Mechanism and Genesis Analysis of Typical Blizzard Weather in Urumqi (Postprint)

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Abstract

Using conventional surface and upper-air observational data, NCEP/NCAR 1°$×$1° reanalysis, and FY satellite data, this study comprehensively compares and analyzes the causes of three typical snowstorm events in Urumqi since 1990 from the perspectives of upper- and lower-level circulation and synoptic system configuration, instability conditions, moisture, dynamics, and changes in Black Body Temperature (TBB). The results indicate that: (1) All three snowstorms occurred under the circulation pattern of a southeastward retreating European high-pressure ridge, which propelled the eastward and southward movement of the West Siberian low trough, combined with a mid-latitude short-wave trough. The upper- and lower-level systems exhibited a "backward-tilting trough" structure, with Urumqi located in the superimposed region of a northwesterly jet at 925–600 hPa and a strong southwesterly jet at 600–200 hPa. The topographic forced lifting of the Tianshan Mountains was conducive to the maintenance and intensification of the snowstorms. (2) Prior to the snowstorms, southeasterly winds existed at 850–700 hPa. Differential advection favored the formation and strengthening of advection inversion, leading to continuous energy accumulation. Subsequently, the intrusion of cold air resulted in cold frontogenesis and the development of stratification instability, providing thermal conditions for the snowstorms. The longer the duration of southeasterly winds and advection inversion, the more energy was stored and the stronger the snowfall. (3) Two moisture transport channels existed in the snowstorm area: southwestern and westward. Mid-level moisture transport was crucial for Urumqi snowstorms, with strong moisture convergence present at 850–600 hPa, peaking at 700 hPa. The intensity and duration of moisture transport and convergence jointly determined the snowstorm intensity. (4) There was a certain correspondence between TBB and snowfall intensity: the lower the TBB, the higher the cloud top height, and the more vigorous the development of mesoscale cloud clusters, resulting in stronger snowfall. The first rapid decrease (increase) in TBB (cloud top height) before snowfall indicated the onset of snowfall. During the snowfall process, decreasing TBB corresponded to enhanced snowfall intensity, and the greater the TBB decrease and the longer the duration of low TBB values, the stronger the snowfall.

Full Text

Preamble

Mechanisms and Causes of Typical Snowstorms in Urumqi

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Abstract: Using conventional surface and upper-air observations, NCEP/NCAR 1°$×$1° reanalysis data, and satellite data, this study conducts a comprehensive comparative analysis of three typical snowstorm events in Urumqi, examining large-scale circulation and synoptic system configurations, instability conditions, water vapor, dynamic mechanisms, and black body temperature (TBB) variations. The results show that: (1) All three snowstorms occurred under a circulation pattern characterized by the southeastward retreat of a European high-pressure ridge, which propelled the eastward and southward movement of a West Siberian low trough that subsequently merged with a mid-latitude short-wave trough. The upper and lower-level systems exhibited a "backward-tilting trough" structure, with Urumqi located in the overlapping region of a 925-600 hPa northwest jet and a 600-200 hPa strong southwest jet. Forced orographic lifting by the Tianshan Mountains contributed to the maintenance and intensification of the snowstorms. (2) Southeasterly winds were present at 850-700 hPa in all cases. Differential advection facilitated the formation and strengthening of advective inversions, leading to continuous energy accumulation. Subsequent cold air intrusion triggered cold frontogenesis and destabilized the stratification, providing thermal conditions for the snowstorms. The longer the duration of southeasterly winds and advective inversions, the more energy was stored and the stronger the resulting snowfall. (3) Two water vapor transport channels existed in the snowstorm area: southwest and west paths. Mid-level water vapor transport was crucial for Urumqi snowstorms, with strong water vapor convergence at 850-600 hPa, peaking at 700 hPa. The intensity, convergence strength, and duration of water vapor transport collectively determined snowstorm intensity. (4) TBB was correlated with snowfall intensity: lower TBB values indicated higher cloud tops and more vigorous mesoscale cloud clusters, resulting in stronger snowfall. The first rapid decrease in TBB (increase in cloud top height) signaled the onset of snowfall. During snowfall, TBB decreases generally corresponded to intensity increases, with larger TBB drops and longer maintenance of low TBB values producing stronger snowfall.

Keywords: typical snowstorm; synoptic system configuration; weather mechanism; cause analysis; Urumqi

1. Data and Methods

This study utilizes conventional surface and upper-air observations, NCEP/NCAR 1°$×$1° reanalysis data, and FY satellite data. We selected the three strongest snowstorms in Urumqi since 2010, which occurred on December 11, 2015 (referred to as the "12・11" event), January 23, 2021 (the "01・23" event), and December 8, 2014 (the "12・08" event). Synoptic-dynamical analysis methods were employed to diagnose the large-scale circulation background, instability conditions, dynamic mechanisms, and water vapor characteristics, revealing the synoptic mechanisms and intensity differences among these typical snowstorms.

2. Weather Overview

The three snowstorm events exhibited distinct intensity characteristics. The "12・11" event recorded a maximum daily snowfall of 46.3 mm (20:00 on December 10 to 20:00 on December 11), with a maximum hourly intensity of 2.8 mm and new snow depth of 45 cm, breaking the historical December daily snowfall record. The "01・23" event had a maximum daily snowfall of 35.9 mm (20:00 on January 22 to 20:00 on January 23), a maximum hourly intensity of 2.1 mm, and new snow depth of 19 cm, ranking second in historical winter daily snowfall. The "12・08" event showed a maximum daily snowfall of 17.8 mm (20:00 on December 7 to 20:00 on December 8), maximum hourly intensity of 1.9 mm, and new snow depth of 16 cm. In terms of cumulative snowfall, maximum daily snowfall, hourly intensity, duration, and snow depth, the "12・11" event was the strongest, followed by "01・23," with "12・08" being the weakest .

3.1 Circulation Pattern

At 500 hPa, all three events shared similar large-scale circulation features. Prior to the "12・11" event, a European high-pressure ridge developed northward on December 8, while a low vortex originally over the Ural Mountains moved eastward and developed over West Siberia. On December 10, successive short-wave troughs moved eastward upstream of the ridge. Cold advection and positive thermal wind vorticity advection behind the ridge caused it to retreat southeastward, driving the East Siberian low trough eastward and southward to merge with a mid-latitude short-wave system over the Caspian Sea. The trough extended south of 40°N, with enhanced positive vorticity advection ahead of the trough promoting upward motion. The southwesterly flow ahead of the trough (18 $\mathrm{m \cdot s^{-1}}$) transported mid-latitude moisture into the snowstorm area.

Before the "01 · 23" event, the European ridge developed on January 21 while the Ural low vortex persisted and a trough over the southern Caspian Sea moved eastward. On January 22, a stable short-wave trough attacked the European ridge, causing it to retreat southeastward. The Ural vortex weakened into a trough that moved eastward to West Siberia and was suppressed to 45°N, while the mid-latitude trough extended to 35°N, moving faster than the West Siberian trough and forming a "stepped trough" configuration. The southwest jet ahead of the trough continuously transported warm, moist air northward. On January 23, the West Siberian trough moved rapidly eastward, placing Urumqi under southerly flow (18 $\mathrm{m \cdot s^{-1}}$) ahead of the trough [Figure 12: see original paper].

Prior to the "12 · 08" event, the European ridge developed on December 6. As the ridge retreated, the Ural low vortex weakened into a trough over West Siberia, while a small mid-latitude trough over the southern Caspian Sea moved rapidly eastward, merged with the West Siberian trough, and was suppressed to 45°N. On December 8, the trough moved quickly eastward, placing Urumqi under southwesterly flow (16 $\mathrm{m \cdot s^{-1}}$) ahead of the trough [Figure 1: see original paper].

All three events exhibited a "two-ridge-one-trough" meridional circulation pattern at 500 hPa, with a high-pressure ridge over Europe and a low trough over West Siberia. As the European ridge retreated southeastward, it propelled the low trough eastward and southward to merge with mid-latitude short-wave troughs, strengthening the frontal zone and positive vorticity advection ahead of the trough and enhancing upward motion. The southwesterly flow ahead of the trough facilitated moisture transport from mid-latitudes to the snowstorm area.

At the surface, all three events featured ground cold highs moving into northern Xinjiang along westerly paths, with central intensities of 1047.5 hPa, 1045.0 hPa, and 1060.0 hPa respectively. Stronger high-pressure systems moved faster; the "12 · 08" event moved most rapidly, resulting in shorter snowstorm duration and smaller cumulative snowfall compared to the other two events.

3.2 Upper and Lower-Level Jets

All three snowstorms exhibited distinct upper and lower-level jet structures. At 08:00 on December 11, southwesterly flow ahead of the upper-level trough affected Urumqi, with 600–200 hPa southwesterly winds (maximum 24 $\mathrm{m \cdot s^{-1}}$) and northwesterly winds below 600 hPa (maximum 20 $\mathrm{m \cdot s^{-1}}$). At 02:00 on January 23, 600–200 hPa southwesterly winds (maximum 18 $\mathrm{m \cdot s^{-1}}$) affected the area, with northwesterly winds below 600 hPa (maximum 16 m · s^{-1}). At 02:00 on December 8, 600-200 hPa southwesterly winds (maximum 16 m · s^{-1}) were present, with northwesterly winds below 600 hPa (maximum 8 m · s^{-1}).

The spatial distribution of upper and lower-level jets during the three snowstorms showed that the upper-level jet axes were located over western northern Xinjiang, with wind speeds of 62 m · s^{-1}, 60 m · s^{-1}, and 55 m · s^{-1} respectively, accompanied by northwesterly jets. Urumqi was situated to the right of the upper-level southwest jet entrance region and ahead of the low-level northwesterly jet. The combined effects of the 925-600 hPa northwesterly jet and the 600-200 hPa southwest jet produced the typical snowstorm conditions in Urumqi.

Strong divergence and suction to the right of the upper-level southwest jet entrance region, along with positive vorticity advection ahead of the 300 hPa and 500 hPa troughs, favored upward motion. The eastward and southward movement of the West Siberian trough merging with mid-latitude short-wave troughs strengthened the frontal zone and positive vorticity advection ahead of the trough, enhancing upward motion and the southwesterly flow that transported moisture to the snowstorm area.

4.1.1 Southeasterly Winds, Temperature Advection, and Pseudo-Equivalent Potential Temperature (se)

Analysis of 850 hPa wind characteristics during snowfall events of moderate or greater intensity in Urumqi from 2011 to 2021 shows that the probability of southeasterly winds occurring before moderate snow, heavy snow, and blizzard events was 78%, 85%, and 95% respectively. Under favorable circulation backgrounds, pre-existing southeasterly winds at 850 hPa have significant predictive value for blizzards. But what is the specific relationship between these winds and snowfall intensity?

During the "12 · 11" event, southeasterly winds at 850-700 hPa persisted for approximately 30 hours, with maximum wind speeds of 16 m · s^{-1}. Southeasterly winds extended from the surface upward, and warm advection raised surface temperatures to 2.1°C by 14:00 on December 10. As southeasterly winds intensified (20:00 on December 10 to 20:00 on December 11), warm advection increased temperatures at 850-700 hPa to 11.7°C. Near the surface, northerly winds dominated, with cold advection causing slight temperature decreases. Differential advection thus generated and maintained an advective inversion before snowfall. The se profile showed a concave high-energy tongue, with se lines nearly perpendicular to the ground and significantly increased gradients, indicating cold frontogenesis [Figure 3: see original paper].

During the "01 · 23" event, southeasterly winds at 850-700 hPa persisted for about 24 hours with maximum speeds of 16 m · s^{-1}. Warm advection raised temperatures at 850-700 hPa to 10.8°C, while northerly winds dominated near the surface. Differential advection generated and strengthened the advective inversion, with the se profile showing a concave high-energy tongue. After 08:00 on January 23, low-level southeasterly winds shifted to northwesterly as cold advection reached -4$×10^{-4}$ K·s^{-1}, with cold frontogenesis occurring [Figure 3: see original paper].

For the "12·08" event, southeasterly winds at 850–700 hPa persisted for about 12 hours with weaker speeds of 8 m·s^{-1}. Warm advection was weaker, and the advective inversion was less pronounced than in the other two events. The se profile showed a concave pattern, and after 20:00 on December 8, low-level southeasterly winds shifted to northwesterly with cold advection of -4$×10^{-4}$ K·s^{-1} and cold frontogenesis [Figure 3: see original paper].

In summary, southeasterly winds at 850–700 hPa before all three events, combined with differential advection, generated and maintained advective inversions that allowed continuous energy accumulation. Subsequent cold air intrusion caused cold frontogenesis, enhanced interaction between warm and cold air, and promoted instability growth favorable for blizzard development. Comparison of the three events reveals that the duration and intensity of southeasterly winds, along with the associated warm and cold advection, showed a pattern of "12·11" > "01·23" > "12·08," corresponding exactly to snowfall intensity. Longer maintenance of southeasterly winds produced longer-lasting advective inversions, greater energy storage, and stronger snowfall. Therefore, pre-snowstorm southeasterly winds at 850–700 hPa represent an important forecasting feature for Urumqi blizzards, with their intensity and duration providing predictive guidance for snowfall intensity.

4.1.2 Temperature and Humidity Profiles Before and After Inversion Layer Destruction

An inversion layer, where temperature increases with height, inhibits convective upward motion while storing unstable energy. When cold air invades and destroys the inversion, this unstable energy is released, triggering severe weather. Temperature and humidity profiles before the three blizzards show that all events had inversion layers in the lower troposphere. The "12·11" event had an inversion between 907–850 hPa, with temperature increasing by 11.7°C with height and temperature-dewpoint differences of 1–4°C in the 885–808 hPa layer, indicating a moist layer. The "01·23" event had an inversion between 867–755 hPa, with temperature increasing by 27.8°C and temperature-dewpoint differences of 1–3°C in the 885–860 hPa moist layer. The "12·08" event had two inversions: 911–875 hPa and 801–769 hPa, with temperature increases of 6.5°C and 4.2°C respectively, and temperature-dewpoint differences of 1–3°C in the 911–850 hPa moist layer.

As cold air entered, all inversion layers were destroyed, with the 925–500 hPa layer becoming moist (figure omitted). The thickness of the inversion layer and the temperature increase with height were greatest for the “12 • 11”event, followed by “01 • 23” and then “12 • 08.” The “12 • 11” event also had a saturated layer near the surface, with good coordination between moisture and thermal conditions, resulting in the strongest snowfall intensity. Therefore, under favorable moisture and dynamic conditions, the thickness of the pre-snowstorm inversion layer and the temperature increase with height provide predictive guidance for snowfall intensity.

4.1.3 Changes in Lifting Condensation Level (LCL) Before and After Snowfall

The Lifting Condensation Level (LCL) is the height at which unsaturated moist air becomes saturated through dry adiabatic ascent, primarily determined by near-surface humidity and approximately representing cloud base height. Before the “12 • 11” event, LCL showed an increasing trend, but began decreasing from 08:00 on December 10, reaching its lowest value of 791 hPa at 20:00. Before the “01 • 23” event, LCL decreased from 08:00 on January 22, reaching 884.4 hPa at 20:00. For the “12 • 08” event, LCL decreased from 08:00 on December 8, reaching 910.7 hPa at 20:00.

In all cases, LCL reached its lowest value at the start of snowfall, indicating increased near-surface humidity and lowered cloud base height. When combined with favorable vertical motion, this increased cloud thickness and droplet growth, favoring snowstorm development and maintenance. The “12 • 11” event had the lowest LCL, consistent with its near-surface saturated layer. Thus, LCL changes provide useful guidance for snowfall forecasting.

4.2 Dynamic Conditions

Time-vertical cross-sections of divergence, vorticity, and vertical velocity for the three blizzards show distinct dynamic structures. The “12 • 11” event exhibited negative divergence (convergence) in the 925-700 hPa layer with a central value of -0.5$×10^{-5}$ s^{-1}, positive vorticity in the 850-500 hPa layer with a central value of 0.9$×10^{-4}$ s^{-1}, and upward motion in the 700-500 hPa layer with maximum vertical velocity of -2.0 Pa • s^{-1}, lasting about 30 hours. The “01 • 23” event showed negative divergence in the 925-600 hPa layer (-0.5$×10^{-5}$ s^{-1}), positive vorticity in the 500-300 hPa layer (0.6$×10^{-4}$ s^{-1}), and upward motion in the 700-400 hPa layer (-1.6 Pa • s^{-1}), lasting about 24 hours. The “12 • 08”event had negative divergence in the 925-300 hPa layer (-0.3$×10^{-5}$ s^{-1}), positive vorticity in the 700-500 hPa layer (0.25$×10^{-4}$ s^{-1}), and upward motion in the 700-500 hPa layer (-0.9 Pa • s^{-1}), lasting about 12 hours.

All three events featured lower-level convergence, upper-level divergence, and positive vorticity ahead of the upper-level trough that promoted upward motion development and maintenance, providing dynamic conditions for the blizzards. Comparison of vertical velocities shows the “12 · 11” event had the strongest and most persistent upward motion, corresponding to the most intense snowfall. The “01 · 23” event had weaker upward motion than “12 · 11” but stronger than “12 · 08,” consistent with its intermediate snowfall intensity. Snowfall intensity is influenced not only by systematic vertical motion but also by thermal, moisture, and mesoscale systems.

4.3 Water Vapor Conditions

Water vapor is essential for snowfall, and its transport, convergence intensity, and duration show good positive correlation with blizzard intensity. The “12 · 11” event had water vapor flux of 1.8 g · s^{-1} · cm^{-1} · hPa^{-1} near 500 hPa, with stronger transport in the mid-troposphere. Water vapor convergence occurred at 850-600 hPa with a central value of -6\$×10^{-5}\$ g · s^{-1} · cm^{-2} · hPa^{-1} (near 700 hPa), lasting about 30 hours. The “01 · 23” event had water vapor flux of 1.0 g · s^{-1} · cm^{-1} · hPa^{-1} near 500 hPa, with convergence at 850-500 hPa (-3\$×10^{-5}\$ g · s^{-1} · cm^{-2} · hPa^{-1} near 700 hPa), lasting about 24 hours. The “12 · 08” event had water vapor flux of 0.6 g · s^{-1} · cm^{-1} · hPa^{-1} near 500 hPa, with convergence at 850-400 hPa (-7\$×10^{-6}\$ g · s^{-1} · cm^{-2} · hPa^{-1} near 700 hPa), lasting about 12 hours.

All events showed positive water vapor flux and convergence, with the “12 · 11” event having the most pronounced and deep moisture transport. Mid-level water vapor transport was critical for Urumqi blizzards, with 700 hPa being the strongest level. The intensity, convergence strength, and duration of water vapor transport collectively determined the blizzard intensity. Analysis of 500 hPa water vapor flux revealed that moisture originated from the Red Sea, Mediterranean Sea, Persian Gulf, and Arabian Sea regions, with two transport pathways: a western path from the Red Sea and Persian Gulf moving northeastward along southwesterly flow through the Caspian Sea and Lake Balkhash into Xinjiang, and a southwestern path from the eastern Persian Gulf and Arabian Sea moving northeastward directly into Xinjiang (figure omitted).

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5. Satellite Cloud Imagery

The spatial distribution of TBB (figure omitted) shows that as the West Siberian trough moved eastward and southward, it guided the southeastward movement of a cold front cloud system. Blocked by the Tianshan Mountains, the cloud system slowed after entering Xinjiang and persisted along the northern Tianshan slopes. Relatively independent mesoscale cloud clusters continuously developed ahead of the mid-latitude short-wave trough, moving northeastward along the trough’ s southwesterly flow and intensifying within the cold front cloud system (forming TBB low-value bands or areas). Under the influence of upper-level steering flow, these mesoscale cloud clusters moved northeastward over Urumqi, producing the blizzards.

TBB is negatively correlated with cloud top height: lower TBB indicates higher cloud tops and more vigorous mesoscale cloud cluster development, resulting in stronger snowfall. Analysis of hourly snowfall and TBB changes shows that for the "12 • 11" event, TBB decreased rapidly from -30°C at 14:00 on December 10 to -65°C at 17:00 when snowfall began (a 35°C drop). During snowfall, TBB remained below -50°C, with rapid decreases to -68°C at 06:00 on December 11 corresponding to hourly snow intensities of 2.5 mm. For the "01 • 23" event, TBB decreased from -30°C at 22:00 on January 22 to -61°C at 00:00 on January 23 when snowfall began (a 31°C drop), with subsequent rapid decreases to -56°C corresponding to intensities of 2.1 mm. The "12 • 08" event showed TBB decreasing from -30°C at 18:00 on December 8 to -55°C at 20:00 (a 25°C drop), with subsequent decreases to -55°C corresponding to intensities of 1.9 mm.

In summary, the first rapid decrease of TBB below -30°C indicates snowfall onset. During snowfall, TBB generally shows a slow rising trend, but decreases in TBB mostly correspond to intensity increases. The magnitude of TBB drop, the intensity of low TBB values, and their duration are all greatest for the "12 • 11" event, followed by "01 • 23," then "12 • 08," consistent with snowfall intensity. Therefore, TBB drop magnitude and the maintenance time of low TBB values provide valuable guidance for short-term forecasting of snowfall intensity and duration.

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6. Conclusions

Through comprehensive comparative analysis of the three strongest snowstorms in Urumqi since 2010, this study reveals commonalities in large-scale circulation background and upper-lower level configurations during typical blizzard development, as well as intensity differences in instability conditions, dynamic mechanisms, water vapor characteristics, and mesoscale evolution. The main conclusions are:

(1) The large-scale circulation background for typical Urumqi blizzards involves European ridge development, southward extension of the West Siberian trough, and superposition of northern and southern low-value systems. The synoptic systems exhibit a pronounced backward-tilting trough structure, with Urumqi located in the overlapping region of 925–600 hPa northwest jets and 600–200 hPa southwest jets. Cold high-pressure systems moved eastward along western paths, with cold fronts blocked by the Tianshan Mountains for extended durations. Combined with orographic forced lifting by the Tianshan range, large-scale vertical motion developed, and together with favorable thermal and moisture conditions, produced typical Urumqi blizzard weather.

(2) Southeasterly winds at 850–700 hPa existed before all three blizzards. Differential advection generated and maintained advective inversions, while mid-level "dry warm caps" facilitated continuous energy accumulation. Subsequent cold advection caused cold frontogenesis and destabilized the stratification, providing thermal conditions for the blizzards. The longer the duration and stronger the intensity of pre-snowstorm southeasterly winds, the longer the advective inversion persisted, the more energy was stored, and the stronger the resulting snowfall. Therefore, under favorable moisture and dynamic conditions, the intensity and duration of pre-snowstorm southeasterly winds and advective inversions provide predictive guidance for snowfall intensity.

(3) Water vapor was transported to the blizzard area through southwest and west pathways originating from the Red Sea, Mediterranean Sea, Persian Gulf, and Arabian Sea regions. Mid-level water vapor transport was crucial for Urumqi blizzards, with strong water vapor convergence at 850–600 hPa, peaking at 700 hPa. The intensity, convergence strength, and duration of water vapor transport collectively determined blizzard intensity.

(4) Satellite imagery effectively monitors mesoscale systems in blizzards. TBB is negatively correlated with cloud top height: lower TBB indicates higher cloud tops and more vigorous mesoscale cloud cluster development, resulting in stronger snowfall. The first rapid decrease in TBB (increase in cloud top height) signals snowfall onset. During snowfall, TBB decreases generally correspond to intensity increases. The magnitude of TBB drop and the duration of low TBB values are greatest for the "12・11" event, followed by "01・23," then "12・08," consistent with snowfall intensity. Therefore, TBB drop magnitude and the maintenance time of low TBB values provide valuable guidance for short-term forecasting of snowfall intensity and duration.

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