Postprint of Airborne Observational Experiment on Microphysical Characteristics of Mixed Convective-Stratiform Clouds in the Sanjiangyuan Region

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Date: 2022-10-23T00:00:00+00:00

Abstract

Using aircraft cloud physics sounding experiment data conducted in the Sanjiangyuan region, an analysis was performed on the macro- and microphysical characteristics of a stratiform-cumulus mixed cloud and the characteristics of convective cells in the Zeku area of Sanjiangyuan on September 13, 2020. The results show that: (1) Temperatures within the stratiform-cumulus mixed cloud ranged between -23~-10 ℃, relative humidity was 90%~100%, and liquid supercooled water content was between 0.04~0.70 g · m^{-3}; (2) The average particle number concentration within convective cells was 101 L^{-1} higher than that in the surrounding stratiform cloud, the average effective particle radius was larger, the average liquid supercooled water content was 0.28 g · m^{-3}, approximately 0.03 g · m^{-3} higher than that in the stratiform cloud, and there was a good correspondence between particle number concentration and liquid supercooled water content; (3) The cloud particle spectrum exhibited a multi-modal distribution, with peaks appearing at 50 m, 400 m, and 1000 m, consistent with the distribution characteristics of typical high clouds; (4) Particles in the stratiform-cumulus mixed cloud were predominantly aggregated ice crystals, with small amounts of hexagonal plate-like and columnar ice crystals present at some altitudes; the dominant growth mechanisms in the cloud were riming and aggregation, while depositional growth existed within convective cells, and the precipitation mechanism in the cloud conformed to the "seeder-feeder" mechanism.

Full Text

Experimental Study on Microphysical Characteristics of Stratiform Clouds with Embedded Convection in the Sanjiangyuan Region Using Aircraft Observations

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Abstract: Using aircraft observation data from cloud physical detection experiments conducted in the Sanjiangyuan region, this study analyzes the macro- and microphysical characteristics of stratiform clouds with embedded convection and their convective generating cells. The results indicate that: (1) Temperature within the stratiform cloud with embedded convection ranged between -23°C and -10°C, relative humidity was 90%-100%, and liquid supercooled water content varied from 0.04 $g \cdot m^{-3}$ to 0.70 $g \cdot m^{-3}$; (2) The average particle number concentration inside convective generating cells was higher than in the surrounding stratiform cloud by approximately 10^1 L^{-1}, the average effective particle radius was larger, and the average liquid supercooled water content was 0.28 $g \cdot m^{-3}$, exceeding that of the stratiform cloud by about 0.03 $g \cdot m^{-3}$. A good correspondence existed between particle number concentration and liquid supercooled water content. Cloud particle spectra exhibited multi-peak distributions with peaks at 50 m, 400 m, and 1000 m, consistent with typical high cloud distribution characteristics; (3) Particles in the stratiform cloud with embedded convection were predominantly aggregated ice crystals, with small quantities of hexagonal plate and columnar ice crystals present at certain altitudes. The dominant growth mechanisms were riming and aggregation, with deposition growth occurring within convective cells. The precipitation mechanism in the cloud followed the "seeder-feeder" process.

Keywords: aircraft detection; cloud microphysical characteristics; stratiform cloud with embedded convection; convective generating cells; Sanjiangyuan region

Introduction

Stratiform clouds with embedded convection consist of stratiform cloud layers containing embedded convective cells. These systems have long lifecycles and represent the primary precipitation-producing cloud systems in northern China, making them the main target for aircraft-based artificial precipitation enhancement operations [1-3]. Since the 1990s, numerous aircraft observation studies have been conducted on these cloud systems both domestically and internationally [4-6]. Evans et al. [7] found that convective cells embedded within stratiform clouds exhibit higher liquid water content and stronger updrafts, producing more ice crystals. Fan et al. [8] investigated the vertical structure of stratiform clouds with embedded convection in the Beijing area, reporting that ice crystal shapes primarily include plates, columns, dendrites, and irregular forms, with ice crystal aggregation representing the main particle growth process. Liu et al. [9] discovered significant differences in ice particle shapes and formation processes between stratiform and convective regions within stratiform clouds with embedded convection over North China. The stratiform region contains complex particle shapes including needles, columns, and dendrites, while the convective region is dominated by dendritic particles with evident aggregation and riming processes.

The Sanjiangyuan region, located in the hinterland of the Tibetan Plateau, serves as the source of the Yangtze, Yellow, and Lancang Rivers. It constitutes an important freshwater resource supply area for China and represents a sensitive zone and critical initiation region for climate change across Asia, the Northern Hemisphere, and globally [10-12]. Due to geographical location and climatic characteristics, cloud systems over the plateau exhibit substantial structural and physical differences from those over plain regions. Previous research on plateau cloud physics includes Xu et al. [13], who identified numerous small- and meso-scale convective bubbles over the Tibetan Plateau corresponding to narrow, elongated thermal bubbles. Fu et al. [14] used satellite data to study precipitation cloud clusters over the plateau, finding they often display scattered, block-like horizontal distributions with tower-shaped precipitation patterns. Chang et al. [15] examined summer convective clouds over the Tibetan Plateau, noting that due to plateau heating effects, convective clouds reach maximum intensity between 17:00-18:00. Wang et al. [16] studied the microphysical responses to seeding experiments in autumn stratocumulus clouds over Sanjiangyuan, finding cloud particle median diameters concentrated between 3.5-18.5 m and ice crystals between 21.5-45.5 m. However, limited by observation capabilities, few cloud physics studies have been conducted in the Sanjiangyuan region. Therefore, investigating cloud physics and precipitation characteristics in this region will help understand precipitation formation and evolution patterns, improve the utilization of atmospheric water resources, enhance weather forecasting and weather modification capabilities, and provide essential data support for protecting the alpine wetland ecosystem and water conservation. This study utilizes aircraft observation data from the "Second Comprehensive Scientific Expedition to the Tibetan Plateau" project to analyze the macro- and microphysical characteristics of a stratiform cloud with embedded convection in the Zeku area of Sanjiangyuan, revealing the microphysical structure and precipitation formation mechanisms of these cloud systems to support scientific and effective artificial precipitation enhancement operations.

Data and Methods

1.1 Aircraft Observation Data

The detection platform was a King Air aircraft equipped with a cloud physics detection system comprising three main instruments: (1) the AIMMS (Aircraft Integrated Meteorological Measurement System) for measuring temperature, humidity, wind speed, wind direction, and flight trajectory; (2) the CIP (Cloud Imaging Probe) with a measurement range of 25-1550 m and 62 size bins, resolution of 25 m, for detecting ice crystals and large cloud droplets and outputting two-dimensional images; and (3) the Hotwire Liquid Water Content sensor with a measurement range of 0.01-3.00 $g \cdot m^{-3}$ for detecting liquid water content in clouds. All instruments were regularly calibrated by domestic professional institutions and maintained before each flight, ensuring stable operation and reliable data quality.

Raw CIP data consisted of image data, which were processed using the SODA (System for OAP Data Analysis) software developed by the National Center for Atmospheric Research. Particle image correction and shattering correction were applied based on particle arrival time to eliminate shattered particles, following the methods described in Field et al. [17]. To minimize instrument errors, the first size bin of the CIP data was excluded from the analysis. The Hotwire LWC sensor was calibrated in clear-sky conditions before each flight to ensure accurate measurement of liquid water content within clouds.

1.2.1 Study Area Overview

The study area, Zeku County (101°28 14 E, 35°02 19 N) in Huangnan Tibetan Autonomous Prefecture, Qinghai Province, is located in the eastern section of the Sanjiangyuan region at the first bend of the upper Yellow River. With an elevation of approximately 3662 m, the area experiences a plateau continental monsoon climate classified as a plateau sub-frigid humid climate zone, with an annual mean temperature of -0.7°C and annual precipitation of 548 mm that is unevenly distributed. This region serves as an important water source conservation and runoff generation area in the upper Yellow River basin. Meteorological observation data indicate that precipitation cloud systems in the Sanjiangyuan region are primarily opaque altostratus. Influenced by the complex plateau topography, orographic cumulus clouds often form during the early stages of weather systems, creating stratiform clouds with embedded convection and triggering severe convective precipitation through meso- and small-scale weather systems. Additionally, originally stable stratocumulus clouds frequently evolve into cumulus clouds accompanied by opaque altostratus and orographic cumulus, producing substantial precipitation [18].

1.2.2 Weather Background

As shown in Figure 2 [Figure 2: see original paper], a plateau trough separated from the Asian trough moved eastward, combining with a northward-moving trough to form extensive precipitation over the eastern Tibetan Plateau. On September 13, 2020, the plateau trough gradually moved out of the region. During the detection period at 500 hPa, the wind direction was westerly. The cloud system was positioned mainly east of the observation area, which was covered by non-uniform mixed cloud systems during the aircraft observations.

1.2.3 Flight Overview

The aircraft flight period was 08:53-11:29 BT (Beijing Time, hereinafter), with a total flight duration of 2 hours 13 minutes. The cloud detection period was 09:40-10:30, targeting a stratiform cloud with embedded convection at altitudes of 7850-6600 m. Level flight detection was conducted at five altitudes (7850 m, 7500 m, 7200 m, 6900 m, and 6600 m) for a total of 50 minutes, yielding 50 sample datasets. The flight path and detection trajectory are shown in Figure 3 [Figure 3: see original paper].

Results

2.1 Temporal Evolution of Cloud Macro- and Microphysical Parameters

Figure 4 [Figure 4: see original paper] presents the temporal variations of temperature (T), altitude, relative humidity (RH), and liquid water content (LWC) during the detection phase. Temperature within the cloud ranged from -23°C to -10°C, while relative humidity varied between 90% and 100%. Liquid supercooled water content ranged from 0.04 $g \cdot m^{-3}$ to 0.70 $g \cdot m^{-3}$, gradually increasing with decreasing altitude and remaining relatively stable between 7850 m and 6900 m. Larger fluctuations occurred during the aircraft descent phase, likely due to measurement errors caused by aircraft speed and tilt angle exceeding the AIMMS measurement range.

2.2 Vertical Distribution Characteristics of Clouds

Figure 5 [Figure 5: see original paper] shows the vertical profiles of average cloud particle concentration, LWC, temperature, and cloud particle concentration spectra during the detection phase. Cloud particle concentration was relatively uniform and increased with decreasing altitude between 7200 m and 6900 m, reaching approximately 10^1 L^{-1}. An obvious high-value region existed because the aircraft detection occurred within convective bubbles during this period, while other descent stages were in stratiform cloud areas. Cloud particle spectra exhibited multi-peak distributions, with peaks at 50 m, 400 m, and 1000 m, consistent with typical high cloud characteristics. At altitudes below 6900 m, cloud particle diameter concentrated around 500 m, while between 7200 m and 6900 m, larger particles were observed with diameters concentrated around 500-900 m.

2.3 Characteristics of Convective Generating Cells

Figure 6 [Figure 6: see original paper] presents the instantaneous spectral distributions of LWC and RH, and particle number concentration (ND) and effective diameter (ED) at different altitudes during level flight detection. Table 1 summarizes the average microphysical parameters of convective cells and stratiform clouds at different flight levels.

At 7850 m, the detection position was at cloud top, which was non-uniform with protruding portions higher than surrounding cloud areas. The convective generating cells within the stratiform cloud were located at this altitude. Except for relative humidity, all other physical parameters showed significant differences between convective cells and surrounding stratiform clouds. The average LWC in convective cells was 0.07 $g \cdot m^{-3}$, while in surrounding clouds it was 0.01 $g \cdot m^{-3}$. Cloud particle number concentration was approximately 10^1 L^{-1} higher in convective cells than in surrounding clouds. The average effective particle radius in convective cells was 17.14 m larger than in surrounding stratiform clouds.

At 7500 m, the average LWC in convective cells was 0.24 $g \cdot m^{-3}$, significantly higher than the 0.03 $g \cdot m^{-3}$ in surrounding stratiform clouds. Cloud particle number concentration in convective cells was about 10^1 L^{-1} higher than in surrounding clouds. The average effective particle radius was 138.41 m in convective cells and 169.37 m in surrounding clouds, with convective cells showing values approximately 10^1 L^{-1} higher than stratiform clouds.

At 7200 m, the average LWC in convective cells was 0.17 $g \cdot m^{-3}$, while surrounding stratiform clouds had 0.07 $g \cdot m^{-3}$. Cloud particle number concentration in convective cells was about 10^1 L^{-1} higher than in surrounding clouds. The average effective particle radius was 139.20 m in convective cells and 232.24 m in surrounding clouds, with convective cells showing values approximately 10^1 L^{-1} higher than stratiform clouds. During this detection period, fluctuations occurred but without the significant changes in particle number concentration observed at other altitudes, suggesting this region represented stratiform cloud conditions.

At 6900 m, no convective cells were detected during this phase. As mentioned previously, the aircraft passed through the corresponding convective cell position between 7200 m and 6900 m, but at 6900 m the aircraft did not reach that location. The average LWC was 0.03 $g \cdot m^{-3}$, and average cloud particle number concentration was approximately 10^1 L^{-1}.

Overall, at altitudes between 7850 m and 7500 m, both cloud particle number concentration and effective particle radius showed significant increasing trends. Between 7500 m and 6600 m, LWC continued to increase while cloud particle number concentration and effective particle radius decreased continuously. The average LWC in convective cells ranged from 0.07 $g \cdot m^{-3}$ to 0.53 $g \cdot m^{-3}$, higher than the 0.01-0.12 $g \cdot m^{-3}$ in surrounding stratiform clouds. At the lowest detection level of 6600 m, convective cell LWC was 0.28 $g \cdot m^{-3}$, about 0.15 $g \cdot m^{-3}$ higher than surrounding clouds. Cloud particle number concentration in convective cells was nearly 10^1 L^{-1} higher than in stratiform clouds at 7500 m, but the difference was not as pronounced at 6600 m, likely due to the limited detection time as convective cells developed only to about 7500 m depth.

The precipitation mechanism in stratiform clouds with embedded convection follows the "seeder-feeder" process, where convective cells act as ice particle "seeders" and the surrounding stratiform clouds serve as moisture "feeders" at the base of the convective cells. High supercooled liquid water content is crucial for enhancing deposition and aggregation processes in convective cells. Plummer et al. [19] observed that convective cells in continental winter cyclones had temperatures between -31.4°C and -11.1°C, with LWC values of 0.09-0.12 $g \cdot m^{-3}$ and high-value regions reaching 0.14-0.28 $g \cdot m^{-3}$. Zhang et al. [20] found that convective cells within stratiform clouds under a Huanghuai cyclone system had average LWC of 0.06-0.50 $g \cdot m^{-3}$, with maximum values appearing at temperatures around -16°C.

2.4 Cloud Particle Spectrum and Growth Mechanisms

Figure 7 [Figure 7: see original paper] shows the average particle spectrum during the aircraft level flight detection period. The particle spectrum distribution exhibited a triple-peak pattern with peaks at 50 m, 400 m, and 1000 m. At 7850 m, particle concentrations were lowest in both convective cells and stratiform clouds, with maximum and minimum values opposite to those inside convective cells. Except at the lowest altitude of 6600 m, particle concentrations in convective cells were higher than in stratiform clouds at all altitudes, though the spectral widths were consistent between convective cells and stratiform clouds at different levels.

Figure 8 [Figure 8: see original paper] presents two-dimensional particle images from CIP detection in convective cells and stratiform clouds during level flight. Regular-shaped ice crystals were rare in the stratiform cloud with embedded convection. Small quantities of hexagonal plate ice crystals and columnar particles existed at certain altitudes, but most particles were aggregated ice-phase particles. The dominant growth mechanisms were riming and aggregation, with deposition growth occurring in convective cells.

At 7850 m, particles in both convective cells and stratiform clouds showed plate-like and aggregated forms, though particles in stratiform clouds were significantly smaller. Convective cells contained a higher proportion of aggregated particles, indicating favorable moisture diffusion and dominant deposition and riming growth mechanisms. The stronger updrafts in convective cells produced more aggregated ice crystals.

At 7500 m, convective cells contained plate-like, columnar, and aggregated particles, with growth dominated by vapor diffusion (deposition). At 7200 m and 6600 m, stratiform clouds contained small quantities of plate-like and needlelike ice crystals, with most particles being aggregated and growth dominated by deposition and riming.

Overall, the high supercooled water content in convective cells is key to enhancing deposition and aggregation processes. Previous observations have shown more pronounced dendritic structures and relatively larger particles in convective cells. In this study, the highest cloud particle number concentration and largest effective particle radius occurred at 7500 m. Limited by aircraft maximum safe altitude and actual flight conditions, the detection covered cloud top to upper cloud levels. At 7850 m, particles were already relatively large, indicating formation of condensation nuclei and cloud particles at upper levels—a phenomenon also observed in stratiform cloud studies over Shanxi Province [21]. Cloud particle concentration decreased with altitude, but two-dimensional images revealed that particles gradually grew larger as altitude decreased, eventually exceeding the detection range. However, cloud particle number concentration did not increase correspondingly during descent, indicating the presence of a "seeder-feeder" precipitation mechanism.

Conclusions

This study analyzed aircraft detection data from a stratiform cloud with embedded convection in the Sanjiangyuan region on September 13, 2020, using an airborne cloud physics detection system. The main conclusions are:

1. Temperature within the stratiform cloud with embedded convection ranged from -23°C to -10°C, with relative humidity of 90%-100% and liquid supercooled water content of 0.04-0.70 $g \cdot m^{-3}$. The average particle number concentration in convective cells was about 10^1 L^{-1} higher than in surrounding stratiform clouds, with average effective particle radius of 270.47 m and average liquid supercooled water content of 0.28 $g \cdot m^{-3}$, all exceeding stratiform cloud values. The average LWC in surrounding stratiform clouds was 0.07-0.53 $g \cdot m^{-3}$, with an average value of 0.25 $g \cdot m^{-3}$. Therefore, conducting aircraft artificial precipitation operations in stratiform clouds with embedded convection in the Sanjiangyuan region at temperatures between -23°C and -9°C will be more conducive to improving seeding effectiveness.

2. Cloud particle spectra in stratiform clouds with embedded convection showed multi-peak distributions with peaks at 50 m, 400 m, and 1000 m. Except at the lowest altitude of 6600 m, particle concentrations in convective cells were higher than in surrounding stratiform clouds at all levels, though spectral widths were consistent between convective cells and stratiform clouds at different altitudes.

3. The dominant growth mechanisms were riming and aggregation. Regular-shaped ice crystals were rare, with small quantities of hexagonal plate ice crystals and columnar particles present at certain altitudes, while most particles were aggregated ice-phase particles. Supercooled water content

and effective particle radius gradually increased with decreasing altitude. Particle images differed significantly between convective cells and stratiform clouds, with hexagonal plate ice crystals visible in stratiform clouds. The precipitation mechanism in stratiform clouds with embedded convection follows the "seeder-feeder" process.

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