Postprint: Aircraft Observations of Cloud Microphysical Characteristics in a Stratiform Precipitation Event over the Central Qilian Mountains

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Abstract

Using aircraft observational data, the microphysical characteristics of a stratiform precipitation cloud system in the central Qilian Mountains on August 27, 2022 were analyzed. The results show that cloud microphysical characteristics vary significantly across different altitude layers and regions. Supercooled liquid water content in the cloud decreases with increasing altitude: in the -6 to -3 ℃ layer, the average supercooled liquid water content is 0.05 $g \cdot m^{-3}$, while in the higher -15 to -12 ℃ layer, it is only 0.015 $g \cdot m^{-3}$, less than one-third of that in the lower layer. Riming plays an important role in particle growth at all altitude layers. The average diameter of cloud particles can reach several hundred micrometers, and the combined action of riming and aggregation processes can result in particle size distribution widths exceeding 6 mm. The average particle diameter in the -6 to -3 ℃ layer is smaller than that in the upper layer, which may be caused by evaporation and breakup of large particles during their descent. On the southwestern side of the mountain range, low-level southerly airflow carrying abundant water vapor is lifted by the terrain, condensing and producing numerous cloud droplets. The concentration of small particles is one order of magnitude higher than on the northeastern side of the mountain range, and the supercooled liquid water content is also higher. On the southwestern side, particles are dominated by supercooled cloud droplets and graupel particles, with less pronounced aggregation and higher particle number concentrations. The northeastern side is dominated by aggregated ice particles and graupel particles, where the low concentration of small particles leads to larger average particle sizes.

Full Text

Aircraft Observation of Cloud Microphysical Characteristics of Stratiform Precipitation in the Central Qilian Mountains

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Abstract

Using aircraft observation data, this study analyzed the microphysical characteristics of a stratiform precipitation cloud system in the central Qilian Mountains on August 27, 2022. The results indicate significant differences in cloud microphysical features across various altitudes and regions. Supercooled liquid water content decreased with increasing altitude, averaging 0.05 $g\cdot m^{-3}$ in the -6 to -3°C layer, while in the higher -15 to -12°C layer, it was only 0.015 $g\cdot m^{-3}$—less than one-third of the lower layer. The riming process played a crucial role in particle growth at all altitudes, with mean particle diameters in the cloud reaching several hundred micrometers. Through the combined effects of riming and aggregation, the particle spectrum width could exceed 6 mm. The mean particle diameter in the -6 to -3°C layer was smaller than in the upper layer, likely due to evaporation and fragmentation of large particles during descent. On the southwestern side of the mountain range, low-level southerly airflow carrying abundant moisture was lifted by the terrain, resulting in condensation and production of numerous cloud droplets. Small particle concentrations were one order of magnitude higher than on the northeastern side, and supercooled liquid water content was also greater. On the southwestern side, particles consisted primarily of supercooled cloud droplets and graupel, with less pronounced aggregation, higher number concentrations, and narrower spectra. On the northeastern side, aggregated ice particles and graupel dominated, and the lower concentration of small particles led to larger mean particle sizes.

Keywords: cloud microphysical characteristics; aircraft observation; orographic stratiform clouds; Qilian Mountains

Introduction

The Qilian Mountains stretch along the northeastern edge of the Tibetan Plateau, forming a 2062 km border between northeastern Qinghai Province and western Gansu Province. Composed of multiple parallel mountain ranges and wide valleys oriented northwest-southeast, with elevations of 4000–6000 m and widths of 200–500 km, the Qilian Mountains serve as the headwaters for numerous inland rivers including the Shiyang, Heihe, and Shule Rivers, holding significant ecological importance for the arid and semi-arid regions of northwestern China. The unique terrain of the Qilian Mountains exerts substantial dynamic, thermodynamic, and cloud-physical effects on precipitation, attracting increasing attention from researchers.

Cloud microphysical processes determine the size, shape, and phase changes of hydrometeors, influencing latent heat release and interacting with dynamic processes to govern the development, evolution, and dissipation of weather systems. These processes affect precipitation by altering the distribution of liquid water and the growth mechanisms of precipitation particles. The shape of cloud particles serves as a crucial parameter for cloud microphysical characteristics, and accurate particle shape information is essential for calculating cloud microphysical parameters such as water content and phase. Aircraft penetration observations represent the most direct method for obtaining in-situ microphysical characteristics, understanding cloud microphysical processes, and investigating precipitation formation mechanisms. These observational data can be applied to studies of cloud structure, microphysical process mechanisms, and the physical mechanisms and operational effectiveness of weather modification. Therefore, using airborne cloud particle measurement systems to obtain cloud particle shapes, size distributions, and images constitutes an important approach for studying cloud physical structure and precipitation formation mechanisms.

In the Qilian Mountains region, precipitation distribution is closely related to terrain, with significant differences in precipitation across different altitudes and between the northern and southern slopes. However, due to altitude and terrain constraints, research on the structure and formation mechanisms of clouds and precipitation in this region has been limited. The primary reason is the scarcity of aircraft penetration observation data obtained in the Qilian Mountains hinterland and on both the northern and southern slopes, resulting in fewer studies on cloud microphysical characteristics and precipitation mechanisms.

This study utilizes data from a stratiform precipitation cloud detection flight conducted by the Qinghai Weather Modification Office using a King Air 350ER aircraft (B3586) in the central Qilian Mountains, combined with multi-source data from satellites, soundings, and ground observations, to analyze the microphysical structure characteristics of clouds under the influence of terrain on both the northern and southern sides of the central Qilian Mountains, as well as the physical mechanisms of precipitation particle formation and precipitation generation in this region. The findings aim to improve the selection of optimal seeding timing and locations, thereby enhancing the effectiveness of artificial precipitation enhancement operations.

1 Instruments and Data Processing

The aircraft was equipped with DMT particle detection equipment capable of measuring cloud and precipitation particle images and concentrations for particle sizes ranging from 0.54 to 6200 m. The Aircraft Integrated Meteorological

Measurement System (AIMMS) collected conventional meteorological parameters including latitude, longitude, altitude, temperature, pressure, and airflow velocity. A hotwire liquid water content sensor (Hotwire_{LWC}) measured liquid water content. Table 1 summarizes the main airborne detection equipment and parameters.

Table 1 Main airborne detection equipment and parameters

Equipment	Measurement Range	Resolution
Cloud and Aerosol Spectrometer (CAS)	0.54-50 m	0.7-5 m
Cloud Imaging Probe (CIP)	25-1550 m	25 m
Precipitation Imaging Probe (PIP)	100-6200 m	100 m
Hotwire LWC Sensor	0-3 $g \cdot m^{-3}$	-
AIMMS-20	Temperature, altitude, airflow velocity, latitude/longitude, etc.	-

Based on the measured particle diameters, this study defines particles of 2-50 m as cloud particles and particles larger than 50 m as precipitation particles. During the flight observations, some probes malfunctioned, affecting data collection. These data were excluded, retaining only sampling data when probes functioned normally. Additionally, due to high-speed sampling and aircraft turbulence, the flight observation data exhibited jump pulse anomalies. Preliminary quality control was applied to remove these outliers.

The calculation methods for particle number concentration and mean diameter followed standard procedures. For concentration calculations, sampling from the 300-6200 m channels was used, excluding the 1500 m (rain) channel. The formulas are:

$$\mathrm{Ncon} = \Sigma\ \mathrm{Ncnt}\ / (\Delta \mathrm{D} \cdot \mathrm{V})$$

$$\mathrm{MD} = (1/\mathrm{Ncon})\ \Sigma\ \mathrm{Ncon} \cdot \mathrm{D}$$

where Ncon is the particle number concentration (cm^{-3}), Ncnt is the number of particles in the i-th bin, ΔD is the width of the i-th bin, V is the sampling volume, D is the median diameter of particles in the i-th bin, and MD is the mean particle diameter.

Hobbs proposed that for cloud water zones, the total concentration of particles larger than 25 m in temperate cyclone cloud systems and orographic clouds should exceed 10 cm^{-3}. This study adopts the criterion that a cloud water zone is identified when continuous records satisfy cloud particle number concentration (Nc) greater than 10 cm^{-3} and cloud liquid water content (LWC) greater than 0.001 $g \cdot m^{-3}$. Using both criteria eliminates the influence of aerosols on cloud droplet samples.

For circulation analysis, 500 hPa and 700 hPa weather maps from the Central Meteorological Observatory were used, including geopotential height, temperature, horizontal wind, and specific humidity. Satellite imagery utilized the FY2G blackbody temperature (TBB) product with 10 km spatial resolution. Additionally, sounding data from Zhangye and Xining were analyzed to characterize atmospheric stratification.

2.1 Weather Background

On August 27, 2022, a precipitation event occurred in the Qilian Mountains region, with moderate rain throughout the mountains. The heavy precipitation area exhibited a distribution along the mountains, with the precipitation center reaching heavy rainfall intensity in the Yeniugou to Qilian area. The Qilian observation station recorded 5.6 mm of hourly precipitation at 17:00, showing characteristics of short-duration heavy precipitation.

At 08:00, the 500 hPa pattern featured a "two troughs and one ridge" configuration at high latitudes (Fig. 1 [Figure 1: see original paper]). The Hexi Corridor and Qilian Mountains region were situated in the westerly flow between the Xinjiang upper-level trough and the subtropical high. The Xinjiang upper-level trough continuously split cold air eastward to the central Hexi region. At 700 hPa, a significant shear line between northwest and southeast winds existed over western Jiuquan, while easterly airflow transported moisture westward along the plateau slope in central-eastern Hexi. The specific humidity in central-eastern Hexi and most of the Qilian Mountains region reached 10 $g \cdot kg^{-1}$. The sounding profiles from Zhangye (Fig. 2 [Figure 2: see original paper]a) and Xining (Fig. 2 [Figure 2: see original paper]b) at 08:00 showed that the atmospheric stratification was nearly saturated at both locations. Zhangye, located on the northeastern side of the Qilian Mountains, showed northwest winds below 2500 m and southwest/west winds above 2500 m. Xining, to the southeast of the Qilian Mountains, showed southeast winds below 3000 m and west winds at 3000–5000 m, indicating that the lower levels of the southeastern Qilian Mountains were influenced by southeasterly airflow. Local convective available potential energy (CAPE) values exceeding 100 $J \cdot kg^{-1}$ existed in the Qilian Mountains region, with abundant moisture conditions and favorable energy and dynamic lifting conditions. Under the combined influence of westerly and low-level southeasterly airflow, together with upper-level cold advection, an environment with cold and dry air aloft and warm and moist air below formed, which could trigger convection locally over the complex terrain from the northern foothills of the Qilian Mountains to the Hexi Corridor.

Satellite imagery (Fig. 3 [Figure 3: see original paper]) shows that on the morning of the 27th, the cloud system moved out of the central Qinghai-Tibet Plateau and covered the central and eastern Qilian Mountains, oriented northeast-southwest and moving from southwest to northeast. The horizontal distribution of the cloud system was extensive, with the lowest blackbody temperature over the central Qilian Mountains reaching approximately -40°C at 08:00 and -30°C at 12:00. In summary, the precipitation cloud system in the Qilian Mountains region had a wide distribution range, with abundant moisture throughout the Hexi region and favorable conditions for precipitation formation.

2.2 Aircraft Flight Detection

The King Air 350ER aircraft (Beijing time, hereafter) took off from Qinghai Caojiabao International Airport (elevation 2146 m) at 08:37 and landed at 12:37, covering a distance of 2091 km. The maximum flight altitude exceeded 8000 m. Figure 4 [Figure 4: see original paper] shows the flight altitude variation over time and the flight track.

After takeoff, the aircraft flew level at 8230 m altitude (Fig. 4 [Figure 4: see original paper]a). At 08:53, it began a circling descent vertical sounding over the southwestern side of the mountains (B section). At 09:30, the aircraft began a circling ascent vertical sounding from 6600 m. At 09:53, it flew northward level to the northeastern side of the mountains at 7899 m altitude, then conducted a circling descent vertical sounding (C section) from 7890–6256 m. At 10:31, the aircraft returned to the southwestern side at 6260 m altitude and conducted vertical soundings crossing the mountain range between 10:31–11:10. At 11:25, on the southwestern side at 7885 m altitude, the aircraft flew eastward level to the northeastern side and conducted circling descent and ascent vertical soundings (D section) from 11:52–12:00. At 12:10, the aircraft began its return flight, flying level at 7900 m altitude before landing at 12:37 to complete the observation experiment.

The B section (blue track) represents observations on the southwestern side of the mountains, while the C section (red track) represents observations on the northeastern side. The D section involved crossing between both sides. All vertical sounding processes included horizontal observations at different altitudes. Data screening revealed few observations in the A section, making it difficult to meet cloud entry criteria continuously. The B and C sections observed both the southwestern and northeastern sides of the mountains with relatively short intervals between them, and the B section obtained relatively more data. Therefore, this study focuses on the vertical sounding results from the B and C sections, with an interval of only 6 minutes between observations on the two sides.

3 Cloud Microphysical Characteristics Analysis

This analysis primarily utilizes vertical sounding data obtained on both the southern and northern sides of the main Qilian Mountains peak (the B and C sections in Fig. 4 [Figure 4: see original paper]) to examine cloud microphysical characteristics and compare differences in cloud structure between the two sides.

The aircraft detection area primarily consisted of stratiform precipitation clouds. Excluding takeoff and landing phases, the entire flight included continuous vertical soundings, with two soundings on the southwestern side (B and D sections) and two on the northeastern side (C and D sections). The following sections present detailed analyses.

3.1 Cloud Microphysical Characteristics on the Southwestern Side

During level flight at 8230 m altitude on the southwestern side of the mountains (Fig. 5 [Figure 5: see original paper]), the ambient temperature ranged from -12 to -11.6°C, with supercooled liquid water content not exceeding 0.02 $g \cdot m^{-3}$ and averaging 0.014 $g \cdot m^{-3}$. Particle concentrations in the cloud were low and unevenly distributed. The B section vertical sounding (9:30-9:47) was conducted between 7899-6600 m, with temperatures ranging from -14 to -4°C. The aircraft also performed level flights at 7300 m, 7600 m, and 6900 m during this period. Supercooled water content was relatively high, decreasing with altitude from 0.046-0.063 $g \cdot m^{-3}$ (average 0.055 $g \cdot m^{-3}$) at 6600 m to 0.015 $g \cdot m^{-3}$ at 8230 m—approximately half the value at lower levels. Regions with high supercooled water content corresponded to higher particle concentrations.

At 8230 m, cloud droplets were small (below 10 m) with concentrations reaching 34802.81 L^{-1}, while particles larger than 500 m were essentially absent. The particle spectrum showed a single peak at 10 m, indicating small cloud droplets. At 6600 m, the CIP probe measured a particle spectrum width up to 1500 m, showing a single peak distribution at 100 m, though peaks also appeared at 500 m, indicating aggregation growth processes. The maximum particle number concentration was 1306.31 L^{-1}, with an average of 991.27 L^{-1} and mean diameter of 396.0 m. The PIP probe measured a single-peaked spectrum at 1000 m, though the spectrum was discontinuous, with a mean particle diameter of 525.5 m and maximum concentration of 127.74 L^{-1}.

During 9:27-9:30 at 6600 m altitude over the southern mountains, the temperature averaged -4.7°C, with supercooled water content ranging from 0.046-0.063 $g \cdot m^{-3}$ (average 0.055 $g \cdot m^{-3}$)—about four times that at 8230 m. At this altitude, cloud droplets were small (below 10 m) with concentrations reaching 25828.1 L^{-1}, while the CIP probe measured maximum and average particle concentrations of 81.39 L^{-1} and 10.18 L^{-1}, respectively, with mean diameter of 180.7 m. The PIP probe measured maximum and average concentrations of 7.22 L^{-1} and 0.42 L^{-1}, respectively, with mean diameter of 390.2 m. The particle spectrum was narrower than at 8230 m, with particles concentrated below 100 m.

Overall, observations on the southwestern side showed that supercooled water content decreased with increasing altitude. In the 6-7 km layer, temperatures were not lower than -12°C, with relatively high supercooled water content that changed little with height. Above 7.5 km, supercooled water content decreased with altitude, with an average of only 0.015 $\mathrm{g \cdot m^{-3}}$ at 7.5-7.9 km—half that in the 6.5-7.0 km layer. Particle spectra were narrow and particle sizes were small in the upper layer, though broader spectra and larger particles existed at lower levels.

3.2 Cloud Microphysical Characteristics on the Northeastern Side

The C section vertical sounding (9:53-10:21) on the northeastern side of the mountains followed immediately after the B section. The temperature range during vertical sounding was -15 to -1°C, with level flights included near 7.2 km, 6.9 km, and 6.6 km. The CAS probe measured maximum and average particle concentrations of 53.21 $\mathrm{L^{-1}}$ and 2.48 $\mathrm{L^{-1}}$, respectively, with particles primarily below 200 m and mean diameter of 215.1 m. The CIP probe measured maximum and average concentrations of 2.86 $\mathrm{L^{-1}}$ and 0.51 $\mathrm{L^{-1}}$, respectively, with mean diameter of 479.6 m. The PIP probe measured maximum and average concentrations of 0.09 $\mathrm{L^{-1}}$ and 0.18 $\mathrm{L^{-1}}$, respectively, with mean diameter of 642.4 m. The particle spectrum width was generally below 1000 m, with low and discontinuous concentrations. Liquid water content also decreased with increasing altitude.

During level flight at 6650-6765 m, the average temperature was -4.5 to -4°C, with mean liquid water content of 0.048 $\mathrm{g \cdot m^{-3}}$. The CAS probe measured maximum and average particle concentrations of 64.5 $\mathrm{L^{-1}}$ and 4.2 $\mathrm{L^{-1}}$, respectively. The CIP probe measured maximum and average concentrations of 10.03 $\mathrm{L^{-1}}$ and 0.61 $\mathrm{L^{-1}}$, respectively, with mean diameter of 648.7 m. The PIP probe measured maximum and average concentrations of 4.39 $\mathrm{L^{-1}}$ and 0.18 $\mathrm{L^{-1}}$, respectively, with mean diameter of 579.6 m. Similar to the southwestern side, the 6-7 km layer had the highest liquid water content, with the riming growth process being significant. On the northeastern side, particles consisted mainly of graupel and aggregated ice particles.

At 7230 m altitude, the average temperature was -8.82°C, with liquid water content between 0.015-0.032 $\mathrm{g \cdot m^{-3}}$ (average 0.024 $\mathrm{g \cdot m^{-3}}$). The CAS probe measured maximum and average particle concentrations of 20.24 $\mathrm{L^{-1}}$ and 1.0 $\mathrm{L^{-1}}$, respectively. The CIP probe measured maximum and average concentrations of 120.56 $\mathrm{L^{-1}}$ and 16.44 $\mathrm{L^{-1}}$, respectively, with mean diameter of 416.1 m. The PIP probe measured maximum and average concentrations of 10.8 $\mathrm{L^{-1}}$ and 0.6 $\mathrm{L^{-1}}$, respectively, with mean diameter of 477.2 m. At this altitude, particle concentrations and sizes were both small.

3.3 Differences in Cloud Microphysical Characteristics Between Mountain Sides

On both the northern and southern sides of the mountains, particles exhibited unimodal distributions at different temperature layers (Fig. 8 [Figure 8: see original paper]), with spectral peaks at the small particle end. In the -15 to -12°C layer, the spectrum was broader, with more large particles at the millimeter scale at upper levels. Throughout the vertical sounding, the -6 to -3°C layer had the highest liquid water content, with the riming growth process being significant. Both sides contained numerous graupel particles. On the northeastern side, aggregated ice particles dominated, while on the southwestern side, supercooled droplets and graupel were predominant with less obvious aggregation, resulting in fewer large particles and narrower spectra than on the northeastern side.

Table 2 and Table 3 present the mean liquid water content, mean particle diameters, and particle concentrations at different temperature layers on both sides. In the -6 to -3°C layer, the southwestern side had small particle concentrations one order of magnitude higher than the northeastern side (6567.9 L^{-1} vs. 3100.9 L^{-1}), and supercooled water content was also higher. Particle concentrations on the southwestern side were higher by one order of magnitude, though the mean particle diameter was smaller (187.4 m vs. 418.2 m on the northeastern side). In the -15 to -12°C layer, the differences in supercooled water content, small particle (1–50 m) concentration, and mean particle size were relatively small between the two sides, but the southwestern side had higher concentrations of large particles (above 75 m).

Typical particle images from the CIP and PIP probes (Fig. 9 [Figure 9: see original paper]) show that both sides had needle, columnar, plate, and dendritic ice particles at upper levels, with obvious riming processes producing dense ice particles reaching millimeter scale. The northeastern side had more plate ice and snow crystals. The southwestern side lacked observations in the -9 to -6°C layer, while on the northeastern side, particle concentration in this layer was 10.8 L^{-1}, decreasing with altitude. In addition to plate and dendritic ice and snow crystals, the combined effects of aggregation and riming produced large-scale ice particles. Cloud droplet concentrations were also higher in the -6 to -3°C layer.

4 Conclusions

Based on aircraft detection data, this study summarizes the cloud structure characteristics of this precipitation event in the central Qilian Mountains:

1) The precipitation cloud system exhibited significant differences in microphysical characteristics across altitude layers. Supercooled water content decreased with altitude, averaging 0.05 $g \cdot m^{-3}$ in the -6 to -3°C layer, while in the higher -15 to -12°C layer, it was only 0.015 $g \cdot m^{-3}$—less than one-third of the lower layer. Cloud particles showed low concentration and large size distributions, with mean diameters reaching several hundred micrometers. The riming process was important for particle growth at all altitudes. Observations on both mountain sides showed that mean particle diameter in the -6 to -3°C layer was smaller than in the upper layer, likely due to evaporation and fragmentation of large particles during descent.

2) Particle concentrations were higher on the southwestern side of the mountains. Low-level southerly airflow carrying moisture was lifted by the

> terrain, resulting in small particle concentrations one order of magnitude higher than on the northeastern side in the -6 to -3°C layer, along with higher supercooled water content. Particles on the southwestern side consisted primarily of supercooled droplets and graupel with less aggregation, fewer large particles, and narrower spectra. On the northeastern side, graupel and aggregated ice particles dominated. In the higher -15 to -12°C layer, precipitation cloud systems on the southwestern side had large particle concentrations one order of magnitude higher than on the northeastern side. Through combined riming and aggregation processes, particle spectrum width could exceed 6 mm.

This study summarizes the cloud structure characteristics of the precipitation process in the central Qilian Mountains based on limited aircraft cloud penetration observations. Some conclusions may require further observational validation, particularly regarding differences in cloud structure characteristics between altitude layers and mountain sides. Additionally, all aircraft vertical soundings were conducted above the -6°C layer; liquid-phase processes at and above this layer warrant future investigation.

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