Microphysical Characteristics of Rainfall under Acoustic Wave Intervention in Arid Inland Regions: Postprint

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Date: 2021-08-01T00:00:00+00:00

Abstract

Using data from disdrometers and rain gauges in the arid inland region of Qinghai Province from June to September 2019, and employing physical validation methods and statistical approaches, we analyzed changes in near-surface rainfall microphysical characteristics under ultra-high-power focused strong acoustic wave intervention. The results indicate that: (1) Under acoustic intervention, cumulative rainfall increased, with cases of rainfall increase and decrease accounting for 60.87% and 39.13% of the total number of cases studied, respectively. The mean values of microphysical parameters including mean particle diameter, liquid water content, radar reflectivity factor, rain intensity, and rainfall kinetic energy increased significantly, with rain intensity and kinetic energy exhibiting the most pronounced increases at 36.00% and 69.20%, respectively. (2) Under acoustic intervention, the particle number concentration at the large-particle end of the average spectrum (>0.8 mm) increased, and the effect became more pronounced with greater rain intensity. (3) In terms of spatial distribution, rain intensity within a 3 km radius of the operation center increased significantly under acoustic intervention.

Full Text

Microphysical Characteristics of Precipitation under Acoustic Intervention in Inland Arid Regions

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Abstract: Using raindrop spectrometer and rain gauge data from the arid inland region of Qinghai Province collected between June and September 2019, this study employs physical inspection and statistical methods to analyze changes in near-surface precipitation microphysical characteristics under ultra-high-power focused acoustic wave intervention. The results demonstrate that: (1) Under acoustic intervention, accumulated precipitation increased, with precipitation-enhanced and precipitation-reduced events accounting for 60.87% and 39.13% of the total 23 cases, respectively. The mean values of microphysical parameters—including average particle size, liquid water content, radar reflectivity factor, rainfall intensity, and rainfall kinetic energy—increased to varying degrees, with rainfall intensity and kinetic energy exhibiting the most pronounced increases of 36.00% and 69.20%, respectively. (2) Particle number concentration increased, with the enhancement effect becoming more significant at higher rainfall intensities. (3) Spatial analysis reveals that rainfall intensity increased significantly within 3 km of the operation center under acoustic intervention. These findings provide new insights into the microphysical mechanisms of acoustic precipitation enhancement in inland arid regions and offer a scientific basis for evaluating the effectiveness of acoustic rain enhancement operations.

Keywords: acoustic; artificial precipitation enhancement; raindrop size distribution; microphysical characteristics of precipitation; Qaidam Basin

Introduction

Precipitation constitutes a critical component of the global water cycle and serves as a key driver of natural ecosystems while governing human activities and social production. Uneven water vapor distribution and water resource scarcity severely constrain economic development in northwestern China. The Qaidam Basin, one of China' s most arid regions, experiences low total precipitation and infrequent heavy precipitation events. Artificial weather modification technologies that tap into atmospheric water resources to increase precipitation are particularly crucial in such inland arid areas. Traditional weather modification techniques, developed over many decades, involve seeding clouds with catalysts delivered via rockets, artillery, ground-based furnaces, or aircraft to alter cloud particle phase states and size distributions. Recently, a novel catalyst-free approach using directional acoustic wave emission has attracted widespread attention due to its environmental friendliness, low cost, and high mobility. The principle of acoustic rain enhancement involves using wave energy to create disturbances in the air medium, promoting collisions among cloud and rain microdroplets carried by airflow and accelerating water vapor condensation to trigger precipitation. Although previous studies have confirmed that acoustic waves can influence droplet aggregation behavior, research on surface precipitation microphysical characteristics and spatial distribution changes under acoustic intervention remains limited. Therefore, this study investigates near-surface precipitation microphysical characteristics under acoustic intervention using raindrop spectrometer and rain gauge monitoring data from acoustic rain enhancement field experiments conducted in the Qaidam Basin from June to September 2019. This research is significant for deepening understanding of acoustic rain enhancement mechanisms in northwestern China and for evaluating artificial precipitation enhancement effectiveness.

1.1 Study Area Overview

The experimental site (37°27 36 E, 96°48 00 N) is located in Delingha City, Haixi Mongolian-Tibetan Autonomous Prefecture, Qinghai Province. Situated on the northeastern edge of the Qaidam Basin at an average elevation of 2980 m, the region has a highland continental climate characterized by dryness and low rainfall. According to monitoring data from the Delingha National Meteorological Station (37°22 12 E, 97°22 12 N), the average annual precipitation is 204.7 mm, with monthly precipitation concentrated primarily from June to August. Prevailing near-surface maximum wind directions are westerly (W) and east-northeasterly (ENE). The acoustic rain enhancement equipment and raindrop spectrometer were positioned at the operation center, while rain gauge stations were deployed at distances of 0.5 km, 1.0 km, 2.0 km, 3.0 km, and 4.0 km from the center in east-west and north-south directions (Fig. 1[Figure 1: see original paper]).

1.2 Experimental Equipment

The acoustic rain enhancement equipment consists of a low-frequency acoustic generation system, acoustic radiator, control system, power supply system, and 云台机构 (cloud platform mechanism). An air compressor delivers compressed air to the low-frequency acoustic generation system to produce low-frequency strong acoustic waves, which the acoustic radiation system then propagates to high altitudes. The acoustic frequency response ranges from 25-50 Hz, with maximum sound pressure levels of 100-165 dB and a maximum sound pressure level no less than 100 dB within 2-3 km.

The primary microphysical parameters examined in this study include average particle size, rainfall intensity (R, mm · h^{-1}), radar reflectivity factor (Z, dBZ), spatial particle number concentration (N, m^{-3}), liquid water content (W, g · m^{-3}), rainfall kinetic energy (E, J · m^{-2} · h^{-1}), and normalized intercept parameter (N_w, mm^{-1} · m^{-3}), calculated as follows:

$$D_m = \frac{\sum_i D_i^4 N_i}{\sum_i D_i^3 N_i}$$

$$R = \frac{\pi}{6} \sum_i D_i^3 N_i V_i$$

$$Z = \sum_i D_i^6 N_i$$

$$N = \sum_i N_i$$

$$W = \frac{\pi}{6}\rho_w \sum_i D_i^3 N_i$$

$$E = \frac{1}{2}\sum_i m_i V_i^2 = \frac{\pi}{12}\rho_w \sum_i D_i^3 N_i V_i^2$$

$$N_w = \frac{4^4}{\pi\rho_w}\left(\frac{10^3 W}{D_m^4}\right)$$

The raindrop spectrometer is a German OTT Parsivel second-generation laser particle spectrometer, which measures droplet size and velocity across 32 unequally spaced channels. The first three channels are negligible due to instrument signal-to-noise ratio, and the sampling interval is 1 min. The SLJ-2 rain gauge is a tipping-bucket type using solid-state storage, with a measurement accuracy of 0.1 mm, range of 0–4 mm $\cdot$ min^{-1}, and sampling interval of 2 min.

1.3 Data Processing

Due to the limited number of rainfall events in the region, acoustic rain enhancement experiments employed a combination of random and non-random methods. When the first experiment of the day was non-random, subsequent consecutive experiments were conducted at equal time intervals to randomize later cases. Based on Qiu et al.' s research, the acoustic onset delay time is 0–15 min, and the rain enhancement effect also dissipates 0–15 min after acoustic shutdown. Considering equipment performance and cloud response to acoustic waves, the acoustic rain enhancement equipment operation time was fixed at 40 min, with shutdown time also fixed at 40 min, enabling segmented study of microphysical quantities before and after intervention.

Experiments followed a pattern of 40 min acoustic on and 40 min acoustic off, with one complete on-off cycle constituting a single case, repeated sequentially until termination. Due to factors such as manual operation time, equipment malfunction, and weather conditions, some cases had unequal on/off durations. After excluding these cases, 23 valid samples remained.

Rainfall cloud systems were classified based on maximum rainfall intensity $R_{\max}$ and its standard deviation σ: when $R_{\max} < 5$ mm $\cdot$ h^{-1} and $\sigma < 0.5$ mm $\cdot$ h^{-1}, the sample was classified as stratiform rain (S); when $R_{\max} \geq 5$ mm $\cdot$ h^{-1} and $\sigma \geq 0.5$ mm $\cdot$ h^{-1}, as convective rain (C); other cases as mixed rain (T).

The raindrop size distribution (DSD) describes the distribution of precipitation particles of different sizes per unit volume and can be fitted using functions such as the Gamma distribution. As the Gamma distribution introduces a shape factor μ based on the Marshall-Palmer distribution, it provides higher fitting accuracy. Therefore, this study uses the Gamma distribution function to fit the average spectrum:

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

where $N(D)$ is the raindrop number concentration per unit volume and size interval ($m^{-3} \cdot mm^{-1}$); N_0 is the intercept parameter ($mm^{-1-} \cdot m^{-3}$); μ is the shape factor; λ is the slope parameter (mm^{-1}); and D is the raindrop diameter (mm).

2.1.1 Mean Microphysical Quantities

Statistical analysis of 23 acoustic intervention cases reveals changes in precipitation and microphysical quantity means (Table 1), where P represents accumulated precipitation. Comparing 40-min periods before and after acoustic activation, 14 cases showed increased accumulated precipitation while 9 cases showed decreases, accounting for 60.87% and 39.13% respectively. Among these, stratiform and convective rain cases showing increased precipitation accounted for 56.25% and 50.00%, respectively, while decreases accounted for 43.75% and 50.00%.

Microphysical quantities generally followed the same increasing/decreasing trend as precipitation, with rainfall intensity and kinetic energy showing the most significant changes. However, average particle size and spatial particle number concentration showed inconsistent trends in 5 and 3 cases respectively, likely due to acoustic effects on near-surface raindrops causing anomalies in these parameters.

Table 1 presents the variation of mean microphysical parameters for precipitation cases under acoustic intervention, including case numbers, times, cloud types, and changes in P, D_m, N, W, Z, E, and R.

2.1.2 Spectrum Analysis

As shown in Fig. 2[Figure 2: see original paper], under natural conditions, convective rain exhibits greater spectrum width (difference between maximum and minimum diameters) and spectral peak (maximum particle number concentration) than stratiform rain. The maximum particle number concentration for convective rain (1473.49 m^{-1}) also exceeds that for stratiform rain (609.26 m^{-1}).

Under acoustic intervention, particle concentration begins increasing at approximately 0.8 mm diameter, indicating reduced concentration for small particles (<0.8 mm) and increased concentration for large particles (>0.8 mm). Combined with Table 3, the shape factor μ during acoustic operation (1.79) is smaller than during acoustic shutdown (2.45), suggesting that with constant water content, small droplet concentration decreases while large droplet concentration increases.

Comparison of average spectrum patterns between natural and acoustic conditions shows that the acoustic intervention spectrum generally resembles stratiform rain patterns, consistent with the higher proportion of stratiform rain cases in the total sample.

Table 2 compares average microphysical quantities under natural conditions and acoustic intervention, revealing that all microphysical quantity means increase from stratiform to convective rain under natural conditions. Acoustic operation yields higher mean values than acoustic shutdown for all microphysical parameters.

2.1.3 Parameter Relationships

Drop size distribution parameter relationships are crucial for cloud physical models and radar-based precipitation retrieval. The three Gamma distribution parameters are not mutually independent except for μ. Additionally, the N_w-R relationship characterizes DSD variations. The mass-weighted mean diameter D_m indicates the proportion of large particles, with larger values signifying more large particles. The normalized intercept parameter N_w independently measures particle number concentration, where higher N_w indicates greater concentration.

The λ-μ relationship under acoustic and natural conditions is shown in Fig. 3[Figure 3: see original paper]. The slope parameter λ increases gradually with shape factor μ, with fitting significance below 0.001. For $\mu < 2$, λ values during acoustic operation are lower than during shutdown for the same μ. Combined with the relationship $\lambda D_m = 3.67 + \mu$, this indicates that D_m increases during acoustic operation, meaning more large raindrops.

The $\log N_w$-R relationship (Fig. 3[Figure 3: see original paper]) shows that $\log N_w$ increases with rainfall intensity R, with fitting significance below 0.001. The curve exhibits an inflection point at $R = 0.8\ \mathrm{mm \cdot h^{-1}}$. When R exceeds this value, particle number concentration increases during acoustic operation; otherwise, it decreases. Thus, under acoustic intervention, greater rainfall intensity produces more pronounced increases in particle number concentration.

The Z-R relationship provides correction parameters for radar-based precipitation estimation and varies with region, time, and precipitation type. Fig. 4[Figure 4: see original paper] presents fitted Z-R curves under natural and acoustic conditions. All three Z-R relationships (acoustic on, acoustic off, and natural) pass significance tests at the 0.05 level. The curves show consistent trends, with Z increasing as R increases. An inflection point occurs at approximately $Z = 23$ dBZ. When radar reflectivity exceeds this value, rainfall intensity during acoustic operation exceeds that during shutdown, demonstrating significant correlation between radar reflectivity and rainfall intensity under acoustic intervention.

2.2 Spatial Distribution of Rainfall Intensity

Rain gauge stations at various distances are distributed as shown in Fig. 1[Figure 1: see original paper]. Statistical analysis of measured rainfall intensity data from each station is presented in Fig. 5[Figure 5: see original paper], where the x-axis represents rainfall intensity at different distances during 40-min acoustic operation and the y-axis represents intensity during 40-min shutdown. The dashed line indicates the $y = x$ distribution. Scatter points tilt to the lower right of the $y = x$ line, toward the acoustic operation side. Skewness values for rainfall intensity during acoustic on and off periods are 0.42 and -0.31, respectively, with a skewness ratio of 1.35, indicating significant acoustic effects on rainfall intensity within 3 km of the origin.

Conclusions

Based on observations from Parsivel disdrometers and rain gauges during acoustic rain enhancement experiments conducted from June to September 2019 in the Qaidam Basin, this study analyzed variations in surface precipitation microphysical characteristics, precipitation amount, and rainfall intensity distribution. The main conclusions are:

(1) Compared with periods when the acoustic equipment was off, accumulated precipitation increased when the equipment was on, with precipitation-increasing and precipitation-decreasing cases accounting for 60.87% and 39.13% of total cases, respectively. Mean values of microphysical parameters—including average particle size, liquid water content, radar reflectivity factor, rainfall intensity, and kinetic energy—increased to varying degrees after acoustic activation. Average particle size increased by 3.23%, radar reflectivity factor and liquid water content increased by 6.12% and 11.43%, respectively, while rainfall intensity and kinetic energy showed the most significant increases of 36.00% and 69.20%. For different cloud systems under natural conditions, all microphysical quantity means increased from stratiform to convective rain, with convective rain exhibiting wider spectrum width and higher particle number concentration than stratiform rain.

(2) For the total sample average spectrum, the mean spectrum changed after acoustic activation, with the fitted distribution shape factor μ decreasing. This indicates that with constant water content, small droplet concentration decreased while large droplet concentration increased, particularly for droplets larger than approximately 0.8 mm. Analysis of the relationship between normalized intercept parameter and rainfall intensity under acoustic intervention shows that particle number concentration increases with rainfall intensity, with the enhancement effect becoming more pronounced at higher intensities.

(3) Comparison of rainfall intensity at various distances from the experimental origin before and after acoustic activation reveals significant intensity increases within 3 km when the acoustic equipment was on, demonstrating that acoustic intervention exerts certain influences on surrounding precipitation.

Unlike traditional precipitation enhancement studies based on catalyst seeding technology, this research focuses on the novel approach of acoustic rain enhancement. Through detailed analysis of surface precipitation microphysical characteristic changes, precipitation amount variations, and rainfall intensity distribution under acoustic intervention, this study provides a scientific basis for future field acoustic rain enhancement experiments and offers valuable reference for evaluating acoustic rain enhancement effectiveness.

Acknowledgments

We thank Wang Shengchun, Liu Qi, Wang Yuan, Wang Jinzhao, Zhao Kang, Yang Haijiao, Shi Jinhe, Jie Yongsheng, Tang Chenyang, and others for their assistance during field experiments.

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