Spatiotemporal Variation Characteristics of Snow Cover End Dates in Xinjiang, 2000-2019 (Postprint)

Authors: Mekhmetjan Wijdan

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Abstract

Based on the Google Earth Engine (GEE) remote sensing cloud platform, MODIS snow cover product data from 2000-2019 were utilized to extract and calculate snow cover end date information for Xinjiang. Trend analysis, coefficient of variation, and other methods were employed to analyze the spatiotemporal variation characteristics and changing trends of snow cover end dates in Xinjiang. The results indicate: (1) Snow cover end dates in Xinjiang are demarcated by the Tianshan Mountains, with durations longer to the north than to the south. Mountainous areas constitute high-value regions for snow cover end dates, while basins represent low-value regions. In northern Xinjiang, the Junggar Basin and Ili River Valley exhibit snow cover end dates ranging from 75-114 d, whereas the Tarim Basin in southern Xinjiang, ranging from 0-31 d, belongs to low-value regions. The Altai Mountains, Tianshan Mountains, and Kunlun Mountains regions, with snow cover end dates of 224-365 d, belong to high-value regions. (2) Significant spatiotemporal differences in snow cover end dates exist between southern and northern Xinjiang. During 2000-2019, the Junggar Basin and high-altitude mountainous areas in northern Xinjiang demonstrated a significant delaying trend in snow cover end dates, with a delay magnitude reaching 14 d, accounting for 8% of Xinjiang' s total area. The Tarim Basin in southern Xinjiang and the eastern Xinjiang region exhibited a significant advancing trend, with an advance magnitude reaching 16 d, accounting for approximately 44% of Xinjiang' s total area. The Tarim Basin and Junggar Basin display opposite changing trends. (3) The interannual variation of snow cover end dates in Xinjiang shows substantial differences. The central Tianshan Mountains and northern Xinjiang exhibit unstable conditions in snow cover end dates. The central Tianshan Mountains from 2002-2009 generally display an "M-shaped" characteristic, i.e., obvious peaks and troughs appear in the multi-year mean values of snowmelt dates. Northern Xinjiang from 2009-2019 shows considerable interannual variation in snow cover end

dates, presenting unstable conditions with distinct peaks and troughs and large interannual variability.

Full Text

Temporal and Spatial Variation Characteristics of Snow Cover Cessation Day in Xinjiang from 2000 to 2019

Maihemutijiang WEIJIDAN[1], Yusufujiang RUSULI[1,2], QIU Zhongli[1]

[1]College of Geographic Science and Tourism, Xinjiang Normal University, Urumqi 830054, Xinjiang, China
[2]Xinjiang Key Laboratory of Lake Environment and Resources in Arid Zone, Xinjiang Normal University, Urumqi 830054, Xinjiang, China

Abstract

Based on the Google Earth Engine (GEE) remote sensing cloud platform, this study extracted and calculated snow cover cessation day information in Xinjiang using MODIS snow product data from 2000 to 2019. Temporal and spatial variation characteristics and trends were analyzed using trend analysis and coefficient of variation methods. The results show: (1) With the Tianshan Mountains as the boundary, snow cover cessation day in northern Xinjiang is longer than in southern Xinjiang. Mountainous areas are high-value regions for snow cover cessation day, while basins are low-value regions. The Junggar Basin and Ili River Valley in northern Xinjiang have snow cover cessation days of 75–114 days, the Tarim Basin in southern Xinjiang is a low-value area of 0–31 days, and the Altai Mountains, Tianshan Mountains, and Kunlun Mountains are high-value areas of 224–365 days. (2) There are obvious spatiotemporal differences in snow cover cessation day between southern and northern Xinjiang. From 2000 to 2019, the Junggar Basin and high-altitude mountains in northern Xinjiang showed a significant delaying trend with a delay of 14 days, accounting for 8% of Xinjiang' s total area. The Tarim Basin and eastern Xinjiang regions showed a significant advancing trend with an advance of 16 days, accounting for 44% of Xinjiang' s total area. The Tarim Basin and Junggar Basin show opposite trends. (3) Snow cover cessation day in Xinjiang varied significantly from year to year, with the central Tianshan Mountains and northern Xinjiang showing instability. The central Tianshan Mountains showed an overall "M" -shaped characteristic curve, with the annual average snow melting days showing obvious peaks and troughs during 2002–2009. Moreover, northern Xinjiang showed large interannual changes with instability during 2009–2019, with obvious peaks and troughs as well as large interannual variability.

Keywords: GEE cloud computing; snow cover cessation day; temporal and spatial distribution; change trend

1 Study Area Overview

Xinjiang is located in the center of the Eurasian continent, in the northwestern border region of China, spanning 73°45 -96°39 E and 34°34 -49°17 N, with a total area of approximately 1.66×10^{6} km^2. The Altai Mountains lie to the north, the Kunlun Mountains to the south, and the Tianshan Mountains traverse the central region, dividing Xinjiang into northern and southern Xinjiang. The Junggar Basin in northern Xinjiang and the Tarim Basin in southern Xinjiang, together with these three major mountain systems, form a unique "three mountains sandwiching two basins" geomorphological pattern (Fig. 1). Xinjiang has typical inland arid and semi-arid climate characteristics, with glacier and snow-covered mountains surrounding the basin margins and extensive deserts and lakes distributed within the basins. During the deep winter period, snow cover in Xinjiang reaches 181.8×10^{4} km^2, with the richest winter snow storage in China at 100×10^{8} m^3 water equivalent, accounting for 33.9% of the national average winter snow storage. The spatial and temporal distribution of precipitation across Xinjiang is uneven, with average annual precipitation of approximately 145 mm (about 100 mm in southern Xinjiang and 150–200 mm in northern Xinjiang) and evaporation of 2000–2500 mm, resulting in aridity. Due to its special geographical location, topography, and climatic conditions, Xinjiang's ecosystem is generally fragile and sensitive.

2 Data and Methods

2.1 Data Sources

Snow cover data: The MODIS snow product data used in this study were obtained from the National Snow and Ice Data Center (NSIDC) of the United States (https://nsidc.org/data/MOD10A1), comprising global daily snow cover products from the MODIS/Terra sensor with a spatial resolution of 500 m. Snow cover is identified using the Normalized Difference Snow Index (NDSI) and a series of algorithms designed to reduce errors and flag uncertain snow detection results. The snow cover cessation day is defined as the date of the last snow occurrence each year, specifically the date when no pixels on land surfaces are identified as snow-covered. The study defines a snow year as ending on August 31.

Topographic data: The elevation data were derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM V2.0), a product completed through collaboration between NASA and Japan's Ministry of Economy, Trade and Industry (METI). The elevation data underwent projection conversion and resampling to a unified 500 m spatial resolution, matching that of the snow cover data and the projection system.

2.2 Research Methods

The snow cover cessation day parameters in this study were identified on a pixel-by-pixel basis using the Google Earth Engine platform. Google Earth Engine is a cloud-based platform for Earth observation data analysis. Users can access the platform after registering at https://earthengine.google.com. On this platform, MOD10A1 products are used and regularly updated along with other satellite images and products (e.g., Landsat, Sentinel-1, Sentinel-2) globally. Raster and vector data not directly available can also be easily extracted.

Remote sensing data processing: Based on the GEE cloud platform, time-series remote sensing data were rapidly acquired and preprocessed according to image acquisition time and quality, including cloud and shadow masking, mosaicking, and clipping. This study calculated annual snow cover cessation day on a pixel basis. The final statistical analysis was performed after several processing steps: masking pixels rarely covered by snow, analyzing only pixels with snow cover during the current year, and masking pixels with long-term snow cover (snow-covered days within a year).

Linear trend analysis: A unary linear regression model can simulate temporal changes in snow cover cessation day for each pixel in space. The slope represents the trend of snow cover cessation day change over time and is calculated using the least squares method:

$$\text{Slope} = \frac{n\sum_{i=1}^{n}(i \cdot p_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} p_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where n is the cumulative number of years, p is the snowmelt time value in year i, and Slope is the slope of the unary linear regression equation. A positive Slope indicates a delaying trend in snow cover cessation day over time, while a negative value indicates an advancing trend.

Coefficient of variation method: The coefficient of variation (Cv) was used to analyze the stability of spatial pattern changes in annual snow cover cessation day across the study area. Cv is an important indicator reflecting the degree of variation in observed values, calculated as the ratio of standard deviation to the multi-year average:

$$C_v = \frac{\sigma}{\mu}$$

where σ is the standard deviation of each grid cell and is the multi-year average of snow cover cessation day.

In this study, the programming language was used based on an integrated development environment to calculate snow cover cessation day parameters. Code development, including data extraction, preprocessing, snow cover cessation day calculation, statistical analysis, and final map export, was conducted on the platform. Due to the potentially intensive computation of long time-series daily data for Xinjiang, a hierarchical solution was adopted. First, dynamic data processing was used for code development and debugging. Second, annual snow products and products from different periods within each year were saved separately, followed by final statistical analysis of these files.

3 Results and Analysis

3.1 Spatial Variation Characteristics of Snow Cover Cessation Day in Xinjiang

Based on the distribution of snow cover cessation day, Xinjiang was divided into three regions for spatial analysis: northern Xinjiang, southern Xinjiang, and the central Tianshan Mountains. The spatial distribution of snow cover cessation day in Xinjiang from 2000 to 2019 showed significant differences, generally presenting a pattern where northern Xinjiang had later snow cover cessation than southern Xinjiang, and mountainous areas had later cessation than basins. The spatial distribution patterns of these two regions were distinctly different. The Altai Mountains, Ili River Valley, western Tianshan Mountains, and Kunlun Mountains had significantly later snow cover cessation days (299–365 days) than other regions. The Junggar Basin and Ili River Valley in northern Xinjiang had snow cover cessation days of 76–152 days, clearly later than southern Xinjiang. Hami and the Tarim Basin in southern Xinjiang had significantly earlier snow cover cessation days (0–31 days) than northern Xinjiang. With climate warming, snow cover cessation days showed different changes in northern Xinjiang versus southern Xinjiang and in mountainous areas versus basins. Snow cover cessation days in the Tarim Basin and eastern Xinjiang gradually advanced from 2003, while those in the Junggar Basin and Ili River Valley gradually delayed. High-altitude mountainous areas in both northern and southern Xinjiang also showed delaying trends, demonstrating that snow cover cessation day varies with different altitudes and latitudes.

3.2 Comparison of Initial and Final Changes in Snow Cover Cessation Day

By selecting data from 2000 and 2019 and calculating their differences, the variation in snow cover cessation day between the beginning and end of the study period shows significant differences. Overall, snow cover cessation day in the Tarim Basin, Altai Mountains, and eastern Xinjiang in 2019 was earlier than in 2000, while the Junggar Basin, central Tianshan Mountains, and Kunlun Mountains showed significant delays compared to 2000. The spatial distribution patterns of the Junggar Basin and Tarim Basin are opposite: the Tarim Basin had earlier snow cover cessation in 2019 than in 2000, while the Junggar Basin was later. Northern and southern Xinjiang, as well as high-altitude mountainous areas and basins, show opposite change characteristics. In the difference of snow cover cessation day between 2000 and 2019, areas with advanced snow cover cessation account for 44% of Xinjiang' s total area, while delayed areas account for 8%, and basically unchanged areas account for 33.57%.

3.3 Trend Analysis of Snow Cover Cessation Day in Xinjiang

The spatial distribution of snow cover cessation day trends over the past 20 years shows that snow cover cessation day has a delaying trend in the western and southern Junggar Basin, Altai Mountains, Tianshan Mountains, and parts of the Kunlun Mountains high-altitude areas, with a maximum delay of 75–114 days, accounting for 8% of Xinjiang' s total area. The central Junggar Basin, western Ili River Valley, and eastern Tarim Basin remain basically unchanged, accounting for 33.57% of the total area. Snow cover cessation day shows an advancing trend in the Tarim Basin, eastern Xinjiang, northern Junggar Basin, southern Tianshan slopes, and some high-altitude areas. Areas with slight and significant advancement account for approximately 40.31% of Xinjiang' s total area. Significantly advanced areas are mainly distributed on southern Tianshan slopes, northwestern Tarim Basin, and eastern Xinjiang, with an advancement of 70–80 days. Overall, the area with advancing trends in Xinjiang' s snow cover cessation day is significantly larger than that with delaying trends.

3.4 Interannual Variation Degree of Snow Cover Cessation Day

Xinjiang' s snow cover cessation day shows predominantly moderate interannual variation. The coefficient of variation (Cv) was classified into three intervals: slight variation, moderate variation, and significant variation (Table 1). Areas with significant variation account for 26.12% of Xinjiang's total area, mainly distributed in southern Xinjiang. Areas with slight variation account for 33.57%, mainly distributed in northern Xinjiang. Areas with moderate variation account for 40.31% of the total area. Thus, Xinjiang' s snow cover cessation day has been unstable in recent years, with the greatest volatility in southern Xinjiang, moderate volatility in eastern Xinjiang, and slight volatility in northern Xinjiang.

Table 1 Classification of Cv spatial distribution of interannual snow cover cessation day in Xinjiang

Cv Value Range	Variation Classification
$0.037 < Cv \leq 1.038$	Slight variation
$1.038 < Cv \leq 2.320$	Moderate variation
$2.320 < Cv \leq 4.514$	Significant variation

Note: Cv is the coefficient of variation.

3.5 Annual Average Temporal Variation Characteristics

Based on snow cover cessation day data for the central Tianshan Mountains, northern Xinjiang, and southern Xinjiang, the annual average values were calculated for each region. The central Tianshan Mountains show an "M"-shaped fluctuation characteristic, with annual average values increasing from 2000, peaking in 2002, decreasing to a low in 2009, and then showing unstable conditions. Northern Xinjiang' s annual average snow cover cessation day remained relatively stable from 2000 to 2009, then became unstable from 2009 to 2019, with rapid decrease to a low level followed by increase to a high level. Southern Xinjiang' s annual average values increased from 2000, peaked in 2002, then gradually decreased, showing unstable conditions from 2009 (Fig. 6).

3.6 Relationship Between Snow Cover Cessation Day and Altitude

Analysis of the relationship between Xinjiang' s annual average snow cover cessation day and altitude shows significant differences among southern Xinjiang, northern Xinjiang, and the central Tianshan Mountains at different elevations (Fig. 7). Most snow cover cessation days in northern Xinjiang are distributed at altitudes of 150-1000 m, with values of 60-90 days, increasing with altitude. In southern Xinjiang, most snow cover cessation days are distributed at altitudes of 900-1000 m, with values of 0-25 days. Some areas show increasing snow cover cessation with altitude, but most high-altitude areas have values of 0-20 days, closely related to precipitation airflow sources. In the central Tianshan Mountains, areas with less precipitation have snow cover cessation days mainly at 500-1500 m altitude, while high precipitation areas show significant increase in snow cover cessation days with altitude, primarily appearing at 200-1500 m altitude with values of 75-100 days. The linear correlation between snow cover cessation day and altitude is strongest in northern Xinjiang, moderate in the central Tianshan Mountains, and weakest in southern Xinjiang.

4 Discussion

This study analyzed the temporal and spatial distribution characteristics of snow cover cessation day in Xinjiang using only remote sensing time-series data. Future work should focus on combining snow remote sensing data with other auxiliary materials to conduct in-depth research on snow cover period and snow depth changes and trends. Additionally, the reasons and formation mechanisms for the "M" -shaped characteristic of annual average snow cover cessation day values are not yet clear and require further investigation. This study only analyzed the temporal and spatial variation characteristics of annual snow cover cessation day; future research should include correlation studies between meteorological factors at annual and seasonal scales and snow cover cessation day. Longer time-series snow data are also needed for more in-depth research on the response relationship between Xinjiang' s snow cover cessation day variation patterns and climatic factors.

From the trend analysis of Xinjiang' s snow cover cessation day from 2000 to 2019, areas with advanced snow cover cessation account for 44% of Xinjiang' s total area, mainly distributed in the Tarim Basin and eastern Xinjiang. Delayed areas account for 8%, mainly distributed in the Altai Mountains, western Junggar Basin, central Tianshan Mountains, and high-altitude mountainous areas of northern and southern Xinjiang. Unchanged areas account for 33.57%, mainly in the central Junggar Basin. The Tarim Basin and Junggar Basin show opposite trends. From the perspective of interannual variation degree, Xinjiang' s snow cover cessation day has shown instability in recent 20 years; by geographic location, northern Xinjiang shows slight variation, southern Xinjiang shows the greatest volatility, and eastern Xinjiang shows moderate variation. This instability may be related to Xinjiang' s special terrain, geomorphology, and research data acquisition time series. To some extent, this reflects not only the instability of intra-annual variation in Xinjiang' s snow cover cessation day but also the regional particularity of snow cover changes in different areas. Regarding the relationship between annual average snow cover cessation day and altitude, snow cover cessation days in southern Xinjiang, northern Xinjiang, and the central Tianshan Mountains show significant differences at different altitudes, mainly related to precipitation airflow sources. Against the background of global climate warming, Xinjiang' s climate is also experiencing significant warming, and the impact of global climate warming on snow cover cessation day in different regions of Xinjiang varies.

5 Conclusions

(1) **Spatially**, snow cover cessation day in Xinjiang from 2000 to 2019 showed obvious spatial differentiation characteristics, with the spatial distribution demonstrating a pattern of northern Xinjiang > southern Xinjiang and eastern > western regions. The Altai Mountains, Ili River Valley, Junggar Basin, central Tianshan Mountains, and high-altitude areas of southern Xinjiang have longer snow cover cessation days, while Hami and low-altitude areas of the Tarim Basin have shorter snow cover cessation days. The distribution of snow cover cessation day in northern Xinjiang is significantly longer than in southern Xinjiang. According to multi-year changes, snow cover cessation day in the Tarim Basin gradually shortened from 2003, while that in northern Xinjiang gradually lengthened, showing obvious changes from the multi-year average distribution.

(2) **Temporally**, the annual average snow cover cessation day changed significantly in northern Xinjiang and the central Tianshan Mountains from 2000 to 2019. The central Tianshan Mountains showed an "M" -shaped fluctuation pattern, with average values at high levels in 2002 and low levels in 2009. Northern Xinjiang' s annual average rapidly decreased to low levels in 2009 and reached high levels in 2015. In northern Xinjiang, snow cover cessation day lengthens with increasing altitude, while the correlation between snow cover cessation day and altitude is more complex

in southern Xinjiang and the central Tianshan Mountains.

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