Spatiotemporal Variation Characteristics of Extreme Snowfall on the Mongolian Plateau from 1980 to 2021 and Their Response to Different Influencing Factors

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Abstract

Against the background of global warming, extreme climate events have become more frequent and intense, especially extreme snowfall events, whose changes not only pose challenges to the ecosystems of the Mongolian Plateau but may also have significant impacts on the local socioeconomic system. Understanding the patterns and causes of changes in extreme snowfall is of crucial importance for protecting the ecological environment and improving disaster resilience. Taking the Mongolian Plateau as the study area, this paper uses methods such as correlation analysis and trend analysis to conduct spatiotemporal dynamic monitoring of snowfall and extreme snowfall on the Mongolian Plateau from 1980 to 2021, and analyzes the spatiotemporal variation characteristics and driving factors of extreme snowfall on the Mongolian Plateau under global warming. The results show that: (1) From 1980 to 2021, total snowfall on the Mongolian Plateau showed a decreasing trend, with an overall spatial distribution pattern in which snowfall gradually increased from south to north. (2) Extreme snowfall R95P, extreme snowfall contribution rate R95C, and maximum one-day snowfall Rx1 decreased at rates of 0.11 mm, 0.004%, and 0.01 mm per year, respectively, while heavy snowfall total R10P and heavy snowfall days R10D increased at rates of 0.05 mm and 0.001 d per year, respectively. (3) Snowfall, R95P, R95C, and Rx1 were negatively correlated with temperature during the snow season, whereas R10P and R10D were positively correlated with it. Within the study area, snowfall and most extreme snowfall indices increased with increasing latitude and elevation. Therefore, studying the spatiotemporal distribution characteristics of extreme snowfall can provide a key scientific basis for predicting the risk of extreme snowfall on the Mongolian Plateau, formulating precise emergency management strategies, and enhancing regional disaster prevention and mitigation capacity.

Full Text

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Spatiotemporal Variation Characteristics of Extreme Snowfall on the Mongolian Plateau from 1980 to 2021 and Their Response to Different Influencing Factors

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Abstract: Against the background of global warming, extreme climate events have become more frequent and more intense, especially extreme snowfall events. Their changes not only pose challenges to the ecosystems of the Mongolian Plateau, but may also have important impacts on the local social economy. Understanding the patterns and causes of changes in extreme snowfall is of vital significance for protecting the ecological environment and improving disaster resilience. Taking the Mongolian Plateau as the study area, this study used correlation analysis, trend analysis, and other methods to conduct spatiotemporal dynamic monitoring of snowfall and extreme snowfall on the Mongolian Plateau from 1980 to 2021, and analyzed the spatiotemporal variation characteristics of extreme snowfall on the Mongolian Plateau under the background of global warming and its driving factors. The results show that: (1) From 1980 to 2021, the total snowfall on the Mongolian Plateau showed a decreasing trend, with an overall spatial distribution pattern in which snowfall gradually increased from south to north. (2) Extreme snowfall amount R95P, extreme snowfall contribution rate R95C, and maximum one-day snowfall Rx1 decreased at rates of 0.11 mm, 0.004%, and 0.01 mm per year, respectively, while heavy-snowfall total R10P and heavy-snowfall days R10D increased at rates of 0.05 mm and 0.001 d per year, respectively. (3) Snowfall amount, R95P, R95C, and Rx1 were negatively correlated with snow-season temperature, whereas R10P and R10D were positively correlated with it. Within the study area, snowfall amount and most extreme snowfall indices increased with latitude and elevation. Therefore, studying the spatiotemporal distribution characteristics of extreme snowfall can provide a key scientific decision-making basis for predicting the risk of extreme snowfall on the Mongolian Plateau, formulating precise emergency-management strategies, and improving regional disaster prevention and mitigation capacity.

Keywords: extreme snowfall; spatiotemporal distribution; driving analysis; Mongolian Plateau

In recent decades, climate change, characterized primarily by global warming, has received extensive attention from the international community[1-2], and it can seriously affect the frequency, intensity, and duration of extreme climate events[3]. Snowfall and extreme snowfall are important components of the Earth’ s cryosphere and are also key factors affecting hydrological systems in mid- and high-latitude regions[4]. Snowfall of different intensities produces different hydrological effects[5-6]. Moderate snowfall replenishes soil moisture and has a certain promoting effect on vegetation growth, whereas extreme snowfall weather can easily trigger numerous disasters such as white disasters and avalanches, posing a serious threat to people’ s lives and safety[5,7-9]. At the same time, as the main form of winter-spring precipitation on the Mongolian Plateau, extreme snowfall not only guarantees the replenishment of water resources in arid and semi-arid regions[7], but also is of great significance for human social development and climate regulation[10]. Therefore, studying extreme snowfall on the Mongolian Plateau and its influencing factors is of critical importance.

At present, extreme events occur frequently[11-12], and extreme snowfall disaster events show pronounced extremity and regional characteristics, and are closely related to climate change. Some scholars have conducted comparative studies of the conditions under which extreme snowfall events and ordinary snowfall events occur, and the results indicate that the significant increase in extreme snowfall is mainly affected by climate warming. For example, Zhao Qiudong et al.[4] found that climate warming is the main cause of the significant increase in extreme snowfall in the arid region of Northwest China; Sun et al.[13] demonstrated that global warming will lead to a significant decreasing trend in snowfall and extreme snowfall indices in the high-mountain regions of Asia. However, current studies on extreme snowfall on the Mongolian Plateau mostly focus on the spatiotemporal variation characteristics of extreme snowfall under the background of climate warming[8]. Li et al.[14] found that, under the background of global warming, snow depth and extreme snowfall increased in the northern part of the Mongolian Plateau and decreased in the southern part; Feng Xiaojing et al.[11] found that extreme snowfall events in Inner Mongolia are mainly concentrated in the eastern region, and that the extreme snowfall threshold gradually decreases from east to west. Overall, the spatiotemporal variation characteristics of extreme snowfall events and their influencing factors have important scientific significance and reference value for promoting the protection of the ecological environment of the Mongolian Plateau. However, existing research on extreme snowfall disasters

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There remains regional imbalance. Although research on extreme snowfall under the background of global warming has attracted extensive attention, systematic studies focused on the Mongolian Plateau, a key region, are still relatively scarce. Therefore, studying the spatiotemporal distribution pattern of extreme snowfall on the Mongolian Plateau and analyzing its variation characteristics and driving factors at multiple scales have important practical significance and scientific value.

Against the background of climate warming, extreme snowfall shows obvious changing characteristics. Some scholars have used global climate models for simulations and found that climate warming is a cause of significant increases in winter snowfall[13,15]; Blanchet et al.[16], based on station-observation data, found that snowfall shows an increasing trend at elevations between 400 and 2,200 m. In addition to elevation and climatic factors, changes in snowfall in China are mainly influenced by the western Pacific subtropical high, the Antarctic and Arctic Oscillations, and the North Atlantic Oscillation, although the influencing factors differ among regions[17–18]. In addition, under the background of climate warming and increasing atmospheric saturation specific humidity, the frequency and intensity of extreme snowfall events in some regions show a sustained increasing trend[19–20]; Ombadi et al.[15] showed that climate warming can lead to large-scale decreases in snowfall and extreme snowfall amounts. The above studies indicate that extreme snowfall is highly sensitive to climate change and has a relatively high correlation with temperature[5,21].

The Mongolian Plateau lies in an arid and semi-arid climatic zone. Its ecological environment is fragile, yet it possesses rich ecosystems and snow resources[22]. Therefore, it is particularly important to study the spatiotemporal evolution of extreme snowfall in this region under the background of climate change. This paper selects extreme snowfall indices and, by combining temporal and spatial scales, analyzes the synergistic effects of factors such as climate, elevation, and latitude. It comprehensively reveals the variation characteristics and scale differences of extreme snowfall on the Mongolian Plateau and explores the driving factors behind intra-regional differences. Through the above research, this paper provides a scientific reference for monitoring and evaluating extreme climatic events on the Mongolian Plateau, offers theoretical support for regional disaster prevention and mitigation, ecological protection, optimized water-resource allocation, and precise decision-making in response to climate change, and also provides a typical regional case for the study of extreme snowfall in arid and semi-arid regions of the global mid- and high latitudes.

1 Overview of the Study Area and Data Sources

1.1 Overview of the Study Area

The Mongolian Plateau mainly includes Mongolia and the Inner Mongolia Autonomous Region of China (Fig. 1), and is located at 88°43′–126°04′E and 37°24′–53°23′N[23]. The northern part of the Mongolian Plateau is bounded by the Sayan Mountains, the Khentii Mountains, and the Yablonovy Mountains; the eastern part connects with the Greater Khingan Mountains; the southern part reaches the Yinshan Mountains; and the western part contains the Mongolian Altai Mountains, the Sayan Mountains, and the Khangai Mountains[24]. Overall, the terrain is higher in the west and lower in the east, with a maximum elevation of 3,971 m. The study area has a temperate continental climate, with mean annual precipitation of approximately 200 mm. Vegetation cover is distributed from east to west as meadow steppe, typical steppe, and desert steppe, while agricultural vegetation is mainly distributed in the eastern and southern parts[25].

Note: The base map was prepared using the standard map of the Ministry of Natural Resources; the map approval number is GS(2021)5443, and the boundaries of the base map were not modified. The same applies below.

Figure 1. Topographic map of the Mongolian Plateau

Fig. 1 Topographic map of the Mongolian Plateau

1.2 Data Sources

To calculate and extract long time-series snowfall and extreme snowfall data for the Mongolian Plateau, the meteorological data used in this paper include near-surface temperature, precipitation, air pressure, and relative humidity from the ERA5-land reanalysis product dataset released by the European Centre for Medium-Range Weather Forecasts (ECMWF). The temporal span covers the snow seasons from October 1980 to March 2021. The spatial resolution of this dataset is 0.1° × 0.1°, and the temporal resolution is h. The data were downloaded from https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land-timeseries?tab=overview, and the downloaded hourly dataset was processed into daily data. This dataset has made major improvements in spatiotemporal resolution, model development, and the assimilation system[23,26], and can better satisfy the data requirements of different research directions. Existing studies have shown that the ERA-5 dataset has strong applicability in arid and semi-arid regions and relatively high validation accuracy[27–29].

The elevation data used in this paper are ASTER GDEM data with a spatial resolution of 30 m, produced by the National Aeronautics and Space Administration (NASA) of the United States (http://lpdaac.usgs.gov/products/).

2 Research Methods

2.1 Calculation of Wet-Bulb Temperature

Existing studies have shown that wet-bulb temperature is the temperature in saturated air. It is closer to the actual temperature during precipitation and therefore better distinguishes between rain and snow, showing good rationality[30–32]. Therefore, in this study, air pressure, temperature, and relative humidity were used to calculate the wet-bulb temperature of the Mongolian Plateau through a numerical solution method, and an appropriate temperature type for snowfall on the Mongolian Plateau was extracted. The formula for calculating wet-bulb temperature is as follows:

$$e_{sat}(T_a) = 6.1078 \exp\left(\frac{17.27T_a}{T_a + 237.3}\right) \quad (1)$$

$$T_w = T_a - \frac{e_{sat}(T_a)(1-RH)}{0.000643P_s + \frac{\partial e_{sat}}{\partial T_a}} \quad (2)$$

where e_{sat} is the saturated vapor pressure; $e_{sat}(T_a)$ is the saturated vapor pressure at T_a; T_a is air temperature; T_w is wet-bulb temperature; P_s is air pressure; and RH is relative humidity, ranging from 0 to 1.

2.2 Method for Defining Snowfall

At present, using the daily mean wet-bulb temperature $T_w \leq -1.5\,^\circ\mathrm{C}$ together with daily precipitation > 0.1 mm shows good consistency in identifying snowfall. Therefore, in this study, this criterion was used to screen and extract daily mean wet-bulb temperature and daily precipitation over the Mongolian Plateau. Combining the dual conditions of temperature and precipitation, if the precipitation on a given day simultaneously satisfied: (1) daily mean wet-bulb temperature $T_w \leq -1.5\,^\circ\mathrm{C}$; and (2) daily precipitation > 0.1 mm, then that day was identified as a snowfall day in the Mongolian Plateau, and the precipitation amount on that day was taken as the snowfall amount for that day. Thus, a daily snowfall dataset for the Mongolian Plateau during 1980–2021 was obtained. All subsequent analyses in this study are based on this dataset.

2.3 Method for Defining Extreme Snowfall

For extreme weather and climate events, internationally the absolute-threshold method and the relative-threshold method are commonly used to calculate thresholds for extreme events[33–34]. According to the national standard, a 24 h snowfall amount of 10.0 mm $\leq RR \leq$ 19.9 mm is defined as a snowstorm[35]. Therefore, this study uses a daily snowfall amount of 10.0 mm as the absolute threshold for extreme snowfall over the Mongolian Plateau; snowfall events with daily snowfall exceeding 10.0 mm are identified as extreme snowfall events. In addition, for each grid point, the subsample of all daily snowfall amounts during the annual snow-cover season (October to March of the following year) was sorted in ascending order, and the commonly used international 95th percentile was taken as the threshold for extreme snowfall events in the snow-cover season at that grid point. If the daily snowfall amount on a certain day was higher than this threshold, that day was considered to have experienced an extreme snowfall event[8,15]. The extreme snowfall indices used in this study were provided by the World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI)[8]. This study selected five indices of different types for analysis. Among them, R95P denotes the cumulative snowfall amount on days with daily snowfall $RR \geq$ the 95th percentile, and the contribution of the cumulative snowfall amount on days with daily snowfall $RR \geq$ the 95th percentile to the total snowfall during the snow-cover season is denoted by R95C. R10P and R10D denote, respectively, the cumulative snowfall amount and the cumulative number of snowfall days with daily snowfall $RR \geq 10$ mm. The maximum one-day snowfall amount in each annual snow-cover season is denoted by Rx1 (Table 1).

Table 1 Names and definitions of extreme snowfall indices

Index	Name	Definition	Unit
R10D	Heavy-snow days	Cumulative number of snowfall days in the snow-cover season with $RR \geq 10.0$ mm	d
R10P	Total heavy-snow amount	Cumulative snowfall amount in the snow-cover season with $RR \geq 10.0$ mm	mm
R95P	Extreme snowfall amount	Cumulative snowfall amount in the snow-cover season with $RR \geq$ the 95th percentile	mm
R95C	Extreme snowfall contribution rate	Percentage of R95P in the snow-cover-season snowfall RR	%
Rx1	Maximum one-day snowfall	Maximum daily snowfall amount in the snow-cover season	mm

2.4 Trend Analysis Method

A univariate linear regression method[36] was used to calculate, grid point by grid point, the interannual variations in snowfall and extreme-snowfall-index elements. The calculation formula for the slope, *Slope*, is as follows:

$$Slope = \frac{n\sum_{i=1}^{n}(iw_i) - \sum_{i=1}^{n} i \cdot \sum_{i=1}^{n} w_i}{n\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{3}$$

where *Slope* represents the rate of trend change of snowfall/extreme snowfall indices and temperature and other elements during the study period; i denotes the number of the year; n denotes the length of the time series; and w_i denotes the snowfall/extreme snowfall amount in year i. If $Slope > 0$ ($Slope < 0$), this indicates that snowfall/extreme snowfall during the snow-cover season increased (decreased) relative to the preceding period; if $Slope = 0$, this indicates that no change occurred relative to the preceding period.

2.5 Correlation Analysis Method

Correlation analysis refers to the visualization of data relationships through correlation coefficients or scatterplots[37], thereby indicating causal relationships among data. In this study, correlation analysis was used to calculate the correlation between snowfall/extreme snowfall over the Mongolian Plateau and temperature advection. The specific formula is as follows:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (4)$$

where r_{xy} is the correlation coefficient between variables x and y; x_i and y_i are, respectively, the values of snowfall/extreme snowfall and of each influencing factor in year i; and $\bar{x}$ and $\bar{y}$ are, respectively, the multiyear mean values of the variables. If $r > 0$, this indicates a positive correlation between the two; if $r < 0$, it indicates a negative correlation. The larger $|r|$ is, the stronger the correlation between the two.

3 Results and Analysis

3.1 Spatiotemporal Evolution Characteristics of Snowfall

As shown in Figure 2, during 1980–2021, the mean snowfall amount in the snow-cover season showed a significant decreasing trend at a rate of 0.19 $\text{mm} \cdot \text{a}^{-1}$. The peak occurred in 2012, at 42.33 mm, and the trough occurred in 2018, at 21.17 mm. The trends in the annual mean number of snowfall days and snowfall amount were consistent: the number of snowfall days decreased by an average of 0.25 d per year. The peak in the number of snowfall days occurred in 1980, at 50.04 d, while the trough again occurred in 2018, at 26.13 d.

Fig. 2 Annual variations in the seasonal average snowfall and number of snowy days on the Mongolian Plateau from 1980 to 2021.

(a) Temporal variation of snowfall
Legend: snowfall; 5-year moving average; linear trend.
Vertical axis: snowfall/mm; horizontal axis: year.

$$y = -0.186x + 404.17$$

$$R^2 = 0.16,\ P < 0.01$$

(b) Temporal variation of the number of snowy days
Legend: number of snowy days; 5-year moving average; linear trend.
Vertical axis: number of snowy days/d; horizontal axis: year.

$$y = -0.2484x + 42.612$$

$$R^2 = 0.29,\ P < 0.01$$

Fig. 2 Annual variations in the Mongolian Plateau seasonal average snowfall (a) and number of snowy days (b) from 1980 to 2021

As shown in Fig. 3, the distribution of snowfall within the study area exhibits a very clear pattern of spatial differentiation. Specifically, snowfall gradually increases from south to north; the northern region is markedly higher than the southern region, and an evident altitudinal-gradient characteristic is present. In the northwestern part of the study area, snowfall is greatest in the high-elevation areas of the Mongolian Altai Mountains, the Khangai Mountains, the Sayan Mountains, and the Khentii Mountains ($ $80 mm). Snowfall in the areas surrounding the mountains is between 50 and 70 mm, whereas the low-lying area between the Mongolian Altai Mountains and the Khangai Mountains has the lowest snowfall, generally $ 20mm.AcrossInnerMongoliaasawhole,snowfallincreasessuccessivelyfromwesttoeast.Amongtheseareas, mm), while the high-value snowfall areas are located in the Hulunbuir Plateau and Xilin Gol Plateau regions of Inner Mongolia, where snowfall can reach 60-90 mm.

Fig. 3 Spatial distribution of the average seasonal snowfall on the Mongolian Plateau from 1980 to 2021.
Legend: national boundary; study-area boundary; multi-year average snowfall/mm, 271–2; scale: 0–300 km.

Fig. 3 Spatial distribution of the average seasonal snowfall in the Mongolian Plateau from 1980 to 2021

It can be seen from Fig. 4 that, during 1980–2021, snowfall within the study area showed a decreasing trend. In Inner Mongolia, except for the eastern Tongliao region, the remaining areas all showed a decreasing trend. Overall, within the study area, snowfall around the Mongolian Altai Mountains and the Sayan Mountains showed a nonsignificant increasing trend, and in the northern part of the Mongolian Altai Mountains there was a significant-increase area whose areal proportion was only 0.01%.

Fig. 4 Seasonal snowfall in the Mongolian Plateau: interannual spatial variation and significance changes from 1980 to 2021.

(a) Spatial variation
Legend: national boundary; study-area boundary; snowfall change/(mm · a^{-1}), 1.17 to −0.85; scale: 0–300 km.

(b) Significance
Legend: national boundary; study-area boundary; significance change: significant decrease; nonsignificant decrease; nonsignificant increase; significant increase; scale: 0–300 km.

Fig. 4 Seasonal snowfall in the Mongolian Plateau interannual spatial variation (a) and significant changes (b) from 1980 to 2021

3.2 Spatiotemporal Evolution Characteristics of Extreme Snowfall Indices

3.2.1 Spatial Distribution Characteristics of Extreme Snowfall Indices

According to the distribution of R95P in Fig. 5a, the high-value areas are mainly concentrated in the higher-elevation regions of the Mongolian Altai Mountains, the Khangai Mountains, the Sayan Mountains, and the Khentii Mountains in the northwestern part of the study area. The multi-year average extreme snowfall in these areas is ≥ 40 mm, indicating that regions with greater snowfall also have larger extreme snowfall amounts. As shown in Fig. 5b, the spatial distributions of R95C and R95P exhibit opposite patterns: specifically, areas with smaller extreme snowfall amounts instead have larger contributions from extreme snowfall. The contribution rate of extreme snowfall is highest in the southern Mongolian Plateau, reaching even above 90%. Analysis of R10P (Fig. 5c) shows that, from 1980 to 2021, there were many areas in the Mongolian Plateau where extreme heavy-snowfall events occurred; regions with a multi-year average heavy-snowfall amount exceeding 24 mm mainly appeared in the northwestern, central, and eastern parts of the study area. From the spatial distribution of R10D, it can be seen that in most areas of the central Mongolian Plateau, the duration of extreme heavy snowfall was relatively short, whereas in the high-elevation mountain regions of the study area, the multi-year average number of extreme heavy-snowfall days could exceed 3 d. Analysis of the spatial distribution of Rx1 indicates that in the arid desert zone in the southern part of the study area and in the low-elevation zones between mountain ranges, the multi-year average maximum one-day snowfall was < 3 mm. In some heavy-snowfall zones, such as the high-elevation mountain regions in the western and northern Mongolian Plateau and the northeastern part of Inner Mongolia, the maximum one-day heavy snowfall could exceed 9 mm, with maxima reaching above 15 mm. The areas with high values are consistent with the spatial distribution pattern of high R95P values for extreme snowfall, indicating that regions with greater extreme snowfall amounts also have relatively stronger extreme snowfall intensity.

Figure panel labels and legends:

(a) R95P; (b) R95C; (c) R10P; (d) R10D; (e) Rx1.
Legend: national boundary; study-area boundary. Scale: 0–300 km.
Color bars: R95P/mm: 2–114; R95C/%: 0.3–100; R10P/mm: 0–76; R10D/d: 0–5.28; Rx1/mm: 0.9–19.3.

Figure 5 Spatial distribution of extreme snowfall indices in the Mongolian Plateau from 1980 to 2021

Fig. 5 Spatial distribution of extreme snowfall index in the Mongolian Plateau from 1980 to 2021

3.2.2 Spatiotemporal variation characteristics of extreme snowfall indices

As can be seen from Fig. 6, R95P reached its maximum extreme snowfall amount in 2012 (28.79 mm) and its minimum in 2014 (12.11 mm). The maximum value of Rx1 occurred in 1992, when the regional mean snowfall on that day reached 6.71 mm. Overall, R95P, R95C, and Rx1 decreased at rates of 0.11 mm yr^{-1}, 0.004% yr^{-1}, and 0.01 mm yr^{-1}, respectively, whereas R10P and R10D increased at rates of 0.05 mm yr^{-1} and 0.001 d yr^{-1}, respectively. Compared with the extreme snowfall intensity indices, the decreasing trend in the contribution rate of extreme snowfall was extremely slow and far lower than the decline rate of extreme snowfall amount, indicating that during 1980–2021, extreme snowfall in the study area still accounted for a large proportion of the total snowfall during the snow-cover season. The trends of R10P and R10D indicate that over the past 42 years, snowfall amount has decreased, whereas the intensity and frequency of snowfall events at or above the heavy-snow level have increased, and the possibility of extremely heavy snowfall has also risen. This suggests that the likelihood of extreme heavy-snowfall weather in the Mongolian Plateau has increased markedly in recent years.

As can be seen from Fig. 7, the extreme snowfall indices in the Mongolian Plateau region

Figure 6. Time variation of extreme snowfall indices in the Mongolian Plateau from 1980 to 2021.

Visible subfigure labels and annotations:

- **(a) R95P**
  Legend: R95P; 5-a moving; linear trend.
  Axes: R95P/mm; Year.
  $y = -0.1094x + 239.27$
  $R^2 = 0.1,\ P > 0.01$
- **(b) R95C**
  Legend: R95C; 5-a moving; linear trend.
  Axes: R95C/%; Year.

$y = -0.0038x + 91.689$
$R^2 = 0.0007,\ P > 0.05$

- **(c) R10P**
  Legend: R10P; 5-a moving; linear trend.
  Axes: R10P/mm; Year.
  $y = 0.0537x - 92.053$
  $R^2 = 0.08,\ P > 0.05$

- **(d) R10D**
  Legend: R10D; 5-a moving; linear trend.
  Axes: R10D/d; Year.
  $y = 0.0011x + 1.1471$
  $R^2 = 0.01,\ P > 0.05$

- **(e) Rx1**
  Legend: Rx1; 5-a moving; linear trend.
  Axes: Rx1/mm; Year.
  $y = -0.014x + 33.23$
  $R^2 = 0.05,\ P > 0.05$

Fig. 6 Time variation of extreme snowfall index in the Mongolian Plateau from 1980 to 2021

Figure 7 Spatial variation (a1–e1) and significance changes (a2–e2) of extreme snowfall indices on the Mongolian Plateau from 1980 to 2021.

Panels and visible legends:

- **(a1) R95P**
  Legend: national boundary; study-area boundary; 0–300 km.
  R95P / ($\mathrm{mm \cdot a^{-1}}$): 0.91 to -0.57.

- **(a2) R95P**
  Legend: national boundary; study-area boundary; 0–300 km.
  Significance change: significant decrease; nonsignificant decrease; nonsignificant increase; significant increase.

- **(b1) R95C**
  Legend: national boundary; study-area boundary; 0–300 km.
  R95C / ($\% \cdot \mathrm{a^{-1}}$): 0.50 to -0.55.

- **(b2) R95C**
  Legend: national boundary; study-area boundary; 0–300 km.
  Significance change: significant decrease; nonsignificant decrease; nonsignificant increase; significant increase.

- **(c1) R10P**
  Legend: national boundary; study-area boundary; 0–300 km.
  R10P / ($\mathrm{mm \cdot a^{-1}}$): 0.81 to -0.34.

- **(c2) R10P**
  Legend: national boundary; study-area boundary; 0–300 km.
  Significance change: significant decrease; nonsignificant decrease; nonsignificant increase; significant increase.
- **(d1) R10D**
  Legend: national boundary; study-area boundary; 0–300 km.
  R10D / $(\mathrm{d} \cdot \mathrm{a}^{-1})$: 0.05 to −0.02.
- **(d2) R10D**
  Legend: national boundary; study-area boundary; 0–300 km.
  Significance change: significant decrease; nonsignificant decrease; nonsignificant increase; significant increase.
- **(e1) Rx1**
  Legend: national boundary; study-area boundary; 0–300 km.
  Rx1 / $(\mathrm{mm} \cdot \mathrm{a}^{-1})$: 0.16 to −0.14.
- **(e2) Rx1**
  Legend: national boundary; study-area boundary; 0–300 km.
  Significance change: significant decrease; nonsignificant decrease; nonsignificant increase; significant increase.

Fig. 7 Spatial variation (a1–e1) and significant change (a2–e2) of extreme snowfall index in the Mongolian Plateau from 1980 to 2021.

The area is dominated by decreasing trends, among which the decreasing trend in R95P is the most significant. Figure 7b1 shows the trend changes in R95C. Compared with the spatial pattern of R95P, the area showing an increasing trend in R95C increases markedly. In conjunction with Figure 7b2, the area in which R95C shows an increasing trend accounts for 49.12%, while the area with a decreasing trend accounts for 50.88%. In addition, the areas where R95C decreases significantly (3.63%) occur only as scattered zones in the central part of the study area and in western Inner Mongolia. As shown in Figure 7a2, R95P mostly exhibits an insignificant increasing trend; a significant increasing trend appears only in northern Mongolian Altai Mountains and in small parts of the Sayan Mountains, accounting for only 0.44% of the total area. Figures 7c1 and 7d1 show that the high-value areas where the intensity and frequency of extreme heavy snowfall increase are similarly distributed within the study area, mainly in the northwestern, northern, northeastern, and southeastern parts of the Mongolian Plateau, with the most pronounced increases in the northwest and southeast. The areas where the two extreme snowfall indices show increasing trends account for 39.7% and 39.73% of the entire study area, respectively, which are almost identical. Figures 7e1 and 7e2 indicate that Rx1 still generally shows a decreasing trend. The area with a significant decrease accounts for 6.27%, mainly located in the central, western, and eastern parts of the study area; the area with a significant increasing trend accounts for only 0.46%, and is essentially scattered in the high-elevation mountainous areas in the northwestern part of the study area.

3.3 Effects of temperature, altitude, and latitude factors on extreme snowfall

3.3.1 Effect of snow-season temperature on extreme snowfall To further explore the influence of snow-season temperature on extreme snowfall over the Mongolian Plateau, correlation analysis was conducted, and the results are shown in Table 2. Snow-season temperature over the Mongolian Plateau is negatively correlated with snowfall, R95P, R95C, and Rx1, among which the correlation with snowfall

Table 2 Correlation coefficients between snowfall and extreme snowfall indices and snow-season temperature on the Mongolian Plateau during 1980–2021

Tab. 2 Correlation coefficients between snowfall, extreme snowfall indices, and snow season temperatures on the Mongolian Plateau from 1980 to 2021

	$t_{2\ \mathrm{m}}$	snow	R95P	R95C	R10P	R10D	Rx1
$t_{2\ \mathrm{m}}$	1						
snow	-0.629^{**}	1					
R95P	-0.593^{**}	0.975^{**}	1				
R95C	-0.082	0.601^{**}	0.741^{**}	1			
R10P	0.159	0.072	0.064	0.042	1		
R10D	0.072	0.166	0.158	0.083	0.813^{**}	1	
Rx1	-0.261	0.713^{**}	0.778^{**}	0.712^{**}	0.109	-0.03	1

Note: $t_{2\ \mathrm{m}}$ denotes snow-season temperature at a height of 2 m; snow denotes snowfall; * indicates significance at the $P < 0.05$ level; ** indicates significance at the $P < 0.01$ level.

has the largest coefficient, with a correlation coefficient of −0.629, and the correlations with snowfall and the extreme snowfall intensity index R95P pass the 99% significance test. Snow-season temperature shows insignificant positive correlations with the extreme snowfall indices R10P and R10D, with correlation coefficients of 0.159 and 0.072, respectively.

As can be seen from Table 2, under the background of climate warming, snowfall and the extreme snowfall indices change with temperature. Scatterplot analyses were conducted for snowfall and each extreme snowfall index against snow-season temperature, and the results are shown in Figure 8. It can be seen that for every 1 °C increase in snow-season temperature, snowfall decreases by 3.11 mm, R95P decreases by 2.04 mm, R95C decreases by 0.11%, and Rx1 decreases by 0.18 mm. For every 1 °C increase in snow-season temperature, extreme heavy snowfall amount R10P increases by 0.16 mm, and extreme heavy snowfall days R10D increase by 0.003 d. Combined with the correlation coefficients, it can be inferred that under the background of climate warming, snowfall, R95P, R95C, and Rx1 are negatively correlated with temperature; except for snowfall, the extreme snowfall index most strongly correlated with snow-season temperature is R95P. By contrast, R10P and R10D are positively correlated with snow-season temperature.

As shown in Figure 9, the spatial correlation between snowfall and snow-season temperature in the study area is dominated by negative correlations, mainly distributed in the western and southwestern parts of the Mongolian Plateau. This indicates that as snow-season temperature rises, snowfall in the above regions decreases accordingly. The spatial correlation between R95P and snow-season temperature is markedly stronger; in the central and southeastern parts of the study area, R95P decreases as snow-season temperature increases. The spatial distribution of the correlation between the extreme snowfall contribution index R95C and snow-season temperature is shown in Figure 9c. Compared with Figure 9b, the area with a significant negative correlation is reduced. This indicates that in some regions where R95P is significantly negatively correlated with snow-season temperature, the significance of the negative correlation between R95C and temperature is weakening. Moreover, R95C in the central Mongolian Plateau is more strongly affected negatively by snow-season temperature, whereas in some northern, eastern, and southern parts of the study area, R95C instead increases with rising snow-season temperature, indicating that the probability of extreme snowfall occurrence is increasing in these areas. Overall, the correlation distributions of extreme heavy snowfall intensity R10P and extreme heavy snowfall days R10D with snow-season temperature show that the area of positive correlation is larger than that of negative correlation. In the high-elevation areas in the northwestern part of the study area, the southern and southeastern parts, and northern Hulunbuir in Inner Mongolia, as snow-season temperature continues to rise, the intensity of extreme heavy snowfall increases accordingly, and its frequency also rises. In the central-eastern part of Inner Mongolia and the low-elevation areas of Mongolia, however, the intensity of extreme heavy snowfall weakens as snow-season temperature increases. As shown in Figure 9f, Rx1 is negatively correlated with snow-season temperature in central-eastern Inner Mongolia and most areas of Mongolia, whereas in western and northeastern Inner Mongolia···

Figure 8. Interannual variations of snowfall, extreme snowfall, and snow-season temperature in the Mongolian Plateau from 1980 to 2021

- **(a)** Snowfall; linear trend. Y-axis: Snowfall/mm. X-axis: Snow-season temperature/°C.

$$y = -3.1064x + 5.471, \qquad R^2 = 0.38,\ P < 0.01$$

- **(b)** R95P; linear trend. Y-axis: R95P/mm. X-axis: Snow-season temperature/°C.

$$y = -2.0354x + 2.9302, \qquad R^2 = 0.28,\ P < 0.01$$

- **(c)** R95C; linear trend. Y-axis: R95C/%. X-axis: Snow-season temperature/°C.

$$y = -0.1106x + 83.226, \qquad R^2 = 0.01,\ P > 0.05$$

- **(d)** R10P; linear relationship. Y-axis: R10P/mm. X-axis: Snow-season temperature/°C.

$$y = 0.1598x + 16.554, \qquad R^2 = 0.01,\ P > 0.05$$

- **(e)** R10D; linear relationship. Y-axis: R10D/d. X-axis: Snow-season temperature/°C.

$$y = 0.0032x + 1.1, \qquad R^2 = 0.001,\ P > 0.05$$

- **(f)** Rx1; linear relationship. Y-axis: Rx1/mm. X-axis: Snow-season temperature/°C.

$$y = -0.1792x + 3.7089, \qquad R^2 = 0.06,\ P > 0.05$$

In sporadically distributed areas of Mongolia, Rx1 is positively correlated with snow-season temperature.

3.3.2 Influence of Elevation on Extreme Snowfall

In addition to the influence of temperature, elevation is also particularly important for extreme snowfall over the Mongolian Plateau. The northwestern part of the Mongolian Plateau is mostly mountainous, the southeastern part consists of extensive Gobi terrain, and the central and eastern parts are dominated by broad hills. The mean elevation is 1580 m, and the terrain gradually decreases from west to east. The relatively large differences in mean temperature thereby affect changes in snowfall in this region. As shown in Fig. 10, snowfall, R95P, R10P, R10D, and Rx1 over the Mongolian Plateau all show the lowest snowfall intensity and frequency within the elevation range of 1000–2000 m, whereas within the range above 3000 m the snowfall intensity and frequency reach their greatest changes. R95C shows the opposite pattern: the contribution rate of extreme snowfall is largest within the elevation range of 1000–2000 m and smallest in the elevation range above 3000 m. In addition, in 1987, snowfall and extreme snowfall over the Mongolian Plateau exhibited the largest fluctuation amplitude with increasing elevation.

3.3.3 Influence of Latitude on Extreme Snowfall

As shown in Fig. 11, with increasing latitude, snowfall within the study area increases. Snowfall is greatest in areas north of 48°N, where the multi-year mean snowfall can reach 49.21 mm; snowfall is smallest in areas below 44°N, at 17.14

mm. Except for the extreme-snowfall contribution rate R95C, the remaining extreme snowfall indices all show a changing trend consistent with snowfall, that is,

Fig. 9 Correlation coefficients between snowfall, extreme snowfall, and snow-season temperature in the Mongolian Plateau from 1980 to 2021

Panel labels:
(a) Snowfall; (b) R95P; (c) R95C; (d) R10P; (e) R10D; (f) Rx1.
Map legends: national boundary; study-area boundary; scale 0–300 km; correlation coefficient.
Correlation-coefficient ranges shown: (a) 0.35 to −0.69; (b) 0.46 to −0.73; (c) 0.56 to −0.46; (d) 0.42 to −0.61; (e) 0.48 to −0.48; (f) 0.43 to −0.61.

With increasing latitude, snowfall intensity and frequency tend to increase successively. By contrast, R95C shows a gradual decline in the contribution rate of extreme snowfall with increasing latitude. In low-latitude areas below 44°N, R95C can reach about 83.75%, whereas in high-latitude areas north of 48°N it decreases to as low as 56.70%.

4 Discussion

Using ERA-5 reanalysis data, this study calculated extreme-snowfall data for the Mongolian Plateau from 1980 to 2021, analyzed the spatiotemporal distribution and variation characteristics of extreme snowfall in the study area over the past 42 years, and quantified the response of extreme snowfall on the Mongolian Plateau. From the perspective of snowfall trends on the Mongolian Plateau, total snowfall in the study area has shown a decreasing trend over the past 42 years and exhibits clear differentiation patterns, which is basically consistent with the findings of Sachula et al. [38] on snow-cover area over the Mongolian Plateau. Snowfall in the northern part of the study area is significantly higher than that in the southern part and shows a pronounced elevation-gradient characteristic, which is consistent with the conclusions of Li Chenhao et al. [22] regarding the spatiotemporal variation of snowfall on the Mongolian Plateau. In terms of the spatiotemporal pattern, the average snowfall during the snow season over the past 42 years still shows a decreasing trend, but snowfall and the number of snowfall days peaked in 2012. In that year, Inner Mongolia experienced widespread cold-wave snowfall events, and in many places snowfall and snow depth exceeded historical extremes; this may have been caused by relatively low temperatures in the study area and repeated occurrences of extremely cold weather [39]. In addition, in more than half of the Mongolian Plateau, snowfall and the number of snowfall days

In-figure labels: Legend: `<1000 m`; `1000-2000 m`; `2000-3000 m`; `>3000 m`. Panels: (a) Snowfall; (b) R95P; (c) R95C; (d) R10P; (e) R10D; (f) Rx1. Axis labels: Year; Snowfall/mm; R95P/mm; R95C/%; R10P/mm; R10D/d; Rx1/mm.

Fig. 10 Changes in snowfall and extreme snowfall with elevation in the Mongolian Plateau from 1980 to 2021

The decrease also corroborates the phenomenon that snow-cover area in the Northern Hemisphere shows a declining trend [21,40–41].

Through an in-depth study of the spatiotemporal variation characteristics of extreme snowfall indices on the Mongolian Plateau, it was found that extreme snowfall during the snow-cover season on the Mongolian Plateau occurs mainly in the northwestern part of the study area, including the Mongolian Altai Mountains, the Khangai Mountains, the Sayan Mountains, and the Khentii Mountains, and that snow cover is relatively deep in the northern, northwestern, and northeastern parts of the Mongolian Plateau [17]. Among the five selected extreme snowfall indices, R95P, R95C, and Rx1 show decreasing trends, whereas R10P and R10D show the opposite. This indicates that, as climate change intensifies, the extreme snowfall indices of the Mongolian Plateau as a whole exhibit a decreasing trend, which is opposite to the trends in some regions of China, such as the Three-River Source region and the Qinghai–Tibet Plateau [18]. This phenomenon is related to the decrease in snowfall over the entire study area [42]. However, the number of heavy snowfall events within the study area is increasing, indicating that even though the frequency of extreme snowfall events in the study area is declining, the intensity of extreme snowfall is still increasing.

By analyzing the effects of factors such as latitude, elevation, and temperature on extreme snowfall indices, it can be seen that temperature during the snow-cover season is the main factor influencing extreme snowfall indices on the Mongolian Plateau. Snowfall and extreme snowfall are highly sensitive to climate change and have a relatively high correlation with air temperature [5,17]. Considering that R95P, R95C, and Rx1 are negatively correlated with temperature during the snow-cover season, it can be concluded that

Figure 11 (visible chart labels). Legend: `<44°N`; `44°-46°N`; `46°-48°N`; `>48°N`. Panels: (a) Snowfall, y-axis: Snowfall/mm, x-axis: Year; (b) R95P, y-axis: R95P/mm, x-axis: Year; (c) R95C, y-axis: R95C/%, x-axis: Year; (d) R10P, y-axis: R10P/mm, x-axis: Year; (e) R10D, y-axis: R10D/d, x-axis: Year; (f) Rx1, y-axis: Rx1/mm, x-axis: Year.

Fig. 11 Changes in snowfall and extreme snowfall by latitude in the Mongolian Plateau from 1980 to 2021

Fig. 11 Changes in snowfall and extreme snowfall by latitude in the Mongolian Plateau from 1980 to 2021

Under the influence of snow-season temperature, cold waves and snowfall events occurring in the study area will decrease to some extent, but the extremity intensity of some snowfall events will increase [43]. Among them, the increasing trend shown by extreme snowfall in some high-altitude areas, mountainous areas, and desert areas may be related to the relatively large differences in temperature changes within the region.

At the same time, this study has certain limitations. First, this paper selected extreme snowfall indices mainly from the two aspects of the intensity and frequency of extreme snowfall, and lacks certain statistics on continuous snowfall among the extreme snowfall indices. Therefore, in future research, the analysis of extreme snowfall indices should be further improved in order to make the data results more comprehensive. Second, when calculating extreme snowfall over the Mongolian Plateau, the years selected in this study were 1980–2021; for studies of extreme weather events over long time series, appropriately extending the data period may still be considered. In addition, in examining the occurrence of extreme snowfall events, this study considered only the influences of air temperature, latitude, and elevation changes, and still lacks analysis of the responses to more factors such as sea surface temperature and circulation. In future studies of extreme

In studies of events, the interrelationships among factors should be analyzed from multiple perspectives, and the mechanisms affecting the occurrence of extreme events should be explored by examining the interactions among these factors. In addition, although the ERA5-land dataset used in this paper has the advantage of spatiotemporal continuity in snowfall research over the Mongolian Plateau, the complex terrain and multiple landforms of the study area, together with limitations in the spatial accuracy of air-temperature distributions in the ERA5-Land data themselves, may lead to biases in the extreme snowfall indices. Future research may further explore regionally adaptive improvement methods, and may validate or correct the data by combining in situ observations or other high-resolution data products, so as to reduce systematic errors and improve the applicability of the data in heterogeneous environments.

5 Conclusions

(1) From 1980 to 2021, the distribution of total snowfall over the Mongolian Plateau showed a very clear regional pattern. Specifically, snowfall increased gradually from south to north; the northern region was markedly greater than the southern region, and snowfall showed a strong tendency to vary with elevation.

(2) From 1980 to 2021, the variation trends of the multi-year mean extreme snowfall indices over the Mongolian Plateau were mainly divided into two groups. Among them, $R95P$, $R95C$, and $Rx1$ decreased at rates of 0.11 mm, 0.004%, and 0.01 mm per year, respectively, while $R10P$ and $R10D$ increased at rates of 0.05 mm and 0.001 d per year, respectively.

(3) Snowfall amount, extreme snowfall amount $R95P$, the contribution rate of extreme snowfall $R95C$, and maximum one-day extreme snowfall $Rx1$ were negatively correlated with snow-season temperature, whereas extreme heavy-snowfall amount $R10P$ and the number of extreme heavy-snowfall days $R10D$ were positively correlated with snow-season temperature.

(4) With increasing latitude and elevation, snowfall in the study area increased. Snowfall was greatest in areas north of 48°N, and smallest in areas below 44°N. Snowfall amount, $R95P$, $R10P$, $R10D$, and $Rx1$ reached their greatest changes in snowfall intensity and frequency within the elevation range > 3000 m, whereas $R95C$ showed the opposite pattern.

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Temporal and spatial variations in extreme snowfall over the Mongolian Plateau from 1980 to 2021 and their response to different influencing factors

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Abstract: Against the backdrop of global warming, extreme climate events have grown more frequent and intense, particularly extreme snowfall events. Changes in extreme snowfall not only pose challenges to the ecosystem of the Mongolian Plateau but may also exert considerable effects on the local socioeconomy. Understanding the patterns and causes of changes in extreme snowfall is therefore of great importance for ecological protection and the improvement of disaster resilience. Taking the Mongolian Plateau as the study area, this paper monitors the spatiotemporal dynamics of snowfall and extreme snowfall on the Mongolian Plateau from 1980 to 2021 by employing methods such as correlation analysis and trend analysis, to analyze the spatiotemporal variation characteristics and driving factors of extreme snowfall under the backdrop of global warming. The results show the following: (1) Total snowfall on the Mongolian Plateau exhibited a decreasing trend from 1980 to 2021, and its spatial distribution generally followed the pattern of a gradual increase from south to north. (2) The extreme snowfall amount (R95P), the contribution rate of extreme snowfall (R95C), and the maximum daily snowfall (Rx1) decreased at rates of 0.11 mm, 0.004%, and 0.01 mm per year, respectively, while the total heavy snowfall (R10P) and heavy snow days (R10D) increased at rates of 0.05 mm and 0.001 d per year, respectively. (3) Snowfall amount, R95P, R95C, and Rx1 were negatively correlated with the temperature in the snow cover season, whereas R10P and R10D showed a positive correlation with it. Snowfall amount and most extreme snowfall indices in the study area increased with rising latitude and altitude. The findings on the spatiotemporal distribution characteristics of extreme snowfall can provide a key scientific basis for predicting the occurrence risk of extreme snowfall on the Mongolian Plateau, formulating targeted emergency management strategies, and enhancing the regional capacity for disaster prevention and mitigation.

Keywords: extreme snowfall; spatiotemporal distribution; driving factors analysis; Mongolian Plateau

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