Spatial and temporal distribution of snow water content and response to air temperature in seasonal snow in the western Tianshan Mountains, China

Xi Han, Wenshou Wei, Mingzhe Liu, Heng Lu, Xia Chen and Wen Hong

ABSTRACT

The snow water content was measured with a portable instrument (Snow Fork) in the Tianshan Station for Snow-cover and Avalanche, Chinese Academy of Sciences (TS) during the snow period in the winter of 2009–2010. The results indicated that the variation of snow water content increases exponentially over time. In the accumulation-stable period, the migration of liquid water is from the bottom to the surface of the snow profile. In the snowmelt period, the migration direction is reversed. In the transition period, both directions of transfer exist simultaneously. There are three different types of response to air temperature: (a) when the average temperature is below −7 °C, the snow water content has a best fit with the accumulated air temperature with a simple linear function; (b) when the average temperature is between −7 and −1 °C, the snow water content has a best fit with the average air temperature, with an exponential function; and (c) when the average air temperature is higher than −1 °C, the snow water content has a best fit with the maximum air temperature, with an exponential function.

Key words | best fit, snow water content, water migration, western Tianshan Mountains

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INTRODUCTION

Snow cover can be either dry or wet snow. Dry snow is a mixture of snow crystals and air, while wet snow is a combination of snow crystals, air and liquid water. Snow water content is also known as snow liquid (or free) water content. The liquid water may come from rainfall or snowmelt. When there is no rainfall, the liquid water comes from snowmelt generated by air temperature and solar radiation. Snow water content, which directly dominates the material migration and energy exchange in the snowpack, is an important physical parameter of seasonal snow cover (Yang *et al.* 1992; Tseng *et al.* 1994). Vapor diffusion occurs more rapidly as snow temperature approaches 0°, and can lead to a denser snowpack of well-bonded, rounded ice grains. Vapor diffusion due to temperature gradient can cause large ice grains' growth near the base of snowpack, termed depth hoar. This is tightly associated with structural weakness and avalanching (Yokoyama & Kuroda 1990; Zhou *et al.* 2003). In the snowmelt season, the increase of liquid water could accelerate the material migration from small to large ice grains. This process creates more large ice grains and develops a weak structure in the snowpack (Brun 1989; Denoth 2003). In these conditions, snowmelt water can rapidly penetrate from the superficial layer down to the bottom layer and form a melt water layer, which contributes greatly to whole layer wet-snow avalanching (Zhang 1986; Mitterer *et al.* 2009). In the snowmelt season, snow

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cover is one of the important sources of river water. The infiltration and outflow of liquid water have significant meaning in the study of the snowmelt mechanism (Conway & Benedict 1994; Waldner *et al.* 2004) and the simulation of snow runoff (Bathurst & Cooley 1996; Li & Simonovic 2002). As the water content increased, the snow dielectric permittivity also changed, which is important for snowmelt monitoring by remote sensing technologies (Wismann 2000).

Snow water content is an important physical parameter of snow cover, but because it is difficult to measure, there has been relatively little study of snow water content. The main measuring methods include the dielectric permittivity method (Schneebeli & Coléou 1998), the calorimeters method (Howell 1983) and the parallel-probe saturation profiler (Kapil *et al.* 2009). Remote sensing technology approaches have enabled the measuring of snow water content in the superficial layer across a large area (Dozier & Painter 2004). There have been several exploratory studies. Brun & Rey (1987) reported that increased water content could affect the shear strength of snow cover. Niang *et al.* (2006) simulated the snowpack density and water content characteristics using Looyenga's mixing coefficient model. Wei *et al.* (2001) proposed that the low-temperature environment was the primary cause of low snow water content across China's northwestern region. Li *et al.* (2007) established the relationship between water content in superficial snow cover of sea ice and the ambient temperature in summer in the Arctic. There has been relatively little study of the variation trend of water content throughout the whole snow cover period. The aim of this paper is to analyze the snow water content throughout the whole snow cover period at Tianshan Station for Snow-cover and Avalanche, Chinese Academy of Sciences (TS) using Snow Fork. This analysis provides basic data for snow characteristics research as well as snow cover hydrological process.

STUDY SITE

The study was carried out at TS (43°16′ N, 84°24′ E, and 1,776 m a.s.l.). Located in the middle mountain zone of the western Tianshan Mountains and upstream to the Kunes River, TS is an ideal base for researching the theoretical and applied issue of dry and cold snow cover. The area has a multi-year mean air temperature of 1.3 °C, monthly average air temperatures of −14.4 and 13.8 °C in January and July, respectively, and a multi-year mean precipitations of 867.3 mm, to which a solid precipitation in winter contributes more than 30%. At TS, the multi-year mean and peak value of maximum snow height are 78 and 152 cm (in 2000), respectively, and the snow cover period lasts for 6 months from November to April.

METHODOLOGY

According to the variation trend of daily mean air temperature and daily air temperature range (Figure 1), February 17, 2010, with the highest value of daily mean air temperature, was chosen as the boundary between the early and late phases of the snow cover period. The day with the highest value of daily air temperature range during the early phase was taken as the boundary between the accumulation period (December 13, 2009–January 6, 2010) and the stable period (January 7, 2010–February 17, 2010). The stable period is a snow period with little changed snow height and snow water content. March 24, 2010, the day when the water outflow was observed, divided the late phase into the transition period (February 18, 2010–March 23, 2010) and the snowmelt period (March 24, 2010–April 27, 2010). The snow height variation is shown in Figure 2.

A snow property analyzer – Snow Fork (model LK, Ins. toimisto Toikka Oy, Espoo, Finland) – was used to measure the volumetric water content of snow. The operation of the Snow Fork is based on measuring the dielectric permittivity (real and imaginary part) of snow around 1 GHz. The imaginary part of the dielectric permittivity is directly related to the wetness, while the real part is dependent on both the density and the wetness. The water content and density of snow can thus be calculated by the semi-empirical equations. The snow fork has been calibrated in air as a reference for consecutive measurements, if the frequency is between 889 and 891 MHz, the attenuation ratio is among 1,200 and 1,500 and the 3 dB bandwidths varied from 19 to 21 MHz, the data are the valid data. The relative accuracy in wetness determination is about 10% when the wetness is around 1%, and less than 5% when the wetness is 5% or more (Sihvola & Tiuri 1986), which means the accuracy in wetness

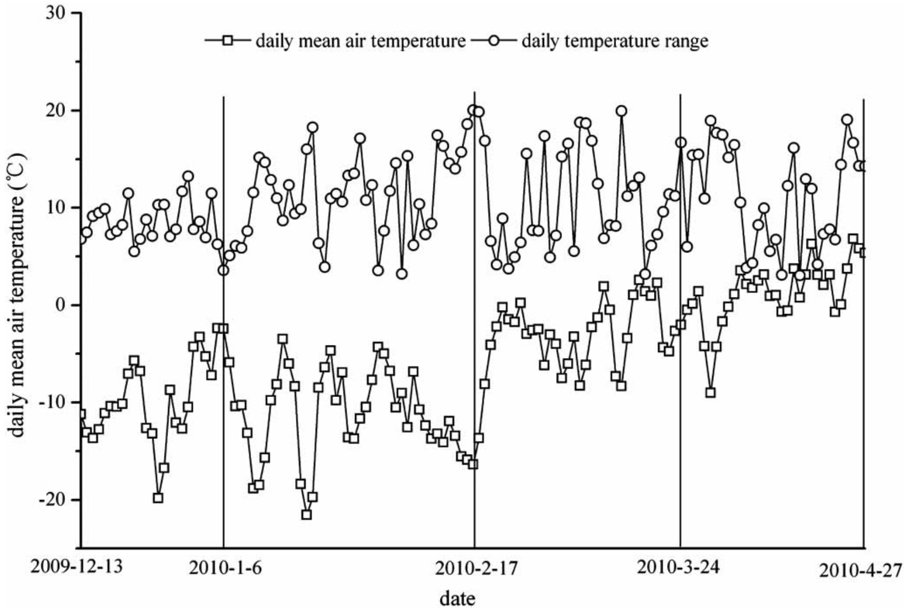

Figure 1 | Variation trend of daily mean air temperature and daily temperature range.

determination is 0.1% around 1% and less than 0.25% when wetness is 5% or more. So, 0.1% is assumed to be the lowest value measured by the Snow Fork. The values well below the accuracy of the Snow Fork are the calculated 'mean values'. The sphere of influence of each measuring is about 20 cm^3.

The experiment was conducted at a 10 m × 10 m observation site on flat grassland between December 13, 2009 and April 27, 2010. The snow profile was dug forward at least 30 cm from the previous profile location to avoid the lateral impact by solar radiation. The measurement was conducted stratigraphically with intervals of 2 cm before sunrise (influenced by the decreasing temperature at night) and after sunset (influenced by the rising temperature and solar radiation). After the Snow Fork was turned on, its probe was

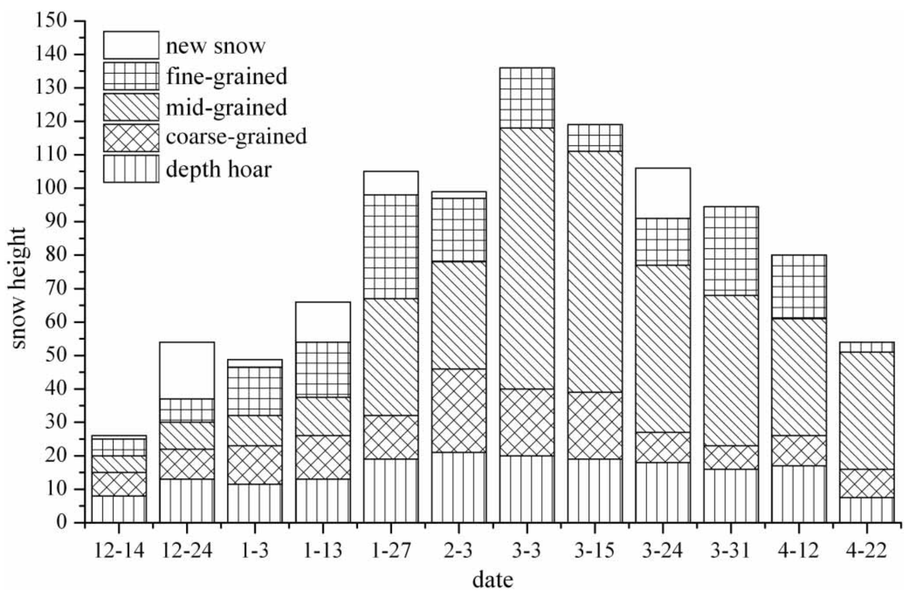

Figure 2 | Height distribution of different snow types.

left stationary in the air for 15 min. Valid data of water content was measured with the attenuation ratio between 1,200 and 1,500 and the 3 dB bandwidth between 19 and 21. Three consecutive sunny days were chosen at intervals of about 10 days to represent each period. The whole-layer average values (arithmetic average, similarly hereafter) of the 12 days' data were used to analyze the variation trends of the whole-layer average water content.

According to the classification defined by Wang Yanlong for China's avalanche zones, the snow profile is classified into five types from the top down. The corresponding classes of international snow classification (Colbeck *et al.* 1990) are added after each class. The five types are: newly-fallen snow (grain size: 0.1–0.4 mm; very fine: <0.2 mm, fine: 0.2–0.5 mm); fine-grained snow (grain size: 0.5–1 mm, medium: 0.5–1.0 mm); mid-grained snow (grain size: 1–2 mm, coarse: 1–2 mm); coarse-grained snow (grain size: 2–3 mm, very coarse: 2–5 mm); and depth hoar (grain size: 3–6 mm, extreme: >5 mm). In order to measure the grain size of different snow layers, we used a small brush to make sure that the greatest extension of the grain was taken on the microscopic photos. Using the distribution of grain size, and the snow density, the snow profile was divided into five snow type layers. The variation trend and vertical distribution of the average water content of each snow type layers were studied.

A single-channel automatic temperature recorder (RC-30, Jingchuang Electrics Co., Ltd, Shanghai) was used to measure the air temperature. The temperature was calculated by measuring the resistance of a platinum resistance thermometer (PRT), with a precision of $\pm 0.1\,^{\circ}$C. The time interval of the recorder was set to 5 min and its probe was mounted in an instrument shelter 150 cm above the ground, which was the standard height for the thermometer to be installed. The difference between the data measured by the temperature recorder and the data obtained from the weather station was determined by the paired sample *T*-test, it is not significantly different from the test difference (0) at the 0.01 level. Therefore, the systematic error caused by the drastic change of distance from the recorder to the snow surface can be omitted. After eliminating the obvious false data, air temperature indices of daily average air temperature, maximum air temperature, minimum air temperature, daily air temperature range ($T_{\max-\min}$), and accumulated air temperature were statistically calculated to examine how these different air temperature indices affect the water content. The accumulated air temperature is the summation of the hourly average air temperature higher than 0 °C, $T_{ac} = \sum_{i=0}^{23} \overline{T}_{hi}, \overline{T}_{hi} > 0$, the temperature above 0 can force the ice crystals to melt in the daytime or at night, in order to totally reflect this effect, hourly data were chosen for calculating the accumulated air temperature, the accuracy of $\overline{T}_{hi}$ and T_{ac} are ± 0.1 and $\pm 2.4\,^{\circ}$C, respectively.

RESULTS AND DISCUSSION

Negative temperature gradient

The negative temperature gradient is a local derivative ($\nabla T_z = dT/dz$, with direction downwards), which means that with every unit distance change downward, the snow temperature increased.

In the accumulation period, the air temperature decreased continuously, the snow height was small, but the ground temperature still high, so the negative temperature gradient reached the highest value among all the periods. The representative value of the temperature gradient is about 0.2 °C/cm at the bottom of the snow (Figure 3(a)). In the stable period, the snow height grew quickly, but the differences between air temperature and temperature at the snow/ground interface did not change much, so the negative temperature gradient attenuated, it decreased to less than 0.1 °C/cm at the bottom of the snow cover (Figure 3(b)). As the air temperature increased, the differences between air temperature and temperature at the snow/ground interface decreased, so the negative temperature gradient was weakened greatly, nearly 0 °C/cm temperature gradient was found at the bottom layer (Figure 3(c)). The ground temperature starts to recover in the snowmelt period, it exceeded 0 °C. The temperature of the whole snow layer (except the surface layer) tends to have the same value –0 °C, so the negative temperature gradient almost disappeared in this period (Figure 3(d)).

Variation trend of snow water content

The average water content in the whole snow layer approximately increases exponentially (Figure 4). During the

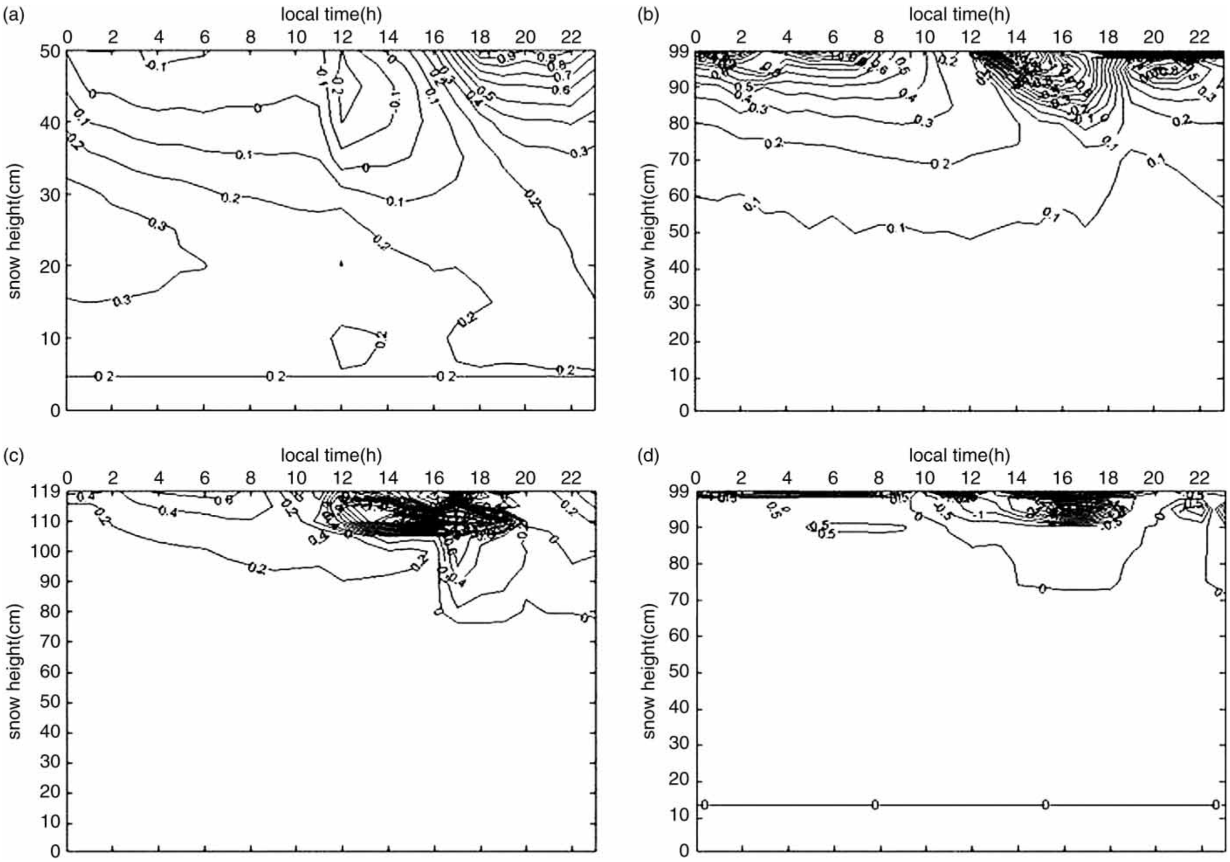

Figure 3 | Isogram of temperature gradient in snow layer ((a) December 28; (b) January 29; (c) March 9; (d) April 1).

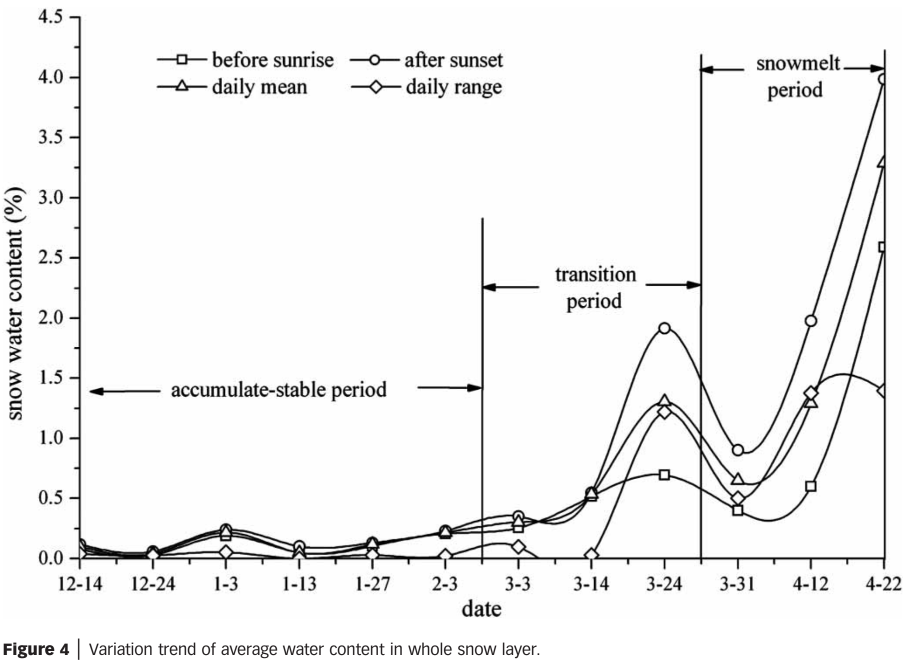

Figure 4 | Variation trend of average water content in whole snow layer.

accumulation-stable period, the water content was as low as 0.12% on average, and rose slowly at a rate of 0.0023% d^{-1} on average. The value before sunrise differed little from the value after sunset, resulting in an average daily range of 0.04%. During the transition period, the water content averaged 0.71%, and began to increase as sharply as 0.045% d^{-1}, 18.9 times greater than the rate during the accumulation-stable period. The daily range reached as high as 0.449% due to the considerable difference on March 24 in this period. The snowmelt period saw the highest average of water content – 1.74%, and the fastest increase rate – 0.115% d^{-1}, which is 1.5 times higher than the rate during the transition period. Moreover, the water content after sunset was apparently greater than before sunrise, leading to a large daily range average of 1.1%.

Snow that fell in the accumulation-stable period, which featured low ambient temperature, easily retained the characteristic of zero water content when it had just fallen. However, as the snow accumulated, liquid water appeared as a result of vapor migration, caused by the negative temperature gradient and the crystals rounding off in the snow. This resulted in a low increase of water content across the snow cover. The apparent increase of water content in the transition period was mainly attributed to the rise of air temperature. On March 24, after several consecutive sunny days, the increased air temperature caused the snow cover to melt after sunset. This greatly increased the average water content in the whole snow layer, and led to a relatively large daily range. The snowmelt period saw the fastest increase of water content, as a result of much higher daily average air temperature and accumulated air temperature. After the melting of superficial snow in the daytime, the water content after sunset was much greater than that before sunrise. The daily average water content reached the peak of the entire snow cover period.

Water migration

The variation trend of snow water content in each snow type layer follows an exponential increase similar to that of the whole-layer average. It can be divided into three stages: accumulation-stable period, transition period and snowmelt period. Both the averages and the daily range of snow water content increased over time.

It can be seen in Table 1 that the water content remains low, and less than the whole-layer average in the fine-grained layer due to the low air temperature; but it increases stratigraphically from the fine-grained snow layer to the depth hoar during the accumulation-stable period. This may be due to the water migration caused by soil moisture diffusion under a negative temperature gradient. The depth hoar therefore contributes most to the average water content of the whole layer. When the air temperature increases during the transition period, the fine-grained snow can easily absorb external energy and melt. Therefore, its average water content increases to the maximum value across all layers in the same period. The water content drops in the mid-grained snow layer, which receives less heat conducted from the upper layer. However, the water content in the depth hoar is less than that in the coarse-grained snow layer because of continuous vapor migration resulting from negative temperature gradient at the snow bottom. The water content of the snowpack is therefore affected by both the air temperature and negative temperature gradient during the transition period. As a result, water migrates both upwards and downwards, so that the fine-grained snow layer contributes most to the average water content of the whole layer.

Table 1 | Variation of snow water content in different snow types

	Accumulated-stable period		Transition period		Snowmelt period	
	Average (%)	Daily range (%)	Average (%)	Daily range (%)	Average (%)	Daily range (%)
Whole-layer snow	0.12	0.04	0.71	0.449	1.74	1.11
Fine-grained snow	0.046	0.023	0.93	1.325	2.04	2.9
Mid-grained snow	0.134	0.021	0.650	0.333	1.58	0.678
Coarse-grained snow	0.184	0.06	0.653	0.19	1.59	0.298
Depth hoar	0.205	0.04	0.575	0.14	2.18	0.54

During the snowmelt period, the surface snow melted as a result of the rapidly rising air temperature. Therefore, the fine-grained snow layer sees an increased water content that is greater than the whole-layer average, and the largest daily range of water content of all the snow layers. The water content drops in the mid-grained snow layer because less heat is conducted from the upper layer. The water content increases from the coarse-grained snow layer to the depth hoar due to the deeper frozen soil's barrier effect on melt water and the snow melting heated by the ground, the temperature of which has risen to above zero. During this period, the negative temperature gradient at the bottom of the snowpack disappeared, so the snow water content is mainly affected by the air temperature and ground temperature. Since water infiltrates downward and no water migration occurs at the snow bottom, the depth hoar and fine-grained snow layer contribute most to the average water content of the whole layer during the snowmelt period.

Spatial distribution of snow water content

Different snow types, namely, depth hoar, coarse-grained snow, mid-grained snow, fine-grained snow and newly-fallen snow, are distributed from the ground surface to the snow surface. The distribution of the average water content of different snow types can thus represent the spatial distribution of water content in the snowpack. The variation of average water content of different snow types in different periods shows the spatial variation pattern of snow water content (Figure 5).

During the accumulation period, the snow water content before sunrise and after sunset decreased from the bottom up in the snowpack (Figure 5(a) and 5(b)). This variation trend was also followed by the daily average water content, whose value was relatively low, the maximum water content in depth hoar was still less than 0.25% (Figure 5(c)). Since the snow cover in this region is of the typical 'dry cold' snow, we used the Snow Fork to measure

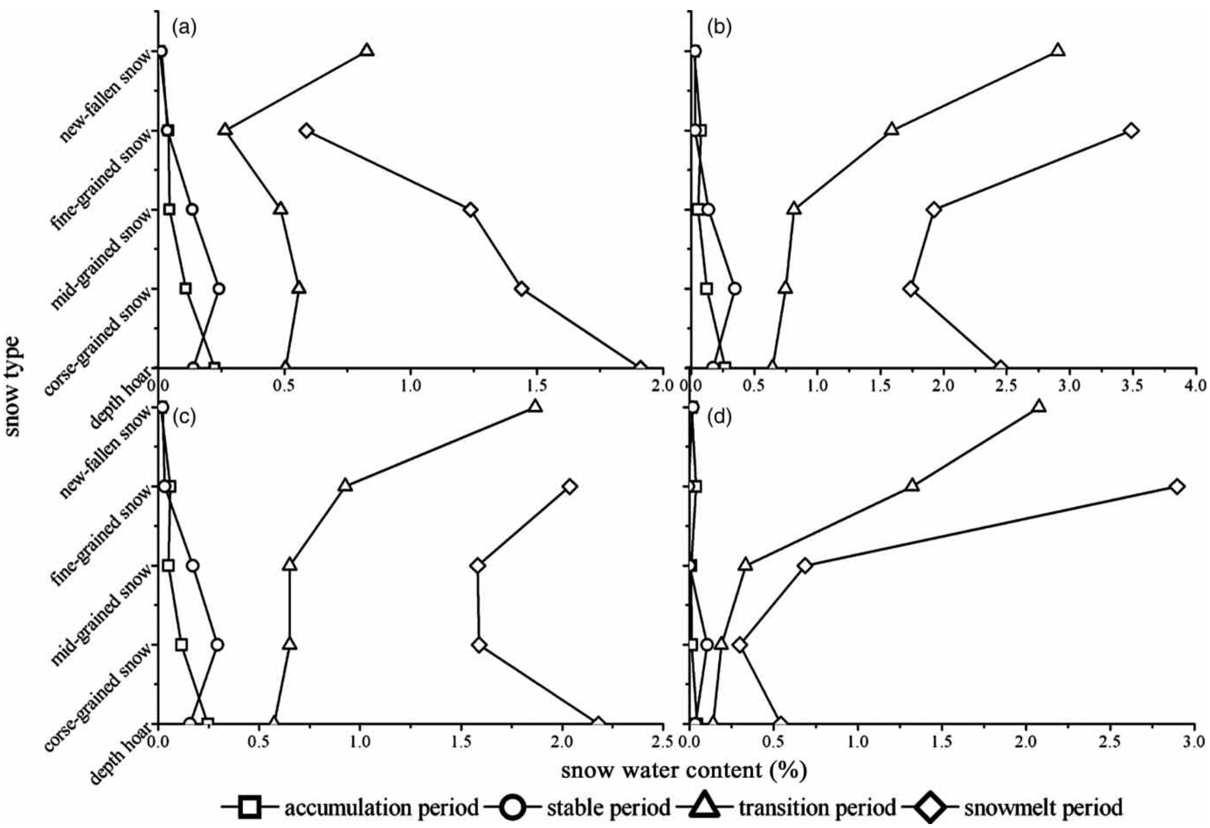

Figure 5 | Vertical distribution of snow water content along snow profile ((a) before sunrise; (b) after sunset; (c) daily mean; (d) daily range).

the water content, most of the measuring values were zero, so the newly-fallen snow is estimated at nearly zero, leading to a persistent zero water content in the top layers, which cannot melt in the low air temperature during this period. However, the relatively high ground temperature results in a high negative temperature gradient in the snowpack. This introduces the development of depth hoar that accounted for almost half of the snow height during the winter of 1972–1973. Water vapor migrates upwards from the soil, leading to an increase in the water content in the depth hoar. As a consequence, there is a clear boundary between the top dry snow and the depth hoar. When the snow piles up during the accumulation period, the bottom snow sees a vapor diffusion of the rounding off process, which causes liquid water to appear under pressure of the upper snow's weight. However, the vapor diffusion cannot compare to the vapor migration resulting from negative temperature gradient, which is why the water content gets less from the bottom up. According to Figure 5(d), the water content after sunset is slightly greater than before sunrise in any snow layer. This indicates that the alternation between day and night may have a low influence on the snow water content. It intensifies the vapor diffusion by accelerating the rounding off process under increased air temperature in the daytime, during the accumulation period.

During the stable period, the snow water content before sunrise varies in a similar way to that after sunset: it goes up from the depth hoar to the coarse-grained snow, and then goes down to the newly-fallen snow (Figure 5(a) and 5(b)). The water content in the depth hoar is less than during the accumulation period because of the attenuated negative temperature gradient due to the rising snow height in the stable period. Moreover, during this period, the depth hoar continuingly developed, causing the vapor to migrate from the depth hoar to the coarse-grained snow. As a result, the water content in the coarse-grained snow was greater than in the depth hoar. From coarse-grained snow to fine-grained snow, the water content decreased, keeping the variation characteristics influenced by both the rounding off process and the negative temperature gradient in the accumulation period. The small difference of the water content between before sunrise and after sunset (Figure 5(d)) implies that the effect of day and night alternation on the snow water content can safely be ignored.

During the transition period, the water content after sunset tends to increase from the bottom up. The variation of water content can be divided into two segments at an obvious deflection point in the mid-grained snow layer. This indicated that the water variation trends are different from any other period due to the intense influences from both ground surface energy and atmospheric energy. The increase of water content from depth hoar to coarse-grained snow is not so great because of the vapor migration attenuated under the weakened negative temperature gradient caused by the increase in air temperature. Meanwhile, daytime solar radiation and air temperature generates a distribution of energy gradient across the top snow layer. This distribution causes snow to melt at various degrees according to the layer. In addition, the permeation of melt water is not immediate, so there is a sharp gradient of the water content from the fine-grained to the coarse-grained snow layer. The water content after sunset is much greater than before sunrise, most significantly in the newly-fallen and fine-grained snow layers (Figure 5(d)). The further permeation of melt water before sunrise causes the water content to increase from the fine-grained snow to the coarse-grained snow. The relatively high water content in newly-fallen snow is due to its relatively strong water-holding capacity. The decreased water content in the depth hoar is caused by the upward vapor migration. In addition, night freezing considerably decreases the water content before sunrise. The daily average water content follows similar variation characteristics to, but is less than, after sunset.

During the snowmelt period, the water content before sunrise increases from the top down (Figure 5(a)). After sunset, it decreases from the fine-grained snow to the coarse-grained snow, then increases to the depth hoar (Figure 5(b)). This period features a snow height as shallow as 69 cm on average, high air temperature, long sunshine and alternation of melting in the daytime and freezing at night. In the daytime, more water melts in the top layer. However, the melt water does not infiltrate immediately, leading to the high water content in the fine-grained snow on the surface, and relatively low water content in the mid-grained and coarse-grained snow in the middle. In the depth hoar, a water-rich zone appears caused by the deeper frozen soil that prevents melt water from permeating downwards and by the recovered ground temperature that heats and melts the snow. Before midnight, the melt water evenly permeates down to the bottom snow layer. After midnight, the liquid water in the snow pores partially freezes due to the temperature falling below 0 °C, causing the water content to increase from the top down before the next sunrise, and causing less than the average water content after sunset in each snow layer.

Response to air temperature

Snow water content is most significantly affected by air temperature. This is indicated by the fact that the whole layer average water content is significantly and positively correlated with the daily average, maximum, minimum and accumulated air temperature, and is significantly and positively correlated with the daily range of air temperature (Table 2). These four temperature indices of daily average air temperature, maximum air temperature, minimum air temperature, and accumulated air temperature, are selected to examine how the water content is affected. Considering the lag response of snowmelt to the air temperature, and the difficulty in collecting data, the 5-day moving average temperature indices were applied to fit the variation of water content.

The whole layer average water content exponentially increases with the average air temperature, the maximum air temperature and minimum air temperature (Figure 6(a) and 6(c)). However, different temperature indices have different relations to the water content. The water content remains stable and less than 0.25% during the early phase, when the air temperature is low. The water content increases exponentially with the air temperature after the air temperature reaches some critical values: −5 °C of daily average air temperature; 0 °C of daily maximum air temperature; and −10 °C of daily minimum air temperature, which appear during approximately the same period at the start of the transition period. According to Figure 6(d), the water content is linearly and positively correlated with the accumulated air temperature. When the accumulated air temperature is low and even close to zero, water content is as low as below 0.5% and varied in a small range. When accumulated air temperature ascends, water content significantly and linearly increases with accumulated air temperature. The significant increase appears at the same time with the critical values of daily average, maximum and minimum air temperature that appeared at the start of the transition period.

Based on the least-squares method, the variation of average water content in the whole layer is applied to fit with different temperature indices. The fit function with daily average, maximum and minimum air temperature is expressed as Equation (1), with coefficient of determination R^2 of 0.841, 0.865 and 0.519, and residuals of 0.45, 0.41, and 0.77, respectively, reaching an extremely significant 0.01. The fit function of water content with the accumulated air temperature is a simple linear function as shown in Equation (2), with the determination coefficient R^2 of 0.858 and residual of 0.42, reaching an extremely significant 0.01 (see Table 3 for the fit parameters). It can be seen that the best fit is provided by the maximum air temperature throughout the snow cover period, followed by the accumulated air temperature and daily average air temperature.

$$W_1 = ae^{T_1/b} + c \quad (1)$$

$$W_2 = a'T_2 + b' \quad (2)$$

where T_1 is the daily average, maximum, or minimum air temperature (°C); T_2 is the accumulated air temperature (°C); W_1 is the snow water content in snow cover (%) as fitted with T_1; W_2 is the snow water content in snow cover (%) as fitted with T_2; a, b, and c are the fit parameters in

Table 2 | Correlation between the whole layer average water content and different temperature indices

	Daily average air temperature	Maximum air temperature	Minimum air temperature	Accumulated air temperature	Air temperature range
Snow water content	0.817[b]	0.85[b]	0.715[b]	0.863[b]	0.248[a]

[a]Has passed the significance test of 0.05; [b]Has passed the significance test of 0.01.

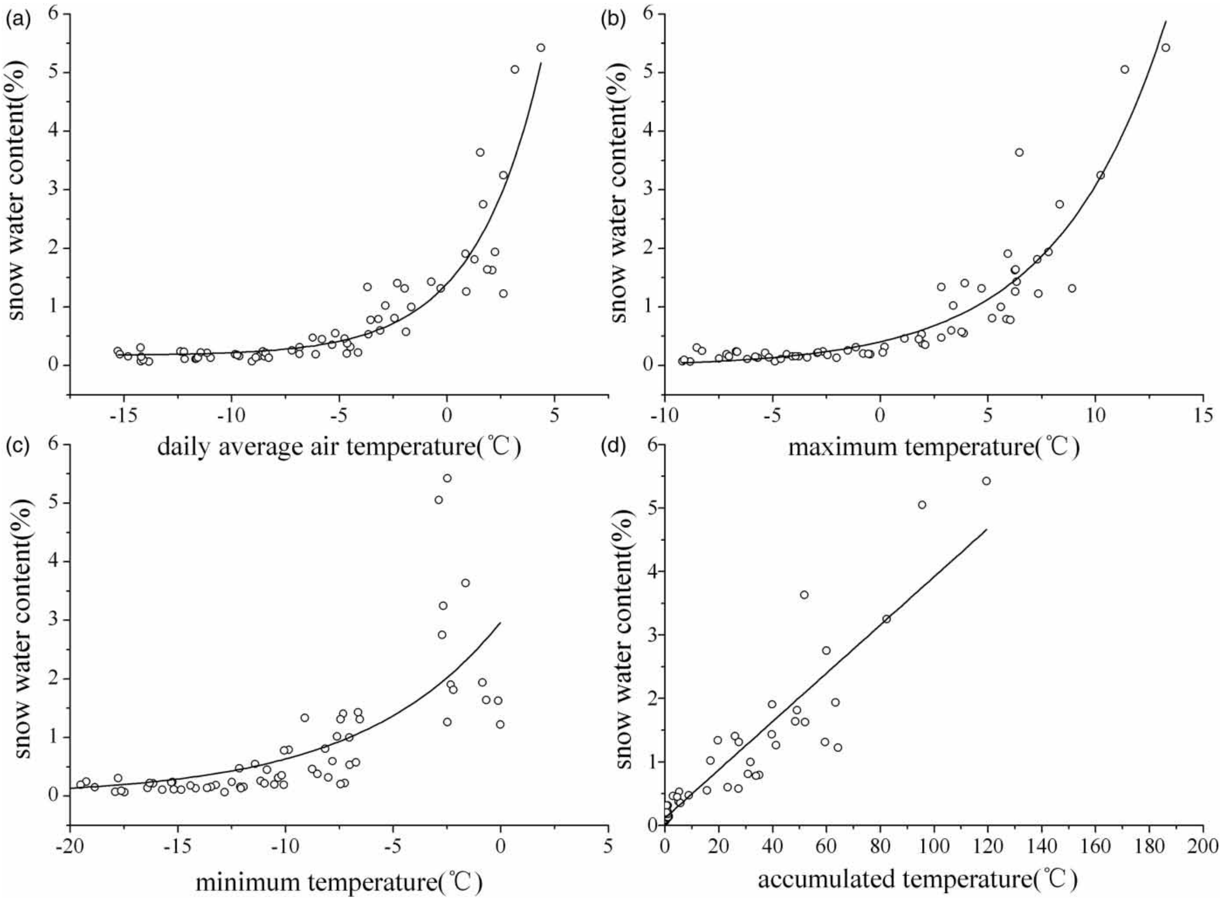

Figure 6 | Relationship between 5-day moving average values of each temperature index and the average water content in whole snow layer.

the fit formula with T_1; and a' and b' are the fit parameters in the fit formula with T_2.

The residual fit of the snow water content with temperature indices tends to increase over time and is specific to each index in each period (Figure 7), resulting in index-specific fitting precision. When the temperature is below $-7\,^{\circ}$C, the accumulated air temperature provides a better fit than average air temperature or maximum air temperature, with the average relative deviation ratio of 6.3% (relative deviation = |Fitted water content − Measured water content|/Measured water content). When the temperature is between −7 and $-1\,^{\circ}$C, the average air temperature provides a better fit than accumulated air temperature or maximum air temperature, with the relative deviation ratio of 13.2%. When the average air temperature is higher than $-1\,^{\circ}$C, the maximum air temperature provides a better fit than accumulated air temperature or average air temperature, with the relative deviation ratio of 28.2%. The transition period occurs at this temperature, when precipitation mainly occurs in the form of rain or sleet, which would lead to extreme values of snow water content. In such a case, considerable error will be introduced if water

Table 3 | Parameters of fit snow water content with daily average, maximum, minimum and accumulated air temperature

	a (%)	b (°C)	C (%)	a′ (%/°C)	b′ (%)
Daily average air temperature	1.23	3.114	0.169	–	–
Maximum air temperature	0.432	5.067	−0.027	–	–
Minimum air temperature	2.976	0.155	0	–	–
Accumulated temperature	–	–	–	0.038	0.117

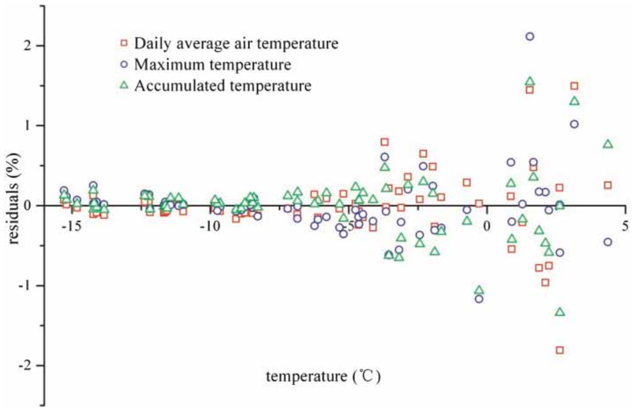

Figure 7 | Residual trends of fitting snow water content with daily average, maximum and accumulated air temperature.

content is fitted with a single temperature index. This is why the relative deviation ratio of the fit apparently increases in the late phase. To minimize the error, the content may be fitted with different indices during different snow cover periods, as shown in Equation (3).

$$W = \begin{cases} 0.38T_{ac} + 0.117 & T_a < -7^{\circ}C \\ 1.23e^{T_a/3.114} + 0.169 & -7^{\circ}C < T_a < -1^{\circ}C \\ 0.432e^{T_m/5.067} - 0.027 & T_a > -1^{\circ}C \end{cases} \quad (3)$$

where T_{ac} is the accumulated air temperature (°C); T_a is the average air temperature (°C); T_m is the maximum air temperature (°C); and W is the snow water content in snow cover (%).

CONCLUSIONS

The variation trend of snow water content in each snow type layer follows an exponential increase similar to that of the whole-layer average. Under the influence of negative temperature gradient, the water migrates upwards during the accumulation-stable period. Under the influence of both air temperature and negative temperature gradient, the water migrates both upwards and downwards. Under the influence of the air temperature and ground temperature, the water migrates downward.

The spatial distribution of water content in the snowpack was divided into four periods. During the accumulation period and stable period, the daily mean snow water content decreases from the bottom up due to the water migrating upwards, unless the water content increased from the depth hoar to the coarse-grained snow in the stable period due to the stronger negative temperature gradient which forces the water to migrate from the depth hoar to the coarse-grained snow. The effect of day and night alternation on the snow water content can safely be ignored in both the periods. During the transition period, the difference of the water content is greater between before sunrise and after sunset. The daily mean water content descends from new-fallen snow to mid-grained snow quickly and from mid-grained snow to depth hoar slowly. This is influenced by the negative temperature gradient and increasing air temperature. During the snowmelt period, the greatest difference occurs between before sunrise and after sunset. The daily mean average of the water content has the same distribution as after sunset, which descends from the fine-grained snow to the coarse-grained snow, and increases from the coarse-grained snow to the depth hoar.

Snow water content is significantly affected by air temperature. The best fit is provided by the maximum air temperature throughout the whole period, followed by the accumulated air temperature and daily average air temperature. When the average temperature is below −7 °C, the snow water content has a best fit with the accumulated air temperature, with a simple linear function. When the average temperature is between −7 and −1 °C, the snow water content has a best fit with the average temperature, with an exponential function. When the average temperature is higher than −1 °C, the snow water content has a best fit with the maximum air temperature, with an exponential function.

The typical ‘dry cold’ snow in northwestern China was taken as the research object. The conclusion is similar in this region; however. we need to verify the finding in other sites in future research.

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