Postprint: Response of Snow Cover Ablation on the Mongolian Plateau to Air Temperature

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Abstract

Using MODIS snow cover product data, this study investigated the spatiotemporal variation characteristics of the snowmelt period on the Mongolian Plateau from 2003 to 2022, and tracked the movement of the snowmelt line toward higher latitudes at 15-day intervals and its response to air temperature. The results show: (1) From 2003 to 2022, snow cover accounted for 55.59%~87.61% of the total area of the Mongolian Plateau. Among these years, the snow cover area was smallest in 2018 and largest in 2009. Additionally, temporally, over the past 20 years, the snowmelt timing on the Mongolian Plateau showed a significant advancing trend at a rate of 0.18 d·(10a)-1 ($P<0.05$), while stable snow cover areas showed a delaying trend. (2) Spatially, the snowmelt timing in the northern regions of the Mongolian Plateau was significantly later than in the southern regions. Stable snow cover areas were mainly distributed in the western part of Mongolia and the northeastern part of Inner Mongolia, where snowmelt timing was generally later, with 64.9% of these areas showing an advancing trend. (3) Through observational studies at half-monthly scale during winter on the Mongolian Plateau (starting from January), it was found that the movement trends of the snowmelt line and the -5 ℃ and 0 ℃ isotherms successively exhibited synchrony. Moreover, the correlation between snowmelt line position and temperature was consistently in a high range of 0.72~0.98, except for 2018, indicating that temperature is a key factor influencing the position of the snowmelt line.

Full Text

Preamble

Snowmelt Response to Air Temperature on the Mongolian Plateau

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Abstract: Using MODIS snow product data, this study investigates the spatiotemporal variation characteristics of the snowmelt period across the Mongolian Plateau during the 2003–2022 hydrological years, tracking the poleward movement of the snowmelt line at 15-day intervals and its response to air temperature. The results show that: (1) The proportion of snow-covered area to the total plateau area ranged from 55.59% to 87.61%, with the minimum snow cover occurring in 2018 and the maximum in 2009. Additionally, over the past 20 years, the snowmelt end date on the Mongolian Plateau exhibited a significant advancing trend at a rate of 0.18 $d \cdot (10a)^{-1}$ ($P < 0.05$), while snowmelt occurred significantly later in northern regions than in southern areas. Stable snow cover zones were primarily distributed in western Mongolia and northeastern Inner Mongolia, where snowmelt times were generally later. (2) Spatially, approximately 64.9% of the stable snow cover area showed an advancing trend, while regions with delaying trends were mainly concentrated in the northwestern part of the study area. (3) Through half-monthly scale observations from winter (starting January) across the plateau, the movement of the snowmelt line and isotherms demonstrated successive synchronization. The correlation between snowmelt line position and temperature remained in a high range of 0.72–0.98 for all years except 2018, indicating that temperature is a key factor influencing snowmelt line position.

Keywords: snow end day; snowmelt line; isotherm; temperature response; Mongolian Plateau

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Introduction

Snow cover, as one of the most sensitive climate elements to global warming, plays a crucial role in regional and global water cycles and climate systems. Over the past century, Earth has experienced significant warming, particularly after 1990, with an accelerated warming rate. According to the IPCC Sixth Assessment Report "Climate Change 2023," global surface temperature has risen by 1.1°C compared to pre-industrial levels, with unprecedented changes in climate systems affecting all regions worldwide. The direct impact of rising temperatures is the reduction of snow cover area and changes in snow phenology, including snow onset date (SOD), snow end date (SED), and snow duration days (SDD). These changes affect snowmelt runoff cycles, increase rain-to-snow ratios (more precipitation falling as rain rather than snow), reduce streamflow, and cause habitat loss for certain species in high-latitude ecosystems. Among these, SED is one of the most intuitive and critical indicators of climate warming impacts on Earth' s surface.

Previous studies have shown that most regions in the Northern Hemisphere have experienced decreasing snow cover trends in recent years, which affects agricultural irrigation districts dependent on snowmelt water and consequently impacts food production and regional socioeconomic development. Research methods for snow phenology at regional or global scales can be categorized into two main types: ground observation based on meteorological station data, and remote sensing retrieval based on satellite observations. The former relies on long-term snow records from meteorological stations, offering high accuracy but limited spatial coverage and significant discontinuities. The latter obtains large-scale snow dynamics information through satellite remote sensing, offering advantages in broad coverage and timeliness. With the public release of high spatiotemporal resolution satellite remote sensing data products such as MODIS, significant progress has been made in regional-scale seasonal snow phenology research, revealing spatiotemporal distributions of snow phenology, snow water equivalent, and snow depth, as well as their relationships with climate change.

Numerous studies have quantified snow phenology changes across various regions. For example, research using passive microwave remote sensing snow depth data from 1980–2017 on the Tibetan Plateau revealed advancing trends in SED at high latitudes and high altitudes in the Northern Hemisphere, while mid-latitude regions showed relative delays. Other studies using MODIS data have documented significant advances in snow cover area proportion and SED in Northern Xinjiang from 1980–2019, though SOD and snow cover duration showed no significant changes. In Northeast China, significant decreasing trends in snow cover and duration were observed from 1980–2020. In the Yurungkax River Basin of the West Kunlun Mountains, temperature was found to be the main factor affecting snow area changes in spring and summer at low elevations, while precipitation dominated at high elevations in winter and spring.

The Mongolian Plateau is located deep inland, far from oceans, with limited water vapor transport, strong evaporation, and a typical arid to semi-arid climate, nurturing an ecosystem dominated by temperate grasslands and desert steppes. During the dry and low-precipitation spring, rising temperatures cause extensive snowmelt while soil layers remain frozen, preventing infiltration. With low vegetation coverage and minimal evapotranspiration, meltwater flows into rivers, becoming an important water source for local lakes and rivers. Studies show that lakes on the Mongolian Plateau have exhibited significant reductions in number and area, decreasing by 1443.92 km^2 overall. Therefore, studying snowmelt dynamics on the Mongolian Plateau is crucial for understanding spatiotemporal evolution trends of water resources and the convergence effects between temperature and snow cover under deepening climate change.

Although recent research has gradually focused on spatiotemporal changes in snow phenology on the Mongolian Plateau and its relationship with climate variability, the latitudinal movement characteristics of snowmelt dynamics and its association and synchronization with different isotherms remain unclear, making it difficult to visually present the poleward and upward migration process of snowmelt.

This study utilizes daily MODIS snow products MOD10C1 and MYD10C1, processed through maximum value composition and masking to obtain daily snow cover data for the study area. Combined with ERA5-Land reanalysis temperature data, we analyze spatiotemporal variations in snow distribution area and SED from 2003-2022, and examine the response process of the snowmelt line to temperature at the pixel scale.

1.1 Study Area Overview

The Mongolian Plateau is situated in central Asia, located between 37°22 -53°20 N and 87°43 -126°04 E. Topographically, it extends from the Mongolian Altai Mountains in the west to the Greater Khingan Mountains in the east, bounded by the Sayan and Khentii Mountains in the north, with the vast Gobi Desert to the south, demarcated by the Yinshan Mountains. The main area includes the entire territory of Mongolia and China' s Inner Mongolia, covering approximately 2.75$\times 10^{6}$ km^2. The plateau is characterized by high plains and mountainous terrain with an average elevation of 1580 m, increasing from east to west. It has a temperate continental climate with an average annual precipitation of about 200 mm, transitioning from arid to semi-arid zones from west to east.

1.2 Data Sources

1.2.1 MODIS Snow Data The data sources for this study are MODIS snow products MOD10C1 and MYD10C1, both with a spatial resolution of 0.05°$\times$0.05° *andtemporalresolutionofoneday.Thesetwoproductsobservethesameregiontwicedaily(morninga*
dailyglobalsnowextentmap, dailysnowmapclearindex, dailycloudobscurationpercentage, andgeneralQAofdat
pixel, ranging from 0-100, where 0 indicates no snow cover and 100 indicates complete snow cover.

Considering that high-altitude areas of the Mongolian Plateau typically begin receiving snowfall after approximately day 244 (early September) and snow generally melts completely by mid-May of the following year, this study defines a hydrological year from day 244 to day 243 of the following year. Global daily snow extent data from 2003-2022 were selected for snow phenology identification (data from 2010 were excluded due to missing and discontinuous records). To reduce impacts from cloud cover and atmospheric factors, maximum value composition was applied to MOD10C1 and MYD10C1 data, which were then clipped along the Mongolian Plateau boundary to obtain final daily snow cover data for the study area.

1.2.2 Meteorological Data Meteorological data were obtained from the ERA5-Land reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts' Copernicus Climate Change Service. This dataset spans from January 1981 to present with a spatial resolution of 0.1°. Compared to its predecessor ERA5 (0.25° monthly single-level data) and earlier climate research datasets (0.50°), ERA5-Land shows significant improvements in spatial resolution and data accuracy. ERA5-Land employs a tiled scheme for land surface exchange that has proven suitable for ground modeling. This study utilized 2-meter air temperature data from this dataset, processed through online data extraction, conversion to daily data, clipping, and conversion from Kelvin to Celsius to obtain daily temperature spatial distribution data for analyzing snow response to temperature.

1.3 Methods

1.3.1 Snow Phenology Analysis To reduce potential errors from clouds and "temporary snow" that is thin, prone to melting, or wind-drifted, and considering the actual spatial distribution of precipitation on the Mongolian Plateau (with annual precipitation below 100 mm in the southwestern Gobi Desert, and some areas even below 50 mm), this study recorded pixels with snow cover percentage ≥ 4 as snow-covered and set their value to 1, while pixels with < 4 were recorded as snow-free and set to 0. The proportion of snow-covered area each year was calculated by counting snow pixels relative to total pixels in the study area. Following Yuan Zhihui' s method, SED was defined as the maximum day-of-year (DOY) when snow cover was identified at a pixel, SOD as the minimum DOY, and SDD as the number of days between SED and SOD. The formulas are:

$$SED = \max\{j|S(j) = 1\}$$

$$SOD = \min\{j|S(j) = 1\}$$

$$SDD = SED - SOD$$

where i represents the DOY from 1–365 in a hydrological year, j represents the DOY from 244 to 243 of the following year, and n represents the number of snow cover days.

1.3.2 Trend Analysis To analyze the changing trend of SED on the Mongolian Plateau from 2003–2022, linear regression was performed between SED and year, with the regression slope representing the change rate (interannual variation rate). The formulas are:

$$b = \frac{n\sum_{i=1}^{n} iy_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where b is the linear regression trend slope. A positive slope indicates a delaying trend, while a negative slope indicates an advancing trend; n is the time series length (20 years in this study); and y_i is the SED value in year i. The F-test was applied to assess trend significance, with trends classified as: significantly delaying ($b > 0,\ P < 0.05$), significantly advancing ($b < 0,\ P < 0.05$), non-significantly delaying ($b > 0,\ P > 0.05$), and non-significantly advancing ($b < 0,\ P > 0.05$).

1.3.3 Synchronization Analysis Between Isotherms and Snowmelt Line In previous studies, the concept of the snowmelt line has been defined differently depending on application. In this paper, it is defined as the boundary between snow-covered and snow-free areas. To systematically analyze the response mechanism of snowmelt processes to temperature changes on the Mongolian Plateau, this study examines the dynamic coupling between the snowmelt line and isotherms.

Regarding temporal scale selection: if the interval is too short, spatial fluctuations of isotherms are limited, making it difficult to capture effective change characteristics; if too long, temporal lags may occur between temperature field evolution and snowmelt boundary advancement, weakening dynamic correlations. Therefore, this study adopts a half-monthly time scale. Starting from the last day of the hydrological year, a sliding window with 15-day steps forward identifies the first occurrence where at least one daily snow cover event is recorded (value = 1), which is recorded as SED. Similarly, starting from day 244 of the hydrological year, a backward sliding window with 15-day steps identifies the first occurrence of snow cover (value = 1), defined as SOD for that pixel.

Isotherms are drawn based on the half-monthly average temperature data, reflecting spatial distribution characteristics of thermal conditions during that period. This temporal scale selection ensures effective characterization of regional thermal gradients by isotherms while accurately capturing progressive changes in snowmelt boundaries following temperature accumulation effects, providing a suitable analytical framework for revealing spatiotemporal coupling patterns between snowmelt processes and temperature fields.

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2 Results

2.1 Temporal Variation Characteristics of SED

Figure 2 shows the proportion of snow-covered pixels to total plateau pixels on the Mongolian Plateau from 2003–2022. Over the past 20 years, the proportion of snow-covered area has shown considerable interannual variability. The smallest snow cover occurred in 2018, accounting for 55.59% of the study area, while the largest occurred in 2009, reaching 87.61%. Overall, SED showed a significant advancing trend at a rate of 0.18 d · $(10a)^{-1}$ ($P < 0.05$), concentrated between days 155-235 (early June to late August), with the earliest SED in 2018 (day 184) and the latest in 2009 (day 203).

2.2 Spatial Variation Characteristics of SED

Figure 3 presents the multi-year average SED spatial distribution and corresponding snowfall frequency across the Mongolian Plateau from 2003-2022. Overall, SED shows a distinct pattern of earlier melting in the south and later melting in the north, primarily concentrated in June–August (days 155-235). The southern Mongolian Plateau is climatically arid with low precipitation and overall less frequent snowfall over the years. Moving northward, conditions become increasingly humid with more abundant snowfall, and combined with lower temperatures compared to the south, SED occurs progressively later. Due to annual variations in snow-covered area size, distribution, and location, the years with maximum (2009) and minimum (2018) snow cover are selected for detailed spatial distribution analysis.

In 2009 (the year with maximum snow cover), SED showed strong spatial heterogeneity, with areas north of 45°N generally later, typically after day 195 (mid-July). These later regions accounted for 42.74% of the total area, mainly distributed in high-altitude mountainous areas such as the Mongolian Altai, Sayan, Hangay, and Khentii Mountains, as well as the open grassland regions of eastern Mongolia and the Hulunbuir area of northeastern Inner Mongolia with richer precipitation. In 2018 (the year with minimum snow cover), SED was relatively earlier, mainly concentrated between days 193-238 (mid-July to late August), with an average of day 217. The snow-free area increased by 44.4%, distributed in central and southern plateau regions.

For the stable snow cover area (pixels with snow cover every year), the multi-year average SED and its trend are shown in Figure 3e–f. Stable snow zones are mainly concentrated in high-latitude, high-altitude regions of northwestern Mongolia and the humid northeastern areas, with an average SED 27 days later than the entire Mongolian Plateau. In terms of trends, 64.9% of the stable snow area showed a significant advancing trend, primarily distributed in western Hulunbuir and northern Mongolia, while 35.1% showed a delaying trend, mainly in western Mongolia and northeastern Inner Mongolia. The significant latitudinal and altitudinal differences across the Mongolian Plateau create varying climate conditions that result in uneven snow distribution, making spatial analysis of stable snow zones particularly important.

2.3 Movement of Snowmelt Line and Isotherms

Considering that snowmelt generally begins in spring, this study employs a half-monthly scale, selecting SED spatial distribution maps from January to May of the following year across the 20-year period to analyze dynamic coupling between isotherms and the snowmelt line.

From day 274 (early January), the -5°C isotherm gradually emerges from the southern plateau, while snowmelt areas appear sporadically. During this phase, the -5°C isotherm and snowmelt line show no synchronization. Starting day 304 (early February), large-scale snowmelt begins in northern Mongolia with substantial temperature increases, and the snowmelt line gradually synchronizes with the -5°C isotherm. Notably, the -2°C isotherm appears during this period but does not synchronize with the snowmelt line in early stages, likely because accumulated temperature remains insufficient for snowmelt. From day 334 (early March) to day 4 (mid-March), the -2°C isotherm and snowmelt line begin showing synchronization. It is worth noting that regions with snow duration >80 days and annual precipitation >200 mm more readily exhibit synchronization between isotherms and the snowmelt line, while areas with snow duration <80 days and precipitation <200 mm do not.

During days 19–34 (late March to early April), snowmelt areas are small and scattered, mainly in high-altitude mountainous regions such as the Altai and Hangay Mountains, with the snowmelt line still synchronizing with the -5°C isotherm. From days 49–64 (mid-to-late April), the -2°C isotherm begins moving poleward, and the snowmelt line gradually aligns with it while diverging from the -5°C isotherm, indicating that snowmelt processes during this stage primarily follow the -2°C isotherm movement.

Figure 4 shows the spatial distribution characteristics of SED at 15-day intervals over the past 20 years, along with isotherms, annual cumulative precipitation, and SDD. The -5°C and 0°C isotherms demonstrate highly consistent northward movement trends with the snowmelt line. This phenomenon essentially reflects enhanced convergence effects from deepening climate change—continuous temperature increases cause boundaries of different thermal zones (snowmelt line, isotherms) to become spatially coupled, representing a coordinated regional climate system response to warming and providing direct evidence for systematic climate change impacts.

Figure 5 illustrates the latitudinal and longitudinal movement of the half-monthly snowmelt line and 0°C isotherm. All three lines show significant upward trends in latitude, moving overall from south to north, with the 0°C isotherm moving fastest at approximately 2.147° northward per half-month. In longitude, both isotherms show significant downward trends, moving overall from east to west, with the 0°C isotherm moving fastest at approximately 2.086° westward per half-month. The latitudinal movement trend of the 0°C isotherm more closely matches the snowmelt line than the longitudinal trend.

Figure 6 shows the geodesic distance between the half-monthly snowmelt line and adjacent -5°C and 0°C isotherms. The shortest distance between the snowmelt line and isotherms gradually decreases, reflecting the progressive warming process. The isotherms move poleward faster than the snowmelt line, particularly during early May when distance reduction is most significant, indicating rapid temperature increases. In early-to-mid May, distances between the snowmelt line and both isotherms become minimal, with the 0°C isotherm showing the most synchronous movement.

Figure 7 presents the correlation between half-monthly mean air temperature and snowmelt line latitude on the Mongolian Plateau from 2003–2022. Excluding 2018 (the year with minimum snow cover), R^2 values range between 0.72–0.98, demonstrating that temperature is a crucial factor influencing snowmelt line latitude. Higher mean temperatures correspond to higher average latitudes of the snowmelt line, with the highest correlation in 2009 ($R^2 = 0.9702$) and the lowest in 2018 ($R^2 = 0.6461$). Years with R^2 between 0.7–0.8 correspond to periods when the snowmelt line and 0°C isotherm showed the most synchronous movement. This indicates that less snow cover results in weaker temperature response patterns.

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3 Discussion

This study analyzed spatiotemporal variation characteristics of SED and its response to temperature on the Mongolian Plateau using MODIS daily snow products and ERA5-Land reanalysis data. Although snowmelt processes on the Mongolian Plateau primarily change with the movement of the -2°C isotherm, the critical temperature for snowmelt is between -5°C and -2°C. This phenomenon may involve multiple factors including geographic location shifts, latent heat requirements, and differences between actual snow surface temperature and air temperature. Additionally, the snowmelt line and isotherms show synchronous movement in northern study areas, while southern inland regions with Gobi and deserts exhibit asynchronous movement due to low precipitation (<200 mm), thin winter snowpack, and short snow duration.

The spatial distribution pattern of SED results from combined effects of topography, latitude, and climate, particularly precipitation patterns. Water vapor from the Arctic Ocean and Pacific Ocean easily converges in northern Mongolia, resulting in relatively abundant snow cover. Additionally, high latitudes lead to later SOD, limiting solar radiation during snow cover periods as most radiation is reflected by snow, further lowering surface temperatures. In contrast, central and southern Gobi and desert regions, located deep inland with scarce precipitation and higher temperatures, experience earlier SED due to snow sublimation and evaporation. This spatial pattern aligns with findings from Sun et al. and Li et al. regarding snow phenology on the Mongolian Plateau.

To comprehensively analyze spatiotemporal characteristics of snow end dates, this study further examined stable snow cover zones. Results show that 64.9% of stable snow areas exhibited advancing trends, mainly in western Hulunbuir and northern Mongolia, consistent with Zhang' s findings and likely related to accelerated snowmelt from climate warming. Stable snow zones are concentrated in high-altitude regions of northwestern Mongolia and the Greater Khingan Mountains in northeastern Inner Mongolia, with average SED of day 227—27 days later than the overall plateau average. In these regions, 64.9% showed advancing trends while 35.1% showed delaying trends.

Numerous studies have shown that snow phenology changes are influenced by temperature and precipitation, but few have investigated how snowmelt processes change with critical temperatures. Snow cover is a comprehensive product of temperature and precipitation, and its development and maintenance depend on temperature. This study found that snowmelt trends show clear latitudinal variation characteristics with the movement of the -2°C isotherm. As the Mongolian Plateau warms from south to north, the -5°C isotherm first appears at the southernmost edge, with snowmelt areas initially scattered and showing no association with isotherm movement. By early February, the snowmelt line gradually synchronizes with the -5°C isotherm. From early March, the -2°C isotherm appears and the snowmelt line gradually aligns with it. The period from early March to early May shows the most synchronous movement between the snowmelt line and 0°C isotherm.

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4 Conclusions

Using MODIS snow product data and ERA5-Land temperature reanalysis data, this study analyzed spatiotemporal distribution characteristics of snowmelt on the Mongolian Plateau and examined the response relationship between the snowmelt line and temperature at half-monthly scales. The main conclusions are:

1. **Interannual snow cover variation:** From 2003–2022, snow-covered area fluctuated between 55.59%-87.61% of the total plateau area. The minimum snow cover occurred in 2018 and the maximum in 2009. Over the past 20 years, SED showed a significant advancing trend at 0.18 $\mathrm{d} \cdot (10\mathrm{a})^{-1}$ ($P < 0.05$), while stable snow cover areas showed a delaying trend at 2.14 $\mathrm{d} \cdot (10\mathrm{a})^{-1}$. The average SED in stable snow zones was 27 days later than the overall plateau average.
2. **Spatial distribution patterns:** SED exhibited a clear south-early, north-late pattern, concentrated in June–August. In the year with maximum snow cover (2009), areas north of 45°N showed later SED (generally after day 195), accounting for 42.74% of the total area. In the year with minimum snow cover (2018), SED was relatively earlier (days 193–238), with snow-free area increasing by 44.4% in central and southern regions. Stable snow zones were mainly concentrated in high-altitude regions of northwestern Mongolia and the Greater Khingan Mountains in northeastern Inner Mongolia, where 64.9% of the area showed advancing trends and 35.1% showed delaying trends.

3. **Snowmelt line and isotherm synchronization:** Over the 20-year period, the northward movement of the winter snowmelt line on the Mongolian Plateau showed high consistency with the -5°C and 0°C isotherms. This reflects enhanced convergence effects from deepening climate change—continuous warming causes boundaries of different thermal zones to become spatially coupled. The correlation between snowmelt line latitude and temperature, except for 2018 (minimum snow year), ranged from 0.72-0.98, indicating temperature is a key factor controlling snowmelt line position. The synchronous movement between the snowmelt line and 0°C isotherm was most pronounced from early March to early May, providing direct evidence for systematic climate change impacts.

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