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# Snow cover influences the thermal regime of active layer in Urumqi River Source, Tianshan Mountains, China

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**Abstract:** Snow cover is characterized by the high albedo, low thermal conductivity, and notable heat transition during phase changes. Thus, snow cover significantly affects the ground thermal regime. A comparison of the snow cover in high latitudes or high-altitude snowy mountain regions indicates that the eastern Tianshan Mountains (China) show a characteristically thin snow cover (snow depth below 15 cm) with remarkable temporal variability. Based on snow depth, heat flux, and ground temperature from 2014 to 2015 in the Urumqi River source, the spatial-temporal characteristics of snow cover and snow cover influences on the thermal conditions of active layer in the permafrost area were analyzed. During the autumn (Sept. - Oct.), thin and discontinuous snow cover can noticeably accelerate the exothermic process of the ground, producing a cooling effect on the shallow soil. During the winter (Nov. - Mar.), it is inferred that the effective thermal insulation starts with snow depth exceeding 10 cm during early winter. However, the snow depth in this area is generally below 15 cm, and the resulting snow-induced thermal insulation during the winter is very limited. Due to common heavy snowfalls in the spring (Apr. to May), the monthly mean snow thickness in April reached to 15 cm and remained until mid-May. Snow cover during the spring significantly retarded the ground warming. Broadly, snow cover in the study area exerts a cooling effect on the active layer and plays a positive role in the development and preservation of permafrost.

**Keywords:** Snow cover; Permafrost; Ground temperature; Tianshan Mountains; Heat flux

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## Introduction

Cold climate is the most important factor for the formation and development of permafrost, but other local factors also are involved. These local factors include snow cover, vegetation, topography, lithology, and ground water content; however, the effects of these factors on the active layer dynamics are different (French 2007). Snow cover is considered to be one of most important influencing factors that affect the thermal regime of permafrost. This is due to several fundamental physical properties of snow, mainly including the high surface albedo, the low thermal conductivity, and considerable latent heat (Goodrich 1982; Zhang 2005).

Snow cover actively participates in the heat exchange between the atmosphere and the ground, thus affecting the surface and ground temperature, and determining the seasonal thawing characteristics of soil (Armstrong and Brun 2008; Callaghan et al. 2011). Important processes related to the snow cover dynamics mainly include snow warming and cooling (Luetschg et al. 2008), melting and refreezing (Christiansen 2004; Ramos et al. 2017), water percolation (Woo 2012), and periglacial process (Oliva et al. 2009; Pisabarro et al. 2017). Winter thick snow cover effectively hinders the active layer from releasing heat into the atmosphere, allowing the ground surface temperature (GST) of 10°C–15°C warmer than the overlying atmosphere (Zhang et al. 1997; Ishikawa 2003; Lafrenièr et al. 2013). Based on the relationship between the bottom temperature of the snow cover during late winter and the ground temperature in the Alps, Haeberli (1973, 1978) proposed Bottom Temperature of the Snow cover (BTS) and successfully utilized it to map the distribution of permafrost in thick snow areas in the Alps and other areas (Ishikawa and Hirakawa 2000; Ketil et al. 2002; Lewkowicz and Ednie 2004). Stieglitz et al. (2003) and Park et al. (2015) reported that in addition to air temperature warming, snow cover variability also play an important role in the observed increase of Arctic permafrost temperature. Poglioti et al (2015) suggested that snow likely plays a major role only on the inter-annual variability of active layer thickness (ALT) in the Cime Bianche, Alps. Numerous studies have shown that snow cover is a driving factor of permafrost presence and the thermal regime of seasonal frost ground (bedrock) or the active layer in mid-latitude high mountain regions, (e.g., Alps, Sierra Nevada (Spain), Qinghai-Tibet Plateau, etc.) (Luetschg et al. 2004; Gadek et al. 2010; Haberkorn et al. 2015; Jin et al. 2008; Chang et al. 2014; Magnin et al. 2015, 2017; Oliva et al. 2014, 2016), Arctic or sub- Arctic (Zhang et al. 1997; Zhang 2005; Lafrenière et al. 2013; Davesne et al. 2017), and Antarctic (Vieira et al. 2010; Oliva et al. 2017; Ferreira et al. 2017).

The influence of the snow cover on the active layers or ground mainly depends on the thickness and spatial-temporal characteristics of snow cover, including the timing and the duration of snow cover (Goodrich 1982; Zhang 2005; Luetschg et al. 2008; Magnin et al. 2015, 2017; Oliva et al. 2014, 2017). The heterogeneity of snow cover thickness is the main factor controlling the spatial variability of GST and ALT at a small distance of tens to hundreds of meters (Poglioti et al. 2015; Davesne et al. 2017). A thin (< 20 cm) snow cover with low thermal insulation leads to ground cooling due to an increase in long-wave emissivity and albedo on the surface (Daniel 2001; Keller and Tamás 2003; Pogliotti 2010; Zhou et al. 2013; Davesne et al. 2017). In contrast, thick snow cover (>40 cm) shows high thermal resistance (Zhang 2005). Numerous observations and numerical simulations suggested that 0.6-0.8 m is a threshold isolating the active layer thermally from the atmosphere (Hanson et al. 2004; Luetschg 2008; Magnin et al. 2015, 2017). This thermal insulation is maximal during the fall and early winter, while the albedo effect of snow is maximal during the spring (Ling and Zhang 2003; Zhang 2005). Haberkorn et al. (2015) reported the delayed appearance of a thick snow cover in early winter led to lower ground surface temperature and faster response to cold air. This results in a lower ground surface temperature in the winter even under thick snow cover. In contrast, the early accumulation of a thick snow cover led to an increase of active layer temperature. Magnin et al. (2017) also reported that snow cover in the spring and early summer can retard the heating of active layer and reduce ALT. Romas et al. (2017) reported that an increase of the duration of snow cover in the spring and summer led to a decrease trend of 1.5 cm/a in the seasonal thaw depth between 2006 and 2014 in Deception Island, Antarctica.

Despite the surging interest in the role of snow cover on permafrost in polar regions and other alpine areas, only limited attention has been given to the influence of thin snow cover on the thermal regime of active layer in mid-latitude high altitude mountain areas in central Asia. Our study area focuses on the alpine areas in eastern Tianshan

Mountains (TS Mt.), which show a characteristically thin snow cover with remarkable temporal variability during cold seasons. And most of the current studies analyze the impact of snow on active layer by ground surface temperature, active layer temperature and ALT. But in this study, besides the ground temperature, we mainly select soil heat flux, surface temperature to analyze the impact of snow on active layer heat budget. The purpose of this paper is, based on the spatial-temporal characteristics of snow cover (the timing, duration, and thickness) in study area, to identify the effects of snow cover on shallow soil heat flux and ground temperatures, as well as the role of snow cover and its significance for the distribution and development of permafrost in the eastern TS Mt.

## 1 Study Area

### 1.1 Regional setting

The TS Mt. are a large system of mountain ranges located in Central Asia. TS Mt. in Xinjiang, China stretch over 1700 km with an average elevation of about 4000 m. Although the TS Mt. in China are located between the hot dry Junggar and Tarim Basin in China, they can still accept heavy precipitation from warm and humid air flow from the Arctic and the Atlantic Ocean, thus forming the "Tianshan Wet Island" in arid regions. In addition, snow cover, glaciers, and permafrost are widely distributed due to the cold and humid climate all year round in high altitudes in the TS Mt.. The annual precipitation around the TS Mt. areas ranges between 300 mm and 800 mm, of which the snowfalls accounts for more than one-third of the total precipitation (Hu et al. 2004).

### 1.2 Monitoring site

The monitoring site is located at the headwaters of the Urumqi River, about 120 km southwest of Urumqi, Xinjiang, China (Figure 1). Investigations of permafrost in the study area haven been conducted in previous studies. According to Qiu et al. (1993), the lower permafrost limit was influenced by the slope aspect, which was about 3200 m for sunny slopes and about 2900 m for shady slopes. Jin et al. (1993) reported that the mean annual ground temperature at the depth of 16m was -1.8°C at 3549 m, while a temperature of -4.9°C was found on the east-facing gneiss slope at 3900 m which was covered by coarse sand gravels. At an altitude of 3805 m, the study site is situated at the outlet of the Empty Cirque Basin (43°07'13.7"N, 86°49'46.4"E), which is predominantly southeast-facing. The modern glacier terminals are at about 3775-3848 m (2015). The climate in the East TS is characterized by wet summers and dry winters. The mean annual air temperature ($T_a$) in monitoring site in 2014 and 2015 were -6.59°C and -5.27°C, respectively and

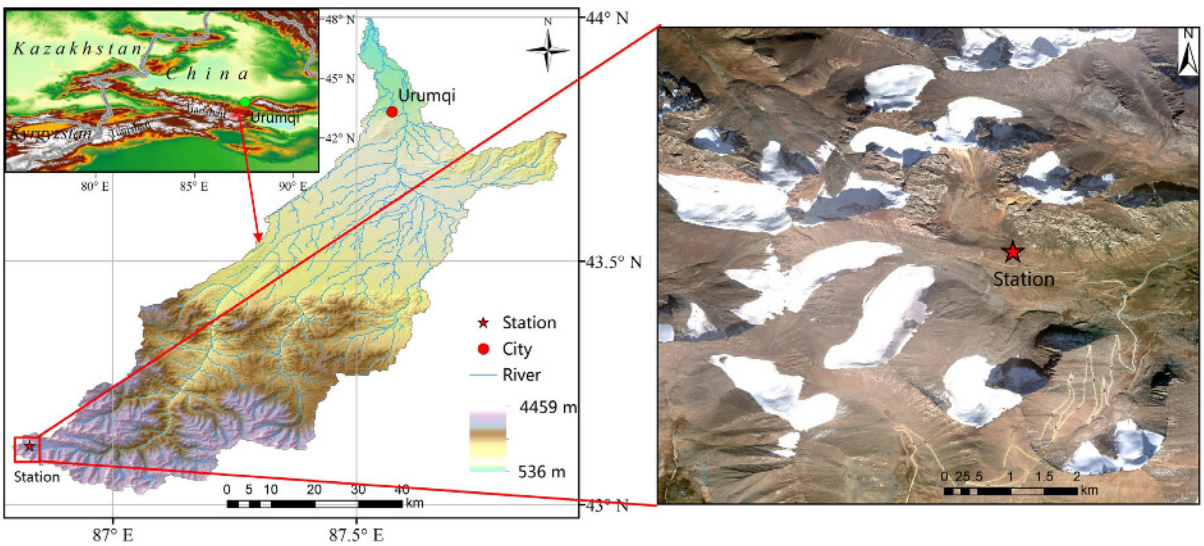


**Figure 1** Locations and landform of the Empty Cirque station (3805 m) at the headwaters of the Urumqi River, Tianshan.

the period with a mean daily $T_a$ below 0°C in 2014 and 2015 were 262 and 255 days, respectively. The precipitation increases with elevation, reaching 600 to 700 mm or more at the snow line and having strong seasonality with concentration in Jun.-Aug. (Yang et al. 1992). The mean annual precipitation at the monitoring site in 2014 and 2015 were 638.1 and 639.0 mm, respectively.

## 2 Materials and Methods

### 2.1 Air and surface temperature, heat flux, and precipitation

An automatic meteorological station was installed and debugged in Nov. 2013. Air temperature ($T_a$) and surface temperature ($T_s$) were recorded by the HMP155A-L air temperature sensor (Vaisala, ±0.2°C) and the SI-111 surface infrared temperature sensor (Apogee, ±0.2°C) at 2.0 m above the ground surface. Variations in soil heat fluxes at 5 cm ($G_{5cm}$) and 10 cm depth were monitored by HFP01-10 heat flux sensors (Hukseflux, 50 μV/W·m$^2$). The precipitation is measured at 1.5 m above the ground surface by the T-200B all weather precipitation-rain gauge (Geonor, ±0.1 mm). The monitoring data were stored in a data memory card at 30 min resolution.

### 2.2 Ground temperature

In Oct., 2013, a borehole with a depth of 22 m was drilled. A ground temperature monitoring cable was installed in this borehole on Dec. 1, 2013. Ground temperatures ($T_g$) were measured at 30 min resolution at depths from 0.5 to 22 m using the SKLFSE-TS probe manufactured by the State Key Laboratory of Frozen Soil Engineering (SKLFSE, China, ±0.05°C). According to the Chinese classification system, the shallow soil of the active layer is defined as alpine meadow soils, which is also approximately referred as gelic leptosols, according to the IUSS WG WRB (2014). They are underdeveloped gravel soil with a thin layer about 30-50 cm and characterized by cryoturbation and organic material about 5%-15%. The soil (0.5-2.8 m) is composed of 75% clay soil and 25% gravel blocks, and the deep soil > 2.8 m is mainly composed of gravel blocks.

### 2.3 Snow depth

The snow depth (SD) is an important parameter for evaluating the snow pack. Other information about the snow cover presence, timing, and duration can be obtained from snow depth data. At present, two main methods of automatic snow depth measurement in extreme field environments are used: temperature differences-snow depth estimation and ultrasonic depth detection. The first method requires that an array of miniature temperature loggers to be mounted at small height intervals on a vertical wooden stake (Lewkowicz et al. 2008; de Pabblo et al. 2017). Then, the snow depth can be estimated by the temperature differences between the snow beneath the snow surface and air. Since the equipment is very convenient to install and does not require a power supply system, this method is routinely applied in areas with thick snow cover, especially in Antarctic regions. This method generally underestimates the snow depth and is more suitable for stable thick snow areas. The latter is a remote measurement of snow cover thickness based on ultrasonic pulse-transit technique and can reflect temporal variation of snow depth in thin snow area. A sensor transmits ultrasonic pulses to the snow cover and subsequently receives their reflected signals. Based upon the elapsed time between emission and return of the pulse, the sensor then calculates the current snow depth. An air temperature measurement is required to correct for variations of the speed of sound in air depending on temperature.

The SR50A is an ultrasonic sensor with an accuracy of ±1 cm (Campbell Scientific Corp., USA) for the precise, continuous and non-contact recording of snow depths and is commonly used in the alpine environment (Zhou et al. 2013). The snow thickness in our study was measured at an interval of 30 min with a SR50A snow depth sensor. The snow depth sensor was mounted at a horizontal mast at 2 m above the ground surface. The field of measurement beneath the sensor was well leveled and maintained in every physical visit to the site. The air temperature data used to correct the snow depth parameters has been provided by an air temperature sensor (HMP155A-L) at the study site. Snow depth sensors sometimes obtained abnormal values, such as particularly high values

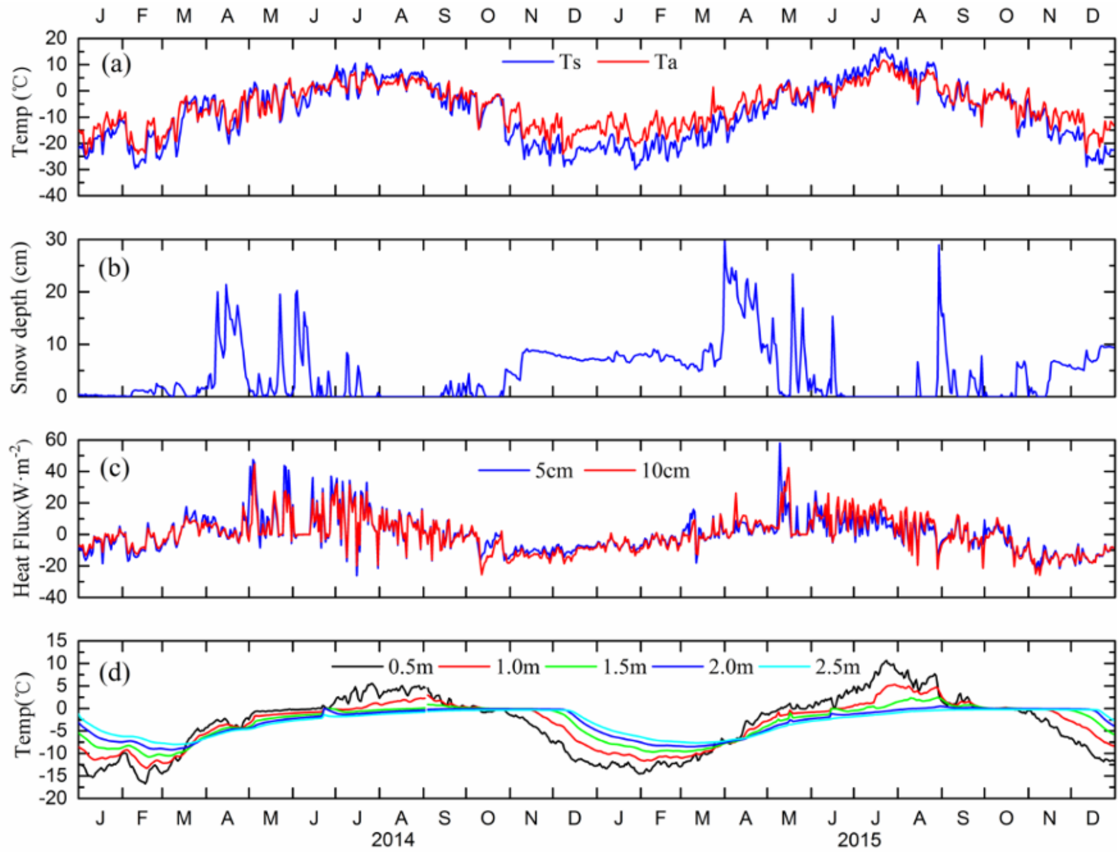


**Figure 2** Variations of daily means of air temperature (a), surface temperature (a), snow depth (b), soil heat flux (c), and ground temperature (d) during 2014-2015 at the Empty Cirque station, the headwaters of the Urumqi River.

or negative values for many reasons, and these values were filtered and interpolated. Figure 2 shows variations of daily means of $T_a$, $T_s$, *SD*, $G_{5cm}$, and $T_g$ during 2014-2015.

## 3 Results

### 3.1 Variations of surface temperature, snow depth, soil heat flux and ground temperature

#### *3.1.1 Variations of air and surface temperatures*

From our observational data (Figure 2a, Table 1), the mean daily $T_a$ and $T_s$ both remained below 0°C for eight months of the year (from mid-Sept. to mid-May). The highest daily mean $T_a$ during the study period was 11.74°C on Jul. 22, 2015, corresponding to the highest $T_s$ of 16.41°C. The second lowest daily mean $T_a$ in 2014 and 2015 was -23.68°C on Dec. 12, 2015, corresponding to the lowest $T_s$ of -28.87°C. The $T_s$ actually refers to two temperatures: snow surface temperature ($T_{ss}$), which is obtained from the snow cover surface when snow covered the ground; ground surface temperature ($T_{gs}$), which indicates the temperatures from the bare ground. The difference between $T_s$ and $T_a$ ($\delta T$, $T_s - T_a$) in the winter highly depended on snow conditions. For instance, the $\delta T$ in mid-winter (from Jan. to Feb.), 2015 was approximately -7°C. In contrast, the $\delta T$ ($T_{gs} - T_a$) of 2014 was only -4°C. This indicates that snow cover will result in lower surface temperature.

Figure 3 shows the relationship between the mean daily $T_a$ and $T_s$ from Jan. 1, 2014 to Dec. 31, 2015 during snow-free and snow-covered periods, respectively. During the snow-free period, $T_a$ and $T_{gs}$ showed a good linear relationship with a coefficient of determination ($R^2$) of 0.95. During the snow period, however, the linear relationship between $T_a$ and $T_{ss}$ weakened slightly with a $R^2$ of 0.87. According to the fitting equations, $T_{ss}$ was significantly lower than $T_{gs}$ under the same $T_a$. For a daily mean $T_a$ of -10°C, the simulated daily mean

**Table 1** Summary of annual and monthly mean values of observations in 2014-2015

| Month | 2014 | | | | 2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_a$ (°C) | $T_s$(°C) | $T_{0.5m}$(°C) | $G_{5cm}$ (W·m$^{-2}$) | $T_a$(°C) | $T_s$(°C) | $T_{0.5m}$(°C) | $G_{5cm}$ (W·m$^{-2}$) |
| Jan. | -14.82 | -18.76 | -13.22 | -6.40 | -14.63 | -21.98 | -12.85 | -6.62 |
| Feb. | -17.83 | -21.81 | -13.61 | -7.47 | -14.25 | -21.84 | -12.84 | -3.85 |
| Mar. | -9.79 | -11.37 | -9.07 | 4.14 | -10.43 | -16.18 | -10.19 | 1.59 |
| Apr. | -7.62 | -9.46 | -3.31 | 3.69 | -5.94 | -9.91 | -4.56 | 3.46 |
| May | -2.91 | -2.47 | -0.65 | 15.62 | -1.41 | -2.47 | -0.04 | 9.76 |
| June | 0.34 | -1.28 | 0.03 | 7.56 | 0.84 | 2.18 | 1.99 | 8.40 |
| July | 3.72 | 5.27 | 3.27 | 11.88 | 6.90 | 10.75 | 7.15 | 6.59 |
| Aug. | 3.48 | 5.28 | 4.04 | 5.66 | 4.35 | 6.28 | 6.19 | 0.31 |
| Sept. | -0.70 | -1.40 | 1.90 | -0.52 | -2.59 | -3.64 | 1.15 | -1.36 |
| Oct. | -5.29 | -6.49 | -0.33 | -5.52 | -3.54 | -4.54 | -0.25 | -2.77 |
| Nov. | -12.95 | -19.95 | -3.72 | -10.75 | -8.96 | -12.83 | -3.59 | -14.82 |
| Dem. | -15.64 | -23.19 | -10.37 | -9.03 | -14.37 | -22.12 | -9.70 | -13.26 |
| A. M. | -6.59 | -8.70 | -3.70 | 0.81 | -5.27 | -7.93 | -3.07 | -1.02 |

**Notes:** $T_a$ = Air temperature; $T_s$= Surface temperature; $G_{5cm}$= Soil heat flux at a depth of 5 cm; $T_{0.5m}$= Ground temperature at a depth of 0.5 m; A. M. = Annual Mean values.

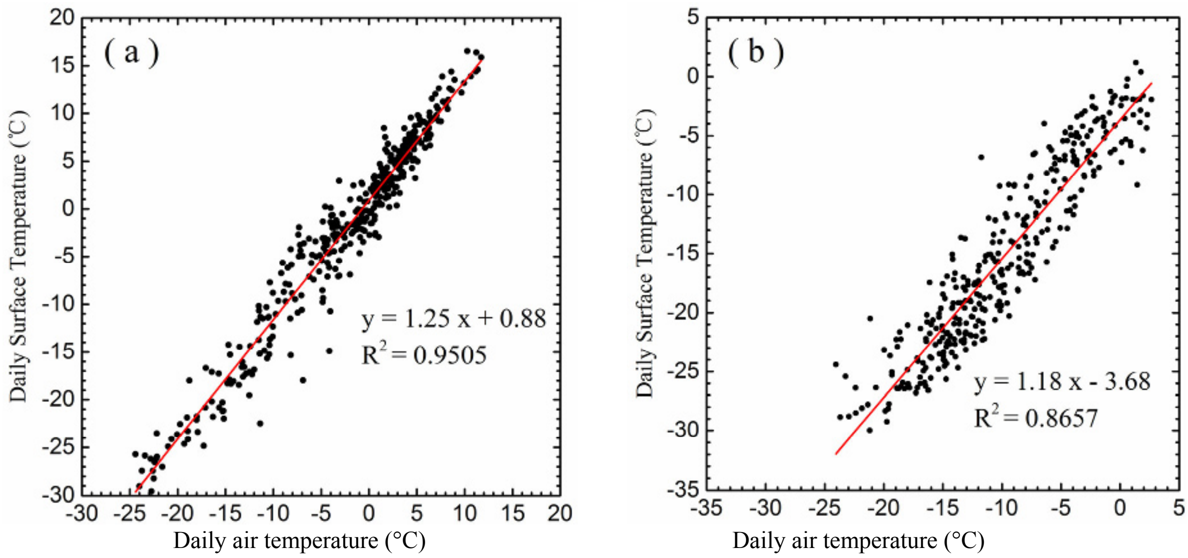


**Figure 3** Relationship between daily air temperature and daily surface temperature during snow-free (a) and snow-covered (b) periods.

$T_{ss}$ would be -15.48°C, which is 3.86°C lower than the daily mean $T_{gs}$.

### *3.1.2 Snow depth*

Figure 2b shows that snowfall may occur any time throughout the year. The numbers of snow days in 2014 and 2015 were 185 and 233, respectively. The snowfall in 2014 and 2015 exceeded 300 mm based on the daily $T_a$<0°C. More than two-thirds of the snowfall occurred during the spring and early summer (Apr. - Jun.). Except for the snow depth (38.5 cm) on Aug. 30, 2015, the highest snow depths in 2014 and 2015 both occurred in Apr., reaching 26 cm and 36 cm, respectively. In April, due to the low $T_a$ and heavy snowfalls, SD increased significantly, and the mean monthly SD reached to 15 cm. From May to Jun., although the intensity and frequency of heavy snowfall events were high, higher $T_a$ and stronger solar radiation could stimulate snow melting, which made the snow cover could keep for less than one week. From Sept. to mid-Oct., there was the thin and discontinuous snow cover due to the small snowfall. The winter precipitation (from Nov. to Mar.) was very small, generally remaining below 15 mm; therefore, the last snowfall in late autumn and early winter determined the snow cover condition during the winter. For instance, there were no heavy snowfalls during the early winter, 2013/2014; consequently, the ground was not covered with snow from Jan. to Mar., 2014. In contrast, the snowfalls on Oct. 28 and Nov. 29, 2014 led to the long-term snow cover that lasted for six months from Nov., 2014 to Apr., 2015, which was earlier than the establishment (Nov. 15) of snow cover in the winter of 2015.

#### *3.1.3 Shallow soil heat flux and ground temperature*

The mean annual values of $G_{5cm}$ for 2014 and 2015 were 0.81 W·m$^{-2}$ and -1.02 W·m$^{-2}$ (Table 1), respectively (positive values indicate heat absorption), which indicates that the heat budgets of the soil surface was almost balanced. The mean monthly $G_{5cm}$ (Table 1 and Figure 2c) were negative from Sept. to Feb., indicating that the shallow soil released heat during this period. During Nov., the amount of heat released from shallow soil was maximal and the monthly mean $G_{5cm}$ reached -10.75 and -14.82 W·m$^{-2}$ in Nov., 2014 and 2015, respectively. $G_{5cm}$ were positive from Mar. to Aug. and the maximal monthly mean $G_{5cm}$ reached 15.64 and 9.76 W·m$^{-2}$ in May, 2014 and 2015, respectively.

As the result of a missing measurement of shallow ground temperature (0-0.5 m), the daily mean ground temperature at 0.5-2.5 m was used to evaluate the effect of snow cover (Figure 2d). The mean annual temperature at depth of 0.5 m ($T_{0.5m}$) between 2014 and 2015 was -3.40°C with the lowest temperature record of -16.74°C in Feb. 17, 2014 and the highest temperature of 10.73°C in Jul. 24, 2015. The mean annual $T_g$ of the deeper active layer increased with depth, but the annual amplitude of $T_g$ became smaller in deeper. During the study period, seasonal thawing front could penetrate to depths beyond 1.9 (2014) to 2.2 m (2015) in early of Oct., the ground below 2.2 m remains frozen throughout the year. Due to the phase transition of soil moisture during the spring and autumn (May, Sept., and Oct.), the freezing-thawing interface would remain at a certain depth for a long time, forming the "Zero Curtain". The duration of this phenomenon progressively decreased towards the ground surface.

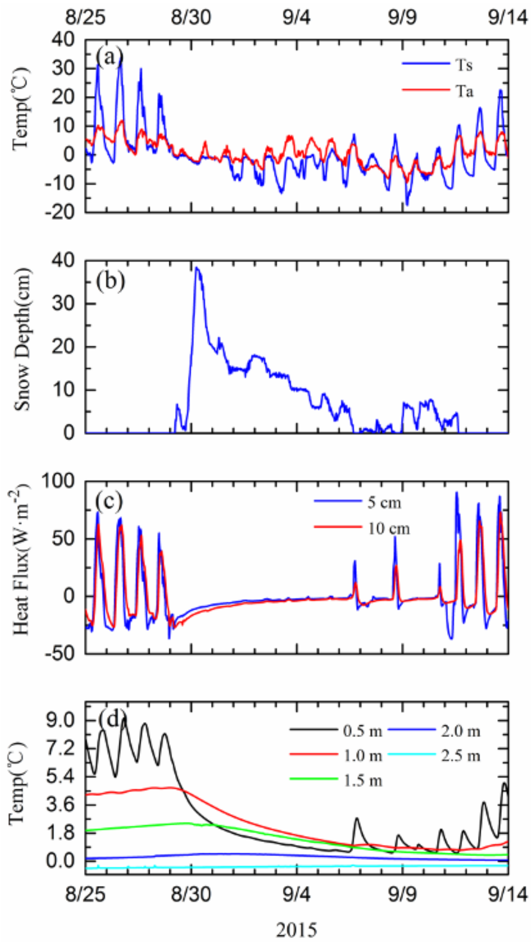


**Figure 4** Variations in $T_s$ (a), snow depth (b), heat flux (c), and ground temperature (d) before and after typical snowfall in early autumn of 2015.

**Table 2** Comparison between the parameters before and after snowfall on Aug. 29, 2015

| Period | $T_s$-$T_a$ | $G_{5cm}$ | A_$G_{5cm}$ | $T_{0.5m}$ | A_$T_{0.5m}$ |
|---|---|---|---|---|---|
| 8.26~8.27 | 4.39 | 4.07 | 46.86 | 7.32 | 1.56 |
| 9.2~9.3 | -5.86 | -3.01 | 0.98 | 1.19 | 0.12 |
| 9.12~9.13 | -0.18 | 9.9 | 55.32 | 2.4 | 1.62 |

**Notes:** A_$G_{5cm}$, A_$T_{0.5m}$ =Amplitude of $G_{5cm}$ and $T_{0.5m}$.

### 3.2 Detailed seasonal patterns in surface temperature, soil heat flux and ground temperature

According to the daily mean $T_a$ and $T_s$ for 2014/2015, the four seasons in the study area can be divided into autumn (Sept. to Oct.), winter (Nov. to Mar.), spring (Apr. to May), and summer (Jun. to Aug.).

#### *3.2.1 Autumn*

Figure 4 and Table 2 indicate the changes of several parameters before and after a heavy snowfall on Aug. 29, 2015 with a maximum snow depth of 38.5 cm. Table 2 shows that $G_{5cm}$ decreased from 4.07 to -3.01W·m$^{-2}$, indicating that the shallow soil released heat to the snow cover after the snowfall. The $T_g$ at the depths of 0.5 m, 1.0 m and 1.5 m decreased, which was delayed with depth. The daily mean 0.5 m-ground temperature ($T_{0.5m}$) dropped from 7.32°C to 1.19°C during the three days. After Sept. 11, no snow cover was recorded and $G_{5cm}$ was restored to 9.90 W·m⁻², while $T_{0.5m}$ increased from 1.19°C to 2.40°C.

Figure 5 shows the changes in $T_a$ and $T_s$, snow depth, $G_{5cm}$, and $T_g$ from Sept. 15 to Oct. 15, 2014. During this period, short-time snow fell frequently. During the snow-free period, the shallow soil absorbed heat during daytime and the daily maxima of $G_{5cm}$ reached more than 40 W·m⁻² (Table 3). During the snow-covered period, the daily maxima of $G_{5cm}$ decreased to about 5 W·m⁻², which led to a negative daily net heat flux. For instance, after the snowfall on Sept. 26, the daily maxima of $G_{5cm}$ decreased from 69.78 to -0.86 W·m⁻². This indicates that solar radiation is still larger during the autumn, but the snow can significantly weaken the absorption of solar radiation by the ground. In addition, the number (14 days) of snow days from Sept. 15 to Oct. 15, 2014 exceeded that (6 days) of the same period of 2015. This led to the early freezing of 0.5 m-soil, which occurred on Oct. 11, 2014, which was 6 days earlier than the same period in 2015.

### *3.2.2 Winter*

A snowfall with a thickness of 5 cm was recorded on Oct. 28, 2014 (Figure 6) and the difference between the daily mean $T_s$ and $T_a$ was about -0.60°C before the snowfall. However, this value increased to -6.73°C after the snowfall. Furthermore, $G_{5cm}$ dropped from -0.55 to -12.21 W·m⁻² with a notable decline in diurnal amplitude (from 58.8 to 13.5 W·m⁻²) (Table 4), and $T_{0.5m}$ also dropped from -0.3°C (Oct. 27) to -1.5°C (Nov. 1) in five days. The above changes indicated that 5 cm-snow cover did not have effective thermal resistance. The monitoring data recorded another snowfall event on Nov. 9, 2014, where the SD reached 10 cm (Figure 6). After this snowfall, both $T_s$ and $T_a$ decreased by 6°C-8°C; however, the daily mean $G_{5cm}$ increased slightly (from -12.21 to -11.31 W·m⁻²) with a further decreasing amplitude (from 13.5 to 6.3 W·m⁻²) and the cooling rate of the ground barely changed (Table 4). Similar changes have also been found during Nov., 2015.

Table 1 shows that the monthly mean $T_a$ in Nov., 2014 was 3.99°C lower than that in 2015, while the monthly mean $G_{5cm}$ in Nov, 2014 was -

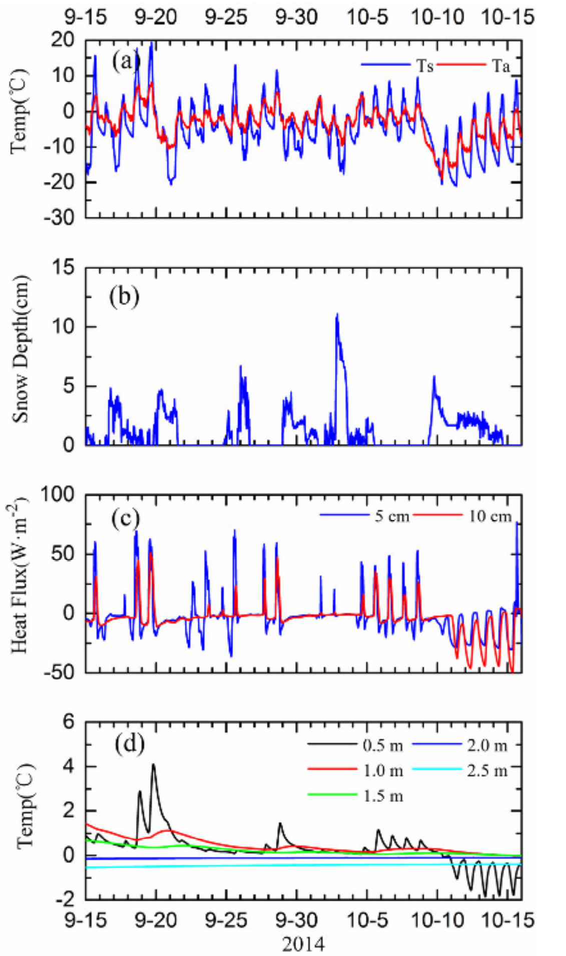


**Figure 5** Variations of $T_s$ (a), snow depth (b), heat flux (c), and ground temperature (d) from Sep. 15 to Oct. 15 in 2014.

**Table 3** Comparison of $G_{5cm}$ between snow periods and snow-free periods from Sep. 15 to Oct. 15, 2014 and from May 1 to 31, 2015

| Periods | Sep. 15 to Oct. 15, 2014 | | | May 1 to 31, 2015 | | |
|---|---|---|---|---|---|---|
| | $G_{5cm}$ | Max_$G_{5cm}$ | Min_$G_{5cm}$ | $G_{5cm}$ | Max_$G_{5cm}$ | Min_$G_{5cm}$ |
| Snow-free | 0.65 | 48.25 | -20.22 | 22.32 | 148.79 | -15.66 |
| Snow | -6.36 | 1.24 | -12.95 | 0.94 | 5.15 | -3.10 |

**Notes:** Max_$G_{5cm}$, Min_$G_{5cm}$ = the mean daily maxima and minima of $G_{5cm}$.

10.75 W·m$^{-2}$. This was noticeably smaller compared to that (-14.82 W·m$^{-2}$) in Nov., 2015. This difference was likely caused by the early establishment of the long-term snow cover on Oct. 29, 2014, which was earlier than that in 2015 (Nov. 15). Compared to the mean monthly values of Jan., 2014, in the case of the same monthly mean $T_a$ (-14.63°C), the lower $T_{ss}$ (-21.98°C) did not result in a larger heat loss in Jan., 2015 (Table 1). This illustrated that the 8 cm-snow cover in mid- winter did not have a warming effect.

The monthly mean $T_a$ in Mar. 2014 was 0.64°C higher than that in 2015, while the monthly mean $G_{5cm}$ in Mar. 2014 was 4.14 W·m$^{-2}$, 2.6 times of that (1.59 W·m$^{-2}$) of Mar. 2015 (Table 1). During Mar. 2014, both $T_{0.5m}$ and $T_{1.0m}$ increased by 10.23°C and 6.57°C. However, the corresponding values for Mar., 2015 were only 5.7°C and 3.3°C, respectively. This differences indicate that snow cover in Mar., 2015 hindered the heat absorption of soil.

**Table 4** Variations of $T_s$ and $G_{5cm}$ before and after long-term snow cover in Oct., 2014

| Period | $T_s$ | $G_{5cm}$ | Max_$G_{5cm}$ | Min_$G_{5cm}$ |
|---|---|---|---|---|
| 10.21~10.27 | -2.60 | -0.55 | 75.45 | -42.31 |
| 10.28~11.8 | -15.61 | -12.21 | 5.45 | -21.58 |
| 11.9~11.22 | -21.41 | -11.31 | -2.49 | -14.94 |

**Notes:** Max_$G_{5cm}$, Min_$G_{5cm}$ = the mean daily maxima and minima of $G_{5cm}$.

### *3.2.3 Spring*

Many heavy snowfalls lead to different snow cover characteristics during the spring compared to those of other seasons. Especially during the Apr., the ground generally remained covered by the thick snow (*SD* > 15 cm), which had a great impact on the underlying ground. For instance, after the snowfall on Apr. 7, 2014 (Figure 6), the mean daily $G_{5cm}$ decreased from 9.7 to 2.68 W·m$^{-2}$, and $T_{0.5m}$ no longer increased. After the snowfall on Apr. 14, 2014, the heat flux continued to decrease to -0.83 W·m$^{-2}$, $T_{0.5m}$ and $T_{1.0m}$ decreased by 1.7°C and 0.5°C

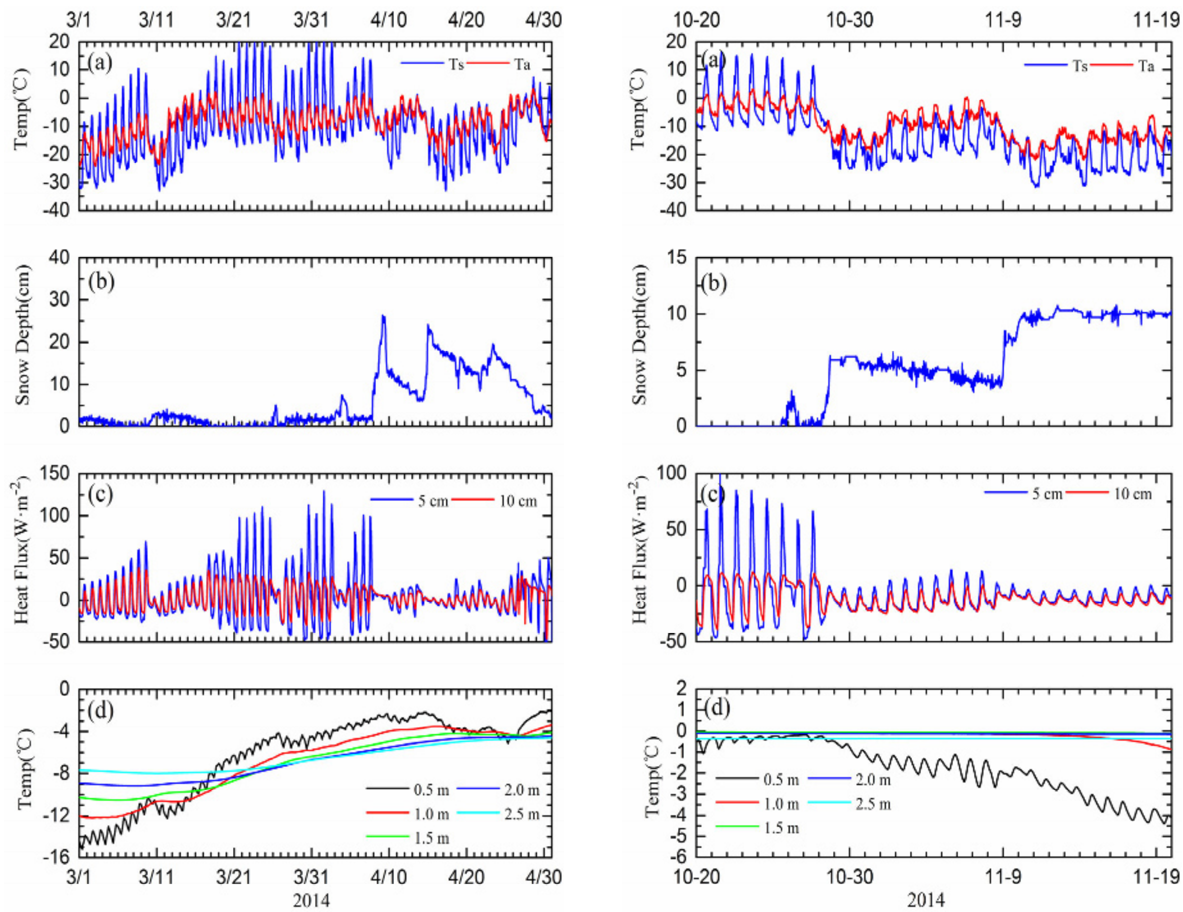


**Figure 6** Comparison of $T_s$ (a), snow depth (b), $G_{5cm}$ (c), and ground temperature (d) in snow and snow-free periods in the late winter, early spring (from Mar. 1 to Apr.31) and early winter (from Oct. 20 to Nov. 20), 2014.

during a week. These changes indicated that the long-term thick snow during Apr., 2014 hindered the increase in ground temperature. This was supported by the difference between the increase of $T_{0.5m}$ (1.81°C) during Apr., 2014 and that (10.23°C) of Mar., 2014 (snow free period).

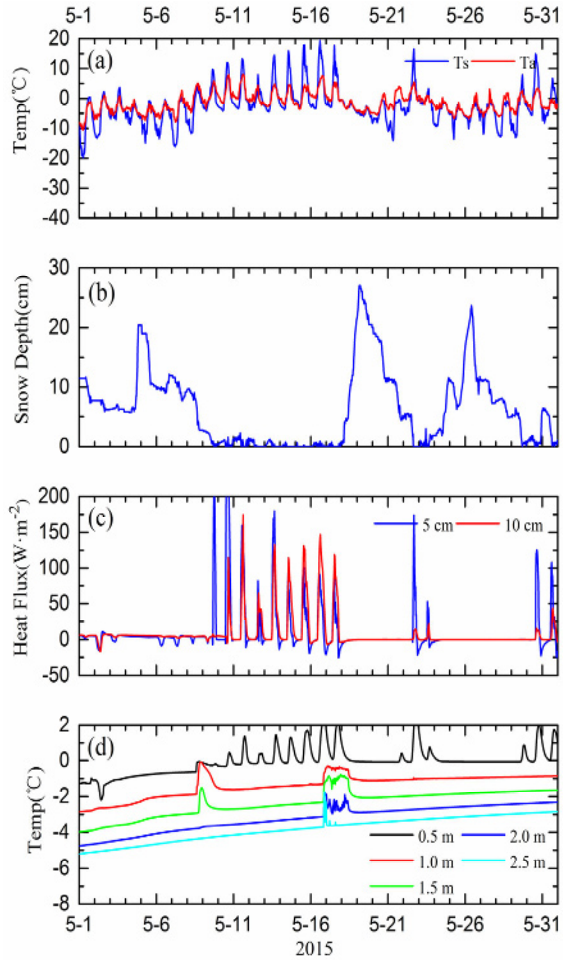


**Figure 7** Comparison of $T_s$ (a), snow depth (b), $G_{5cm}$ (c), and $T_g$ (d) in snow periods and snow-free periods during the period from May 1 to 31, 2015.

In May, snow intermittently covered the ground and significantly affected the diurnal cycle of $G_{5cm}$ and the rise of $T_g$ (Figure 7). From our statistical results for SD, $G_{5cm}$, and $T_{0.5m}$, the daily mean $G_{5cm}$ during the snow-free period in May, 2015 was found to reach 22.32 W·m$^{-2}$ with the diurnal fluctuation range from -15.66 to 148.79 W·m$^{-2}$ and the rate of $T_{0.5m}$ from May 9 to 16 was only 0.15°C/day, while in snow period the daily mean $G_{5cm}$ decreased to 0.94 W·m$^{-2}$ with an amplitude of 4.12 W·m$^{-2}$ (Table 3) and the daily mean $T_{0.5m}$ decreased from 1.10 (May 17) to -0.07°C (May 28). Furthermore, the monthly mean $G_{5cm}$ (9.76 W·m$^{-2}$) in May, 2015 was significantly lower than that (15.62 W·m$^{-2}$) of 2014 (Table 1). This difference is likely caused by the 19-day duration of snow cover in May, 2015 was 19 days, which was 11 days longer than that in the same period in 2014.

### *3.2.4 Summer*

A number of snowfalls also occur in the summer in the study area. During summer, both $T_a$ and $T_g$ are above freezing point. When snow covers the ground for a short time, solar radiation on the surface is mainly used to melt snow. In addition, the shallow soil will release heat to melt the snow due to the high $T_g$, which will cause a short-term decline of temperature in the shallow soil. There were snowfall events on Jul. 16 and 18, 2014 with a maximal snow depth of 10 cm (Figure 8). After the snowfall, the daily mean $G_{5cm}$ decreased sharply from 23.11 (Jul. 14) to -26.05 W·m$^{-2}$ (Jul. 16) with a

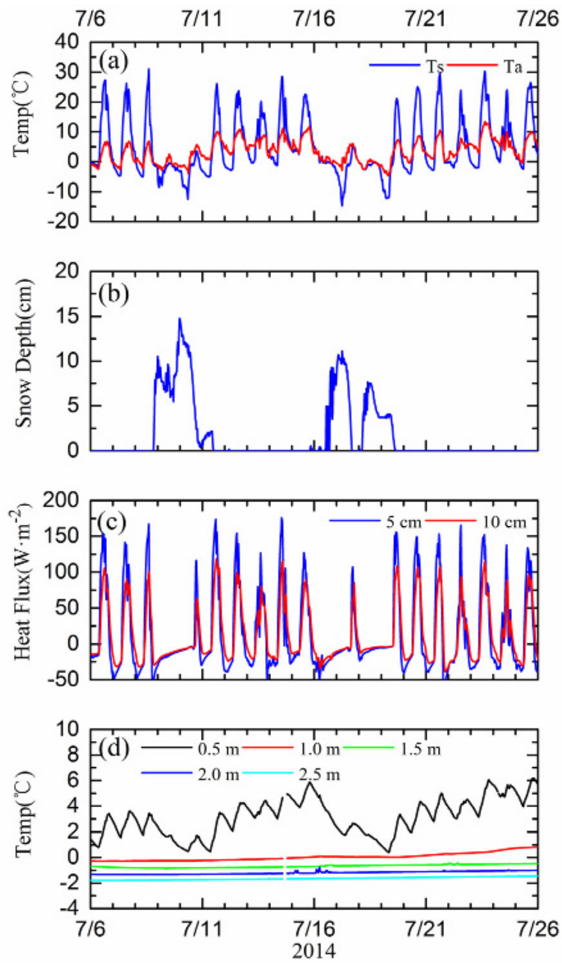


**Figure 8** Variations in $T_s$ (a), snow depth (b), $G_{5cm}$ (c), and $T_g$ (d) before and after typical summer snowfalls, 2014.

significant drop of daily amplitude (from 103.5 to 21.3 W·m $^{-2}$); $T_{0.5m}$ decreased rapidly from 3.96°C to 2.23°C. Once the snow disappeared, $G_{5cm}$ recovered rapidly and $T_{0.5m}$ began to increase.

## 4 Discussion

The results mainly focus on a comparison of the variations in the temperature of air and surface, shallow soil heat flux, and ground temperature under different snow conditions in the period of Jan. 1 2014 to Dec. 31, 2015. Our study demonstrates that the reflective effect of snow cover caused a reduction of the surface temperature. A thin snow cover in the winter mainly buffers the heat exchange between the ground and the overlying atmosphere, while the thermal insulation of snow cover is very limited. The snow cover in the study area exerts a cooling effect on the active layer, and especially the snow cover in the late cold season can significantly delay the heating of the active layer.

### 4.1 Surface temperature

In cold regions, when snow covers the ground, land surface temperature (LST) refers to snow surface temperature ($T_{ss}$), which is important for the snowmelt energy balance and land-atmosphere interactions (Qu et al. 2006). Lian et al. (2017) reported that in high latitudes, snow cover result in significantly lower LST than $T_a$ and in mid-latitudes, the seasonality of snow cover can account for the seasonal variation of $\delta T$ (LST − $T_a$). Our data shows that during the cold season, in the case of the same $T_a$, $T_{ss}$ was 3°C ~4°C lower than that of $T_{gs}$ in study area. For instance, the monthly mean $T_{ss}$ for Jan. in 2015 was 3.22°C lower than the $T_{gs}$ of 2014 (Table 1), which was caused by the lower $T_{ss}$ during the daytime compared to bare ground. Thus, the lower $T_{ss}$ should be considered in many land surface process models. Furthermore, the lower daily maximum of $T_{ss}$ may be used to determine whether there is snow cover on the ground or not, which is similar to the method for determining the last day of the snow via comparison the daily amplitude of $T_{gs}$ (Zhang et al. 1997).

### 4.2 Timing of snow cover

Variations in the timing and duration of the seasonal snow cover result in variations in the ground thermal regime, both in magnitude and in its vector (cooling or warming) (Zhang 2005). The effect of snow cover on the thermal regime of active layer is different, depending on the time period of the interest. In the early autumn, the $T_a$ and $T_s$ are above freezing point, the heavy snowfall, such as the snowfall in Aug. 29, 2015 resulted in a change of heat flux direction and a sharp drop in active layer temperature (Figure 4) due to the cold properties of snow itself and infiltration of cold snowmelt water (Scherler et al. 2010; Wen et al. 2014). And the thin, discontinuous snow cover in mid-autumn, 2014 weaken the effects of air temperature and solar radiation, having a positive effect on the cooling process of active layer (Figure 5, Table 3), which is in accordance with the results in previous studies (Keller and Tamás 2003; Pogliotti 2010; Magnin et al. 2017). Other studies have demonstrated that the onset time of long-term snow cover in the winter affect the cooling or freezing process of the ground and active layer in thick snow cover areas due to thermal insulation (Zhang 2005; Luetschg et al. 2008; Magnin et al. 2017; Oliva et al. 2014, 2017). Our heat flux data shows in the case of lower $T_a$, the lost heat from the ground ($G_{5cm}$ = -10.75 W·m$^{-2}$) in Nov., 2014 was significantly less than that (-14.82 W·m$^{-2}$) of 2015 (Table 1). This may be caused by the early establishment (in the end of Oct.) of long-term snow cover and thicker snow (10 cm) in the winter of 2014/2015, retarding the heat releasing to atmosphere. Regarding the effect of the duration of snow cover in the cold season on the ground regime condition, Oliva et al. (2014, 2016) observed that in the Rio Seco cirque, Sierra Nevada (Spain), the snow cover remained longer in the snowy year and resulted in the lower the mean soil temperature than others with less snow. However, due to the short monitoring period in our site, the analysis of this aspect has not been carried out effectively in this paper and need long-term snow cover and geothermal data in the next deeper study.

Most studies have a clear conclusion about the cooling effect of snow cover on the active layer in late winter or spring due to the high albedo and buffering effect of snow. Our observations confirm this conclusion again. During the snow-free period in Mar., 2014, $T_{0.5m}$ increased rapidly at a rate of

0.38°C/day; however, due to the presence of snow cover, the rate of soil warming was only 0.17°C/day for Mar., 2015. And due to the effect of albedo and thermal insulation of snow cover, in the case of the further increase in $T_a$ and $T_s$ in Apr., 2014, $G_{5cm}$ beneath 10 cm-snow cover did not increase. In addition, many studies have confirmed that the offset time of spring snow will affect the active layer, including ground temperature and the summer thawing depth of active layer (Luetschg et al. 2008; Magnin et al. 2017; Romas et al. 2017). In the Veleta peak, Sierra Nevada (Spain), owing to the sudden disappearance of the thick snow cover, the thermal increase of 10°C in the 0-2 m bedrock temperatures within 2 to 3 weeks was recorded in the late May or early June (Oliva et al. 2016). In our site, due to the difference of snow characteristics, geotechnical conditions, the sudden warming of ground temperatures should be smaller than that of Veleta peak, and this was not clearly verified due to the lack of monitoring of ground temperature from 0 to 50 cm. However, the heat flux data shows the $G_{5cm}$ had a sharp increase when the spring snow cover had completely melted in the end of Apr. or early of May (Figure 2, 7 and Table 1). Due to the shorter duration of snow cover, the monthly heat flux in May, 2014 was significantly larger than that in May, 2015 (Table 1). These results demonstrate the snow cover in late cold season could greatly prevent ground heating and delayed the thaw season in study area.

### 4.3 Snow cover thickness

The snow thickness is one of important factors that controls the thermal insulation effect of snow on the ground thermal regime (Zhang 2005; Luetschg et al. 2008). When the snow cover exceeds a certain thickness, the conductivity effects of snow outweigh the albedo effects. Numerous studies focused on the thick snow areas, e.g., Arctic or Sub-arctic, Antarctic, and the Alps, etc. and arrived at a clear conclusion that the thick (60~80 cm) snow cover in these areas can blocks the penetration of cold air to the ground and therefore exerts a warming effect on the active layer (Hanson et al. 2004; Luetschg et al. 2008; Magnin et al. 2017). In contrast, a thin (< 20 cm) and patchy snow cover in the winter leads to ground cooling due to the high albedo and a low thermal resistance of thin snow cover (Luetschg et al. 2008; Pogliotti 2010; Haberkorn et al. 2015; Oliva et al. 2017). Zhou et al. (2013) reported in the Qilian Mt., China that the shallow snow pack (< 20 cm) contributes to the conservation of permafrost. Jin et al. (2008) inferred that the threshold of snow depth when snow cover has a warming effect on the ground, is 20 cm for Qinghai-Tibet Plateau. The monitoring results of Chang et al. (2014) showed that in the Qinghai-Tibet Plateau, 15 cm of snow cover could postpone both the freeze-fall and thaw-rise onset times of soil temperature. Oliva et al. (2016) observed that in Veleta peak, Sierra Nevada (Spain), due to the unusual decrease in snowfall in some winter (e.g. 2006–2007), the snow-free or thin snow (probably < 20 cm) facilitated the penetration of the negative temperatures into the ground. In our study area, the snow depth during the cold season is small and generally does not exceed 20 cm, except for April. From the observation data, the thin snow cover in our study area (snow depth ≤5 cm) during the early winter did not provide effective thermal resistance, except for a drop daily amplitude. For instance, after the snowfall event on Oct. 28, 2014, the ground was covered by 5 cm-snow cover, the daily mean $G_{5cm}$ dropped considerably from -0.31 W·m$^{-2}$ with a diurnal amplitude of 60 W·m$^{-2}$ to -12.30 W·m$^{-2}$ with a diurnal amplitude of 10 W·m$^{-2}$. Then, snow thickness accumulated to 10 cm on Nov. 9, 2014 and $T_a$ and $T_s$ decreased significantly (Figure 6), but the heat released from the ground decreased little (from -12.21 to -11.31 W·m$^{-2}$) (Table 4). This illustrates that during early winter, the 10 cm-snow cover offered the thermal insulation. In addition, compared to $G_{5cm}$ during the snow-free stage in Jan., 2014, the snow cover with 8~9 cm thickness in Jan., 2015 did not lead to a decrease of the monthly mean $G_{5cm}$ (Table 1). Combined with the above analysis, it may be inferred that in study area the effective thermal insulation starts with snow depth exceeding 10 cm during early winter, which is not in accordance with the critical threshold (around 20 cm) reported in previous studies (Jin et al. 2008; Zhou et al. 2013; Haberkorn et al. 2015; Oliva et al. 2017). That also means that the snow cover below 10 cm may have a certain cooling effect resulted from the larger temperature gradient due to the lower snow surface temperature. Thus, in the study period, limited by the snow cover thickness, the winter snow cover could not effectively hinder the infiltration of cold temperature.

Compared with other similar mid-latitude alpine areas, the snow cover in this study area has distinctive characteristics, including the smaller thickness and shorter duration of snow cover in cold winter. The 10 cm-snow in the autumn and winter in this study area had not effective thermal insulation on the ground; the spring snow showed obvious cooling effect, which is in accordance with the results in many research results. Generally, in our study area, the main driving factor affecting the thermal regime of the active layer is still the climate conditions, especially the air temperature, seasonal snow cover only plays a supplementary role which have some certain impacts on the ground temperature in some special period.

In addition, the results presented in this paper are limited to only one monitoring station and a relatively short time of observation (only two years). The obtained results should be interpreted with caution; however, they could be clearly indicate that the effective warming effect of snow cover on the active layer did not appear during the study period. In addition, many factors, including aspect, micro-topography and wind-blown snow, can cause the heterogeneity of snow thickness in alpine areas. However, the data in this paper only originates from one monitoring site, and future research about the role of snow cover in development of permafrost requires more data from more monitoring sites in study area. And the shallow soil temperature sensors (0-0.5 m) need be installed to better explain the response of ground temperature to snow cover.

## 5 Conclusion

Based on observational data of snow depth, surface temperature, shallow soil heat flux and ground temperature for 2014-2015 in the alpine permafrost area of the East Tianshan Mountains (China), the effects of seasonal snow cover on the thermal regime of the active layer were analyzed. The following conclusions have been obtained:

1. The annual snowfall in study area exceeded 300 mm and the main snowfalls were concentrated on the spring, early summer (from Apr. to Jun.), and autumn (from Sep. to Oct). The last snowfalls in the end of Oct. and early Nov. generally determined the snow conditions (thickness and duration) throughout the winter. In our monitoring period, the winter snow thickness was below 10 cm. Due to many heavy snowfalls and low air temperature, the mean snow thickness in the spring reached to 15 cm, resulting in a 15 cm snow cover remained for more than one month.

2. The snow cover in study area played different roles during different periods. In the autumn, the snow cover accelerated the cooling process of the active layer. In early winter, thick snow exerted thermal insulating effect on the active layer and prevented loss of heat by the ground; however, this influence is very limited. During late winter and spring, the snow cover can prevent the ground heating and noticeably slow down the increase rate of the ground temperature. In general, snow cover plays a positive role in the development and preservation of permafrost in study area.

3. In study area the effective thermal insulation starts with snow depth exceeding 10 cm during early winter. The winter 10-15 cm snow cover did not show its obvious warming effect on the ground in 2014-2015.

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