Spatiotemporal Variation of Snow Cover in the Yarkant River Basin, 2002-2018: Postprint

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Abstract

Snow cover is a relatively active factor in the cryosphere, sensitive to climate and environmental changes, and its variations affect global climate and hydrological changes. Snow cover days (SCD), snow onset date (SCOD), and snow melt date (SCMD) are the main factors affecting surface material and energy balance. Using MODIS cloud-free snow products, daily snow cover percentage (SCP) in the Yarkant River Basin from July 2002 to June 2018 was extracted, SCD, SCOD, and SCMD were calculated based on pixels, their spatial distribution and variation characteristics were systematically analyzed, and the causes of their changes and the relationship between anomalous snow area variations and ENSO were discussed. The results show that: (1) During the study period, the snow cover area in the basin showed a weak decreasing trend, was significantly negatively correlated with temperature, and significantly positively correlated with precipitation; from 2002 to 2018, SCP showed a clear linear increasing trend with elevation (R2=0.92, P<0.01); the month of maximum SCP in each elevation zone was generally delayed with increasing elevation, while the month of minimum SCP showed no significant change (concentrated in August); below 4000 m elevation, spring SCP was less than winter SCP, while above 4000 m elevation, spring SCP was greater than winter SCP. (2) SCD, SCOD, and SCMD showed clear elevation gradients; within the basin, from northeast to southwest, they exhibited characteristics of increasing SCD, earlier SCOD, and later SCMD; in terms of variation trends, SCD decreased in 91.9% of the basin area, SCOD showed a trend of later onset in 65.6% of the area, and SCMD showed a trend of earlier melt in 77.4% of the area. (3) Snow cover area was anomalously large in 2006, 2008, and 2017, but anomalously small in 2010, possibly because ENSO affected snow cover variations. (4) In high-altitude regions dominated by the Karakoram, including parts of the eastern Pamir Plateau, SCD, SCOD, and SCMD exhibited trends of increase, earlier onset, and later melt, respectively; these changes were related to continuously decreasing spring and autumn temperatures and increasing precipitation.

Full Text

Preamble

Spatiotemporal Variation of Snow Cover in the Yarkant River Basin during 2002–2018

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Abstract: Snow cover is one of the most active elements in the cryosphere, highly sensitive to climatic and environmental changes. Its variations influence global climate and hydrological cycles, while surface mass and energy balances are primarily affected by snow-covered days (SCD), snow cover onset dates (SCOD), and snow cover melting dates (SCMD). Using MODIS daily cloud-free snow cover products, we extracted snow cover percentage (SCP) for the Yarkant River Basin from July 2002 to June 2018. Based on pixel-level calculations, we systematically analyzed the spatial distribution and variation characteristics of SCD, SCOD, and SCMD, and explored the causes of these changes and the relationship between anomalous snow cover area and ENSO. The results show that: (1) During the study period, basin-wide snow cover area exhibited a slight decreasing trend, with a significant negative correlation with temperature and a significant positive correlation with precipitation. SCP showed a clear linear increase trend with altitude ($R^2 = 0.92$, $P < 0.01$). The month of maximum SCP occurrence showed no significant change across elevations (concentrated in February), while the month of minimum SCP occurrence was delayed with increasing altitude. Below 4000 m, spring SCP was less than winter SCP, whereas above 4000 m, spring SCP exceeded winter SCP. (2) Significant elevation gradients were observed for SCD, SCOD, and SCMD. From northeast to southwest across the basin, SCD increased, SCOD was delayed, and SCMD advanced. In terms of trends, SCD decreased in 91.9% of the basin, SCOD was delayed in 65.6% of the area, and SCMD advanced in 77.4% of the region. (3) Snow cover area was abnormally large in 2006, 2008, and 2017, but abnormally small in 2010, likely due to ENSO events affecting snowfall and snow accumulation. (4) High-altitude regions dominated by the Karakoram Mountains, including parts of the eastern Pamir Plateau, showed increasing SCD, advancing SCOD, and delayed SCMD, changes associated with persistently low temperatures and increased precipitation in spring and autumn.

Keywords: Yarkant River Basin; snow-covered days; snow cover onset dates; snow cover melting dates

1. Study Area Overview

The Yarkant River Basin is located on the northwestern edge of the Tibetan Plateau, between 35°28 -39°45 N and 73°41 -78°47 E, covering a total area of 98,241 km^2. The basin features the Karakoram Mountains in the south, West Kunlun Mountains in the west, Pamir Plateau in the northwest, and the Taklamakan Desert margin in the east, with alluvial plains in the northeast. The terrain slopes from high elevations in the southwest to lower elevations in the northeast, with an average altitude of approximately 3,339 m. Based on geographic location and topography, the basin can be divided into two major climate zones: a plateau cold-arid semi-arid climate in the mountainous area and an arid semi-arid climate in the plains, characterized by dry conditions year-round. The basin hosts extensive glaciers (Figure 1, using data from China' s Second Glacier Inventory), with meltwater contributing 43.1% of the river' s multi-year average runoff, rainfall and snowmelt accounting for 22.6%, and groundwater contributing 13.4%. Surface observations indicate multi-year average temperatures range from 3.6 to 12.7 °C, and annual precipitation ranges from 57.3 to 78.8 mm. Controlled by westerly airflow, precipitation concentrates in winter and spring. The towering mountains and high-altitude cold storage cause precipitation to fall mainly as solid water, and the ability of high mountains to intercept atmospheric moisture provides abundant material for persistent snow development.

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2. Data and Methods

2.1 Data Sources

2.1.1 Snow Cover Data Snow cover data were obtained from the daily cloud-free snow product for the Tibetan Plateau [30], with a spatial resolution of 500 m and temporal coverage from July 2002 to June 2018, provided by the Chinese Academy of Sciences Data Center (http://www.csdata.org/en/p/). To validate the accuracy of MODIS snow cover data in the study area, we used Landsat OLI data (sourced from USGS, https://landsatlook.usgs.gov/viewer.html) with a spatial resolution of 30 m. Snow areas were extracted using the snowmap algorithm, and accuracy was assessed using coefficient of determination (R^2), bias, root mean square error (RMSE), and relative RMSE (rRMSE). Validation data were selected for scenes with cloud coverage less than 10% in the study area (path/row: 152/35) during the 2017-2018 snow season. Statistics showed good consistency between MODIS and Landsat OLI snow data, demonstrating that MODIS products can effectively reflect spatiotemporal snow distribution characteristics in the study area (Figure 2).

2.1.2 Meteorological Data Due to the limited number of meteorological stations in the study area, we used gridded meteorological data to study the influence of spatial variations in temperature and precipitation on snow distribution and changes. Data were obtained from the Climatic Research Unit (CRU) TS dataset (version 4.03, https://crudata.uea.ac.uk/cru/data/hrg/cru_{ts}4.03/), which provides monthly data at 0.5° × 0.5° resolution. Additionally, we used temperature and precipitation observations from Shache and Kashgar meteorological stations within the basin from July 2002 to June 2018 [China Ground Climate Daily Dataset (V3.0), from the National Meteorological Information Center, http://data.cma.cn/] to validate the CRU data. The correlation coefficient between station and CRU precipitation data reached 0.63-0.67, and for temperature data it was 0.92, indicating high accuracy and suitability for research needs.

2.1.3 DEM Data DEM data were obtained from the SRTM (Shuttle Radar Topography Mission) dataset, version SRTMGL1v003, with a spatial resolution of 30 m, provided by the US Geological Survey (USGS, https://lpdaac.usgs.gov/products/srtmgl1v003/). To analyze snow characteristics at different elevations and match the snow data resolution and projection, the DEM was resampled and reprojected to align with the snow cover data.

2.1.4 ENSO Index The Multivariate ENSO Index (MEI) was used to characterize El Niño-Southern Oscillation (ENSO) conditions (https://www.esrl.noaa.gov/psd/enso/mei/). Compared to other indices, MEI more completely and effectively describes the Niño 3.4 SST phenomenon, better reflects air-sea coupling characteristics, and is less affected by random errors from data updates [32]. This study used MEI to explore the relationship between snow cover anomalies and atmospheric circulation anomalies.

2.2 Methods

2.2.1 Extraction of Snow Cover Parameters Snow cover percentage (SCP) represents the relative snow cover area, calculated as the percentage of snow-covered area relative to the total basin area. Snow-covered days (SCD) represent the number of days with snow cover in a snow year. Snow cover onset dates (SCOD) represent the date of the first snowfall in a snow year, and snow cover melting dates (SCMD) represent the date when snow begins to melt. Based on the algorithm proposed by [33], we calculated SCOD and SCMD for each snow year. For this study, a snow year was defined from July 1 to June 30 of the following year.

Using daily snow cover products, we calculated SCP for the Yarkant River Basin and computed SCD, SCOD, and SCMD for each pixel. The specific formulas are as follows:

$$\mathrm{SCP} = \frac{P_s}{P} \times 100\%$$

$$\mathrm{SCD} = \sum_{i=1}^{n} S_i$$

$$\mathrm{SCOD} = F_{d1} - \mathrm{SCD}_1$$

$$\mathrm{SCMD} = F_{d2} + \mathrm{SCD}_2$$

where P_s represents the snow-covered area in the study region, P represents the total area of the study region, n represents the number of days in a snow year, S_i indicates a snow day (value of 1) or non-snow day (value of 0), F_{d1} is a fixed day in the cold season (set at day 336, as snowfall generally begins after this date), SCD_1 is the number of snow-covered days before F_{d1}, F_{d2} is a fixed day in the cold season (set at day 32, as snowmelt generally occurs after this date), and SCD_2 is the number of snow-covered days after F_{d2}.

2.2.2 Time Series Decomposition Since both snow cover and meteorological data are time series, decomposition is necessary to identify specific variation characteristics. The Seasonal-Trend decomposition procedure based on Loess (STL) is a commonly used method in meteorological and hydrological research that decomposes a time series Y into trend component T, seasonal component S, and remainder R to characterize variations at different scales [36]. For a time series Y, the decomposition at time i can be expressed as:

$$Y_i = T_i + S_i + R_i, \quad i = 1, 2, \cdots, n$$

In this study, STL decomposition was applied to SCP, temperature, and precipitation time series to analyze component characteristics and extract meaningful information.

2.2.3 Trend Analysis Methods We employed the non-parametric Mann-Kendall trend test and Theil-Sen median slope estimator for trend analysis at the pixel scale [37, 38]. The Mann-Kendall test is widely used for detecting trends in hydrometeorological time series, while the Theil-Sen estimator provides a robust slope estimation.

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3. Results and Analysis

3.1 Spatiotemporal Variation of Snow Cover Extent

Figure 3 shows the annual cycle of SCP in the Yarkant River Basin from 2002 to 2018. Snow accumulation began in October, slowly increasing until January, then rapidly growing to peak in February (35.94%). With spring warming, snow melted rapidly, reaching a minimum in August. Notably, SCP showed large fluctuations in winter, particularly in January, while summer fluctuations were relatively small, with the least variation in July.

To analyze interannual variation characteristics, we performed linear trend fitting on the SCP time series, obtaining a slope of -0.03%$\cdot$a^{-1}, indicating a slight decreasing trend in snow cover area from 2002 to 2018. STL decomposition of SCP, temperature, and precipitation time series revealed distinct seasonal patterns (Figure 4). The seasonal component of SCP showed clear cyclical behavior, with February as the peak period and August as the trough. The trend component revealed that snow cover area increased from 2002 to 2006, then sharply decreased from 2006 to 2010 as temperatures rose and precipitation declined. From 2010 to 2015, snow cover showed a weak fluctuating increase, followed by another sharp decrease to 2018 with rising temperatures and reduced precipitation. Overall, SCP showed consistent variation with precipitation but opposite variation with temperature.

Correlation analysis between monthly SCP and temperature/precipitation (Table 1) revealed a significant negative correlation with temperature ($r = -0.63$, $P < 0.01$) and a significant positive correlation with precipitation ($r = 0.47$, $P < 0.01$), indicating that snow cover area is influenced by both temperature and precipitation, with greater sensitivity to temperature.

The remainder component reflects snow cover fluctuations and can indicate extreme climate events. Figure 4 shows that SCP residuals were abnormally large in 2006, 2008, and 2017, but abnormally small in 2010, likely related to climate anomalies in these years.

SCP showed a clear elevation gradient, increasing linearly with altitude ($R^2 = 0.92$, $P < 0.01$). Snow-covered area followed a normal distribution centered on the 5200–5250 m elevation band (Figure 5). Analysis of multi-year average SCP variations across elevation zones revealed that higher altitudes had smaller intra-annual fluctuations. Above 6500 m, monthly SCP variations were minimal. Below 4000 m, spring SCP was less than winter SCP, while above 4000 m, spring SCP exceeded winter SCP, likely due to snow sublimation and wind redistribution causing significant snow loss at higher elevations in winter [49]. The maximum SCP month was generally delayed with increasing altitude: from November at 2000–3000 m to December at 3000–4000 m, January at 4000–5000 m, and February at 5000–6000 m. Minimum SCP consistently occurred in August across all elevation zones.

3.2 Spatiotemporal Variation of Snow Cover Parameters

The multi-year average SCD, SCOD, and SCMD from 2002 to 2018 showed distinct spatial patterns (Figure 7). SCD was largest in high-altitude glacier areas such as the Karakoram, West Kunlun, and eastern Pamir Plateau, with values exceeding 240 days. Low SCD areas were mainly distributed in lower-elevation river valleys and alluvial plains. SCOD showed a clear elevation gradient, with snow appearing earlier at higher elevations. Snow began accumulating in early September in high-altitude glacier regions of the Karakoram and eastern Pamir, gradually delaying to early November in lower-elevation river valleys and downstream areas. SCMD exhibited a northeast-to-southwest advancement pattern, with melting beginning in early March in lower valleys and downstream areas, progressively delaying to early June in high-altitude glacier regions.

Trend analysis revealed that 91.9% of the basin showed decreasing SCD, with significant reductions mainly in parts of the Pamir and West Kunlun regions. SCOD was delayed in 65.58% of the basin, though only 2.06% showed significant delay, primarily in the West Kunlun and eastern Pamir. SCMD advanced in 77.4% of the basin, with 2.06% showing significant advancement, mainly in the West Kunlun Mountains and eastern Pamir, while delayed SCMD occurred in high-altitude Karakoram regions and parts of the eastern Pamir Plateau.

Elevation-based analysis (Figure 8) showed that SCD increased with altitude, SCOD was delayed with altitude, and SCMD advanced with altitude. These patterns reflect the influence of topography and climate, with high-altitude glacier regions experiencing longer snow cover duration, earlier onset, and later melting.

3.3 Relationship Between Snow Cover Anomalies and ENSO

As identified in Section 3.1, snow cover area was abnormally large in 2006, 2008, and 2017, but abnormally small in 2010. To explore these anomalies, we analyzed the relationship between SCP residuals and MEI, as well as temperature and precipitation residuals (Figure 9). The results show that in 2006, 2008, and 2017, MEI values were continuously negative for several months, indicating La Niña events, while winter and spring temperatures were lower and precipitation was higher. Conversely, in 2010, MEI values were continuously positive, indicating an El Niño event, with higher temperatures and lower precipitation. This suggests that anomalous increases (decreases) in snow cover area may result from La Niña (El Niño) events influencing regional climate through atmospheric teleconnections, thereby causing snowfall and snow accumulation anomalies.

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4. Discussion

4.1 Atmospheric Circulation and Snow Cover Variation

Snow cover variation is primarily a result of large-scale atmospheric circulation or climate forcing [51], such as westerly circulation, monsoons, Arctic Oscillation, and Southern Oscillation. The Yarkant River Basin, located in the northwestern Tibetan Plateau, has snow distribution characteristics influenced by westerly airflow paths and water vapor transport. When upper-level westerly cold troughs pass over the northwestern Tibetan Plateau, they bifurcate due to topographic blocking: the northern branch bypasses the Tianshan Mountains, while the southern branch moves southward along the western side of the plateau. The Pamir Plateau in the west and the Karakoram Mountains in the southwest of the basin are located in the ascending motion region of the southern branch, receiving more precipitation that falls as snow at high altitudes, resulting in larger SCD. As air flows climb over these mountains and moves northeastward, remaining moisture decreases, causing lower precipitation and SCD in the northern mountains despite their high elevation [61].

Snow cover anomalies are closely related to atmospheric circulation anomalies. When circulation patterns change abnormally, they directly affect weather and climate, potentially triggering extreme climate events and causing snowfall and snow anomalies [55]. ENSO is the most typical example, with a quasi-period of 2-7 years, playing an important role in seasonal climate variations [57]. Studies show that atmospheric teleconnections alter temperature, precipitation, and atmospheric dynamics/thermodynamics, thereby affecting snow cover [52].

4.2 Snow Cover Variation and Climate Change

Snow cover variation is closely related to climate change, with temperature and precipitation as the main meteorological factors. Analyzing their spatial heterogeneity, variation characteristics, and relationship with snow cover is crucial for revealing the causes of snow distribution and change. Previous studies indicate that temperature is the primary factor affecting snow cover change, more so than precipitation [59]. Our correlation analysis shows that SCP has a stronger correlation with temperature than with precipitation in this region, confirming that temperature is the dominant factor influencing snow cover area variation in the Yarkant River Basin.

Affected by topography, the basin' s annual average temperature increases from southwest to northeast, while annual precipitation generally decreases from southwest to northeast. High-altitude mountainous regions dominated by the Karakoram (north slope), West Kunlun, and eastern Pamir have annual average temperatures below zero and annual precipitation totals above 200 mm. This spatial heterogeneity of temperature and precipitation creates a southwest-to-northeast decreasing pattern in SCD.

SCOD is determined by autumn precipitation and average temperature changes, while SCMD is determined by spring precipitation and average temperature changes. Correlation analysis between SCOD/SCMD and seasonal precipitation/temperature (Table 2) shows that SCOD is negatively correlated with autumn precipitation and positively correlated with autumn temperature, while SCMD is positively correlated with spring precipitation and negatively correlated with spring temperature. This indicates that increased autumn precipitation and decreased temperature advance SCOD, while increased spring precipitation and decreased temperature delay SCMD. As noted in previous research [16], even with warming temperatures, increased precipitation can lead to greater snow depth when temperatures remain below freezing.

Figure 10 shows that the eastern Pamir Plateau and southwestern Karakoram region exhibited slightly increasing autumn precipitation trends. Against a background of autumn average temperatures below zero, increased precipitation promoted greater snow depth, advancing SCOD. Similarly, spring precipitation increased in the Karakoram and eastern Pamir regions, with spring average temperatures below zero. The combination of low temperatures and increased precipitation enhanced snow depth, thereby delaying SCMD.

5. Conclusions

From 2002 to 2018, snow cover area in the Yarkant River Basin showed a slight decreasing trend, with significant negative correlation with temperature and significant positive correlation with precipitation. Seasonally, snow cover area peaked in February and reached its minimum in August. Spatially, SCP increased linearly with altitude ($R^2 = 0.92$, $P < 0.01$), with snow-covered area following a normal distribution centered on the 5200–5250 m elevation band. Below 4000 m, spring snow cover was less than winter snow cover, while above 4000 m, spring snow cover exceeded winter snow cover. The month of maximum SCP occurrence was delayed with increasing altitude, while the month of minimum SCP showed no significant change (concentrated in August).

Significant elevation gradients were observed for SCD, SCOD, and SCMD. Across the basin from northeast to southwest, SCD increased, SCOD was delayed, and SCMD advanced. From 2002 to 2018, SCD decreased in 91.9% of the basin, SCOD was delayed in 65.58% of the area, and SCMD advanced in 77.4% of the region.

Snow cover area was abnormally large in 2006, 2008, and 2017, but abnormally small in 2010, likely due to ENSO events affecting snowfall and snow accumulation anomalies.

High-altitude regions dominated by the Karakoram Mountains, including parts of the eastern Pamir Plateau, showed increasing SCD, advancing SCOD, and delayed SCMD. These changes were associated with persistently low temperatures and increased precipitation in spring and autumn, providing new insights for flood, debris flow, and snow disaster early warning in the Yarkant River Basin, and offering new references for rational utilization of ice and snow water resources.

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Note: Figure translations are in progress. See original paper for figures.