Variation of snow cover in the Nyang River basin of southeastern Tibetan Plateau, China

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ABSTRACT

Snow cover is highly sensitive to global climate change and strongly influences the climate at global and regional scales. Because of limited \textit{in situ} observations, snow cover dynamics in the Nyang River basin (NRB) have been examined in few studies. Five snow cover indices derived from observation and remote sensing data from 2000 to 2018 were used to investigate the spatial and temporal variation of snow cover in the NRB. There was clear seasonality in the snow cover throughout the entire basin. The maximum snow-covered area was 8,751.35 km\textsuperscript{2}, about 50\% of the total basin area, and occurred in March. The maximum snow depth (SD) was 5.35 cm and was found at the northern edge of the middle reaches of the basin. Snow cover frequency, SD, and fraction of snow cover area increased with elevation. The decrease in SD was the most marked in the elevation range of 5,000–6,000 m. Above 6,000 m, the snow water equivalent showed a slight upward trend. There was a significant negative correlation between snow cover and temperature. The results of this study could improve our understanding of changes in snow cover in the NRB from multivariate perspectives. It is better for water resources management.

Key words: climate variability, Nyang River, Tibetan Plateau, snow cover, spatial extent

HIGHLIGHTS

- Different snow cover indices were used to evaluate the snow cover characteristics of Nyang River basin. Snow cover days data were collected for calculating snow cover frequency to evaluate the character of the basin.
- The temporal and spatial distribution of snow cover in Nyang River basin was clarified.
- There is a significant negative correlation between snow cover and air temperature.

INTRODUCTION

Snow cover refers to the layer that is formed when snow falls and covers the ground or ice surface. Its characteristics (e.g., snow cover area, snow depth (SD), amount of snowfall, and snow water equivalent (SWE)) play an important role in the global energy and hydrological cycles, especially in alpine regions (Kang \textit{et al.} 2010; Zuo \textit{et al.} 2012; She \textit{et al.} 2015; Yang...
et al. 2019). Snow is one of the most active natural elements on the Earth's surface; it plays a very important role in material migration and energy conversion on the Earth's surface and forms an important part of the Earth's surface (Dye 2002). As an important component of the cryosphere, snow cover has a significant impact on global energy balance, climate change, the hydrological cycle, and ecosystems (Qin 2006; Qin et al. 2014; Wei & Dong 2018). Snow cover greatly reduces the shortwave solar radiation received by the underlying surface and impedes heat exchange between the underlying surface and the atmosphere. It also changes the albedo feedback of the underlying surface (Flanner et al. 2011). In Northwest China, snow cover over the mountains is also an important water resource; it provides most of the streamflow runoff in this region, an area with a prevalently arid and semi-arid climate (Viviroli et al. 2007; Shi et al. 2011). Spatial and temporal variations of snow cover are important indicators and parameters of climate change (She et al. 2015), because of interactions and feedbacks between snow cover and the climate system. Snowmelt is a significant contributor to total runoff (Singh et al. 2010). Therefore, it is essential to conduct hydrological studies to understand the snow-covered area (SCA) extent and melting patterns in mountain regions (Gupta et al. 2007; Minora et al. 2015), and it is also important to investigate the changes in snow regimes because SCA variability impacts the timing and magnitude of snowmelt runoff (Srivastava et al. 2014).

SD is an important parameter for estimating the SWE, studying watershed water balance, and simulating spring snowmelt runoff (Matson 1991). The determination of SD is mainly based on active and passive microwave sensors. Because SCA and SD cannot quantitatively describe the proportion of snow in the water cycle, the inversion of SWE is gradually produced in the later stage.

Water resources are distributed unevenly both spatially and temporally. Snow cover is an important water resource in the Qinghai–Tibetan Plateau and mainly forms in the winter months (Wei & Dong 2018). Under climate change, the timing of ice and permafrost degradation in the mountains and plateaus of western China has changed in recent years, and the frequency of flood events caused by glacier melting and snow melt has also increased significantly (Qin et al. 2014). In recent decades, scholars in China and abroad have studied the spatio-temporal variation of snow cover and found that the Qinghai–Tibet Plateau is the region with the strongest snow cover anomaly in the Northern Hemisphere (Brown 2000). However, the SCA in some areas of the Qinghai–Tibet Plateau is increasing under climate change, in sharp contrast to that in the temperate lowlands of the Northern Hemisphere, which is decreasing with the increase of temperature (Brown 2000; Dong 2018). Quantitative analyses of the temporal and spatial dynamic changes of snow cover remain difficult because of the heterogeneity of the elevation distribution of snow cover and differences between data sources (Dong 2018).

The Qinghai–Tibet Plateau is the source of the Indus, Ganges, Brahmaputra, Yellow, and Yangtze rivers. It is particularly important to understand snow cover changes because ice melt and snow melt are also important hydrological processes. Observations from the latter part of the 20th century indicate that high-altitude regions are especially sensitive to global climate change. The albedo of the snow is an important factor underlying warming at high altitudes (Dong 2018). Rangwala et al. (2009) simulated climate variables over the Qinghai–Tibet Plateau using a global climate model and studied the climate trends and the correlations with other factors indicating that the atmosphere will continue to warm in the future. Their results showed that the temperature on the Qinghai–Tibet Plateau increased and the amount of snow decreased with elevation. In stark contrast to the conclusion of Rangwala et al. (2009), Qin and coworkers (Qin 2006) showed that the annual SD in western China has been increasing. Examinations of the response of the snow cover on the Qinghai–Tibet Plateau to climate change indicate that snow cover in western China has shown a small long-term upward trend and large interannual variability.

However, time series data of snow cover at different elevations are needed to verify model simulation results. In the Nyang River basin (NRB), weather stations are mostly located at low altitudes on flat land (Figure 1). Consequently, data coverage is discontinuous and uneven, and the resulting data cannot accurately reflect the temporal and spatial distribution of snow cover, especially in high-altitude mountainous areas. Satellite remote sensing is a new tool that provides data on snow cover over large areas, allowing snow cover dynamics to be monitored (Qian et al. 2003).

Previous studies have suggested that snow accumulation and depletion mainly depend on the latitude, altitude, topography, and weather conditions of the basin. Variation of SCA with altitude can be accurately characterized according to the distribution of the temperature lapse rate (Kattel et al. 2012; Thayyen & Dimri 2018). Misra et al. (2020) studied the Mandakini River and found that the topography and meteorological conditions of the basin influence the dynamics of snow cover. Jabbar et al. (2020) studied the Upper Indus basin and found that snow cover changes were influenced by temperature change. However, the relationships between snow cover dynamics and temperature and precipitation changes in the NRB have rarely been investigated, and there is a lack of research on snow cover variability in this region.

Because of the importance of snow cover dynamics, this study focuses on quantifying the spatio-temporal variation of snow cover in the NRB of the Tibetan Plateau, an area for which there has been little research.
STUDY AREA

The NRB is located at 29°28′–30°31′ N, 92°10′–94°35′ E (Figure 1). It originates from a glacial lake on the southern slope of Mount Nyainqentanglha, flows southeastward, and merges into the Yarlung Zangbo River near Nuxia. It is the second largest tributary of the Yarlung Zangbo River basin. The main channel in the NRB is 309 km long with an average slope of 7.35%. The NRB drainage area is approximately 17,500 km² (Zhang et al. 2011). The drainage network is very dense and it is the longest tributary of Yarlung Zangbo River basin. The Ba River is the longest tributary of the NRB, and its drainage area comprises 24% of the total NRB drainage area. Glaciers cover 953 km², which is about 5.3% of the total area of the NRB.

In the NRB, the average altitude is 4,700 m above sea level, and 68.3% of the total area is above 4,500 m. The climate is mild, characterized by cool summers and warm winters. The average annual temperature is 8.6 °C (Jin et al. 2019). In summer, the southwest monsoon from the Indian Ocean is dominant; thus, the rainy season is generally concentrated from May to October (Zhang et al. 2002). The average precipitation in the rainy season is 765 mm, accounting for 90% of the annual precipitation. Internal runoff accounts for about 90% of total annual runoff and mainly occurs between June and September. During non-flood seasons, meltwater from ice and snow is the main source of runoff replenishment in the NRB. Therefore, variations in annual runoff are relatively apparent, and floods caused by rainfall and meltwater occur frequently.

MATERIALS AND METHODOLOGY

Data acquisition

Meteorological (such as precipitation and air temperature) and spatial datasets (such as the digital elevation model, DEM) were used in this study. Annual meteorological data between 2000 and 2018 were obtained from the National Tibetan Plateau
Data Center (Yang & He 2018). Because there are few stations in the basin, and the data time series of hydrological stations are short, the meteorological data of the hydrological stations were mainly used for the correction of meteorological station data. The snow cover indices were derived from observation data and remote sensing data. In this study, we mainly used five indices: SCA, SCD, SD, snow cover frequency (SCF), and SWE, all of which were from 2000 to 2018. The Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn) provided the SCA product from passive microwave sensors, which served as the basic dataset for this study. We used the data between 2000 and 2018 from the long-term SD dataset of China, which is observational data and has a spatial resolution of 25 km (Che et al. 2015). Passive microwave sensors are not affected by clouds or darkness and can thus provide daily SCA measurements, although the pixel size is large (Foster 1999). Passive microwave data were used to assess long-term trends in SCA in the NRB, which is our study area (Figure 1). SWE and SCD data were obtained from the Science Data Bank (Qiu et al. 2016).

**Methodology**

### Snow indices

The SCD of each pixel was calculated by ArcGIS10.3. The cumulative SCD of a single pixel in a given time interval was calculated as follows (Tang et al. 2013):

\[
SCD = \sum_{i=1}^{N} \text{Ceil}(D_i \geq 50)
\]  

(1)

where \( N \) is the total number of days (images) within a year and \( D_i \) is the snow cover fraction (%) in a pixel (0 \( \leq D_i \leq 100 \)). The value \( \text{Ceil}(D_i > 50) \) counts the numbers of \( D_i \geq 50 \). For instance, if the pixel value of the image is 55, the SCD adds 1. If the pixel value on the image is 0, the SCD adds 0 and is unchanged.

Snow cover days (SCD, d), the snow start date (SOD), and the snow end date (SED) were three indices used for monitoring seasonal snow cover (Dong 2018); SOD and SED denote the Julian dates of the first and last snowfalls of the snow season; SCD is the number of days between the SOD and SED. For areas with persistent snow cover, the hydrological year was determined in advance. For example, the hydrological year could commence on August 1 and end on the following July 31. In this hydrological year, the SED is the date of the last snowfall of the year.

For regions with little snow, calculating the SOD and SED from January 1, taken as the start of the hydrological year, may be more appropriate. Therefore, values of SOD and SED exceeding 366 indicate that the start of snow accumulation has been delayed or the end of snow accumulation has advanced (366 mainly refers to leap years). Monthly data for SCA in the basin over the study period were obtained from calculations of daily SCA. Monthly cumulative mean composite SCA was derived from average SCA in the month. SWE was mainly determined based on SD and snow particle size. The advantage of SWE is that it can quantitatively describe the amount of water formed after snow melting. The beginning and end dates of snow cover are often closely related to climate change and thus have gradually become snow parameters of interest in the context of global climate change (Wang et al. 2017). Continuous time series of the spatial and temporal parameters of snow cover (SCA, SCD, SOD, and SED) can be used to study the spatial and temporal dynamics of snow cover. In addition, quantity parameters (SWE and SD) can be used to estimate the water storage in the snow cover. These two types of indices are important for assessing snow cover changes under the background of climate change; and thus for water resources management (Niedzielski et al. 2019). The number of times of snow cover for a pixel is the SCF of the pixel (Liang et al. 2019). In this study, the characteristics of snow cover in the NRB were analysed using SCA, SCD, SWE, SD, and SCF. The definition of each index is shown in Table 1.

In this study, Pearson correlation analysis was used to calculate the relationship between the climate variables and snow indices (Pearson 1895).

\[
R = \frac{n\overline{xy} - \overline{x}\overline{y}}{\sqrt{n\overline{x}^2 - (\overline{x})^2} \sqrt{n\overline{y}^2 - (\overline{y})^2}}
\]  

(2)

where \( x \) and \( y \) are snow indices and climate variables, respectively; \( R \) is the correlation coefficient (CC) of these two variables; and \( n \) is the number of data pairs. The correlation was computed at the 0.05 and 0.01 statistical significance levels.
RESULTS

Temporal characteristics of snow cover

Seasonal variability

Figure 2 shows the SCF in the NRB for different seasons. Over the study period, the SCF decreased in all seasons. SCF was highest in winter, followed by spring, then autumn, and lowest in summer. In winter, SCF increased between 2000 and 2004 and decreased between 2004 and 2018. In the other seasons, there was considerable interannual variability in SCF, and the downward trend was less marked. The decreased rate of SCF in winter was the highest, with a value of 0.34. However, the downward trend was not significant in all seasons ($P > 0.05$).

Figure 3(a) and 3(b) show SCA variations in the NRB. The SCA varied seasonally in the NRB. It was highest in spring and lowest in summer. Over the study period, the monthly SCA decreased. The variation of SCA presented double peaks, generally occurring predominantly in spring, and in winter for a few years. The maximum SCA was 75% of the catchment area.

The multi-year monthly average SCA in the NRB is shown in Figure 3(b). The SCA of the drainage basin was smaller between June and September and larger between January and April. Maxima of monthly SCA occurred in March, whereas minima occurred in July. SCA changes were smaller in summer and larger in winter and spring.

Figure 3(c) shows variations of monthly SWE (divided by 2) in the NRB. Monthly SWE showed a similar trend with SCA. There was clear seasonality. Over the study period, SWE decreased. Figure 3(d) shows that maxima of multi-year monthly SWE occurred between the end of December and the beginning of January; SWE was lower between July and September and higher between November and February. Additionally, both SCA and SWE had lower values in summer and higher values in spring and winter.

Table 1 | Indices of snow cover and their definition

| Indices                               | Definition                                                                 | Unit  |
|---------------------------------------|---------------------------------------------------------------------------|-------|
| Snow cover days (SCD)                 | The accumulation of snow cover within each pixel                          | days  |
| Snow cover area (SCA)                 | The sum of snow pixels                                                    | km²   |
| Snow cover frequency (SCF)            | The number of days with snow cover divided by the total number of days in the period | %     |
| Snow depth (SD)                       | *In situ* measurements of snow depth                                       | cm    |
| Snow water equivalent (SWE)           | The available water content in snow                                        | mm    |

Figure 2 | Average snow cover frequency in the NRB.
Figure 4 shows that the seasonal variability of snow cover in the NRB was very high. The SCA was highest in spring, followed by winter, then autumn, and lowest in summer. In spring, snow covered the whole basin. In summer, snow was mainly concentrated in the high-altitude mountain areas to the south and north. The SCA was higher in autumn than in summer. It was also distributed in the upper reaches of the basin. In winter, the snow cover extended to the downstream area of the drainage basin. The snow season began with the southern and northern marginal mountain areas being covered by snow (summer). Then, the snow cover in the upstream marginal mountain areas increased (autumn). Finally, the snow cover in the downstream marginal mountain areas increased (winter and spring).

**Interannual variability**

Figure 5 shows the variations of snow cover indices in the NRB over time. Figure 5(a) shows the variation of SCF. Figure 5(b) shows the variation of annual SCA. Figure 5(c) shows the variation of SWE (divided by 2). The SCF increased between 2000 and 2004 and decreased between 2004 and 2018. Over the study period, annual SCF decreased. The value of annual SCF is constrained between 0.1 and 0.2. Over the study period, SCF was the highest in 2004 and lowest in 2016. This trend is also reflected in the winter SCF. Winter snow cover accounted for the largest proportion of the annual snow cover. Figure 5(b) shows that the annual average SCA decreased over the last 10 years. Over the study period, the SCA was the lowest in 2010, about 4,041 km². The maximum annual SCA was 6,098 km² in 2004, accounting for 34.8% of the total basin area. Figure 5(c) shows that fluctuations in SWE over the study period had no obvious trend ($P > 0.05$). This may also depend on the length of the study period.

**Spatial characteristics of snow cover**

**Spatial distribution**

The study of the spatial distribution of snow cover is key to understanding the runoff process. Figure 6(a) shows the distribution of average annual SWE (divided by 2) in the NRB. The highest SWE was approximately 310 mm and was found at
the northern edge of the middle reaches of the NRB; the SWE in the upper reaches was higher than that in the lower reaches. The lowest SWE was approximately 120 mm and was found in the downstream area of the basin.

SD data were pre-processed, and the average SD for 2000–2018 was calculated. Figure 6(b) shows the distribution of average SD for many years in the NRB. The maximum SD was 5.35 cm and was found at the northern edge of the middle reaches of the basin. The minimum SD was 1.82 cm and was found at the western edge of the upper reaches of the basin. The average SD of the basin was 3.83 cm. In general, SD in the middle reaches was higher than that in the upper reaches and lower reaches.

The general situation of the spatial distribution of snow cover in the NRB is represented in Figure 6(c), which shows the annual average SCD between 2000 and 2018. Snow was mainly found in the northern and southeastern regions of the upper
reaches of the NRB, as well as at the northern edges of the middle reaches. In these areas, the SCD exceeded 103 days, and the vegetation is mostly mountain grassland and shrubbery. SCDs were below 103 days in the upper reaches (except in the southeast and at the western edge) and the middle reaches (except at the northern edge) of the NRB. These areas are mostly arid grassland where evaporation is high and precipitation is low.

Distribution of snow cover with elevation

Figure 7(a)–7(c) shows the variation of snow cover characteristics with elevation in the NRB. Figure 7(a) shows the variation of SCF with elevation in the basin. Elevation was positively correlated with SCF in the basin. The highest SCF was 0.39. Figure 7(b) shows the variation of SD with elevation in the NRB. The annual mean SD was positively correlated with elevation. At low altitudes, SD fluctuated. The highest SD in the basin was 4.7 cm. Figure 7(c) shows the variation of SWE with elevation in the NRB. Below 5,500 m, there was no significant correlation between SWE and elevation. Above 5,500 m, SWE increased with elevation. The highest SWE was approximately 300 mm. These results are partially consistent with those reported by previous studies (Groisman et al. 1994).
Figure 7(d)–7(f) shows the variations of snow cover indices at different elevations in the NRB, and it mainly shows the changes of different snow cover indexes with time at different elevations. Figure 7(d) shows the variations of SCF at different elevations in the NRB. Over 5,000 m above sea level, the SCF slightly increased over the study period. At higher altitudes, the SCF began to exhibit a downward trend in 2008. The rate of decrease of the SCF over the study period increased with altitude. Figure 7(e) shows the variation of SD in the NRB. Variations in SD exhibited similar trends at different elevations. The average SD decreased between 2000 and 2004 at all elevations, increased between 2005 and 2006, decreased between 2007 and 2010, and increased between 2010 and 2018, against a background of fluctuations. Over the entire study period of 2000–2018, SD exhibited a downward trend. The decline in SD was the most marked in the elevation range of 5,000–6,000 m. In the range of 2,943–3,500 m, SD exhibited a slight upward trend. Figure 7(f) shows variations of SWE in the NRB. The SWE increased above 6,000 m and decreased below 6,000 m. The lowest SWE was recorded in 2,009 below 6,000 m above sea level.

DISCUSSION AND CONCLUSIONS

Snow cover is affected by precipitation and temperature and changes with altitude and season. Because of the complex terrain and changeable climate conditions, the relative importance of temperature and precipitation has changed in space (You et al. 2020).

The main reasons for the decrease of SCA in NRB that showed a downward trend during the study period is the decrease of snowfall and the increases in temperature and liquid precipitation. As shown in Figure 8, the snow cover accumulation in the NRB mainly started in September and snow melt started in April. The maximum value of snow cover area occurred from late January to mid-February each year, and the minimum value occurred between mid- and late August. Figure 8 shows that
during the study period, the maximum SCA showed a downward trend, but not an obvious one, and the minimum SCA showed a slight upward trend. The decreasing trend of the maximum SCA may reflect the decrease of the average precipitation rate and maximum precipitation rate, which is related to the decrease of the average temperature and maximum temperature. Previous studies found that there had been no significant trend in SCA in western China since 1957, although climate change in the middle latitudes of the Northern Hemisphere has led to the decrease of SCD on the Tibetan Plateau since the 1970s (Déry & Brown 2007; McCabe & Wolock 2009; Shen et al. 2014). In the study area, SCD and SWE generally decreased, with more marked decreases at high elevation. However, SCA increased with elevation when the elevation was lower than 2,000 m and decreased with elevation at higher elevations. Our results are consistent with the previous study (Shen et al. 2014).

In high-altitude areas, because of the melting of snow, the positive effect of snowfall on snow cover has become more and more important, and the negative effects of precipitation and temperature on snow cover have also become greater (Yang et al. 2019). We observed a significant reduction in snow cover in areas where temperature increased significantly. The decrease of SCA at higher altitudes (especially above 5,000 m) may indicate that continuous snow cover and glacier melting are intensified due to higher temperatures. This is consistent with the study that reported that temperatures around 5,000 m have considerably increased (Rangwala et al. 2010). The increase of annual rainfall, especially in summer, may also be an important factor leading to continuous snow melting in summer.

SCDs exhibited an overall downward trend over most of the basin area. Between 2000 and 2018, there was little change in the SCD spatial distribution, indicating that although there were temporal and spatial interannual variations of snow beginning and melting, the overall distribution of SCD was mainly controlled by the terrain and climate conditions in a certain region. Previous studies on SCD over the Tibetan Plateau based on satellite data found that SCD decreased from 2000 to 2010 (Tang et al. 2013; Qin et al. 2014); our study results are consistent with this finding.
The decreases of SCD and SWE in the NRB during the study period were mainly caused by the decrease in snowfall and increase in rainfall and temperature, which is consistent with a previous study (Zhang et al. 2012). Based on our research results, it can be inferred that with the increase of temperature and precipitation, SCA gradually decreases; the snow rapidly melts at the end of the snow season, and the permanent snow area of the whole basin continues to decrease.

On a monthly scale, the SCA was mainly negatively correlated with temperature and positively correlated with precipitation, although there were large differences between the correlation coefficients (Figure 8). The decrease (increase) of SCA was mainly related to the decrease (increase) of precipitation or warming (cooling), which is roughly consistent with the results from a previous study that analysed the relationship between snow cover and climate in the study area using only data from meteorological stations (Singh et al. 2016). The data were de-trended and the following results were obtained (Table 2). In general, the correlation coefficients between SCA and temperature were higher than those between SCA and precipitation (except for in the autumn months), and there is a significant negative correlation between SCA and temperature (Table 2), which indicates that the interannual variability of the snow cover in the NRB was mainly caused by temperature.

**CONCLUSION**

In this study, we examined variations of different snow cover indices, including SCA, SCD, SCF, SD, and SWE, in the NRB over the study period of 2000–2018. We analysed the changes of snow cover and drew the following conclusions:

(1) During the study period, SCF showed a downward trend. Interannual variability in snow cover was highest during midwinter. On the monthly scale, the influence of temperature on snow cover was more significant than that of precipitation.

(2) Snow cover of the NRB was mainly concentrated in high-altitude mountain areas to the south and the north. The maximum SWE was also found in such a region, with a value of approximately 310 mm. The SWE in the upper reaches was higher than that in the lower reaches of the basin.

(3) In the mountain area to the north, which is in the middle reaches of the basin, the SCD exceeded 103 days, and the maximum SD was about 5.35 cm. The SD in the middle reaches was higher than that in the upper reaches of the basin.

(4) There was clear seasonality in snow cover indices. All indices exhibited downward trends. Correlation coefficients showed that the snow cover indices were positively correlated with altitude.

Snow cover indices in the basin were affected by geographical location, topography, and climate change. This study has demonstrated the temporal and spatial distributions of snow cover and their relationships with precipitation and temperature in the NRB, which is helpful for the scientific community to understand the relationship between snow dynamics and climate change, and fills a gap in the study of snow cover in the high-altitude area of this region.

### Table 2 | The correlation coefficients of snow cover with precipitation and temperature obtained by Pearson correlation analysis

| Month | SCA & Pre | SCA & Tem |
|-------|-----------|-----------|
| Jan   | 0.37      | −0.47*    |
| Feb   | 0.67**    | −0.68***  |
| Mar   | 0.33      | −0.39     |
| Apr   | 0.35      | −0.72*    |
| May   | 0.34      | −0.49*    |
| Jun   | 0.50      | −0.53*    |
| Jul   | 0.30      | −0.31*    |
| Aug   | 0.35      | −0.16     |
| Sept  | 0.66      | −0.12     |
| Oct   | 0.45*     | −0.63**   |
| Nov   | 0.39      | −0.75***  |
| Dec   | 0.49*     | −0.64*    |

*: 0.05 significance level.  
**: 0.01 significance level.
Because of the low resolution (25 km) of the snow data used in this study, the number of meteorological stations used, and the short time span, there are some uncertainties. Most of the meteorological stations are located in river valleys or plains, where the altitude is low and there is usually less snow. Conventional meteorological data are limited for areas at high altitudes and in steep terrain. Therefore, measurements of snow cover can be obtained from remote sensing data, which are often limited by the presence of clouds. Thus, more field observations are needed to accurately describe the temporal and spatial changes of snow cover in NRB.

**ACKNOWLEDGEMENTS**

This project is funded by the National Natural Science Foundation of China (91647202).

**DATA AVAILABILITY STATEMENT**

All relevant data are available from an online repository or repositories. China meteorological forcing dataset (1979-2018) can be downloaded from http://data.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49/. Snow Depth dataset can be downloaded from http://data.tpdc.ac.cn/zh-hans/. Snow Cover Area dataset can be downloaded from http://westdc.westgis.ac.cn. Snow Water Equivalent dataset can be downloaded from https://www.scidb.cn/

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