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Characteristics of Hourly Snowfall and Synoptic Systems Influencing Heavy Snowstorms in Northern Xinjiang (Postprint)

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Abstract

Northern Xinjiang is one of the high-frequency snowfall regions in China. With global warming, snowfall has shown a significant increasing trend, exerting an important influence on Xinjiang' s climate. Due to limitations in observational data, research on hourly snowfall in this region has not yet been conducted, which affects the improvement of refined snowfall forecasting and service capabilities. Therefore, using hourly snowfall observational data from 50 national meteorological stations in the Tianshan mountainous area and regions north of it (hereinafter referred to as "Northern Xinjiang") from November 2012 to February 2021, this study analyzes the characteristics of hourly snowfall during the cold season (November–February of the following year), and selects 30 heavy snowstorm processes based on daily snowfall amounts from high to low to analyze their hourly snowfall characteristics, influencing systems, and typical circulation configurations. The results show that: (1) Northern Altay, the Tacheng Basin, and the Ili River Valley are high-frequency zones for snowfall hours (SHN), reaching over 200 $h \cdot a^{-1}$; the high-frequency SHN zone in the Tianshan mountainous area is the mid-mountain belt at an altitude of 1800–2000 m, reaching 127.3 $h \cdot a^{-1}$, with very little snowfall above 2000 m. (2) The proportions of SHN with hourly snowfall amount (R) $ 1.0mm · h^{-1}$ in Northern Xinjiang and the Tianshan mountainous area are 91.7% and 91.9%, respectively, contributing 70.7% and 68.9% to the total snowfall amount; R>1.0 $mm \cdot h^{-1}$ represents hourly extreme snowfall events, contributing 29.3% and 31.1% to the snowfall amount in Northern Xinjiang and the Tianshan mountainous area, respectively. (3) The average SHN for extreme snowstorm processes is 25.5 h, the average snowfall amount is 30.7 mm, and the snow intensity is approximately 1.2 $mm \cdot h^{-1}$. Heavy snowstorm processes are caused by long-duration snowfall, and snowfall duration is a key factor for conducting heavy snowstorm research and forecasting services. The main influencing systems causing heavy snowstorm

processes include the Central Asian long-wave trough, Central Asian low vortex, Ural long-wave trough, and West Siberian low vortex (trough), accounting for 30.0%, 6.7%, 13.3%, and 50.0%, respectively, with mid-latitude long-wave trough (vortex) and northern West Siberian low vortex (trough) systems each accounting for 50.0%.

Full Text

Hourly Snowfall Characteristics and Influence Systems of Heavy Snowstorm Weather in Northern Xinjiang

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Abstract: Northern Xinjiang is one of China' s high-frequency snowfall regions. With global warming, snowfall has shown a significant increasing trend, exerting important impacts on Xinjiang' s climate. Due to limitations in observational data, research on hourly snowfall in this region has not yet been conducted, hindering improvements in refined snowfall forecasting and service capabilities. Therefore, using hourly snowfall observation data from 50 national meteorological stations in the Tianshan Mountains area and north of it (hereinafter referred to as "Northern Xinjiang") from November 2012 to February 2021, this study analyzes the characteristics of hourly snowfall during the cold season (November–February). Thirty heavy snowstorm processes were selected based on daily snowfall amount (from high to low) to analyze their hourly snowfall characteristics, influence systems, and typical circulation configurations. The results show: (1) The high-frequency areas for snowfall hourly number (SHN) are northern Altay Prefecture, the Tacheng Basin, and the Ili River Valley, reaching 200 $\mathrm{h \cdot a^{-1}}$; the middle mountain belt of the Tianshan Mountains at 1800–2000 m altitude is also a high-frequency area with 127.3 $\mathrm{h \cdot a^{-1}}$. There is little snow above 2000 m. (2) In Northern Xinjiang and the Tianshan Mountains, the proportion of SHN with $R \leq 1.0\ \mathrm{mm \cdot h^{-1}}$ is 91.7% and 91.9%, respectively, contributing 70.7% and 68.9% to total snowfall. $R > 1.0\ \mathrm{mm \cdot h^{-1}}$ represents hourly extreme snowfall events, contributing 29.3% and 31.1% to snowfall in Northern Xinjiang and the Tianshan Mountains, respectively. (3) Heavy snowstorm processes have an average duration of 25.5 h and average snowfall of 30.7 mm, with intensity of about 1.2 $\mathrm{mm \cdot h^{-1}}$. Heavy snowstorms are caused by prolonged snowfall, making duration the key factor for research, forecasting, and service. The main influence systems are Central Asian long-wave trough, Central Asian vortex, Ural long-wave trough, and West Siberian vortex (trough), accounting for 30.0%, 6.7%, 13.3%, and 50.0%, respectively.

Keywords: hourly snowfall; spatial-temporal distribution; heavy snowstorm; influence system; Northern Xinjiang

1.1 Data Sources

This study utilizes hourly automatic snowfall observation data from 50 national surface meteorological stations in Northern Xinjiang from November 2012 to February 2021, obtained from the Xinjiang Meteorological Information Centre and subjected to rigorous quality control. Daily precipitation data were used to check extreme values at each station, and comparisons with duty records were conducted. Two situations affect data quality: (1) Snow accumulation in the weighing rain gauge' s snow receiver that falls into the bucket in a single hour, recorded according to observation standards as snowfall for that hour but actually representing accumulation from previous hours; and (2) High wind speeds causing blowing snow to be measured together with falling snow. While these situations comply with automatic station observation standards for daily cumulative values, they cannot be used for hourly snowfall and extreme value analysis. Therefore, hourly solid precipitation data were strictly quality-controlled before application.

In Xinjiang meteorological operations, snowfall magnitude is classified as: light snow (0.1-2.0 mm), moderate snow (2.1-4.0 mm), large snow (4.1-6.0 mm), heavy snow (6.1-12.0 mm), snowstorm (12.1-24.0 mm), heavy snowstorm (24.1-48.0 mm), and extreme snowstorm ($ 48.1*mm*)*basedon*24 − *hoursnowfallamount*(*R*_{24}$). This study selected the top 30 heavy snowstorm processes (24.0 mm $\leq$ R_{24} < 48.0 mm) by daily snowfall amount for analysis of hourly snowfall characteristics and influence systems.

1.2 Methodology

The study area includes the Northern Xinjiang region north of the Tianshan Mountains, with the Tianshan Mountains area defined as stations at altitudes $ $1800 m. The 50 stations include Daxigou (3539 m), Bayinbuluke (2458 m), Tianchi (1942 m), Xiaoyanggou (1871 m), Xiaoquzi (1851 m), and Zhaosu County (1930 m)—the same representative stations used in Xinjiang meteorological operations. The cold season (November–February) is the focus of this analysis of hourly snowfall characteristics and heavy snowstorm influence systems.

Hourly snowfall amount (R) represents snowfall occurring in a given hour, recorded as a snowfall hour number (SHN) when R $\geq$ 0.1 mm. Since hourly snowfall observations in Xinjiang only became standardized in 2012 and no classification exists for winter hourly snowfall magnitude, this study analyzed intervals of R > 1.0 $\mathrm{mm \cdot h^{-1}}$ based on research findings that smaller proportions are negligible. The analysis uses intervals of 0.1–0.3 mm, 0.4–0.6 mm, 0.7–1.0 mm, 1.1-1.5 mm, 1.6–2.0 mm, and $ $2.1 mm for hourly snowfall classification.

2 Results and Analysis

Previous studies have examined diurnal variation of snowfall in Xinjiang, showing single-peak patterns in western and central Ili River Valley with peak periods at 09:00–12:00 Beijing Time. However, detailed characteristics of hourly snowfall magnitude, spatial distribution, and variation with altitude in Northern Xinjiang have not been thoroughly investigated. Since 2012, standardized and complete hourly snowfall observations from 50 national meteorological stations in Northern Xinjiang have provided a foundation for climatic characteristic research. This study uses these data to analyze hourly snowfall features during the cold season, revealing refined characteristics of different hourly snowfall magnitudes and the features and influence systems of heavy snowstorm processes, thereby providing scientific support for refined weather forecasting, regional numerical model verification, water resource utilization, and service delivery.

2.1 Spatial Distribution of Cold Season Snowfall Hourly Number (SHN)

The spatial distribution of annual average SHN in Northern Xinjiang [Figure 1: see original paper] shows high-frequency centers in northern Altay, the Tacheng Basin, and the Ili River Valley, with annual averages exceeding 150 $h \cdot a^{-1}$. The maximum occurs in Tacheng City (280.4 $h \cdot a^{-1}$), followed by Yining City (256.3 $h \cdot a^{-1}$). High-value areas are closely related to terrain, located at piedmont zones where basins meet mountains. Some areas along the Tianshan Mountains in Northern Xinjiang, such as Wusu City, Urumqi City, and Qitai County, also exceed 150 $h \cdot a^{-1}$, while the Junggar Basin edge shows low values of 40–100 $h \cdot a^{-1}$.

The Tianshan Mountains' high-frequency area is the middle mountain belt at 1800–2000 m altitude, with SHN of 127.3 $h \cdot a^{-1}$. Stations like Daxigou, Bayinbuluke, Tianchi, Xiaoyanggou, Xiaoquzi, and Zhaosu County show annual averages of 159.8 $h \cdot a^{-1}$, 141.0 $h \cdot a^{-1}$, 121.3 $h \cdot a^{-1}$, 150.0 $h \cdot a^{1}$, 109.6 $h \cdot a^{-1}$, and 183.1 $h \cdot a^{-1}$, respectively, demonstrating strong altitudinal zonality in cold season hourly snowfall distribution with little snow above 2000 m.

Monthly distribution shows that Northern Xinjiang' s annual average SHN is 104.8 $h \cdot a^{-1}$, with monthly values of 45.4 $h \cdot a^{-1}$, 39.6 $h \cdot a^{-1}$, 35.3 $h \cdot a^{-1}$, and 23.2 $h \cdot a^{-1}$ from November to February. The Tianshan Mountains show 133.5 $h \cdot a^{-1}$ annually, with 53.9 $h \cdot a^{-1}$, 46.7 $h \cdot a^{-1}$, 39.6 $h \cdot a^{-1}$, and 20.7 $h \cdot a^{-1}$ monthly. Early winter (November–December) has more snowfall hours and amount than late winter (January–February), as active cold air in early winter creates more snowfall, while the Siberian High' s stable control in late winter only allows snowfall when large-scale circulation patterns adjust.

Analysis of maximum hourly snowfall distribution shows the Tacheng Basin, Ili River Valley, and the area from Jinghe County to Shihezi City along the Tianshan Mountains have maximum hourly intensities of 4–5 $mm \cdot h^{-1}$, with Tacheng City and Yumin County reaching the highest intensities (9.7 $mm \cdot h^{-1}$

and 10.9 $mm \cdot h^{-1}$, respectively). This is related to warm-sector snowstorms in these areas, where abundant moisture creates larger snowfall amounts and intensities. Most other stations in Northern Xinjiang range from 2-4 $mm \cdot h^{-1}$, far smaller than summer hourly rainfall maxima of 67.2 $mm \cdot h^{-1}$.

2.2 Characteristics of Snowfall Hourly Number (SHN) and Snowfall Amount

Northern Xinjiang and the Tianshan Mountains have annual average SHN of 104.8 $h \cdot a^{-1}$ and 133.5 $h \cdot a^{-1}$, respectively, with annual average snowfall amounts of 65.1 $mm \cdot a^{-1}$ and 46.7 $mm \cdot a^{-1}$. Monthly distributions show decreasing trends from November to February . The average hourly snowfall is less than 1.0 $mm \cdot h^{-1}$, indicating that despite small hourly amounts, their cumulative contribution is substantial.

2.3 Distribution Characteristics of Different Hourly Snowfall Magnitudes

Classification of hourly snowfall in Northern Xinjiang shows rapidly decreasing frequency with increasing magnitude. The 0.1-0.3 $mm \cdot h^{-1}$ category occurs 73.6 $h \cdot a^{-1}$ (55.2% of all magnitudes) but contributes only 24.0% to total snowfall. The 0.4-0.6 $mm \cdot h^{-1}$ category occurs 33.8 $h \cdot a^{-1}$ (25.3% of events) and contributes the most to snowfall (26.7%). The 0.7-1.0 $mm \cdot h^{-1}$ category occurs 15.0 $h \cdot a^{-1}$ (11.2% of events), contributing 20.0%. Categories \$ $2.1 mm \cdot h$^{-1}\$ occur only 1.8 $h \cdot a^{-1}$ (1.4% of events) but contribute 7.0% to snowfall, representing extreme hourly snowfall events.

Hourly snowfall is dominated by small magnitudes ($R \leq 1.0$ $mm \cdot h^{-1}$), accounting for 91.7% of SHN and contributing 70.7% to total snowfall in Northern Xinjiang. Extreme events ($R > 1.0$ $mm \cdot h^{-1}$) contribute 29.3% despite their rarity. The Tianshan Mountains show similar patterns (91.9% of SHN for R $\leq$ 1.0 $mm \cdot h^{-1}$, contributing 68.9%), with extreme events contributing 31.1%. High-value areas are located on windward slopes where terrain forces air uplift and cooling, creating clouds and snowfall. Differences in atmospheric temperature and freezing level height also contribute to the three maximum snowfall belts, requiring further research combining terrain, slope aspect, and microphysical processes.

2.4.1 Hourly Snowfall Characteristics and Influence Systems of Heavy Snowstorm Processes

Thirty heavy snowstorm processes in Northern Xinjiang from 2012–2021 had average durations of 25.5 h, average snowfall of 30.7 mm, and average intensity of 1.2 $mm \cdot h^{-1}$. The longest process lasted 53.9 mm over 8–14 h in Tacheng City on March 16-17, 2020, with maximum hourly intensity of 4.7 $mm \cdot h^{-1}$. The shortest occurred in Huoerguosi City (23.5 mm over 2–9 h) with average intensity of 2.93 $mm \cdot h^{-1}$ and maximum of 4.0 $mm \cdot h^{-1}$. Among 767 hourly snowfall measurements across 30 processes, 79.3% had intensity <2.0 mm $\cdot$ h^{-1}, 44.2% <1.0 mm $\cdot$ h^{-1}, and only 14.2% $ 3.0mm · h^{-1}$, confirming that prolonged duration rather than extreme intensity is the key factor for heavy snowstorms in Xinjiang.

The main influence systems are synoptic-scale Central Asian long-wave trough (30.0%), Central Asian vortex (6.7%), Ural long-wave trough (13.3%), and West Siberian vortex (trough) (50.0%) . West Siberian systems include long-wave troughs, vortices moving south to form transverse troughs over the Aral Sea, and strong frontal zones at vortex bottoms. These systems create meridional circulation across Eurasia with developed long-wave troughs and ridges, causing strong cold air intrusion into Xinjiang. Central Asian vortices feature southwest jets >40 m $\cdot$ s^{-1} at 500 hPa and >24 m $\cdot$ s^{-1} at 700 hPa, with vortex center temperatures <-40 °C, moving southeastward to create heavy snowstorms.

2.4.2 Typical Circulation Patterns of Heavy Snowstorm Processes

Typical 500 hPa height and temperature field configurations for heavy snowstorms [Figure 2: see original paper] include:

Central Asian long-wave trough pattern: Eurasian mid-high latitudes show a two-ridge-one-trough pattern, with a long-wave trough over Central Asia and strong ridges over Europe and Lake Baikal. The powerful European ridge guides strong cold air from Novaya Zemlya southward into the Central Asian trough, whose front features strong southwest flow. As the trough develops and moves eastward, it creates heavy snowstorms in Northern Xinjiang, with a 700 hPa southwest jet >24 m $\cdot$ s^{-1} providing moisture.

Central Asian vortex pattern: Eurasia shows a three-ridge-two-trough meridional pattern, with ridges over Western Europe, eastern Xinjiang, and East Asia, and troughs over the Urals and Lake Baikal. A cutoff vortex forms in Central Asia with center temperature <-44 °C. Northern Xinjiang lies in the strong frontal zone under the polar vortex bottom, with a 700 hPa westerly jet >16 m $\cdot$ s^{-1} providing dynamic and moisture conditions.

Ural long-wave trough pattern: Eurasia shows a two-trough-one-ridge pattern, with a long-wave ridge over the Urals and broad troughs over Western Europe and West Siberia. A strong westerly jet >40 m $\cdot$ s^{-1} exists ahead of the Ural trough, which moves rapidly eastward causing heavy snowstorms.

West Siberian vortex pattern: Eurasian mid-high latitudes feature a European ridge and West Siberian trough, with a cutoff vortex forming over West Siberia (center temperature <-44 °C). The powerful frontal zone at the vortex bottom creates heavy snowstorms.

3 Conclusions

Using hourly snowfall data from 50 national meteorological stations, this study analyzed cold season (November–February) hourly snowfall spatial distribution, different magnitude characteristics, and heavy snowstorm processes in Northern Xinjiang, providing scientific basis for refined forecasting and research:

1. **Spatial distribution:** Annual average SHN is 104.8 $h \cdot a^{-1}$ in Northern Xinjiang and 133.5 $h \cdot a^{-1}$ in the Tianshan Mountains. High-frequency areas include northern Altay, Tacheng Basin, and Ili River Valley (>200 $h \cdot a^{-1}$), and the Tianshan middle mountain belt at 1800-2000 m (127.3 $h \cdot a^{-1}$). Little snow occurs above 2000 m. The proportion of SHN with R $\leq$ 1.0 $mm \cdot h^{-1}$ is 91.7% (Northern Xinjiang) and 91.9% (Tianshan Mountains), contributing 70.7% and 68.9% to snowfall, respectively. Extreme events (R > 1.0 $mm \cdot h^{-1}$) contribute 29.3% and 31.1%, respectively. Maximum hourly intensities in Tacheng Basin, Ili River Valley, and along the Tianshan Mountains reach 4-5 $mm \cdot h^{-1}$ (maximum 9.7-10.9 $mm \cdot h^{-1}$ in Tacheng City and Yumin County), while most other areas range 2-4 $mm \cdot h^{-1}$.

2. **Heavy snowstorm processes:** Average duration is 25.5 h with 30.7 mm snowfall and intensity of 1.2 $mm \cdot h^{-1}$. Duration is the critical factor for heavy snowstorms. Main influence systems are Central Asian long-wave trough (30.0%), Central Asian vortex (6.7%), Ural long-wave trough (13.3%), and West Siberian vortex (trough) (50.0%). All feature meridional circulation across Eurasia with developed long-wave troughs/ridges and strong cold air intrusion, accompanied by jets at 500 hPa and 700 hPa—necessary conditions for blizzards.

Northern Xinjiang's complex terrain and underlying surface, including the Tianshan and Altay Mountains, Tacheng Basin, and Gurbantünggüt Desert, create significant snowfall differences. Mesoscale systems directly affect snowfall location and magnitude, which also relate to terrain, slope aspect, atmospheric temperature, and freezing level height. Hourly snowfall observations provide a foundation for further research on these relationships.

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