Raindrop Size Distribution Characteristics and Z-R Relationships of Different Summer Precipitation Cloud Systems over the Southern Foothills of the Qilian Mountains (Postprint)

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Abstract

Using laser disdrometer observations from August–September 2019, we analyzed raindrop microphysical characteristics, drop size distribution, particle fall speed, and Z-R relationships for different precipitation cloud systems (stratiform and convective) in summer over the southern foothills of the Qilian Mountains. The results show that: (1) All microphysical parameters of raindrops from convective cloud precipitation exceed those from stratiform cloud precipitation, and different stages of convective cloud development in mountainous areas significantly affect rainfall intensity and raindrop microphysical parameters; (2) The Gamma distribution more closely approximates the actual summer drop size distribution in the Qilian Mountains, yet both M-P and Gamma distributions result in overestimation of raindrop number concentration; (3) The fall speeds of raindrop particles vary with size; the range of fall speeds for convective precipitation particles is slightly larger than that for stratiform precipitation at the same size, and traditional parameterizations of particle fall speed significantly underestimate actual values in the Qilian Mountains; (4) The Z-R relationship for summer stratiform precipitation is Z=445R1.50, while that for convective precipitation is Z=427R1.88; the use of traditional radar-based precipitation estimation methods would lead to underestimation of precipitation in this region.

Full Text

Characteristics of Raindrop Size Distribution and Z-R Relationships for Different Precipitation Cloud Systems in Summer at the Southern Foothills of the Qilian Mountains

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Abstract

Using laser raindrop spectrometer observations from August to September 2019, this study analyzed the microphysical characteristics of raindrops, raindrop size distribution, particle falling velocity, and Z-R relationships for different precipitation cloud systems (stratiform cloud and convective cloud) in summer at the southern foothills of the Qilian Mountains. The results demonstrate that: (1) All microphysical parameters of convective cloud precipitation exceeded those of stratiform cloud precipitation, with different stages of convective cloud development in mountainous areas exerting substantial influence on rain intensity and microphysical parameters; (2) Both M-P and Gamma distributions overestimated raindrop number concentration, though the Gamma distribution more closely approximated the actual raindrop size distribution in the Qilian Mountains during summer; (3) Falling velocities varied across raindrop scales, with convective cloud precipitation exhibiting a slightly larger velocity range than stratiform cloud precipitation at equivalent scales, while traditional particle falling velocity fitting showed significant underestimation in this region; (4) The Z-R relationship for summer stratiform cloud precipitation was Z = 445R1.50, while for convective cloud precipitation it was Z = 427R1.88, indicating that traditional radar precipitation estimation methods would substantially underestimate precipitation in this region.

Keywords: raindrop size distribution; convective precipitation; stratiform precipitation; microphysical characteristics; Qilian Mountains

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1 Data and Methods

1.1 Instrumentation

The Parsivel laser raindrop spectrometer, developed by OTT, operates on the principle of laser obscuration. It calculates and measures the size and velocity of precipitation particles by detecting their interruption of a laser beam, enabling monitoring of precipitation type, particle number density, rain intensity, and cumulative precipitation. The instrument can identify eight precipitation types: drizzle, light rain, rain, rain mixed with snow, snow, snow grains, freezing rain, and hail. Technical specifications include 32 size channels and 32 velocity channels, with a particle size range of 0.2–25 mm, velocity range of 0.2–20 m · s-1, sampling area of 54 cm2, and sampling time of 60 s.

1.2 Data Processing

Due to gravitational effects, falling raindrops typically assume an ellipsoidal shape. Since the raindrop spectrometer only measures the horizontal dimension (the major axis diameter) of these ellipsoidal drops, measurement values can be biased high. Following the method of Battaglia et al. [22], we applied deformation corrections:

$$D = \begin{cases} 1.075D_{\text{par}} - 0.075D_{\text{par}}^2, & D_{\text{par}} \leq 1.0 \text{ mm} \\ 1.00D_{\text{par}}, & 1.00 \text{ mm} < D_{\text{par}} \leq 5.00 \text{ mm} \\ D_{\text{par}}, & D_{\text{par}} > 5.00 \text{ mm} \end{cases}$$

where D_{par} is the diameter measured by the Parsivel instrument and D is the corrected equivalent spherical diameter.

Raindrop number concentration $N(D_i)$ (m-3 mm-1) is calculated as:

$$N(D_i) = \frac{1}{A\Delta t} \sum_j n_{ij}$$

where n_{ij} represents the number of raindrops in diameter interval i and velocity interval j, A is the instrument sampling area, and Δt is the sampling time. D_i and ΔD_i denote the central diameter and width of the i-th size interval, while V_j represents the central velocity of the j-th velocity interval.

Rain intensity R (mm · h-1), water content W (g · m-3), and radar reflectivity factor Z (mm6 · m-3) are calculated as:

$$R = \frac{\pi}{6} \frac{1}{A\Delta t} \sum_i \sum_j n_{ij} D_i^3 V_j$$

$$W = \frac{\pi}{6} \rho \frac{1}{A\Delta t} \sum_i \sum_j n_{ij} D_i^3$$

$$Z = \frac{1}{A\Delta t} \sum_i \sum_j n_{ij} D_i^6$$

The Gamma distribution function is widely used to describe raindrop size distributions:

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

where N_0 is the intercept parameter (mm-1- · m-3), μ is the shape factor, and λ is the slope parameter (mm-1). We employed the moment method to fit distribution parameters, introducing the n-th moment M_n:

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

The mass-weighted mean diameter D_m and generalized intercept parameter N_w can be expressed as:

$$D_m = \frac{M_4}{M_3}$$

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

where $\rho_w = 1.0$ g · cm-3 is water density and W is rainwater content.

1.3 Observation Sites

Three laser raindrop spectrometers were deployed at the southern foothills of the Qilian Mountains in Menyuan and Qilian counties, Qinghai Province [Figure 1: see original paper]. The Laolongwan station (101°44 E, 37°20 N, 3114 m altitude) and Taola station (102°00 E, 37°24 N, 2910 m altitude) are located in Menyuan County, while the Daladong station (100°18 E, 38°11 N, 2957 m altitude) is located in Qilian County. Observations were conducted from August to September 2019. Raw data were screened to remove artifacts, excluding particles < 0.2 mm, rain intensity < 0.1 mm · h-1, fewer than 10 raindrops per sample, and precipitation events lasting < 30 minutes.

1.4 Precipitation Type Classification

As raindrop size distributions vary considerably among precipitation types, we adopted the classification method of Bringi et al. [5] to categorize precipitation based on raindrop spectrum data. The observation periods and sample characteristics are summarized in . Throughout the observation period, stratiform cloud precipitation samples outnumbered convective cloud precipitation samples.

[Figure 2: see original paper] illustrates the frequency distributions of rain intensity and their cumulative contributions to total precipitation at the three stations. Frequency decreases with increasing rain intensity. For stratiform precipitation with intensity < 5 mm · h-1, Laolongwan station showed the highest occurrence frequency, while for intensities > 5 mm · h-1, Taola station exhibited the highest frequency. Across all intensity ranges, cumulative precipitation contributions ranked as: Daladong > Taola > Laolongwan. For convective precipitation, occurrence frequencies ranked as: Laolongwan > Daladong > Taola, while contributions to total precipitation ranked as: Taola > Daladong > Laolongwan.

2 Results and Analysis

2.1 Distribution Characteristics of Raindrop Microphysical Parameters

Microphysical parameters effectively reflect fundamental precipitation characteristics. [Figure 3: see original paper] presents statistical values of microphysical parameters for different cloud systems at each station. Atmospheric water vapor content in the Qilian Mountains increases gradually from northwest to southeast [26], with Daladong station experiencing relatively favorable moisture conditions. Precipitation characteristics correlate well with altitude [27], though altitude differences among the three stations are minor, with geographic distribution being the primary influence on precipitation characteristics.

Mean statistics reveal that all microphysical parameters of convective cloud precipitation exceeded those of stratiform cloud precipitation, consistent with findings from other studies [2, 27-28]. For mountainous convective precipitation, different stages of convective cloud development significantly influenced rain intensity and microphysical parameters. Taola station, located deeper in the mountainous area, often experienced the initial development stage of convective clouds, resulting in lower convective precipitation intensity R, number concentration N_D, and water content W compared to stratiform precipitation at the same site. Laolongwan station, also in the initial development stage but located further west than Taola, showed slightly higher convective precipitation R than stratiform precipitation, with other microphysical parameters marginally larger except for N_D, which was smaller. Daladong station, typically experiencing the mature stage of convective development, exhibited convective precipitation R and all other microphysical parameters greater than those of stratiform precipitation.

Stratiform precipitation processes usually reached their mature stage when passing Laolongwan station but were essentially dissipated by the time they reached Taola station, resulting in higher rain intensity and other microphysical parameters at Laolongwan. Daladong station in Qilian County is geographically distant from the other two stations and generally experiences separate weather systems, making direct comparisons inappropriate.

2.2 Characteristics of Average Raindrop Size Distribution

The Gamma distribution is the primary analytical function describing raindrop size distributions and is widely applied in precipitation detection and numerical model parameterization schemes. Fitting observed average raindrop spectra revealed distinct differences between cloud systems [Figure 4: see original paper]. Stratiform precipitation exhibited narrower spectrum widths, with maximum values at Taola station reaching only 4.5 mm and minimum values at Laolongwan station of 3.2 mm. Peak number concentrations ranged from 1355 m-3 · mm-1 at Laolongwan to 2190 m-3 · mm-1 at Taola. Convective precipitation showed broader spectra, with maximum width at Taola station reaching 5.2

mm and minimum at Daladong station of 3.2 mm. Peak number concentrations reached 3138 m-3 · mm-1 at Daladong and 1306 m-3 · mm-1 at Taola.

Both M-P and Gamma distributions overestimated raindrop number concentrations, though the Gamma distribution showed better overall agreement with observed spectra, more closely approximating the actual raindrop size distribution in the mountainous region. presents fitted parameters for both distributions. The Gamma distribution performed well for both precipitation types in the Qilian Mountains, with correlation coefficients reaching 0.96. The M-P distribution showed slightly better performance for stratiform precipitation, with correlation coefficients of 0.97.

The slope parameter λ directly reflects the steepness of the fitted curve, indicating the rate at which particle concentration decreases with increasing diameter. Larger λ values produce steeper curves with narrower spectrum widths. In the Qilian Mountains, λ values for stratiform precipitation exceeded those for convective precipitation, consistent with the narrower spectra of stratiform clouds and broader spectra of convective clouds. The intercept parameter N_0 of the Gamma distribution was significantly higher than that of the M-P distribution.

The shape factor μ enables the Gamma distribution to better represent curvature characteristics of fitted spectra. Positive μ values produce upward-curving spectra, while negative values produce downward curvature. Previous research indicates that $\mu < 0$ primarily occurs in orographic cloud precipitation with numerous small drops and wide spectra, $\mu > 0$ is typical of thunderstorm precipitation, and stratiform precipitation shows variable but generally positive μ values [30]. In the Qilian Mountains, both stratiform and convective precipitation exhibited $\mu < 0$, indicating precipitation dominated by small raindrops.

2.3 Raindrop Velocity Spectrum Distribution

Particle falling velocity plays a crucial role in precipitation formation. Variations in velocity among particles of different sizes, phases, and shapes influence collision-coalescence processes and internal charge redistribution. [Figure 5: see original paper] demonstrates that each size category corresponds to a range of falling velocities, with convective precipitation exhibiting slightly larger velocity ranges than stratiform precipitation at equivalent scales, indicating that falling velocity depends on factors beyond just particle size.

Stratiform precipitation particle velocities concentrated between 0.5–1.5 m · s-1, while convective precipitation particles ranged from 0.5–2.5 m · s-1. The solid black line in [Figure 5: see original paper] represents the standard terminal velocity fitting curve from Atlas et al. [31] for sea-level conditions, corresponding to an air density of 1.23 kg · m-3. The Qilian Mountain observation sites are all at approximately 3000 m altitude, where air density differs substantially from sea-level values. Based on automatic weather station data collected concurrently with raindrop spectra, mean air densities were 0.84 kg · m-3 at Laolongwan (3114 m), 0.87 kg · m-3 at Taola (2910 m), and 0.88 kg · m-3 at Daladong (2957 m).

The standard fitting curve significantly underestimates particle velocities, while curves corrected using the air density adjustment factor from Atlas et al. [31] show better agreement with observations. The lower air density at high altitudes in the Qilian Mountains is the primary cause of observed velocities exceeding standard sea-level values. However, falling velocity is also influenced by drop collision, vertical air motion, turbulence, and other factors requiring further investigation.

2.4 Z-R Relationship Analysis

The relationship between precipitation intensity R and radar reflectivity factor Z forms the basis for radar quantitative precipitation estimation, yet uncertainty in Z-R relationships represents a major source of error. The relationship follows a power law: $Z = aR^b$, where coefficient a and exponent b vary substantially with region, season, precipitation type, and raindrop spectrum characteristics. Both radar reflectivity and precipitation intensity depend on raindrop size distribution.

Scatter plots and fitted curves for the three stations are shown in [Figure 6: see original paper], with parameters listed in . For stratiform precipitation, coefficient a ranged from 202–616 (mean = 445) and exponent b from 1.21–1.49 (mean = 1.50). For convective precipitation, a ranged from 263–777 (mean = 427) and b from 1.40–1.80 (mean = 1.88). Overall, the Z-R relationship for stratiform precipitation in the Qilian Mountains is $Z = 445R^{1.50}$, while for convective precipitation it is $Z = 427R^{1.88}$. Both the coefficient and exponent are lower than those in the conventional formula ($Z = 300R^{1.4}$) used in operational weather radar quantitative precipitation estimation, indicating that traditional radar methods would underestimate precipitation in this region.

Comparisons with other regional studies reveal considerable variation in Z-R relationships across China due to different weather backgrounds and topographic influences. In plateau regions, coefficient a is notably higher during heavy precipitation, typically ranging 400–700, while exponent b shows less variation around 1.5. Plain areas generally have a values of 100–200. In Shandong Province, both a and b are relatively small. Improving radar quantitative precipitation estimation accuracy requires comprehensive consideration of precipitation type, geographic location, and altitude, as conventional formulas lack universal applicability.

3 Conclusions

Based on observations from three laser raindrop spectrometers deployed at the southern foothills of the Qilian Mountains, this study analyzed microphysical characteristics, average raindrop size distributions, falling velocities, and Z-R relationships for stratiform and convective precipitation in mountainous areas. The main conclusions are:

(1) All microphysical parameters of convective cloud precipitation raindrops exceeded those of stratiform cloud precipitation in the Qilian Mountains. For mountainous convective precipitation processes, different stages of convective cloud development significantly influenced rain intensity and microphysical parameters.

(2) Distinct differences existed in raindrop size distributions between precipitation cloud systems. Stratiform precipitation exhibited narrower spectrum widths, while convective precipitation showed broader widths. The Gamma distribution provided good fits for both precipitation types in the Qilian Mountains but overestimated raindrop number concentration. Compared with the M-P distribution, the Gamma distribution showed better overall agreement with observed spectra, more closely approximating the actual raindrop size distribution in this mountainous region.

(3) Falling velocities varied among different raindrop scales. Convective precipitation particles exhibited slightly larger velocity ranges than stratiform precipitation at equivalent scales. Traditional particle falling velocity fitting showed significant underestimation at the southern Qilian Mountains foothills. After correction using observed site air density, results improved substantially. The lower air density at the observation sites was the primary reason for observed velocities exceeding standard terminal velocities.

(4) The Z-R relationship for stratiform precipitation at the southern Qilian Mountains foothills is $Z = 445R^{1.50}$, while for convective precipitation it is $Z = 427R^{1.88}$. Using conventional radar precipitation estimation methods would underestimate precipitation in this region.

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