Statistical Analysis of Ground-Based Raindrop Size Distribution Characteristics in the Liupan Mountain Area of Ningxia (Postprint)

Authors: Ma Simin[1,2], Zhiliang Shu[1],[2], Chang Zhuolin[1],[2], Zhou Nan 1,2, Liu Shijun 3

Date: 2023-08-26T00:00:00+00:00

Abstract

Using raindrop spectrum data from different stations during 58 rainfall events in the Liupan Mountains from 2020 to 2021, we analyzed the microphysical parameters, average characteristics of raindrop spectra, and Gamma distribution parameters for three types of rainfall: stratiform clouds, convective clouds, and cumulus-stratiform mixed clouds. The results show that: (1) At the same station, all microphysical parameters and mean characteristic diameters exhibit the following relationship: convective clouds > cumulus-stratiform mixed clouds > stratiform clouds; in stratiform and cumulus-stratiform mixed clouds, the average diameter (Dave) and mode diameter (Dmode) are larger at the mountainside than at the mountain top and base, and as altitude increases on both the eastern and western slopes, the maximum diameter (Dmax), mass-weighted mean diameter (Dm), rainfall intensity (R), radar reflectivity (Z), and liquid water content (Q) gradually increase; (2) In stratiform and cumulus-stratiform mixed clouds, small raindrops contribute the most to both rainfall intensity and number concentration, while in convective clouds, small raindrops contribute the most to number concentration, and medium-sized raindrops contribute the most to rainfall intensity; (3) The Gamma distribution parameters N0 (intercept parameter), (shape parameter), and λ (slope parameter) decrease with increasing altitude, and the slope of the -λ fitted curve is closely related to precipitation type; (4) The raindrop particle number concentration (Nw) at mountain-top stations decreases compared with that at mountain-base stations, while the mean scale (Dm) increases; (5) The characteristic diameter parameters and microphysical parameters of raindrop spectra under the northwest airflow pattern are greater than those under the east-high-west-low pattern and the straight airflow pattern.

Full Text

Statistical Analysis of Surface Raindrop Size Distribution Characteristics in the Liupan Mountains of Ningxia

MA Simin[12], SHU Zhiliang[12], CHANG Zhuolin[12], ZHOU Nan[12], LIU Shijun[3]

[1]Key Laboratory for Meteorological Disaster Monitoring and Early Warning and Risk Management of Characteristic Agriculture in Arid Regions, CMA, Yinchuan 750002, Ningxia, China
[2]Ningxia Key Laboratory of Meteorological Disaster Prevention and Mitigation, Yinchuan 750002, Ningxia, China
[3]Wuhai Meteorological Bureau, Wuhai 016000, Inner Mongolia, China

Abstract

Using raindrop spectrum data from different stations during 58 rainfall processes in the Liupan Mountains from 2020 to 2021, we analyzed the microphysical parameters, average characteristics of raindrop spectra, and Gamma distribution parameters for three types of rainfall: stratiform, convective, and stratocumulus. The results show that: (1) At the same station, the mean values of microphysical parameters and characteristic diameters follow the pattern: convective > stratocumulus > stratiform clouds. In stratiform and stratocumulus rainfall, the average diameter (D) and mode diameter (D) were larger on the mountainside than at the mountaintop and foothills, while the maximum diameter (D), mass-weighted mean diameter (D), rain rate (R), radar reflectivity (Z), and liquid water content (Q) increased with elevation on both eastern and western slopes. (2) In stratiform and stratocumulus rainfall, small raindrops contributed most to both rain rate and number concentration, whereas in convective rainfall, small raindrops contributed most to number concentration while medium-sized raindrops contributed most to rain rate. (3) The Gamma distribution parameters N_0 (intercept parameter), (shape parameter), and λ (slope parameter) decreased with increasing altitude. The slope of the -λ fitting curve was closely related to precipitation type. (4) Compared with foothill stations, the mountaintop station showed decreased raindrop number concentration (N) but increased mean scale (D). (5) The characteristic diameters and microphysical parameters under northwesterly flow patterns were greater than those under east-high-west-low patterns and straight flow patterns.

Keywords: Liupan Mountains; raindrop spectrum; microphysical characteristics; Gamma distribution

Introduction

Raindrops are the final product of comprehensive cloud dynamic and microphysical processes, representing the culmination of macro- and micro-scale precipitation processes. Raindrop size distribution (RSD) describes the number concentration of raindrops per unit volume as a function of their diameter. Studying RSD is crucial for understanding natural precipitation mechanisms, evaluating artificial rain enhancement potential, conducting effect verification, guiding weather modification operations, and improving the accuracy of radar-based quantitative precipitation estimation.

The concept of RSD was first introduced by Marshall and Palmer in 1948, who proposed that an exponential equation could adequately describe the relationship between raindrop size and concentration (referred to as the M-P distribution). However, subsequent research revealed significant discrepancies between this distribution and actual precipitation characteristics, particularly in the distribution of small raindrops. Ulbrich subsequently proposed a three-parameter Gamma distribution model that incorporates a shape parameter , enabling better representation of small raindrop variations. Numerous studies have demonstrated that the Gamma distribution more accurately characterizes the RSD features of stratocumulus and cumuliform precipitation compared to the M-P distribution.

In recent years, Chinese researchers have conducted extensive studies using ground-based laser disdrometers, revealing significant regional variations in RSD characteristics across different precipitation types, altitudes, and weather systems. For instance, Niu et al. analyzed RSD characteristics under different circulation patterns in various regions of Ningxia, while Zhang examined summer convective and stratiform rainfall spectra at the southern foothills of the Qilian Mountains, finding that convective rainfall particles of the same size had slightly higher fall speeds than stratiform clouds. Wang et al. analyzed microphysical structural characteristics of three rainfall types in the Tianshan Mountains, noting that mountainous terrain resulted in high concentrations of small raindrops with small sizes, indicating substantial rain enhancement potential. Li et al. demonstrated that in Huangshan, stratiform cloud RSD varied more stably with height than convective clouds, with larger raindrop sizes at mid-mountain positions compared to summit and base stations. Similar patterns were observed by Zhang et al. in Lushan, where small raindrops accounted for a larger proportion at higher altitudes, while same-sized raindrops had greater terminal velocities at lower altitudes. Cheng et al. found that high-altitude stations in the Qilian Mountains exhibited smaller raindrop diameters but higher concentrations.

The Liupan Mountains are one of China’ s few nearly north-south oriented narrow mountain ranges, with its main peak reaching 2942 m. The western slope is gentle (10°-20°), while the eastern slope is steep (20°-35°), providing favorable conditions for studying airflow propagation over continuous mountains and cloud-precipitation physical processes. As a major water conservation area in northwest China, the Liupan Mountains region is dominated by southeasterly warm-moist airflow at 750 hPa, which undergoes orographic lifting and condensation when encountering the steep eastern slope, forming deep convective clouds. Previous studies in this region, such as Tao et al.' s analysis of microphysical characteristics during a severe convective hail event and Cao et al.' s comparison of microphysical features among convective, stratiform, and shallow cumulus clouds using micro-rain radar, have lacked comprehensive analysis of continuous observational data and comparative studies of RSD characteristics at different topographic positions. This study utilizes raindrop spectrum data from 2020-2021 to investigate microphysical parameters, average RSD characteristics, and Gamma distribution parameters across different precipitation types and locations, aiming to reveal surface rainfall microphysical features and advance understanding of orographic cloud precipitation development mechanisms in the Liupan Mountains region.

1. Data and Methods

1.1 Equipment and Data Description This study utilized DSG5 laser disdrometers deployed at the Liupan Mountain Atmospheric Science Field Experiment Base for year-round observations. Figure 1 shows the geographic locations of the instruments, and Table 1 provides basic information for each observation site. The DSG5 laser disdrometer operates based on the principle of laser attenuation by precipitation particles, featuring 54 non-equidistant diameter channels and 32 non-equidistant velocity channels. The instrument measures precipitation particle diameters from 0.2-25 mm and fall speeds from 0.2-20 $\mathrm{m \cdot s^{-1}}$. Previous studies have shown that through calibration and monitoring, the error range remains within \$±\$5%. Table 2 lists the main technical specifications.

We selected data from 58 rainfall processes during 2020-2021, using observations from five disdrometer stations in the Liupan Mountains. Rainfall types were classified based on data from a new-generation Doppler weather radar (located at Liupan Mountain Station, 106.2°E, 35.68°N, 2860 m) and satellite imagery. The selected cases included 23 stratiform rainfall events, 13 convective rainfall events, and 22 stratocumulus rainfall events. After quality control, precipitation duration at each station exceeded 30 minutes. Due to the localized nature of convective precipitation, we selected cases observed by at least three disdrometer stations simultaneously. The start and end times for each case corresponded to the earliest and latest times precipitation particles were observed across all stations.

Based on the 500 hPa circulation patterns over the Liupan Mountains region, the 58 rainfall processes were categorized into three types: east-high-west-low pattern, northwesterly flow pattern, and straight flow pattern. The east-high-west-low pattern occurred most frequently (24 times, 41.4%), followed by the northwesterly flow pattern (22 times, 37.9%), and the straight flow pattern (12 times, 20.7%). Among stratiform and stratocumulus rainfall events, the east-high-west-low pattern was most common, while convective rainfall events were dominated by the northwesterly flow pattern.

1.2 Data Quality Control Due to limitations in sensitivity and sampling area, laser disdrometer data require quality control. The first two size bins (0.05-0.25 mm) are prone to turbulence and ground splash effects with low signal-to-noise ratios, and raindrops smaller than 0.3 mm rarely occur naturally. Therefore, we excluded the first two size bins and data with diameters >8 mm during quality control. To eliminate potential non-precipitation samples, we removed data with rain rates <0.01 $\mathrm{mm \cdot h^{-1}}$. Additionally, following Atlas et al.' s empirical velocity-diameter formula, we filtered out anomalous data exceeding this relationship. Figure 2 illustrates the quality control process for raindrop spectrum data.

1.3 Calculation of Microphysical Parameters and Gamma Distribution After quality control, various microphysical parameters were retrieved through calculation. The number concentration per unit volume and size interval, N(D), is calculated as:

$$N(D) = \frac{\sum_j n_{ij}}{A_i \Delta t V_j \Delta D_i}$$

where n represents the number of raindrops in the i-th diameter bin and j-th velocity bin; A is the effective sampling area of the disdrometer ($\mathrm{m^2}$); Δt is the sampling time interval (s); V is the terminal fall velocity of raindrops in the j-th velocity bin ($\mathrm{m \cdot s^{-1}}$); and ΔD is the width of the i-th diameter bin (mm). The DSG5 disdrometer has a sampling interval of 60 seconds.

From this, we derived precipitation microphysical parameters including raindrop number concentration N ($\mathrm{m^{-3}}$), liquid water content Q ($\mathrm{g \cdot m^{-3}}$), mass-weighted mean diameter D (mm), rain rate R ($\mathrm{mm \cdot h^{-1}}$), radar reflectivity factor Z ($\mathrm{mm^6 \cdot m^{-3}}$), and generalized intercept parameter N ($\mathrm{mm^{-1} \cdot m^{-3}}$), where is water density ($\mathrm{g \cdot cm^{-3}}$). The specific formulas are:

$$N_v = \int_0^\infty N(D)dD$$

$$R = 6\pi \times 10^{-4} \int_0^\infty D^3 N(D) V(D) dD$$

$$Q = \frac{\pi}{6000} \int_0^\infty D^3 N(D) dD$$

$$Z = \int_0^\infty D^6 N(D) dD$$

$$D_m = \frac{\int_0^\infty D^4 N(D)dD}{\int_0^\infty D^3 N(D)dD}$$

$$N_w = \frac{4^4}{\pi\rho_w}\frac{Q}{D_m^4}$$

The Gamma distribution model was used to fit the observed raindrop spectra:

$$N(D) = N_0 D^\mu \exp(-\lambda D)$$

where D is the raindrop equivalent diameter (mm); N_0 is the intercept parameter ($\mathrm{mm}^{-1-}\ \cdot \mathrm{m}^{-3}$); is the shape parameter describing variations in small raindrops; and λ is the slope parameter (mm^{-1}). We employed the moment method to estimate these three parameters, with the n-th moment defined as:

$$M_n = \int_0^\infty D^n N(D)dD$$

Following Huang et al.’ s method, we calculated N_0, , and λ using the moment method.

2. Results and Analysis

2.1 Microphysical Parameter Characteristics of Different Precipitation Types Precipitation characteristics in mountainous regions show strong correlation with altitude. The Liupan Mountains, a narrow north-south oriented range, feature a gentle western slope and steep eastern slope. The Liupan Mountain Station represents the summit site at the highest elevation, while Chenjin and Chengguan stations on the western slope have a mean altitude of 2269 m, and Dawan and Huitai stations on the eastern slope average 1968 m.

Analysis of characteristic diameters (Figure 3) reveals that at the same location, convective rainfall exhibited the largest mean values for all characteristic diameters, followed by stratocumulus, with stratiform rainfall showing the smallest values. The differences in D among stations were minimal: 0.6 mm for stratiform, 0.66 mm for stratocumulus, and 0.81 mm for convective rainfall. In contrast, D showed the greatest variation: 1.71 mm for stratiform, 2.54 mm for stratocumulus, and 2.9 mm for convective rainfall.

In stratiform and stratocumulus rainfall, the Liupan Mountain summit site showed the smallest D but the largest D , being 0.1 mm smaller than Huitai station (which had the largest D) but 1.36 mm larger than Dawan station (which had the smallest D). This indicates that the summit site had numerous small raindrops but also relatively large mean drop sizes, likely because the summit is closer to or within the cloud base where moisture is abundant and evaporation/fragmentation processes are less pronounced. The western slope Chenjin and Chengguan stations showed similar characteristic diameters, differing by only 0.01-0.07 mm. On the eastern slope, Huitai station had the largest D , while Dawan station had relatively small characteristic diameters overall, likely due to its lowest altitude where raindrop fragmentation and evaporation during descent are significant, and its location at the northernmost part of the mountain range with poorer moisture transport conditions. This is corroborated by Dawan station' s lower cumulative precipitation compared to other sites.

The correlation between characteristic diameters and altitude showed that D and D increased with elevation, while D and D were larger at mid-mountain positions. This differs partially from Huangshan studies, possibly because the altitude difference between summit and base stations in Huangshan (1396 m) exceeds that in the Liupan Mountains (892 m). In convective rainfall, the Liupan Mountain summit site showed the largest characteristic diameters, while the western slope Chenjin and Chengguan stations were similar (differences <0.07 mm). The eastern slope Huitai station had larger D than Chenjin and Chengguan but smaller D , while Dawan station showed the smallest characteristic diameters overall, reflecting the localized nature of convective precipitation.

Microphysical parameters (number concentration N , radar reflectivity Z, liquid water content Q, and rain rate R) consistently ranked as: convective > stratocumulus > stratiform rainfall. Mean rain rates were 0.32 $\mathrm{mm \cdot h^{-1}}$ for stratiform, 0.95 $\mathrm{mm \cdot h^{-1}}$ for stratocumulus, and 2.9 $\mathrm{mm \cdot h^{-1}}$ for convective rainfall. The lowest-altitude Dawan station showed the highest N (103.7 $\mathrm{m^{-3}}$), while Chenjin station had the lowest (48.1 $\mathrm{m^{-3}}$), indicating higher raindrop concentrations at summit and foothill sites compared to mid-slope positions. The Liupan Mountain summit site exhibited larger R and Z values than other stations, exceeding the lowest values by 0.21 $\mathrm{mm \cdot h^{-1}}$ and 6.15 dBZ, respectively. On both eastern and western slopes, R, Z, and Q increased with altitude. However, in convective rainfall, the western slope Chenjin station showed maximum values for R, N , and Q, while the summit site had maximum Z, and eastern slope stations showed smaller Q, R, and Z than western slope stations—patterns inconsistent with altitude correlations observed in stratiform and stratocumulus rainfall.

To investigate contributions from different raindrop sizes, we classified raindrops into four categories: (1) $D < 1$ mm, (2) $1 \leq D < 2$ mm, (3) $2 \leq D < 3$ mm, and (4) $D \geq 3$ mm, then calculated their contributions to N and R. Figure 5 shows that stratiform and stratocumulus rainfall exhibited similar patterns, with small raindrops dominating. Category 1 raindrops contributed over 70% to N at all stations, with summit and western slope stations showing higher contributions than eastern slope stations. Medium raindrops (categories 2 and 3) accounted for a higher proportion in stratocumulus than stratiform rainfall. For category 3 large raindrops, the Liupan Mountain summit site showed the largest proportion, consistent with its maximum D and D values. Category 1 raindrops also contributed most to rain rate (exceeding 50%) in stratiform and stratocumulus rainfall.

In convective rainfall, category 1 raindrops similarly dominated N contributions (exceeding 60%), with the Liupan Mountain summit site showing the smallest proportion. However, their contribution to rain rate was not maximal (all <40%). Category 2 raindrops contributed most to rain rate, while the summit site showed the largest proportion of category 4 large raindrops and correspondingly the greatest rain rate contribution.

2.2 Raindrop Spectrum Distribution Characteristics and Gamma Function Fitting The Gamma distribution model provides better representation of actual RSD than the exponential distribution due to its shape parameter . Stratiform rainfall showed the narrowest spectrum width (3.75-6.5 mm), while convective and stratocumulus rainfall exhibited wider spectra (up to 7.5 mm). In stratiform rainfall, Dawan station showed the highest number density at the small-drop end ($D > 1$ mm) due to its low altitude and pronounced raindrop fragmentation. The Liupan Mountain summit site, being slightly higher than Chenjin station, and Huitai station, being slightly higher than Dawan station, showed lower small-drop densities but higher densities for $D > 1$ mm compared to Chenjin and Dawan stations.

In stratocumulus rainfall, the Liupan Mountain summit site showed higher number density at the large-drop end ($D > 3$ mm) than other stations, while Dawan station dominated the small-drop end ($D < 1$ mm). In convective rainfall, Chenjin station exhibited the highest number density for drops with $D < 1$ mm, while differences between Liupan Mountain and Chenjin stations were minimal at the large-drop end ($D > 3$ mm). Eastern slope Huitai and Dawan stations showed significantly lower number densities than other sites.

Overall, Gamma distribution fitting showed correlation coefficients exceeding 0.85 for stratiform and stratocumulus rainfall, while convective rainfall correlations were above 0.75 except at Dawan station (0.68). Using the moment method, we calculated the three Gamma parameters (Table 4). The intercept parameter N_0 was generally largest for stratiform and smallest for convective rainfall, indicating higher small raindrop concentrations in stratiform precipitation. The slope parameter λ characterizes the rate at which raindrop concentration decreases with diameter—smaller λ values indicate gentler curves and wider spectra. In the Liupan Mountains, λ was typically largest for stratiform, smallest for convective, and intermediate for stratocumulus rainfall, consistent with observed raindrop size characteristics. The shape parameter   describes curve curvature (> 0 indicates upward curvature). Mean   values were positive for all stations, generally largest for stratiform and smallest for convective rainfall, indicating less curvature and higher large-drop concentrations in convective precipitation.

The N_0, , and λ parameters generally decreased with altitude, reflecting lower small-drop concentrations and higher large-drop concentrations with wider spectra at higher elevations. To further investigate the -λ relationship, we fitted -λ curves for different rainfall types (Table 5). All rainfall types showed positive correlations following quadratic relationships, with stratiform rainfall exhibiting the steepest slope and convective rainfall the gentlest. Since D $= (\ + 4)/\lambda$, the slope is inversely related to D , confirming that the -λ fitting curve slope is closely associated with precipitation type.

2.3 Distribution of Microphysical Characteristic Parameters The mass-weighted mean diameter D and generalized intercept parameter N can reflect overall raindrop concentration and size characteristics. Figure 7 shows scatter plots of lgN versus D for all samples, distinguished by rain rate. The generalized intercept parameter N decreased with increasing D , with scatter concentrated at the small D end, indicating dominance by small raindrops. As rain rate increased, scatters extended upward and rightward, with both N and D showing increasing trends. For the same station, convective and stratocumulus raindrops exhibited significantly higher concentrations and larger sizes than stratiform raindrops.

The Liupan Mountain summit site scatters were mainly distributed in the range N 0.5-4.5 and D 1.2-4.5 mm, Chenjin station in N 0.5-6.0 and D 1.3-4.4 mm, Chengguan station in N 0.5-5.0 and D 0.6-4.5 mm, Dawan station in N 0.5-4.5 and D 1.2-4.8 mm, and Huitai station in N 0.56-4.1 and D 1.5-4.5 mm. The summit site showed a "downward-rightward" scatter pattern compared to foothill sites, likely because the summit' s abundant moisture and minimal evaporation/fragmentation processes resulted in reduced number concentration but increased mean drop size.

2.4 Microphysical Parameter Characteristics Under Different Circulation Patterns Raindrop spectrum characteristics vary significantly not only with precipitation type but also with circulation patterns. We classified the 58 rainfall processes into three 500 hPa circulation patterns: east-high-west-low, northwesterly flow, and straight flow. Averaging all samples across the five stations revealed that the northwesterly flow pattern exhibited the largest characteristic diameters and microphysical parameters (Table 6), primarily because convective rainfall cases were most frequent under this pattern. The straight flow pattern showed the smallest values, with the east-high-west-low pattern intermediate. Additionally, Gamma distribution parameters averaged across circulation patterns showed that northwesterly flow had the smallest N_0, , and λ values, while straight flow had the largest, closely correlating with precipitation properties under different circulation patterns. These conclusions differ from previous studies in Ningxia using filter paper methods, which found straight flow patterns produced the largest microphysical parameters and smallest λ values, possibly due to regional differences, topographic effects, and climate variations.

3. Conclusions

Based on quality-controlled and calculated data from 58 rainfall processes at five stations in the Liupan Mountains from 2020-2021, we analyzed microphysical parameters, average raindrop spectrum characteristics, and Gamma distribution features for stratiform, convective, and stratocumulus rainfall. The main conclusions are:

(1) At the same station, microphysical parameters and characteristic diameters ranked as: convective > stratocumulus > stratiform rainfall. In stratiform and stratocumulus rainfall, the mode diameter was smaller at the summit and foothills but larger on the mountainside, while maximum diameter and mass-weighted mean diameter increased with altitude on both slopes. This suggests the summit is closer to or within the cloud base with abundant moisture and minimal evaporation/fragmentation. Eastern slope stations showed larger rain rate, radar reflectivity, and liquid water content than western slope stations, with these parameters increasing with altitude on both slopes.

(2) In stratiform and stratocumulus rainfall, small raindrops contributed most to both rain rate and number concentration. In convective rainfall, small raindrops dominated number concentration while medium raindrops contributed most to rain rate.

(3) Stratiform rainfall showed the narrowest spectrum width, while convective and stratocumulus rainfall exhibited wider spectra. Gamma distribution fitting was most effective for stratiform rainfall. The N_0, , and λ parameters generally decreased with altitude, and the -λ fitting curve slope was closely related to precipitation type.

(4) The generalized intercept parameter N decreased with increasing mass-weighted mean diameter D , with scatters concentrated at the small D end. As rain rate increased, both N and D showed upward-rightward trends. The summit site exhibited decreased number concentration but increased mean scale compared to foothill sites.

(5) The northwesterly flow pattern produced larger characteristic diameters and microphysical parameters than east-high-west-low and straight flow patterns, closely related to precipitation properties under different circulation patterns.

References

[1] Zhu Yaqiao, Liu Yuanbo. Advances in measurement techniques and statistics features of surface raindrop size distribution[J]. Advances in Earth Science, 2013, 28(6): 685-694.

[2] Gong Fujiu, Liu Jicheng, Li Zihua. Study of the raindrop size distributions for three types of precipitation[J]. Chinese Journal of Atmospheric Sciences, 1997, 21(5): 607-614.

[3] Fang Bin, Ban Xianxiu, Guo Xueliang, et al. Area rainfall estimation by using radar, raingauge, and particle laser based optical instrument[J]. Chinese

Journal of Atmospheric Sciences, 2010, 34(3): 513-519.

[4] Marshall J S, Palmer W M K. The distribution of raindrops with size[J]. Journal of Meteorology, 1948, 5: 165-166.

[5] Ulbrich C W. Natural variations in the analytical form of the raindrop size distribution[J]. Journal of Climate and Applied Meteorology, 1983, 22: 1764-1775.

[6] Chen Baojun, Li Zihua, Liu Jicheng, et al. Model of raindrop size distribution in three types of precipitation[J]. Acta Meteorologica Sinica, 1998, 56(4): 506-512.

[7] Fang Bin, Guo Xueliang, Xiao Hui. A study on characteristics of spectral parameters and characteristic variables of raindrop size distribution for different cloud systems in Liaoning Province[J]. Chinese Journal of Atmospheric Sciences, 2016, 40(6): 1154-1164.

[8] Li Shanshan, Wang Xiaofang, Wan Rong, et al. The characteristics of raindrop spectrum in different altitude region on the eastern slope of Qinghai-Tibet Plateau[J]. Plateau Meteorology, 2020, 39(5): 899-911.

[9] Wang Yun, Wang Xu, Liao Feijia, et al. Micro structural characteristics of raindrop spectra of precipitation in the Tianshan Mountains[J]. Journal of Glaciology and Geocryology, 2018, 40(4): 695-701.

[10] Li Hui, Yin Yan, Shan Yunpeng, et al. Statistical characteristics of raindrop size distribution for stratiform and convective precipitation at different altitudes in Mt. Huangshan[J]. Chinese Journal of Atmospheric Sciences, 2018, 42(2): 268-280.

[11] Chen Cong, Yin Yan, Chen Baojun. Raindrop size distribution at different altitudes in Mt. Huang[J]. Transactions of Atmospheric Sciences, 2015, 38(3): 388-395.

[12] Zhang Hao, Pu Jiangping, Li Jing, et al. Analysis of characteristics of raindrop size distribution at different altitudes in Lushan[J]. Meteorology and Disaster Reduction Research, 2011, 34(2): 43-50.

[13] Cheng Peng, Chang Yi, Liu Qin, et al. A case study of raindrop size distribution and orographic impact characteristics in spring stratiform precipitation over the Qilian Mountains[J]. Chinese Journal of Atmospheric Sciences, 2021, 45(6): 1232-1248.

[14] Niu Shengjie, An Xialan, Sang Jianren. Observational research on physical feature of summer rain dropsize distribution under synoptic systems in Ningxia[J]. Plateau Meteorology, 2002, 21(1): 37-44.

[15] Zhang Yuxin, Han Huibang, Guo Shiyu, et al. Statistical characteristics of raindrop size distribution and its relationship for different precipitation clouds in summer in the Qilian Mountains[J]. Arid Zone Research, 2021, 38(4): 1048-1057.

[16] Tao Tao, Zhang Lixin, Sang Jianren, et al. A case analysis of microphysical characteristics of atypical hail formation over Liupan Mountain, China[J]. Arid Land Geography, 2020, 43(2): 299-307.

[17] Cao Ning, Zhang Lixin, Sang Jianren, et al. Observation and analysis on the macroscopic and microcosmic characteristics of topography, cloud and precipitation in Liupan Mountain area based on micro rain radar[J]. Journal of the Meteorological Sciences, 2019, 39(6): 775-785.

[18] Tokay A, Bashor P G. An experimental study of small scale variability of raindrop size distribution[J]. Journal of Applied Meteorology and Climatology, 2010, 49(11): 2348-2365.

[19] Atlas D, Srivastava R C, Sekhon R S. Doppler radar characteristics of precipitation at vertical incidence[J]. Reviews of Geophysics and Space Physics, 1973, 11(1): 1-35.

[20] Huang Xingyou, Yin Jianan, Ma Lei, et al. Comprehensive statistical analysis of rain drop size distribution parameters and their application to weather radar measurement in Nanjing[J]. Chinese Journal of Atmospheric Sciences, 2019, 43(3): 691-704.

[21] Shi Jinsen, Zhang Wu, Chen Tianyu, et al. Raindrop size distribution characteristics of the northern face of Qilian Mountains in the summer of 2006[J]. Journal of Lanzhou University (Natural Sciences Edition), 2008, 44(4): 60-66.

[22] Li Yanyin, Zhang Qiang, Xu Xia, et al. Relationship between precipitation and terrain over the Qilian Mountains and their ambient areas[J]. Journal of Glaciology and Geocryology, 2010, 32(1): 52-61.

[23] Wang M J, Zhao K, Xue M, et al. Precipitation microphysics characteristics of a Typhoon Matmo(2014) rainband after landfall over eastern China based on polarimetric radar observations[J]. Journal of Geophysical Research: Atmospheres, 2016, 121(20): 12415-12434.

[24] Zhang G F, Vivekanandan J, Brandes E A, et al. The shape slope relation in observed gamma raindrop size distributions: Statistical error or useful information?[J]. Journal of Atmospheric and Oceanic Technology, 2003, 20(8): 1106-1119.

[25] Zheng Jiaoheng, Chen Baojun. Comparative study of exponentail and Gamma functional fits to observed raindrop size distribution[J]. Scientia Meteorologica Sinica, 2007, 27(1): 17-25.

[26] Du Bo, Ma Shuqing, Liu Daxin, et al. Design and study of raindrop spectrum precipitation phenomenon instrument[J]. Meteorological Science and Technology, 2018, 46(1): 56-63.

[27] Zhou Liming, Wang Jun, Gong Dianli, et al. Rainfall response of Larix principis-rupprechtii planta-soil water content on a slope in the semi arid Liupan Mountains[J]. Arid Zone Research, 2023, 40(4): 594-604.

[28] Deng Peiyun, Sang Jianren, Yang Meng, et al. Analysis of different characteristics of precipitation and air water vapor conditions over east and west slopes of Liupan Mountain in recent 30 years[J]. Meteorological Science and Technology, 2021, 49(1): 77-85.

[29] Shi Jianzhou, Liu Xiande, Tian Qing, et al. A study on the distribution of raindrop size in three types of precipitation in Shandong Province[J]. Transactions of Atmospheric Sciences, 2014, 37(2): 216-222.

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