Characteristics of Heavy Snow and Blizzard Events in Tacheng, Xinjiang and Their Relationship with Atmospheric Circulation and Sea Surface Temperature (Postprint)

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Abstract

Using daily observational data from meteorological stations, sea surface temperature, and circulation index data in the Tacheng region of Xinjiang from 1961 to 2018, we analyzed the spatiotemporal distribution of heavy snow and blizzard events in the Tacheng region and their relationships with atmospheric circulation and sea surface temperature. The results show that: (1) Heavy snow and blizzard events in the Tacheng region exhibit distinct dispersive and local characteristics in their spatial distribution, with the highest frequency occurring in the Ta-E Basin and the lowest in the northern mountainous areas; the average frequency over the past 58 years is 1.44 times $\cdot$ a^{-1}, with an average annual snowfall of 17.9 mm, increasing at nonsignificant rates of 0.16 times $\cdot$ $(10a)^{-1}$ and 2.35 mm $\cdot$ $(10a)^{-1}$, respectively, with 42.9% of stations showing a significant increasing trend; heavy snow and blizzard events occur mainly in November, December, and March, accounting for 65.2% of the total. (2) The annual frequency of heavy snow and blizzard events in the Tacheng region shows a significant negative correlation with the contemporaneous NAO/AO (correlation coefficients of -0.35/-0.46), while correlations with AAO and SOI are not significant. (3) The annual frequency of heavy snow and blizzard events in the Tacheng region shows a significant positive correlation with contemporaneous sea surface temperature indices (AMO, NTA, TSA, TNA, Niño3.4, Niño4), with correlation coefficients ranging from 0.27 to 0.45; the influence of monthly-scale sea surface temperature in different regions on the monthly frequency of heavy snow and blizzard events exhibits significant differences, and anomalous signals in preceding SST have predictive significance for the occurrence of heavy snow and blizzard events. (4) Over the past 58 years, Atlantic sea surface temperature has shown a significant warming trend, which is conducive to increased moisture transport eastward along the westerly belt, while sea temperature changes

influence and drive changes or anomalies in mid-to-high latitude atmospheric circulation through ocean-atmosphere coupling, exerting an important impact on heavy snow and blizzard events in the downstream Tacheng region.

Full Text

Characteristics of Heavy Snowstorms in Tacheng Region, Xinjiang and Their Relationship with Atmospheric Circulation and Sea Surface Temperature

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Abstract: Based on daily observation data from seven national meteorological stations in Tacheng Region, together with sea surface temperature (SST) and atmospheric circulation indices for the period 1961-2018, this study analyzes the temporal and spatial distribution characteristics of heavy snowstorm events and their relationship with atmospheric circulation and SST using statistical methods including linear regression, wavelet analysis, and correlation analysis. The results reveal that heavy snowstorm events exhibit obvious dispersive and local characteristics in their spatial distribution, with the highest frequency occurring in the Tacheng-Emin Basin and the lowest in the northern mountainous area. The mean annual frequency of heavy snowstorms is 1.44 times, with an average annual snowfall of 17.9 mm and a process snowfall of 12.5 mm per event. The snowstorm frequency shows an insignificant increasing trend at a rate of 0.16 times per decade, while snowfall amount increases at 2.35 mm per decade, with 42.9% of stations showing a significant increasing trend. Snowstorms mainly occur in November, December, and March, accounting for 65.2% of the total. The annual frequency of heavy snowstorms is significantly negatively correlated with the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices, with correlation coefficients of -0.35 and -0.46, respectively. Snowstorm events respond to various SST indices including the Atlantic Multidecadal Oscillation, Tropical North Atlantic SST index, Tropical South Atlantic index, Caribbean SST index, and Central Tropical Pacific SST, with correlation coefficients ranging from 0.27 to 0.45. However, the influence of monthly SST from different regions on monthly snowstorm frequency shows significant differences. The abnormal SST signals in the early stage can be used to predict changes in monthly snowstorm frequency. Over the past 58 years, Atlantic SST has shown a significant warming trend, while the Northern Hemisphere and Asian polar vortex area (intensity) indices have significantly decreased (weakened). Due to the significant increase in Atlantic SST, moisture content in the upper ocean has increased and been transported eastward via the westerlies. Simultaneously,

atmospheric circulation in the mid-high latitudes has changed. This abnormal SST may cause abnormal changes in atmospheric circulation, which in turn influences heavy snowstorm events in the Tacheng Region.

Keywords: heavy snowstorm events; temporal and spatial distribution characteristics; sea surface temperature; atmospheric circulation indices; Tacheng Region

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1.1 Study Area Overview

Tacheng Region is located in northwestern Xinjiang, geographically positioned between 82°16 –87°21 E and 43°25 –47°15 N, covering a total area of 10.45$\times10^{4}$ km^2. The region extends approximately 437 km from east to west and 394 km from north to south. The terrain is distinctive, featuring significant regional climate characteristics. According to geographical landforms and climate features, the region is classified into three sub-regions: the Tacheng-Emin Basin, southern plain, and northern mountainous area. The Tacheng-Emin Basin (including Tacheng, Emin, and Yumin) is surrounded by mountains on three sides with an opening to the west, forming a "funnel-shaped" topography favorable for receiving moist air from the Atlantic. The southern plain (Wusu and Shawan) is located on the windward slope at the northern foothills of the Tianshan Mountains, where forced uplift and convergence facilitate precipitation generation. The northern mountainous area (Hoboksar and Toli) is situated on the leeward slope or at the edge of mountain ranges, where topographic barriers hinder water vapor transport, resulting in the least snowfall.

1.2 Data Sources

Daily precipitation, weather phenomena, and snow depth observations for the period 1961–2018 from seven surface meteorological stations in Tacheng Region were obtained from the Xinjiang Meteorological Information Center. Monthly atmospheric circulation indices for the same period, including the Atlantic Multidecadal Oscillation (AMO), Tropical North Atlantic SST index (TNA), Tropical South Atlantic index (TSA), Caribbean SST index (CAR), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Antarctic Oscillation (AAO), and Southern Oscillation Index (SOI), were sourced from the NOAA Earth System Research Laboratory. Monthly SST indices for various Niño regions were also obtained from the same source.

1.3 Research Methods

Heavy snowstorm events were defined using both snowfall amount and snow depth criteria. According to the Xinjiang Precipitation Standard, a daily accumulated snowfall of $ $9.0 mm was used as the threshold indicator. Mixed-phase precipitation events were identified separately, and ground snow depth $ $1 cm or increasing snow depth were included in the snowstorm event statistics. In the statistical process, if any station in Tacheng Region reached the heavy snowstorm standard, it was counted as one station occurrence. The annual frequency was calculated for the period from July to June of the following year. Snowstorm intensity was defined as the ratio of total snowfall to frequency.

1.3.1 Climate Tendency Rate The long-term trends of climatic variables such as snowstorm frequency, snowfall amount, and intensity were described using simple linear regression:

$$Y = a + bt$$

where Y represents the variable, t represents time, a is the regression constant, and b is the linear trend term. The sign of b indicates whether the climate variable is increasing or decreasing, and its magnitude reflects the rate of change. The climate tendency rate is expressed as $10b$. Significance testing was performed using F-test, with $p < 0.05$ as the threshold for statistical significance.

1.3.2 Correlation Analysis The correlation coefficient is a statistical indicator reflecting the degree of correlation between variables, generally denoted by r:

$$r_{ab} = \frac{\sum_{i=1}^{n}(a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum_{i=1}^{n}(a_i - \bar{a})^2 \sum_{i=1}^{n}(b_i - \bar{b})^2}}$$

where r_{ab} is the correlation coefficient, a and b are two correlated factors, and $\bar{a}$ and $\bar{b}$ are their multi-year averages. The correlation coefficient was tested for significance using t-test.

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2 Results and Analysis

2.1 Spatial Distribution Characteristics

2.1.1 Spatial Distribution of Heavy Snowstorm Frequency Statistical analysis of heavy snowstorm frequency, snowfall amount, and intensity in Tacheng Region from 1961 to 2018 shows that the region experienced 84 heavy snowstorm events, averaging 1.44 events per year. The Tacheng-Emin Basin had the highest occurrence frequency (71.6% of the total), while the northern mountainous area had the lowest (19.8%). The spatial distribution of snowfall amount was generally consistent with frequency, with the maximum center at Tacheng Station (36.2 mm), followed by Shawan Station (17.9 mm), and the minimum at Hoboksar Station (16.6 mm). Snowstorm intensity was lowest at Hoboksar Station (9.79 mm$\cdot$event^{-1}) and highest at Tacheng Station (13.0 mm$\cdot$

event^{-1}). The spatial heterogeneity of heavy snowstorms is primarily caused by topographic differences.

2.1.2 Spatial Distribution of Trends The frequency and snowfall amount of heavy snowstorms in Tacheng Region increased at rates of 0.16 events $\cdot$ (10a)$^{-1}$ and 2.35 mm $\cdot$ (10a)$^{-1}$, respectively, though these trends were not statistically significant. Snowfall intensity increased at a rate of 0.20 mm $\cdot$ (10a)$^{-1}$. Among the stations, Yumin showed the largest increase in both frequency and snowfall amount, while Wusu and Shawan showed the most significant increasing trends. Overall, 42.9% of stations exhibited a significant increasing trend, while the remaining stations showed non-significant increasing trends.

2.2 Temporal Distribution Characteristics

2.2.1 Monthly Distribution Features Heavy snowstorm events in Tacheng Region mainly occur in November (primary peak), December, and March (secondary peak), accounting for 65.2% of the total annual occurrences. This pattern is consistent with previous research indicating that heavy snowfall in northern China primarily occurs in early winter and early spring. The frequent alternation of cold and warm air masses during seasonal transition periods is the main reason for the high frequency of snowstorms. In mid-winter, Tacheng Region is located behind the Mongolian High, where cold air masses dominate and warm-moist air activity is limited, making it difficult to meet the moisture conditions required for heavy snowfall. In the three sub-regions, the Tacheng-Emin Basin shows the highest frequency in November, followed by March; the southern plain and northern mountainous area have February as their peak month.

2.2.2 Interannual and Interdecadal Variations Heavy snowstorm events in Tacheng Region show significant interannual and interdecadal variations. The Tacheng-Emin Basin experienced a low-frequency period from the 1960s to the mid-1980s, followed by a significant increase after the mid-1990s. The southern plain showed a decreasing trend before the mid-1980s, then a rapid increase. The northern mountainous area was dominated by below-normal frequency before the mid-1990s, entering an above-normal period after 2000. Since the 1990s, interdecadal fluctuations have intensified.

2.2.3 Periodic Analysis Wavelet power spectrum analysis reveals that Tacheng Region and the Tacheng-Emin Basin exhibit similar periodic characteristics, with a primary period of 3–4 years from the mid-1960s to the mid-1980s, and a 6–8 year period after the 1990s. The southern plain shows a 3–4 year period from the early 1960s to the mid-1970s and after 2000, and a 6–8 year period from the late 1970s to the late 1990s. The northern mountainous area is dominated by a 3–4 year period before the late 1990s and a 6–8 year period from the late 1990s to the 2000s. The wavelet global power spectrum shows that the main periods passing the 0.05 significance level are 3–4 years and 6–8 years.

2.2.4 Persistence Analysis The rescaled range analysis (R/S) is a nonlinear scientific prediction method that can forecast future trends. When the Hurst exponent $H > 0.5$, it indicates that the future trend will be consistent with the past, with stronger persistence as H approaches 1. When $H < 0.5$, it indicates that the future trend will be opposite to the past, showing anti-persistence. Analysis of heavy snowstorm frequency in Tacheng Region shows $H = 0.53$, indicating weak persistence, with the increasing trend likely to continue. The southern plain ($H = 0.49$) shows weak anti-persistence, while the northern mountainous area ($H = 0.47$) shows very weak anti-persistence.

2.3 Relationships with Atmospheric Circulation and SST

2.3.1 Oscillation Indices The interannual variation of NAO/AO reflects the strength of mid-latitude westerlies, affecting the trough-ridge systems in the westerly belt and consequently influencing downstream precipitation and temperature in Xinjiang. Correlation analysis between annual heavy snowstorm frequency and concurrent NAO/AO indices shows a significant negative correlation (correlation coefficients of -0.35 and -0.46), particularly strong in the Tacheng-Emin Basin. Heavy snowstorm events correspond well with the negative phase of NAO/AO. During the negative phase, meridional circulation prevails, the Ural blocking high is active, and its front northwest or northerly airflow guides persistent southward movement of polar cold air, providing dynamic lifting conditions favorable for heavy snowfall.

2.3.2 Sea Surface Temperature SST changes affect atmospheric moisture conditions and water vapor transport. On a monthly scale, heavy snowstorm frequency shows significant positive correlation with concurrent and preceding 1–3 month SST in the Atlantic region, with correlations beginning to decrease from the 4th month preceding the event. The Niño4 region shows the most significant impact, with the Niño3.4 region also having a notable influence. This indicates that if the Atlantic SST is in a warm anomaly phase, the probability of heavy snowstorm events is higher.

ENSO is a large-scale ocean-atmosphere interaction phenomenon with important impacts on global climate change. Tropical Pacific SST warming enhances the direct thermal circulation, strengthens vertical upward motion, and alters large-scale circulation patterns. Correlation analysis between annual heavy snowstorm frequency and concurrent Niño indices shows positive correlations, significant in 70.0% of cases, particularly in the southern plain. The response to moderate and above-intensity warm events is especially pronounced, with a corresponding probability of 80.0% for above-normal snowstorm frequency in the same or following year. During warm events, the average frequency is 1.87 occurrences, 87.3% higher than the multi-year average.

2.3.3 Atmospheric Circulation Correlation analysis between monthly atmospheric circulation indices and concurrent heavy snowstorm frequency reveals that favorable circulation configurations for heavy snowstorm events are characterized by: (1) In late autumn and early winter (November), small polar vortex area over the Atlantic-Europe sector and large Asian polar vortex area (intensity) with enhanced Eurasian meridionality, guiding polar cold air southward; (2) In early winter (December-January), continuous southward intrusion of cold air, expanded Northern Hemisphere polar vortex area, and zonal circulation over the Atlantic-Europe sector facilitating westerly moisture transport; (3) In early spring (March), rapid temperature rise and snowmelt in Tacheng Region strengthen low-level upward motion, and if the Northern Hemisphere polar vortex area is large and Asian polar vortex intensity is strong, the upper-level dry-cold and low-level warm-moist structure creates atmospheric instability.

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3 Discussion

Heavy snowstorm events, as extreme weather phenomena, are significantly influenced by changing climate backgrounds and regional circulation anomalies. The IPCC Fifth Assessment Report indicates that global upper-ocean temperatures are warming significantly, with the fastest warming rate of $0.13°C \cdot (10a)^{-1}$ in the near-surface layer. Changes in ocean thermal conditions importantly affect atmospheric moisture content and transport. Previous studies show that Atlantic SST changes influence the NAO through teleconnection processes and Rossby wave propagation, affecting downstream regions. The interaction between mid-high latitude and mid-low latitude circulations significantly impacts heavy snowfall events.

Our correlation analysis results demonstrate that warming Atlantic SST increases atmospheric moisture content and enhances water vapor transport along the westerlies. The NAO/AO, through coupling with SST, significantly influences the distribution of Northern Hemisphere sea level pressure and polar vortex area (intensity), driving mid-high latitude atmospheric circulation anomalies that affect heavy snowstorm events in Tacheng Region. The positive correlation between heavy snowstorm frequency and Niño1+2/Niño4 indices can serve as an important factor for climate prediction.

Heavy snowstorms bring abundant snowfall that benefits pasture growth, agricultural irrigation, and reservoir storage in the following year, but also cause severe impacts on animal husbandry and transportation. The relationships identified in this study between heavy snowstorm monthly frequency and SST indices provide valuable predictive signals.

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4 Conclusions

1) The annual frequency of heavy snowstorms in Tacheng Region averages 1.44 times, with spatial distribution showing the highest frequency in the

Tacheng-Emin Basin and the lowest in the northern mountainous area. Over the past 58 years, snowstorm frequency, snowfall amount, and intensity have all shown increasing trends.

2) Heavy snowstorms mainly occur in November, December, and March, accounting for 65.2% of the total. Since the 1990s, interdecadal fluctuations have intensified, with primary periods of 3–4 years and 6–8 years. The Hurst exponent of 0.53 indicates weak persistence, suggesting the increasing trend will continue.

3) Annual heavy snowstorm frequency is significantly negatively correlated with concurrent NAO/AO indices, and significantly positively correlated with Atlantic and equatorial Pacific SST indices. Monthly-scale response analysis shows that abnormal SST signals in the Niño4 region and Atlantic region in preceding months can serve as early warning indicators for heavy snowstorm events.

4) The significant warming of Atlantic SST has increased moisture content, enhanced westerly water vapor transport, and driven mid-high latitude atmospheric circulation anomalies through ocean-atmosphere coupling, exerting important influences on heavy snowstorm events in downstream Tacheng Region.

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