Spatiotemporal Variation Characteristics of Snow-Cover Days on the Qinghai-Tibet Plateau

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Abstract

To address the unclear changes in snow cover and the insufficient research on snow cover days in the high-altitude mountainous areas of the Qinghai-Tibet Plateau, the NOAA IMS snow and ice product was used to analyze snow cover days on the Qinghai-Tibet Plateau from 2004 to 2021. The results show that over the past 17 a, snow cover days on the Qinghai-Tibet Plateau exhibited a significant increasing trend, with an increase of 11.5 d・(10a)-1. Among them, the central-eastern and northern alpine regions of the plateau were dominated by increasing trends, while the southern and northwestern high mountainous areas were dominated by decreasing trends. Snow cover days on the Qinghai-Tibet Plateau showed a highly significant elevation dependence: the higher the elevation, the longer the snow duration and the greater the number of cover days. Below 2000 m, the average number of cover days was less than 5 d, whereas above 6000 m it averaged more than 157 d. The annual average number of snow cover days on the Qinghai-Tibet Plateau was 71.1 d, with the highest seasonal average in winter at 27.2 d, followed by spring (22.1 d) and autumn (14.5 d), and the lowest in summer, at only 5.3 d. Against the background of overall warming and wetting of the climate on the Qinghai-Tibet Plateau, the increase in snow cover caused by increased precipitation in high-altitude and high-latitude regions has effectively offset the decreasing trend in plateau snow cover caused by rising temperatures.

Full Text

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Spatiotemporal Variation Characteristics of Snow-Cover Days on the Qinghai–Tibet Plateau

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Abstract: To address such problems as unclear changes in snow cover on the Qinghai–Tibet Plateau and insufficient research on snow-cover days, NOAA IMS snow and ice products were used to analyze snow-cover days on the Qinghai–Tibet Plateau from 2004 to 2021. The results show that over the past nearly 17 years, snow-cover days on the Qinghai–Tibet Plateau have shown a significant increasing trend, with an increase of 11.5 d・(10a)^{-1}. Among them, the central-eastern part of the plateau and the northern alpine-cold region are dominated by an increasing trend, whereas the southern and northwestern high-mountain areas are dominated by a decreasing trend. Snow-cover days on the Qinghai–Tibet Plateau show a very significant dependence on elevation: the higher the elevation, the longer the snow-cover duration and the more snow-cover days. Below 2000 m, the average number of snow-cover days is fewer than 5 d, whereas above 6000 m the average exceeds 157 d. The annual mean number of snow-cover days on the Qinghai–Tibet Plateau is 71.1 d; the winter mean is the largest, at 27.2 d, followed by spring (22.1 d) and autumn (14.5 d), while the summer mean is the smallest, only 5.3 d. Against the overall background of climate warming and wetting on the Qinghai–Tibet Plateau, the increase in snow cover caused by increased precipitation in high-mountain and high-latitude regions has effectively compensated for the decreasing trend in plateau snow cover caused by rising air temperature.

Keywords: snow-cover days; NOAA IMS product; ground observation; DEM; Qinghai–Tibet Plateau

In September 2019, the IPCC officially released the *Special Report on the Ocean and Cryosphere in a Changing Climate* (SROCC). This was the first IPCC assessment report to take high-mountain regions, the polar cryosphere, and the ocean as its themes, and it was the third special report released by the IPCC. The report points out that, against the background of global climate warming, the cryosphere in high-mountain regions and polar regions is generally retreating and will continue to melt in the future, further intensifying disaster risks faced by high-mountain and polar regions[1–3]. The cryosphere is an important component of high-mountain regions, mainly including glaciers, frozen ground, and snow cover. As global temperature continues to rise, the cryosphere and its related elements in high-mountain regions are undergoing significant changes, and the various risks they face will continue to increase[4–7].

Over the past several decades, global warming has already led to the widespread retreat of the cryosphere. Since the mid-20th century, snow cover in almost all high-mountain regions worldwide has been decreasing, with significant interdecadal variability[1–2]. In particular, since the 21st century, snow-cover duration, mean snow depth, and snow water equivalent in low-elevation mountainous areas have all shown decreasing trends. Rising air temperature causes more precipitation in low-elevation mountainous areas to occur as rainfall, thereby accelerating snowmelt and areal reduction of snow cover across different elevation belts in mountainous regions[8–10].

The Qinghai–Tibet Plateau is the core area of Asia' s high-mountain region and an important part of the world' s mountains. The Qinghai–Tibet Plateau and its surrounding areas contain the most extensive cryosphere on Earth outside the Antarctic and Arctic, and are known as the "Third Pole." Snow cover is the main form of the cryosphere on the Qinghai–Tibet Plateau and the land-surface feature with the fastest seasonal changes; it constitutes the largest high-mountain ice-and-snow-covered area in the Northern Hemisphere and the principal snow-covered area of Asia' s high-mountain region[11–13]. Against the background of global climate warming, snow cover on the Qinghai–Tibet Plateau, as an important regional water resource, a climate regulator, and a sensitive factor in global climate change, has attracted considerable attention[14–19]. Different scholars have carried out extensive research on snow-cover changes on the Qinghai–Tibet Plateau using ground observations and satellite remote sensing.

Analyses based on ground observation data show that snow cover on the Qinghai–Tibet Plateau increased from the 1960s to the end of the 1990s, but after entering the 21st century it decreased markedly[20–27]. However, meteorological observation stations on the Qinghai–Tibet Plateau are mainly distributed in the eastern and southern parts of the plateau; stations in the western and northwestern parts are extremely sparse and are concentrated in river valleys and lower-elevation areas. Snow cover, however, is more widely distributed in high mountains and alpine-cold regions. Therefore, it is difficult to obtain complete spatiotemporal information on snow-cover characteristics in the complex terrain of the Qinghai–Tibet Plateau using ground-station observation data. Satellite remote-sensing technology provides a new approach for snow-cover observation and can relatively accurately characterize changes in snow cover in high-mountain and high-elevation regions.

Analyses based on satellite remote-sensing data indicate that, from the beginning of the 21st century, snow cover on the Qinghai–Tibet Plateau decreased significantly, and by 2016 the plateau was basically in a period of low snow cover[28–31]. Beginning in 2017, however, snow cover on the plateau showed a marked rebound[27,32]. Because from the 1980s to the 1990s, the Qinghai-Tibet Plateau' s

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…snow cover generally remained at a relatively high level; therefore, based on long time-series satellite remote-sensing data, snow cover over the Tibetan Plateau has shown an overall decreasing trend from the 1980s to recent years

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Because snow has high reflectance in the visible-light band and optical imagery has high spatial resolution, optical remote sensing has incomparable advantages in monitoring the areal extent of surface snow cover. However, cloud interference is the greatest adverse factor affecting surface snow monitoring by optical remote sensing. Taking the Terra MODIS daily snow product MOD10A1 as an example, the average cloud-cover rate over the Tibetan Plateau is 46.6%; for the afternoon Aqua MODIS satellite, the cloud-cover rate is even higher, reaching 55.1%

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. In recent years, cloud-removal algorithms based on MODIS and various other satellite remote-sensing products, as well as the cloud-free snow products generated from them, still require further validation and improvement in accuracy. MOD10A2 is a snow product obtained from MODIS daily snow products using an 8-day maximum-composite method, with the aim of ensuring the maximum snow-covered area within image pixels and minimizing the influence of clouds

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. This product has been widely applied in studies of the spatiotemporal characteristics of large-scale snow-cover change. In addition, the Tibetan Plateau is located in the mid- and low-latitudes of the Northern Hemisphere. Under the influence of meteorological and climatic conditions such as a dry and clean atmosphere and strong solar radiation, snow cover on the Tibetan Plateau generally exhibits a patchy distribution; surface snow is relatively thin and persists for a short time. Especially in spring, surface snow melts rapidly. Therefore, snow-cover products composited over 8 days are likewise unable to objectively reflect the complete snow-cover characteristics and change information of the Tibetan Plateau; in particular, they cannot obtain spatiotemporal change information for daily snow cover days (SCD, Snow Cover Days).

NOAA IMS (Interactive Multi-sensor Snow and Ice Mapping System) is a multi-source data-fusion product

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that provides daily cloud-free snow-cover products for the Northern Hemisphere, and its spatial resolution has been improved to 1 km. Studies have shown that the IMS 4 km snow product has relatively high accuracy in snow monitoring over the Tibetan Plateau, with an overall accuracy exceeding 80%, and can be used for monitoring large-scale snow-cover changes on the Tibetan Plateau

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. Therefore, in view of current issues such as the unknown or uncertain overall spatiotemporal characteristics of snow cover days in the high-mountain and alpine regions of the Tibetan Plateau, this study uses the daily IMS snow and ice product to analyze the spatial distribution and temporal evolution characteristics of snow cover days on the Tibetan Plateau during 2004–2021, and to obtain information on the complete spatial distribution and temporal variation characteristics of snow cover on the Tibetan Plateau based on daily time-scale snow products. This work is of important scientific significance for gaining a deeper understanding of the spatiotemporal variation characteristics of snow on the Tibetan Plateau, clarifying inconsistencies in current conclusions regarding snow-cover changes on the Tibetan Plateau, optimizing the management of cryospheric water resources, and formulating measures to address climate change.

1 Data and Methods

1.1 Overview of the Study Area

The Tibetan Plateau is located in southwestern China, with an average elevation above 4000 m. It is the world's highest and largest plateau. Its main body lies in the Tibet Autonomous Region and Qinghai Province, and it also includes parts of western Sichuan, northern Yunnan, southern Xinjiang, and western Gansu (Fig. 1). The boundary of the study area was determined by taking natural topography and geomorphology as the dominant factors, while…

Fig. 1 Major mountain ranges, rivers, lakes and topography in the Tibetan Plateau

Comprehensively considering the principles of elevation, plateau surface, and mountain integrity, the boundary of the Tibetan Plateau within China was determined[42]. Its extent begins in the west at the Pamir Plateau and extends eastward to the Hengduan Mountains, spanning 31 degrees of longitude and about 2945 km from east to west; it extends southward from the southern margin of the Himalayas and northward to the northern sides of the Kunlun-Qilian Mountains, spanning about 13 degrees of latitude and reaching 1532 km from north to south. Its area is 2.57×10^6 km^2, accounting for about 26.8% of China' s total land area.

The Tibetan Plateau is located in the mid-low-latitude westerly belt of the Northern Hemisphere and stands in the middle of the troposphere. In winter, it is mainly influenced by the westerly circulation; in summer, it is mainly influenced by the South Asian and East Asian monsoons; spring and autumn are transition periods between the winter and summer atmospheric circulations. The climate types of the Tibetan Plateau are complex and diverse. Overall, the plateau is dominated by a high-cold climate, characterized by dry air, strong solar radiation, low mean temperature, large diurnal temperature range, small interannual variation, a gradual decrease in temperature from southeast to northwest, and a gradual decrease in precipitation from southeast to northwest.

1.2 IMS Snow and Ice Products

The IMS snow and ice product was first developed and produced by the NOAA National Environmental Satellite, Data, and Information Service (NESDIS). It is the longest historical snow-cover product, providing daily snow-cover extent products for the Northern Hemisphere[43-44]. It was initially developed to provide snow and ice initial fields for NOAA' s Numerical Weather Prediction (NWP) model[38]. With the development of satellite remote-sensing technology, more satellite remote-sensing data have been integrated into IMS products, continuously improving their spatial resolution and product accuracy, and enabling broader application in global snow and ice monitoring and related scientific research.

IMS has successively integrated satellite data from many geostationary and polar-orbiting satellites, including the geostationary satellite GOES, Japan' s GMS geostationary meteorological satellite, Japan' s MTSAT multifunctional satellite, the European geostationary meteorological satellite (METEOSAT), NOAA-series polar-orbiting satellites, U.S. Department of Defense polar orbiters (USDOD polar orbiters), and the U.S. Defense Meteorological Satellite Program (DMSP), as well as radar and ground-observation data. IMS also integrates Northern Hemisphere weekly sea-ice analysis products developed by the U.S. National Ice Center (NIC) and U.S. Air Force snow and ice analysis products[38,44]. Beginning in February 2001, data from AVHRR channel 3A were integrated into the IMS product; beginning in February 2004, MODIS channel 1 data were also integrated into the product, increasing its spatial resolution from the original 24 km to 4 km. Since December 2, 2014, the spatial resolution of IMS has again been improved to 1 km. The IMS mapping algorithm uses a series of decision trees to classify snow-covered and snow-free areas in the Northern Hemisphere, taking the snow-cover image from the previous day as the initial state and producing the snow-cover extent product for the current day according to the snow-cover extent monitored by satellites on that day.

The IMS image-processing procedure is generally as follows: first, Northern Hemisphere IMS snow and ice images in TIFF format are downloaded from the NSIDC or NIC website, and the TIFF format is converted to ArcGIS GRID format; next, the data projection is converted from polar stereographic projection to Albers projection; then, using the boundary of the study area, the IMS images within the Tibetan Plateau are clipped one by one; finally, IMS images at different temporal scales are overlaid for statistical analysis and trend calculation.

1.3 Research Methods

The mathematical statistical methods mainly use a univariate linear regression model to analyze trends in the spatiotemporal changes of snow-cover days and area. Pearson correlation analysis is used to measure the strength and direction of the linear relationships between snow elements, or between snow elements and meteorological factors such as temperature and precipitation, so as to quantitatively characterize the main meteorological and climatic drivers of changes in snow elements. Significance tests of regression analysis and correlation coefficients can determine whether a linear slope or correlation coefficient is significant. In addition, the standard deviation is used to represent the degree to which a snow element deviates from its mean value, or the dispersion of the variable. If the absolute distance of a variable from the mean is greater than twice the standard deviation, it reaches the criterion for identifying an anomaly.

2 Results and Analysis

2.1 Spatial Variation Characteristics of Snow Cover

2.1.1 Spatial distribution

Snow cover on the Tibetan Plateau is widely distributed, but because of the combined influence of numerous factors such as topography, landforms, and atmospheric climate, the spatial distribution differs markedly. Figure 2 shows the calculated spatial distribution characteristics of snow-cover days (SCD) on the Tibetan Plateau, with more snow-cover days around the plateau margins and in the interior high mountains and high-cold regions, and fewer cover days in the southern river valleys and lake basins and the northern basins. Specifically, the high-cold areas of the southern and central-eastern plateau mountains such as the Nyainqêntanglha Mountains and their eastward-extending high mountains, the Tanggula Mountains, the Bayan Har Mountains, and the Anyemaqen Mountains, as well as the Himalayas, the Karakoram Mountains, the Kunlun Mountains, and the Qilian Mountains

Fig. 2 Annual mean SCD on the Tibetan Plateau from February 2004 to August 2021

···mountains and other high mountains around the plateau are high-value areas of snow-cover days on the Tibetan Plateau, generally exceeding 130 d and accounting for 16.6% of the total plateau area. The southern valleys, the central-western part of the northern Tibetan Qiangtang Plateau, the northern Qaidam Basin, and the basin south of Qinghai Lake extending eastward from it are low-value areas of snow-cover days, generally below 20 d and accounting for 24.2% of the total plateau area. The annual mean number of snow-cover days on the Tibetan Plateau is 71.1 d.

Among the four seasons, the spatial distribution of snow-cover days on the Tibetan Plateau in spring is basically consistent with the annual mean: snow-cover days are numerous in alpine and cold regions of high mountains, and fewer in valleys, lakes, and basins. However, in spring, snow-cover days in the southern and western high-mountain areas of the plateau are markedly more numerous than in the northern and central-eastern alpine cold regions (Fig. 3a). The spring mean number of snow-cover days on the plateau is 22.1 d. Summer is the rainy season on the plateau and the season with the highest mean temperature; snow cover on the plateau is very limited, occurring only in high-mountain and alpine regions (Fig. 3b). Among these, the eastern extension of the Nyainqentanglha Mountains in southeastern Tibet has the broadest relative distribution, followed by the Karakoram and western Kunlun Mountains in the northwest, and these areas are mostly zones of perennial mountain snow and glaciers. The summer mean number of snow-cover days on the plateau is 5.3 d.

In autumn, the mean number of snow-cover days on the plateau similarly exhibits a spatial pattern in which snow-cover days are numerous in the high mountains around the plateau and in inland alpine cold regions, while they are few in valleys and basins (Fig. 3c). Specifically, the high mountains around the plateau—including the Himalayas, the Karakoram Mountains, the Kunlun Mountains, and the Qilian Mountains—as well as the inland central-eastern alpine cold regions, including the Nyainqentanglha Mountains and their eastward extension, the Tanggula Mountains–Bayan Har Mountains–Anemaqen Mountains, have more snow-cover days. Most of western Tibet, the Qaidam Basin and its eastward-extending lake basins, and the valley areas in the southeastern plateau have the fewest snow-cover days. The autumn mean number of snow-cover days on the plateau is 14.5 d, and the area with no snow cover accounts for 14.1% of the total area. The winter mean number of snow-cover days on the plateau is 27.2 d, the highest among the four seasons (Fig. 3d). The overall spatial distribution shows a pattern of more snow-cover days in the high mountains around the plateau and in inland central-eastern alpine cold regions, and fewer in valleys and basins. Compared with spring, snow-cover days and their extent increase markedly in winter in areas other than the northern and western high mountains of the plateau; only in the eastern Nyainqentanglha Mountains in the southern plateau and the eastern Himalayan mountain section does snow cover decrease slightly relative to spring.

Figure 3 Spatial distribution of seasonal mean snow-cover days on the Tibetan Plateau from February 2004 to August 2021: spring (a), summer (b), autumn (c), and winter (d).

Legend in each panel: mean snow-cover days/d; classes: 0–6, 7–14, 15–23, 24–33, 34–43, 44–53, 54–63, 64–73, 74–82, 83–90.

For the multi-year monthly mean distribution of snow-cover days on the Tibetan Plateau, January has the largest mean number of covered days, reaching 10.2 d; the means for February and March differ little, at 8.7 d and 8.5 d, respectively. August has the fewest mean covered days, only 0.8 d on average, while July averages 1.2 d. After August, the plateau' s monthly mean number of covered days again increases gradually. The relative increase from September to October is large, whereas November and December differ little, with multi-year means of 7.3 d and 7.4 d, respectively. Conversely, the proportion of area without snow cover in January averages 7.3%, the smallest monthly mean; this proportion is largest in August, reaching 87.8%, and then gradually decreases to 11.5% in December.

Studies have shown that snow distribution on the Tibetan Plateau has pronounced spatial differentiation and vertical zonality. Snow is mainly distributed in the surrounding high mountains and inland alpine cold regions, while snow cover is sparse in the plateau' s interior valleys and lake-basin areas[^19][^33–^34]. At the seasonal scale, snow distribution is most extensive in winter, followed by spring and autumn, while the extent of snow cover in summer is extremely limited[^28–^30]. Mean snow cover reaches its maximum in January and declines to its minimum in August. Within the year, mean snow cover shows periodic variation opposite to that of meteorological factors such as mean air temperature and precipitation.

2.1.2 Spatial variation

From 2005 to 2020, the area where annual snow-cover days showed an increasing trend accounted for 71.4% of the total plateau area; areas with decreasing trends of varying degrees accounted for 21.0%, and areas with no trend accounted for 7.6% (Table 1). Thus, over the past 16 a, snow-cover days on the Tibetan Plateau were generally dominated by an increasing trend, with a mean increase of 1.15 d · a^-1. Specifically, increasing trends prevailed in the broad alpine cold regions of the central-eastern plateau, including the northern Qiangtang Plateau-Kunlun Mountains and the Nyainqentanglha Mountains–Tanggula Mountains–Bayan Har Mountains–Anemaqen Mountains, as well as north of Qinghai Lake and on the northern side of the southwestern Himalayas. Among these, the increasing trend was most pronounced from east of the Bayan Har Mountains to northern Qinghai Lake and the northern Kunlun Mountains, with increases reaching 2.1–4.0 d · a^-1. In contrast, the decreasing trend was most pronounced in the high-mountain areas of the southern plateau, including the Himalayas and the Hengduan Mountains to their east, the northern Qaidam Basin, and the Karakoram watershed in the northwest; in some areas, the mean annual decrease reached 2.1–4.0 d (Fig. 4). Areas with no significant trend in snow-cover days were mostly distributed in the southeastern plateau valleys and the southern low-latitude regions.

Table 1 Changes in SCD on the Tibetan Plateau from February 2004 to August 2021

Trend range /(d · a^-1)	Year percentage /%	Spring percentage /%	Summer percentage /%	Autumn percentage /%	Winter percentage /%
<−4.0	0.8	0.0	0.0	0.0	0.0
−4.0–−2.1	2.5	0.5	0.8	0.7	0.4
−2.0–−0.6	8.8	6.6	7.5	15.8	8.1
−0.5–−0.1	8.9	13.8	10.4	25.9	15.4
0	7.6	21.0	58.4	24.2	13.7
0.1–0.5	14.1	27.8	17.3	21.8	26.9
0.6–2.0	30.4	27.5	4.7	11.1	33.7
2.1–4.0	19.1	2.8	0.8	0.5	1.8
>4.0	7.8	0.0	0.1	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0

In spring, the area where snow-cover days showed an increasing trend accounted for 58.2% of the total area, the area with a decreasing trend was 20.8%, and areas with no trend accounted for 21.0%. It can therefore be seen that, over the past 17 a, spring snow-cover days on the Tibetan Plateau were generally dominated by an increasing trend, with a mean increase of 0.33 d • a^-1. Among them, the decreasing trend was pronounced in the southeastern plateau, with decreases exceeding 2 d • a^-1 in some areas; by contrast, increases were evident in the plateau' s inland alpine cold regions from the Nyainqentanglha Mountains to the Anemaqen Mountains, from the northern Qiangtang Plateau to the Kunlun Mountains, north of Qinghai Lake, and on the northern side of the southwestern Himalayas, with increases exceeding 2 d • a^-1 in some areas (Fig. 5a). Areas with no trend in snow-cover days were most widely distributed in regions with low snow-cover days on the plateau, such as the Qaidam Basin and central and southern Tibet.

In summer, snow cover decreased markedly in the southern plateau, including the Himalayas, the Nyainqentanglha Mountains and their eastward-extending mountains, and the Hengduan Mountains; increasing trends predominated in the northern Qiangtang Plateau, the Kunlun Mountains, the Karakoram Mountains, the western section of the Gangdise Mountains, and the central alpine cold regions (Fig. 5b). Over the 17 a, the area where summer snow-cover days showed an increasing trend accounted for 22.9%, while the area with a decreasing trend was 18.8%; the remainder showed no significant trend. In autumn, mean snow-cover days were 14.5 d; areas with increasing trends accounted for 33.3%, areas with decreasing trends accounted for 42.5%, and 24.2% of the area showed no trend. It can be seen that autumn snow-cover days on the plateau showed a slight decreasing trend, with a mean annual decrease of 0.07 d; among them, areas with decreases $ $1 d • a^-1 accounted for 7.5% of the total plateau area. In autumn, the southwestern and southern parts of the plateau were dominated by decreasing trends, with particularly pronounced decreases within Tibet, whereas in the eastern part of the plateau

Fig. 4 Trend of annual SCD on the Tibetan Plateau from February 2004 to August 2021

Fig. 5 Trends of seasonal SCD on the Tibetan Plateau in spring (a), summer (b), autumn (c), and winter (d) from February 2004 to August 2021

Panel labels: (a) Spring; (b) Summer; (c) Autumn; (d) Winter.
Legend: Trend in snow-cover days / ($d \cdot a^{-1}$): $-4.7 \sim -1.3$, $-1.2 \sim -0.5$, $-0.4 \sim 0.1$, $0.2 \sim 0.5$, $0.6 \sim 1.1$, $1.2 \sim 1.9$, $2 \sim 5.2$; Lakes.

···the northern part increased markedly, mainly in the northern Qinghai Lake region, the eastern section of the Anyemaqen Mountains, the Karakoram Mountains, and the northern Kunlun Mountains (Fig. 5c).

Among the four seasons, winter had the largest mean number of snow-cover days, reaching 27.2 d. Areas where snow-cover days showed an increasing trend accounted for 62.4% of the total area; areas with decreasing trends of varying degrees accounted for 24.0%; and 13.7% of the area showed no trend. Clearly, during 2004–2021, the increasing trend in winter snow-cover days on the Plateau was relatively pronounced, with an average increase of 0.34 $d \cdot a^{-1}$, and the regional differences were large (Fig. 5d). Specifically, except for the Qaidam Basin, the broad alpine regions in the northern and central Plateau and the northern side of the southwestern Himalayas were dominated by increasing trends, with increases in some areas reaching $2.0 \sim 4.6$ d $\cdot$ a^{-1}. The southeastern and western Plateau, as well as the Qaidam Basin, were dominated by decreasing trends, with decreases in some areas reaching $1.0 \sim 4.3$ d $\cdot$ a^{-1}.

In summary, from 2004 to 2021, snow-cover days on the Tibetan Plateau showed a significant increasing trend, with an increase of 11.5 d $\cdot$ (10a)$^{-1}$. The central-eastern Plateau and northern alpine regions were dominated by increasing trends, whereas the southern and western high-mountain regions were dominated by decreasing trends. According to observational data from 94 meteorological stations on the Tibetan Plateau, air temperature at all stations on the Tibetan Plateau showed an upward trend during 1981–2020, with more pronounced increases in areas at higher elevations and latitudes; the temperature increase reached 0.43 °C $\cdot$ (10a)$^{-1}$. Over the same period, precipitation at most stations also showed an increasing trend, with an average increase of 11 mm $\cdot$ (10a)$^{-1}$, indicating clear warming and humidification of the Tibetan Plateau. In recent decades, precipitation has increased markedly in the alpine regions of the central-eastern Plateau and in the north [27, 45–46]. Increased precipitation in the Qinghai Lake Basin enlarged the snow-covered area; in particular, since 2017, snow-cover area has increased substantially [46], contributing to the continuous expansion of Qinghai Lake since 2004 [47]. Rising temperature leads to a reduction in the extent of snow cover. However, under the background of warming and humidification on the Tibetan Plateau, the increase in snow cover caused by increased precipitation in high mountains and northern alpine regions has offset the tendency for Plateau snow cover to decrease as a result of rising temperature.

An analysis based on AVHRR and MODIS daily cloud-free remote-sensing snow-cover data for 1980–2020 shows that snow-cover days on the Tibetan Plateau decreased significantly at a rate of 0.47 d $\cdot$ a^{-1}. Across 71.4% of the Plateau, snow-cover days showed a decreasing trend, of which areas with significant decreases accounted for approximately 55.3%; in 17.1% of the area, snow-cover days showed a significant···

showed an increasing trend, and were mainly distributed in high mountain areas above 5,200 m a.s.l.[33]. A study based on the NOAA AVHRR 5 km long-term daily snow-cover dataset showed that during 1980–2016, the annual mean number of snow-cover days decreased over most of the Tibetan Plateau; areas with decreases greater than 2 d $\cdot$ a^{-1} accounted for about one half of the total plateau area[34]. During 1980–2021, the number of snow-cover days decreased over most of the Tibetan Plateau, and areas with decreases greater than 1 d$\cdot$a^{-1} accounted for about one half of the entire plateau area; however, snow cover showed an increasing trend over the broad region between the Qaidam Basin and the Tanggula Mountains in the northern plateau[35].

Analyses based on surface observational data indicate that from 1960 to the mid-to-late 1990s, the number of snow-cover days on the Tibetan Plateau increased, and in 1997 there was an obvious turning point from more to fewer snow-cover days[20]. From 1951 to 1997, snow cover in western China showed a slow increasing trend and exhibited substantial interdecadal variability[14]. During 1979–2006, the number of winter snow-cover days observed at ground stations on the Tibetan Plateau showed a gradual decreasing trend, displaying characteristics completely opposite to snow-cover changes in Xinjiang and Northeast China[21]. From 1980 to 2016, the number of snow-cover days decreased year by year over most of the Tibetan Plateau; snow depth fluctuated greatly before 2000 and then showed a significant downward tendency[27]. Taking the 1990s as the turning period, snow cover on the Tibetan Plateau exhibited an overall trend of first increasing and then decreasing. Since the late 1990s it has been significantly below normal, but in the most recent 20 a the decreasing trend has slowed, and even a slight increasing trend has appeared[27]. During 1961–2014, the annual mean snow depth and number of snow-cover days on the Tibetan Plateau were 0.26 cm and 23.78 d, respectively; their distributions were uneven at spatial and seasonal scales, and the areas with large snow depth and many snow-cover days were not consistent. The number of snow-cover days on the plateau showed a downward trend, but it was not significant; the rate of decrease was $0.64\ \mathrm{d} \cdot (10\mathrm{a})^{-1}$, and interdecadal variability was evident[26].

The above surface observations and satellite remote-sensing monitoring both show that snow cover on the Tibetan Plateau has distinct interdecadal variability. Although the plateau snow depth and number of snow-cover days derived from surface observations show inconsistencies in spatial distribution and the high-value areas do not overlap, their overall trends are consistent: in the 1960s, the mean snow depth on the Tibetan Plateau was relatively shallow and the number of snow-cover days was small; afterward, both mean snow depth and the number of snow-cover days increased markedly, remaining at relatively high levels in the 1980s and 1990s. They reached a peak in the late 1990s, and around 1997 a climatic abrupt change from more to fewer snow-cover days occurred, after which the decreasing trend became evident.

The wide application of satellite remote sensing in monitoring surface parameters such as snow cover and in numerical weather prediction began in 1979. The longest time series of daily cloud-free snow-cover remote-sensing data was produced from NOAA AVHRR multispectral data, with the dataset starting in 1980. Because snow depth and the number of snow-cover days on the Tibetan Plateau were both relatively large in the 1980s and late 1990s, long-term time-series analyses indicate a decreasing trend in Tibetan Plateau snow cover. In addition, since the 21st century, the Tibetan Plateau has entered a stage with relatively little snow cover. During 2000–2015, plateau snow cover was basically decreasing or showed no obvious change[16,29]. After 2016, however, snow cover on the Tibetan Plateau rebounded markedly, causing snow-cover area to show an increasing trend during 2004–2020.

Figure 6. Monthly mean snow-cover area on the Tibetan Plateau from February 2004 to August 2021. Legend: monthly mean snow-cover area; linear trend. Vertical axis: area / 10^4 km^2; horizontal axis: date / year-month.

Figure 1: Figure 6. Monthly mean snow-cover area on the Tibetan Plateau from February 2004 to August 2021. Legend: monthly mean snow-cover area; linear trend. Vertical axis: area / 10^4 km^2; horizontal axis: date / year-month.

2.2 Temporal Variation Characteristics of Snow Cover

2.2.1 Monthly Mean Changes

Figure 6 presents the time series of monthly mean snow-cover area (SCA, Snow Cover Area) on the plateau from February 2004 to August 2021. Snow-cover area on the Tibetan Plateau exhibits seasonal variability characterized by extensive snow cover in winter and spring and little cover in summer, and overall it shows an upward trend. The mean value for all months was 50.3×10^4 km^2, accounting for 19.5% of the total plateau area. In terms of monthly means, the maximum mean snow-cover area generally occurred in January. Among these, January 2020 had the largest mean area, 148×10^4 km^2, reaching 57.5% of the total plateau area; next were January 2019 and January 2015, accounting for 51.0% and 50.9% of the total plateau area, respectively, while all other months were less than half of the total plateau area. The minimum monthly mean snow cover on the plateau generally occurred in August, among which 2006

Figure 6 Monthly mean snow-cover area on the Tibetan Plateau from February 2004 to August 2021

Fig. 6 Monthly mean SCA on the Tibetan Plateau from February 2004 to August 2021

The average snow cover in August is the smallest, accounting for only 1.6% of the total plateau area; next is August 2012, with an average accounting for 1.8% of the total plateau area. All other months exceed 2% of the total plateau area. Thus, the maximum monthly mean snow cover on the plateau generally occurs in January, whereas the minimum basically occurs in August.

As can be seen from Fig. 7, the mean snow-cover area in January is the largest, at 88.3×10^4 km^2, and its standard deviation is also the largest, at 30.3×10^4 km^2, indicating that its interannual variation in snow cover is the greatest. This is followed by February and March, with areas of 85.7×10^4 km^2 and 79.6×10^4 km^2, respectively. Beginning in April, snow cover on the plateau decreases markedly, reaching the lowest monthly mean in August: it drops from 66.9×10^4 km^2 in April to 6.9×10^4 km^2 in August. The standard deviation in August is also the lowest among monthly means, only 2.5×10^4 km^2, indicating that August has not only the least mean snow cover on the plateau but also the lowest interannual variation among months. Thereafter, as temperature gradually decreases, snow cover begins to increase from the inland alpine and high-mountain regions of the plateau, reaching an average of 65.8×10^4 km^2 in November, the second peak within the year. The average value in December is slightly lower than that in November, decreasing on average by 0.5×10^4 km^2.

2.2.2 Annual and seasonal variations

As shown in Fig. 8 and Table 2, the interdecadal variation in snow-cover area on the plateau is evident, with a mean area of 51.0×10^4 km^2. Before 2011, the plateau was in a period of relatively low mean snow cover. Except for 2005, which showed a positive anomaly of 1.3×10^4 km^2, all other years had large negative anomalies; the minimum occurred in 2010, which was 10.6×10^4 km^2 below the multi-year mean. During 2011–2015, the mean snow-cover area varied little, all within 3.5×10^4 km^2. During 2017–2020, the mean snow-cover area on the plateau increased markedly, with all years showing large positive anomalies. Among them, the mean snow-cover area in 2019 was 15.2×10^4 km^2 greater than the multi-year mean, making it an anomalously snowy year. Because the mean snow-cover area on the plateau increased markedly in the most recent 4 years, and because the plateau was basically in low-snow years before 2017, the annual mean snow-cover area on the Tibetan Plateau showed a significant increasing trend during 2005–2020, passing the significance test of $P < 0.05$, with an increase of 8.8×10^4 km$^2 \cdot (10a)^{-1}$.

Over the same period, the mean spring snow-cover area on the plateau showed an increasing trend, with an annual increase of 1.1×10^4 km^2, but it was not significant (figure omitted). Before 2011, spring snow cover was low; except for 2005, when the mean was 7.7×10^4 km^2 above normal, all other years showed negative anomalies, with 2004 having the most pronounced deficit, reaching 17.3×10^4 km^2. During 2011–2016, spring snow-cover variability was relatively small: 2011 and 2012 had positive anomalies, whereas 2013 and 2016 had negative anomalies. Beginning in 2017, snow cover on the plateau increased markedly. Except for spring 2021, which had a negative anomaly, all other spring seasons had positive anomalies; among them, spring 2017 had the largest snow-cover area, 22.0×10^4 km^2 above the multi-year mean, but it did not reach an anomalous level. Overall, the interdecadal variation is characterized by a period of below-normal spring snow-cover area on the plateau before 2011, relatively small interannual variation in spring during 2011–2016, and, beginning in 2017,

Fig. 7 Monthly mean snow-cover area and standard deviation on the Tibetan Plateau from February 2004 to August 2021
Fig. 7 Monthly mean SCA and standard deviations on the Tibetan Plateau from February 2004 to August 2021

Fig. 8 Changes in annual mean snow-cover area on the Tibetan Plateau from 2005 to 2020
Fig. 8 Annual mean SCA on the Tibetan Plateau from 2005 to 2020

In Fig. 8, the fitted line is $y = 0.8787x + 43.545$, with $R^2 = 0.3649$.

Table 2 Characteristics of changes in snow-cover area on the Tibetan Plateau from February 2004 to August 2021
Tab. 2 Statistical summary of SCA variations on the Tibetan Plateau from February 2004 to August 2021

Time	Mean area /10^4 km^2	Area percentage /%	Standard deviation /10^4 km^2	Years with anomalous snow cover	Trend /(10^4 $km^2 \cdot a^{-1}$)	Correlation coefficient with time series
Year	51.0	19.8	6.9	2019 anomalously high	0.88^*	0.604
Spring	64.2	24.9	12.5		1.08	0.460
Summer	15.6	6.0	4.7	2017 anomalously high	−0.03	0.036
Autumn	42.5	16.5	11.1		−0.20	0.090
Winter	79.7	30.9	20.3	2019 anomalously high	1.06	0.264

Note: $*$ indicates passing the significance test at $\alpha = 0.05$.

Snow cover showed a relatively obvious increase.

The mean summer snow cover accounted for only 6.0% of the total area of the Plateau, but its interannual variation was also obvious (figure omitted). During the study period, the mean snow-cover area in the first 3 years was relatively large; in 2004, there was a positive anomaly of 7.2×10^4 km^2. The period 2007–2016 was a stage with relatively little summer snow cover. Except for positive anomalies in 2011 and 2015, all other years had negative anomalies; in particular, the mean summer snow-cover area in 2014 was the smallest, with a negative anomaly of -5.6×10^4 km^2. After 2017, summer snow cover showed an overall increasing trend; in 2017, the snow-cover area reached its maximum value of 27.7×10^4 km^2, a year with anomalously high snow cover. In 2021, the summer snow-cover area declined somewhat, with a negative anomaly of -3.0×10^4 km^2.

The anomaly of mean autumn snow-cover area on the Tibetan Plateau was stable, with a slight decreasing trend overall (figure omitted). Its interannual variation was likewise obvious. Before 2013, the snow-cover area generally showed an increasing trend. Except for negative anomalies of less than -10×10^4 km^2 in 2012 and 2007, the other years basically showed positive anomalies. In 2013, the autumn snow-cover area reached its maximum, exceeding the multi-year mean by 18.9×10^4 km^2, but it did not reach the anomaly criterion. After 2013, autumn snow-cover area on the Plateau underwent a process of decrease. Except for positive anomalies in 2018 and 2019, the other years all had relatively large negative anomalies. In particular, 2020 was 18.9×10^4 km^2 below the mean, making it the year with the smallest mean snow-cover area and leading to an overall decreasing trend in autumn snow cover on the Plateau, though not a significant one.

Winter is the season with the largest mean snow-cover area on the Plateau, with an average coverage of 30.9% of the total Plateau area. During 2004-2021, mean winter snow cover showed a slight increasing trend overall, but it was not significant (figure omitted). In terms of interdecadal variation, the mean snow-cover area before 2011 was relatively small; in 2005 it was the smallest, with a negative anomaly of -30.6×10^4 km^2, while the magnitudes of the positive anomalies were all relatively small. During 2011-2017, the interannual variation was small, all within $\pm 17 \times 10^4$ km^2, and the interannual variation was relatively stable. Winter snow cover increased markedly in 2018 and 2019, with anomalies of 37.3×10^4 km^2 and 45.3×10^4 km^2, respectively; 2019 reached the criterion for an anomalously snow-rich year. In 2020, there was again a clear decrease, 27.2×10^4 km^2 below the multi-year mean. In summary, during 2005-2020 the annual mean snow cover on the Tibetan Plateau increased significantly, by an average of 8.8×10^4 km^2 per 10 a; this was mainly caused by increases in snow cover in winter and spring, the two seasons with relatively extensive snow cover on the Plateau.

Studies have shown that during 2000-2006, the snow-cover rate on the Tibetan Plateau showed a slight decreasing trend[28]; during 2001-2010, the snow-cover area in the main lake basins of the Tibetan Plateau showed no obvious trend of change[31]; and during 2000-2013, apart from relatively large interannual and seasonal variations, the snow-cover area of the Tibetan Plateau showed no obvious overall trend[29]. Since 1998, under the background of accelerated warming on the Tibetan Plateau, the snow-cover area on the Plateau remained relatively stable during 2001-2015, and no widespread decrease in snow-cover area occurred over those 15 years[16]. A study based on MOD10A2 v6 indicated that during 2000-2019, the snow-cover rate on the Tibetan Plateau showed a slight increasing trend overall, with an average increase of about $0.16\% \cdot (10a)^{-1}$; among them, winter snow cover in the eastern and southern Plateau increased significantly, autumn and spring snow cover decreased significantly, snow cover in the western and northern Plateau increased significantly, and summer snow cover over the Plateau as a whole decreased significantly. Changes in the extent of snow cover were negatively correlated with air temperature and positively correlated with precipitation[32]. The annual mean snow-cover area on the Tibetan Plateau was relatively large in the 1980s-1990s and decreased significantly after 2000[27]. Analysis of long-term time-series remote-sensing data showed that during 1980–2021, the snow-cover extent on the Tibetan Plateau exhibited a decreasing trend[34–35].

Beginning in the early 21st century, snow cover on the Tibetan Plateau entered a period of pronounced decrease. Until 2016, the Plateau was basically in a snow-deficient period, whereas from 2017 onward there was again a marked rebound and relatively large interannual variation. In addition, anomalous increases in snow cover on the Tibetan Plateau are often caused by snowfall weather processes over broad areas of the Plateau in winter. In winter 2019, because of the excessive influence of the Bay of Bengal tropical storm "Phethai," historically rare extensive snowfall and persistent snow cover occurred on the Tibetan Plateau. In winter 2019, precipitation in Qinghai was anomalously high, and severe pastoral snow disasters occurred in places such as the southern Qinghai pastoral areas and the Qilian Mountains[46]. In 2019, snow cover in the Yarlung Zangbo River basin in the southern Plateau also reached a historic high[48], 27.7% higher than the normal level. After the snowfall, air temperature dropped sharply, and the lowest temperatures at many stations set new historical records.

2.3 Relationship between Snow-Cover Days and Elevation

As can be seen from Fig. 9, snow-cover days on the Tibetan Plateau have an obvious dependence on elevation, and snow-cover days increase significantly with elevation.

Fig. 9 Relationship between annual mean snow-cover days and elevation on the Tibetan Plateau

Fig. 9 Relationships between SCD and elevations on the Tibetan Plateau

···trend. Below an elevation of 2,000 m, the number of snow-cover days is less than 5 d; at 4,500 m, the number of cover days reaches 78 d; after 5,500 m, the number of snow-cover days increases rapidly, and at 6,500 m the number of cover days reaches 267 d. Further analysis indicates that there is an extremely significant linear relationship between the number of snow-cover days on the Qinghai–Tibet Plateau and elevation: the higher the elevation, the longer the duration of snow cover and the greater the number of cover days, and vice versa.

The spatial distribution of snow cover on the Qinghai–Tibet Plateau is highly uneven. It is characterized by abundant snow, high coverage, and long duration in the high mountains around the plateau and in its central part, whereas inland basins and valleys have little snow, low coverage, and short duration[^15]. Elevation on the Qinghai–Tibet Plateau has an important influence on the spatial distribution of snow cover. The higher the elevation, the lower the temperature, which is more favorable for the persistence of surface snow; in lower-elevation regions, because of the constraint of higher temperatures, precipitation is mainly rainfall, and snow melts quickly after snowfall in the cold season, resulting in a short duration. Below 3,000 m on the Qinghai–Tibet Plateau, the snow-cover fraction is less than 4%, whereas above 6,500 m it reaches more than 78%[^19]. In the low-latitude parts of the plateau, rising temperatures are associated with a reduction in the duration of snow cover; in high-elevation areas, however, increased precipitation effectively offsets the tendency toward reduced snow caused by warming[^13]. In the mid- and low-latitude regions of the Northern Hemisphere, the alpine cold climate caused by high elevation is the main condition enabling the formation and maintenance of snow cover on the Qinghai–Tibet Plateau.

3 Conclusions

Using the IMS 4 km daily snow-cover product, this study analyzed the number of snow-cover days on the Qinghai–Tibet Plateau during 2004–2021, and, in combination with digital elevation model (DEM) data, explored the elevation dependence of snow-cover days. The results were compared and discussed with conclusions from previous studies. The main conclusions are as follows:

(1) Over the past nearly 17 years, the number of snow-cover days and the snow-covered area on the Qinghai–Tibet Plateau have shown significant increasing trends, with rates of increase reaching 11.5 d $\cdot$ (10a)$^{-1}$ and 8.8$\times10^4$ km$^2 \cdot$ (10a)$^{-1}$, respectively. Among these, increasing trends dominate in the central-eastern part of the plateau and in the northern alpine cold regions, whereas decreasing trends dominate in the southern and northwestern mountainous regions. Against the overall background of warming and wetting on the Qinghai–Tibet Plateau, rising temperature is the main cause of reduced snow cover on the plateau; however, increased precipitation has resulted in more snow in high-mountain alpine cold regions, and thus the plateau' s snow cover has increased overall.

(2) The number of snow-cover days on the Qinghai–Tibet Plateau has a very significant elevation dependence. The annual mean number of cover days is 71.1 d; among the seasons, winter has the largest mean value, 27.2 d, followed by spring (22.1 d) and autumn (14.5 d), while summer has the smallest mean value, only 5.3 d. Among the four seasons, winter and spring show obvious increases, whereas summer and autumn show slight decreasing trends. The increase in the number of snow-cover days on the plateau is attributable to the marked increases in winter and spring snow-cover days, and the contributions of the two are basically consistent.

(3) According to ground-observation data, in the 1960s the mean snow depth on the Qinghai–Tibet Plateau was relatively shallow and snow cover was relatively limited. Thereafter, snow depth and the number of snow days increased markedly, remaining at relatively high levels in both the 1980s and 1990s. Snow cover reached a peak at the end of the 1990s, and around 1997 a climatic shift occurred in which plateau snow cover changed from abundant to scarce. After entering the 21st century, snow cover decreased markedly. Since 2017, snow cover on the plateau has rebounded

significantly.

(4) Satellite remote sensing can relatively objectively and accurately characterize the spatiotemporal variation characteristics of snow cover in the complex terrain of the Qinghai–Tibet Plateau, but the time series of the data is limited. Because snow on the Qinghai–Tibet Plateau—both snow depth and the number of snow-cover days—remained at relatively high levels from the 1980s to the 1990s, long time-series satellite remote-sensing data beginning in 1980 indicate a decreasing trend in snow cover on the Qinghai–Tibet Plateau from the 1980s to the present.

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Spatiotemporal Variations of Snow Cover Days on the Tibetan Plateau

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Abstract: Snow cover, as the main form of the cryosphere on the Tibetan Plateau, is the fastest-changing surface feature on seasonal time scales. The Tibetan Plateau constitutes the largest high-mountain snow- and ice-covered region in the Northern Hemisphere and the principal snow-covered area in High Mountain Asia. Considering that changes in snow cover in the high-mountain regions of the Tibetan Plateau remain largely unknown and that research on snow cover days (SCDs) on the Tibetan Plateau is still inadequate, we analyzed the spatiotemporal variations in the number of SCDs on the Tibetan Plateau from 2004 to 2021 based on the daily NOAA IMS 4 km snow and ice products. The results indicate the following. (1) Over the past 17 years, the number of SCDs on the Tibetan Plateau has increased markedly at a rate of 11.5 $\mathrm{d}\cdot(10a)^{-1}$. Spatially, the number of SCDs in high-altitude areas increased mainly in the central and eastern parts but decreased in the south and northwest. (2) The number of SCDs on the Tibetan Plateau exhibits considerable dependence on elevation: the higher the elevation, the longer the snow-cover duration and the greater the number of SCDs. The mean number of SCDs is less than 5 days below 2000 m a.s.l., whereas it exceeds 157 d at 6000 m a.s.l. (3) The annual mean number of SCDs is 71.1 d, with the highest value in winter (27.2 d), followed by spring (22.1 d), autumn (14.5 d), and summer (5.3 d). (4) Under the general warming and wetting environment of the Tibetan Plateau, the increase in snow cover over the past decade due to increased precipitation in high-altitude and high-latitude areas has effectively compensated for the decrease in snow cover caused by rising temperatures.

Keywords: snow cover days; NOAA IMS products; surface observation; DEM; Tibetan Plateau

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