climate change. Active-layer thicknesses have increased by at least 42 cm and the mean annual ground temperatures have increased by up to 0.2 °C in the past 10 years over the basin. A permafrost distribution map was produced based on ecotypes, suggesting that permafrost underlies 64% of the study region.

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1. Introduction

Recent increases in near-surface air temperature have been pronounced in many regions of the world. This has led to permafrost degradation as ground temperatures and the active-layer thickness increase (Vaughan et al., 2013). These permafrost responses to warming climate are expected to continue in the coming decades based on predictions by general circulation models (GCM) (Lawrence et al., 2012).

In China, permafrost is mainly distributed on the Qinghai-Tibet Plateau (QTP), the largest lower-latitude permafrost region in the world (1.05×10^6 km^2). Permafrost on the QTP is thinner and warmer than in high latitude environments such as North America and Russia (Zhou et al., 2000). Thus, it is more sensitive to climate change and environmental disturbances that alter the surface energy balance. Increases in permafrost temperature during the last few decades are well documented along the Qinghai-Tibet Engineering Corridor (QTEC) (e.g. Li et al., 2012; Wu and Zhang, 2008, 2010; Wu et al., 2012). Changes in the active-layer thickness and permafrost temperature due to climate warming and surface disturbances have major ecological and engineering implications (e.g. Cheng and Wu, 2007; Jin et al., 2008; Wu et al., 2013; Yang et al., 2010). The thaw of ice-rich permafrost has impacts on the stability of slopes and thermokarst (Lin et al., 2010; Ma et al., 2006; Niu et al., 2011), which may lead to instability along the Qinghai-Tibet Railway (QTR, a critical infrastructure) (Niu et al., 2012).

It is important to understand the conditions and active processes controlling the present state of permafrost on the QTP. However, most investigations are focused along sections of the QTEC, or consist of sparse observations in large regions. The distribution and characteristics of mountain permafrost have only been assessed at a coarse scale due to the difficultly accessing such terrain on the QTP. Furthermore, spatial datasets of local environmental factors that control permafrost conditions are commonly either highly generalised or may not exist. Local factors such as slope, aspect, local hydrology, vegetation cover, geology, and snow cover strongly affect local microclimate and the surface energy balance (e.g. Hasler et al., 2015; Jones et al., 2016; Morse et al., 2016; Smith, 1975). Therefore, it is important to understand the relative influences of these effects on permafrost conditions, as it may allow the development of cold region engineering techniques (Cheng, 2004; Niu et al., 2015, 2016), and the calibration and validation of spatially distributed permafrost models (e.g. Riseborough et al., 2008). However, field measurements of permafrost conditions are difficult to obtain because permafrost is buried underground, and also is heterogeneous in nature, and largely found in remote locations. Remote sensing techniques for permafrost monitoring tool are continuously developing, making use of fine spatial and temporal resolution data from satellites such as Landsat-8, SPOT-5 and GF-1 and 2. Current approaches of permafrost monitoring utilize surface indicators such as vegetation cover, geomorphology, or combinations of different surface features (e.g. Stow et al., 2004; Etzelmuller et al., 2006; Panda et al., 2010) to infer permafrost conditions qualitatively. Remote sensing has the potential to provide a valuable and cost-effective means for mapping and monitoring near-surface permafrost conditions as well as seasonally frozen ground (Zhang, 2004; Westermann et al., 2015).

Beiluhe basin is located in central QTP, about 320 km from Golmud (Fig. 1). This area is underlain primarily by ice-rich (volumetric ice content > 25%), warm (mean annual ground temperature (MAGT) > −1.0 °C) permafrost. The basin is covered by vegetation and soils characteristic of the QTP. Therefore, Beiluhe basin is an appropriate area for studying the combined effects of local environmental factors and climate change on permafrost conditions on the QTP. A permafrost observation network was recently established in the basin to investigate the response of permafrost to climate, vegetation, and hydrology change, by the State Key Laboratory of Frozen Soils Engineering, Chinese Academy of Sciences. The goal of this investigation is to investigate the thermal conditions of permafrost and its distribution in Beiluhe basin using field and satellite-based methods. The specific objectives are to:

1) investigate the occurrence and thermal conditions of near-surface permafrost;
2) discuss the spatial variation of the ground thermal regime in different vegetation and soils;
3) investigate the effects of local factors and climate on permafrost;
4) produce a map of permafrost distribution in Beiluhe basin based on the field investigations and remotely-sensed imagery.

2. Study area

The Beiluhe basin has an average elevation of 4628 m (Fig. 1). The basin is in flat terrain with most slopes <10°, except the Gu mountain (>5000 m a.s.l), which runs east-west. Fluvial and deluvial sediments formed the upland plain landforms. The surficial sediments are dominated by fine to gravelly sands.

Beiluhe basin is located in an extremely continental climate zone, favoring clear skies and high solar radiation. The mean annual air temperature (MAAT) and precipitation (MAP) are recorded by Beiluhe Weather Station (BWS) (Fig. 2a). The MAAT is about −3.4 °C, while the MAP is about 369.8 mm yr^{-1} (2005–2014). Over 90% of precipitation falls between May and September when air temperatures remain above 0 °C, so there is little snow cover in winter (Fig. 2a). The mean annual potential evaporation (MAPE) is about 1317 mm yr^{-1}, much higher than the MAP.

The basin is speculated to be within the continuous ice-rich (30–50% volumetric ice content) permafrost zone. The MAGTs from boreholes drilled along the QTR are between −1.8 and −0.5 °C. The active-layer thickness (ALT) ranges from 1.6 to 3.4 m (Wu et al., 2015). However, the spatial variation in ground temperature and active-layer thickness has not been extensively investigated.

Vegetation in the study area is characterized by the cold-temperate regions hemicryptophyte (Kachroo et al., 1977). Ten ecotopes have been identified in the study region (Table 1, Fig. 3) based on our field investigations and recent investigations by Wu et al. (2015) and Wang et al. (2016) (Fig. 4). The detailed classification method and distribution will be discussed in detail in Sections 3.2 and 4.1.

3. Methods

3.1. Vegetation and soil surveys

Vegetation and soil surveys were conducted in the August 2013 and 2015. The slope, aspect, local hydrology, vegetation cover, and geology in the basin were examined. Vegetation types were identified by inspection in 2 m × 2 m grids. Vegetation coverage in grids was determined using images captured with a Nikon D7000 camera. Nine photographs were taken at different locations 1.0 m above each site and processed with ENVI 5.0. Soil moisture content, an important control on the ground thermal regime due to the latent heat of fusion, was determined gravimetrically for 71 soil samples collected from the upper 0.5 m. Grain size distributions of soil samples were determined by sieving. Soil thermal properties (0–1.0 m) were measured using a portable thermal characteristic analyzer (KD 2 Pro, Decagon, USA) with an accuracy of 95% for the volumetric heat capacity (C), 95% for the thermal conductivity (k), and 90% for the thermal diffusivity (D).

3.2. Remote sensing

3.2.1. Vegetation types

The GF-1 satellite was launched by China in 2013. GF-1 imagery is useful to spatially extrapolate field survey results due to its high spatial resolution (2.0 m × 2.0 m) and wide area coverage (>60 km × 60 km). GF-1 data consist of five spectral bands: panchromatic (0.45–0.90 μm), blue (0.45–0.52 μm), green (0.52–0.59 μm), red (0.63–0.69 μm), and

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