Article

Comprehensive Efficiency Evaluation of Aircraft Artificial Cloud Seeding in Hunan Province, China, Based on Numerical Simulation Catalytic Method

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Abstract: Aircraft cloud seeding refers to the use of equipment on aircraft to release chemicals into clouds, changing their physical and chemical properties to increase rainfall or snowfall. The purpose of precipitation enhancement is to alleviate drought and water scarcity issues. Due to the complexity of the technology, the precise control of factors such as cloud characteristics and chemical release amounts is necessary. Therefore, a scientific evaluation of the potential of aircraft cloud seeding can help to improve the effectiveness of the process, and is currently a technical challenge in weather modification. This study used the mesoscale numerical model WRF coupled with a catalytic process to simulate and evaluate the seven aircraft cloud seeding operations conducted in Hunan Province in 2021. The results show that WRF can effectively evaluate the effectiveness of cloud seeding. When the water vapor conditions are suitable, the airborne dispersion of silver iodide (AgI) can significantly increase the content of large particles of high-altitude ice crystals, snow, and graupel, resulting in an increase in low-level rainwater content and, correspondingly, an increase in ground precipitation. When the water vapor conditions are insufficient, the dispersion of AgI does not trigger effective precipitation, consistent with the results of station observations and actual flight evaluations. This study provides an effective method for scientifically evaluating the potential and effectiveness of aircraft cloud seeding operations.

Keywords: weather modification; aircraft cloud seeding; simulation; catalytic process

1. Introduction

Weather modification refers to the use of artificial means to control and intervene in weather and climate systems. The modern era of weather modification activities commenced with pioneering experiments in the late 1940s. Schaefer's groundbreaking demonstrations of dry ice seeding [1] and Vonnegut's [2] discovery of silver iodide's ice nucleating ability set the stage for glaciogenic seeding experiments using dry ice and silver iodide [3]. These early experiments marked the beginning of a new era in weather modification [4]. In 1958, Chinese meteorologists began to study the physical characteristics of clouds in depth and explored cloud seeding technology [5] based on the basic laws of cloud physics. In the late 1970s and early 1980s, China began to carry out the practical operations of artificial rain and achieved success.

The theory of weather modification has undergone continuous improvements as our understanding of cloud and precipitation physics processes has advanced. Through both theoretical analysis and practical experimentation, artificial rainfall has been proven to be viable methods of weather modification under appropriate conditions. Artificial rainfall technology is primarily employed in foggy and drought-affected areas to supplement water resources. On the other hand, artificial hail suppression technology is an extension of artificial rainfall and hail prevention techniques.

By harnessing the static or dynamic forces within clouds, the natural precipitation state or process can be altered [6]. This allows for the reduction in precipitation efficiency, as well as the ability to advance or delay precipitation, thereby redistributing the spatial distribution of rainfall and ensuring a more equitable allocation of airborne water resources. This technology finds applications in various areas such as airport aviation, military exercises, large-scale outdoor performances, and other domains where ensuring airspace safety is crucial [7]. As our knowledge of cloud physics and weather systems continues to advance, the potential for weather modification technologies to address water resource management, disaster prevention, and other societal needs becomes increasingly significant. Ongoing research and advancements in this field will contribute to our ability to harness and optimize natural precipitation processes for the benefit of various sectors and regions.

In general, weather modification is a continuously evolving and innovative technology that has significant implications for human responses to climate change and disasters. Although weather modification techniques have achieved some success, they still face great challenges. One of the most significant issues is its effectiveness. Due to the complexity of weather and climate systems, the effects of weather modification techniques are often unstable and difficult to predict. Evaluation and verification of the effectiveness of artificial rainfall are crucial and difficult scientific issues. Therefore, the objective, scientific, and quantitative evaluation of artificial rainfall effectiveness can not only promote the development of weather modification but also provide a scientific basis for artificial rainfall operations. Comprehensive evaluation methods for artificial rainfall operations include statistical tests, physical tests, and numerical simulation tests. With the development of computer technology and the continuous improvement in cloud physics research, small- and medium-scale numerical models can now simulate the occurrence and development of clouds, and numerical simulation tests can gradually meet the basic requirements of objectivity, repeatability, and predictability for evaluating the effectiveness of weather modification techniques.

In China, cold cloud seeding techniques are commonly used for weather modification. These techniques involve introducing refrigerants and artificial ice nuclei through the Bergeron process during cold cloud precipitation. In contrast, warm cloud seeding utilizes hygroscopic flares based on warm cloud augmentation techniques [8]. Large cloud condensation nuclei (CCN) are dispersed below the cloud base, competing with natural CCN. The larger CCN have higher water vapor absorption capacity, effectively reducing cloud base supersaturation and decreasing cloud droplet number concentration. This process broadens the cloud droplet spectrum, leading to faster coalescence and raindrop formation [9,10]. Cold cloud seeding is commonly adopted in local meteorological departments in China due to their stable and well-developed technical equipment. However, it is worth noting that recent increases in weather modification activities in southern China, coupled with higher cloud base temperatures in northern China during summer, pose challenges for utilizing cold cloud catalyzation techniques based on the Bergeron process.

Cloud seeding effects are inferred through the numerical simulation of cloud catalysis. For example, Hsie added a conservation scheme for silver iodide (AgI) particles to the two-dimensional cumulus model to simulate the effect of cloud seeding [11]. Kopp et al. studied ice crystal concentrations to simulate the different characteristics of ice crystal cloud seeding and dry ice cloud seeding, and compared the simulation results with the actual cloud seeding effects [12]. Koenig and Murray studied the impact of increasing the ice crystal concentration on precipitation using a two-dimensional time-varying model [13]. Levy and Cotton studied the dynamic effects of increasing the ice crystal concentration using a three-dimensional time-varying cloud model [14], which resulted in a 10–20% increase in the maximum upward velocity after cloud seeding. Farley and Orville divided hailstones into 20 categories and conducted catalytic experiments [15]. Vali et al. studied the effect of cloud seeding on precipitation using a one-dimensional steady-state model [16]. Farley et al. used a three-dimensional cloud model to study the motion of AgI and inert gases in clouds and the impact of AgI on clouds and precipitation [17]. However, the boundary conditions

of cloud models are relatively simplified, with the boundary conditions of underlying surfaces often assumed to be uniformly distributed. In reality, the non-uniformity of the underlying surface directly affects the generation and development of convection. Xue et al. coupled AgI cloud seeding parameterization within the WRF model's Thompson microphysics scheme to investigate the effects of glaciogenic cloud seeding [18]. They validated the rationality of the parameterization scheme through idealized 2D experiments. The coupled model was utilized in large-eddy simulation experiments with a horizontal resolution of 100 m to investigate the dispersion of AgI particles and compare them with observations [19].

The principle of the cumulus cloud model is to superimpose a certain range of moist or warm disturbances on a horizontally uniform initial field to excite the convection process of clouds. However, the specific range and intensity of such disturbances are difficult to accurately predict, which limits the cumulus cloud model to be used for case studies, and it lacks the ability to provide operational forecasts. Due to the small scale of cumulus cloud models, numerical experiments and research on regulating convective cloud precipitation mainly focus on changes in the precipitation of individual clouds, while ignoring the changes of convective cloud clusters. Therefore, using mesoscale models with more realistic initial and boundary conditions for catalytic numerical simulation analysis is an effective method for forecasting the effectiveness of cumulus cloud seeding.

In this study, we employed the WRF (Weather Research and Forecasting) model coupled with the catalytic process to numerically simulate and assess the effects of aircraft cloud seeding operations. By utilizing numerical simulations, we aim to provide a feasible method for scientifically evaluating and forecasting the potential of aircraft cloud seeding operations. The article consists of the following sections. First is the introduction of the methodology, which includes the coupled AgI catalytic process in the model, the experimental design and parameter settings, and the specific details of the aircraft rain enhancement operations. The second section is the analysis of simulation results, including the climatic background and the evaluation of catalytic simulation effects. Finally, a summary is provided for this study.

2. Methodology

Catalytic Process in the Model

In clouds, the growth of AgI particles involves two distinct nucleation mechanisms, as described by Huang and Xu [20]. The first mechanism is contact freezing nucleation, which occurs as a result of the Brownian motion and inertial collisions between artificial ice nuclei and cloud droplets or raindrops. This process leads to the formation of ice crystals on the surface of the AgI particles. The second mechanism is condensation nucleation, where water vapor present in the cloud condenses onto the artificial ice nuclei. This causes the AgI particles to grow in size as water molecules adhere to their surface. To account for the AgI catalytic process in cloud simulations, it has been integrated into the Weather Research and Forecasting (WRF) model. The catalytic process of AgI can be expressed by the following equation:

$$\frac{dR_s}{dt} = -SUB_{R_s} + \text{Source} + \text{Sink}$$

In this equation, R_s is the mass-mixing ratio of AgI particles, $\frac{dR_s}{dt}$ represents the rate of change in R_s over time. SUB_{R_s} represents the sub-grid scale mixing term for R_s. Source represents the source term for AgI, and Sink represents the sink term for AgI. The equation for Sink term is composed as follows:

$$\text{Sink} = S_{bc} + S_{ic} + S_{br} + S_{ir} + S_{dv}$$

S_{bc} represents the collision–freezing nucleation process between cloud droplets and artificial ice nuclei due to the Brownian motion. In this process, cloud droplets collide with the AgI particles, leading to the freezing of the droplets and the subsequent formation of

ice crystals. S_{ic} represents the aforementioned collision–freezing nucleation process due to inertial impaction. This process occurs when cloud droplets are influenced by the inertial forces caused by air turbulence or cloud dynamics. The impact of these forces causes the droplets to collide with the AgI particles, resulting in their freezing and the formation of ice crystals. S_{br} and S_{ir} represent the collision–freezing nucleation process between raindrops and artificial ice nuclei due to the Brownian motion and inertial impaction, respectively. These processes occur when raindrops come into contact with the AgI particles. The collisions cause the freezing of the raindrops and the subsequent formation of ice crystals. S_{dv} represents the deposition nucleation process of water vapor onto artificial ice nuclei. In this process, water vapor in the cloud condenses onto the surface of the AgI particles, leading to their growth through the deposition of water molecules.

3. Design of Modelling Experiments

The Weather Research and Forecasting Model (WRF) is a mesoscale non-hydrostatic numerical weather prediction model developed by the National Center for Atmospheric Research [21]. WRF uses the Arakawa C-grid in the horizontal direction, terrain-following coordinate in the vertical direction, and has multiple nesting and many parameterization scheme designs, which can meet both weather forecast and atmospheric science research needs. In this study, WRF version 4.0 [22] was used.

The simulation area and topography are shown in Figure 1. WRF was run using one nested domain with a horizontal grid size of 250 × 240 and a spatial resolution of 3 km, and 42 vertical layers from the ground to 50 hPa. Meteorological initial and boundary conditions were obtained from the ERA5 reanalysis data provided by the European Centre for Medium-Range Weather Forecasts with a horizontal resolution of 0.25° × 0.25°, 38 vertical levels, and a time integration step of 10 s. We tested various combinations of physical parameterization schemes and selected a set of parameterization schemes that were most suitable for the study area, as shown in Table 1. To minimize errors caused during the integration and improve the simulation accuracy, we used the Grid Nudging method [23] to make the model approach the ERA5 wind, temperature, and water-vapor-mixing ratio data of the entire atmosphere every hour [24,25]. The WRF model outputs were generated hourly. The initial one hour of the simulation period was considered the spin-up time for the WRF model to reach statistical equilibrium, and the results during this one hour were not used for analysis. A total of seven experiments were conducted, each of which were divided into two parts: with and without the catalytic process. The difference between the two can be considered as a simulation of the aircraft cloud seeding effects.

Due to the high resolution of the simulated experiments, reaching the scale of convective resolving, the parameterization scheme of cumulus convection is no longer used in the model [26]. As a result, the simulated precipitation is sensitive to cloud microphysical processes [27] and can produce more than 60% differences in mean precipitation [28]. Through comprehensive comparisons, this study adopts the Thompson microphysics scheme [29,30]. Using the Thompson scheme in the convective-resolving model may increase the lifespan of mesoscale convective systems, thus affecting the simulation of precipitation [31].

Table 1. Configuration of model experiments.

Model Configuration and Parameterization	Option Details
Projection	Lambert
Horizontal grid	250 × 240
Horizontal resolution	3 km
Vertical layers	52
Microphysics parameterization	Thompson [29,30]
Shortwave radiation parameterization	Dudhia [32]
Longwave radiation parameterization	RRTM [33]
Boundary layer parameterization	YSU [34]
Land surface process module	Noah [35]
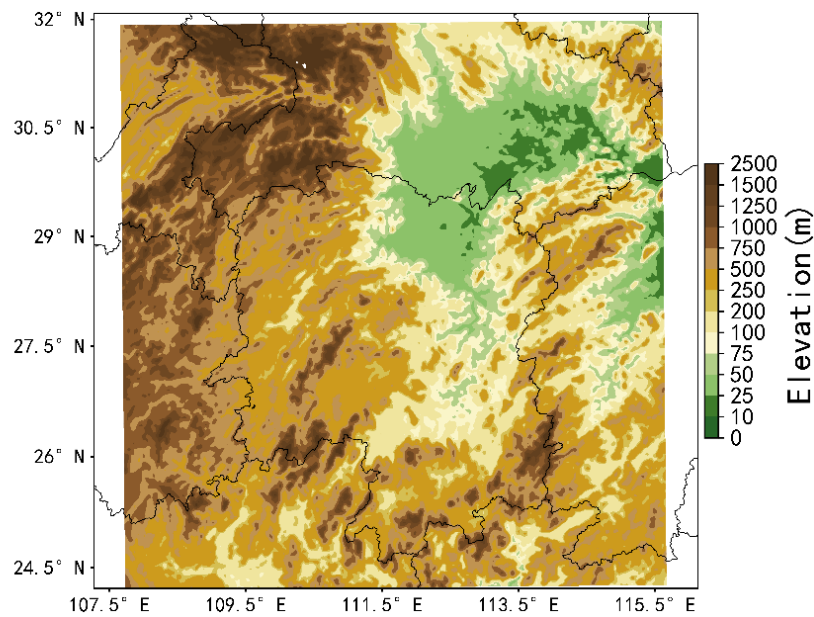
Figure 1. Model domain and elevation (unit: m).
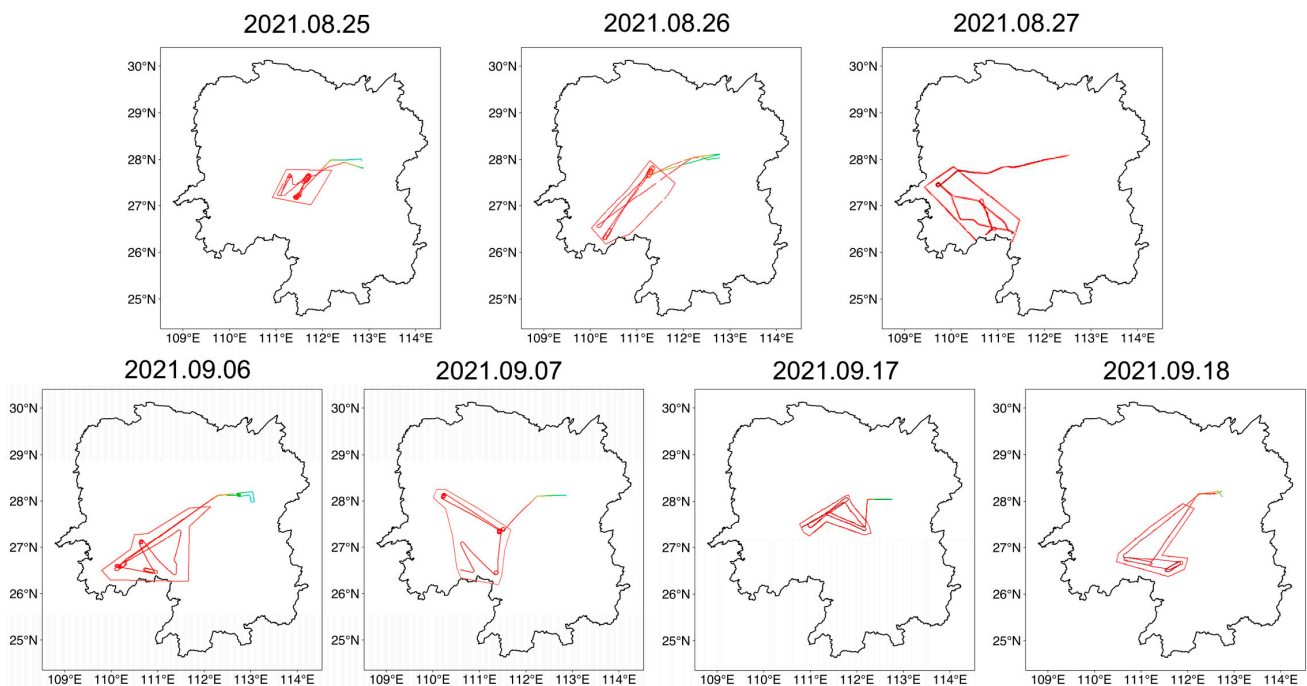
4. Cloud Seeding by Aircraft

During the period from 25 August to 18 September, 2021, the Hunan Province Weather Modification Office implemented a series of aircraft cloud seeding operations. The aircraft used for cloud seeding in Hunan Province is the Yun-7 aircraft, with each aircraft carrying 24 units of flares, totaling 3 kg of AgI. The aircraft cruised at an altitude of around 5000 m. The catalyst used for cold cloud operations is the ZY-1 flare, with nucleation rates ranging from -20 to -7 °C, reaching up to 10^{13} g^{-1}. In Hunan Province, during autumn, the temperature layer suitable for catalyzing stratiform cloud systems within cumulonimbus mixed cloud systems is -15 to -5 °C, and the spraying altitude is approximately 5000 to 6000 m. For catalyzing stratiform cloud systems within cumulonimbus mixed cloud systems, the suitable operational region is within the upper-level cloud layer, with a catalyst concentration of 30 L^{-1} of ice crystals. This requires the simultaneous burning of two flares. For catalyzing convective cells within cumulonimbus mixed cloud systems, the suitable operational region for cold cloud seeding is near the cloud top of supercooled clouds. In addition to static seeding, if the convective clouds develop to a considerable height, the cloud top temperature is below -10 °C, and the supercooled layer is relatively thick, dynamic seeding can be employed. The temperature layer for dynamic seeding should be -15 to -7 °C, and the catalyst dosage should be at least 100 L^{-1}, requiring the simultaneous burning of at least seven flares.

The flight routes and designated operation areas for these operations can be observed in Figure 2, providing a visual representation of the geographical scope covered. For a more detailed overview of the flight schedule, please refer to Table 2, which outlines the specific timings and sequences of the aircraft's activities throughout the duration of the operations.

Table 2. Flight schedule of cloud seeding.

Serial Number	Time (UTC)
1	25 August 2021, 01:00–05:20
2	26 August 2021, 05:20–09:20
3	27 August 2021, 03:20–07:00
4	6 September 2021, 00:30–05:30
5	7 September 2021, 05:00–09:50
6	16 September 2021, 06:30–10:20
7	17 September 2021, 01:30–04:30

Figure 2. Flight route map for aircraft cloud seeding operations for artificial rainfall in Hunan Province from August to September 2021.

5. Catalytic Simulation

Figure 3 presents the cumulative distribution of precipitation (measured in millimeters) as recorded by 3545 meteorological stations, including automatic weather stations, across Hunan Province during the period of seven aircraft cloud seeding operations conducted from August to September 2021. The red box within the figure delineates the specific area influenced by the aircraft cloud seeding activities. In the middle column, the precipitation distribution is depicted without simulating the catalytic process, while the right column represents the results obtained when the catalytic process is simulated using AgI. The analysis of the cumulative precipitation distribution provides valuable insights into the effectiveness of the aircraft cloud seeding operations. By comparing the middle and right columns, it becomes evident that the simulation of the catalytic process using AgI has a notable impact on the precipitation patterns. The areas within the red box, where the cloud seeding activities took place, show a distinct increase in precipitation when the catalytic process is considered in the simulation. This observation indicates that the introduction of AgI particles through cloud seeding plays a significant role in enhancing precipitation in the targeted areas.

The distribution of cumulative precipitation across the meteorological stations offers valuable information on the spatial extent and magnitude of the precipitation increase resulting from the aircraft cloud seeding operations. It allows for a comprehensive evaluation of the efficacy and spatial coverage of the cloud seeding activities, providing valuable data for assessing the success of the cloud seeding operations and further refining the cloud seeding strategies to optimize their impact on precipitation patterns in Hunan Province.

First and foremost, the WRF model demonstrates its capability to accurately simulate the position of the rain belt and corresponding precipitation levels in Hunan Province. For instance, on 25 August 2021, the precipitation belt exhibited a spatial distribution that decreased gradually from the southeast to the northwest, with the highest recorded precipitation exceeding 100 mm. Similarly, on 6 September, the rain belt displayed a decreasing distribution pattern from the south to the north. The WRF model successfully captured these prominent features, although there were some minor discrepancies in certain instances. For instance, the model underestimated the precipitation on September 17 and

overestimated it on 18 September. It is important to note that these simulation errors may stem from inherent deviations present in the ERA5 driving field, which were not entirely eliminated during the dynamic downscaling process. Despite these occasional discrepancies, the WRF model overall exhibits commendable simulation capabilities when it comes to predicting precipitation patterns in Hunan Province. The accurate simulation of the rain belt position and precipitation distribution by the WRF model provides valuable insights into the spatial and temporal patterns of rainfall in the region. This information is crucial for the evaluation of weather modification through the model approaches.

Secondly, when comparing the middle and right columns in Figure 3, it becomes evident that the simulation results incorporating the catalytic process exhibit higher levels of precipitation compared to those without it. This clear distinction suggests the effectiveness of the catalytic process implemented in the model. To illustrate, on 25 August, the observed precipitation belt, representing the region influenced by aircraft cloud seeding, extended eastward up to 111.6° E. Remarkably, the simulation that accounted for the catalytic process accurately captured this extension, aligning closely with the observed precipitation distribution. Conversely, the simulation without the catalytic process displayed considerably less precipitation in this specific location.

These findings emphasize the positive impact of the catalytic process on precipitation enhancement. The simulation results highlight the significant contribution of cloud seeding to the augmentation of rainfall in targeted areas. By simulating the catalytic process, the model effectively reproduces the observed changes in precipitation patterns, supporting the notion that artificial cloud seeding can influence and intensify rainfall in the designated regions.

We conducted an analysis of the cloud seeding within the designated area indicated by the red box, and the results are presented in Table 3. The findings reveal significant catalytic effects in the model simulations of the six aircraft cloud seeding operations, except for 7 September. The maximum precipitation enhancement rate was observed on 27 August, reaching an impressive 171.4%, with a total increase in precipitation of 41.582 million tons.

However, it is worth noting that on September 7, no effective precipitation was observed, which is consistent with the actual observation. The simulated precipitation was very low in both the catalyzed and non-catalyzed experiments, but not zero. The simulation results suggest that the lack of precipitation on this particular day can be attributed to weak water vapor conditions that were insufficient to promote the formation of precipitation. This observation underscores the importance of favorable atmospheric conditions, particularly adequate moisture content, for the success of cloud seeding operations.

This validation enhances our confidence in the model's ability to simulate and predict the outcomes of future cloud seeding operations. By incorporating the catalytic process into the simulation, researchers and meteorologists can better understand and evaluate the potential outcomes of cloud seeding activities, aiding in the optimization and improvement of cloud seeding strategies for water resource management and agricultural practices.

To gain deeper insights into the impact of the catalytic process, we conducted a detailed analysis using the aircraft cloud seeding operation on 25 August 2021 as an example. By comparing the microphysical properties of the catalyzed and uncatalyzed clouds, we can better understand the effects of the cloud seeding process. Figure 4 presents the meridional–vertical profiles of various microphysical properties during the period of 10:00–16:00 (UTC).

The results demonstrated that one hour after the aircraft cloud seeding operation, the simulated high-level clouds exhibited an increased content of ice and snow compared to the corresponding substances in the uncatalyzed clouds. Specifically, Figure 4a,c indicate a higher concentration of ice and snow in the catalyzed clouds, while Figure 4b,d represent the respective substances in the uncatalyzed clouds. This observation indicates that the introduction of AgI particles effectively enhanced the concentration of ice crystal nuclei in the high-level clouds, demonstrating an efficient catalytic process.
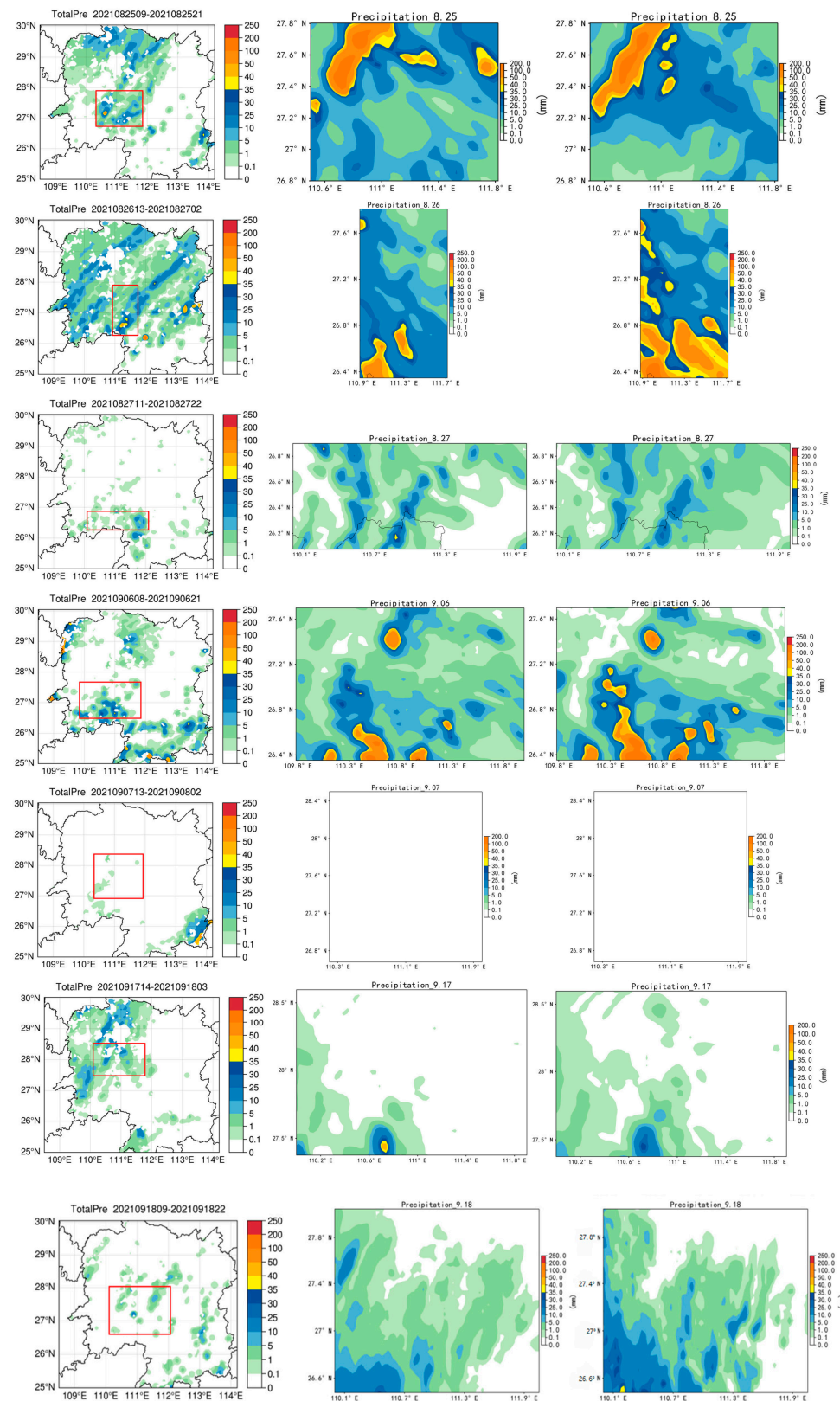
Figure 3. Distribution of cumulative precipitation during seven aircraft cloud seeding operations in Hunan Province from August to September 2021 (unit: mm) (left column), with the red box indicating the area affected by aircraft rainfall. The middle column shows the cumulative precipitation without considering catalytic effects, and the right column shows the cumulative precipitation involving catalytic effects (unit: mm).
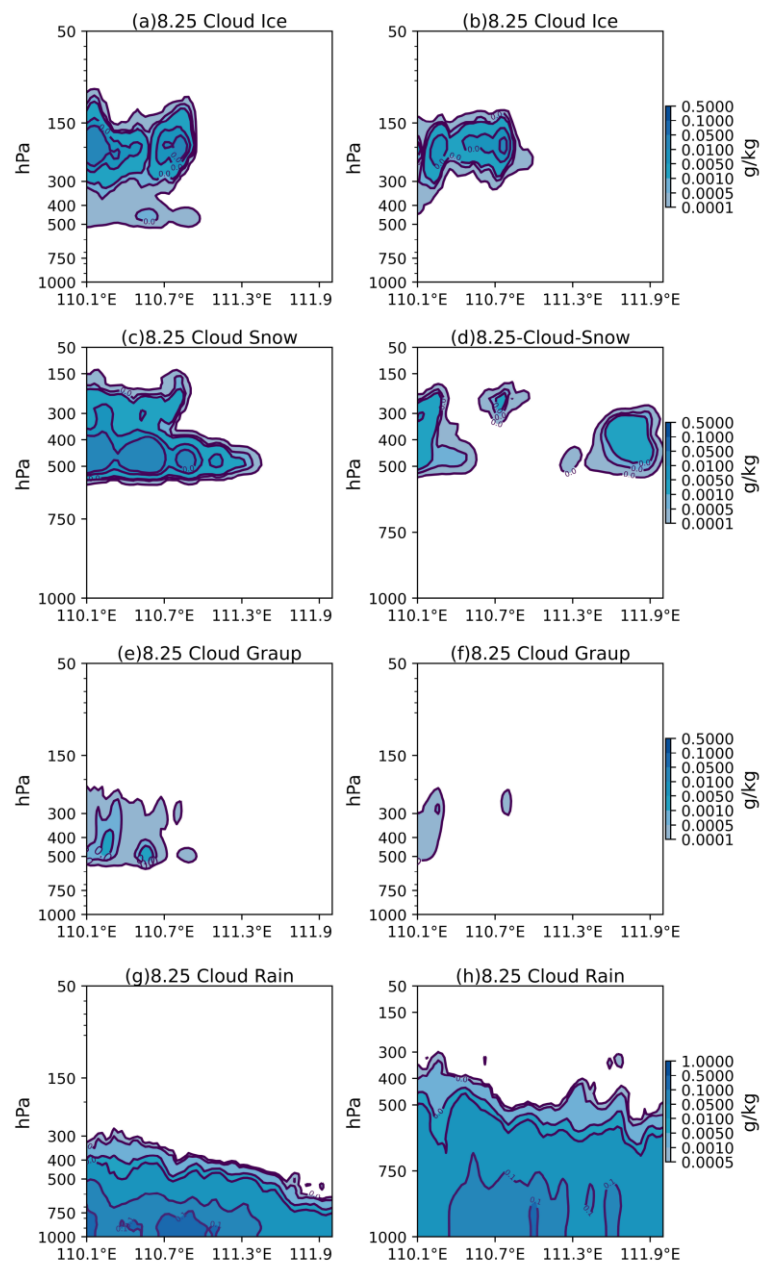
Figure 4. Vertical cross-sections of the ice-mixing ratio (**a**,**b**), snow-mixing ratio (**c**,**d**), graupel-mixing ratio (**e**,**f**), and cloud-water-mixing ratio (**g**,**h**) over the area influenced by aircraft cloud seeding with (**a**,**c**,**e**,**g**) and without (**b**,**d**,**f**,**h**) the catalytic effect at 10:00–16:00 (UTC) on 25 August 2021 (units: g/kg). The ordinate is the pressure level heights (hPa).

Table 3. Cloud seeding by aircraft in the influenced area (red box).

No.	Average Precipitation (Uncatalyzed) (Units: mm)	Average Precipitation (Catalyzed) (Units: mm)	Influenced Area (Units: km^2)	Total Precipitation Enhancement (Units: 10,000 tons)	Precipitation Enhancement Rate (Units: %)
1	16.6	20.4	10,752	4085.8	22.9%
2	28.4	31.6	12,064	3860.4	11.3%
3	1.4	3.8	17,326	4158.2	171.4%
4	5.7	7.2	27,027	4054.1	26.3%
5	0.0	0.0	30,800	0.0	0.0%
6	0.3	0.4	21,692	2169.2	33%
7	1.2	2.6	30,670	4293.8	116.7%

Furthermore, we observed a corresponding increase in the content of graupel in the catalyzed clouds (Figure 4e,f), which aligns with the elevated levels of ice and snow. As the large ice particles from the high-altitude regions descended into the lower layer and melted, they transformed into large cloud droplets. This process significantly augmented the content of rainwater in the lower layer (Figure 4g,h), ultimately leading to an increase in surface precipitation.

We note that the simulation results in Guo et al. indicate that the peak value of graupel is lower in seeded clouds compared to unseeded clouds [36], which was partly different from our results. We believe that the presence of completely different conclusions in these two case studies means that the simulation results are subject to uncertainties and biases due to various reasons. It is noted that Guo et al. emphasizes process analysis [36], while we are more concerned with the average state of the results. For instance, Guo et al. highlights changes in peak values [36], whereas we focus on changes in average quantities. However, regardless of these differences, the cloud microphysical processes associated with precipitation are extremely complex, and models can only achieve more accurate and reliable results when they are adequately combined with observations.

These findings provide evidence of the positive influence of the catalytic process in aircraft cloud seeding operations. The enhanced concentrations of ice crystal nuclei, along with the subsequent formation of large cloud droplets, contribute to the overall increase in precipitation. Understanding these mechanisms is crucial for optimizing cloud seeding strategies and improving our ability to manipulate precipitation patterns in a targeted manner.

6. Conclusions

The technology of artificial weather modification has developed rapidly, but its effectiveness is unstable and difficult to predict, especially in evaluating the effect of artificial rainfall. The objective, scientific, and quantitative evaluation of artificial rainfall is crucial to the development and practice of this technology. In this study, the Weather Research and Forecasting (WRF) model was used to simulate and evaluate the seven aircraft cloud seeding operations in Hunan Province from August to September 2021. The results showed that the WRF model coupled with catalytic processes could effectively evaluate the rainfall enhancement effect. When the water vapor condition was appropriate, the silver iodide dispersed in the air could significantly increase the content of large ice crystals, snow, and hail particles in the upper atmosphere, resulting in an increase in low-altitude rainfall and ground precipitation. When the water vapor condition was insufficient, the dispersion of silver iodide did not produce effective precipitation, which was consistent with the observation and actual flight operation results. This study is beneficial for the Chinese meteorological business to conduct a preliminary evaluation of the comprehensive efficiency of aircraft cloud seeding through catalytic simulation experiments, and to guide the operators to carry out artificial rainfall operations efficiently and reasonably in favorable weather conditions.

However, this study also has some limitations. For example, the WRF model has certain errors in simulating high-resolution precipitation, which come from various sources, including errors in the driving field and uncertainties in cloud microphysics schemes. For example, Crawford et al. demonstrated that the Hallett–Mossop process was a crucial mechanism for producing high ice concentrations and had the potential to significantly impact precipitation [37]. The representation of precipitation in climate models is a major manifestation of forecast errors, which can to some extent affect the assessment of aircraft cloud seeding efficiency. Therefore, improving prediction capabilities is an important area of future focus. This includes considering the introduction and improvement of assimilation techniques and enhancing the parameterization schemes for large-scale cloud precipitation in order to enhance the model's ability to simulate precipitation. Additionally, improving the accuracy of the current model's simulations, especially in terms of computational capabilities, is also crucial and needs urgent attention.

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