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Permafrost temperatures and thickness on the Qinghai-Tibet Plateau

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ABSTRACT

Based on permafrost temperature measurements from 190 boreholes along the Qinghai-Tibet Highway/Railway since the early 1960s, we present spatial variations of permafrost temperatures, thermal gradients, and thickness on the Qinghai-Tibet Plateau. Overall, permafrost temperatures at 15 m depth are higher than −4.0 °C and about half of the permafrost has its temperature higher than −1.0 °C. The lowest average permafrost temperature is about −3.8 °C in the Fenghuo Mts. area. Permafrost temperatures are strongly controlled by elevation and latitude on the Qinghai-Tibet Plateau. Permafrost temperatures at 15 m depth decrease at a rate of 0.57 °C per 100 m altitude increase and 0.79 °C per latitude moving north. Permafrost temperature gradients change dramatically along the Qinghai-Tibet Highway/Railway, ranging from about 1.0 °C/100 m in Liangdaohe basin of southern Plateau to 8.0 °C/100 m in Kunlun Mts. area of northern Plateau. Assuming thermal conductivity of 2.0 $\mathrm{Wm^{-1}\,°C^{-1}}$ of bedrocks at depth, geothermal heat flux varies from 0.02 $\mathrm{Wm^{-2}}$ to 0.16 $\mathrm{Wm^{-2}}$. Permafrost thickness ranges from less than 10 m to over 300 m along the Qinghai-Tibet Highway/Railway. Besides elevation and latitude, geothermal heat flux also plays a key role in controlling permafrost temperature and thickness.

1. Introduction

Permafrost regions occupy approximately 53% of the land area on the Qinghai-Tibet Plateau, the highest and most extensive high altitude permafrost on Earth (Cheng, 1984) and one of the sensitive regions to climate change (Liu and Chen, 2000). Change in permafrost thermal regimes is an excellent indicator and integrator of climate change (Lachenbruch and Marshall, 1986; Pavlov, 1994; Guglielmin and Dramis, 1999; Anisimov and Reneva, 2006; Osterkamp, 2007). Changes in permafrost conditions have significant impacts on land surface hydrology, ecosystems and carbon cycle, landscape and geomorphologic processes, and engineering constructions (Hinzman et al., 2005; Cheng and Wu, 2007; Lemke et al., 2007). For these reasons, permafrost investigation has received significant attentions in recent years over the Qinghai-Tibet Plateau regions (Cheng and Wu, 2007, Wu and Zhang, 2008). Permafrost temperatures and thickness are two key parameters to describe local and regional permafrost conditions and their climatological means provide primary reference for any change detections and engineering design and constructions.

During the past two decades, extensive measurements of permafrost temperatures and thickness were conducted due to the construction of the Qinghai-Tibet Highway/Railway. These data and information can help us to better understand spatial characteristics of permafrost temperature and thickness on the Qinghai-Tibet Plateau. In this study, we intend to collect all data and information of permafrost temperature and thickness from various sources to investigate their spatial variations along the Qinghai-Tibet Highway/Railway. We will further estimate permafrost thicknesses using permafrost temperature gradients. Finally, we will discuss the relationships among permafrost temperatures, permafrost thermal gradients, and permafrost thickness. The ultimate goal is to describe the thermal state of permafrost along the Qinghai-Tibet Highway/Railway.

2. Data and methods

Data used in this study include permafrost temperatures at the 15 m depth, permafrost temperature gradients, and permafrost thickness. Permafrost study on the Qinghai-Tibet Plateau goes back to the early 1960s. Some limited but reliable borehole permafrost temperature measurements were conducted in the 1960s and 1970s. In this study, we only use data from sites where boreholes penetrate through the permafrost base. Furthermore, we only use permafrost thickness data determined from these permafrost temperature profiles. Permafrost temperatures at 15 m depth measured prior to the 1980s are not used since they have increased significantly. However, we assume that during this period, change in permafrost thickness during this period is minimal and negligible. Parts of these measurements have been published (Tong and Li, 1983; Wang and Li, 1983; Jin et al., 2000; Zhou et al., 2000; Wu and Liu, 2004; Cheng and Wu, 2007; Jin et al., 2008) and related data are available for this study.

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Systematic permafrost temperature measurements have been conducted since the mid 1990s due to the Qinghai-Tibet Railway/Railway construction. Most of them have been abandoned due to high costs of maintenance. Generally, permafrost temperature was measured after 1 year of drilling to eliminate any potential thermal disturbance during drilling. At most of sites, permafrost temperature was measured at least one or two times after 1 year of drilling.

Prior to 1990, all permafrost temperatures were measured by a mercury thermometer of tardily variation with accuracy of ±0.2 °C and borehole temperature measurements at most cases were conducted once or twice a year. Since 1990, all permafrost temperatures were measured using a string of thermistors made by the State Key Laboratory of Frozen Soil Engineering (SKLFSE) at Lanzhou, Chinese Academy of Sciences. Temperature sensitivity of these thermistors at laboratory is within ±0.05 °C. The in-situ measurements were manually conducted by well-trained technicians and professionals following standard guidelines. Fig. 1 shows geographical locations of borehole sites along the Qinghai-Tibet Highway/Railway.

Permafrost thickness was determined from permafrost temperature profiles. When boreholes penetrate through the permafrost base, permafrost thickness was determined as the distance between the permafrost table and the permafrost base at the depth of 0 °C isotherm. Fig. 1b shows sites where boreholes penetrate through the permafrost base and permafrost thickness was determined directly from permafrost temperature profiles. When boreholes do not penetrate through the permafrost base, the depth of the 0 °C isotherm is determined through extrapolation using temperature gradients, assuming that permafrost temperature varies linearly with depth. Fig. 1a shows sites where permafrost thickness was estimated using the extrapolation method.

There are 190 boreholes along the Qinghai-Tibet Highway/Railway where permafrost temperatures were measured since the early 1960s, most of them since 2000 (Fig. 1). Average permafrost temperatures with depth at each site were obtained based on the number of measurements at that site. Then, spatial variations of permafrost temperatures are averaged for every 0.1° latitude (approximately 10 km) when there are at least two or more boreholes within each 0.1° latitude interval. The standard deviation from its mean is also estimated to demonstrate permafrost temperature local variability within each 0.1° latitude interval.

3. Results

3.1. Permafrost temperature

Permafrost temperatures at 15 m depth from all borehole sites are used for analysis in this study. This is because the depth of zero amplitude ranges from 10 to 15 m depth on the Qinghai-Tibetan Plateau (Zhou et al., 2000). We choose 15 m depth to avoid any seasonal temperature variation effect. Overall, permafrost temperatures at 15 m depth on the Qinghai-Tibet Plateau are generally within −2 °C from the freezing point except a few mountain areas such as the Kunlun Mts., Kekexili Mts., Fenghuo Mts., and Tangula Mts. (Fig. 2a,b). Approximately half of permafrost from all sites (Fig. 1) in the Qinghai-Tibet Plateau is warm permafrost. The warm permafrost is defined as permafrost with temperature at or higher than −1.0 °C (Cheng and Wu, 2007; Wu and Zhang, 2008). Approximately 2/3 permafrost from all sites (Fig. 1) has its temperature within −1.5 °C from the thawing. The highest measured permafrost temperatures are at −0.2 °C and the lowest permafrost temperature is very close to −4.0 °C at Fenghuo Mts. (Fig. 2b).

Spatial variations of permafrost temperature on the Qinghai-Tibetan Plateau are strongly controlled by elevation. In high mountain regions, permafrost temperatures at 15 m depth range from −3.5 °C in Kunlun Mts. and Fenghuo Mts. to about −2.0 °C in Tanggula Mts. (Figs. 2b and 3b). In relatively middle high mountain regions, permafrost temperatures at 15 m depth vary from −2.0 °C to −1.0 °C (Figs. 2b and 3b). Over high plain regions, permafrost temperatures at 15 m depth are usually at or above −1.0 °C (Figs. 2b and 3a). In basin and valley areas, permafrost temperatures at 15 m depth are higher than −0.5 °C. On average, permafrost temperatures decrease with altitude at a rate of about 0.57 °C/100 m.

Spatial variation of permafrost temperatures on the Qinghai-Tibetan Plateau is also strongly influenced by latitude. For example, Tanggula Mts. is about 300 m and 500 m higher than Fenghuo Mts. and Kunlun Mts., respectively, while permafrost temperature at 15 m depth in the Tanggula Mt. regions is about 1 °C to 2 °C higher than those in Fenghuo Mts. and Kunlun Mts. Regions. This is because Tanggula Mts. is about 1.5° to 2.5° south of Fenghuo Mts. and Kunlun Mts., respectively, (Fig. 2a). On average, permafrost temperature at 15 m depth increases by about 0.79 °C for each latitude moving southward. This rate of permafrost temperature change with latitude on the Qinghai-Tibetan Plateau is higher than the earlier value of 0.5 °C per latitude reported by Zhou et al. (2000). We believe that the lower rate of 0.5 °C per latitude is due to the limited borehole temperature measurements during the 1960s–1970s.

Based on data and information from 190 borehole sites, changes in permafrost temperatures with elevation and latitude on the Qinghai-Tibet Plateau can be estimated using the following:

$$T = 52.78 - 0.79L - 0.57H \quad (1)$$

where T is permafrost temperature (°C) at 15 m depth, L is latitude (°) and H is altitude (100 m). Fig. 4 shows spatial variations of permafrost temperatures at 15 m depth with elevation and latitude on the Qinghai-Tibetan Plateau.

Permafrost temperatures are also strongly controlled by site specific factors, such as slope aspects, vegetation, soil type, soil moisture, rivers, and lakes. It is difficult to distinguish the impact of individual site specific variables on permafrost temperatures. Standard deviation of permafrost temperature from its means at each 0.1° latitude interval catches impacts of these site specific factors. On average, site specific factors can change permafrost temperature by about ±0.4 °C with range from ±0.2 to ±0.7 °C. In addition, instrument system errors and field condition effect could also contribute to the standard deviation from their means within each 0.1° latitude interval.

3.2. Thermal gradient

Thermal gradient within permafrost is an important parameter influencing permafrost thickness and ground heat flux. We estimated permafrost temperature gradients based on permafrost temperature measurements below 20 m from the ground surface. We also obtained permafrost temperature gradients from published literature (Wang and Li, 1983; Zhou et al., 2000).

Based on data and information from Fig. 2c and Table 1, geothermal gradients within permafrost along the Qinghai-Tibet Highway/Railway range from 1.0 °C/100 m to 8.0 °C/100 m with an average of 3.7 °C/100 m. Of 28 boreholes as listed in Table 1, there are eight boreholes that have permafrost temperature gradients higher than 4.0 °C/100 m. These sites with high thermal gradients are generally located along active faults. Except for Kunlun Mountain regions, geothermal gradients within permafrost along the Qinghai-Tibet Highway/Railway are generally lower than 4.0 °C/100 m with an average of 2.3 °C/100 m.

3.3. Permafrost thickness

In this study, permafrost thickness was obtained using two methods: direct borehole measurements and indirect estimate using