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Challenges from North to South
Des défis du Nord au Sud

Permafrost thermal regime at north and south aspects, Kunlun Mountain, Qinghai-Tibet Plateau

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ABSTRACT
Ground temperatures from 0.5 to 15 m depth were measured for six years (2008-2013) at sites with south and north aspects in Kunlun Mountain, Qinghai-Tibet Plateau, to characterize the ground thermal regime and determine if the variations in ground temperature were associated with the slope aspect. Climate conditions at north slope were similar to those at south slope, but the ground temperatures were very different. At the near-surface, about 50 cm depth, the mean annual ground surface temperature (T_s) at north slope was approximately 0.6 °C colder than that at south slope, resulting in an 1-m increase in active layer thickness (ALT) at south slope. As a result, the mean annual ground temperature at the top of permafrost (T_{ps}) was about 1 °C colder at north slope than that at south slope, and 0.2 °C colder at 15 m depth (T_g). The significantly different ground temperature showed an important effect of slope aspect on permafrost, especially in shallower permafrost layers.

RÉSUMÉ
Les températures du sol, de 0,5 à 15 m de profondeur, ont été mesurées pendant six ans (2008-2013) au sud et au nord de la montagne Kunlun, au plateau Qinghai-Tibet, pour caractériser le régime thermique du sol et déterminer si les variations de température du sol étaient associées à l'effet de pente. Les conditions climatiques de la pente nord sont proches de celles de la pente sud, mais les températures du sol étaient grandement diversifiées. Près de la surface, à environ 50 cm de profondeur, la température de surface annuelle moyenne du sol (T_s) au versant nord était environ 0,6 °C plus froide que celle au versant sud entrainant ainsi une augmentation de 1 m d'épaisseur de la couche active (ALT) au versant sud. Par conséquent, la température moyenne annuelle du sol en haut du pergélisol (T_{ps}) était d'environ 1 °C plus froide au versant nord que celle au versant sud, et 0,2 °C plus froide que la température annuelle moyenne du sol à 15 m de profondeur (T_g). La différence significative de température du sol a montré un effet important sur le pergélisol due à l'effet de pente, en particulier dans les couches de pergélisol moins profondes.

1 INTRODUCTION

1.1 Background

Permafrost is a geologic manifestation of climate and forms in areas of high latitude or altitude where the intensity and duration of the freezing season allow frozen ground to persist through the following thawing season (Burn 1994, 1998). The largest body of high elevation permafrost is in Qinghai-Tibet Plateau and its area is approximately 1.05×10^6 km^2 (Ran et al. 2012). About 80% of the area is above 4000 m in elevation while a portion of it exceeds 5000 m (Zhou et al., 2000). The continuous permafrost in QTP is unlike the continuous permafrost in North America or Russia and it is characterized by high ground temperature and high volumetric ice content (Cheng et al., 1993; Zhou et al., 2000). The permafrost on the plateau is relatively thin, but its thickness increases in the higher elevation terrain of mountains ranges, such as the Kunlun Mountains (Zhou et al., 2000). Although the permafrost generally results from the cold climate, local factors, e.g. vegetation, water body, slope degree and direction, and micro-environment, etc., may impact greatly the thermal regime of permafrost and its spatial distribution at the local scale.

The Kunlunshan Mountain is one of the high mountains across the QTP and the elevation at the Kunlun Mountain Pass is 4767 m. The permafrost here is classified as stable low-temperature permafrost with temperatures of -3 to -4 °C. Similar vegetation species and surface conditions exist at the two sites, with only different slope aspects. In this paper, the purpose of our investigation was to characterize the thermal regime of low-temperature permafrost at the two sites and determine whether the observed differences of permafrost at the two slopes were associated with the slope aspect.

1.2 Study Area and Study Sites

The QTP lies in the west of China (Figure 1). It is influenced mostly by the Southern Asian monsoon and has a continental climate, characterized by a long cold season and short warm season (Li et al., 1996; Jin et al., 2008a, Niu., 2011). The mean annual air temperature (MAAT) is less than -4 °C, with minimum temperatures close to -30 °C in January, and the maximum value of approximately 25 °C in July (Jin et al., 2008a). The mean annual precipitation is 50 to 400 mm, while the potential evaporation is 1300 to 1500 mm (Wu et al., 2008).

The permafrost on QTP has a high temperature and high near-surface ground ice content. In most high plateaus or valleys, the mean annual ground temperature (MAGT) is above -1.5 °C and the permafrost thickness is less than 70 m. In hills and mountains at relatively higher elevations, the MAGT is lower than -1.5°C and permafrost thickness exceeds 130 m. The volumetric ice content from the surface of permafrost to depth of 5 m is more than 20% (Cheng et al., 1993; Zhou et al., 2000).

The Kunlun Mountain Pass is on the north of the QTP (N35°38′, E094°04′), about 200 km southwest of Golmud. It is the first high peak from Golmud to Lhasa along the Qinghai-Tibet Highway (QTH). Its north slope contains the Luanshigou Valley and the Xidatan Basin, which is the northern limit of permafrost. The south slope is adjacent to the Kunlunshan Basin and extends to the Budongquan Valley. The north slope is sharply steep, but the south slope is gentle. The distance from Xidatan to Kunlun Mountain Pass is approximately 19 km and the elevation increases by about 280 m. While at south slope, over nearly the same distance from Kunlun Mountain Pass to Budongquan Valley elevation decreases by about 160 m.

The vegetation is sparse and crushed rock covers the almost exposed surface on the north slope. However, the terrain is dominated by outwash and lacustrine deposits at south slope and there are some small sporadic thermokarst lakes. The vegetation on the south aspect is close to that on the north. The depth of permafrost table is about 1 to 3 m and the permafrost thickness is about 12 to 200 m at north slope. While at south slope, the depth to the top of permafrost is 1 to 3.5 m and the permafrost thickness is about 25 to 200 m. The mean annual ground temperature is 0 to -3.9°C at north aspect and -0.4 to -3.9°C at south aspect.

The study site at north slope lies on the hillside at an altitude of 4650m. The terrain is undulating with sparse vegetation and surface fine sands or gravelly sands (Figure 2(A)). The vegetation coverage is less than 30%. It lies within the continuous permafrost zone and the thickness of the active layer is less than 1.0 m. Based on drill cores, the surface has a 0.3 m thick layer of organic soil. Below that, there is a layer of 2 m of gravel soil containing a little clay overlying massive icy permafrost 2 to 3 m thick, which in turn overlies clay with gravel and well-weathered shale stones (Figure 2 (B)). The soil moisture contents range within 10 to 20% at most depths except 50 to 60% in 2 to 3 m deep (Figure 2(C)).

The study site at south slope is located in the Kunlunshan Basin, about 7 km away from Kunlun Mountain Pass at an altitude of 4702m. The terrain is gentle and covered by sparse vegetation or gravelly sands (Figure 2 (D)). The vegetation cover is close to 30 to 40%. It also lies in the continuous permafrost zone and the thickness of the active layer is more than 1.8 m. According to the drill cores, the ground above 8 m deep is similar to the north slope, but the difference is below 8 m deep where there is well-weathered muddy stone at south slope (Figure 2(E)). The changes in soil moisture contents are basically the same in both two slopes (Figure 2(F)).

Meteorological conditions for both sites are given in Table 1. The data at north slope were from a simple Weather Station located at Xidatan, while at south slope the data were from Wudaoliang Weather Station located in the south of the Budongquan Valley. The subzero period lasts for 8 months per year and the MAAT was about -6°C at north slope and -5.6°C at south slope. Precipitation at north slope was close to that at south slope, with mean annual precipitation about 313mm at north slope and 266mm at south slope. Often, the snow cover is virtually absent in areas of elevated relief due to strong winds in the cold season; wind speed is greater at south slope than that at north slope.

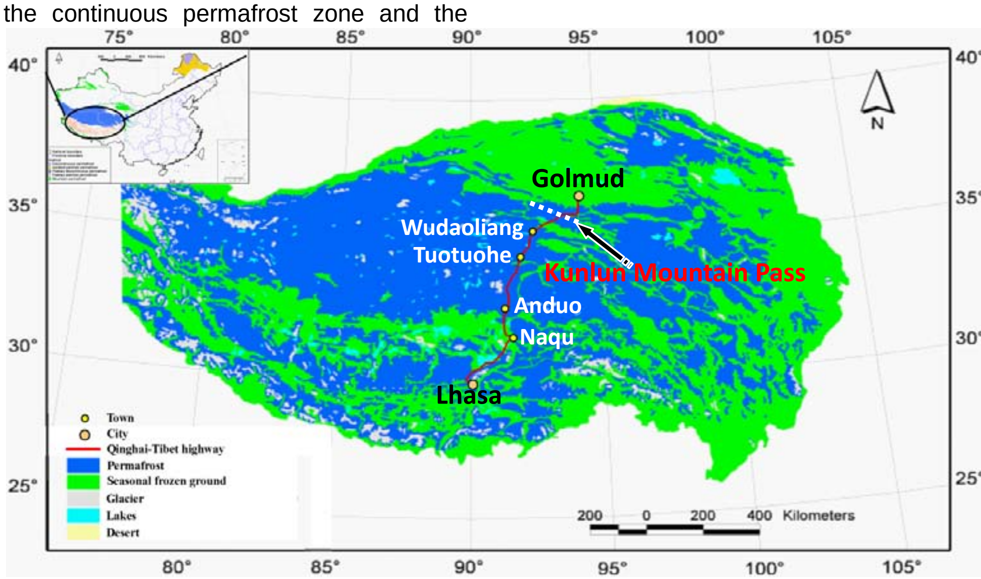

Figure 1 Location of the study area in the Qinghai-Tibet Plateau in the continuous permafrost zone. These data are from the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China and the figure is revised from Niu et al. (2012)

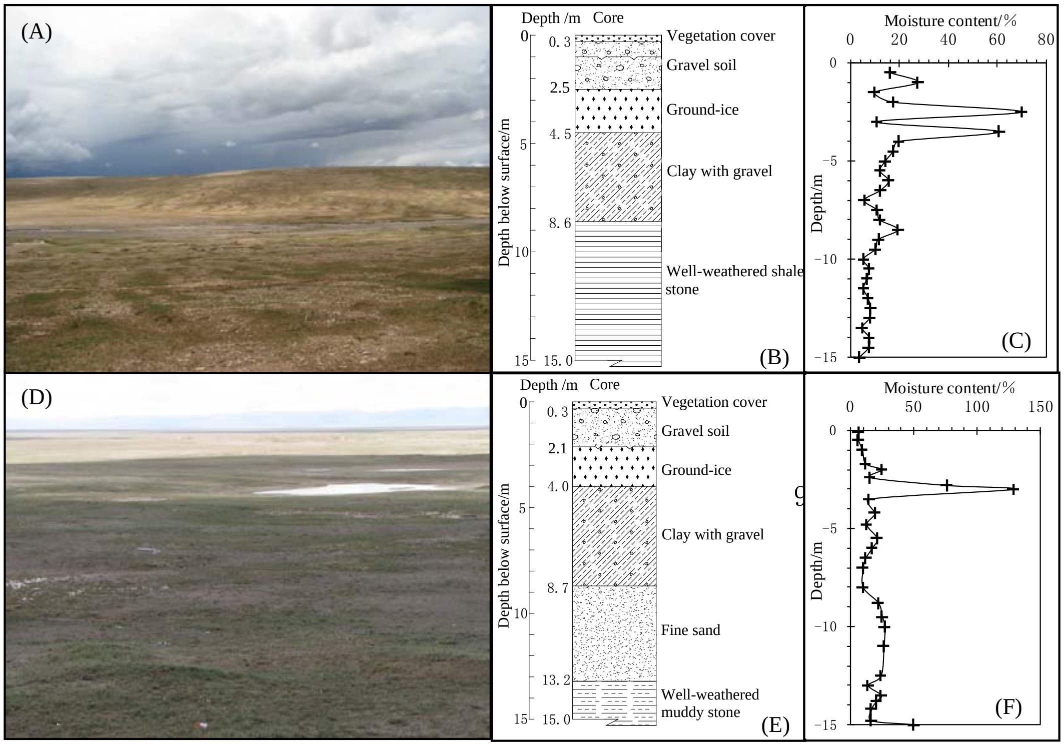

Figure 2. Aerial view of the north slope (A) and south slope (D), showing the sparse vegetation and gravel surface. Soil properties at north slope (B and C) and at south slope (E and F) and massive ground ice are about 2m thick

Table 1 Mean monthly and annual air temperature, precipitation, and wind speed on the north and south slope at Kunlun Mountain.

Sites	Items	Month												
		1	2	3	4	5	6	7	8	9	10	11	12	Mean
N-site	MAAT /°C	-17.3	-15.2	-10.9	-5.8	-1.2	2.2	5.0	4.7	0.8	-5.5	-12.8	-15.9	-6.0
	P/mm	0.6	2.1	9.1	3.6	33.2	70.8	94.5	45.8	44.9	7.2	0.4	0.6	312.8
	W/m.s^{-1}	4.4	4.7	4.1	3.4	3	2.7	2.6	2.7	4.2	3.1	3.2	4.2	3.4
S-site	MAAT /°C	-16.9	-14.8	-10.5	-5.4	-0.8	2.6	5.4	5.0	1.2	-5.1	-12.4	-15.5	-5.6
	P/mm	0.9	1.7	2.5	6.7	21.8	46.2	72.9	64.1	39.9	7.4	0.9	0.8	265.8
	W/m.s^{-1}	6.0	6.4	6.1	5.0	4.6	4.3	4.0	3.5	3.6	3.8	4.6	5.7	4.8

2 METHODOLOGY

Two permafrost monitoring sites were established at both slopes in Kunlun Mountain Pass in September to November 2007. At each site, four boreholes at 10 m intervals along slope were drilled to 15m depth to monitor the changing of ground temperatures from 0.5 to 15m depth (N-Site B1-4, S-Site B1-4). Ground temperature cables were installed and cased with an antirust tube. The number of thermistors in each borehole is 26; and spacing is 0.5m within 10m deep and 1m between 10 and 15m. The data acquisition system at each site includes a CR3000 data-logger (made by Campbell DataTaker Ltd) and is powered by solar batteries and thermistor cables (assembled in the State Key Laboratory of Frozen Soil Engineering, Chinese Academy of Sciences). The measurement accuracy of the probes is ±0.05°C, and the precision of the system is 0.3%. Readings were obtained six times per day.

In addition, during the past ten years, there were hundreds of boreholes along the QTH and Qinghai-Tibet Railway (QTR) for monitoring permafrost changes and embankment stability. About 20 boreholes with a depth of 15 m were drilled from Xidatan to Budongquan. The MAGT, thickness of active layer (TAL), and permafrost thickness (PT) were obtained from these boreholes.

3 RESULTS

3.1 Thermal Regime of Soil at North Slope

The thickness of active layer (TAL) and the monthly and annual soil temperatures at the surface (T_s) and at a depth of 0.5m ($T_{0.5}$) show the thermal regime within the active layer. The mean annual temperature at the surface was -3.22°C at north site in 2008 (Table 2), while the MAAT was -6.0°C. The ratio of T_s to MAAT is about 0.5, showing the surface conditions maintain warmth well at this site. The maximum mean monthly temperature at the surface reached 6.92°C in July 2008, the minimum mean monthly value was -17.1°C in January, and the amplitude of temperature was approximately 24°C. Extreme mean monthly temperatures are synchronized with the air temperature, and the seasonal soil temperature variations at the surface closely follow the air temperatures patterns because of relatively little snow on the ground in winter and lack of vegetation in summer. At a depth of 0.5 m, the mean annual soil temperature was -3.76°C and it was lower by about 0.5°C than at the surface. The maximum mean monthly temperature at this depth was close to 1°C in August 2008, the minimum mean monthly value was -12.2 °C in February, and the amplitude of temperature was approximately 13°C. The warmest and coldest mean monthly temperatures at 0.5 m deep lag those at surface by one month. The ground surface began to thaw in beginning of May and by the end of August the TAL reached the maximum of approximately 75 cm in 2008. The records from the early 2000s show that the TAL varied from 0.9 to 3.2 m from Mountain Pass to the northern edge of permafrost at north slope along the QTH (Figure 3(A)). The mean TAL at north site is thinnest in all records, but is close to that at Mountain Pass.

Table 2. Mean monthly and annual soil temperatures at the surface (T_s) and at depths of 0.5m (T0.5), 1.0m (T1.0), 2.5m (T2.5), 5.0m (T5.0), 10m (T10), 15m (T15) and the thickness of active layer (TAL) at north site in 2008. These data are means from four boreholes.

Sites	Items	Month												
		1	2	3	4	5	6	7	8	9	10	11	12	Mean
N-S (n=4)	T_s/°C	-17.1	-14.7	-7.86	-2.92	3.62	5.42	6.92	6.60	4.14	-2.33	-7.51	-12.3	-3.22
	$T_{0.5}$/°C	-11.2	-12.2	-8.57	-4.68	-1.68	-0.69	0.44	0.96	0.55	-0.17	-1.29	-6.52	-3.76
	$T_{1.0}$/°C	-8.38	-10.4	-8.46	-5.60	-3.13	-2.02	-1.44	-0.94	-0.72	-0.68	-0.74	-3.20	-3.80
	$T_{2.5}$/°C	-4.48	-6.82	-7.13	-6.09	-4.68	-3.65	-3.05	-2.61	-2.28	-2.07	-1.92	-1.91	-3.89
	$T_{5.0}$/°C	-3.07	-3.72	-4.50	-4.88	-4.77	-4.42	-4.08	-3.78	-3.53	-3.32	-3.14	-3.00	-3.85
	T_{10}/°C	-3.60	-3.55	-3.53	-3.55	-3.61	-3.69	-3.75	-3.78	-3.77	-3.75	-3.71	-3.67	-3.66
	T_{15}/°C	-3.56	-3.56	-3.55	-3.54	-3.54	-3.53	-3.53	-3.53	-3.54	-3.54	-3.55	-3.55	-3.54
	TAL/cm	0.0	0.0	0.0	0.0	37	45	62	75	72	0.0	0.0	0.0	75※

Permafrost underlies the active layer at 75 cm depth. The monthly and annual soil temperatures at depths of 1.0 m (T1.0), 2.5 m (T2.5), 5.0 m (T5.0), 10 m (T10), and 15 m (T_{15}) show the thermal regime of the upper permafrost. At 1.0 m depth at north site in 2008 (Table 2), generally believed to be the topmost permafrost, the mean annual temperature was about -3.8°C and the temperature difference with the 0.5 m depth is only within a few hundredths of a degree Centigrade. The mean monthly temperatures were all subzero throughout the year. The maximum mean monthly temperature was -0.72°C in September, the minimum mean monthly value was -10.4°C in February, and the amplitude of temperature was approximately 11°C. With the increase of depth, the maximum mean monthly ground temperatures gradually decrease, the minimum mean monthly ground temperatures gradually increase, and the amplitudes of temperature were gradually reduced. The extreme mean monthly temperatures lag about half to one month, too. To 10m depth, the mean annual temperature was about -3.66°C, the maximum mean monthly temperature was -3.53°C in March, the minimum mean monthly value was -3.78°C in August, and the amplitude of temperature was approximately 0.3°C. The thickness of the layer of annual temperature fluctuations at north site is about 14 to 15 m, and the values of T_{15} are virtually equal to the temperature at the bottom of this layer. The mean annual temperature at this depth was about -3.54°C, the maximum mean monthly temperature was a little more than -3.5°C in warm season, the minimum mean monthly value was a little less than -3.5°C in cold season, and the amplitude of temperature did not exceed 0.1°C.

There are no measured data to show the thermal regime of permafrost below 15 m at north site. According to historical records along the QTH, the thicknesses of permafrost at north slope were about 200 to 40 m from Mountain Pass to the northern edge of permafrost (Figure.3 (A)). On the hillside where the MAGT are -3.5 to -3.7°C, the thicknesses of permafrost are about 150 to 170 m. Based on the ground temperatures in boreholes at north site, the geothermal gradient is about 3.1 to 2.4°C/100m. The permafrost thickness is about 125 to 155 m by calculation using equations developed by Lachenbruch (1957), which is close to the historical records.

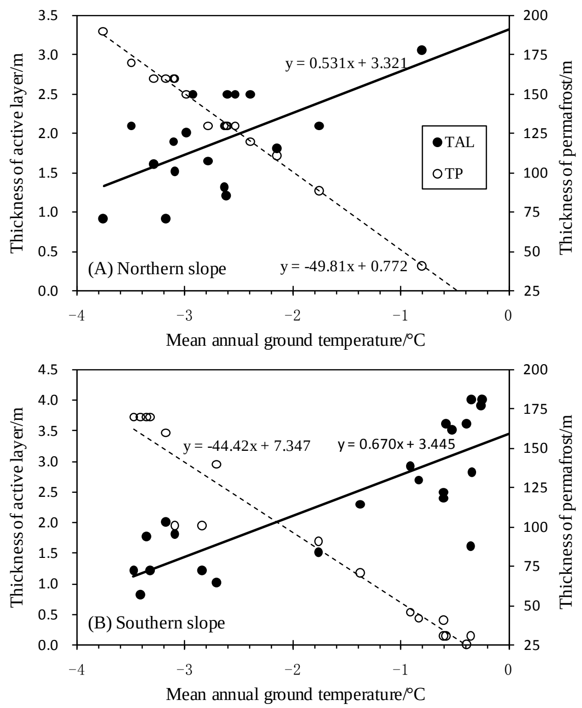

Figure 3. The relationships between the mean annual ground temperature and the thickness of active layer (TAL) and thickness of permafrost (TP) on the north slope from the Pass to the northern edge of permafrost along QTH (A) and on the south slope from the Pass to Budongquan Valley (B). These data are from boreholes drilled during the period of reconstruction and maintenance of the QTH in the early 2000s.

3.2 Thermal Regime of Soil at South Slope

The mean annual temperature at the surface (T_s) was -2.50°C at south site in 2008 (Table 3), the MAAT was -5.6°C (Table 1), and their ratio (T_s/T_a) is about 0.4. The warmest mean monthly temperature at the surface reached 9.16°C in July 2008, the coldest mean monthly value was -16.3°C in January, and the amplitude of temperature was more than 25°C. Soil surface temperature is strongly linked with air temperature. At a depth of 0.5 m, the mean annual soil temperature was -3.14°C. The extreme mean monthly temperature occurred synchronously with the surface, although the maximum mean monthly temperature declined by over 4°C, the minimum mean monthly value increased by about 3°C, and the amplitude of temperature reduced by 7°C. At this site, the ground temperatures at 1.0 and 1.5 m depth still alternated between freezing and thawing and the mean annual ground temperatures were -3.07°C and -3.05°C, respectively. But the extreme mean monthly temperatures lagged one month behind those at 0.5 m deep and the amplitude of temperature was also reduced by about 3 to 7°C. In beginning of May, the ground surface began to thaw and the depth of seasonal thawing increased gradually, to the end of August and September. The TAL reached the maximum of approximately 181cm in 2008. The soil temperatures above 1.8 m depth show the thermal regime within the active layer. Earlier records show that the TAL on the south slope varied from 0.8 to 4 m from Mountain Pass to Budongquan Valley (Figure.3 (B)). In Kunlunshan basin, the TAL are generally 1.7 to 2.6 m, while along the river banks in the Budongquan Valley and in some sections with surface water or thermokarst lakes, the TAL exceed 3 to 4 m.

Table 3 Mean monthly and annual soil temperatures at the surface (Ts) and at depths of 0.5m (T0.5), 1.0m (T1.0), 1.5m (T1.5), 2.0m (T2.0), 5.0m (T5.0), 10m (T10), 15m (T15) and the thickness of active layer (TAL) at south site in 2008. These data are means from four boreholes

Sites	Items	Month												
		1	2	3	4	5	6	7	8	9	10	11	12	Mean
S-S (n=4)	T_s/°C	-16.3	-14.9	-7.41	-1.26	4.91	7.23	9.16	8.02	4.59	-1.53	-9.59	-12.9	-2.50
	$T_{0.5}$/°C	-13.4	-13.4	-8.19	-3.52	0.09	2.77	5.01	4.70	2.37	-0.20	-4.42	-9.58	-3.14
	$T_{1.0}$/°C	-11.2	-11.9	-7.90	-4.03	-1.22	0.16	2.14	2.93	1.59	0.15	-1.17	-6.38	-3.07
	$T_{1.5}$/°C	-8.57	-9.88	-7.55	-4.68	-2.29	-1.20	-0.25	0.82	0.50	-0.02	-0.16	-3.34	-3.05
	$T_{2.0}$/°C	-6.21	-7.86	-6.95	-5.01	-3.05	-2.01	-1.22	-0.50	-0.32	-0.31	-0.35	-1.81	-2.97
	T_5/°C	-2.41	-2.80	-3.60	-4.03	-3.93	-3.63	-3.36	-3.12	-2.90	-2.73	-2.58	-2.46	-3.13
	T_{10}/°C	-3.28	-3.26	-3.24	-3.23	-3.24	-3.26	-3.29	-3.31	-3.32	-3.32	-3.31	-3.29	-3.28
	T_{15}/°C	-3.35	-3.35	-3.35	-3.35	-3.35	-3.35	-3.35	-3.34	-3.34	-3.34	-3.34	-3.34	-3.34
	TAL/cm	0.0	0.0	0.0	0.0	53	106	145	181	181	150	0.0	0.0	181※

The permafrost underlies the active layer at 181cm depth. The monthly and annual soil temperatures at depths of 2.0 m (T2.0), 5.0 m (T5.0), 10 m (T10), and 15 m (T15) at south site in 2008 are shown in Table 3. At the top of permafrost at 2.0 m depth, the mean annual temperature was about -2.97°C, the maximum mean monthly temperature was -0.31°C in September, the minimum mean monthly value was -7.86°C in February, and the amplitude of temperature exceeded approximately 8°C. Down to 10 m depth，the maximum mean monthly ground temperatures gradually decreased by about 3°C, the minimum mean monthly ground temperatures gradually increased by over 4°C, the amplitudes of temperature was reduced by about 7°C, but the variation of mean annual temperature did not exceed 0.3°C. At 10 m depth, the variation of mean monthly temperature was close to 0.1°C, so the thickness of the layer of annual temperature fluctuations at south site is about 10 m.

According to the records along the QTH, the thicknesses of permafrost along the south slope were about 170 to 25 m from Mountain Pass to Budongquan Valley (Figure. 3(B)). At the Kunlunshan Basin where the MAGT are about -3.3°C, the thicknesses of permafrost are about 140 to 160 m. Based on the ground temperatures of boreholes, the geothermal gradient is about 1.8 to 2.6°C/100 m. The calculated permafrost thickness is 110 to 160 m, which is close to the historical records.

3.3 Thermal Differences at North and South Slope

According to the historical records on the south and north slopes and the observational data at south and north sites between 2008 and 2013, there are large differences in the ground between the two aspects. At the surface in 2008, the mean annual temperature at north site (-3.2°C) was 0.7°C colder than at south site (-2.5°C), the maximum monthly temperature was more than 2°C colder, and the minimum monthly temperature was 0.8°C colder (compare Tables 2 and 3). At 2-3 m depth, the difference in mean annual soil temperature between the two sites reached a maximum of approximately 1°C in 2008 (Figure 4). At greater depths, the temperature difference diminished gradually and a minimum temperature difference of about 0.2°C occurred at 15 m depth.

From 2008 to 2013 (Table 4), the mean annual temperatures at 0.5 m depth (T0.5) were between -3.55 and -3.76°C, with a mean value of -3.68°C at north site, while at south site they were between -2.58 and -3.26°C, with a mean value of -3.00°C. At this depth, there is an average temperature difference of 0.7°C between the two sites. At the top of permafrost at 2 m depth, the mean annual soil temperatures ranged from -2.98 to -3.89°C, with a mean value of -3.61°C at north site, while at south site they ranged from -2.86 to -3.13°C, with a mean value of -2.98°C. The mean temperature difference exceeds 0.6°C. At the layer of annual temperature fluctuations (15 m), the mean annual ground temperatures were -3.30 to -3.54°C, with a mean value of -3.42°C at north site, while at south site they ranged from -3.27 to -3.34°C, with a mean value of -3.31°C. The difference of just 0.1°C shows there is hardly any variation in soil temperature below this depth.

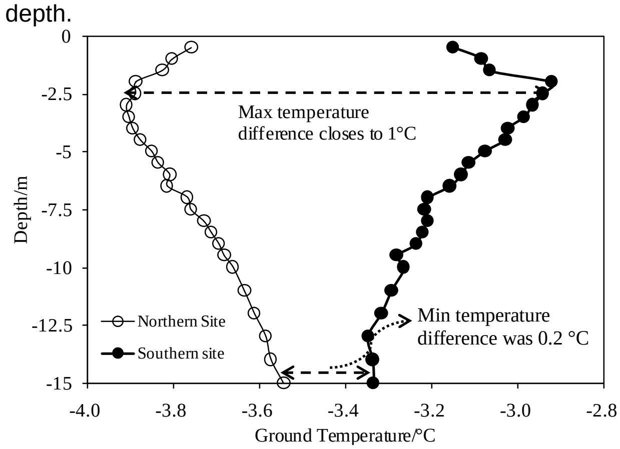

Figure 4. The relationships between the mean annual ground temperature and the depth at both sites in 2008. The maximum temperature difference reached about 1°C near the top of permafrost and the minimum value was close to 0.2 °C at 15m depth.

Besides that the differences in mean annual temperature, the maximum and minimum temperatures and their inter-annual variations at the two sites were also different. For example at 1.0 m depth in 2008 and 2009 (Figure 5A), the maximum soil temperature was 3.7°C at the end of July, the minimum temperature was -13.2°C at the beginning of February, and the amplitude was close to 17°C at south site. Whereas at north site, the maximum soil temperature was -0.6°C at the end of September, the minimum temperature was -10.6°C in the middle of February, and the amplitude just exceeds 10°C. These significant differences show that the inter-annual variations at south site are more dramatic than those at north site and the maximum and minimum temperatures also occur earlier. This is related to the different microclimate and aspect of the two slopes.

Table 4. Mean annual soil temperatures within the active layer (T0.5m) and upper permafrost (T2m and T15m) and the thickness of active layer from 2008 to 2013.

Items		Site	2008	2009	2010	2011	2012	2013	Mean	Difference (N-S)
Temperature /°C	$T_{0.5}$	N-s	-3.76	-3.69	-3.55	-3.74	-3.66	no※	-3.68	-0.7
		S-s	-3.14	-3.16	-2.69	-2.58	-3.26	-3.16	-3.00	
	T_{2m}	N-s	-3.89	-3.76	-2.98	-3.68	-3.75	no※	-3.61	-0.6
		S-s	-2.97	-2.88	-3.13	-2.86	-3.11	-2.95	-2.98	
	T_{15m}	N-s	-3.54	-3.50	-3.43	-3.35	-3.30	n※	-3.42	-0.1
		S-s	-3.34	-3.33	-3.31	-3.29	-3.28	-3.27	-3.31	
TAL/cm		N-s	84	94	104	97	96	108	97	106
		S-s	186	190	208	204	207	223	203	

However, at 5.0 m depth (Figure 5B), the large differences in amplitude and the lag disappear and the temperature difference is synchronous. The maximum soil temperature was -2.4 °C at south site and -2.9°C at north site in the middle of January and the minimum soil temperature was -4.1 °C at south site and -4.9°C at north site at the end of April. The annual amplitude at the two sites was also similar.

The differences in soil temperatures can cause the differential thickness of the active layer (TAL). The difference in TAL from 2008 to 2013 is shown in Table 4. At north site, the maximum TAL was 84 cm in 2008 and increased to 108 cm in 2013, resulting in a mean value of 97 cm for the six years. However at south site, the TAL had a dramatic increase. In 2008, it was 186 cm and increased to 223 cm in 2013. The mean value was 203 cm. The difference of the mean TAL at the two sites was more than 1 m (106 cm), showing a very significant thermal variation within the active layer. As the active layer freezes, ground cooling is inhibited by the release of latent heat. Long freeze back periods result in high mean ground temperatures on an annual basis and for the freezing season. South site, freeze back (65-70 day) of the active layer regularly took about 40-50% of the freezing season because of thicker active layers. North site, where active layer is thinner, freeze back did not take more than 30%, which allowed the ground to cool for the majority of the winter. The duration of the active-layer freeze back period is an important factor for variation in the ground thermal regime in continuous permafrost zone.

4 CONCLUSIONS

This paper has examined the thermal regime at two sites with south and north aspects in Kunlun Mountain, Qinghai-Tibet Plateau. We present the following significant conclusions based on a detailed examination of temperatures over 6 years.

1. The mean annual T0.5 at north slope was measured in 2008-2013 to range between -3.76 and -3.55°C, while it was -3.26 to -2.58 °C at south slope, and the mean difference between them was approximately 0.7 °C.

2. The active layer depth at two slopes showed large variation due to the local environment factors. The actual difference was about 1 m.

3. Measurements of the annual mean T_{ps} and T_s at two sites in 2008-2013 showed nearly similar trends, but it was colder at north slope than that at south slope, demonstrating the influence of slope direction on the permafrost.

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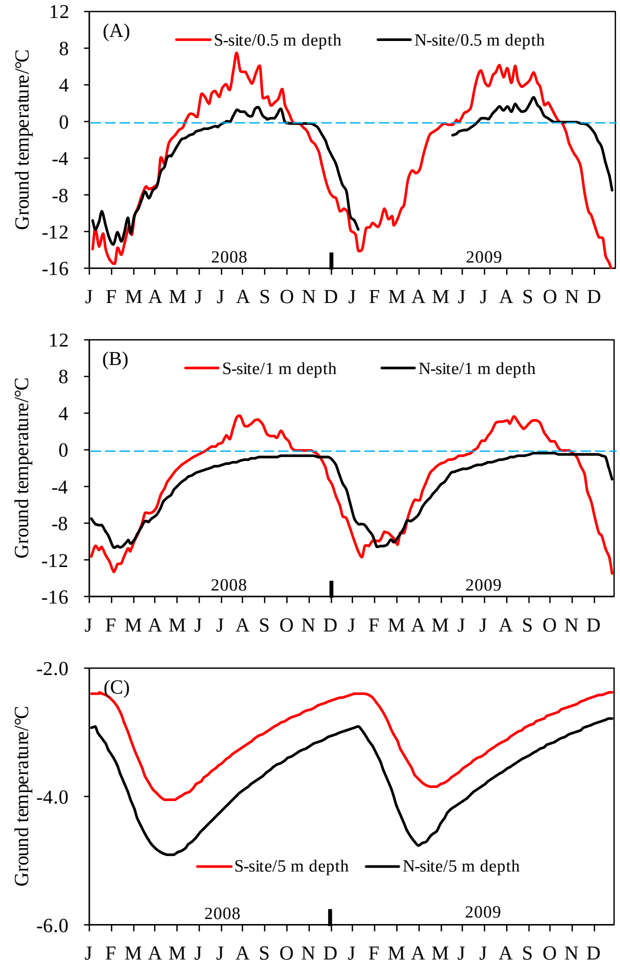

Figure 5. Changes in (A) soil temperatures with the time in 1 m depth at north and south site from 2008 to 2009; and (B) in 5 m depth.

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