

Article

Spatiotemporal Variations in Snow Cover on the Tibetan Plateau from 2003 to 2020

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Abstract: The variations in snow cover on the Tibetan Plateau play a pivotal role in comprehending climate change patterns and governing hydrological processes within the region. This study leverages daily snow cover data and the NASA Digital Elevation Model (DEM) from 2003 to 2020 to analyze spatiotemporal snow cover days and assess their responsiveness to climatic shifts by integrating meteorological data. The results reveal significant spatial heterogeneity in snow cover across the Plateau, with a slight decreasing trend in annual average snow cover duration. Snow cover is predominantly observed during the spring and winter seasons, constituting approximately 32% of the total snow cover days annually. The onset and cessation of snow cover occur within a range of 120–220 days. Additionally, an increasing trend in snow cover duration below 5000 m altitude was observed, in addition to a decreasing trend above 5000 m altitude. Sub-basin analysis delineates the Tarim River Basin as exhibiting the lengthiest average annual snow cover duration of 83 days, while the Yellow River Basin records the shortest duration of 31 days. The decreasing trend in snow cover duration closely aligns with climate warming trends, characterized by a warming rate of 0.17 ± 0.54 °C per decade, coupled with a concurrent increase in precipitation at a rate of 3.09 ± 3.81 mm per year. Temperature exerts a more pronounced influence on annual snow cover duration variation compared to precipitation, as evidenced by a strong negative correlation ($CC = -0.67$). This study significantly augments the comprehension of hydrological cycle dynamics on the Tibetan Plateau, furnishing essential insights for informed decision-making in water resource management and ecological conservation efforts.

Keywords: snow cover; spatiotemporal variation characteristics; climate change; Tibetan Plateau



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1. Introduction

Snow stands as a pivotal constituent within the intricate framework of the global climate system. Its extent, depth, and duration wield a profound influence over the dynamics of the global water cycle, particularly in regions characterized by elevated altitudes. Furthermore, the high albedo and low thermal conductivity of snow exert notable impacts on local climate patterns within specific locales [1–5]. Moreover, snow assumes a fundamental role within hydrological systems spanning mid- to high-altitude regions, serving as a natural reservoir and modulating runoff dynamics and associated environmental processes within watersheds [6–8]. The Tibetan Plateau, renowned as the highest plateau globally, boasts an average elevation surpassing 4000 m. Its delicately balanced ecological milieu renders it acutely susceptible to the vicissitudes of climate change. Dubbed as the “Third Pole”, the plateau’s idiosyncratic attributes and extreme environmental conditions substantially influence global climate dynamics [9]. Distinguished for harboring the most extensive repositories of snow, glaciers, and permafrost beyond the polar realms, the plateau ranks among China’s foremost snowfall-rich regions [10–12]. Consequently, a comprehensive

inquiry into the evolving patterns of snow cover and climate phenomena across the Tibetan Plateau assumes paramount significance.

Traditional snowfall observation relies on manual observations at meteorological stations, offering accuracy but limited coverage for large-scale studies due to uneven distribution. Remote sensing technology has emerged as a solution, providing wide coverage, timely data, and high frequencies, enabling large-scale spatiotemporal studies with enhanced resolution. It has become a primary method for snow research, offering microwave and visible light snow products based on satellite sensors. Microwave products are weather-independent but have lower spatial resolution, while visible light products offer higher resolution but are weather-sensitive. Among these, MODIS snow products are favored for their accuracy, high spatial and temporal resolution, free availability, and global coverage [13,14].

Numerous studies have examined snow cover changes in the Tibetan Plateau and its surroundings using diverse datasets. Some have relied on meteorological station data to analyze snow depth and duration changes across different regions, including the eastern, central, and entire plateau, as well as at a national scale [15–18]. There are also studies that have investigated variations in snow cover and the snowline altitude in the Tibetan Plateau [19–22]. Others have employed remote sensing data, particularly MODIS snow products, to investigate snow cover extent and snow water equivalents in the plateau region [23–27]. Pu et al. discovered that the longest snow cover duration was found on the southern and western edges of the Tibetan Plateau using MODIS snow products [28]. Wang et al. observed, using daily cloud-free snow cover products based on MODIS and AMSR-E data, that the maximum snow cover days decreased from 2003 to 2010 on the Tibetan Plateau [29]. Li et al. also found that the snow cover decreased by 1.1% between 2001 and 2014 on the Tibetan Plateau [30]. Jin et al. discovered that high snow cover days were primarily concentrated in the Nyainqentanglha Mountains, Karakoram Mountains, and Himalayas regions from 2003 to 2014 using long time-series data of snow cover area on the Tibetan Plateau [31]. Although numerous studies have contributed to understanding the snow cover changes on the Tibetan Plateau, they have often overlooked variations in snow cover within the plateau's internal basins, thereby limiting a comprehensive understanding of snow changes across the entire Tibetan Plateau. Moreover, MODIS snow products are susceptible to cloud cover issues, potentially introducing errors into the derived snow cover data.

Hence, this study aimed to investigate the changes in snow cover days on the Tibetan Plateau and its sub-basins over the past two decades (2003–2020). Meanwhile, global climate change, characterized by significant warming, has profound implications for human survival and development [32,33]. This study also investigated the response of snow cover changes to climate change. There were three primary objectives that we aimed to achieve in this study: (1) explore the spatiotemporal characteristics of snow cover duration on the plateau, including snow cover days, onset dates, and end dates; (2) analyze snow cover changes within the plateau's internal basins; and (3) assess the impact of climate change on snow cover dynamics. By fulfilling these objectives, this research seeks to advance our understanding of the hydrological system cycle on the entire Tibetan Plateau and its subbasins, providing a scientific foundation for water resource management, ecological environmental protection, and natural disaster protection in the Tibetan Plateau and surrounding areas. This study can also further enrich the research direction of snow cover changes in the alpine region, and provide references for studying snow cover in similar regions.

2. Data and Methods

2.1. Study Area

The Tibetan Plateau, the world's highest and largest plateau, spans an average latitude–longitude range of 26°00'12" N–39°46'50" N and 73°18'52" E–104°46'59" E (Figure 1). Extending from the Altun Mountains and Qilian Mountains in the north to the Hengduan

Mountains and Himalayas in the south, and connecting to the central part of the Eurasian continent in the west, the plateau is characterized by a typical cold and arid climate. Its winters are prolonged and severe, contrasting with brief and mild summers. Abundant sunlight contributes to significant diurnal temperature fluctuations. Precipitation and snowfall exhibit uneven distribution throughout the year, with much of the plateau experiencing sub-zero temperatures even during the warmest months. Snowfall primarily occurs from October to May, with minimal occurrences in September and June, and it is virtually absent during July and August [34].

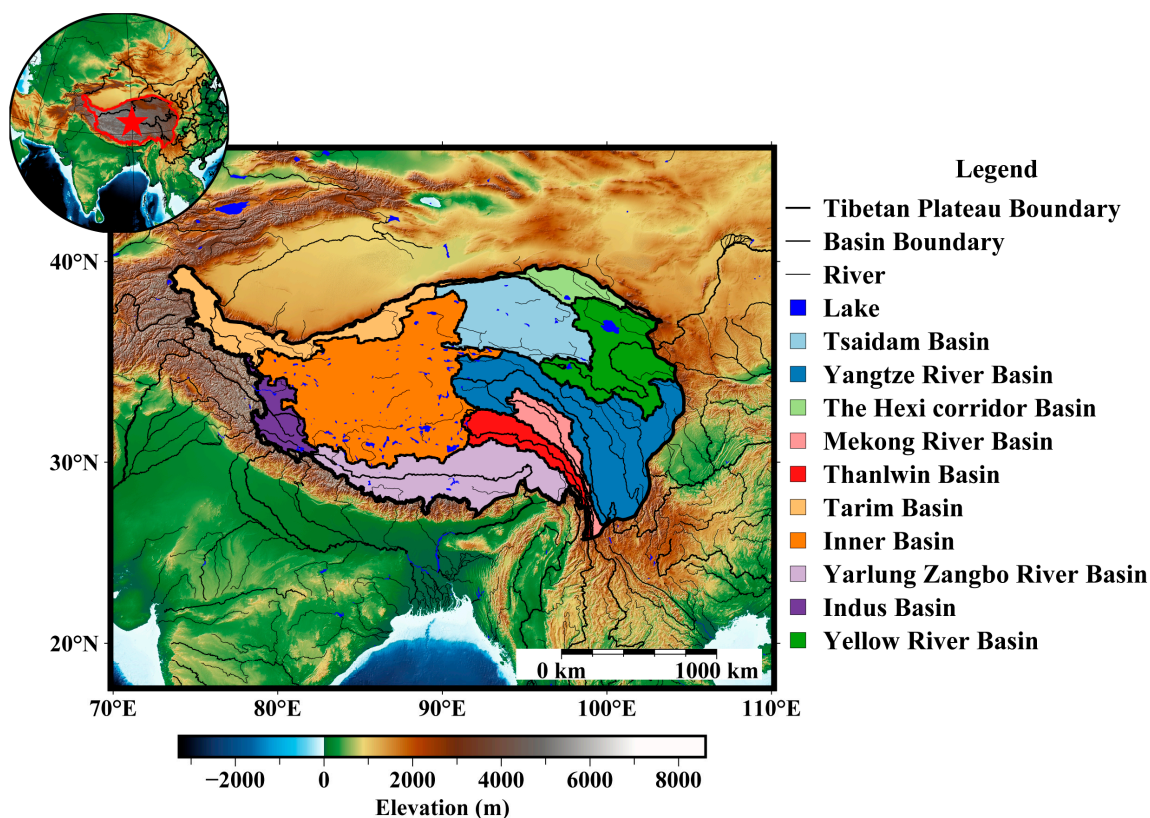


Figure 1. Study area of the Tibetan Plateau and ten major basins, the red star symbol in the upper right corner represents the location of the Tibetan Plateau.

The Tibetan Plateau is subdivided into 10 river basins, each characterized by distinct climatic influences. Among these, the Yellow River Basin, Yangtze River Basin, Mekong River Basin, and Salween River Basin are situated within the monsoon-controlled region and primarily experience the effects of the monsoon. Conversely, the Tarim Basin and the Indus River Basin, located in the western part of the plateau, are predominantly influenced by westerly winds. The Yarlung Zangbo River Basin, positioned in the southern plateau, is impacted by both monsoonal and westerly systems. In contrast, the Chaidamu Inland Basin and the Inland Basin of the Tibetan Plateau, located centrally within the plateau, experience less influence from both monsoonal and westerly winds.

2.2. Data

The data include snow cover duration products, the Digital Elevation Model (DEM), and meteorological data (i.e., temperature and precipitation) (Table 1). The snow cover duration products include HMRFS-TP (the long-term daily gap-free snow cover products over the Tibetan Plateau from 2002 to 2021 based on a hidden Markov random field model by East China Normal University) and daily cloud-free MODIS NDSI and a snow phenology dataset over High-Mountain Asia. The HMRFS-TP comprises long-term daily gap-free snow cover products covering the Tibetan Plateau. Utilizing the Hidden Markov

Random Field (HMRF) modeling technique, it generates daily snow cover data with a spatial resolution of 500 m without any gaps spanning from 2002 to 2022 across the Tibetan Plateau. The HMRF framework effectively integrates spectral, temporal, and environmental information to fill data gaps resulting from frequent cloud cover while enhancing the accuracy of the original MODIS snow products [35]. In this study, the dataset primarily serves to capture changes in snow cover duration from 2003 to 2020. The latter is derived from MODIS daily snow products, which undergo processing to fuse data from the morning and afternoon overpasses of the same day and apply a three-time spline interpolation algorithm to eliminate clouds. The dataset encompasses hydrological-year (HY) snow phenology data spanning from 2002 to 2020, prepared based on cloud-free MODIS Normalized Difference Snow Index (NDSI) products within each hydrological year [36]. In this study, the dataset primarily facilitates the determination of snow cover start and end dates.

Table 1. Detailed information on the main data used in this study.

Data Type	Data	Period	Spatial Resolution	Temporal Resolution	Data Sources
Snow products	HMRFS-TP: long-term daily gap-free snow cover products over the Tibetan Plateau	2002–2021	500 m	1 d	https://data.tpdc.ac.cn/en/data/ (accessed on 10 January 2024)
	Daily cloud-free MODIS NDSI and snow phenology dataset over High-Mountain Asia (2000–2021)	2002–2020	500 m	1 a	https://data.tpdc.ac.cn/en/data/ (accessed on 10 January 2024)
DEM	NASADEM Merged DEM Global 1 arc second V001	2000	30 m	–	https://search.earthdata.nasa.gov/ (accessed on 3 January 2024)
Meteorological data	GPM IMERG Final Precipitation L3 1 month 0.1 degree $\times$ 0.1 degree V07 (GPM_3IMERGM)	2000–2023	0.10° $\times$ 0.10°	Monthly	https://disc.gsfc.nasa.gov/datasets/ (accessed on 2 January 2024)
	ERA5-Land monthly averaged data from 1950 to present	1980–2022	0.10° $\times$ 0.10°	Monthly	https://cds.climate.copernicus.eu/ (accessed on 2 January 2024)

The Digital Elevation Model (DEM) data released by NASA in February 2020, derived from original telemetry data from the Shuttle Radar Topography Mission (SRTM), was enhanced with an improved algorithm [37]. This NASA DEM incorporates data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3 and ICESat to enhance surface elevation measurements and geolocation accuracy. The void areas within the NASA DEM were filled using GDEMs and the Advanced Land Observing Satellite Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) AW3D30 DEM, supplemented by interpolation techniques. The spatial resolution of the NASA DEM is approximately 1 arc-second (~30 m). In this study, NASA DEM data primarily serve to analyze the elevation distribution of snow cover dates.

The precipitation dataset utilized in this study is the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG). IMERG is a Level 3 precipitation product derived from the GPM satellite, categorized into Early Run, Late Run, and Final Run based on timeliness, with delays of 4 h, 12 h, and 3.5 months, respectively, with data quality improving accordingly [38]. For this paper, the GPM IMERG Final Precipitation L3 1 month V07 dataset spanning from 2003 to 2020 is employed. Additionally, the fifth-generation ECMWF atmospheric reanalysis of global climate (ERA5) land is a reanalysis dataset offering a consistent perspective on the evolution of land variables over several decades at an enhanced resolution of 9 km compared to ERA5 (31 km). The temporal resolution of ERA5 Land is one hour [39]. This study utilizes the 2 m surface temperature data from the ERA5 Land dataset, covering the years 2003 to 2020, to analyze temperature variations in the Tibetan Plateau region.

2.3. Methods

2.3.1. Snow Product Processing

The Hydrological Year (HY) is defined as spanning from September to August of the subsequent year. The four seasons—spring, summer, autumn, and winter—encompass March to May, June to August, September to November, and December to February of the following year, respectively. Snow cover duration denotes the number of days a designated pixel remains covered by snow within a given hydrological year (Equation (1)). The start date of snow cover is determined as the initial date within an HY when there are five consecutive days of snow cover. Similarly, the end date of snow cover is identified as the final date within the HY where there are five consecutive days of snow cover. For this study, both the start and end dates of snow cover span from 1 to 365.

$$SCD = \sum_{i=1}^n S_i \quad (1)$$

where SCD ranges from 0 to 365 (or 366 in leap years), and n represents the total number of days within the HY. When a pixel is covered by snow, S_i is equal to 1; otherwise, S_i is equal to 0. In the snow product used in this study, a pixel is assigned a value of 1 when covered by snow, and 0 otherwise.

2.3.2. Linear Regression

The linear trend of meteorological data is estimated using a linear regression model, which can be expressed as follows:

$$x_i = a \cdot t_i + b \quad (2)$$

where a is the regression coefficient; b is the regression constant; i is the serial number; t_i is the time x_i ; x_i is time-series data corresponding to t_i , i.e., temperature, precipitation, etc., in this work. The coefficients of a and b can be estimated by the least squares method as follows:

$$b = \frac{\sum_{i=1}^n x_i t_i - \frac{1}{n} (\sum_{i=1}^n x_i) (\sum_{i=1}^n t_i)}{\sum_{i=1}^n t_i^2 - \frac{1}{n} (\sum_{i=1}^n t_i)^2} \quad (3)$$

$$a = \frac{1}{n} \sum_{i=1}^n x_i - b \frac{1}{n} \sum_{i=1}^n t_i \quad (4)$$

where n is the total number of data. The coefficient of a (i.e., slope) represents the linear trend, and $a > 0$ indicates an upward trend, while $a < 0$ means a downward trend. The magnitude of a reflects the rate of rise or fall as a trend.

3. Results

3.1. Temporal and Spatial Variations in Snow Cover Duration

3.1.1. Overall Trends in Snow Cover Duration (SCD)

Strong spatial heterogeneity of snow cover variation is observed in Figure 2. The elevated SCD was observed in the southern and northwestern mountainous regions, including the Yarlung Zangbo River Basin near the Nyenchen Tanglha Mountains and the Tarim Basin in the northwest, where SCD can exceed 180 days. Similarly, in the western and northeastern sectors of the plateau, such as the Hexi Corridor Basin, SCD hovers around 100 days, signifying these areas as primary stable snow cover zones. In contrast, the central plateau exhibited comparatively lower SCD, with inland basins, like the Chaidamu Basin, and sections of the Hengduan Mountains displaying minimal snow cover throughout the year. This phenomenon was ascribed to the surrounding high mountain topography impeding moisture influx, resulting in diminished precipitation and elevated temperatures, thereby posing challenges for sustained snow cover. The average annual SCD on the Tibetan Plateau registers at 45.2 days. Over the study period, the overall SCD has depicted relative stability, indicating a subtle declining trend. Before 2014, the variability in annual SCD remained relatively steady (Standard Deviation, $SD = 4.72$), averaging approximately

32 days. However, a greater fluctuation in annual SCD was evident ($SD = 12.34$) after 2014. The minimum SCD was recorded in 2016 (31.4 days), while the maximum occurred in 2019 (63.4 days).

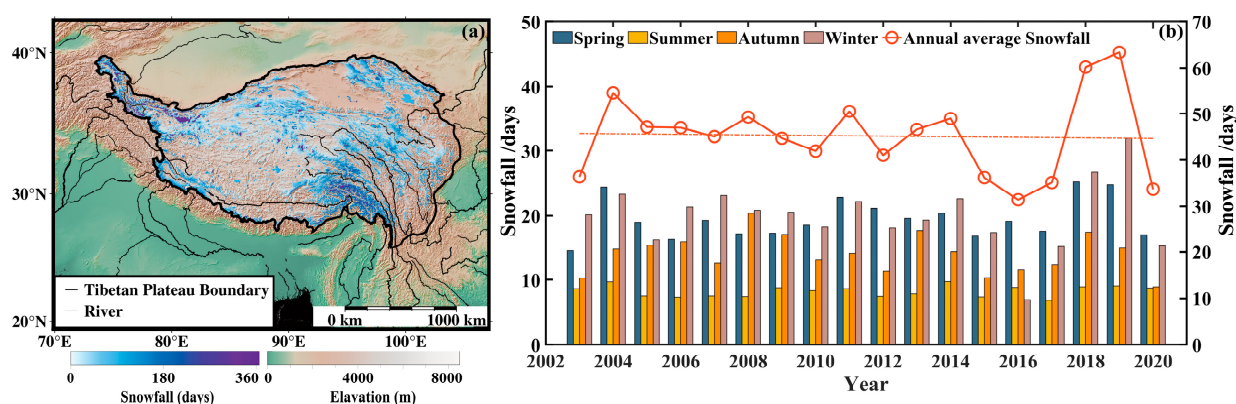


Figure 2. Spatial distribution (a) and temporal (b) characteristics of annual snow cover duration on the Tibetan Plateau (2003–2020 hydrological years). Both the left and right axes of the line chart (right) represent the number of snowfall days, and the left y -axis represents snowfall days in a particular season, while the right y -axis represents snowfall days in a hydrological year. The red dotted line represents the line trend of annual average snowfall days (non-significant).

From a seasonal perspective, snow cover predominantly occurred in spring and winter, with each season accounting for approximately 20 days, collectively representing 32% of the total annual snow cover duration. The variability in annual snow cover duration exhibited a strong correlation with changes in winter snow cover duration (correlation coefficient, $CC = 0.87$), followed by spring ($CC = 0.76$) and autumn ($CC = 0.67$), while the lowest correlation was observed in summer ($CC = 0.36$). This underscores the primary influence of winter snow cover on the annual snow cover duration. Notably, in 2016, the annual snow cover duration reached its nadir, coinciding with the lowest winter snow cover duration (6.94 days), which even descended below the duration of summer snow cover.

3.1.2. Variations in Onset Date and End Date of Snow Cover

The snow onset date (SOD) and snow end date (SED) showed notable spatial heterogeneity across the Tibetan Plateau (Figure 3). The SOD typically occurred after around 120 days and extended beyond approximately 220 days. In select areas within the southern part of the plateau's inland basins, the SOD might occur later than 120 days, persisting into the subsequent January. Conversely, in the southern and northwestern regions of the plateau, the SOD tended to be earliest, generally occurring around 60 days prior. In specific locations, such as the southeastern section of the Yarlung Zangbo River Basin and the western portion of the Tarim Basin, the SOD may even be preceded by more than 30 days. Furthermore, in these regions, the SED also extended later, typically around 300 days (early summer of the following year), with perennial snow cover areas enduring until the end of the ensuing summer. In the western reaches of the Tibetan Plateau, the SOD typically ranged from 30 to 60 days before, with snow cover persisting until around 270 days (early spring of the following year). Conversely, in the central and northeastern sectors of the plateau, the SOD tended to be delayed, while the end date was earlier. For instance, within the Hexi Corridor Basin and the Yellow River Basin, certain areas may witness snow accumulation that begins in winter but ends in early spring of the following year.

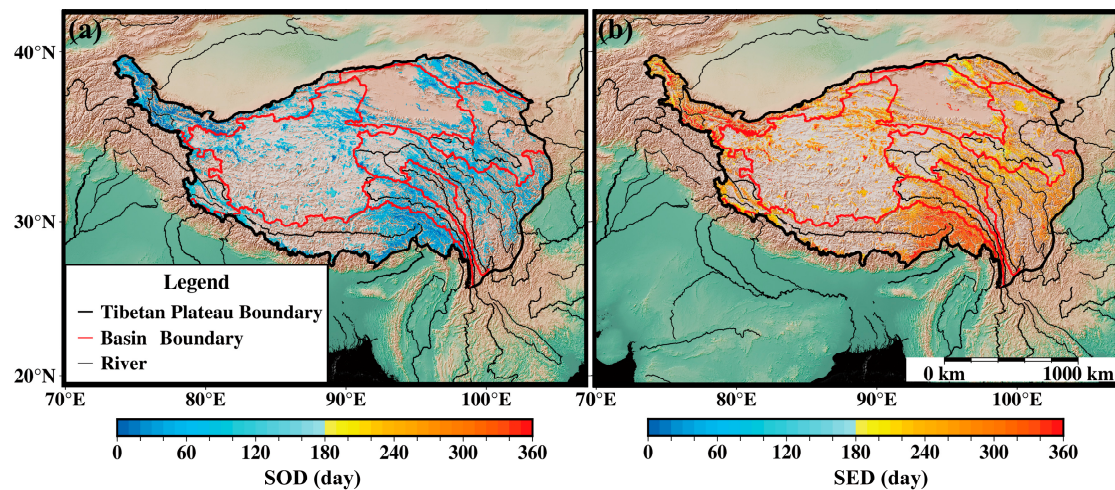


Figure 3. The spatial distribution of the SOD (a) and SED (b) across the Tibetan Plateau.

3.1.3. Altitude Distribution Characteristics of SCD, SOD, and SED Changes

Accompanied by an earlier SOD, the SCD increased with elevation, while no significant delay in SED was observed (Figure 4). The highest SCD was observed at elevations exceeding 6000 m, with an annual average value of approximately 297 days, significantly exceeding the durations in other elevation zones. Below 5000 m, SCD demonstrated an increasing trend, whereas above 5000 m, a decreasing trend was evident in SCD.

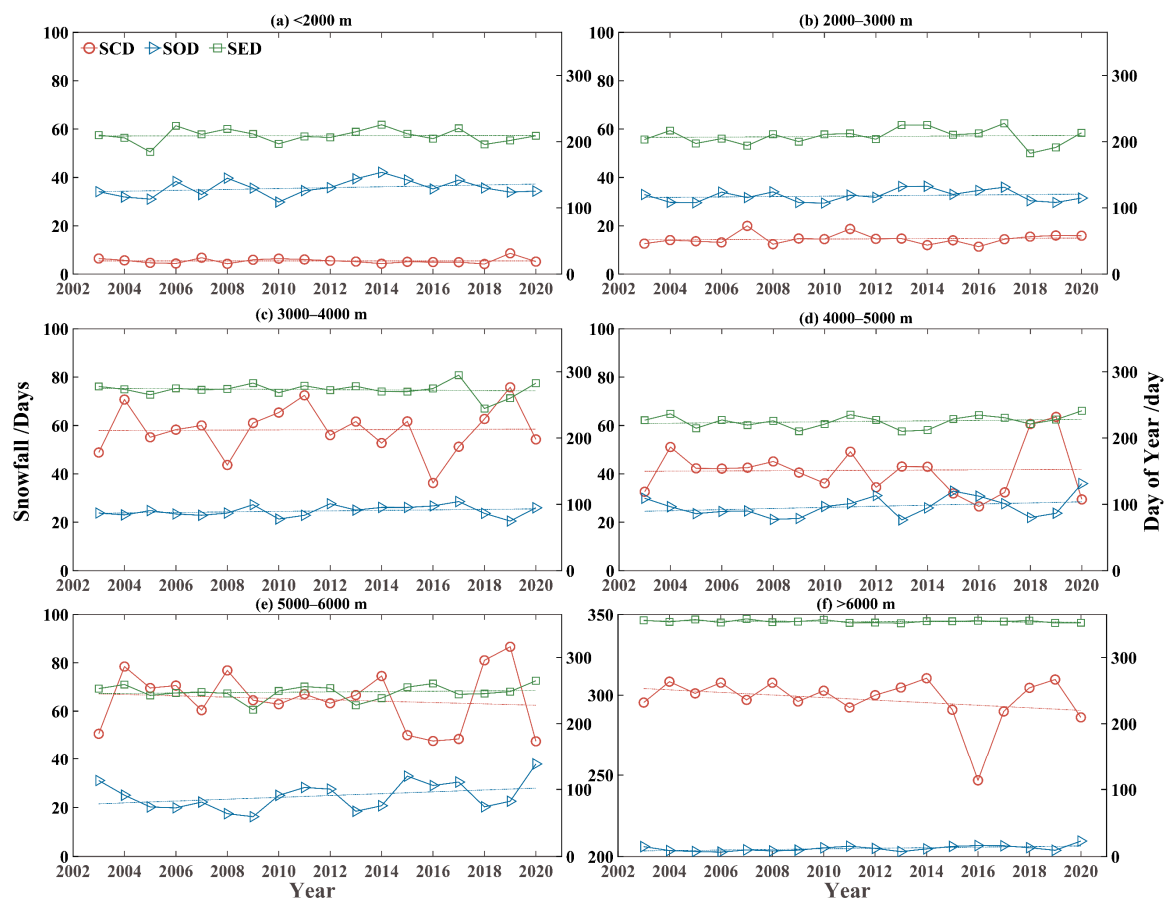


Figure 4. The variations in SCD in different altitude bins of the Tibetan Plateau during the hydrological years of 2003–2020. The SOD (subfigure(f)) shows a significant increasing trend ($p < 0.05$, F test), and the other trends are non-significant.

3.2. Snow Cover Variations in Sub-Basins of the Tibetan Plateau

Figure 5 illustrates the variation in snow cover duration across the ten major basins of the Tibetan Plateau. Overall, the Tarim Basin had the highest average annual SCD, lasting up to 83 days, with significant snowfall throughout all four seasons (SCD exceeding 20 days for each season). In contrast, the Yellow River Basin exhibited the lowest average annual SCD, with an average of only 31 days, mostly occurring in winter (15 days). Furthermore, most basins showed a decreasing trend in average annual snow cover duration, including the Hexi Corridor Basin, Salween River Basin, Tarim Basin, Yarlung Zangbo River Basin, Indus River Basin, and Yangtze River Basin. Among them, the Tarim Basin experienced the most rapid decline rate at -0.49 days/a. The average annual SCD showed an increasing trend in the Yellow River Basin and the Qaidam Basin, while it tended to remain stable in the inland basins. On an interannual scale, the maximum SCD on the Tibetan Plateau was mainly concentrated in 2003 (e.g., the Yellow River Basin and the inland basin), 2016 (e.g., the Qaidam Basin, the Tarim Basin, the Yarlung Zangbo River Basin, and the Indus River Basin), and 2020 (e.g., the Hexi Corridor Basin, the Mekong River Basin, the Salween River Basin, and the Yangtze River Basin). In terms of seasons, SCDs were generally similar in spring and winter in most basins, including the Qaidam Basin, the Hexi Corridor Basin, the Yellow River Basin, and the inland basins. SCDs showed a decreasing trend ($p < 0.10$, F test) in autumn (eight basins) and winter (six basins), while an increasing trend ($p < 0.10$, F test) was observed in the spring (nine basins) and summer (eight basins).

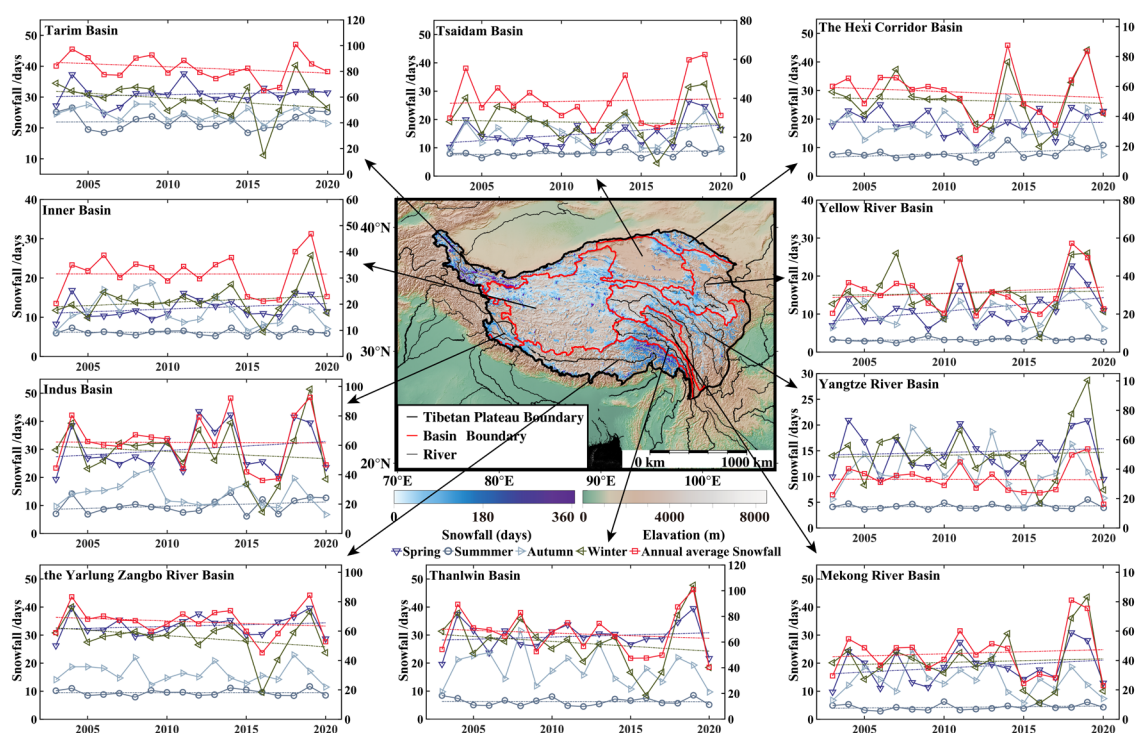


Figure 5. The characteristics of SCD changes in the Tibetan Plateau from 2003 to 2020 (hydrological year). Both the left and right axes of the line charts represent the number of snowfall days, and the left y -axis represents snowfall days in a particular season, while the right y -axis represents snowfall days in a hydrological year. The trend of SCD in the Tarim Basin (Autumn) is significantly decreasing ($p < 0.10$, F test), and trends of SCD in the Tsaidam Basin (Spring), Yellow River Basin (Spring), and Hexi Corridor Basin (Summer) are significantly increasing ($p < 0.10$, F test). The other trends of SCD are non-significant.

Figure 6 shows the spatial distribution of SCD across seasons. Generally, SCD increased from autumn to winter, and then reached its maximum in spring, with the area extending from the surrounding areas of the plateau towards the central regions. As in

most areas experiencing snowmelt in summer, the SCD sharply decreases. However, the high-altitude regions in the northwest and south of the Tibetan Plateau maintain year-round snow cover due to their low temperature. In terms of the basins, both the Tarim Basin and Yarlung Zangbo River Basin experience relatively high snow cover durations throughout the year. SCD exceeded 60 days in some areas of the inner basin, even in summer. Snow cover durations were high during the snow seasons (i.e., spring, autumn, and winter) in eastern regions, like the Hexi Corridor Basin, but relatively low in summer. Contrarily, the Tarim Basin and Yarlung Zangbo River Basin maintain some amount of snow cover almost year round. Overall, in the Inner Basin and the Qaidam Basin, snow cover durations typically rank in the order of winter > spring > autumn, whereas the extent of snow cover follows the order of spring > winter > autumn. The snow accumulation generally begins in autumn and thus the area presents a minimum. Despite a low temperature in winter, scarce precipitation hindered the expansion of snow cover. With rising temperature in spring, snow began to melt and resulted in a decrease in SCD. Moreover, increased precipitation promoted the expansion of snow cover once again to some extent.

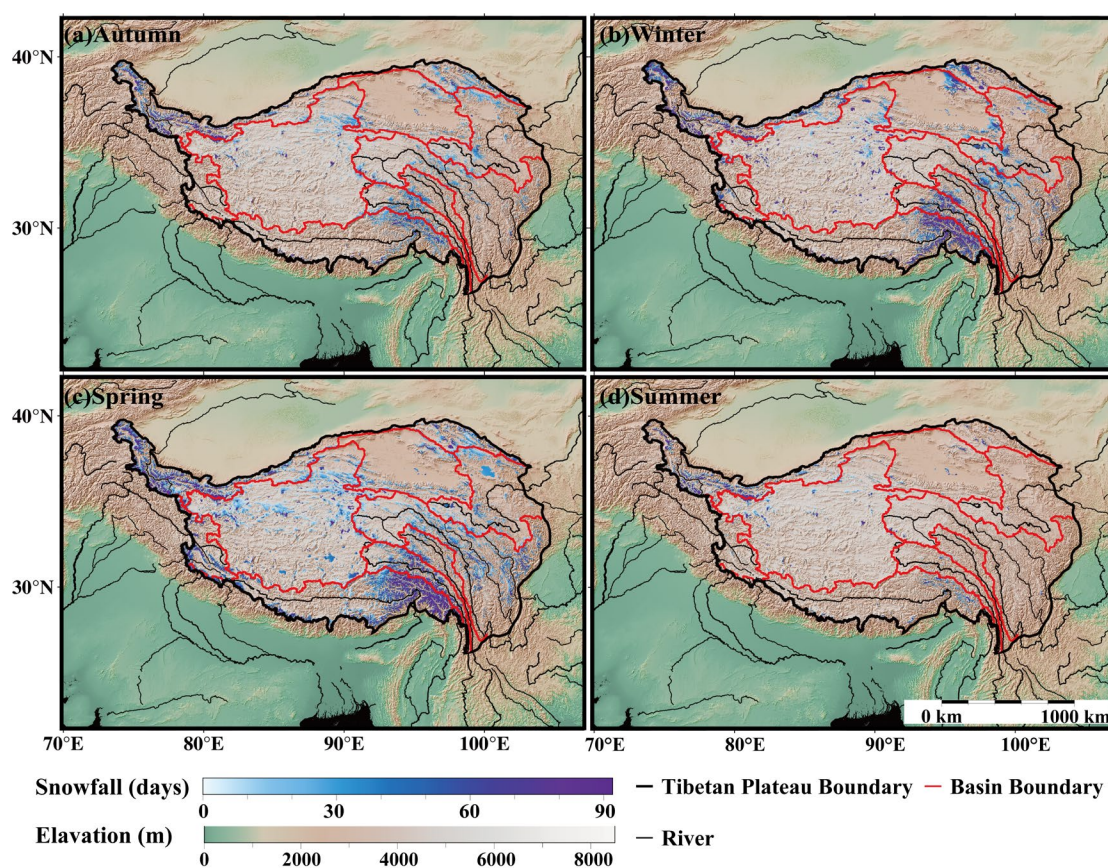


Figure 6. The spatial distribution of SCD across seasons from 2003 to 2020 (hydrological year) on the Tibetan Plateau.

3.3. The Response of Snow Cover Variability to Climate Change

The dynamic change mechanisms in snow cover on the Tibetan Plateau are fairly complex. Meteorological factors, such as temperature and precipitation, primarily govern snow accumulation and melting [25,30,40]. Figure 7 shows the annual and seasonal variations in temperature and precipitation from 2003 to 2020. The Tibetan Plateau has experienced an overall surface air warming and moistening, characterized by gradual increases in temperature and precipitation from west to east. The northwestern region has the lowest temperature and the most arid conditions, whereas the southeastern region exhibits a higher temperature and more abundant precipitation. The annual mean temperature was

around 1.23 ± 0.48 °C, increasing at a rate of 0.17 ± 0.54 °C/10a, lower than the global warming rate [41]. The temperature span ranged from a minimum of 0.26 °C in 2018 to a maximum of 2.03 °C in 2020. The annual mean precipitation was 421.5 ± 34.26 mm, with an increasing rate of 3.09 ± 3.81 mm/a ($p < 0.05$, F test). Compared to precipitation, the temperature had a stronger impact on the annual snow cover changes on the Tibetan Plateau ($CC = -0.67$), particularly during 2019 and 2020, as the highest temperature was observed (2.03 °C) and the snow cover days decreased by half (nearly 30 days).

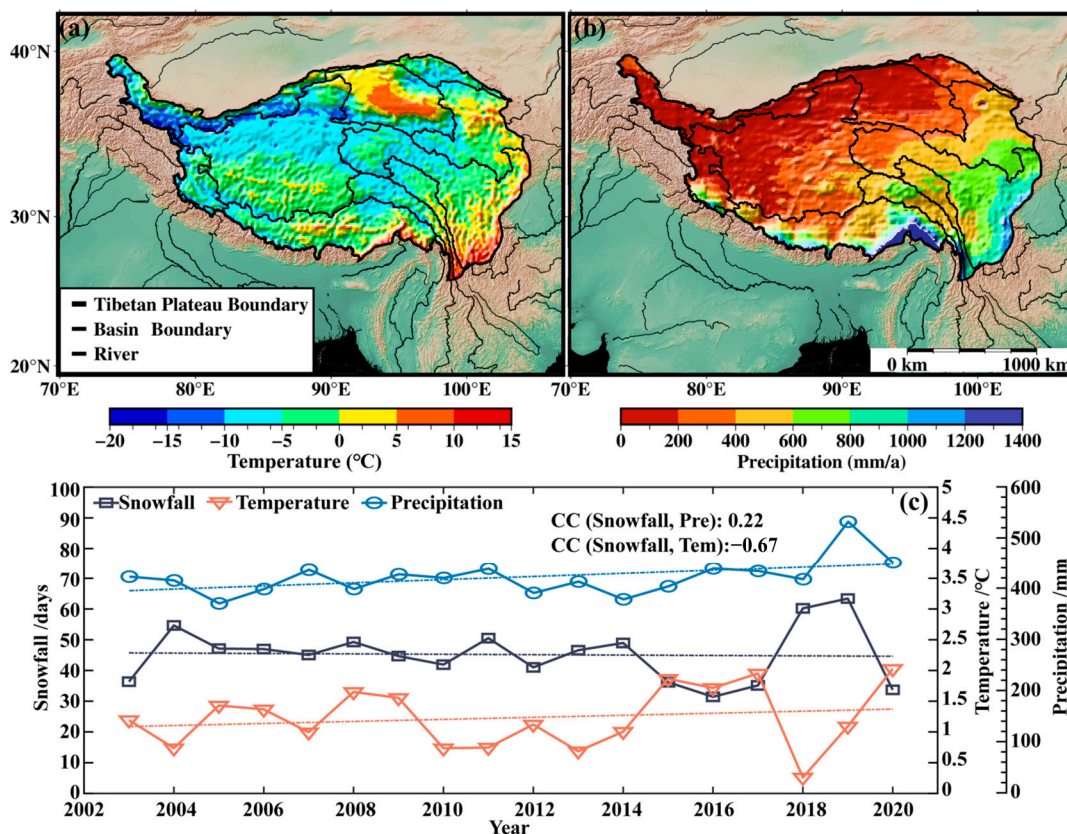


Figure 7. Spatial distribution of temperature (a) and precipitation (b) on the Tibetan Plateau from 2003 to 2020 (hydrological year), and the trend changes in snow cover days, temperature, and precipitation variation (c). Both the precipitation and temperature show increasing trends, with the former presenting statistically significant ($p < 0.05$, F test), while the snowfall showed a decreasing trend (non-significant).

Figure 8 illustrates the seasonal variations in temperature and precipitation. Temperature showed a decreasing trend during spring (-0.11 ± 0.07 °C/10a) but an increasing trend during autumn (0.48 ± 0.79 °C/10a). This may be the reason as to why the amount of snow cover days was higher in spring than in autumn and there was a decreasing trend of snow cover days in autumn. The temperature had the most significant impact on snow cover days ($CC = -0.74$) in spring compared to other seasons, which is consistent with previous studies [42]. During the summer season, the temperature reached a peak at an average value of around 11 °C. Meanwhile, precipitation peaked at 248.25 ± 25.20 mm, which accounts for approximately half of the annual precipitation. Due to the rapid rise in temperature over summer, snow melting occurred, resulting in a sharp decrease in snow cover days. However, the ample precipitation partly mitigated the impact of the temperature rising; hence, snow cover days remain relatively stable during summer. Contrastingly, during winter, the temperature drops to its lowest (<0) and precipitation shows a minimum of 16.60 ± 4.33 mm. Moreover, precipitation increased at the slowest rate (0.09 ± 0.48 mm/a) during this season. The precipitation shows a stronger correlation

($CC = 0.70$) with snow cover days compared to temperature ($CC = -0.68$), indicating its dominant role in influencing snow change.

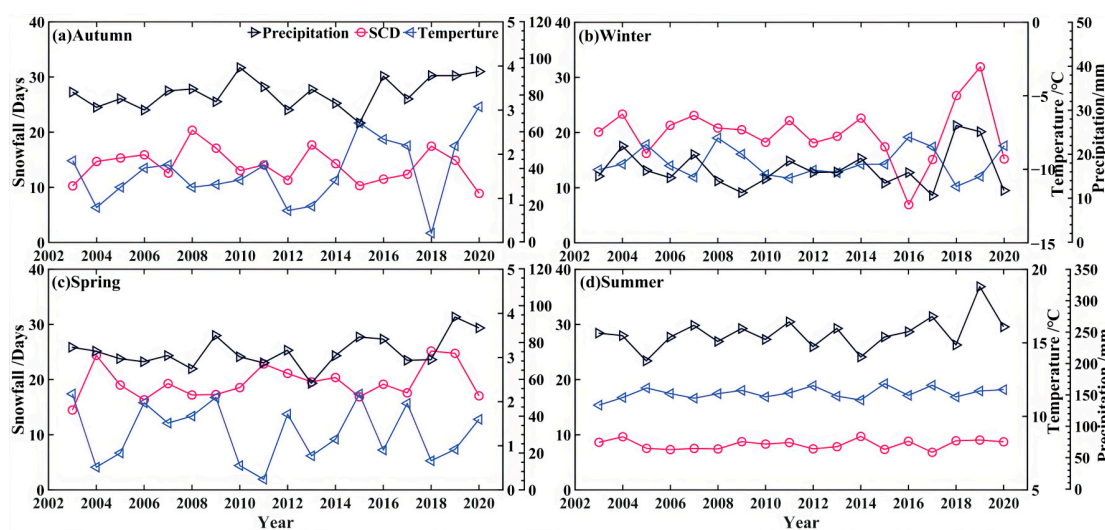


Figure 8. The trend changes in seasonal snow cover days and meteorological factors on the Tibetan Plateau during the hydrological years from 2003 to 2020.

4. Discussion

Significant spatial heterogeneity and seasonality in the SCD over the Tibetan Plateau were observed in this study. Spatially, a longer SCD is predominantly concentrated in the southeastern and northwestern parts of the Tibetan Plateau. This mostly resulted from a higher altitude and lower temperature, providing suitable conditions for snow cover in the northwestern Tibetan Plateau. The monsoon resulted in increased precipitation, which is a further contribution to snow accumulation in the region. Seasonally, significant seasonal variability could be attributed to the similar temperatures occurring between spring and winter. In early spring, there might be lower temperatures, same as those in winter, and then precipitation may supplement snow as rain with temperature rising during late spring. Thus, the SCD seems to be close between these two seasons. We also found that temperature has a greater influence on the SCD than precipitation most of the time. The exception is in the winter when precipitation plays a dominant role in SCD. This might be because the temperature was consistently below 0°C during winter, which made the impact of temperature rise on snow melting less significant compared to other seasons. Precipitation, occurring as snow, effectively replenishes the snow cover during this time. Hence, precipitation has a greater influence on SCD compared to temperature during winter.

Due to the complex terrain conditions and the differences in climate patterns among the plateau's internal basins, it is essential to assess the snow cover changes more accurately and comprehensively in various subbasins. The Tarim Basin exhibits the longest SCD among these subbasins, which may be attributed to the proximity of the Tarim Basin to the Kunlun and Karakoram Mountains, where glaciers are abundant and temperature is low, facilitating prolonged snow accumulation. Contrarily, the adjacent region of the Inner Basin shows less snow cover (Figure 5). This is mostly because the Karakoram and Kunlun Mountains slow the westerlies, thus impeding snow accumulation. The Yellow River Basin has a dry climate (i.e., low precipitation and high temperature), which is less conducive to snow accumulation, hence resulting in a shorter SCD. Overall, although these subbasins are geographically adjacent, they display various climate and terrain conditions, thus leading to different changes in snow cover. A detailed analysis of subbasins, not the whole Tibetan Plateau, is helpful for regional water resource management.

A number of previous studies have analyzed the changes in snow cover on the Tibetan Plateau using various datasets (Table 2). Although You et al. [17] and Yang et al. [43] achieved long-term observations of snow cover changes using station data and multi-source remote sensing data, they focused more on the relationship between snow depth and SCD and did not consider the influence of climate change on snow cover. Meanwhile, spatial variations in snow cover within the Tibetan Plateau remain important to consider. Jin et al. [31] and Wang et al. [29] accounted for spatial variations, but they did not delve into the specific basins within the Tibetan Plateau. Moreover, the influence of climate on snow cover was overlooked in studies of Pu et al. [28], You et al. [17], and Yang et al. [43]. This study explored the SCD conditions across the Tibetan Plateau and 10 subbasins, and analyzed the response of SCD to climate change throughout the year and across different seasons using meteorological data. This deepened our understanding of the hydrological cycle in the Tibetan Plateau, providing a scientific basis for water resource management in the Tibetan Plateau and surrounding areas, and offering valuable references for related research.

Table 2. Comparison of this study with the previous study.

Source	Dataset	Period	Result
This study	HMRFS-TP: long-term daily gap-free snow cover products over the Tibetan Plateau and Daily cloud-free MODIS NDSI and snow phenology dataset over High Mountain Asia (2000–2021)	2003–2020	Trend (SCD): -0.06 days/a; Location (High SC): Southeast and Northwest of TP; CC (SCD, Pre): 0.70 (Winter); CC (SCD, Tem): -0.74 (Annual);
Pu et al. (2007) [28]	MODIS snow cover data	2000–2006	Trend (SCF): -0.34% /a; Location (High SC): South and Northwest of TP
You et al. (2011) [17]	In situ data of snow depth and days	1961–2005	Trend (SCD) in Winter: 0.40 days/10a (1961–1990), -1.59 days/10a (1991–2005);
Wang et al. (2015) [29]	Daily cloud-free snow-cover products based on MODIS and AMSR-E data	2003–2010	Trend (SCD): Slightly Decrease (Qualitative)
Li et al. (2018) [30]	MODIS snow cover data	2001–2014	Trend (SCF): -0.08% /a; CC (SC, Pre): -0.35 ; CC (SC, Tem): 0.05 ; Location (High SCD): South and Northwest of TP;
Jin et al. (2022) [31]	Long time-series data of snow cover area on Qinghai–Tibet Plateau dataset	2003–2014	CC (SCR, Pre): -0.07 ; CC (SCR, Tem): -0.52 ; Location (High SC): Southeast of TP
Yang et al. (2023) [43]	Multi-source data fusion snow cover dataset	2000–2021	Trend (SCD): -1.5 days/a (Southeast of TP); Trend (SCD): 2.1 days/a (Northwest of TP); Location (High SC): Northwest of TP

Note: “TP” is Tibetan Plateau; “SC” means snow cover; and High SC shows the large area of snow cover; “SCD” represents snow cover duration; “SCF” means snow cover fraction, which is the percentage of the snow cover area to the total area; “SCR” is snow cover ratio, which is the ratio of the snow cover time of a certain pixel to the total time.

5. Conclusions

This study analyzes the spatiotemporal characteristics of snow cover days on the Tibetan Plateau from 2003 to 2020 using HMRFS-TP, ERA5-Land, and GPM IMERG datasets, and further explores the relationship between meteorological changes (precipitation and temperature) and snow cover variations. The findings are as follows:

- (1) The average annual SCD on the Tibetan Plateau is 45.2 days, showing a slight downward trend. SCD is longer in spring (19.5 days) and winter (20.0 days), but shorter in summer. The snow cover presents significant spatial heterogeneity over the Tibetan Plateau, with SCD exceeding 180 days in the southern and northwestern regions, but 0 days in the central plateau.
- (2) The snow cover is significantly different in the various plateaus' inner basins, although they are geographically adjacent. The Tarim River Basin records the highest average annual SCD (83 days), while the adjoining area of the Inner Basin shows less snow cover (32 days). The Yellow River Basin has the lowest (31 days), especially in winter (15 days).
- (3) The Tibetan Plateau is experiencing surface air warming and moistening, with the annual mean temperature rising at a rate of 0.17 ± 0.54 °C/10a and the annual mean precipitation increasing at a rate of 3.09 ± 3.81 mm/a. Temperature has a greater impact on snow cover changes ($CC = -0.67$) compared to precipitation. However, precipitation has a greater influence on SCD ($CC = 0.70$) than temperature in winter.

This study will improve the understanding of snow cover variations and provide insights into the region's hydrological cycle. Further, it will contribute to broader efforts aimed at enhancing climate resilience, informing sustainable resource management practices, and safeguarding the ecological integrity over the Tibetan Plateau and its subbasins.

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