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Effects of Seasonal Snow Cover on Hydrothermal Conditions of the Active Layer in the Northeastern Qinghai-Tibet Plateau

Ji Chen[1,2], Yu Sheng[1], Qingbai Wu[1,2], Lin Zhao[3], Jing Li[1], Jingyi Zhao[1,2]

[1]State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science, Lanzhou, 730000, China

[2] Beiluhe Observation Station of Frozen soil Environment and Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science, Lanzhou, 730000, China

[3]Cryosphere Research Station on the Qinghai-Tibetan Plateau, Chinese Academy of Sciences, Lanzhou, 730000, China

Corresponding to: chenji@lzb.ac.cn

Abstract. Snow cover significantly influences the moisture and thermal properties of the active layer in permafrost regions. Seasonal snow cover, soil temperature, and moisture were monitored in the northeastern Qinghai-Tibet Plateau (QTP) from December 2012 to February 2015. According to field data, the following conclusions were drawn. (1) The snow season in this region is predominantly during spring (March to May) and autumn (September to November), the thickness of individual snowfall events is usually less than 5 cm, and the duration of land surface snow cover is generally no longer than 5 days. (2) Removal of seasonal snow cover is beneficial for cooling the active layer in a whole year and in other seasons with the exception of summer. Further analysis on the ground temperature in the active layer shows that the cooling effect of the snow removal maybe results from the high thermal resistivity of snow, the delay of snowfall time in autumn, and the drastic decrease of moisture content in the active layer. (3) Seasonal snow cover maintains the high water content of the active layer. Snow removal can therefore lead to a rapid decrease of soil moisture content. A small decrease in water content of the active layer at the natural snow site (NSS) is related with less rainfall during the monitoring period. Significant differences between the NSS and the snow removal site (SRS) may depend predominantly on the inhibitory action of snow cover on the evaporation capacity of surface soil because of its cooling and shading effects during the daytime and in summer.

Keywords: Seasonal snow cover, Active layer, Soil temperature, Soil moisture, Qinghai-Tibet Plateau

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1. Introduction

The active layer is defined as the top layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost (Washburn, 1979). The active layer over permafrost plays a significant role in the surface energy balance, the hydrologic cycle, carbon exchange between the atmosphere and the land surface, ecosystems, landscape processes, and human infrastructure in cold regions (Brownet al., 2000; Lemkeet al., 2007; Wang et al., 2009; Han et al., 2010). Due to the impact of global climate change and human engineering activities, active layer thickness and temperature have increased over the past few decades in the Arctic, Antarctic, Alpine, QTP, and other areas (Brown et al., 2000; Jin et al., 2000; Zhao et al., 2000; Harris et al., 2003; Nelson et al., 2004; Zhao et al., 2004; Wu and Liu, 2004; Zhang et al., 2005; Cheng and Wu, 2007; Zhao et al., 2008; Wu and Zhang, 2010; Zhao et al., 2010; Wu et al., 2012; Guglielmin and Vieira, 2014).

Aside from the climate and human activities, changes in the active layer are strongly linked to factors such as the physical and thermal properties of the surface soil, vegetation, soil moisture content, and seasonal snow cover (Brown et al., 2000; Hinkel et al., 2003). Seasonal snow cover has significant and complex effects on the hydrothermal regime of the active layer as a result of its unique thermal properties. The high albedo of snow cover (98%) is helpful for reducing the snow surface temperature. In high latitude areas, the average temperature of the nival surface in winter is 0.5-2.0 ºC lower than the air temperature (Weller, 1974; Yershov, 1998). The large latent heat (335 kJ/kg) delays the snow cover thawing process and the ground heating rate by a significant amount (Zhang, 2005). In addition, the evaporation of snow meltwater can also help to reduce the land surface temperature. Good thermal insulation occurs in thick layers of snow because of the small thermal conductivity coefficient of snow cover (0.15 W/m·k) (Zhang et al., 1996). However, the thermal conductivity coefficient of snow cover is not fixed (Sturm et al., 1997). Monitoring results from the Alps indicate that the increase rate of the snow cover thermal conductivity coefficient is 0.01 W/m·k·d (Morin et al., 2010). A remarkable increase in this value, even by an order of magnitude (Reimer, 1980), can be caused by the wind (Yen, 1965).

Dramatic spatio-temporal differences in the effects of snow cover on the active layer have been observed due to the thermal properties mentioned above (Zhang, 2005).In high latitude areas with thick snow cover, the temperature of both the active layer underneath the snow cover and the permafrost is often significantly higher than that of bare land, with a 20 ºC temperature difference in some areas (Smith, 1975). In Alaska, ground temperatures at depths of 0.29 m and 3.0 m dropped by 1.48 ºC and 0.72 ºC, respectively, when the snow cover thickness reduced from 40 cm to 20 cm (Ling and Zhang, 2006). Daniel (2001) discovered that snow cover with a thickness greater than 80 cm will have remarkable thermal insulation, and a decrease of 10 cm in snow cover thickness can reduce the mean annual ground temperature (MAGT) by 0.3 ºC. In the Amur region of the Greater Khingan Mountains, snow cover 21-36 cm thick can increase the mean annual ground surface temperature (MAGST) by 2.8-5.0 ºC (Liang et al., 1993). In the Altai Mountains in northwestern China, seasonal snow cover increases the temperature difference between the ground surface and the atmosphere, which reaches 4.6-7.0 ºC in the lower mountain belt and 10ºC in the medium mountain belt (Tong et al., 1986).In contrast with the thermal insulation generally discovered in the Arctic Pole and the subarctic region, the effects of snow cover on active layer temperature in the Antarctic Pole and mid-latitude regions are linked to snow cover thickness. In the Antarctic continent, a cooling effect was observed when the snow cover thickness was less than 0.6 m (Goyanes et al., 2014; Guglielmin et al., 2014). In mid-latitude areas of the Alps, results from bottom temperature of snow (BTS) measurements indicate that 0.8 m is the critical thickness for thermal insulation of the snow cover (Keller and Gubler, 1993), while numerical simulation results show a critical thickness of 0.6 m (Luetschg et al., 2008). Jin et al (2008) analyzed previous research data and proposed that, in eastern parts of the QTP, thermal insulation occurs in seasonal snow cover when its thickness is more than 20 cm, which is similar to monitoring results from the Qilian Mountain ice groove (Hao et al., 2009) and predictions using the Coupmodel (Zhou et al., 2013). In addition, snow cover formation and thawing time can also deeply influence the active layer temperature. Daniel (2001)analyzed the thermal regime of the active layer over the Corvatsch site in the Alps and found that snow cover 5-15 cm thick in late autumn could more effectively cool the shallow soil mass.

Snow cover influences not only the temperature and thickness of the active layer, but also the soil moisture content. In spring, water content in the active layer increases remarkably, even reaching saturation conditions, because of the infiltration of melted snow (Hinzman et al., 1991; Hinkel et al., 2001). In winter, the permafrost shell thickness of the surface layer significantly influences the infiltration of melted snow, while a permafrost shell more than 0.4 m thick could impede infiltration (Iwata et al., 2011). Using observation results from high latitude areas, the SNOW-17 snow cover energy and water balance model has been developed, which theoretically discusses the effects of seasonal snow cover on the water content of the active layer (Anderson, 1976).

Previous studies have shown that seasonal snow cover remarkably influences the hydrothermal regime of the active layer, producing significant spatio-temporal differences. In this study, the western section of the Qilian Mountains in the northeastern QTP is investigated, where mountain island permafrost dominates (Li et al., 2012; Li et al., 2014), and a wide distribution of snow cover exists (Zeng et al., 1985; Chen et al., 1991). During the period from 2003 to 2010, there has been a remarkable decrease in the number of average snow days and a gradual increase in the stable snow cover (Sun et al., 2014). Because of differences in geographical location, the area in this study differs significantly from the more commonly studied high latitude and Alpine regions with respect to radiation, climate, and snow cover characteristics. Recent studies on snow cover effects on the active layer in this area have mainly focused on numerical simulations and the shallow soil layer at a depth of about 50 cm (Jin et al., 2008; Wang et al., 2011; Zhou et al., 2013; Xiang et al., 2013). As the active layer thickness of the Qinghai-Tibet Plateau is usually 2-3 m (Wu and Zhang, 2010), it is very difficult to objectively evaluate the effects of seasonal snow cover on the hydrothermal regime of the active layer in this area without deep hydrothermal monitoring.

2. Description of Monitoring Site and Equipment

2.1 Description of monitoring site

The monitoring snow site, including the NSS and SRS, is located in the Yashatu basin of the western Qilian Mountains in the northeast of Qinghai-Tibet Plateau, about 80 km from Delingha city, Haixi Prefecture, Qinghai Province in the southeast and about 30 km from the Qaidam Basin margin in the south, at 96.516° E and 37.6952° N (Fig.1a, b).The average altitude of this site is approximately 4040 m. The snow site and its surrounding areas are flat with a maximal gradient of 0.5°. The Zongwulong Mountain, which runs nearly east to west at an altitude of 4500 m, is located between the Yashatu basin where the snow site lies and the Qaidam Basin. There is a

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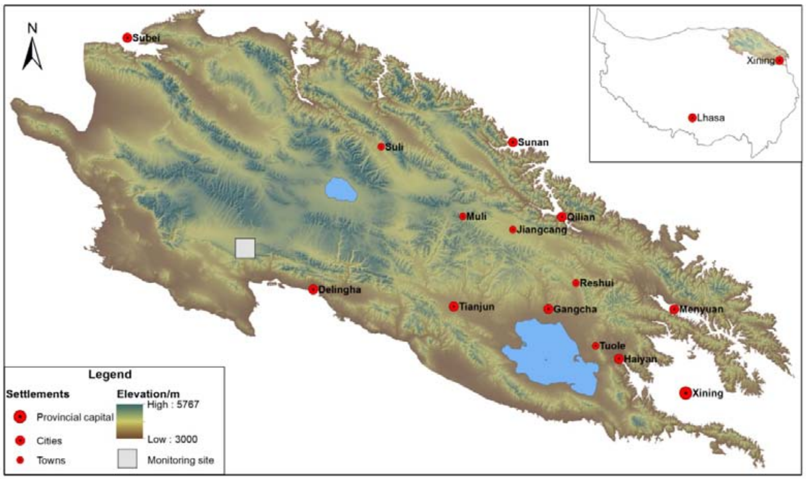
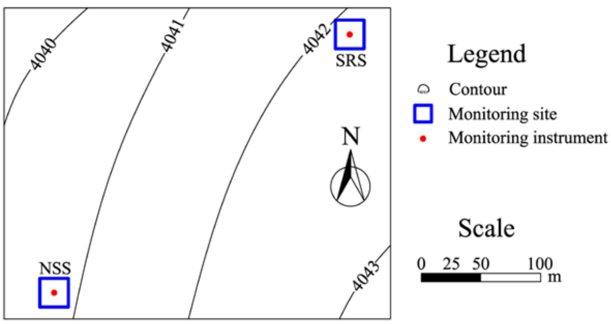
The Cryosphere Discussions

remarkable difference in the climate of Yashatu and Delingha city, attributed to influences of the Zongwulong Mountain and the altitude contrast.

a. Site location



b. Layout of the NSS and SRS, and the positions of the instruments



c. Semi-desert landscape

d. Vegetation near the river

Figure 1 Location and layout of the NSS and SRS, the positions of the instruments, and typical landscapes over the Yashatu basin in the Qilian Mountains, QTP

According to monitoring results from Yashatu Basin during the period from November 2009 to February 2015, the region has a minimum air temperature of -32.6 ºC, a maximum air

The Cryosphere Discuss., doi:10.5194/tc-2016-134, 2016
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temperature of 22.9 ºC, an average annual temperature of -3.0-4.5 ºC, an atmospheric pressure of 610-630 hpa, and an annual precipitation of 100-200 mm. West, south, and southeast are the predominant wind directions in this area where the mean annual wind speed is 3.3 m s^{-1} and the mean annual maximum half-hour wind speed is 18.3 m s^{-1}. Except for the two sides of the river where Myricaria prostrata and some Koeleria tibetica are found, other parts of the Yashatu Basin have vegetation coverage below 20%. Some areas even have bare surfaces, and describe typical half-desert or desert landscapes (Figure1c and d).

According to drilling results from 2009 and pitting results from 2010, the depth of the active layer in the snow site is 3.0-4.0 m, mainly consisting of sandy soil, sandy-gravelly soil, gravelly soil, and mudstone. Mudstone is located 5.0 m below the NSS and 3.6 m below the SRS (Figure 2), where the total ice content is less than 10%. Based on a less than 0.1 ºC standard temperature fluctuation, the annual ground temperature propagation depth of the snow site is less than 5.0 m, and the MAGT increased from -0.5 ºC in 2009 to -0.4 ºC in 2014. The MAGT at a depth of 15.0 m fluctuated between -0.32--0.30 ºC during the period from 2009 to 2014, yet, due to the accuracy of the equipment and the probe, there has been effectively no change in ground temperature at a depth of 15.0 m over the past 4 years.

a-NSS

Site type	NSS	Longitude	96°31'	Latitude	37°42'	Vegetation cover	<20%
Total depth	15 m	Altitude	4040 m	Slope gradient	0.5°	Slope orientation	225°

Depth /m	Thick. /m	Column 1:100	Stratigraphic description	W.C. Depth /m	W.C. %	Notes
0.6	0.6		Sandy-gravelly soil, earthy yellow, slight wet	0.5	5.5	In this graph, W.C. is derived from weight method and represents the mass water content in the active layer.
3.0	2.4		Sandy-gravelly soil, yellowish brown, gravel content equal to approximate 20%, water saturated	1.0 1.5 2.1 2.6 2.8 3.0	3.5 7.1 2.6 10.2 15.8 36.9	
4.3	1.3		Sandy soil, reddish, with a few silty clay samdwich, frozen, ice rich			
5.0	0.7		Silty sand, steel gray, slightly sticky, frozen, total ice poor except for several ice-rich soil layer	4.7	30.0	
6.0	1.0		Mudstone, red, very sticky, frozen, total ice content <10%, except for seldom ice-rich soil layer	5.5	25.5	

b-SRS

Site type	SRS	Longitude	96°31'	Latitude	37°42'	Vegetation cover	<10%
Total depth	50 m	Altitude	4043 m	Slope gradient	0.5°	Slope orientation	305°

Depth /m	Thick. /m	Column 1:100	Stratigraphic description	W.C. Depth /m	W.C. %	Notes
0.4	0.4		Sandy soil with little gravel, yellowish brown	0.3	2.9	In this graph, W.C. is derived from weight method and represents the mass water content in the active layer.
0.8	0.4		Sandy loam with a lot of gravel, grayish yellow	0.8	6.5	
2.0	1.2		Gravelly soil, steel gray, proportion of rock with diameter > 2 cm is more than 30%, water saturated	1.5	10.4	
2.7	0.7		Sandy soil with a lot of gravel, gray, proportion of rock with diameter > 2 mm is about 20%	2.5	10.4	
3.6	0.9		Gravelly soil, steel gray, proportion of rock with diameter > 2 mm is about 60%, secondary psephicity; 2.7 m~3.0 m, water saturated; 3.0 m~3.5 m, moist; 3.5 m~3.6 m, frozen, ice poor	3.5	27.8	
6.0	2.4		Mudstone, red, very sticky, frozen, total ice content <10%, except for seldom ice-rich soil layer	4.0	31.6	

Figure 2 Lithological column based on test pit and borehole data from the NSS and the SRS

The field survey of the permafrost site in the Yashatu Basin was carried out in March 2009 and the borehole study was completed by the end of September. Ground temperature and meteorological equipment was installed and used for monitoring by the end of November. Air temperature and humidity were simultaneously monitored by CR3000 (HMP45C) and Hobo (S-THB-M002). Two monitoring locations with a separation distance of approximately 300 m were established by May 2010 (Figure 1b), the NSS and the SRS, which had similar ground vegetation (Figure 1c) and lithologies (Figure 2) i.e. semi-desert landscape with sparse vegetation. Monitoring results during the period of 2010-2012 indicated that the difference in mean annual ground temperature between the two locations was less than 0.05 ºC and the maximum snow season was approximately 2 months.

The hydrothermal probe for the active layer was established by May 2010. Two sets of monitoring devices were installed in the center of the two locations (Figure 1b) in order to perform a comparative study on the effects of snow cover. In 2012, the two sets of monitoring devices were upgraded. Surface albedo and surface infrared temperature probes were added to one site to monitor the snow removal site, and probes for surface albedo, surface infrared degrees, ultrasonic snow depth, and shallow soil thermal flux were added to the other set of equipment to monitor the natural snow site. Detailed information on the type, model, properties, and quantity of the probes is listed in Table 1.

Table 1 Characteristics of probes used at the Yashatu snow site. AT&H = Air temperature and humidity, GST = ground surface temperature, SM = soil moisture, and ST = Soil temperature

Types	Versions	Accuracy	Ranges	Numbers		Brand	Notes
				SRS	NSS		
Wind	05103-L	±1 m s^{-1}	0-100 m s^{-1}	1	/	R.M. Young	/
AT&H	HMP45C	2% RH, ±0.2 °C (20 °C)	0.8%-100%RH, -40 °C to +60 °C	1	/	Vaisala	/
	S-THB-M002	2.5% RH, ±0.2 °C (+50 °C)	0%-100% RH, -40 °C to +75 °C	1	/	Hobo	/
Barometer	CS106	±1.5 mb	500-1100 mb	1	/	Vaisala	/
Rain gauge	TRWS 200E	0.1%	750 mm	1	/	MPS SYSTEM	/
Albedo-1	NR01	<15 W m^{-2}	0-2000 W m^{-2}	1	/	Hukseflux	/
Albedo-2	240-8104	<1 W m^{-2}	0-1500 W m^{-2}	/	1	Novalynx	/
GST	SI-111	±0.2 ºC	-40-70 ºC	1	1	Apogee	/
Snow depth	260-700	±1 cm	0.5-10 m	/	1	NovaLynx Corporation	/
Thermal flux	HFP01	50 μV/ W m^{-2}	-2000-+2000 W m^{-2}	2	2	Hukseflux	※1
SM-1	CS616-L	±2.5%	0-100%	10	/	Campbell Scientific, Inc.	※2
SM-2	SM300	±2.5%	0-50%	/	10	SPECTRUM	※2
ST	SKLFSE-TS	±0.05 ºC	-30- + 30 ºC	10	10	/	※3

Notes：※1: The heat flux plates are laid at depths of 5 cm and 10 cm. ※2: The soil moisture probes are laid at depths of 5 cm, 20 cm, 40 cm, 80 cm, 120 cm, 160 cm, 200 cm, and 250 cm. ※3: The soil temperature probes are laid at depths of 5 cm, 20 cm, 40 cm, 80 cm, 120 cm, 160 cm, 200 cm, 250 cm, 300 cm, and 400 cm.

The propagation rate of sonic waves was adjusted by using the existing temperature probe of the monitoring site to enhance measurement accuracy of the snow depth. In the QTP, the snow

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Manuscript under review for journal The Cryosphere
Published: 6 July 2016

cover thickness of the shallow ground is usually less than 6cm, and the duration of snow cover is generally 2-3 days (French, 2007). High frequency continuous data are needed to analyze the effect of snow cover on the active layer because snow cover changes rapidly. In order to capture the hydrothermal states of the active layer, all sensors including the infrared surface temperature probe, the snow depth probe, and the surface albedo probe were connected to the CR3000 automatic data acquisition instrument with a half hour acquisition time interval. However, due to a power supply problem that was not carefully considered when upgrading the meteorological station, leakage in data acquisition often occurred during the night at the snow removal site.

There is more than one dominant wind direction in this area, and the dominant wind directions differ between seasons. Snow fences were not adopted in the SRS. Snow shovels and brooms were used to remove the snow cover of the SRS. Snow removal was typically completed one day after snowfall. Images of NSS and SRS before and after snow removal are shown in Figure 3.

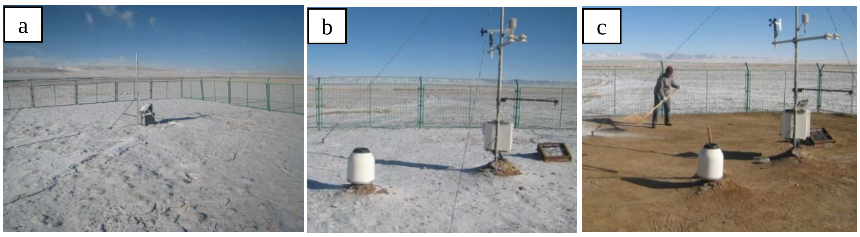

Figure 3 Experiment sites of seasonal snow cover in the Yashatu Basin of Qilian Mountains, QTP. a) NSS after snow fall, b) SRS after snow fall, and c) SRS after snow removal.

2.2 Soil temperature acquisition

The SKLFSE-TS probe manufactured under the supervision of the State Key Laboratory of Frozen Soil Engineering (SKLFSE, China) was adopted to monitor soil temperature at the snow site. The SKLFSE-TS thermistor temperature probe has been widely used since 1982 (Cheng, 1980), currently for permafrost engineering and environmental monitoring along the Qinghai-Tibet railways (Cheng, 2005, 2007; Zhang et al., 2008; Wu and Zhang, 2008; Zhao et al., 2010). The thermistors calibration is also carried out through comparison with the national second-class platinum resistance thermometer in a temperature calibration tank. Detailed calibration process and method are described in the study of Liu et al. (2011). The measuring range of the SKLFSE-TS temperature probe is -30 ºC-+30 ºC, which can be extended to ±40 ºC when standardization is performed under wide temperature ranges. The temperature resolution is 0.01 ºC, temperature accuracy is ±0.05 ºC, and the cable is longer than 300 m (Shen et al., 2012).

2.3 Soil moisture acquisition

The CS616 sensor manufactured by Campbell Scientific INC. U.S.A. was adopted for soil moisture monitoring. The probe has two extensions 300 mm long, 3.2 mm in diameter, and with a 32 mm separation distance. Based on the principle of FDR (Frequency Domain Reflector), CS616 can only be used to measure the volumetric water content in soil (Campbell Scientific Inc., 2004). All water contents mentioned in this paper are volumetric water contents, except for some special cases, discussed below.

Unlike the temperature probes, the soil moisture probes have to be laid in layers by digging a test pit, instead of being laid by drilling. Considering the convenience of construction, the soil moisture monitoring probes are usually laid when the active layer reaches maximum thawing

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Manuscript under review for journal The Cryosphere
Published: 6 July 2016

The Cryosphere Discussions
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penetration. Previous research results indicate that the active layer in permafrost regions in the Qinghai-Tibet Plateau usually reaches the maximum thawing penetration in September and October (Wu and Zhang, 2010). The water probes were due to be installed in October 2009. However, it was found during drilling in September of 2009 that sandy soil and gravelly soil occupied most of the depth from 0-3.6 m where the underground water level was less than 1.0 m. As a result, the water probes were unable to be laid. The probes were finally laid in May 2010 when the active layer was completely frozen and no longer melting. The water probes were laid at 5, 20, 40, 80, 120, 160, 200, and 250 cm depth from the surface. Comparative monitoring of the snow cover over the two locations started in December 2012. Because the hydrothermal probes had been installed in the active layer by 2010, digging of the active layer wouldn't significantly influence the accuracy of monitoring data after December 2012.

The CS616 probe only measures water content in the thawing soil and unfrozen-water content in the frozen soil (Kunio Watanabe and Tomomi Wake, 2009; Gary Parkin et al., 2013). When the active layer is frozen, measurement results are much lower than the true value. In order to discuss the true water content and its variability, only values measured in the thawing period were analyzed in this paper.

3. Monitoring results

3.1 Characteristics of snow cover in the Yashatu Basin

Field observations and automatic data collected from the meteorological data for the period from December 2012 to October 2014 indicate that the MAAT, maximum and minimum temperature are -3.4, 15.4 and -26.5 ºC, respectively, and the mean annual relative humidity is 32.8% (Figure 4). For the same period there are 45 measured snowfalls in the Yashatu Basin, with a total surface snow cover thickness of 69.3 cm, and a 2-year accumulated surface snow cover duration of 77 days.

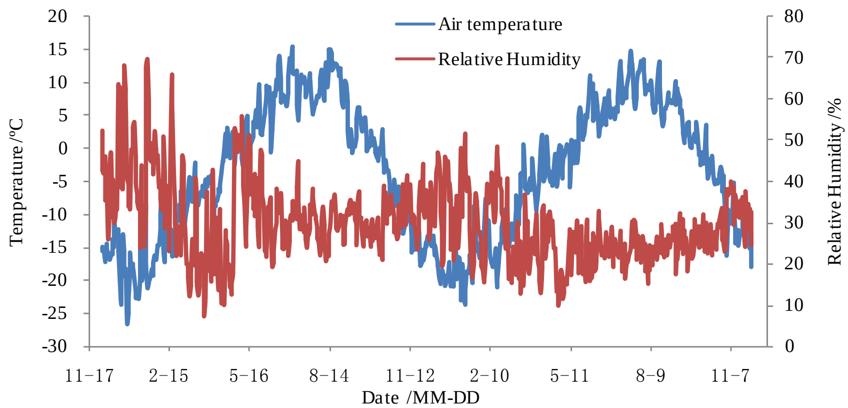

Figure 4 Variation in air temperature and relative humidity from 2012.12 to 2014.11

During the 2-year monitoring period, the distribution of snow cover is highly uneven and changes significantly between months and years (Figure 5). Over the period from December 2012 to November 2013, snowfall occurs in all months except for March, July, and August. The accumulated annual snow cover is 25.5cm, the mean monthly accumulated snow cover is about 2cm, and the maximum monthly snow cover is 6.7cm. From December 2013 to November 2014, snow falls only in six months, mainly in October and November. For 2014-10-30 to 2014-11-15,

The Cryosphere Discuss., doi:10.5194/tc-2016-134, 2016
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the accumulated snow cover thickness is 29.4 cm, and snowfall occurs 15 times. Compared with the previous year, the accumulated snow cover thickness increases by 18.3 cm in 2014.

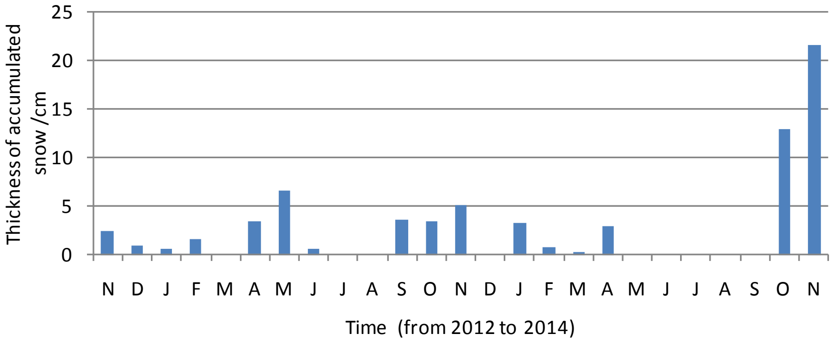

Figure 5 Monthly accumulated snow cover thickness from 2012 to 2014 in the Yashatu Basin

After each snowfall in the Yashatu Basin, the duration of surface snow cover is generally less than 5 days (Figure 6), and the average melting time of each snowfall is less than 2.5 days, while the snow cover duration is typically less than one day. During the period from the end of October to the middle of November 2014, due to low temperatures and more than ten snowfalls, the duration of surface snow cover increases to 17 days, which is the longest continuous snow cover event in the Yashatu Basin over the two years.

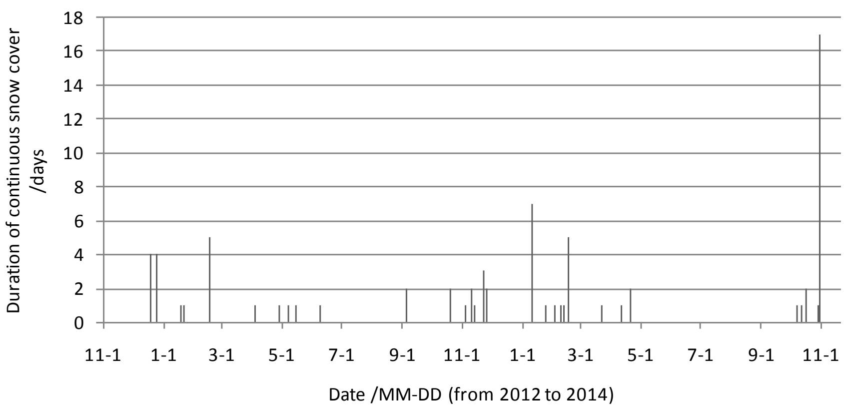

Figure 6 Timing of snowfall and duration of continuous snow cover events from 2012 to 2014 in the Yashatu Basin

Snowfall in the Yashatu Basin shows significant seasonal differences (Table 2).In winter (December-February), the accumulated snow cover thickness is not large, but the duration of snow cover is long because of low air temperatures. Conversely, in spring (March-May), the accumulated surface snow cover thickness is large and the snow cover duration is short because of enhanced surface radiation and increasing air temperatures, and the melting time of single snow cover events is usually less than one day. In summer (June-August), the accumulated snow cover has the lowest thickness, and the melting time is usually within several hours. In autumn (September-November), the accumulated snow cover is thickest, and the surface snow cover duration is the longest.

The Cryosphere Discuss., doi:10.5194/tc-2016-134, 2016
Manuscript under review for journal The Cryosphere
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Table 2 Accumulated thickness and days of snow cover over four seasons in the Yashatu Basin

Start and end time	2012.12-2013.11		2013.12-2014.11	
Seasons	Thickness (cm)	Duration (days)	Thickness (cm)	Duration (days)
Winter (12-2)	3.1	15	5.6	16
Spring (3-5)	10.2	4	3.0	5
Summer (6-8)	0.6	1	0.0	0
Autumn (9-11)	12.1	13	34.7	22

3.2 The active layer thickness (ALT) and soil temperatures in the active layer

According to the definition of Muller (1947), the active layer floor is usually equal to the maximum seasonal depth of the 0 ºC isotherm. This definition has been widely recognized and accepted because it eliminates various field interferences to the freezing-thawing depth, which is helpful to perform quantitative analysis on ALT (Brown et al., 2000). The thawing and refreezing process curves in the NSS and SRS during the period of 2013.3-2014.12 are given in Figure 7 based on the ground temperature monitoring data during the period of 2013.3.1-2014.2.28. As shown in figure 7, the ALTs of the two sites are 339.1cm and 340.6 cm in 2013, and 360.5 cm and 363.4 cm in 2014. Accordingly, the ALTs in the two sites have increased by 21.4 cm and 22.8 cm respectively.

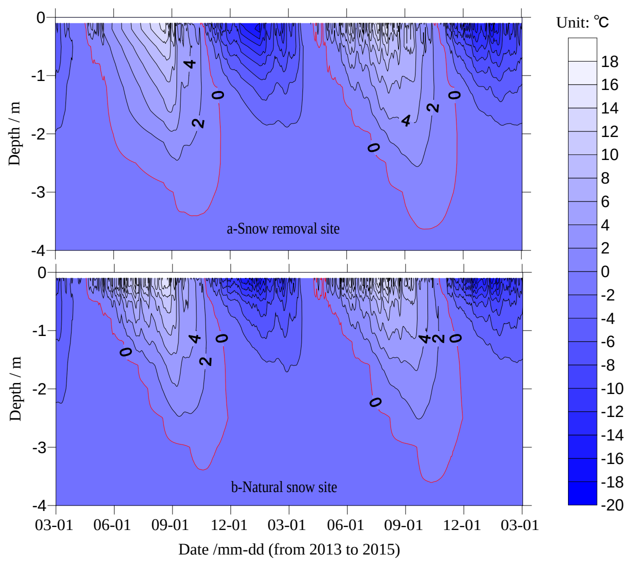

Figure 7 Ground temperature regime in the NSS and the SRS

The soil temperature of the active layer, especially the topsoil, changes greatly throughout the year (Figure 7). It is therefore unsuitable to estimate the thermal effect of seasonal snow cover on the active layer by comparing the ground temperature at one point in time. The mean annual soil temperature is the average value of soil temperatures acquired at a certain frequency in one year, which synthetically reflects the thermal regime of soil at any depth in the active layer, or in a perennial frozen earth layer, and can be used to study trend of the thermal regime of the active layer or permafrost (Wu and Zhang, 2008).

Previous studies suggest that the daily geothermal propagation depth is within 2.0 m (Yershov, 1998). In the QTP, we assume that the depth, where daily soil temperature amplitude is less than

0.1 ºC, is the daily geothermal propagation depth. Excluding the daily meteorological extremes and the effect of human activities, the daily geothermal propagation depth in the quaternary strata is usually less than 0.5 m. The soil temperature of layers above 0.5 m depth varies significantly within one day, and it is not sufficient to obtain the average daily soil temperature of layers at 0.05 m and 0.20 m depth by acquiring ground temperature at a single time, several times, even partial time of each day. Continuous monitoring data of the SRS at night could not be acquired most of the time, therefore the true mean annual soil temperature at depths of 0.0 m, 0.05 m, and 0.20 m in the SRS can also not be determined. The profile of average soil temperature versus depth for different seasons and over one year only at 0.5 m depth and below in the NSS and SRS from 2014.3.1-2015.2.28 is shown in Figure 8. The mean annual temperature profile of the SRS before and after snow removal is also shown in Figure 8f.

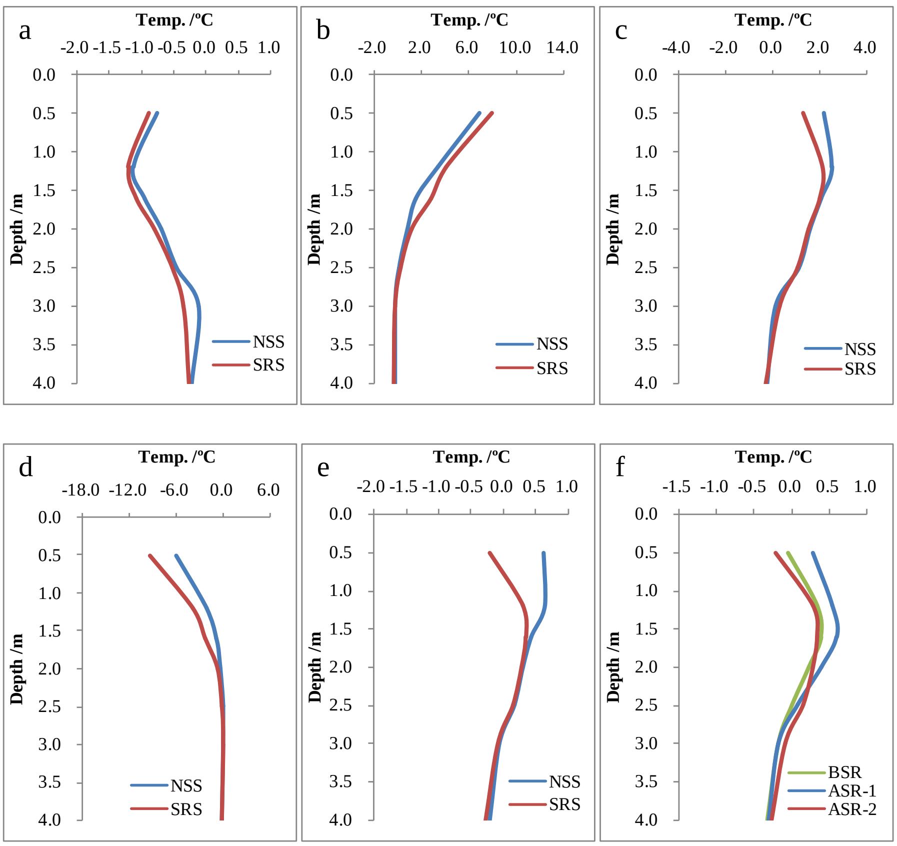

Figure 8 Mean annual soil temperature profile of active layers in the NSS and SRS, where a, b, c, d, and e refer to the average soil temperatures within the active layers of the two sites in spring (March-May), summer (June-August), autumn (September-November), winter (December-February), and the entire year. Panel f shows the mean annual soil temperature at the SRS before and after snow removal. NSS and SRS refer to natural snow site and snow removal site, respectively. BSR means before snow removal in the SRS (2011.12-2012.11), and ASR refers to after snow removal. ASR-1 and ASR-2 indicate the first (2012.12-2013.11) and second

(2013.12-2014.11) years after the start of snow removal, respectively.

In spring, the soil temperature of the active layer in the NSS is higher than that of the SRS, with a temperature difference of generally less than 0.1 ºC, except for the area near 3 m depth (Figure 8a). In summer, the temperature of the NSS at 0.5-2.0 m depth is about 1 ºC lower than that of the SRS, while at 2.5-4.0 m depth, the temperature of the two sites is almost the same (Figure 8b). In autumn, the temperature of the NSS at 0.5-1.5 m depth is approximately 0.5 ºC higher than that of the SRS, and at depths below 1.5 m, the temperature difference of the two sites is less than 0.1 ºC (Figure 8c). In winter, the temperature of the NSS at 0.5-2.0 m depth is at most 3.3 ºC higher than the SRS, while at depths below 2.0 m, the temperature curves of the two sites are basically equal, and the maximum temperature difference is no more than 0.1 ºC (Figure 8d). Ground temperature at all depths in the active layer is higher in the NSS than that in the SRS with exception of summer. Their difference decreases with the depth.

In terms of yearly temperature, the mean annual soil temperature difference in active layers of the two sites also decreases with an increase in depth, and the temperature difference at 0.5 m depth is the greatest, with the NSS being 0.8 ºC warmer than SRS. From 1.6 m to the bottom of the active layer, ground temperatures are all higher in the NSS than that in the SRS. However, the mean annual soil temperature difference of the two sites is generally less than 0.3 ºC (Figure 8e).

Temperature differences are observed in the active layer of the SRS before and after snow removal (Figure 8f). In the first year after snow removal, increases of 0.3 ºC and 0.2 ºC occur at depths of 0.5 m and 2.0 m, respectively. In the second year after snow removal, the temperature of the active layer at 0-2.0 m depth decreases. Compared to the first year, decreases of approximately 0.5 ºC and 0.1 ºC at depths of 0.5 m and 2.0 m are observed, respectively. From 2012 to 2014, the mean annual air temperature of Yashatu is -4.5 ºC, -3.4 ºC, and -3.9 ºC, indicating that changes in shallow soil temperature follow changes in air temperature during the monitoring period, namely, by increasing and then decreasing.

3.3 Soil moisture in the active layer

The moisture profiles of the NSS and SRS from 2013.3.1 to 2015.2.28 are shown in Figure 9. During the period from June-October, soil water content is 10-20% in the shallow soil, 0.2-0.5 m depth, less than 10% at 0.4-0.7 m depth, and 20-40% beneath a depth of 0.4-0.7 m. Compared to the NSS, there is more soil with low water content in the shallow layer and more soil with high water content in the middle and bottom layers.

In October, with maximum thawing penetration, water content based on CS616 can reflect the true soil moisture. From October 2013 to October 2014, soil moisture is redistributed in the active layer and a change of total water content is not apparent in the NSS (Figure 9a), whereas very large changes occur in the SRS (Figure 9b). Soil layers with water contents of more than 70% have disappeared and areas with water contents between 30-40% have significantly reduced.

In order to perform quantitative analysis on soil moisture changes in the active layers of the two sites, moisture content of various layers from the NSS and SRS during maximum thawing penetration in 2012, 2013, and 2014 are shown in Figure 10.

At a depth of 0-50 cm, the range of soil moisture content in the two sites is no more than 4%, and there are no significant changes during the 2012-2014 period. At a depth of 80 cm, soil moisture decreases with time, and soil moisture in the NSS gradually decreases from 40.0% to 18.4% to 16.1%, while soil moisture in the SRS decreases from 34.4% to 4.8% to 4.5%. At depths up to 120 cm, soil moisture in the NSS increases, the maximum annual increase in soil moisture of

The Cryosphere Discuss., doi:10.5194/tc-2016-134, 2016
Manuscript under review for journal The Cryosphere
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The Cryosphere Discussions
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each layer is less than 3%, and the increase over the two years is less than 4%. The change in soil moisture at depths below 120 cm in the SRS differs greatly from that of the NSS. At 120 cm depth the soil moisture gradually decreases from 31.5% to 9.2% to 7.2% and the soil moisture at 160 cm and 200 cm depth first increases then decreases, while the soil moisture at 250 cm depth increases.

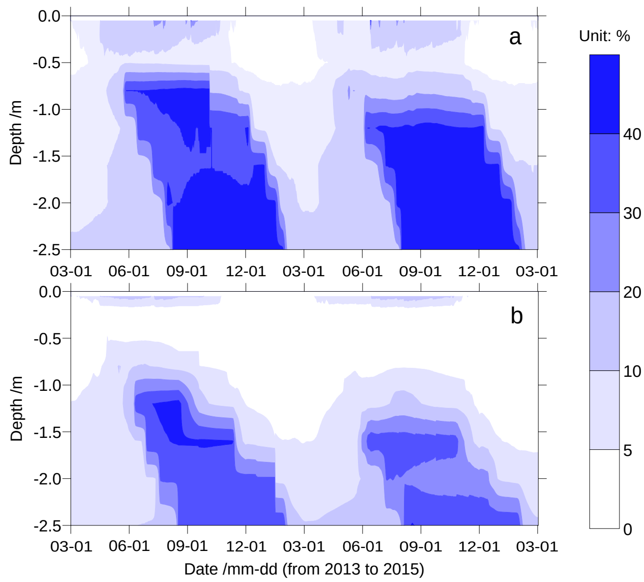

Figure 9 Volumetric moisture content based on the CS616 in (a) the NSS and (b) the SRS from 2013.3.1 to 2015.2.28

Soil moisture content in the active layer changes significantly with depth, so simply comparing the soil moisture at a certain depth is not helpful for understanding the effects of seasonal snow cover on soil moisture in the active layer. The CS616 probe acquires the volumetric water content, under the assumption that the moisture content between the probes changes according to a known law, and therefore the average moisture content within the monitoring scope can be directly acquired from on site monitoring data. Referring to the acquisition method of the 0 ºC isotherm, the linear interpolation method is used in this paper to obtain soil moisture content at various depths, and the overall moisture content of the active layer can be obtained through the following Eq. (1):

$$w = \left[H_1 \times w_1 + \sum_{i=2}^{n}(H_i - H_{i-1}) \times \frac{w_i + w_{i-1}}{2}\right] / H_n \qquad (1)$$

In the above Eq. (1), the moisture content at 0-5 cm depth is the same as that at a depth of 5 cm, w and n refer to the average moisture content within the monitoring scope and the total number of probes in the active layer, respectively, H_i and w_i are the depth and moisture content of the i^{th} probe from top to bottom, and H_n is the depth of the probe at the n^{th} soil layer. The unit for H_i and H_n is cm, and % for w and w_i.

The overall moisture content of active layers in the two sites between 0-2.5 m depth at the maximum thawing penetration in 2012, 2013, and 2014 is obtained according to this method, and the calculation results are listed in Figure 10. From 2012 to 2014, the range in overall moisture content within the active layer at the NSS is 2.7%, and an accumulated decrease of 1.8% is

The Cryosphere Discuss., doi:10.5194/tc-2016-134, 2016
Manuscript under review for journal The Cryosphere
Published: 6 July 2016

observed over the two years. The moisture content in the SRS decreases with time, with decreases of 7.3% and 2.7% observed in 2013 and 2014, respectively, and a total decrease of 10.0% over the two years. The overall moisture content within the active layer of the SRS has decreased by 8.2% more than in the NSS.

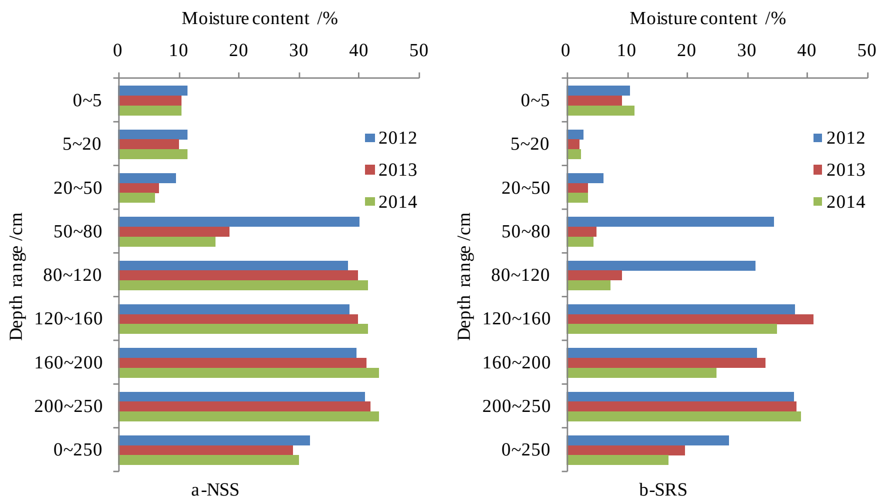

Figure 10 Soil moisture content versus the depth in the active layer in the Yashatu Basin from 2012 to 2014

4. Discussion

4.1 Could thin seasonal snow cover warm the active layer?

Whether in mid-latitude mountainous areas like the Alps(Keller and Gubler, 1993; Luetschg et al., 2008; Beniston et al., 2011; Tobias Rodder and Christof Kneisel, 2012), in high latitude areas such as the South Pole (Guglielmin et al., 2014; Goyanes et al., 2014), or in the Qinghai-Tibet Plateau (Jin et al., 2008; Hao et al., 2009; Zhou et al., 2013), snow cover with a thickness of <0.2 m usually has a net cooling effect, which helps to decrease the temperature of the active layer. The maximum snow cover thickness of Yashatu Basin during the period of 2012.11-2014.11 is only 5 cm (Figure 5), which is much less than the previously determined critical snow cover thickness of 20 cm. Based on previous studies and monitoring results of snow cover thickness, a thin seasonal snow cover should decrease the temperature within the active layer at Yashatu sites. The ground temperature in the SRS should increase after snow removal. However, in reality, air temperature during the two consecutive years was higher than prior to snow removal the thickness of the snow cover was smaller than the critical snow cover thickness, and the average soil temperature of the active layer in the SRS two years after snow removal was lower than both before snow removal and the NSS.

The temperature decrease within the active layer of the SRS may be connected to the high thermal resistivity of snow cover, which decreases the heat dissipation intensity of the active layer in the winter (Goodrich, 1982; Sturm et al., 1992). The temperature decrease in the SRS may also be connected to the timing of snowfall. The observation and simulation results from Alaska indicate that the timing of snowfall influences the temperature within the active layer. A delay of 10 days in snowfall time may result in a drop of 9 ºC in surface temperature, which decreases by

1.1 ºC at a depth of 2 m (Ling and Zhang, 2003). The main snowfall season in the Yashatu Basin is in autumn (Figure 5), and the duration of surface snow cover is quite long (Figure 6). The cooling period of the active layer is also in autumn, when the snow cover significantly decreases heat release and hinders the temperature decrease within the active layer. The increase in ground temperature under snow cover occurs not only in winter, but also throughout the whole year, when the ground temperature may be higher (Williams, 1989). In fact, except for summer (Figure 8b), the shallow soil temperature within the active layer of SRS is lower than that in the NSS in spring, autumn, and winter (Figures8a, 8c, and 8d).

Table 3 Average monthly thermal flux (W m^{-2}) at 5 cm depth from 2015.4-2016.3

Year	2015								2016		
Month	4	5	6	7	8	9	10	11	12	1	2	3
NSS	8.7	11.0	12.7	16.5	9.1	1.8	-4.2	-9.3	-14.0	-12.8	-7.5	0.9
SRS	13.3	13.4	11.6	16.8	13.3	1.6	-4.7	-14.7	-20.5	-17.0	-6.4	2.5

Note: In this table, positive number represents the thermal influx in the active layer. Negative numbers mean that the active layer released its heat towards the atmosphere.

Soil moisture content in the active layer of the SRS has decreased continuously since snow removal experiment began in December 2012 (Figure 10), which not only influences the thawing-freezing process but also alters the thermal balance of active layer. The decrease of moisture content influences the thermal balance in both areas. Firstly, the thermal conductivity decreases, especially in the frozen state, which impedes the thermal release in winter and warms the active layer. Secondly, decrease of moisture content releases the huge latent heat, which may be the thawing latent heat or the evaporating latent heat. The thawing latent heat is 335 kJ kg^{-1} and the evaporating latent heat is 2257 kJ kg^{-1} at 100 ºC under the condition of a standard atmospheric pressure. The thawing and evaporating latent heat for the water with VWC equal to 1% in 1 m^3 soil body is 3350 kJ and 22570 kJ, respectively. When the average thermal capacity in the active layer of the SRS is assumed to be 2267 kJ/(m^3·ºC) and the VWC decreases by 1%, the temperature of the active layer can decrease by 1.5 ºC due to the thawing latent heat and 10.0 ºC due to the evaporating latent heat theoretically. Therefore, the dramatic decrease in moisture content may be the other significant factor which leads to the temperature decrease of the active layer in the SRS.

In order to verify this phenomenon, the problems experienced with the power supply were solved at the SRS in April 2015. Thermal flux data were successfully collected at half-hour intervals during the period from April 2015 to March 2016, and listed in Table 3.According to this data, thermal states of the active layer can be classified into four stages: (a) warming stage (April-August), (b) the first steady stage from warming to cooling (September), (c) cooling stage (October-February), and (d) the second steady stage from cooling to warming (March). Excluding February, heat release from the active layer in the NSS is less than that in the SRS during the cooling stage. Excluding June, active layer heat intake is also less in the NSS than the SRS during the warming stage. Abnormal heat fluxes in February and June are both related to significant snowfall from October to January and from April to May, which leads to less heat release and heat intake in the NSS than the SRS. Therefore, in February and June, when there is little or no snowfall, the heat exchange is much greater in the NSS than in the SRS. During the period from April 2015 to March 2016, the average thermal influx at 5 cm depth is 1.1 W m^{-2} in the NSS and 0.7 W m^{-2} in the SRS. Owing to the higher thermal intake, the average soil temperature of the active layer is higher in the NSS than the SRS.

4.2 What leads to the soil moisture decrease and disparity between the NSS and SRS?

In permafrost areas, the active layer is the soil layer where soil moisture changes are most active. Runoff on the surface and in the active layer, soil properties, as well as evaporation and infiltration, can all alter the soil moisture content of the active layer. As the snow site is located in the bottom of Yashatu Basin where the slope gradient is less than 1°, runoff here can be disregarded because of the flat ground (Neal, 1938). In the process of installing soil moisture probes, digging often changes the soil properties, such as soil structure, grain size distribution, and compactness, etc. Grain size distribution is disturbed vertically and horizontally. However, the soil in the active layer of the NSS and SRS is unstructured coarse sand and gravelly soil with inferior water retention ability. The pit is fully backfilled layer-by-layer with the original soil according to the excavation sequence in May. There is no significant difference between the pit surface and neighboring ground surface in September, including the elevation and other surface characteristics. It shows that the digging's influence on the soil moisture could be ignored in this field site. Permafrost and mudstone, developed below the active layer, are often regarded as an impermeable soil layer. Therefore, the contribution of downward seepage throughout the mudstone-permafrost layer to soil moisture in the active layer is very small (Fetter, 2000).

The accumulated liquid precipitation in the Yashatu Basin during the period of 2012.12.1-2014.11.30 was 175 mm, and the accumulated surface snow cover thickness was 690 mm. According to previous results, the snow cover density in the Qilian Mountain area was 0.16 g cm^{-3} (Hao et al., 2009), and the snow water equivalent (SWE) of two-year snow cover was 110 mm. Considering the liquid and solid precipitation quantities, the total precipitation in the Yashatu Basin during the period of 2012.11-2014.11 was 285 mm. According to the observation results from the neighboring Delingha meteorological station, annual rainfall in the urban area of Delingha is 140 mm, and the evaporation reaches 2230 mm (Lv, 1960). The altitude in Yashatu Basin is 1000 m higher than that of Delingha meteorological station, and according to rainfall trends in mountain areas, the annual rainfall of the former should be larger than that of the latter. In fact, the rainfall in Yashatu Basin during the period of 2012.12-2014.11 was similar to that of Delingha. The rainfall in Yashatu for the year 2013 was only 100 mm, which is even less than that of the urban area in Delingha. The analysis shows that Yashatu Basin experienced a significant dry period in the years 2012-2014. Intense evaporation reduced the water supply from rainfall to the active layer during these dry years, and finally resulted in the slight decrease in moisture content observed in the NSS.

The SRS is influenced by both the dry years and the lack of snow cover compared to the NSS. The SWE of snow in this area over the two years was 110 mm. This result could only increases the moisture content at depth range of 0-2.5 m in the active layer by 4.4% at most, which is significantly less than the 8% moisture content difference between the two sites. Therefore, infiltration of melted snow cover alone cannot sufficiently explain this difference in moisture content.

Infiltration is not the only way that the seasonal snow cover influences the moisture content of the active layer, and the effect of snow cover on evaporation maybe more significant. Firstly, the snow cover has a shielding effect on the surface. By coating the surface, the snow cover changes the contact pattern between the atmosphere and the surface, and greatly reduces the effect of airflow on surface soil evaporation (Penman, 1948; Yeh, 1983). Secondly, the shielding effect of snow cover also significantly reduces surface warming from solar radiation. Compared to the bare surface, the albedo of snow cover is high, and the snow surface temperature is even lower than the air temperature (Yershov, 1998), and much lower than the bare surface. Therefore, the ground surface temperature under the snow cover is lower than that of the SRS during the day or in summer because of the low snow surface temperature. Furthermore, Yashatu Basin is located in the mid-latitude zone, where the annual solar global radiation is fairly strong. Even in winter, solar radiation greatly increases the temperature of the bare surface during the daytime. The monitoring results from the west of Qilian Mountain indicate that the evaporation capacity of the surface soil is enhanced by an increase in surface temperature (Wang and Guo, 2013). Additionally, the heat needed for snow cover thawing comes not only from radiation from the sun and the surrounding atmosphere, but also from the underlying surface soil, which helps to decrease the surface temperature and reduce the evaporation capacity of the active layer.

Influenced by the reduction in precipitation and snow removal, moisture content within the active layer in the SRS decreases significantly and consistently over the two years of this study. Compared to the first year, the range of moisture content decreased in the second year by over 50%.The rate of moisture content decrease in the SRS will drop year by year as the snow removal duration increases, until a new dynamic equilibrium is reached.

5. Conclusions

Based on analysis and discussion on the monitoring data from the monitoring sites of Yashatu Basin in the western Qilian Mountain, Qinghai-Tibet Plateau, during the period of 2012.12.1-2015.2.28, some preliminary conclusions are drawn.

1. In Yashatu Basin, the snow cover is usually less than 5 cm, which can be classified as thin snow cover. The annual accumulated snow cover thickness is usually less than 50 cm. The surface snow cover duration is less than 5 days, which can be classified as short-term surface snow cover.

2. Over a calendar year, the ground temperature in the active layer is higher in the NSS than that in the SRS. Seasonally, the ground temperature in the active layer is also higher in the NSS than that in the SRS in other seasons with exception of summer. This phenomenon may result from the high thermal resistivity of snow, snowfall time, and the marked decrease of moisture content in the active layer.

3. Reduction of moisture content in the active layer of the NSS and SRS is related with less rainfall and intensive evaporation during the period of 2012.12-2014.11. The dramatic decrease of moisture content in the active layer of the SRS maybe depends on the removal of seasonal snow cover.

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