Influence of slope direction on the permafrost degradation: a case study in Qinghai-Tibetan Plateau

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Abstract

Slope direction affects permafrost degradation because of its influence on the surface energy balance. The ground thermal difference between slopes of differing aspect is known, however there are few detailed reports on differences in soil temperature, humidity, and radiation from slopes in permafrost areas that caused permafrost degradation. In this study variations in air and ground thermal regime were compared at two sloping sites with opposing aspect in a permafrost region of the Qinghai-Tibetan Plateau (QTP). The results indicate that air temperatures (Ta) were similar at both sites in September 2016-19. However, ground temperatures, including the ground surface temperature (Ts), the temperature near the permafrost surface (Tps), and the permafrost temperature at 5.0 m depth (Tg), and soil moisture content within the active layer differed greatly between sites. The mean annual Ts, Tps, and Tg over three years (2016-19) were 1.3-1.4 higher at the sunny slope than at the shady slope. The near-surface soil moisture content during the thawing season was 10-13% lower at the sunny slope (~22-27%) than the shady slope (~35-38%), and was significantly and negatively correlated with ground temperature. Shortwave downward radiation (DR) at the sunny slope was higher than at the shady slope. However, net radiation (Rn) was lower at the sunny slope due to the greater surface albedo at the site. The results highlight a complex spatial pattern of ground thermal conditions in mountainous permafrost regions, help define the climate-permafrost relation in the region, and for understanding permafrost degradation on a local scale.

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ABSTRACT

Slope direction affects permafrost degradation because of its influence on the surface energy balance. The ground thermal difference between slopes of differing aspect is known, however there are few detailed reports on differences in soil temperature, humidity, and radiation from slopes in permafrost areas that caused permafrost degradation. In this study variations in air and ground thermal regime were compared at two sloping sites with opposing aspect in a permafrost region of the Qinghai-Tibetan Plateau (QTP). The results indicate that air temperatures (Ta) were similar at both sites in September 2016-19. However, ground temperatures, including the ground surface temperature (Ts), the temperature near the permafrost surface (T_{ps}), and the permafrost temperature at 5.0 m depth (Tg), and soil moisture content within the active layer differed greatly between sites. The mean annual Ts, Tps, and Tg over three years (2016-19) were 1.3-1.4 higher at the sunny slope than at the shady slope. The near-surface soil moisture content during the thawing season was 10-13% lower at the sunny slope (˜22-27%) than the shady slope (˜35-38%), and was significantly and negatively correlated with ground temperature. Shortwave downward radiation (DR) at the sunny slope was higher than at the shady slope. However, net radiation (Rn) was lower at the sunny slope due to the greater surface albedo at the site. The results highlight a complex spatial pattern of ground thermal conditions in mountainous permafrost regions, help define the climate-permafrost relation in the region, and for understanding permafrost degradation on a local scale.

KEYWORDS: Permafrost degradation, Site monitoring, Slope aspect, Qinghai-Tibet Plateau

1. INTRODUCTION

Permafrost results from interactions between the land and atmosphere, so its spatial distribution is mainly determined by climatic conditions (Ferrians and Hobson 1973; Harris, 1981; Cheng and Dramis 1992; Riseborough et al. 2008). However, the influence of local environmental conditions such as slope, aspect, vegetation, snow cover, and soil conditions may outweigh the climatic background, resulting in heterogeneous permafrost conditions (ground temperature, active layer and permafrost thickness) at the local scale (Brown 1973; Williams and Smith 1989; Camill and Clark 1998; Camill, 2000; Cheng 2004; Heggem et al. 2006; Lin et al. 2019; Luo et al. 2019). Local conditions may influence the ground thermal regime of permafrost by controlling, for example, incoming solar radiation, heat convection and conduction processes, and ground ice conditions (Cheng 2003).

The Qinghai-Tibet Plateau (QTP) is one of the highest plateaus in the world, and represents the largest area of high-elevation permafrost area on Earth (Zhou et al. 2000). The occurrence of high-elevation permafrost is mainly controlled by climate, topography, and surface conditions (Cheng 1983; Harris 1986; Gorbunov 1988; Cheng and Dramis 1992). At the global scale, latitude and atmospheric circulation generally control the distribution of permafrost, while local factors such as topography and surface conditions strongly regulate site scale ground thermal conditions (Zhang et al. 2000).

The QTP includes mountainous topography, and the differences in slope aspect are significant. Due to the high elevation, low latitude, and clear air, significant solar radiation reaches the ground surface on QTP (Xu and Chen 2006). As a result, the absorption or reflection of solar radiation differs greatly on slopes depending on aspect (Lin et al. 2015a; Wang et al. 2016), significantly affecting permafrost conditions (e.g., Gorbunov 1978; King 1986).

The influences of slope direction on permafrost have been reported in several areas. For example, in southeast Yukon, Canada, vegetation growth and active layer thickness differed at four sites with similar altitude and geological conditions but different slope directions (Price 1971). At Tianshan Mountain, China, the average annual ground temperature difference between sunny and shady slopes at the same elevation can reach 4.6 (Cheng 2003). The difference in active layer thickness on north and south facing slopes of Kunlun Mountain, China, was ˜1.0 m, and permafrost temperatures differed by 0.5 (Lin et al. 2015a; Luo et al. 2019). The permafrost thickness on the southwest slope of Fenghuo Mountain was about 70 m, and about 120-145 m on the northeast slope. A recent report from discontinuous permafrost regions in northern Mongolia indicated mean ground surface temperature (MGST) differences of 3-4°C between north- and south-facing slopes over short horizontal distances (Munkhjargal et al. 2020). In addition, several studies have focused on the effect of embankment slope aspect on subgrade engineering by examining asymmetrical subsidence along infrastructure in permafrost regions (Hu et al. 2002; Lai et al. 2004; Chou et al. 2008; Niu et al. 2011; 2015; Zhang et al. 2017). Although these studies reported on differences in ground temperature and subsidence on opposing slopes, there has not been an in-depth explanation of the mechanisms responsible for the differences with supporting field data. This study more fully examines differences in air and ground temperature, moisture content, radiation, and soil texture and SOM content at two sloping sites with opposing aspects in an area with warm and ice-rich permafrost on QTP. The aim of the study is to elucidate the climate-permafrost relationship in this mountainous area, and attempt to understand the impacts of permafrost degradation due to slope effect.

2. MATERIALS AND METHODS

2.1 *Study area*

The QTP lies in the west of China, and has a long cold season (October-May) and short warm season (Lin et al. 2015b). The Beiluhe Basin is in central QTP where elevation ranges from 4500-4700 m a.s.l (Figure 1). Alpine meadow and alpine grassland are the main vegetation types, accounting for over 40% of the area (Yin et al. 2017). The vegetation communities are simple, and dominant plant species include*Kobresia pygmaea, Carex moorcroftii, Stipa purpurea, and Littledalea racemose* , etc. (Lin et al. 2019). Most plants are <15 cm tall and the growth period is short. Strong wind erosion on the plateau results in a fragile ecological environment (Li et al. 1996).

Data from Beiluhe Weather Station indicate that the annual mean air temperature was between -4.1 and -2.6 °C from 2005 to 2016, with an average value of -3.4 °C. Annual mean precipitation ranged between 229 and 467 mm (Figure 2), while the annual mean potential evaporation was ˜1588 to 1626 mm in the same period (Lin et al. 2019). About 10% of annual precipitation falls as snow.

The Beiluhe basin is undulating covered with fine to gravelly surface sands. Surficial materials within 30 cm of the surface are predominantly aeolian sand or alluvial deposits (Yin et al. 2017). Thermokarst lakes are widely spread in the basin and have been eroding permafrost (Lin et al. 2010; 2011). Permafrost in the basin is continuous, relatively warm (near 0), and has high volumetric ground ice content with a mean value of ˜16% (Lin et al. 2020; Fan et al. 2021). Active-layer thickness ranges from 1.8 to 3.0 m and the annual mean ground temperature is -1.8 to -0.5 degC. Sediment textures range from clay to sandy gravel, which overlies weathered mudstones and sandstones (Lin et al. 2010).

2.2 *Sites descriptions*

The study examined two sloping sites with opposing aspect (Figure 1). One site was at a south-facing sunny slope (34.8367degN, 92.9206degE) and the other is a north-facing shady slope (34.8486degN, 92.9268degE). The slope angle at the sunny slope is about 7.5deg, and about 8.1deg at the shady slope (Figure 3). The elevation is 4634 m at the sunny site and 4638 m at the shady site. The dominant plant species on the sunny slope are *Stipa purpurea* and *Kobrecia parva* , and the mean vegetation coverage is approximately 16.7%. On the shady slope the dominant plant species are *Androsace tapete maxim, Carex moorcroftii* , and the mean coverage is ˜7.9%. The sediment profile to 5.0 m depth is presented in Figure 3, and includes information on gravimetric moisture content (GMC), excess ice content (EIC), and permafrost table depth (PT). The ground surface at both sites is typically covered by gravel or sandy silt. Below this layer lie coarse-grained deposits that are rich in flake gravel. The stratigraphy is similar up to 5 m depth at both sites, however the ice content differs (Lin et al. 2020). Soil texture information with depth is presented in Figure 4. The near-surface soil at the sunny slope was ˜41% silt, 14% clay, and greater than 50% silt and clay combined. Most of the near-surface samples from the shady slope were sand dominated (63%), with only ˜40% silt and clay combined. The soil at the sunny site was generally >60% silt at 3-4 m depth, and included high excess-ice content in this frost-susceptible layer. The soil organic matter (SOM) content in Beiluhe Basin soils is very low (Liu et al. 2014), and the measured SOM content at the shady slope was higher than that at the sunny slope (Figure 5).

2.3 *Temperatures*

A HOBO Pro v2 (U23-004) external temperature data logger was used to measure air temperature (T_a) and ground surface temperature (T_s) at each site. The built-in sensor was installed in a solar radiation shield at 2.0 m height and an external temperature sensor was used to measure soil temperature at ~1-2 cm depth. The reported measurement accuracy of the sensors is +-0.21 degC from -40 to 100 degC. Data collection began in September 2016 and measurements were recorded every 30 minutes.

A drilling programme to install temperature sensors was conducted at the two sites in July-August 2016. A total of 18 boreholes were instrumented to 5 m depth to determine the variation in ground thermal conditions and associations between permafrost temperatures, soil moisture, and slope aspect. Each site included nine boreholes drilled 5 m apart in a 10 x 10 m rectangular grid. The multiple measurements at each site are meant to improve the evaluated accuracy of ground temperature characterization.

At each borehole, the drill core was extracted with a 10 cm diameter dry drill. Three HOBO soil temperature sensors (TMC20-HD; Onset Computer Corporation, Bourne, MA, USA) were installed at 5 cm, 250 cm, and 500 cm depth. The three measured depths represent the near surface temperature (T_{ns}), the temperature near the permafrost surface (T_{ps}), and the permafrost temperature (T_g), respectively. The three sensors were fixed to the outer wall of a polyethylene aluminium composite tube placed in each borehole. The holes were filled with dry sand and packed with a long rod in order to improve contact between the sensors and surrounding ground.

Ground temperatures were recorded by a HOBO UX120-006M 4-Channel Analog Logger. The reported measurement accuracy of the sensors is +-0.21degC from -20 to 70 degC. Data collection began in September 2016 and measurements were recorded every 4 h.

2.4 *Soil moisture content*

At each site a 1.5 m deep soil profile was excavated. HOBO soil moisture sensors (S-SMD-M005) were inserted directly into the soil profile at depths of 25, 50, 100, and 150 cm. The volumetric moisture content (m^3/m^3) was collected using a HOBO H21-002 Micro Station. The reported measurement accuracy of the sensors is +-0.031 m^3/m^3 (+-3.1%) from 0-50 degC for mineral soil up to 8ds/m and +-0.020 m^3/m^3 (+-2%) with soil specific calibration. Data collection began in September 2016 and measurements were recorded every 4 h.

2.5 *Solar radiation*

A CNR4 Net Radiometer (Kipp&Zonen, Delft-The Netherlands) was installed at 1.5 m height at each site to measure the energy balance between incoming short-wave and long-wave (Far Infrared, FIR) radiation versus surface-reflected short-wave and outgoing long-wave radiation. The CNR4 net radiometer consists of a pyranometer pair, one facing upward, the other facing downward, and a pyrgeometer pair in a similar configuration. All 4 sensors were calibrated individually for optimal accuracy.

The spectral range (50% points) of short wave measurements is 300 to 2800 nm and 4500 to 42000 nm in the long wave spectral range (50% points). The sensitivity of the sensors is 5 to 20 $\mu V/W/m^2$ and the temperature dependence of sensitivity (-10 to +40 ºC) is less than 4 %. The instruments can operate in temperatures of -40 to +80 °C and 0-100% RH. The instruments were factory calibrated. Two data loggers (CR1000, Campbell Scientific, Edmonton, AB, Canada) were separately employed to sample at 30 minute intervals and data were stored as 1 h averages for both sites. Data collection began in September 2016. Following collection, obviously erroneous measurements were removed and gaps were filled by interpolation.

2.6 *Laboratory test of soil texture and SOM*

Samples were collected for transport to the State Key Laboratory of Frozen Soil Engineering (Lanzhou), Chinese Academy of Sciences (CAS) to examine the soil texture and organic content at both sites. The dried soil samples were crushed and put through a 2 mm sieve. The particle-size distribution of soil that passed through the sieve (<2 mm) was determined using a Malvern Mastersizer 2000 Particle Size Analyzer (Malvern Panalytical Ltd, Malvern, UK). The resulting particle-size distributions were divided into three texture classes: (1) sand (2 mm [?] sand > 75 µm), (2) silt (75µm [?] silt > 5 µm), and (3) clay (5 µm [?] clay).

The SOM of the pulverized homogenized samples were quantified by dry combustion using a Vario EL elemental analyzer (Elementra, Hanau, Germany). To measure the soil organic carbon content (SOC), 0.5 g air-dried soil samples were pretreated with HCl (10 mL, 1 mol L-1) for 24 h to remove carbonate.

2.7 *Data processing*

Annual mean air temperature, annual mean ground temperature, the surface offset, and freeze-thaw indices were calculated as outlined in Lin et al. (2019). Net short wave radiation (Rs, W·m^{-2}), net long wave radiation (R_l, W·m^{-2}), and net radiation (R_n, W·m^{-2}) can be computed using four components (eq.1-3):

$Rs = DR - UR$ (1)

$R_l = DLR - ULR$ (2)

$R_n = DR - UR + DLR - ULR$ (3)

Where DR and UR are downward and upward shortwave radiation, respectively. DLR and ULR are downward and upward long-wave radiation, respectively. The four parameters were measured at both sites using the CNR4 Net Radiometer.

3 Results

3.1 *Air temperature* and *Ground surface temperature (T_s)*

Results presented in this paper are from 1 September 2016 to 31 August 2019 (Figure 6a). The annual mean air temperature and derived values are presented in Table 1. There were no significant differences in air temperature ($T_{\mathbf{a}}$) between the sunny and shady slope. The annual mean air temperatures (T_{a}) for 2016-17 and 2017-18 were -2.90 and -2.56 °C at the sunny slope and -2.63 and -2.36 °C at the shady slope. The differences between the sites in the two years were 0.27 and 0.20 °C. Although the annual mean air temperature in 2018-19 was more than 1 °C lower than the previous two years (-4.02 °C at the sunny slope and -3.82 °C at the shady slope), the air temperature difference between both sites was still only 0.2 °C, near the sensor accuracy.

There was little difference in annual freezing degree days (FDD) and thawing degree days (TDD) for the three years at both sites, particularly in the thawing season where the difference was ~20 degree days (Table 1). The difference in calculated air frost number (F) was only 0.01 (0.62 and 0.63), indicating the air temperature conditions at the two sites are very similar.

Daily variations in $T_{\mathbf{s}}$ are presented in Figure 6b. Compared to air temperature, $T_{\mathbf{s}}$ values were significantly different between the sites during the monitoring period. The mean annual $T_{\mathbf{s}}$ for the three years were 0.28 ±0.40 °C at the sunny slope and -1.02 ±0.40 °C at the shady slope, a difference of ~1.3 °C.

3.2 *Ground temperatures (T_{ns}, T_{ps}, T_g)*

Daily variations in ground temperature at 5 cm (T_{ns}), 2.5 m (T_{ps}), and 5 m (T_g) depth are shown in Figure 7. Variations in T_{ns} over the three years were similar to T_s because the thermistors were only 3-5 cm apart. The daily mean T_{ns} for the three years at the sunny slope was always higher than at the shady slope, but the difference in T_{ns} was not as great as for T_s. The average daily temperature gradient between T_s and T_{ns} was lower at the shady slope (0.02 ±0.06 °C) than that at the sunny slope (0.10 ±0.04 °C). The difference in daily mean T_{ns} (T_{ns} at the sunny slope minus T_{ns} at the shady slope) was 0.1-3.6 °C, with a mean value of 1.43 °C. And the annual mean temperature difference ranged 1.3 to 1.6 °C.

The difference in T_{ps} between the sites was significant up to 2.5 m depth (Figure 7b). The daily mean T_{ps}fluctuated about 0 °C at the sunny slope, but was stable below 0 °C at the shady slope. The daily mean T_{ps} for the three years at the sunny slope was also always higher than at the shady slope, with differences between 0.4-3.4 °C, and a mean value of 1.44 °C. The annual mean T_{ps} values at the sunny slope in 2016-2019 were 0.24, 0.30, and -0.12 °C, and -1.21, -1.15, and -1.53 °C at the shady slope, respectively. The annual temperature difference was ~1.4 °C.

At 5.0 m depth (Figure 7c), the daily mean T_g was <0 °C at both sites all year. Daily mean T_g at the sunny slope was always ~-0.1°C over the three years. Because the precision of the sensor is ±0.21 °C, we don't think this value is very accurate. However, it seems that local environmental factors have little effect on T_g, and conclude that there is a strong temperature control effect at this depth. The daily mean T_g at the shady slope fluctuated between -1 to -2 °C over the study period, with a mean annual value of -1.4 ±0.02 °C. The 1.4 °C difference in T_g between the sunny and shady slopes indicate that the thermal regime is strongly affected by slope aspect.

3.3 *Depth of seasonal thawing*

The ground surface begins to thaw when T_s rises above 0 °C with the increase of T_a, and the thaw depth usually reaches its annual maximum at the end of August on QTP (Luo et al., 2019). The maximum seasonal thawing depth at both sites in 2016 was approximated during the drilling campaign in July-August, and the observed results were 2.70±0.1 m among nine boreholes at the sunny slope and 1.74±0.1 m at the shady slope. A nearly 1.0 m difference of the maximum depth of seasonal thawing between sites is likely to result from the large difference in T_s between sites. In 2016-19, the mean annual T_{ps} measured at 2.5 m depth was above 0 °C (~0.14 °C) at the sunny slope, indicating that the maximum depth of seasonal thawing was >2.5 m. At the shady slope, the site mean T_{ps} values and accompanying maximum and minimum values remained below 0 °C (~-1.30 °C), indicating that the maximum depth of seasonal thawing was <2.5 m. The difference in depth of seasonal thawing between the sites is related to the difference in thawing period duration. The thawing period was about 30-40 days shorter at the shady slope than at the sunny slope in 2016-19, resulting in a shallower depth of seasonal thawing at the site.

3.4 *Soil moisture content*

Daily variations in soil moisture content at four different depths within the depth of seasonal thawing (0.25, 0.5, 1.0, and 1.5m) are presented in Figure 8. The difference in moisture content between sites was significant, with the ground at the shady slope always wetter than at the sunny slope. The difference was maintained despite frequent summer precipitation events affecting both sites. The near-surface ground at the shady slope remained relatively moist during the thawing periods. The mean soil moisture content at 0.25 m depth at the shady slope was 0.374±0.003 m^3/m^3 during the three thawing periods, and was 0.250±0.002 m^3/m^3 at the sunny slope (Figure 8a). The difference in moisture content between sites occurred up to 1.5 m depth (Figure 8d). The soil moisture content decreased dramatically after ground freezing commencing at the end of October. The residual moisture content may reflect unfrozen water content, but as the sensors are not calibrated for measurement below 0 °C, unfrozen water is not discussed further.

3.5 *Radiation*

The four components of the radiation budget all showed variation due to seasonal changes in solar altitude (Figure 9). The seasonal variation in shortwave downward radiation (DR) is evident at both sites (Figure 9a). The maximum value of daily mean DR reached ˜400 W·m^{-2} in May-July, then gradually decreased to the minimum value of ˜100 W·m^{-2} in mid-December. In contrast with DR, although shortwave upward radiation (UR) exhibited relatively little seasonal variation, there were many peaks caused by snowfall increasing the surface albedo, especially in March-May (the gray area in Figure 9b). The daily mean UR at the sunny slope was much higher than at the shady slope, and during the cold period, the monthly mean UR was 40% higher (˜12.0 W·m^{-2}) (Table 2).

The daily mean downward long-wave radiation (DLR) showed a similar seasonal pattern as DR, but variations in DLR were smaller and less scattered over the year. The DLR lagged behind DR by a few weeks (Figure 9c) due to the thermal inertia of the Earth system. Seasonal fluctuation in upward long-wave radiation (ULR) was well correlated with DLR. The daily mean ULR was higher at the sunny slope than that at the shady slope in most months, except in March-May of each year (Table 2). The resulting net long-wave radiation (R_l) was always ˜7 W·m^{-2} lower at the sunny slope than at the shady slope during the warm season and ˜5.5 W/m^2 lower during the cold season.

The magnitudes of variation in net radiation (R_n) for both sites were different in each month. However, the daily mean R_n in most months was lower at the sunny slope than that at the shady slope (Figure 10 and Table 2). The mean daily R_n for the whole study period (n=969 days) was 12.5±0.65 W·m^{-2} lower at the sunny slope than at the shady slope. This may be related to differences in surface albedo and surface moisture conditions at the sites. In the warm season, the maximum daily Rn was >850 W·m^{-2} (Figure 10h), and <350 W·m^{-2} in the cold season (Figure 10k).

3.6 *Surface albedo*

Variations in daily mean surface albedo were consistent with variations in UR (Figures 9b, 11), and similar at both sites. However, the daily mean surface albedo was slightly higher at the sunny slope (n=1095, 0.182±0.003) than at the shady slope (n=969, 0.176±0.003). As a result, most of the monthly mean albedo values, and the annual mean albedo was higher are the sunny slope (Table 2). The surface albedo at the two sites fluctuated greatly over the year, with snowfall in winter causing a sharp increase up to a maximum of 0.99. The surface albedo was not significantly higher over the whole cold season (0.175±0.005 and 0.165±0.005) than the warm season (0.178±0.002 and 0.180±0.003) indicating that the snowfall did not persist on the ground for long at the sites. This was confirmed by field observations in winter (Jan. 10-15, 2017, Dec. 9-22, 2018, and Dec. 16-25, 2019).

4. Discussion

4.1. Similar air temperature vs. different ground temperatures

There were no significant differences in daily air temperatures between the two sites, presumably due to their geographic proximity and mixing of air in the study area (Table 1). In contrast, differences in ground temperatures were significant (Figures

6b and 7). The annual mean difference in T_s or T_{ns} between sites was over 1.3 °C, and the ground at the sunny slope was significantly warmer (1-2 °C) than the shady slope.

There was little diurnal variation in T_s at the shady slope compared to the sunny slope (Figure 12). The daily amplitude of T_s was usually ˜5 °C at the shady slope, with a maximum value of ˜10 °C in the warm season (Figures 12f-i), and a minimum value of ˜2 °C in the cold season (Figures 12j-l). In contrast, the daily amplitude of T_s was usually 10-15 °C at sunny slope, with a maximum close to 20 °C in the warm season and a minimum of ˜5 °C in the cold season. The lower T_s throughout the day at the shady slope in the cold season indicate that there is little available heat to offset surface losses at night. As a result the surface offset ($\Delta T_s = T_s - T_a$) was significantly lower at the shady slope than that at the sunny slope (Figure 13).

The surface offset (ΔT_s) is a function of the surface energy balance and is controlled by factors such as vegetation, snow cover, moisture availability, and topography (Eaton et al. 2001; Beltrami and Kellman 2003). The mean surface offset in 2016-19 was 3.54±0.07 °C at the sunny slope and 1.91±0.12 °C at the shady slope. A ˜1.5 °C difference in ΔT_s further highlights the warmer ground surface conditions at the sunny slope.

The results indicate that permafrost degradation should consider differences in surface temperature caused by microenvironment, and particularly the slope aspect in mountainous areas. In this study slope aspect was associated with a difference in annual mean surface temperature of about 1-2 °C, and similar studies have reported that the difference in mean ground surface temperature reached 4.6 °C at Tianshan Mountain, China (Cheng 2003) and 3-4 °C in northern Mongolia (Munkhjargal et al. 2020). The data will help inform realistic boundary conditions for modelling permafrost degradation in mountain permafrost areas.

4.2 Seasonal dynamics of water and thermal at surface

Our observations of relations between T_a and T_s were similar to studies at flat sites in Beiluhe basin, QTP (Lin et al. 2019). With the increase in air temperature in the middle of January, the ground began to warm, but with a lag of about one week. $T_s$neared 0 °C in the middle of April, after which there was a rapid increase in soil moisture induced by downward thawing. T_s reached the maximum value in July and August, at which time the sunny slope was much warmer than the shady slope (Figure 12g and h). The soil moisture content fluctuated drastically with the arrival of monsoon rains in May to October. The higher T_s at the sunny slope may increase the surface evapotranspiration, resulting in lower soil moisture content at the sunny slope than at the shady slope. The higher soil moisture during the entire thawing period was the main control on the energy budget. Though measurements of soil heat flux (G) were attempted in this study, the instruments failed, but G has been shown to be correlated with R_n in Beiluhe Basin (You et al. 2017). The R_n continued to increase and reached their maxima in July-August when the solar altitude is the highest (Figure 14), which was synchronized with variations in T_s. $R_n$in November-January maintained low values with a ˜350 $W \cdot m^{-2}$ of peak value, less than half the maximum value in May-August (Figure 10). When the surface soil froze and vegetation withered in early October, soil moisture content dropped rapidly. The variation in UR and ULR showed strong seasonality, but the albedo did not increase rapidly in winter. The freeze-thaw cycle of the wet surface soil at the shady slope may trigger a drastic energy change in permafrost regions, which is different from the alternations correlated with the onset of the summer. The results are helpful for understanding the dynamic process of surface water thermal energy in mountain permafrost regions.

4.3 Effect of slope aspect on regional permafrost environment

The observational results show the air temperatures were similar at both sites (Figure 6a). However, the difference of slope direction resulted in different ground temperatures during the freezing and thawing periods at both sites. It is generally recognized that net radiation (R_n) on sunny slopes is greater than on shady slopes. However, in this study $R_n$at shady slope was slightly higher (˜13 $W \cdot m^{-2}$) than on the sunny slope. The shortwave downward radiation (DR) at the sunny slope was much greater than at the shady slope. Higher albedo at the sunny slope resulted in higher upward shortwave radiation (UR).

The differences caused by the slope direction were apparent in soil moisture measurements. The sunny slope was much warmer, increasing the potential evaporation and resulting in drier soils (Figure 8). The complex interactions between T_a, T_s, and surface soil water retention and heat exchange between the land surface and the lower atmosphere.

Other partitions in the energy balance (e.g. sensible heat flux (H), latent heat flux (LE)) were not calculated, but a dramatic increase in LE with the rapid increase in soil moisture in thawing period was previously observed on QTP (You et al. 2017). Studies have shown that the LE was the main portion of energy budget in summer (Wang et al. 2005; Chen et al. 2009; Ma et al. 2009). The lower surface temperature at the shady slope reduces heat input to the boundary layer and decreases the temperature lapse rate in the lower atmosphere (Otterman 1974). Although the R_n at the shady slope was slightly higher (˜13 W/m^2) than the sunny slope, the ground surface temperature was lower due to the high soil heat capacity.

The presence of permafrost supports the development of alpine meadow ecosystems (Jin et al. 2009; Wang et al. 2009), and is strongly related to heat insulation resulting from hydrothermal conditions in the active layer. Soil moisture content decreases with increasing active layer thickness for the slope in the study. Permafrost warming and degradation could potentially lead to a reduction in soil moisture and soil nutrient content, resulting in vegetation degradation and possible desertification over the QTP (Xue et al. 2009).

4.4 Effect of slope aspect onsoil texture and SOM

A high frequency of freeze-thaw cycles is effective for mechanical weathering near-surface bedrock or coarse-grained soil, leading to spalling of relatively small rock fragments (Matsuoka 1994), though lack of moisture may considerably reduce the number of effective freeze-thaw cycles (e.g. Prick 2003). The freeze-thaw cycle frequency is proportional to the mechanical weathering rate of surface materials. The soil texture at surface of sunny slope was finer with greater than 50% silt and clay combined (Figure 4), which may be due to a higher freeze-thaw frequency and weathering rate. In addition, soil freezing is accompanied by the migration of moisture to the freezing front (Everett 1961), further driving the movement of fine soil particles. When the frozen soil is thawing, fine particles also move as moisture seeps downslope. As a result, each freeze-thaw cycle will cause soil redistribution that affects soil texture. In general, fine particles may move downslope more at the sunny slope due to the high frequency of freeze-thaw cycles (Figure 4a).

Alluvial material coupled with the low temperatures and low decomposition rates in permafrost regions favors the accumulation of SOM (Dorfer et al. 2013). Vegetation conditions and pedogenesis are usually regarded as the dominant controlling factors for SOM accumulation (Jobbagy and Jackson 2000). In the present study, SOM accumulation was much greater at the shady slope than that at the sunny slope, in contrast with the degree of vegetation coverage. We hypothesize that pedogenesis had an important effect on the SOM distribution since the major distinction between the two sites is the different slope aspect, and the vegetation coverage was relatively low at both sites (sunny slope: 16.7%; shady slope: 7.9%). Higher SOM content is expected in the upper soils at the two sites (Figure 5) because the fallen litter on the ground surface and the turnover of fine roots are considered to be the dominant SOM inputs to natural ecosystems (Zollinger et al. 2013). The observations of SOM were similar to those at Eboling Mountain, northeastern QTP (Mu et al. 2016). SOM content increased with depth in the upper permafrost (3-5 m) at the two sites, which may be because ground ice in this depth range contributes to SOM stabilization (Jorgenson and Shur, 2009; Grosse et al. 2011). High SOM is associated with high proportions of fine soil particles as they tend to stabilize and retain more organic matter (Figure 4). Moreover, the humid soil at the shady slope promotes microbial activities that are beneficial to SOM formation (Mu et al. 2016). Thus, greater SOM accumulated at the shady slope, particularly in the top portion of the active layer.

4.5 Effect of factors on the variations within sites

There are clear differences in ground temperature (T_s, T_{ps}, and T_g) between the two sites, and in maximum seasonal thaw depth, which differed by ˜1.0 m in 2016-19. These differences are related to the effects of local factors in the study areas. The slope aspect is undoubtedly one of the key factors (Lin et al. 2019). In addition, vegetation can strongly control the depth of seasonal thawing in mountainous areas (Wang et al. 2009; Shiklomanov et al. 2010; Shiklomanov and Nelson 2013; Chang et al. 2014a; Wang et al. 2017; Keuper et al 2017). The greater leaf area of vegetation at the sunny slope can reflect and blocks solar radiation, reducing the amount of net radiation to the ground (Fisher et al. 2016). This can have an important effect on surface temperature variations (Chang et al. 2012). The well-vegetated surface is covered with an insulative organic layer, which has a net cooling effect on the ground surface (Cannone and Guglielmin 2009) and slows the rate of change in the active layer temperature (Fisher et al. 2016). In the alpine meadow regions on QTP vegetation can also slow down the response of permafrost to climate warming through the greater water retention capacity of its root zone (Wang et al. 2009). Variation in vegetation cover will also indirectly affect the active layer thermal regime by affecting soil properties and snow cover (Chang et al. 2014b; Fisher et al. 2016). Though the plant heights (<15 cm) and coverage (8-16%) are relatively low, variations in vegetation conditions still likely impact the thermal regime of the active layer and near-surface permafrost at the study sites (Lin et al. 2019).

Seasonal thaw depths are also related to the soil thermal properties, which depend on soil density, porosity, and texture (Pang et al. 2011; Li et al. 2018). Variations in soil moisture caused by the infiltration of summer precipitation may reduce the seasonal amplitude of soil temperatures, decrease mean annual soil temperatures, and thin active layers (Luo et al. 2020). For the shady slope, a cooling effect may thus be caused by liquid water that accumulated and persisted within the active layer.

5 Conclusions

Based on a detailed examination of near-surface temperatures, moisture conditions, and radiation over 3 years, permafrost conditions were compared at two sloping sites with differing aspect in Beiluhe Basin to enrich permafrost degradation impacts observations in the hinterland of QTP. The results show that sunny and shady slope sites had similar air temperatures and precipitation amounts, but the difference in slope direction resulted in a difference in annual mean ground temperature of 1-2 °C. Higher ground surface temperatures at the sunny slope increased the difference between ground and air temperature (ΔT_s), and caused deeper active layer thickness of ~1.0 m. Soil moisture content increased rapidly during the thawing of the active layer, but the higher ground surface temperature increased evaporation at the sunny site, making it much drier than the shady slope. The slope direction caused the downward shortwave radiation (DR) at the sunny slope to be greater than the shady slope, but there was higher net radiation at the shady slope due to differences in surface albedo. Nonetheless, the ground temperatures at the sunny slope were higher. The slope aspect also influenced the soil texture and SOM distribution. The data have improved knowledge on the ground surface boundary conditions in mountain permafrost regions, and indicate that sunny slopes may be >1-2 °C warmer than shady slopes when the permafrost distribution is similar. These results provide accurate information for permafrost degradation in high altitude permafrost areas.

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STATEMENT ON CONFLICT OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that may have influenced the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1 Air temperature (T_a), freezing and thawing indices, and air frost number at both sites for September 2016-2019.

Sites	Items	2016-17	2017-18	2018-19	mean
Sunny slope	T_a (°C)	-2.90	-2.56	-4.02	-3.16
	FDD (°C days)	1716	1708	2083	1836
	TDD (°C days)	658	772	616	682
	F	0.62	0.60	0.65	0.62
	β(°)	82	83	79	81
	T_{wm} (°C)	7.7	7.4	7.0	7.4
	T_{cm} (°C)	-13.6	-12.9	-14.8	-13.8

Sites	Items	2016-17	2017-18	2018-19	mean
	T_{ws} (°C)	4.9	5.5	4.6	5.0
	T_{cs} (°C)	-6.9	-6.6	-8.4	-7.3
	L_{ws} (day)	143	151	140	145
	L_{cs} (day)	222	214	225	220
	A (°C)	21.3	20.3	21.8	21.1
Shady slope	T_a (°C)	-2.63	-2.36	-3.82	-2.94
	FDD (°C days)	1640	1648	2028	1772
	TDD (°C days)	681	788	633	701
	F	0.61	0.59	0.64	0.61
	β(°)	83	83	80	82
	T_{wm} (°C)	7.9	7.6	7.1	7.5
	T_{cm} (°C)	-13.3	-12.5	-14.6	-13.5
	T_{ws} (°C)	5.0	5.6	4.8	5.1
	T_{cs} (°C)	-6.5	-6.4	-8.2	-7.0
	L_{ws} (day)	146	155	141	147
	L_{cs} (day)	219	210	224	218
	A (°C)	21.2	20.1	21.7	21.0

FDD, freezing degree days; TDD, thawing degree days; F , air frost number which is defined as $F = \frac{\sqrt{FDD}}{\sqrt{FDD+\sqrt{TDD}}}$ (Nelson and Outcalt, 1983, 1987); β , frost angle; T_{wm} and T_{cm}, mean temperatures of the warmest and coldest months; T_{ws} and T_{cs}, mean warm and cold season temperatures; L_{ws} and L_{cs}, length of warm and cold season; and A, annual temperature amplitude.

Table 2 Mean monthly, cold and warm periods, and annual mean energy balance components (W/m^2) from January-December 2017.

Site		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	War
Sunny slope	DR	149.2	175.9	229.1	266.4	291.9	252.3	261.5	229.7	207.9	220.4	171.5	146.1	238.
	UR	47.9	49.0	106.0	82.3	79.3	61.7	51.2	43.2	40.8	68.1	93.6	42.4	49.2
	DLR	175.1	188.4	202.8	226.1	240.3	280.9	294.5	300.0	281.6	219.3	182.9	175.0	289.
	ULR	259.5	277.0	279.7	316.6	331.9	341.0	371.9	365.2	342.5	318.2	269.5	272.2	355.
	R_n	16.9	38.4	46.2	93.6	121.1	130.5	133.0	121.3	106.3	53.4	-8.64	6.43	122.
	R_s	101.3	127.0	123.1	184.1	212.6	190.6	210.4	186.5	167.1	152.3	77.9	103.7	188.
	R_l	-84.4	-88.6	-76.9	-90.5	-91.5	-60.1	-77.4	-65.2	-60.9	-98.9	-86.6	-97.2	-66.
	Albedo	0.160	0.150	0.253	0.195	0.191	0.201	0.179	0.186	0.148	0.146	0.134	0.173	0.17
Shady slope	DR	141.1	168.3	225.2	263.3	288.5	252.5	258.8	228.9	200.6	211.9	165.0	138.7	235.
	UR	39.3	40.5	77.4	69.2	77.4	50.8	46.4	37.6	30.7	55.4	66.8	29.8	41.4
	DLR	177.4	191.1	206.8	230.4	242.6	283.5	295.8	303.8	284.3	221.8	185.1	176.8	292.
	ULR	253.4	273.3	282.0	318.4	333.7	339.4	365.3	359.0	338.2	307.9	265.7	267.9	350.
	R_n	25.9	45.6	72.6	106.1	120.0	145.7	142.9	136.1	116.0	70.4	17.6	17.8	135.
	R_s	101.8	127.9	147.8	194.0	211.1	201.7	212.4	191.3	169.9	156.5	98.2	108.9	193.
	R_l	-75.9	-82.2	-75.2	-87.9	-91.2	-56.0	-69.4	-55.2	-53.9	-86.1	-80.6	-91.1	-58.
	Albedo	0.156	0.139	0.202	0.185	0.205	0.178	0.212	0.194	0.135	0.161	0.121	0.152	0.18

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