Postprint: Anomalous Mechanisms and Genesis of a Localized Extreme Heavy Snow Event on the Northern Margin of the Tarim Basin

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Abstract

On April 2, 2021, a catastrophic snowstorm that broke historical records for the same period occurred in Baicheng County on the northern margin of the Tarim Basin. Using ERA5 high-resolution reanalysis data, automatic weather station observations, and FY-2G satellite data, this study analyzes the circulation anomalies, multi-scale circulation characteristics, and physical mechanisms of the extreme snowstorm. The results show that: (1) Anomalies in the upper-level Iranian High and low-latitude easterly airflow led to an abnormal combination of the Central Asian low vortex and the plateau low vortex, which strengthened the anomalous low-level easterly airflow. The easterly jet guided warm and moist air from the South China Sea and Bay of Bengal along the Hexi Corridor to the central Tarim Basin, enhancing water vapor convergence and vertical upward motion. Under the triggering of a surface convergence line, extreme snowfall weather was produced. The stable maintenance of a surface cold high pressure caused continuous cooling in the Tarim Basin. Baicheng is located in shallow mountainous areas above 1000 m altitude, and the combined effect of these two factors resulted in the precipitation phase in Baicheng in April remaining as snow. (2) Vertical potential temperature gradients and westerly wind anomalies led to the development of moist baroclinic instability, forming low-level frontogenesis and moist potential vorticity anomalies in the upper levels and near the surface. Frontogenesis and moist potential vorticity anomalies, in turn, influenced the occurrence and development of snowfall through changes in vertical motion. For Baicheng, the decisive factors were the mid-level upward motion and vertical wind shear between 300-500 hPa. (3) Mesoscale cloud clusters continuously developed and moved northeastward over Baicheng County, increasing the duration and intensity of snowfall. The consistency between the movement direction and propagation direction determined the evolution characteristics of the mesoscale cloud clusters' generation and dissipation. The research results can deepen understanding of the causes

of local extreme snowstorms in the Tarim Basin and provide scientific support for accurate forecasting and precise services.

Full Text

Preamble

Mechanism and Causes of a Local Extreme Snowstorm at the Northern Edge of the Tarim Basin

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Abstract: On April 2, 2021, Baicheng County at the northern edge of the Tarim Basin experienced a catastrophic snowstorm that broke historical records for the same period. Using high-resolution reanalysis data, automatic weather station observations, and FY-2G satellite data, this study analyzes the atmospheric circulation anomalies, multi-scale circulation characteristics, and physical mechanisms of this extreme snowstorm. The results show that: (1) Anomalies in the upper-level Iran subtropical high and low-latitude easterly airflow led to an abnormal combination of the Central Asian vortex and the Tibetan Plateau vortex, which strengthened the anomalous easterly airflow at low levels. The easterly jet guided warm and moist air from the South China Sea and Bay of Bengal along the Hexi Corridor to the central Tarim Basin, enhancing water vapor convergence and vertical upward motion. Under the triggering effect of a surface convergence line, this produced extreme snowfall. (2) The stable maintenance of a surface cold high caused continuous cooling in the Tarim Basin. Baicheng is located in a shallow mountainous area above 1000 m altitude, and the combined effect resulted in snowfall in April. (3) The vertical potential temperature gradient and westerly wind anomalies led to the development of moist baroclinic instability, forming low-level frontogenesis and moist potential vorticity anomalies at both upper levels and near the surface. These anomalies, in turn, influenced the development of snowfall through changes in vertical motion. For Baicheng, the decisive factors were the mid-level upward motion and the vertical wind shear at 300–500 hPa. (4) Mesoscale cloud clusters continuously developed and moved northeastward over Baicheng, increasing both the duration and intensity of snowfall. The consistency between the movement direction and propagation direction determined the evolution characteristics of the mesoscale cloud clusters. These findings can deepen understanding of the causes of local extreme snowstorms in the Tarim Basin and provide scientific support for accurate forecasting and precise services.

Keywords: extreme snowstorm; atmospheric circulation anomaly; baroclinic frontogenesis; mesoscale cloud cluster; Tarim Basin

1. Data and Methods

1.2 Meteorological Data

The study period spans from April 1 to 2, 2021. The data used include: (1) Hourly observations from automatic weather stations in Baicheng County; (2) Fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis data (ERA5) for both upper-air and surface levels, with 37 pressure levels in the vertical direction and a horizontal resolution of 0.25°\$×\$0.25°; (3) Hourly equivalent blackbody brightness temperature (TBB) data from the FY-2G satellite provided by the National Satellite Meteorological Center. Snowfall intensity follows Xinjiang local standards: 6.1–12.0 mm is heavy snow, 12.1–24.0 mm is severe snowstorm, and >24.0 mm is extreme snowstorm.

1.3 Research Methods

This study uses physical quantities such as moist potential vorticity and frontogenesis function to diagnose the causes of the snowstorm.

(1) Moist Potential Vorticity: In p-coordinates, introducing hydrostatic approximation and assuming that horizontal variations in vertical velocity are much smaller than vertical shear of horizontal velocity, the expression for moist potential vorticity is:

$$MPV = -g(\zeta_p + f)\frac{\partial \theta}{\partial p}$$

where MPV is moist potential vorticity (PVU, 1 PVU = 10^{-6} K $\cdot$ m^2 $\cdot$ s^{-1} $\cdot$ kg^{-1}); g is gravitational acceleration (9.8 m $\cdot$ s^{-2}); f is the Coriolis parameter or geostrophic vorticity (s^{-1}); ζ_p is the vertical vorticity component in p-coordinates (s^{-1}); x, y, p are three-dimensional coordinate axes; v is horizontal wind (m $\cdot$ s^{-1}); and θ is potential temperature (K). The concept of moist potential vorticity links atmospheric convective instability and moist baroclinic symmetric instability, with the latter clearly reflected through the baroclinic component of moist potential vorticity.

(2) Frontogenesis Function: This is a physical quantity representing the effects of horizontal motion, vertical motion, diabatic heating, and friction on frontogenesis. The two-dimensional frontogenesis function is expressed as:

$$F = \frac{d|\nabla\theta|}{dt} = D|\nabla\theta|\cos(2\beta) - \delta|\nabla\theta| + \frac{\partial \theta}{\partial p}\frac{\partial \omega}{\partial s}$$

where F represents frontogenesis ($F > 0$) or frontolysis ($F < 0$); θ is potential temperature (K); D is the total deformation term; β is the angle between the expansion axis (x-axis) and the potential temperature gradient; and δ is the divergence term.

2. Results

2.1 Planetary-Scale Circulation Anomaly Characteristics

From the perspective of circulation anomaly before the snowstorm (Figure 2): At 200 hPa, an anomalous anticyclone was located from the Aral Sea to the Iranian Plateau, while western China was controlled by an anomalous cyclone with centers over the Tibetan Plateau and northern Xinjiang. Anomalous upward motion in the central and eastern Tarim Basin reached $0.1\ \text{m}\cdot\text{s}^{-1}$. At 700 hPa, anomalous easterly winds along the bottom of the Mongolian anticyclone penetrated deep into the central Tarim Basin along the Hexi Corridor, with positive vorticity anomalies developing along the easterly airflow. Water vapor transport anomalies showed that moisture from the South China Sea and Bay of Bengal was transported northward and westward along anomalous southerly and easterly flows to Xinjiang, causing anomalous water vapor convergence in the central Tarim Basin. Upper-level planetary-scale circulation anomalies provided the background for mid- and low-level circulation anomalies. Mid-level anomalous anticyclonic systems enhanced cold air replenishment from the north, while warm moist air at low latitudes was transported westward by cyclonic easterlies. The violent confrontation between cold and warm air enhanced water vapor and vertical upward motion. Anomalous low-level easterly flow guided anomalous water vapor transport toward the central and eastern Tarim Basin. The coupling of atmospheric circulation anomalies at upper, middle, and lower levels constitutes the circulation anomaly mechanism of this event.

2.2 Synoptic-Scale Circulation Evolution Characteristics

The previous section analyzed circulation anomalies before the snowstorm. How did various scales of circulation evolve and interact during the snowstorm?

From the evolution of circulation patterns at different levels: At 200 hPa, two anticyclone centers were located over the Arabian Peninsula and the Indochina Peninsula, showing an east-strong-west-weak pattern. The region from southern Xinjiang to the Indian Peninsula was a trough area, with the subtropical westerly jet at mid-latitudes located over the Tibetan Plateau. At 500 hPa, a two-ridge-one-trough pattern dominated mid-latitudes, with ridge areas from the Aral Sea-Iranian Plateau and from the Indochina Peninsula to northeast China. Within the trough were two cyclonic circulations located in Central Asia and southern Tibetan Plateau, with the Central Asian vortex center intensity reaching 540 dagpm accompanied by a -36°C cold center. At 700 hPa, the Central Asian vortex intensified as the Aral Sea ridge weakened and cold air was transported along the northerly flow ahead of the ridge. The southern

Tibetan Plateau vortex weakened into a horizontal shear line and lifted northward. The southwesterly winds of the vortex and the easterly winds of the shear line transported warm moist air to the Tarim Basin, increasing humidity and initiating snowfall.

For the lower levels, when snow intensity peaked, the 850 hPa cold air from the Central Asian vortex entered the Tarim Basin, while easterly winds from the bottom of the Mongolian anticyclone intensified to 16 $m \cdot s^{-1}$ after entering the basin, forming convergence in western Xinjiang with specific humidity reaching 3 $g \cdot kg^{-1}$. At 14:00, northerly winds carried cold air eastward to the central basin, forming convergence with the intensified easterly winds exceeding 16 $m \cdot s^{-1}$, increasing humidity and strengthening upward motion. Combined with the west-high-east-low terrain, the easterly flow climbed along the topography first, then formed wind speed convergence in the central and western basin, further enhancing upward motion.

From the evolution of sea-level pressure (Figure 4), at 08:00 on April 1, the cold high-pressure center was located in Siberia with intensity exceeding 1032 hPa. Within 24 hours, the main body of the cold high slowly moved eastward by 10-15 degrees of longitude. At the time of maximum snow intensity in Baicheng, the cold high split over Mongolia, forming a center reaching 1036 hPa. Part of the cold air entered the basin through lower elevations of the western Tianshan Mountains, while another part entered the basin interior along the northern side of the Kunlun Mountains with the easterly flow. The convergence of easterly and westerly winds occurred at the western edge of the basin. The long-term stable maintenance of the cold high increased the duration of snowfall, thereby affecting total snowfall accumulation.

2.3 Meso- and Small-Scale Physical Mechanisms and Causes

Under favorable synoptic-scale circulation backgrounds, meso- and small-scale systems determine the location and intensity of snowfall. Physical quantities such as water vapor flux, frontogenesis function, and moist potential vorticity can more precisely characterize the spatiotemporal differences in snowfall. Therefore, this study uses these physical quantities to more comprehensively understand this extreme snowstorm.

2.3.1 Water Vapor Conditions Water vapor transport and convergence are crucial for precipitation. From the integrated water vapor flux and divergence (Figure 5): Before snowfall, the Central Asian vortex transported water vapor to southern Tarim Basin via westerly winds, while Baicheng's moisture mainly came from weaker easterly transport from the anticyclone in northern Xinjiang. At 08:00 on April 2, easterly transport from northern Xinjiang weakened, while low-latitude moisture was transported northward along the eastern side of the Tibetan Plateau, then continued westward after intensifying north of the plateau. Water vapor flux in the Tarim Basin increased significantly, with maximum easterly transport exceeding 50 $kg \cdot m^{-1} \cdot s^{-1}$. Meanwhile, the Central Asian vortex weakened and moved northeastward, with its westerly water vapor transport also shifting northward to central and northern Tarim Basin. The convergence of easterly and westerly moisture occurred in central Tarim Basin, with maximum convergence reaching -30×10^{-5} kg $\cdot$ m$^{-2} \cdot$ s^{-1}, coinciding with the time of maximum snow intensity in Baicheng.

From the time-height profile at Baicheng station (Figure 6), throughout the entire period, upward motion corresponded with the moist zone at 500–700 hPa, with the strongest upward motion and maximum water vapor transport both appearing as snowfall ended. From the wind field evolution, the low-level easterly winds, mid-level southerly winds, and upper-level southwesterly winds conform to the "three-branch airflow" model for precipitation in southern Xinjiang. Corresponding to the precipitation start and end times: At the beginning of snowfall (08:00), the vertical wind shear at 300–500 hPa was 16 m $\cdot$ s^{-1}; when precipitation intensified, the vertical wind shear at 300–500 hPa increased to a maximum of about 26 m $\cdot$ s^{-1}; as upper-level westerly winds decelerated, the mid- and upper-level vertical wind shear weakened, and precipitation intensity gradually decreased and stopped. Therefore, mid-level upward motion and vertical wind shear at 300–500 hPa were the main factors for the development of snowfall in Baicheng.

2.3.2 Thermodynamic Causes The previous analysis shows that upward motion for this snowstorm mainly occurred in the middle troposphere. Is this phenomenon related to baroclinic frontogenesis? Figure 7 shows the equivalent potential temperature, frontogenesis function, and wind field cross-section. At the onset of snowfall (08:00), equivalent potential temperature lines tilted northward with height, with a potential temperature gradient of 5 K/100 km from the surface to 500 hPa and frontogenesis intensity of 5×10^{-10} K $\cdot$ m$^{-1} \cdot$ s^{-1}. The vertical wind distribution featured low-level easterly winds and upper-level westerly winds, with upward motion appearing along the frontogenesis zone. As the main cold air body crossed the Tianshan Mountains into the basin (14:00), frontogenesis intensity along the mountains increased to 15×10^{-10} K $\cdot$ m$^{-1} \cdot$ s^{-1}. In the Baicheng region, equivalent potential temperature lines became nearly vertical, with the potential temperature gradient increasing to 8 K/100 km and frontogenesis intensity reaching 10×10^{-10} K $\cdot$ m$^{-1} \cdot$ s^{-1}. The vertical motion also strengthened correspondingly, enhancing snowfall. This analysis indicates that snowfall development was influenced by vertical motion generated by surface frontogenesis and near-surface moist potential vorticity anomalies, with the latter playing a particularly important role. Frontogenesis is closely related to the intensity and thickness of cold air.

Moist potential vorticity anomalies are closely related to moist baroclinic instability. Figure 8 shows that positive moist potential vorticity anomalies were distributed at 300 hPa and near the surface. The meridional wind distribution featured low-level northerly winds and upper-level southerly winds, which interacted with topography to form a vertical circulation near the surface in

Baicheng, with upward motion regions scattered in the mid- and upper-level southerly wind speed convergence zones. At the time of strongest snowfall (14:00), upper-level moist potential vorticity increased, reaching 3 PVU near the surface. With accelerated low-level southerly and northerly winds, the vertical circulation expanded southward and downward, with mid- and low-level upward velocity increasing to 2 $m \cdot s^{-1}$. This shows that the upward motion in the middle troposphere and vertical wind shear at 300–500 hPa were the main factors for the development of snowfall in Baicheng, with moist baroclinic instability intensifying as cold and warm air streams violently confronted each other. Low-level frontogenesis led to the development of baroclinic instability, triggering the surface convergence line and producing heavy snowfall.

2.3.3 Triggering Mechanism Surface meso- and small-scale convergence lines can serve as triggering mechanisms for severe weather. From the evolution of surface meteorological elements (Figure 9): At 20:00 on April 1, the Tarim Basin western region was a moist area with temperature-dewpoint difference less than 2°C. The north-south temperature gradient reached 4°C/100 km, with an east-west wind convergence line located at 80°E. The easterly winds intensified and pushed the convergence line westward and northward into Baicheng, where snowfall began. At 02:00 on April 2, the convergence line intensified, with a weak cyclonic circulation appearing west of Baicheng, where thermal and dynamic conditions cooperated, resulting in the strongest snowfall. At 08:00, warm advection east of Baicheng strengthened, while the convergence line maintained its position, allowing cold and warm air to confront each other for an extended period, favoring continuous heavy snowfall. At 14:00, northerly winds extended eastward while easterly winds retreated eastward, leaving Baicheng under the influence of cold advection from northerly winds only, ending precipitation. Comprehensive analysis shows that mesoscale cloud clusters continuously developed and moved northeastward over Baicheng, causing sustained heavy precipitation. The consistency between movement direction and propagation direction determined the evolution characteristics of the mesoscale cloud clusters.

3. Discussion

Based on the previous analysis, this study addresses the following questions: (1) Why did this weather occur in Baicheng County in central Tarim Basin, with daily snowfall breaking historical records? (2) Why did this snowstorm process occur in April when the average monthly temperature in southern Xinjiang typically rises to 5–10°C by mid-to-late March?

First, in addition to the typical circulation pattern for heavy snowstorms in the southern Xinjiang Basin—featuring an upper-level South Asian high, subtropical trough, and subtropical westerly jet; mid-level Central Asian vortex and Tibetan Plateau vortex; low-level easterly jet and convergence line; and surface cold high and convergence line—this event also showed significant differences. The upper-level Iran subtropical high and low-latitude easterly airflow anomalies led to an abnormal combination of the Central Asian vortex and plateau vortex, causing the main water vapor source to be transported by southeasterly winds along the southeastern side of the Tibetan Plateau, which could only reach the central Tarim Basin. Second, the long-term maintenance of a strong surface cold high allowed cold air to continuously penetrate the Tarim Basin, causing sustained cooling before snowfall. Combined with Baicheng's location in a shallow mountainous area, this resulted in heavy snowfall in April.

Satellite cloud images have the advantage of high spatial and temporal resolution. Figure 10 shows TBB evolution during the Baicheng snowstorm. At 04:00 on April 2, a southwest-northeast oriented meso-β scale cloud cluster appeared with cloud-top brightness temperature below 223 K, with Baicheng located at the southwestern edge of the northeastern cloud cluster. At 06:00, cloud clusters began merging, continuously propagating and moving northeastward over Baicheng. At 08:00, the meso-β scale cloud clusters fully merged, reaching maximum intensity and range, showing frontal cloud system characteristics but with movement direction changing to west-east. At 12:00, due to differences between propagation and movement directions, the cloud clusters weakened and dissipated, and Baicheng snowfall ended.

4. Conclusions

Using multiple meteorological datasets, this study analyzed the circulation anomalies, multi-scale circulation characteristics, and physical mechanisms of a local extreme snowstorm at the northern edge of the Tarim Basin. The main conclusions are:

(1) Before the snowstorm, upper-level anomalies of the Iran subtropical high and low-latitude easterly airflow caused an abnormal combination of the Central Asian vortex and Tibetan Plateau vortex, strengthening low-level anomalous easterly airflow. The easterly jet guided warm and moist air from the South China Sea and Bay of Bengal along the Hexi Corridor to the central Tarim Basin, enhancing water vapor convergence and vertical upward motion. Triggered by a surface convergence line, this produced extreme snowfall. The stable maintenance of a surface cold high caused continuous cooling in the Tarim Basin. Baicheng's location in a shallow mountainous area above 1000 m, combined with these factors, resulted in snowfall in April.

(2) The vertical potential temperature gradient and westerly wind anomalies led to the development of moist baroclinic instability, forming low-level frontogenesis and moist potential vorticity anomalies at upper levels and near the surface. These anomalies influenced the development of snowfall through changes in vertical motion. For Baicheng, the decisive factors were mid-level upward motion and vertical wind shear at 300–500 hPa. As cold and warm air streams violently confronted each other, low-level frontogenesis led to the development of baroclinic instability, and the surface

convergence line triggered heavy snowfall.

(3) Mesoscale cloud clusters continuously developed and moved northeastward over Baicheng, increasing the duration and intensity of snowfall. The consistency between movement direction and propagation direction determined the evolution characteristics of the mesoscale cloud clusters.

These results can enhance understanding of the causes of local extreme snowstorms in the Tarim Basin and provide scientific support for accurate forecasting and precise services for disaster prevention and mitigation.

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