Comparative Analysis of Different Precipitation Types under Topographic Influence in the Northern Foothills of the Qilian Mountains (Postprint)

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Abstract

Utilizing Zhangye CINRAD/CC Doppler radar data in conjunction with meteorological observation data and L-band radiosonde high-resolution data, this study analyzes the orographic influence effects on various types of heavy precipitation processes along the northern foothills of the Qilian Mountains. The results demonstrate that: the formation mechanisms and physical quantity conditions differ among different types of heavy precipitation, and the orographic effects on precipitation also vary accordingly; the high-value zones of each precipitation category are concentrated in mountainous regions or on the northern slopes of mountains, where the forced orographic lifting effect due to terrain elevation is pronounced; the blocking, convergence, and lifting effects of local small-scale topography are notably prominent in strong convective precipitation processes; the train effect arising from the overall lifting of large-scale topography, combined with the convergence effect of local small-scale topography, collectively contributes to short-duration heavy precipitation events; conversely, in precipitation processes influenced by synoptic-scale cold air, the primary manifestation of topographic effects involves the continuous generation and prolonged maintenance of strong echoes within the steering-level flow under the influence of "pocket" -shaped topography; regarding sounding data, the characteristic parameters of upper-level cold cloud precipitation and lower-level warm cloud precipitation exhibit distinct variation patterns.

Full Text

Comparative Analysis of Different Types of Precipitation Characteristics at the Northern Foot of the Qilian Mountains Under Topographic Influence

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Abstract

Using Zhangye CINRAD/CC Doppler radar data combined with conventional meteorological observations and L-band sounding second data, this study analyzes the topographic influence on different types of heavy precipitation processes at the northern foot of the Qilian Mountains. The results demonstrate that formation mechanisms and physical quantity conditions vary among different precipitation types, leading to distinct topographic effects. Large precipitation values concentrate in mountainous areas or on northern slopes, where terrain-induced forced lifting is significant. Local small-scale topography exhibits pronounced blocking, convergence, and lifting effects during strong convective precipitation. Short-duration heavy precipitation results from the combined effects of training phenomena caused by large-scale terrain uplift and convergence from local topography. In systematic cold-air-influenced precipitation, topography primarily manifests through continuous generation and long-term maintenance of strong echoes in the bearing layer airflow under "pocket-shaped" terrain influence. Sounding data reveal differing characteristic variations between upper-level cold cloud precipitation and lower-level warm cloud precipitation.

Keywords: northern foot of the Qilian Mountains; heavy precipitation characteristics; topographic influence; radar echo; sounding second data

Topography exerts substantial influence on precipitation, affecting local weather systems and even global atmospheric circulation through dynamic, thermal, and cloud-physical mechanisms. Research on topographic precipitation effects has spanned over half a century internationally. Hobbs investigated cloud and precipitation characteristics when frontal systems passed over mountains in Washington State, finding that riming and aggregation are universal particle growth pathways. Woods et al. discovered that frontal systems and topography jointly affect cloud microphysical structures, with windward slope uplift increasing cloud water content. Domestic scientists have conducted extensive observational studies on mountain effects on atmospheric motion, local slope circulations, and mountain boundary layer structures since the 1980s, examining mechanisms across various regions including the Tibetan Plateau, Rocky Mountains, Qilian Mountains, Tianshan Mountains, Taihang Mountains, and southern China mountains. These studies reveal that dynamic effects include blocking and friction, while thermal effects through latent heat release can warm mid-to-upper levels and enhance upper-level divergence, forming positive feedback that strengthens topographic amplification. Cloud-physical effects influence precipitation by altering liquid water distribution and particle growth modes, establishing a foundation for China' s topographic precipitation research.

The Qilian Mountains, located on the border between northeastern Qinghai Province and western Gansu Province, consist of multiple parallel northwest-southeast oriented mountain ranges and broad valleys at 4000-6000 m elevation, containing 2,062 glaciers. This alpine snowpack critically stores cloud water resources for mainland China, with its terrain structure, cloud characteristics, and precipitation relationships receiving increasing attention from domestic researchers. Qilian Mountain precipitation serves as an important water source for the Hexi Corridor and downstream areas, with topographic cloud precipitation accounting for a high proportion of total precipitation in the region. Therefore, studying precipitation characteristics at the northern foot of the Qilian Mountains provides scientific guidance for weather modification operations.

Zhangye City in Gansu Province lies at the northern foot of the Qilian Mountains. The Heli and Longshou Mountains form the northern corridor mountains, while the central area comprises an inclined plain at 230-1410 m, creating the Zhangye Basin with its alluvial fan-shaped topography opening southeastward —an important component of the Hexi Corridor. This special funnel-shaped topography facilitates upward air motion, intensifying precipitation, with convergence zones in the funnel area prone to heavy rainfall centers. Doppler radar data and sounding data enable better analysis of topographic precipitation effects and deeper exploration of topographic influences on different precipitation types at the northern foot of the Qilian Mountains.

This paper utilizes CINRAD/CC Doppler radar data, MICAPS data, and sounding second data to conduct comparative analysis of three different heavy precipitation processes in Zhangye: August 8, 2017 (strong convective precipitation), August 31, 2018 (short-duration heavy precipitation), and June 25-26, 2019 (systematic heavy precipitation). The study summarizes topographic influence characteristics on heavy precipitation during different precipitation processes at the northern foot of the Qilian Mountains to reveal macrostructure characteristics and precipitation formation mechanisms of typical Qilian Mountain topographic cloud systems, establishing foundations for weather modification conceptual models and forecast accuracy improvement.

1 Data Sources

Radar data were obtained from the Zhangye CINRAD/CC fully coherent pulse Doppler radar operating in VCP11 mode, with intensity field products processed by RPG/PUP software. Hourly precipitation data came from regional automatic weather stations in Zhangye. Synoptic field data were derived from

MICAPS products. Sounding second data were obtained from Zhangye L-band sounding observations.

2 Weather Situation and Actual Conditions

2.1 Weather Actualities

August 8, 2017: Zhangye experienced severe convective weather including thunderstorms, strong winds, heavy precipitation, and hail. The maximum cumulative precipitation reached 70.4 mm, maximum rainfall intensity was 31.5 $mm \cdot h^{-1}$, maximum wind speed was 23.8 $m \cdot s^{-1}$, and maximum hail diameter was 18.2 mm. This represented the strongest precipitation process in the Hexi region since 2011, with 11 stations recording cumulative precipitation exceeding 30 mm and 6 stations experiencing short-duration heavy precipitation exceeding 50 mm.

August 31, 2018: A regional rainstorm occurred in Zhangye, with 11 stations recording short-duration heavy precipitation. The maximum cumulative precipitation was 62 mm and maximum rainfall intensity was 28.4 $mm \cdot h^{-1}$. This rainstorm induced mountain floods, causing house collapses, road damage, farmland inundation, and severe urban waterlogging, particularly on September 1, with direct economic losses of 86.125 million yuan.

June 25-26, 2019: Continuous precipitation occurred with 6 stations recording cumulative precipitation exceeding 30 mm and maximum cumulative precipitation of 70.4 mm.

Comparative analysis of precipitation spatial distribution and Zhangye topography shows that large precipitation areas for all three events appeared in mountainous regions or on northern slopes [Figure 1: see original paper]. On August 8, 2017, large values occurred at the junction of Sunan, Minle, and Zhangye, north of Linsong Mountain on the northern side of the Hexi Corridor South Mountains. On August 31, 2018, large values appeared west and north of the Sunan northern mountains, near Linsong Mountain, and near Niangniang Mountain in Shandan. On June 25-26, 2019, large values occurred near the northern Qilian Mountains in eastern Shandan and Minle, where terrain undulates dramatically. This demonstrates clear topographic influence on precipitation distribution in Zhangye.

2.2 500 hPa Circulation Pattern Analysis

The August 8, 2017 precipitation was a "northwest airflow type" event. As cold air moved eastward and southward, it was blocked by terrain and forced to lift at the junction of Minle, Zhangye, and Sunan, causing local severe convective weather. The August 31, 2018 precipitation was an "east-high-west-low type" rainstorm. A low trough over central Xinjiang and the 584 dagpm contour line formed a plateau trough west of Zhangye. Superposition of northern and southern troughs in the same phase caused warm moist airflow on the northwest side of the subtropical high to meet cold air from eastern Xinjiang in the central Hexi Corridor. The June 25-26, 2019 precipitation was a "low trough eastward-moving type." Zhangye was controlled by northwesterly flow at 500 hPa, with a cold vortex over northeastern Xinjiang continuously splitting cold air southward, cooperating with low-level warm moist flow to cause this persistent precipitation process. Differences in precipitation systems caused different movement directions of cold/warm and dry/moist airflows, resulting in varying topographic effects on heavy precipitation.

2.3 Comparison of Mesoscale Environmental Field Configurations

Comparison of mesoscale environmental field configurations for the three precipitation events shows that all occurred under favorable circulation backgrounds but with differing physical quantity conditions. The August 8, 2017 event had stronger cold air and more obvious temperature differences between upper and lower levels. Compared with the June 25-26, 2019 event, the August 31, 2018 event more clearly exhibited "subtropical high periphery type" precipitation characteristics with better moisture and energy conditions. The June 25-26, 2019 event had relatively weaker conditions overall, with precipitation mainly caused by successive eastward movements of cold air.

presents the mesoscale environmental field configuration characteristics for the three precipitation processes.

3 Radar Data Analysis

Affected by the complex Qilian Mountains terrain, this analysis primarily uses low-elevation (0.5°-1.5°) radar reflectivity and radial velocity data (elevation not noted in figures is 0.5°, range rings are 30 km and 100 km) to discuss different precipitation processes.

3.1 Intensity Field Analysis

August 8, 2017 Strong Convective Precipitation: Radar echoes showed blocky convective echoes moving from northwest to southeast. The echo enhanced twice near Minle Nangu Station. The first enhancement period (13:19-14:05) saw echo intensity rapidly increase from 45 dBz to 57 dBz, corresponding to 9.9 mm ten-minute precipitation—a rare phenomenon in Hexi region. The second enhancement period (14:34-15:08) showed bow-shaped echoes reaching 59 dBz. Small cumulus echoes from the northwest moved into the Gaoxinba area near Gaotai (15:25-15:31), developing rapidly with expanded scope and enhanced intensity reaching 56 dBz, maintaining strong echoes for 53 minutes. This timing coincided with hail occurrence.

Heavy precipitation and hail locations closely relate to local special topography. Gaotai Xinba lies in a north-by-west opening southward depression on the northern Qilian slope, providing topographic blocking and forced convergence/ lifting of water vapor energy above the condensation level, offering favorable triggering mechanisms for convection. Minle Nangu Station sits at the mountain foot, where northwesterly winds from Xinjiang descending over northwestern mountains favor convection development on lee slopes, with obvious topographic convergence facilitating wind direction changes and precipitation enhancement.

August 31, 2018 Short-Duration Heavy Precipitation: After cold air entered Zhangye, topographic blocking and lifting by northern Qilian foothills and north-south oriented hills near Wutongquan caused local heavy precipitation. The precipitation echo exhibited stratiform-cumuliform mixed characteristics with maximum reflectivity maintaining 35-45 dBz. Echoes enhanced when encountering terrain uplift from Qilian, Longshou, and Heli Mountains. After 18:00, echoes moved eastward and weakened after 22:00.

The precipitation echo body covered a 90-100 km radius centered on the radar station, showing obvious "training effect" with strong precipitation concentrated in southern Gaotai. The mature stage featured merged and developed strong echoes from the west moving northeastward with gradually expanding scope.

June 25-26, 2019 Systematic Cold Air Precipitation: The precipitation process can be divided into three stages [Figure 5: see original paper]. Stage 1 (08:00-12:00) featured low-cloud precipitation formed by cold air lifting at the Longshou Mountains as cold air ahead of the cold front and upper-level westerly trough moved eastward. Stratiform echoes dominated at low elevations (0.5°-1.5°), moving northwest-southeast. At 08:57, the strongest echo in southeastern Shandan reached 53 dBz at low elevation but only 30 dBz at high elevation, showing obvious low-centroid structure favorable for efficient precipitation.

Stage 2 (13:34-21:29) saw numerous scattered convective blocks in southwestern radar coverage moving northeastward, gradually enhancing under Qilian Mountains blocking and lifting, with echoes >35 dBz located south of Shandan and Minle corresponding to significantly enhanced local precipitation.

Stage 3 (after 21:29) featured obvious echo enhancement and development near Minle and Shandan, with heavy precipitation areas again showing low-centroid structure. This process was dominated by stratiform precipitation, transforming into stratiform-cumuliform mixed echoes when encountering terrain uplift from Qilian and Longshou Mountains as cold air split and moved southward. Under bearing layer airflow and "pocket-shaped" topography (high northwest, low southeast, surrounded by mountains on three sides), strong echoes continuously passed through southeastern radar coverage and persisted long-term. The low-centroid structure in reflectivity vertical structure favored precipitation. Particularly in Shandan Chenhu northwest of Yanzhi Mountain, energy lifting from cold air climbing enhanced precipitation intensity.

3.2 Velocity Field Analysis

August 8, 2017: Corresponding to the intensity field, a southwest-northeast oriented negative velocity zone appeared southwest of the radar station at 13:25-13:54, with an adverse wind area surrounded by negative velocity and zero lines near Sunan, horizontal scale 5-6 km. Stage 2 (14:05-14:51) saw the convergence center move southeastward and weaken. Stage 3 (15:03-15:48) featured another convergence center near Minle Nangu lasting 45 minutes, corresponding to heavy precipitation timing. The velocity zero line showed an inverse "S" shape, with cold advection at low levels and southerly winds at mid-upper levels, indicating cold air invasion from low levels gradually penetrating upward. Consequently, mid-level winds above the radar station slowly shifted from southerly to northwesterly.

August 31, 2018: At 14:24, a wind field convergence center reappeared near Minle Nangu, lasting 30 minutes and corresponding to renewed heavy precipitation. The velocity zero line showed a "bow" shape, with radial inflow inside the "bow" forming a convergence flow field maintained until 15:24. After 15:24, the convergence center moved southeastward and precipitation weakened.

June 25-26, 2019: Doppler radial velocity analysis [Figure 8: see original paper] shows that before precipitation (02:56-03:46), the zero velocity line was anti-"S" shaped. The velocity field was embedded with several adverse wind areas surrounded by zero lines, with convergence flow fields and adverse wind structures persisting long-term—the main cause of heavy rain at this location. From 18:27, obvious velocity convergence appeared from Gaotai and Linze southwest to Zhangye, with positive/negative velocity center values increasing significantly. By 20:10, the negative velocity center reached -15.0 $m \cdot s^{-1}$ and the positive center 12.1 $m \cdot s^{-1}$, indicating strengthened low-level northwesterly jet and enhanced speed convergence—the primary reason for short-duration heavy precipitation across Gaotai. By 22:45, the entire radar coverage had shifted to northwesterly winds as cold air completely controlled the area. Near Minle Nangu (the strongest precipitation area), the wind field showed convergence again at 21:47, corresponding to precipitation enhancement.

Radar analysis reveals varying topographic roles in different precipitation types. In strong convective precipitation, small-scale topography dominates through forced lifting of unstable energy and forced convergence from cold air flowing over mountains, causing local heavy precipitation. In short-duration heavy precipitation, large-scale terrain blocking/lifting forms training effects while small-scale topography provides convergence, creating high overall intensity with short-duration heavy precipitation. Systematic cold air processes mainly involve large-scale terrain lifting, bearing layer airflow, and "pocket-shaped" topography effects, manifesting as low-centroid structures from cold air climbing effects.

4 Sounding Data Analysis

4.1 Cloud Layer Characteristics

August 8, 2017 (Process 1): Pre-precipitation clouds were relatively thin with high cloud bases, low starting temperatures, and mixed water vapor/liquid water forms, beginning as mid-level clouds. During precipitation, cloud bases rapidly lowered with significantly increased cloud base temperature; cloud top height also rapidly lowered while cloud thickness slightly increased, dominated by mid-level clouds. After precipitation, clouds quickly dissipated.

August 31, 2018 (Process 2): Pre-precipitation clouds were thick with low cloud bases, high extension, high starting temperature, and water vapor-dominated water content, beginning as low clouds. During precipitation, cloud bases gradually rose while cloud base temperature rapidly decreased; cloud top lowered with significantly increased cloud top temperature, and cloud thickness rapidly decreased, dominated by low-mid level clouds. After precipitation, cloud thickness decreased, cloud base temperature increased, cloud top temperature rapidly decreased, and cloud top height rose, dominated by relatively high mid-level clouds.

June 25-26, 2019 (Process 3): Cloud layer characteristics fell between the two previous processes, showing obvious continuous cold air influence features. Cloud base starting height rose but less than Process 2; cloud base temperature first rapidly decreased then slightly increased; cloud top height rose while cloud top temperature decreased; cloud thickness increased, dominated by mid-high level clouds. Changes during the process were less significant compared to Process 2.

presents cloud characteristic statistics for the three precipitation processes.

4.2 Special Altitude Layer Variations and Precipitation

August 8, 2017 (Process 1): The 0°C layer height gradually rose before and after precipitation, with relative humidity first increasing then decreasing. The -20°C layer height gradually rose with decreasing humidity. The height difference between 0°C and -20°C layers gradually decreased, with wind shear first increasing then decreasing.

August 31, 2018 (Process 2): The 0°C layer height first decreased then rose, with relatively high humidity throughout. The -20°C layer gradually lowered, with humidity first decreasing then increasing. The height difference between 0°C and -20°C layers first decreased then increased, with wind shear first increasing then decreasing.

June 25-26, 2019 (Process 3): The 0°C layer height gradually decreased, with the height difference first increasing then decreasing. Wind shear first decreased, then increased, then decreased again.

Analysis of cloud layer and special altitude layer characteristics reveals that the

August 8, 2017 northwesterly flow severe convection process showed obvious upper-level cold cloud features with rapid characteristic variations. The August 31, 2018 precipitation process showed obvious lower-level warm cloud features with gradual characteristic changes. The June 25-26, 2019 precipitation process fell between these two, with obvious continuous cold air influence features.

presents special altitude layer characteristic statistics for the three precipitation processes.

5 Conclusions

1) Large precipitation values for all three events appeared in mountainous regions or on northern slopes, showing obvious topographic influence with significant forced lifting effects. The intensity of topographic influence on precipitation relates to precipitation type.

2) Precipitation mechanisms differed among the three heavy precipitation processes. The August 8, 2017 event was "upper-level cold trough type" precipitation—local severe convective weather caused by eastward-moving cold air. The August 31, 2018 event was a typical "east-high-west-low type" rainstorm influenced by both cold air and subtropical high periphery. The June 25-26, 2019 event was a "low trough eastward-moving type" continuous precipitation process caused by successive mid-level cold air splitting and moving eastward, cooperating with low-level warm moist flow.

3) In strong convective precipitation, topography mainly functions through blocking, convergence, and lifting by local small-scale terrain. Short-duration heavy precipitation results from the combined effects of training caused by large-scale terrain uplift and convergence from local small-scale terrain. Systematic cold air processes involve large-scale terrain lifting, bearing layer airflow, and "pocket-shaped"topography (high northwest, low southeast, surrounded by mountains on three sides) effects, manifesting as low-centroid structures from cold air climbing effects with continuous strong echo generation and long-term maintenance.

4) Sounding second data show that the August 8, 2017 northwesterly flow severe convection process exhibited obvious upper-level cold cloud features with rapid characteristic variations. The August 31, 2018 precipitation process showed obvious lower-level warm cloud features with gradual characteristic changes. The June 25-26, 2019 precipitation process fell between these two, with obvious continuous cold air influence features.

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