Post-print of Spatiotemporal Variations and Climate Attribution of Snow Depth in the Sanjiangyuan Region from 1980 to 2020 Based on Remote Sensing Monitoring

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Abstract

Snow cover changes in the Sanjiangyuan region have significant impacts on regional and even global climate, hydrological cycles, and ecosystems. However, research systematically monitoring long-term snow depth dynamics and climate attribution across different sub-regions and elevation zones based on remote sensing data remains relatively scarce. This study analyzed the spatiotemporal variation patterns of snow depth in the Sanjiangyuan region from 1980 to 2020 using remote sensing data across sub-regions and elevation zones, and quantified the relative contributions of temperature and precipitation. The results indicate that: (1) Over the past 41 years, snow depth in the Sanjiangyuan region has exhibited significant spatial differences, with average snow depth in high-altitude mountain areas generally exceeding 3 cm and maximum snow depth generally exceeding 6 cm. Average snow depth and maximum snow depth decreased significantly at rates of 0.15 $\text{cm}\cdot(10\text{a})^{-1}$ and 0.49 $\text{cm}\cdot(10\text{a})^{-1}$, respectively; 68.44% of the average snow depth and 63.83% of the maximum snow depth showed a decreasing trend, with significantly decreasing areas accounting for 15.64% and 7.47%, respectively. (2) There are distinct regional and altitudinal differences in snow depth and its variations. The Lancang River source region had the highest average and maximum snow depths (2.41 cm and 9.86 cm, respectively) and the fastest decreasing rates, reaching 0.37 $\text{cm}\cdot(10\text{a})^{-1}$ and 0.81 $\text{cm}\cdot(10\text{a})^{-1}$, respectively. Snow depth increased with elevation, with vertical gradients for average and maximum snow depth being 0.49 $\text{cm}\cdot\text{km}^{-1}$ and 1.29 $\text{cm}\cdot\text{km}^{-1}$, respectively. Except for the 3.5–4.5 km and above 6.0 km elevation zones, the average snow

depth in all other elevation zones showed a decreasing trend; except for the 3.5–4.5 km zone, the maximum snow depth in all other elevation zones also showed a decreasing trend, with the fastest decrease occurring in the 5.0–5.5 km elevation zone. (3) The significant "warming and wetting" climate in the Sanjiangyuan region over the past 41 years is the primary factor leading to the decrease in snow depth, with temperature being the main driving factor. Its influence varies by region and elevation, and the decrease in snow depth is closely related to climate warming, especially in low-altitude (<3.5 km) and high-altitude (>4.5 km) areas. The research results provide a scientific basis for the optimal allocation of snow water resources, ecosystem protection and restoration, and the prediction of regional climate change trends in the Sanjiangyuan region.

Full Text

Preamble

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Spatiotemporal Variations and Climate Attribution of Snow Depth in the Sanjiangyuan Region from 1980 to 2020 Based on Remote Sensing Monitoring

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Abstract: Changes in snow cover in the Sanjiangyuan region have profound impacts on regional and global climate, hydrological cycles, and ecosystems. However, systematic studies monitoring long-term snow depth dynamics and climate attribution across different sub-regions and altitudinal zones using remote sensing data remain scarce. This study analyzed the spatiotemporal variation patterns of snow depth in the Sanjiangyuan region from 1980 to 2020 using remote sensing data and quantified the relative contributions of temperature and precipitation. The results indicate significant spatial heterogeneity in snow depth across the region. In high-altitude mountain areas, the average snow depth generally exceeds 2.41 cm, and the maximum snow depth is typically greater than 9.86 cm. Both average and maximum snow depth exhibited a decreasing trend, with decline rates of $-0.15\ \text{cm}\cdot(10\text{a})^{-1}$ and $-0.49\ \text{cm}\cdot(10\text{a})^{-1}$, respectively. Areas showing significant decreases accounted for 7.47% of the average snow depth and 15.64% of the maximum snow depth. Snow depth and its variations showed distinct regional and altitudinal differences; the Lancang River source area exhibited the highest average and maximum snow depths, as well as the fastest rates of decline, reaching $-0.37\ \text{cm}\cdot(10\text{a})^{-1}$ and $-0.81\ \text{cm}\cdot(10\text{a})^{-1}$, respectively. Snow depth generally increased with altitude, with vertical gradients of 0.49 $\text{cm}\cdot\text{km}^{-1}$ for average snow depth and 1.29 $\text{cm}\cdot\text{km}^{-1}$ for maximum snow depth. Except for the zone above 6.0 km, average snow depth decreased across all altitudinal zones. Similarly, maximum snow depth decreased in all zones except for the 3.5–4.5 km range, with the fastest decrease occurring in the 5.0–5.5 km zone. The significant "warming and wetting" climate in the Sanjiangyuan region is the primary factor leading to the reduction in snow depth, with temperature acting as the dominant driver. The influence of these factors varies by region and altitude, and the reduction in snow depth is closely linked to climate warming, particularly in low-altitude ($<$ 3.5 km) and high-altitude ($>$ 4.5 km) areas. These findings provide a scientific basis for the optimal allocation of snow water resources, ecosystem protection and restoration, and the prediction of regional climate change trends in the Sanjiangyuan region.

Keywords: Sanjiangyuan region; snow depth; climate change; remote sensing monitoring

Snow cover is a critical component of the cryosphere, widely distributed across the mid-to-high latitudes of the Northern Hemisphere and in alpine regions. It significantly influences energy, water, and material cycles, playing a vital regulatory role in regional and global water resources, ecological environments, and climate change [**?**]. As one of the most active natural elements on the Earth' s surface, it is considered a key indicator of climate change [**?**]. Snow depth is a fundamental physical property of snow cover that reflects not only the extent of the snow but also its mass [**?**]. Therefore, accurately obtaining and monitoring snow depth information is essential for understanding climate change and its environmental impacts.

The Sanjiangyuan region is one of the largest ice and snow storage areas on the Qinghai-Tibet Plateau. It serves as the source of several major rivers, including the Yangtze, Yellow, and Lancang Rivers, earning it the title "China' s Water Tower." It is also a "sensitive area" and "trigger zone" for East Asian and global climate change. With an extremely fragile ecosystem [**?**], it serves as a crucial ecological barrier and water conservation area for China and Asia, holding a unique strategic position in national ecological security [**?**]. Its spatiotemporal snow cover dynamics have far-reaching effects on regional and global climate, hydrological cycles, and ecosystems [**?**]. In the context of climate change, the Sanjiangyuan region has experienced a significant warming trend over the past few decades, with an average warming rate of 0.37 $^\circ\text{C}\cdot(10\text{a})^{-1}$. This rate far exceeds the global average and is significantly higher than the averages for similar latitudes and other regions in China.

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Clarifying the spatiotemporal variation patterns of snow depth in the Sanjiangyuan region and quantifying its response to climate change can provide data support for snow water resource regulation and ecological environmental protection in this region.

Research on the spatiotemporal variations and climate attribution of snow cover in the Sanjiangyuan region mostly began in the 1950s, primarily based on meteorological station observations. Studies have shown that since the 1950s, snowfall in the Sanjiangyuan region has been decreasing at a rate of $-14.8\ \mathrm{mm} \cdot (10\mathrm{a})^{-1}$. The period before the 1990s was characterized by higher snowfall, while the period since the 1990s has seen lower snowfall [?]. However, there are only 15 meteorological stations in the Sanjiangyuan region. These stations are sparse, unevenly distributed, and lack spatial continuity, making it difficult to achieve continuous monitoring of large-scale snow cover dynamics. Furthermore, the limited spatial representativeness of these stations can affect the reliability of research results.

In recent years, with the development of satellite remote sensing technology, passive microwave remote sensing has overcome the limitations of traditional station observations regarding spatial continuity and temporal consistency, becoming the mainstream technology for snow depth monitoring [?]. Microwave remote sensing data indicate that from 1980 to 2010, snow cover changes in the Sanjiangyuan region were characterized by a decrease in the number of snow days and snow depth, along with a trend of delayed start dates and earlier end dates for snow cover [?]. Conversely, MODIS data results suggest that since 2000, the Sanjiangyuan region has shown a trend of increasing snow cover area, more snow days, and thickening snow depth [?, ?]. These changes are closely related to rising temperatures and shifting precipitation patterns under global warming. The IPCC assessment reports point out that the reduction of seasonal snow cover due to "warming and wetting" is a common phenomenon in high-altitude regions. Rising temperatures accelerate snowmelt; in the Northern Hemisphere spring, for every 1 °C increase in global mean surface temperature, the snow cover area decreases by approximately 7% ~ 10%. Additionally, the shift in precipitation from snow to rain reduces snow accumulation [?]. Furthermore, topographic factors such as altitude, slope, and aspect indirectly influence snow distribution and variation by affecting temperature, precipitation, and solar radiation [?].

Although the academic community has reached a preliminary consensus on the complex spatiotemporal patterns of climate factors' influence on snow cover in the Sanjiangyuan region, significant uncertainties remain in mechanistic understanding due to limitations in models and observational data. On one hand, previous studies have mostly relied on station observations or short-term remote sensing data after 2000, lacking a systematic analysis of long-term snow depth dynamics, particularly regarding sub-regional and altitudinal variation patterns and their climate driving mechanisms. On the other hand, some studies have pointed out that macro-scale snow depth dynamics and driving mechanisms in the Sanjiangyuan region require further investigation to provide a scientific basis for the optimal allocation of snow water resources, ecosystem restoration, and regional climate trend prediction.

1.1 研究区概况

The Sanjiangyuan region is situated in the heart of the Qinghai-Tibet Plateau, covering an area of approximately 30.25×10^4 km^2 with an average elevation exceeding 4000 m. The topography of the region follows a gradient that is higher in the northwest and lower in the southeast, characterized primarily by vast mountainous landscapes with undulating ranges and rugged, complex terrain.

The area features an intricate network of rivers, numerous scattered lakes, and widely distributed marshy wetlands, alongside extensive coverage of snow-capped mountains and glaciers. The region is characterized by a typical plateau continental climate. Surface cover primarily consists of alpine grasslands, wetlands, glaciers, and permanent snow cover. Seasonal and permanent snow accumulation is concentrated along the high-altitude mountain ranges stretching from the Hoh Xil Mountains to the Geladandong Glacier [Figure 1: see original paper].

1.2.1 遥感雪深数据使用"中国雪深长时间序列

The snow depth data used for analysis was obtained from the National Tibetan Plateau Data Center (https://poles.tpdc.ac.cn). This dataset provides daily snow depth at a spatial resolution of 25 km. To facilitate the study, the data were resampled to a finer spatial resolution using bilinear interpolation.

Based on the "Dataset of spatial representativeness evaluation of snow depth observations from meteorological stations," we selected stations in the Three-River Source Region (TRSR) with high spatial representativeness (Fig. 1) to evaluate the accuracy of the remote sensing dataset using daily ground observations. The results indicate that the annual mean remote sensing snow depth and ground-observed snow depth in the TRSR are correlated, with a Root Mean Square Error (RMSE) of 1.69 cm. The scatter plot is biased toward the vertical axis with a slope of 0.36. At the station level, the correlation coefficients between the annual mean remote sensing snow depth and ground observations for Zeku, Qingshuihe, Gande, and Henan stations were significant, with RMSE values of 0.28 cm, 2.47 cm, 2.25 cm, and 0.36 cm, respectively. These results demonstrate that the downscaled remote sensing snow depth data is in good agreement with ground observations, although an overall overestimation exists; the consistency is notably higher in shallow snow areas. Previous research suggests that while a 25 km resolution cannot resolve micro-topographic effects, it is considered a viable "high-resolution" compromise for regional climatological studies. Despite some overestimation in the complex terrain of the TRSR, this dataset is well-suited for studying snow dynamics and the impact of snow and ice on hydrological processes [?, ?, ?]. Note: The base map was produced based on the standard map (Review No. GS(2024)0650) from the Standard Map Service Website of the Ministry of Natural Resources, with no modifications to the boundaries.

[Figure 1: see original paper] Fig. 1 Schematic diagram of the study area. Note: N, r, and RMSE represent the number of samples, correlation coefficient, and root mean square error, respectively.

[Figure 2: see original paper] Fig. 2 Scatter plot of the correlation between surface snow depth and remotely sensed snow depth in the Three-River Source Region from 1980 to 2020. Cao Xiaoyun et al.: Spatiotemporal variations and climate attribution of snow depth in the Three-River Source Region from 1980 to 2020 based on remote sensing monitoring.

1.2.2 气象驱动数据使用"第三极地区长时间序列

High-Resolution Surface Meteorological Forcing Dataset

The high-resolution surface meteorological forcing dataset (TPMFD) is utilized for climate attribution analysis. This data is sourced from the National Tibetan Plateau Data Center (TPDC). To facilitate detailed spatial analysis, a bilinear interpolation method was applied to downscale the dataset to a spatial resolution of 1/30°.

1.2.3 DEM 数据采用

The SRTM data, with a 90 m spatial resolution, was developed by integrating multi-source information, including station observations, model simulation results, and reanalysis data. Compared to current mainstream reanalysis datasets, its accuracy has been significantly improved [?]. To explore the relationship between different elevation zones and snow depth, this study utilized daily precipitation and temperature data from https://data.tpdc.ac.cn and https://www.gscloud.cn.

After preprocessing the data to match the spatial resolution and projection of the snow depth dataset, the study area was categorized based on elevation, as shown in [Figure 3: see original paper].

[Figure 3: see original paper] Elevation classification in the Three River Source Region

1.3.1 雪深计算定义上年

A hydrological year is defined as the period of one year. Based on the snow depth data, the average and maximum snow depth for each hydrological year were calculated using the following formulas:

$$SD_{mean} = \frac{1}{n}\sum_{i=1}^{n} SD_i$$

$$SD_{max} = \max(SD_1, SD_2, \dots, SD_n)$$

In these equations, SD_{mean} represents the average snow depth; SD_{max} represents the maximum snow depth; i denotes the specific day; n represents the total number of days in the Julian year; and SD_i refers to the snow depth on the i-th day.

1.3.2 趋势分析通过一元线性回归方法 [

Trend analysis was conducted for snow depth, temperature, and precipitation over the hydrological year. The calculation formula is as follows:

$$y = ax + b$$

In this formula, y represents the snow depth, and a represents the slope of the trend. When $a > 0$, it indicates that snow depth is following an increasing trend over time; conversely, when $a < 0$, it indicates a decreasing trend. The variable x represents the time series, while b is a constant. To evaluate the statistical significance of these observed trends and ensure the reliability of the analysis, a t-test was performed.

1.3.3 垂直梯度垂直梯度 [

The vertical gradient refers to the rate at which meteorological or environmental elements (such as temperature, atmospheric pressure, etc.) change with altitude. It is typically expressed as the amount of change in a given element per unit change in height. The calculation formula is:

$$\tau = \frac{\Delta P}{\Delta H}$$

In this formula: τ represents the vertical gradient; ΔP represents the change in the meteorological element; and ΔH represents the change in altitude.

1.3.4 偏相关分析采用偏相关系数 [

To quantitatively characterize the relationship between snow depth and concurrent temperature and precipitation, the partial correlation coefficient is calculated as follows:

$$r_{ab,c} = \frac{r_{ab} - r_{ac} r_{bc}}{\sqrt{(1 - r_{ac}^2)(1 - r_{bc}^2)}}$$

In this formula, $r_{ab,c}$ represents the strength of the net correlation between snow depth and precipitation after removing the influence of temperature. The variables r_{ab}, r_{ac}, and r_{bc} denote the simple correlation coefficients between snow depth and precipitation, snow depth and temperature, and precipitation and temperature, respectively. Statistical significance for these coefficients is determined using the t-test.

2.1 雪深时空分布格局及其动态变化特征

From 1980 to 2020, the multi-year mean snow depth in the Three-River Source Region (TRSR) was 1.51 cm, with a maximum snow depth of 7.07 cm. Snow cover is widely distributed across the region. The multi-year mean snow depth and maximum snow depth exhibit consistent spatial distribution patterns, characterized by significant spatial heterogeneity: values are higher in the west than in the east, and significantly greater in high-altitude mountainous areas than in basins and plains.

Specifically, the southern Qinghai Lake ring, the Gonghe Basin, and the central Hoh Xil region exhibit low snow depth, with mean values below 0.50 cm and maximum values below 2.00 cm. In contrast, the Geladandong Glacier, Anyemaqen Snow Mountain, Tanggula Mountains, Kunlun Mountains, Bayan Har Mountains, and Hoh Xil Mountains are high-value areas. In these regions, mean snow depth generally exceeds 3.00 cm (reaching 6.00 cm in some areas), and maximum snow depth generally exceeds 9.00 cm (surpassing 20.00 cm in some areas).

Regional analysis shows that the Lancang River source area has the highest mean and maximum snow depths at 2.41 cm and 9.86 cm, respectively. This is followed by the Yellow River source area (1.21 cm and 6.62 cm), while the Yangtze River source area has the lowest values (0.86 cm and 5.44 cm). Regarding elevation, snow depth in the TRSR increases with altitude. The vertical lapse rates for mean and maximum snow depth are $0.49\ \text{cm} \cdot \text{km}^{-1}$ and $1.29\ \text{cm} \cdot \text{km}^{-1}$, respectively. Areas below 3.5 km account for only 1.68% of the total area, with a mean snow depth of 0.11 cm and a maximum of 1.49 cm. At 6.0 km, these values reach 3.58 cm and 10.22 cm, respectively. This distribution occurs because the central and western TRSR are dominated by seasonal snow. During the snow season, high-altitude terrain facilitates the convergence of cold Siberian air with warm, moist air from the Bay of Bengal, creating favorable snowfall conditions. Furthermore, persistent low temperatures at high altitudes effectively inhibit snowmelt, providing a critical guarantee for long-term preservation [?, ?, ?, ?]. Conversely, regions like the southern Qinghai Lake ring and Gonghe Basin are blocked by surrounding mountains, resulting in poor moisture transport and terrain conditions that make snow maintenance difficult [?].

[Figure 4: see original paper]

The interannual variation of mean and maximum snow depth in the TRSR from 1980 to 2020 also exhibits significant spatial heterogeneity. Overall, the interannual variation of mean snow depth shows a pattern of increasing in the southeast and decreasing in the northwest. Approximately 68.44% of the total area shows a decreasing trend in mean snow depth, with 15.64% showing a significant decrease. The Lancang River source area experienced the fastest decrease at -0.37 cm $\cdot$ $(10a)^{-1}$, while the Yangtze and Yellow River source areas decreased at rates of -0.02 cm $\cdot$ $(10a)^{-1}$ and -0.06 cm $\cdot$ $(10a)^{-1}$, respectively. Significant decreases are concentrated in the central and western Yangtze source area, most of the Lancang source area, the southern Qinghai Lake ring, and the Gonghe Basin. In contrast, localized areas in the northern and southeastern TRSR show a significant increasing trend, accounting for 2.90% of the total area.

[Figure 5: see original paper]

The interannual variation of maximum snow depth follows a similar spatial pattern. Approximately 63.83% of the area shows a decreasing trend, with 7.47% showing a significant decrease. The Lancang River source area again shows the fastest reduction rate at -0.81 cm $\cdot$ $(10a)^{-1}$, followed by the Yangtze River source area at -0.26 cm $\cdot$ $(10a)^{-1}$. Conversely, the maximum snow depth in the Yellow River source area shows a slight increasing trend at a rate of 0.03 cm $\cdot$ $(10a)^{-1}$. Significant decreases in maximum snow depth (covering 7.24% of the area) are primarily found in the central-western Yangtze source area, eastern Lancang source area, and the Gonghe Basin. Significant increases are limited to 1.52% of the area.

Analysis of snow depth variation across different altitude zones (Figure 6) indicates that between 1980 and 2020, mean snow depth decreased in all altitude bands except for the 3.5–4.5 km range. The fastest reduction occurred in the 5.0–5.5 km band at -0.11 cm $\cdot$ $(10a)^{-1}$. In the 4.5–5.0 km and 5.5–6.0 km bands, reduction rates exceeded -0.08 cm $\cdot$ $(10a)^{-1}$, with significantly decreasing areas accounting for 20.62% and 28.91%, respectively. In contrast, the 3.5–4.5 km and $>$ 6.0 km bands showed slight increases or minimal changes. Specifically, the mean snow depth in the 3.0–3.5 km band decreased at a rate of -0.02 cm $\cdot$ $(10a)^{-1}$, with 61.76% of that area showing a significant decrease.

[Figure 6: see original paper]

Maximum snow depth also showed a general decreasing trend across most altitude bands, except for the 3.5–4.5 km range. The most rapid decrease was observed in the 5.0–5.5 km zone at -0.33 cm $\cdot$ $(10a)^{-1}$. In the 4.5–5.0 km and 5.5–6.0 km bands, the reduction rates were -0.24 cm $\cdot$ $(10a)^{-1}$ and -0.29 cm $\cdot$ $(10a)^{-1}$, respectively. Significant decreases in the 3.0–3.5 km and 4.0–4.5 km bands were also notable.

The time series data from 1980 to 2020 reveals that the mean and maximum snow depths in the TRSR followed a fluctuating downward trend, with interannual variation rates of -0.15 cm $\cdot$ $(10a)^{-1}$ and -0.49 cm $\cdot$ $(10a)^{-1}$, respectively. Peak values occurred in 1983, with a mean snow depth of 4.86 cm and a maximum of 19.41 cm. These high values are attributed to blocking highs, a weak polar vortex, and an active southern branch trough, which facilitated the continuous convergence of cold and warm air masses over the TRSR. Conversely, minimum values were recorded in 2014 (0.34 cm and 3.06 cm, respectively). These lows likely resulted from a straight westerly belt, a positive Arctic Oscillation phase, and a weak southern branch trough, which reduced moisture transport and led to insufficient snowfall. These fluctuations underscore the instability of snow depth in the TRSR and its high sensitivity to climatic factors.

2.2 雪深变化气候归因

From 1980 to 2020, the annual mean temperature in the Three-River Source Region (TRSR) ranged from -4.75 to -1.78 °C, exhibiting a highly significant warming trend with a heating rate of 0.42 °C/10a ($P < 0.01$). During the same period, annual precipitation ranged from 502.19 to 738.97 mm, showing a significant increasing trend at a rate of 18.82 mm/10a ($P < 0.05$). By comparing the interannual variation time series of temperature and precipitation, it is evident that the distinct "warm-humid" climatic shift in the TRSR is the key driver regulating snow depth changes. As shown in [Figure 7: see original paper], snow depth was significantly higher during typical "cold-wet" years, whereas it was generally lower during "warm-dry" years.

The partial correlation coefficients and significance distributions between annual mean snow depth, maximum snow depth, and climatic factors (temperature and precipitation) reveal distinct patterns across the TRSR. Regarding temperature, 99.20% of the region shows a negative correlation between mean snow depth and temperature, with 79.14% of the area exhibiting a significant negative correlation ($P < 0.05$), primarily distributed in the western, central, and northeastern regions. Conversely, parts of the southeast and north show lower correlations between mean snow depth and temperature. Regarding precipitation, 90.79% of the region shows a positive correlation between mean snow depth and precipitation, with 45.04% being significantly positive ($P < 0.05$), mainly in the eastern, southern, and parts of the western regions. The partial correlation patterns for maximum snow depth are highly consistent with those of the mean snow depth. Specifically, 98.68% of the region shows a negative correlation between maximum snow depth and temperature (with 68.80% being significant at $P < 0.05$), while 91.64% shows a positive correlation with precipitation (with 40.40% being significant at $P < 0.05$).

[Figure 8: see original paper] Interannual variation of temperature and precipitation in the Three River Source Region from 1980 to 2020.

The average partial correlation coefficients between mean/maximum snow depth and precipitation indicate that the Lancang River source area experiences the strongest precipitation influence, with coefficients exceeding 0.4. In contrast, the impact of precipitation in the Yangtze River source area is relatively small, with coefficients below 0.2. Research suggests that while high-altitude stations generally benefit from increased precipitation leading to enhanced snow accumulation, the warming effect dominates once the heating rate exceeds a critical threshold. In such cases, rising temperatures shift the precipitation phase from solid to liquid; thus, even if total precipitation increases, the reduced proportion of snowfall inhibits snowpack growth [?]. Furthermore, rising temperatures weaken the accumulation effect of precipitation by extending the ablation period [?]. This indicates that temperature is the primary driver of snow depth variation in the TRSR compared to precipitation, though regional differences exist. Despite the increase in precipitation over recent decades, intensified warming has led to a substantial decrease in snow depth.

From an elevational perspective, the partial correlation coefficients between snow depth and temperature are higher in regions below 3.5 km and above 4.5 km. In the 3.5–4.5 km elevation band, these coefficients are smaller (less than 0.2), likely because temperatures in this range are near the rain-snow transition threshold. In this sensitive zone, temperature non-linearly affects snow depth by regulating the precipitation phase, complicating the temperature-snow relationship. Meanwhile, the partial correlation coefficients between snow depth and precipitation remain low across all elevation intervals (less than 0.2). These findings further confirm that temperature is the dominant factor influencing snow depth in the TRSR, with its impact exhibiting clear regional and elevational gradients. Specifically, climate warming exerts a more pronounced influence on snow depth at lower elevations (< 3.5 km) and higher elevations (> 4.5 km).

3 结论

Temperature linearly influences snow depth, and rising temperatures can weaken the accumulation effect of precipitation by extending the ablation period. Furthermore, factors such as wind redistribution, topography, local circulation, human interference, and snow sublimation can lead to a negative correlation between snow depth and precipitation [?]. This indicates that, compared to precipitation, temperature has a broader and more profound impact on snow depth in the Three-River Source Region (TRSR). Analysis of the regional and altitudinal differences in the partial correlation coefficients between annual mean/maximum snow depth and mean temperature/precipitation from 1980 to 2020 shows that the average partial correlation coefficients for mean and maximum snow depth with temperature are significantly higher ($P < 0.01$ and $P < 0.05$, respectively). Specifically, the influence of temperature on snow depth is most pronounced in the Yangtze River Source Region, where partial correlation coefficients exceed those in other areas ($P < 0.01$). Conversely, the impact of temperature in the Yellow River Source Region is relatively small, with partial correlation coefficients failing to reach statistical significance.

Significant spatial heterogeneity exists in the snow depth of the TRSR. High-altitude areas, such as the Geladandong Glacier and the Anyemaqen Mountains, are high-value zones where the mean snow depth generally exceeds 3.00 cm and the maximum snow depth exceeds 6.00 cm. In contrast, in the southern Qinghai Lake ring and the Gonghe Basin, the mean snow depth is less than 0.50 cm and the maximum snow depth is less than 2.00 cm. Both the mean and maximum snow depth in the TRSR exhibit a significant decreasing trend, with interannual variation rates of -0.15 cm $\cdot$ $(10a)^{-1}$ and -0.49 cm $\cdot$ $(10a)^{-1}$ ($P < 0.05$), respectively. Spatially, 68.44% of the region shows a decreasing trend in mean snow depth, with 15.64% showing a significant decrease. For maximum snow depth, 63.83% of the area exhibits a decreasing trend, with 7.47% showing a significant decrease.

[Figure 9: see original paper] Partial correlation analysis of snow depth with temperature and precipitation in the Three River Source Region from 1980 to 2020.

Snow depth and its variation trends in the TRSR demonstrate distinct regional and altitudinal differences. The Lancang River Source Region recorded the highest mean and maximum snow depths at 2.41 cm and 9.86 cm, respectively, and also exhibited the fastest rate of decline, reaching 0.37 cm $\cdot$ $(10a)^{-1}$ and 0.81 cm $\cdot$ $(10a)^{-1}$. Both mean and maximum snow depths increase with altitude; the vertical gradients for snow depth are 0.49 cm $\cdot$ km^{-1} and 1.29 cm $\cdot$ km^{-1}, respectively. At altitudes above 6.0 km, the mean and maximum snow depths can reach 3.58 cm and 10.22 cm. Except for the 3.5–4.5 km altitudinal zone, the mean snow depth in all other altitudinal belts shows a decreasing trend. Similarly, except for the 3.5–4.5 km zone, the maximum snow depth across all other altitudes is also decreasing, with the fastest rates of decline for both mean and maximum snow depth occurring in the 5.0–5.5 km altitudinal belt.

[Figure 10: see original paper] Differences in bias correlation coefficients of snow depth with temperature and precipitation in the Three River Source Region from 1980 to 2020.

A Structural Equation Model (SEM) of "Climate–Snow Depth" was constructed using the dataset to perform path analysis, aimed at quantifying the direct and indirect effects of various climatic factors on snow depth. In the Three-River Source Region, the mean temperature has risen significantly at a rate of 0.42°C $\cdot$ $(10a)^{-1}$, while precipitation has increased significantly at a rate of 18.82 mm $\cdot$ $(10a)^{-1}$. This prominent "warming and wetting" climate trend serves as the primary driver regulating regional snow depth dynamics.

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···important driving factors of snow depth changes. Among these, air temperature is the dominant factor, and its influence exhibits significant regional and elevational variations. The reduction in snow depth in the Sanjiangyuan region is closely related to climate warming, particularly at low altitudes (< 3.50 km) and high altitudes (> 4.50 km). It should be noted that this study employed bilinear interpolation···

方法降尺度的

Passive microwave remote sensing inversion for snow depth data exhibits good consistency with station observations. However, due to limitations in spatial resolution, errors are inevitable when characterizing subtle snow cover in topographically complex areas. This introduces a degree of uncertainty into the specific analytical results of this study. Consequently, the conclusions drawn are more applicable to the interpretation of macro-regional patterns rather than precise applications at the small watershed or local scale. Future work will focus on overcoming these limitations through downscaling techniques or the fusion of higher-resolution satellite observations with station data to validate and deepen the findings of this study at a finer scale. Furthermore, as the current partial correlation analysis primarily reveals statistical associations, subsequent research will attempt to introduce comprehensive multivariate analysis to better understand these dynamics.

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Spatiotemporal changes of snow depth and climate attribution in the Three River Source Region from 1980 to 2020 based on remote sensing monitoring

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Abstract: Changes in the snowpack in the Three Rivers Source Region have important implications for regional and global climate, the hydrological cycle, and ecosystems. However, systematic, long-term monitoring of snow depth dynamics and climate attribution based on remotely sensed data across regions and elevation gradients remains limited. This study analyzed the spatial and temporal patterns of snow depth change in the Three Rivers Source Region from 1980 to 2020 using remote sensing data stratified by subregions and elevation bands, and quantified the relative contributions of temperature and precipitation. The results show that:

(1) Snow depth in the Three Rivers Source Region exhibited pronounced spatial heterogeneity over the past 41 years, with average snow depth in high-elevation mountain ranges generally exceeding 3 cm and maximum snow depth generally exceeding 6 cm. Average and maximum snow depths decreased significantly at rates of 0.15 cm $(10a)^{-1}$ and 0.49 cm $(10a)^{-1}$, respectively. A decreasing trend was observed in average snow depth across 68.44% of the region and in maximum snow depth across 63.83% of the region, with significantly decreasing areas accounting for 15.64% and 7.47%, respectively.

(2) Pronounced regional and altitudinal differences in snow depth and its changes were observed, with the highest mean and maximum snow depths (2.41 cm and 9.86 cm, respectively) and the fastest decreasing rates [0.37 cm $(10a)^{-1}$ and 0.81 cm $(10a)^{-1}$, respectively] occurring in the Lancang River source area. Snow depth and its rate of decrease generally increased with elevation.

(3) Climate attribution analysis indicates that temperature and precipitation are the primary drivers of snow depth variability. However, the dominant factor varies across different subregions and elevation gradients. Rising temperatures have been the primary cause of the overall reduction in snow depth, particularly at lower elevations, while changes in precipitation patterns have played a more significant role in high-altitude mountainous areas.

Keywords: Three River Source Region; snow depth; remote sensing monitoring; spatiotemporal variation; climate attribution; elevation gradient

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Introduction

The Three River Source Region (TRSR), located in the hinterland of the Qinghai-Tibet Plateau, serves as the headwaters of the Yangtze, Yellow, and Lancang Rivers. As a critical component of the "Third Pole," the TRSR is highly sensitive to global climate change. Snow cover is one of the most important components of the cryosphere in this region, playing a vital role in regulating the surface energy balance, maintaining the hydrological cycle, and supporting alpine ecosystems. Changes in snow depth not only affect regional water resources and livestock production but also have far-reaching impacts on downstream water security and global climate feedback mechanisms.

In recent decades, the Qinghai-Tibet Plateau has experienced significant warming at a rate much higher than the global average. This rapid warming has led to substantial changes in snow cover characteristics. While previous studies have utilized satellite observations to examine snow cover extent and duration, long-term systematic analysis of snow depth—especially its vertical distribution and sub-regional differentiation—remains insufficient. Furthermore, the relative contributions of temperature and precipitation to these changes across different topographic gradients are not yet fully understood.

This study utilizes long-term remote sensing snow depth datasets from 1980 to 2020, combined with high-resolution meteorological data, to investigate the spatiotemporal dynamics of snow depth in the TRSR. By employing statistical analysis methods [**?**], we aim to: (1) characterize the long-term trends and spatial heterogeneity of average and maximum snow depths; (2) analyze how these changes vary across different sub-basins and elevation bands; and (3) quantify the influence of climatic factors on snow depth variations. The findings provide a scientific basis for water resource management, disaster prevention, and ecological conservation in the context of a changing climate [**?**, **?**].

Snow depth increased with altitude, with vertical gradients of 0.49 cm km−1 for mean snow depth and 1.29 cm for maximum snow depth. Mean snow depth declined across all elevation bands except the 3.5−4.5 km and >6.0 km bands, whereas maximum snow depth declined across all elevation bands except the 3.5−4.5 km band, with the fastest decrease occurring in the 5.0−5.5 km band. (3) The pronounced "warming and humidifying" climate trend over the past 41 years is the primary driver of snow depth decline in the Three Rivers Source Region, with tem- perature identified as the dominant controlling factor. The influence of climate change exhibits clear regional and altitudinal differences, with snow depth reductions particularly evident in low- altitude (<3.5 km) and high- alti- tude (>4.5 km) areas. These findings provide a scientific basis for optimizing snow water resource allocation, eco- system protection and restoration, and predicting regional climate change trends in the Three Rivers Source Re- gion.

Keywords: Three River Source Region; snow depth; climate change; remote sensing monitoring

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