Advances in Field Observation Experiments on Cloud and Precipitation Physics in the Western Tianshan Region of China: A Postprint

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Abstract

The western Tianshan region is the most precipitation-abundant area in Central Asia. Its unique westward-opening valley topography and westerly circulation collectively constitute distinctive cloud-precipitation physical processes in the Central Asian region. Precipitation that forms snow, glaciers, and runoff exerts significant impacts on the socioeconomic conditions and ecological environment of Central Asia. With the advancement of the national "Silk Road Economic Belt" initiative, formidable scientific and technological challenges have emerged regarding water resources, meteorological disaster prevention and mitigation, and ecological environmental protection in Central Asia. The observation and research of cloud-precipitation physical processes in this region, which serve as the scientific and technological foundation, remain in their infancy and cannot satisfy the requirements of national strategy and the development of China's meteorological enterprise. Consequently, in 2019, a field observation scientific experiment base for cloud and precipitation physics in the western Tianshan region was established. Research has been conducted on cloud macro- and microphysics, raindrop size distributions of stratiform/convective clouds, comparative characteristics of raindrop size distributions between the central and western Tianshan, microphysics of cold-front snowstorms, among other topics, yielding cutting-edge achievements. This paper provides a distilled summary of these findings to advance the disciplinary development of cloud-precipitation physics in Central Asia.

Progress in Scientific Experimental Research on Cloud and Precipitation Physics Field Observations in the Western Tianshan Mountains of China

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Abstract

The western Tianshan Mountains region receives the highest precipitation in Central Asia. Its unique westward-opening valley topography and westerly circulation create distinctive cloud-precipitation physical processes in Central Asia. Precipitation forms snow, glaciers, and runoff, which significantly impact the socio-economy and ecological environment of Central Asia. With the advancement of the national "Silk Road Economic Belt" initiative, severe scientific and technological challenges have been posed regarding water resources, meteorological disaster prevention and mitigation, and ecological environment protection in Central Asia. Observation and research on cloud-precipitation physical processes in this region form the scientific and technological foundation but remain in their infancy, failing to meet national strategic needs and the development requirements of China's meteorological enterprise. Therefore, in 2019, a field observation scientific experimental base for cloud and precipitation physics was established in the western Tianshan Mountains region. Relevant research has been conducted on cloud macro/microphysics, similarities and differences in raindrop spectrum characteristics between stratiform and convective clouds, and microphysics of cold-front snowstorms, yielding cutting-edge results. This paper summarizes these achievements to promote the development of cloud and precipitation physics in Central Asia.

Keywords: field observation test; cloud precipitation; macro-micro physical characteristics; research progress; western Tianshan Mountains of China

1. Layout of the Cloud and Precipitation Physics Observation Base in the Western Tianshan Mountains

The Ili River Valley is surrounded by mountains on its north, east, and south sides, forming a westward-opening valley that facilitates orographic precipitation on windward slopes under westerly circulation, making it the largest precipitation center in northwestern China and even Central Asia. The annual precipitation in the plains ranges from 200–400 mm, while mountainous areas receive 600–800 mm or more, making this region the most ideal area for cloud-precipitation physics observation experiments in Central Asia. The comprehensive field observation base for cloud-precipitation physics was established in the Ili River Valley.

The observation station layout is shown in [Figure 1: see original paper]. The main observation stations are Yining Station at the western end of the Ili River Valley (81°32 00 E, 43°58 24 N, 771 m) and Xinyuan Station at the eastern end (83°15 25 E, 43°26 25 N, 928.3 m). Xinyuan is the region with the largest precipitation in the Ili River Valley and has been equipped with the most advanced, comprehensive, and diverse observation instruments, forming a superstation. The superstation includes a C-band dual-polarization radar, Ka/Ku dual-frequency cloud radar, boundary layer wind profiler radar, micro rain radar, laser disdrometer, two-dimensional video disdrometer, laser ceilometer, and ground-based microwave radiometer, all installed within the Xinyuan National Basic Meteorological Station observation field. To avoid observation gaps at low elevation angles and blockage by nearby Tianshan terrain, the radar was installed in Xiaoerbulake Town, approximately 30 km west of the Xinyuan observation station. The equipment manufacturers, models, and technical parameters are detailed in , with temporal resolution reaching seconds to minutes and spatial resolution reaching meters, maintaining synchronization with international standards for physical element observation accuracy.

Yining Station has fewer instruments than Xinyuan, lacking only the cloud radar and wind profiler radar. Supplementary observation stations were also established at Gongliu County Station (82.14°E, 43.28°N, 1210.5 m), Nileke Station (83.15°E, 43.48°N, 774.4 m), Zhaosu Station (81.34°E, 43.28°N, 1340 m), Tekesi Station (81.08°E, 43.09°N, 1107.1 m), and Yili Botanical Garden Station (81.42°E, 43.11°N, 1860.2 m). All supplementary stations are equipped with laser disdrometers and GPS/MET water vapor detectors, while Gongliu and Zhaosu stations additionally have micro rain radars. These stations form the comprehensive field observation network for cloud-precipitation physics in the western Tianshan Mountains, covering the entire Ili River Valley region.

To compare and analyze differences in raindrop spectra between the central and western Tianshan Mountains, laser disdrometers and GPS/MET water vapor detectors were also installed at Urumqi Station (87.37°E, 43.53°N, 918.7 m) and Tianchi Station (88.07°E, 43.47°N, 1935.2 m) in the central Tianshan Mountains.

Additionally, 30 GPS/MET water vapor detectors have been installed across

Xinjiang, including the Tianshan Mountains and their flanks, the Altai Mountains foothills, and the northern edge of the Kunlun Mountains. The highest altitude station is at Tianshan Daxigou (3543.8 m). GPS/MET detectors are also installed at Tazhong Station in the Taklamakan Desert hinterland and Karamay Station in the Gurbantunggut Desert, providing an observation foundation for atmospheric precipitable water detection and precipitation forecast and warning in Xinjiang. The distribution is shown in [Figure 2: see original paper].

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2. Observation Products and Data Monitoring and Transmission System

To ensure the integrity and effectiveness of field observation data, dedicated personnel are assigned at each observation base to operate and maintain instruments, monitor data, and ensure transmission, while keeping the observation environment clean. Researchers and manufacturers regularly calibrate and repair instruments, promptly addressing technical issues through communication with manufacturers to ensure normal equipment operation.

For data monitoring, the "West Tianshan Cloud-Precipitation Observation Data Comprehensive Monitoring and Transmission System" was developed, enabling real-time monitoring, storage, and downloading of cloud-precipitation physics field observation data to prevent data loss due to equipment failure or power outages. The observation base began construction and observations in March 2019, with full completion by December 2019. Currently, year-round observations are conducted to provide data support.

The observation products (Table 2) include water vapor, temperature, pressure, wind, precipitation, and macro/microphysical characteristics of clouds and precipitation. The main products are detailed in .

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3. Research Progress

Research using observational data from 2019–2022 has yielded progress in cloud macro/microphysics, stratiform-convective cloud raindrop spectrum characteristics, and cold-front snowstorm microphysics. Results indicate that cloud and precipitation macro/microphysical characteristics in the Tianshan region exhibit regional features distinct from the eastern monsoon region and the Tibetan Plateau.

3.1.1 Cloud Top, Base, and Thickness Characteristics

Based on cloud radar and GPS/MET observations, a dataset of cloud top height, base height, and thickness was established. Studies show that summer has the highest cloud top height (7.43 km), base height, and thickness (4.12 km), while winter has the lowest (cloud top height: 3.31 km, base height: 2.71 km, thickness: 3.33 km). Cloud occurrence frequency shows significant diurnal variation: clouds form frequently at night (19:00–10:00 BJT) in spring, summer, and winter, gradually dissipating during daytime (10:00–17:00 BJT). In autumn, clouds form frequently in the morning (11:00–14:00 BJT) and dissipate during other periods. Seasonal cloud variation is related to high summer temperatures and low winter temperatures, while diurnal variation is associated with valley wind circulation changes caused by the trumpet-shaped topography.

Spring and autumn have two most probable cloud top heights at 4–5 km and 8–9 km, while summer has three at 5–6 km, 7–8 km, and 9–10 km. Winter has only one most probable height at 3–4 km. The vertical distribution of average cloud top heights for low, middle, and high clouds in summer is similar to cloud layers. Under precipitation conditions, cloud top heights are higher than under non-precipitation conditions in all seasons. Winter has the lowest average cloud base and top heights for low, middle, and high clouds. The most probable cloud base heights are mostly 3–4 km. Cloud thickness less than 2 km accounts for 35%–50% of cloud samples, while precipitating clouds have most probable thickness peaks at 5–6 km in spring, summer, and winter, and 7–8 km in autumn. Cloudy samples account for 40%–50% of total samples, with low clouds comprising 40%–50% of cloudy samples in all seasons. Summer has the highest proportion of high clouds and the lowest proportion of middle clouds. This region has high proportions of low and middle clouds, indicating great potential for atmospheric water resource development, with the lowest winter cloud heights being most suitable for artificial snow enhancement operations.

3.1.2 Rainfall Cloud Microphysical Characteristics

Rainfall intensity (R) is classified into light (<1 mm · h^{-1}), moderate (1–3 mm · h^{-1}), and heavy ($ 3mm·h{-1})categories.Studiesshowthattheheightswithstrongaggregationandcoalescencegrowtheffectsare1.8
3}, 4.2g·m{-3}, and7.3g · m{-3}.Liquidwatercontentisthekeyfactordeterminingrainintensity, withthemaximume
surfacereflectivityfactorsforlight, moderate, andheavyrainconcentrateat24–32dBZ, 29–38dBZ, and31–42d
1.4to − 0.6m · s{-1}, whileformoderateandheavyrainitis − 5.5to − 4.0m · s{-1}$ and -7 to -5 m · s^{-1}, respectively, showing stronger vertical motion with increasing rain intensity.

3.1.3 Snowfall Cloud Microphysical Characteristics

Based on snow rate (S), snowfall is classified as light (S $\leq$ 3.0 mm), moderate (3.1 mm $\leq$ S $\leq$ 6.0 mm), and heavy (6.1 mm $\leq$ S $\leq$ 12.0 mm). Analysis of 8 heavy snow, 11 moderate snow, and 16 light snow processes using cloud radar observations shows that light, moderate, and heavy snow clouds are concentrated at 0.15–2.50 km. Reflectivity factors are mostly less than 24 dBZ, with maximum values of 29 dBZ for light snow, 33 dBZ for moderate snow, and 33 dBZ for heavy snow. The normalized frequency distribution of reflectivity factors is similar among the three categories, but heavy snow processes have significantly more reflectivity factors below 29 dBZ due to higher hourly snow intensity. Snow particle water contents for light, moderate, and heavy snow are located at 2.00–7.65 km, 2.20–8.85 km, and 3.0–8.7 km, respectively. Heavy snow cloud water content is 0.04–0.2 $g \cdot m^{-3}$, comparable to Beijing, indicating relatively abundant water vapor in heavy snow processes in arid regions. Light snow processes have the least cloud water content. The average duration is shortest for light snow and longest for heavy snow, with heavy snow cloud water content at 0.1–0.25 $g \cdot m^{-3}$ during peak periods, significantly greater than light and moderate snow processes. Vertical motion differences among various snow intensity processes are small.

3.2.1 Seasonal Raindrop Size Distribution Characteristics

Raindrop spectrum observations reveal that microphysical parameters in this region are generally smaller than those in eastern China, dominated by small particles with local characteristics. Stratiform cloud rainfall shows small variations in raindrop spectrum parameters, while convective cloud rainfall exhibits large variations. During rainfall events, summer (autumn) has the most (least) moderate raindrops (1 mm $<$ diameter $<$ 3 mm) and large raindrops (diameter $\geq$ 3 mm), and the least (most) small raindrops (diameter $\leq$ 1 mm). Summer also has the largest maximum raindrop diameter. In summer (autumn), small raindrops contribute minimally (maximally) to precipitation amount, while moderate and large raindrops contribute maximally (minimally). Small raindrops contribute maximally to total raindrop number concentration, while moderate and large raindrops contribute minimally. The maximum average mass-weighted mean diameter (D) in summer (autumn) is the largest (smallest), with the minimum value being 0.876 mm (1.059 mm). The distribution characteristics of median volume diameter are similar to D . The average normalized intercept parameter reaches its maximum in autumn.

When precipitation is divided into four levels, autumn has the highest small raindrop concentration, while summer has the lowest. As precipitation rate increases, moderate and large raindrop concentrations in spring exceed those in summer, reaching maximum values. The mass-weighted mean diameter, median volume diameter, and reflectivity factor all increase with precipitation rate levels, reaching maximum (minimum) values in summer (autumn) except for the normalized intercept parameter, which reaches maximum (minimum) values in autumn (summer). Raindrop size relationships show distinct seasonal variations that differ significantly from other regions. Summer has the maximum vertically integrated water vapor and the most prominent warm-dry atmospheric vertical environment, with more frequent cold rain processes and strong convective rainfall, contributing to fewer small raindrops and more moderate and large raindrops.

3.2.2 Stratiform and Convective Cloud Precipitation Raindrop Spectrum Characteristics

Raindrop spectrum data show that precipitation in the western Tianshan Mountains is dominated by weak rainfall ($R < 1\ \mathrm{mm} \cdot \mathrm{h}^{-1}$). The mass-weighted mean diameter (D) and precipitation amount for convective rainfall are concentrated at 1.6–2.5 mm and 5.0–6.0 $\mathrm{mm} \cdot \mathrm{h}^{-1}$, respectively, while for stratiform rainfall they are concentrated at 0.6–1.6 mm and 2.0 $\mathrm{mm} \cdot \mathrm{h}^{-1}$. As precipitation amount increases, D increases and its distribution becomes narrower. The raindrop spectrum peaks for convective and stratiform rainfall are at 1.2 mm and 0.7 mm diameters, respectively. For diameters less than 0.7 mm, the two spectra basically overlap, but for diameters greater than 0.7 mm, the convective rainfall spectrum is much larger than the stratiform rainfall spectrum (Figure 3). With increasing precipitation intensity, D increases, spectrum width increases, peak diameter increases, while raindrop number concentration first increases then decreases. When D is small (<0.6 mm), raindrop concentrations are similar across different rainfall rate levels, but when D > 0.6 mm, concentrations for high rainfall rate levels increase significantly.

The Z-R relationship for the Yining area was derived: $Z = 190.36R^{1}.^{80}$ for convective precipitation and $Z = 204.57R^{1}.^{73}$ for stratiform precipitation. The WSR-88D default Z-R relationship underestimates the lower reflectivity values and overestimates the higher reflectivity values for stratiform precipitation, while overall overestimating rainfall rates for convective precipitation. Both coefficient A and exponent b values are smaller than those in eastern China.

3.2.3 Comparison of Precipitation Raindrop Spectra Between Western and Central Tianshan Mountains

Observations from Tianshan Station and Tianchi Station show that rainfall processes in the western Tianshan Mountains have higher concentrations of moderate and large raindrops but lower concentrations of small raindrops compared to the central Tianshan Mountains, likely due to stronger convection in the western Tianshan region. For all rainfall rate levels and types, the western Tianshan Mountains have larger mass-weighted mean diameters and smaller normalized intercept parameters than the central Tianshan Mountains (Figure 4). The raindrop spectra for convective precipitation in both regions can be classified as continental convective rainfall, with maximum raindrop diameters reaching 5.0–7.0 mm but very low number concentrations. The Z-R relationship for stratiform precipitation in the western Tianshan Mountains has higher coefficient A and exponent b values. The Marshall-Palmer Z-R relationship overestimates precipitation at low radar reflectivity values and underestimates it at high reflectivity values for stratiform clouds. The Z-R relationship for convective clouds shows poor correlation and cannot meet confidence test requirements, necessitating dual-polarization radar research to improve quantitative precipitation estimation for heavy rain in this region. Compared with Beijing, Hubei, and Nanjing, convective precipitation particles in the Tianshan region have larger average diameters but much lower concentrations.

3.3 Microphysical Characteristics of Cold Front Snowstorm Processes

A study on the microphysical characteristics of a cold front snowstorm process on February 26–27, 2020, reveals that due to complex particle morphologies in cold cloud precipitation and the influence of breakup, aggregation, and riming processes on solid particles during fallout, snowfall processes contain both snowflakes and graupel. By designing classification parameters for snowflakes and graupel particles based on quality-controlled observations, the study shows: (1) Particles <1 mm are mainly snowflakes, while particles >6 mm are mainly snowflake aggregates; particles around 1 mm are the main contributors to graupel, with some particles >1 mm also present. (2) During the cold front invasion stage, low cloud top temperatures result in numerous atmospheric ice nuclei, adequate water vapor, and appropriate supercooled water, with snowflakes as the main precipitation particles and microphysical processes dominated by deposition growth (Bergeron process), "adhesion" mechanism aggregation, and minor riming. During the cold front control stage, increased cloud top temperatures reduce ice nuclei but provide abundant supercooled water, with both snowflakes and graupel contributing equally, dominated by aggregation and riming processes where competitive growth from aggregation favors riming. During the cold front passage stage, continuously rising cloud top temperatures, decreasing ice nuclei, and appropriate supercooled water reduce competing particles, favoring riming processes. Unlike snowstorm processes in the water-vapor-rich monsoon region of Nanjing, snowstorms in the western Tianshan region have smaller snowflake diameters and snow intensity, with graupel contributing significantly to snow intensity.

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4. Discussion

Future research directions include: (1) Evaluating and cross-validating satellite observations of cloud and precipitation physical parameters in Central Asia using this base's observations, leveraging respective advantages to develop refined assessment and monitoring techniques for cloud water resources based on integrated space-ground observations, providing scientific basis for artificial precipitation enhancement operations. (2) Investigating macro/microphysical characteristics of various precipitation cloud systems (stratiform, mixed, convective) under different seasons, altitudes, and weather backgrounds using observations, and studying cloud precipitation formation processes through comprehensive application of various observation data. (3) Developing three-dimensional microphysical structures and evolution of different convective storm morphologies and their relationships with precipitation, creating quantitative precipitation estimation algorithms based on dual-polarization radar applicable to the Tianshan region, and proposing observation-based optimization schemes for cloud microphysical parameterization in arid regions.

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5. Conclusions

Precipitation physical processes and cloud water resources show strong dependence on climate background, topography, and region. The unique arid climate background and complex desert-ice-snow-mountain-basin topography of Central Asia endow precipitation physical processes and cloud water resources with regional characteristics. The main conclusions are:

1) Cloudy samples account for 40%–50% of total samples, with low clouds comprising 35%–50% of cloudy samples in all seasons. Summer has the highest cloud top, base, and thickness, while winter has the lowest. Clouds form frequently at night (19:00–10:00 BJT) and dissipate gradually during daytime in spring, summer, and winter. In autumn, clouds form frequently in the morning (11:00–14:00 BJT) and dissipate during other periods. Spring, summer, and autumn have two most probable cloud top heights, while winter has only one. With increasing rain intensity, clouds extend higher, with higher reflectivity factors and average liquid water content. Liquid water content is the key factor determining rain intensity. Snowfall clouds are mainly located below 2.50 km, with reflectivity factors mostly less than 24 dBZ and maximum values of 29–33 dBZ. Heavy snow processes have significantly greater reflectivity factors below 29 dBZ and cloud snow particle water content than light and moderate snow processes.

2) Stratiform cloud rainfall dominates in all seasons. Microphysical parameter averages are generally smaller than those in eastern China, dominated by small particles. Summer has the largest microphysical parameter averages, followed by autumn. Mass-weighted mean diameter, median volume diameter, and reflectivity factor all increase with precipitation rate levels, reaching maximum (minimum) values in summer (autumn). Small raindrops contribute little to rain intensity but greatly to total raindrop number concentration, while moderate and large raindrops contribute greatly to rain intensity. Stratiform rainfall has more small raindrops and fewer moderate and large raindrops compared with convective rainfall.

3) The western Tianshan Mountains have higher concentrations of moderate and large raindrops and lower concentrations of small raindrops than the central Tianshan Mountains. For all rainfall rate levels and types, the western Tianshan Mountains have larger mass-weighted mean diameters and smaller normalized intercept parameters. The Z-R relationship for stratiform clouds shows good correlation, while convective clouds show poor correlation, requiring dual-polarization parameters including moderate and large raindrop shapes to improve quantitative precipitation estimation for heavy rain. Compared with Beijing, Hubei, and Nanjing, convective precipitation particles in the Tianshan region have larger average diameters but much lower concentrations. Compared with snowstorm

> processes in the eastern monsoon region, snowstorms in the western Tianshan region have smaller snowflake diameters and snow intensity, with graupel contributing significantly to snow intensity.

The West Tianshan Cloud-Precipitation Physics Field Observation Scientific Experimental Base has been in operation for a short time, with only 3–4 years of data accumulation. The research sample size is limited, and studies have mainly used cloud radar and ground disdrometer observations for preliminary research on cloud and precipitation macro/microphysical characteristics. Comprehensive studies integrating all observation data have not been conducted, particularly lacking research on three-dimensional microphysical structures of strong convective precipitation using C-band dual-polarization weather radar. Microphysical parameter retrieval methods need further improvement.

Future research should strengthen: (1) Algorithm development using double-moment normalization to reconstruct raindrop size distribution, overcoming gamma distribution model limitations to improve retrieval accuracy from C-band dual-polarization radar data; utilizing vertical-pointing dual-frequency cloud radar two-frequency channel return signals to study backward adaptive iteration methods for more accurate retrieval of cloud-precipitation microphysical parameters. (2) Comprehensive application of all observation data to study cloud-precipitation physical processes.

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