Circulation Classification and Genesis Analysis of Blizzards in Urumqi from 1961 to 2019 (Postprint)

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Date: 2022-04-13T23:42:37+00:00

Abstract

Using daily precipitation data from five national meteorological stations in Urumqi during the snowfall period from 1961–2019, together with NCEP daily four-times 0.25°\$×0.25°and1°×\$1° reanalysis data, this study statistically analyzes the characteristics of snowstorms and large-scale circulation patterns in Urumqi, summarizes three typical circulation types associated with snowstorm occurrence, and selects representative cases for each type for diagnostic and comparative analysis. The results show that: (1) The frequency of snowstorms in Urumqi exhibits an increasing trend of 0.3 times per decade, with a quasi-20-year oscillation period. The highest occurrence is in March (40%), followed by November (32%). (2) Snowstorms in Urumqi are classified into the pre-trough southwesterly flow type, eastward-moving upper-level trough type, and strong frontal zone type. The strong frontal zone type has the highest proportion but the smallest snowfall amount; the pre-trough southwesterly flow type has the longest duration and the largest snowfall amount; the eastward-moving upper-level trough type has the lowest frequency but affects a larger area with stronger snowfall intensity. (3) The main influencing systems for snowstorms in Urumqi are the 300 hPa polar front jet, 500 hPa westerly or southwesterly flow, 700 hPa low-level northerly jet, and 850 hPa northwesterly flow. (4) The mechanism for snowstorm formation in Urumqi involves low-level northerly airflow accumulating against mountains, forcing warm and moist air to ascend and form a 'cold pad,' which together with southwesterly flow above 500 hPa creates strong vertical wind shear and a deep frontogenetic zone. However, the reasons for heavy snowfall differ significantly among the three processes due to variations in the duration of strong frontogenesis, frontal slope, and extension height. (5) Water vapor transport for snowstorms mainly follows southwest, west, and northwest pathways. For the pre-trough southwesterly flow type and eastward-moving upper-level trough type, water vapor is directly transported to the snowstorm area under the guidance of southwesterly flow, whereas for the strong frontal zone type, water vapor convergence is formed through relay transport. This study classifies and summarizes the structural characteristics of snowstorm weather systems in Urumqi, providing an effective reference basis for forecasting services.

Full Text

Circulation Classification and Cause Analysis of Snowstorms in Urumqi City from 1961 to 2019

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Abstract

Based on daily precipitation data from five national meteorological stations in Urumqi City during the snowfall period (November to March) from 1961 to 2019, together with NCEP reanalysis data at 0.25°$×0.25°*and*1°×$1° resolution, this study statistically analyzes the characteristics and large-scale circulation patterns of snowstorms in Urumqi. Fifty-three snowstorm events were examined to classify typical circulation types, with representative cases selected for diagnostic and comparative analysis. The results show that: (1) The frequency of snowstorms in Urumqi City exhibits an increasing trend of 0.3 times per decade, with a quasi-20-year oscillation period. Snowstorms occur most frequently in March (40% of events), followed by November (32%), showing a bimodal distribution. (2) Snowstorms in Urumqi can be classified into three main types: southwest airflow ahead of the trough (Type A), eastward-moving upper-level trough (Type B), and strong frontal zone (Type C). Type C occurs most frequently but produces relatively small snowfall amounts. Type A features the longest duration and largest cumulative snowfall, while Type B, though least common, affects the largest area with the strongest snow intensity. (3) The primary influencing systems include the 300 hPa polar front jet, 500 hPa westerly or southwesterly flow, 700 hPa low-level northerly jet, and 850 hPa northwesterly flow. (4) The formation mechanism involves low-level northerly airflow accumulating against the mountains, forcing warm moist air to ascend and form a "cold cushion." This, combined with southwesterly flow above 500 hPa, creates strong vertical wind shear and a deep frontogenetic zone. However, differences in the duration of strong frontogenesis and the slope/height of frontal surfaces among the three types lead to distinct snowstorm characteristics. (5) Water vapor transport occurs primarily via southwest, westerly, and northwest pathways. For Types A and B, water vapor is directly transported to the snowstorm area under southwesterly flow guidance, whereas Type C forms moisture convergence through relay transport. This study systematically classifies the structural characteris-

tics of snowstorm weather systems in Urumqi, providing an effective reference for forecasting services.

Keywords: snowstorm; circulation classification; frontogenesis function; water vapor transport; Urumqi City

1. Introduction

Snowstorms severely impact transportation, agriculture, and animal husbandry. The primary snow regions in China include Northeast China, the northern Tianshan Mountains, the Tibetan Plateau, the middle and lower reaches of the Yangtze River, and North China. Since the 1980s, snowfall in northern Xinjiang and Northeast China has undergone a significant transition from low to high frequency, with a notable increasing trend. The interdecadal and interannual variations of heavy snowfall correlate well with atmospheric circulation, Arctic sea ice, and water vapor budgets. Research on snowstorms in Northeast China shows that slow-moving frontal zones lead to prolonged snowfall duration. Studies on North China snowstorms focus on case diagnostics, revealing that most events are "return-flow" type, where low-level return flow contributes moisture and forms a cold air cushion that facilitates the ascent of warm moist air, enhancing dynamic lifting and vertical motion. The coupling of upper- and low-level jets also plays a crucial role in dynamic lifting and moisture convergence.

Xinjiang scholars have conducted extensive research on snowstorms in northern Xinjiang. Based on snowfall distribution, northern Xinjiang snowstorms can be categorized into western and Tianshan-adjacent types, northern and eastern types, and western and western Tianshan types. Local snowstorms occur far more frequently than regional events, with the highest probability in late winter and early spring. The main high-incidence areas include the Ili River Valley, Tacheng Basin, Tianshan-adjacent region, and Altay area, showing an increasing frequency trend. The optimal configuration of high-, middle-, and low-level airflow provides the key dynamic lifting and water vapor transport mechanisms, with the strongest transport layer located at 650–750 hPa. The stronger the jet, the greater the water vapor transport contribution.

However, no systematic statistical or classification studies have been conducted on Urumqi snowstorms. Conceptual models for water vapor pathways, dynamic-thermal conditions, and mesoscale evolution remain undeveloped, with existing research limited to case analyses. Using the Xinjiang precipitation magnitude standard (revised edition), snowfall $ $12.1 mm is defined as a snowstorm. According to Chinese Meteorological Administration scoring methods, when rain transitions to snow, an increase in snow depth exceeding 10 cm is also considered a snowstorm. Southern branch systems carrying water vapor along southwesterly flow toward Xinjiang, combined with 500 hPa westerly or southwesterly flow, favor heavy snow in Urumqi. However, due to variations in system movement speed and position, snowstorm intensity and distribution differ, making accurate forecasting difficult. Individual case analyses alone cannot satisfy the need for understanding and predicting Urumqi snowstorms, necessitating systematic classification and synthesis of upper- and lower-level configurations.

2. Statistical Characteristics of Snowstorms

Analysis of annual snowstorm frequency in Urumqi from 1961 to 2019 reveals that with climate warming, both snowfall amount and snowstorm days show increasing trends, with a frequency increase coefficient of 0.3 times per decade. The city averages approximately 0.9 snowstorms annually, with a maximum of 4 events in 2000, an extremely strong precipitation year. Urumqi experienced 53 snowstorm days during this period, with no snowstorms for 5 consecutive years from 1973–1977, showing a clear quasi-20-year oscillation cycle.

Monthly distribution shows a bimodal pattern with peaks in March (40% of events) and November (32%). This occurs because: (1) During December–February, northern Xinjiang is dominated by cold high pressure with limited warm moist air, reducing snowstorm potential; (2) In March and November, frequent trough and ridge activity creates intense cold-warm air interactions favorable for heavy snowfall. This aligns with findings that northern China and Tianshan-adjacent regions experience more snowstorms in early winter and early spring, with fewer events in mid-winter. The ten-day distribution shows relatively small differences, with the highest frequency occurring during the 17th–19th ten-day periods.

3. Synoptic Classification

Based on circulation patterns during 53 snowstorm events, classification yields three types: southwest airflow ahead of the trough (Type A), eastward-moving trough/vortex (Type B), and strong frontal zone (Type C). Table 1 shows monthly and total occurrences for each type. Type C occurs most frequently (27 times, 51% of total) but with relatively small snowfall amounts. Type A (14 events) produces the largest snowfall, while Type B (12 events) affects the largest area with the strongest intensity. Type A and B events concentrate in March and November, as heavy snowfall requires greater moisture convergence and stronger cold-warm interactions, conditions more easily met during seasonal transition periods.

3.1 Southwest Airflow Ahead of the Trough Type

This type features a "two ridges, one trough" meridional circulation across Eurasia at 500 hPa, with high-pressure ridges along the European coast and Lake Baikal, and a low trough over West Siberia. The Ural Mountains to the Aral Sea form a longwave trough with strong northerly flow ahead of the upstream ridge, continuously feeding cold air southward into the trough and deepening it. Superposition of the Ural longwave trough with mid-latitude shortwave troughs increases meridional extent and southward extension, strengthening southwesterly flow ahead of the trough that transports Arabian Sea moisture northward to the snowstorm area.

During snowstorms, 200–500 hPa features strong southwesterly flow, with the snowstorm area located in the right entrance region of the upper-level southwest jet from western Xinjiang to northern Lake Baikal. Positive vorticity advection creates divergence, enhancing upward motion through suction effects. At 850 hPa, northwest flow controls northern Xinjiang; blocked by the Altai Mountains, one branch turns and accelerates, forming a northeast jet between Beita Mountain and Urumqi. The snowstorm area lies in the cyclonic shear zone between the northwest flow front and northeast jet exit region. At 700 hPa, northwest flow dominates, with terrain-forced lifting creating convergence and enhancing vertical motion that forms vertical wind shear with mid-upper level southwesterly flow.

Diagnostic analysis of a typical case shows that vertical velocity tilts backward with height over Urumqi. A strong subsidence zone with low-level divergence and upper-level convergence exists east of the city, creating a strong vertical secondary circulation favorable for snowstorm development. Equivalent potential temperature (_{se}) and frontogenesis function (F) reveal the mechanism: a "cold cushion" forms as dry cold air piles against the northern Tianshan slopes, while mid-upper level southerly flow guides warm moist air climbing along this cushion. The _{se} gradient intensifies, forming a dense band at 650–550 hPa. As cold air strengthens, the frontal zone intensifies, with frontogenesis values reaching 13×10^{-10} $K \cdot m^{-1} \cdot s^{-1}$ at 550 hPa. Snowfall intensity exceeds 2 $mm \cdot h^{-1}$ when the front is strongest. Although snow intensity decreases as the frontal zone weakens, slow system movement and continuous cold air replenishment maintain prolonged snowfall, resulting in large accumulations.

Water vapor originates from the Arabian Sea, transported northward by persistent southwesterly flow ahead of the southern branch trough. Before snowfall, a deep moisture convergence zone exists from the surface to 600 hPa, with maximum convergence of -16×10^{-5} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}$. Snowfall peaks when the convergence layer thickness decreases below 550 hPa and intensity weakens.

3.2 Eastward-Moving Trough/Vortex Type

This type divides into two subcategories based on system meridional extent: small trough eastward movement (7 events, 58% of this type) and meridional trough eastward movement (5 events). At 500 hPa, the circulation shows "three troughs, two ridges" across Eurasia, with high-pressure ridges over Eastern Europe and Lake Baikal, low vortices over eastern Europe and the Okhotsk Sea, and multiple shortwaves over Central Asia. The eastern European low vortex develops and moves eastward, causing the upstream ridge southeast of Xinjiang to weaken. The southern part of the Ural trough combines with mid-latitude shortwaves, deepening to 700–850 hPa and moving rapidly eastward, producing

Urumqi snowstorms.

During events, 200–500 hPa maintains strong southwesterly flow, with the snowstorm area in the right entrance region of the southwest jet from southern Xinjiang to western Lake Baikal. At 300 hPa, wind speeds exceed 50 m·s^{-1}, creating divergence through positive vorticity advection. At 850 hPa, a shear line exists between northwest and southerly winds; as cold air enters, northwest flow strengthens to jet intensity between northern Tacheng and Urumqi, placing the snowstorm area in the jet exit region. The 700 hPa southwest jet shows a clear backward-tilting structure.

Water vapor originates from the Barents Sea (high latitude), Caspian and Aral Seas (mid-latitude), and Arabian Sea (low-latitude). The southwest flow ahead of the 500 hPa low trough guides Arabian Sea moisture directly toward the snowstorm area. Under westerly flow, moisture also travels via two paths: directly through the Caspian-Aral-Balkhash region, and through northern Tacheng and Altay before turning northeastward along the Altai Mountains. Both paths converge on the Tianshan northern slopes. Before snowfall, a deep moisture convergence zone exists from the surface to 600 hPa, with maximum convergence of -35$\times10^{-5}$ g·cm^{-2}·hPa^{-1}·s^{-1}. Snowfall peaks when convergence intensity weakens after reaching maximum.

3.3 Strong Frontal Zone Type

This type features a "two ridges, two troughs" meridional circulation at 500 hPa, with ridges over Europe and west of Lake Baikal, and troughs over the Ural Mountains and Northeast China. Multiple Central Asian shortwaves exist at mid-latitudes. The Lake Baikal ridge blocks the slowly moving Ural trough, while faster-moving Central Asian shortwaves merge with the trough's southwestern flow near Balkhash Lake, strengthening the frontal zone that presses southward against the Tianshan northern slopes.

During snowstorms, 200–300 hPa features strong southwesterly flow, with the snowstorm area in the right entrance region of the southwest jet from the Ili River Valley to western Mongolia. At 300 hPa, wind speeds exceed 54 m·s^{-1}. At 850 hPa, a strong northwest jet core (24 m·s^{-1}) extends directly to the Tianshan northern slopes, with the snowstorm area in the jet exit region experiencing significant terrain-induced convergence. A saturated zone ($T_d \leq$ 5°C) accumulates here.

Water vapor originates primarily from the Arabian Sea, with smaller contributions from the Black, Caspian, and Aral Seas. The southern branch trough's southwesterly flow transports Arabian Sea moisture northward to western Xinjiang, while persistent strong westerly flow carries it eastward to the snowstorm area. Before snowfall, a deep moisture convergence zone exists from the surface to 600 hPa, with maximum convergence of -12$\times10^{-5}$ g·cm^{-2}·hPa^{-1}·s^{-1}. Snowfall peaks when the convergence layer descends below 800 hPa.

4. Conclusions

This study statistically classifies 53 snowstorm events in Urumqi City from 1961–2019 and synthesizes the large-scale circulation, vertical configuration, dynamic mechanisms, and water vapor transport characteristics of each type. The main conclusions are:

1. Snowstorm frequency in Urumqi shows an increasing trend of 0.3 times per decade with a quasi-20-year oscillation and bimodal monthly distribution (March and November). The number of snowstorm stations is also increasing.
2. The necessary circulation configuration includes 300 hPa polar front jet, 500 hPa westerly/southwesterly flow, 700 hPa low-level northerly jet, 850 hPa northwesterly flow, and surface convergence between southwesterly and northeasterly winds. A stable surface cold high with eastward-moving cold air amplifies snowfall.
3. Three main types are identified: Type A (southwest airflow ahead of trough, 14 events), Type B (eastward-moving trough/vortex, 12 events), and Type C (strong frontal zone, 27 events). Types A and B occur most frequently in early winter and early spring. Type A features longer wavelengths and slower movement with continuous moisture supply, resulting in long-duration events. Type B has shorter wavelengths and faster movement with intense cold-warm interactions, producing explosive development and stronger snow intensity. Type C involves strong vertical circulation and terrain-forced lifting, with the northern cold trough' s bottom westerly flow forming a "cold cushion" that creates steeper, stronger frontogenesis.
4. Water vapor sources include the high-latitude Barents Sea, mid-latitude Black/Caspian/Aral Seas, and low-latitude Arabian Sea, with transport pathways varying by type. Types A and B feature direct southwest flow transport, while Type C involves relay transport forming moisture convergence with stronger water vapor flux centers. Peak hourly snowfall occurs when moisture convergence concentrates in lower levels and intensity weakens from its maximum.

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