# WARM CLOUD SEEDING EXPERIMENT OF AIRCRAFT PRECIPITATION ENHANCEMENT FOR THE NORTHWARD TYPHOON IN-FA IN CHINA

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Abstract. On July 29, 2021, from 11:51 to 15:14, the Weather Modification Center of Hebei Province in China conducted warm cloud seeding experiments on the periphery cloud system of Typhoon "In-Fa" in the central and southern regions of Hebei Province, using a KingAir-350 aircraft to disperse warm cloud seeding agents (17 sticks of YF-1 warm cloud flares, including hygroscopic agents such as calcium chloride and potassium chloride, 400 g/stick). One hour after the operation, a band-shaped maximum precipitation area appeared downwind, indicating a significant increase in rainfall. The cloud physics detection equipment carried on the aircraft was used to detect the rainband on the periphery cloud system of the typhoon. The airborne detection data showed that the concentration of large particles (>50  $\mu$ m) in warm clouds in the periphery cloud system of the typhoon was significantly higher than in other weather systems. The concentration of large particles had a higher correlation with water content than small particles. The water content of the warm clouds could reach 0.9 g/m<sup>3</sup>. After the warm cloud seeding agent was dispersed, the area where it was dispersed showed an increase in CIP (Cloud Imaging Probe, particle diameter >50 µm) concentration and a decrease in CDP (Cloud Droplet Probe, particle diameter <50 µm) concentration, indicating that the collision-coalescence process in the warm clouds was significantly enhanced. The rapid growth of large droplets due to collision with small droplets was related to the artificial seeding of hygroscopic agents.

**Keywords:** typhoon moving northward, aircraft, warm cloud seeding, warm cloud catalyst, rainfall increase

### Introduction

Due to climate change and rising sea levels, the frequency of northward-moving typhoons has been increasing since 2018 (Su et al., 2020, 2021) in China. Recent observations and simulation studies on the cloud systems of these typhoons in northern China (Yang et al., 2011, 2013, 2020) have shown that their precipitation is characterized by stable stratification, with increasing particle size as altitude decreases, and with a layered cloud structure. The warm cloud layer in these cloud systems has high water content and depth and plays a significant role in rainfall. In recent years, droughts have occurred frequently in Hebei Province, and no significant rainfall has occurred during the flood period. The precipitation brought by northward-moving typhoons can help alleviate severe droughts.

In recent years, the catalytic technology of artificial precipitation in cold cloud is becoming mature (Hobbs, 1974; You, 1994; Hu, 2001; Sun et al., 2015). However, it is highly limited by the catalyst seeding altitude, and many weather systems contain much more water than cold clouds, more and more attention has been paid to the technology of warm cloud seeding artificial precipitation , but research and experiments in this field are lacking and need to be strengthened (Fang et al., 2011; Chen et al., 2015; Sun et al., 2020; Xing et al., 2023).Typhoon "In-Fa" (No. 6) made landfall, moved northward on July 25, 2021, and stayed on land in China for up to 95 hours, the longest since 1949 (Wang et al., 2022; Zhao et al., 2022). It caused significant rainfall in most parts of Hebei Province from July 28 to 30 due to the influence of the outer flow of the typhoon and cold air. The distribution of rainfall was biased towards the east. Given the deep and thick warm cloud layer structure in the typhoon cloud system, on July 29, 2021, from 11:51 to 15:14, the Weather Modification Center of Hebei Provinces used a KingAir-350 aircraft to conduct warm cloud seeding on the outer cloud system of "In-Fa" in central and southern Hebei Province. A cloud physics probe was also used to collect samples during the operation.

## Materials and methods

On July 29th, 2021, from 11:51 to 15:14, the Weather Modification Center of Hebei province in China used a KingAir-350 aircraft to carry out warm cloud seeding operations on the outer cloud system of Typhoon "In-Fa" in the central and southern parts of Hebei province. The seeding site was between Yuanshi and Gaoyi in the south of Shijiazhuang (*Fig. 1a*). The aircraft flew at an altitude of 2500 meters and made circular flights during the seeding, which took place between 14:00 and 14:30 (*Fig. 2*, red line). The radar echo intensity during the seeding operation was between 15-25 dBz, and the design of the weather modification flight plan was conducive to observing the effects of the seeding. The radiosonde data from Xingtai at 8:00 on the 29th (*Fig. 1b*) showed that the 0°C layer was at 4954 m, and the wind at 2500 m was northeast. The area where the aircraft sprayed was perpendicular to the direction of the high-altitude wind, which was conducive to the diffusion of the seeding agent. The aircraft started to descend and return at 14:40, carrying a series of cloud physics detection instruments produced by the American SPEC company, which obtained the microphysical structure of the warm cloud on the periphery of "In-Fa".



*Figure 1.* The path of KingAir-350 at the altitude of 10 km (background image shows the radar echo intensity at 14:36 on the 29th, in units of dBz) and the aircraft sounding area



*Figure 2.* The path of KingAir-350 and the vertical profile of radar reflectivity (unit:dBz). The red line in the figure indicates the period of seeding

KingAir-350 aircraft carries cloud physics series detection instruments produced by Droplet Measurement Technologies Company (DMT) in USA. The Cloud-Related Instruments Aboard the Aircraft Used in this Study are shown in *Table 1*.

Instrument	Variables detected	Range
AIMMS-20	Meteorology (temperature, humidity, and wind)	-
CDP	Size distribution of droplets	2-50µm
CIP	Particle size distribution and shadow-image at 25 µm pixel resolution	25-1550μm
Hot wire LWC	Liquid water content	0.005-3g/m <sup>3</sup>
HVPS	Precipitation particle size distribution	150-19200μm

Table 1. The Cloud-Related Instruments Aboard the Aircraft Used in This Study

China's new generation weather radar data, sounding data, and hourly ground rainfall data adopted in this article are provided by Hebei Meteorological Information Center.

### Analysis of radar echo evolution

*Figure 3* shows the evolution of radar echo every 6 minutes between 14:00 and 14:30 in the seeding area. The radar echoes exhibit a spiral shape, and the seeding area is located at the southern end of the strong echo band, which is the outermost spiral rainband. As the typhoon rainband moves towards the northeast, the outer rainband begins to loosen after 15:30, and precipitation in the seeding area begins to weaken.

*Figure 4* shows that on July 29th at 14:06, there were two obvious spiral rainbands over Hebei Province, one located on the eastern foot of the western Taihang Mountains (*Fig. 4a*), and the other situated on the eastern coast (*Fig. 4b*). Both spiral rainbands had echo tops above 9,000 meters (-20°C), but the the echo top of the eastern rainband was not fully observed due to radar malfunction in Cangzhou. The warm cloud areas of both rainbands had strong echoes, with the 35 dBz echo centre in the warm cloud area of the western rainband located over Baoding, at the height of around 4,000 meters below 0°C. The maximum echo intensity of the aircraft seeding area was 30 dBz. In the warm cloud area of the ground, and the 35 dBz echo top was located near 0°C (4954 meter).



*Figure 3.* The evolution of radar echo intensity (unit:dBz) in the area where the aircraft released the seeding agents. Panel a-f corresponds to every 6 minutes from 14:00 to 14:30



*Figure 4.* Vertical profiles of radar echo intensity (unit: dBz) for two spiral rainbands in the Hebei region

#### Cloud microphysics structure characteristics of seeding area

*Fig.* 5 shows the microphysical characteristics of warm clouds in the seeding area, where the altitude was 2500 meters, and the temperature was 10°C. It can be seen that the concentration of large particles (>50  $\mu$ m) in the warm clouds of the outer cloud band of the typhoon is significantly higher than that of other weather systems, and the concentration of large particles is more strongly correlated with the liquid water content than that of small particles. The liquid water content of the warm clouds can reach 0.9 g/m<sup>3</sup>, and the concentration of large water droplets measured by the CIP (Cloud Imaging Probe, particles with diameter > 50  $\mu$ m) in the clouds is very high, up to 200/L.



**Figure 5.** Temporal evolution of warm cloud microphysical structures in the seeding area. Panel a: The black line represents temperature (unit:°C), and the blue line represents altitude (unit:m). Panel b: The black line represents the concentration of small cloud droplets measured by CDP (unit:/cm<sup>3</sup>), and the blue line represents the concentration of large cloud droplets measured by CIP (unit:/L). Panel c: Liquid water content (LWC, unit: g/m<sup>3</sup>)

From 14:00 to 14:30, after the warm cloud seeding in the seeding area, the CIP concentration, and the CDP (Cloud Droplet Probe, particles with diameter  $< 50 \ \mu m$ ) concentration in the cloud began to show a negative correlation, indicating that the collision-coalescence process in the warm cloud was significantly enhanced. The large droplets coalesced with small droplets and grew rapidly, which is related to the artificial precipitation enhancement.

#### Hourly rainfall distribution on the downwind side of the seeding area

The radiosonde data (*Fig. 1*) indicates a north-northeast wind at 2500 meters in height. As the catalyst in the cloud spreads around the flight route which Move down with the high wind direction, the downwind side of the area covered by the flight route is selected as the catalytic influence area. *Figure 6* displays the hourly distribution of precipitation

at the ground and in the seeding area. It can be seen that there is no clear pattern in the distribution of rainfall in the downwind area of the seeding area at 14:00. However, after one hour of seeding, northeast to southwest strong precipitation band appeared in the Gaoyi (高邑) to Lincheng (临城), which was significantly higher than the non-affected areas on both sides. The maximum hourly precipitation in the band was 1.6 mm at the southern end of the seeding area. The nearest hourly rainfall on the left and right sides of the affected area was 1.1 mm and 0.4 mm, respectively significantly lower. At 16:00, the same strong precipitation band still had three centres of 0.6-0.8 mm, significantly higher than the two sides (less than 0.3 mm). After 17:00, the strong precipitation band in the downwind area of the seeding zone disappeared.



**Figure 6.** Distribution of hourly rainfall (unit: mm) in the seeding area and on the ground, panel a-d corresponds to every hour from 14:00 to 17:00. The red box indicates the catalytic influence area. Place names in the picture 高邑: Gaoyi, 临城: Lincheng

The microphysical characteristics and ground precipitation distribution suggest that the warm cloud seeding was effective. Multiple strong precipitation centres appeared on the ground within 1.5-2 hours after seeding in the downwind area.

## **Conclusion and discussion**

The concentration of large particles (> 50  $\mu$ m) in the warm clouds on the periphery cloud system of Typhoon "In-Fa" was significantly higher than that of other weather systems. The concentration of large particles was more closely related to the liquid water content than that of small particles. The liquid water content in the warm clouds could

reach 0.9 g/m<sup>3</sup>, and the concentration of large water droplets in the clouds measured by the Cloud Imaging Probe (CIP) was very high, with a maximum of 200 /L. Between 14:00 and 14:30 after seeding, there were several occasions where the CIP concentration was negatively correlated with the Cloud Droplet Probe (CDP) concentration, indicating that the coalescence process was significantly enhanced in the warm clouds, and the large cloud droplets grew rapidly. In the downwind area, multiple strong precipitation centres appeared within 1-2 hours after seeding, which was related to using hygroscopic seeding material for artificial precipitation enhancement.

The microphysical characteristics of the warm clouds and the ground rainfall characteristics indicate that the warm cloud seeding effect was significant in this case.

Due to the direct seeding of aircraft into the cloud, the favorable cloud physical conditions can be accurately selected, and the affected cloud area is large, compared with the use of ground catalytic tools such as rockets, aircraft rainfall enhancement has irreplaceable advantages.

However, the warm cloud artificial precipitation enhancement technology needs more theoretical and practical exploration.

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#### REFERENCES

- [1] Chen, S. Q., Ye, D. B., Lin, C. C. (2015): Analysis of the operation effect of Zhouning Reservoir in Fujian province. Meteorological science and technology 43(2): 338-342. DOI:10.3969/j.ISSN.1671-6345.2015.02.029.
- [2] Fang, W., Zheng, G. (2011): The Effect of Giant Cloud Condensation Nuclei on Warm-Cloud Precipitation. – Chinese Journal of Atmospheric Sciences 35(5): 938-944.
- [3] Hobbs, P. V. (1974): Ice Physics. Oxford University Press, Oxford.
- [4] Hu, Z. J. (2001): Discussion on mechanisms, conditions, and methods of precipitation enhancement in stratiform clouds. – Journal of Applied Meteorological Science 12 (supplementary issue): 10-13.
- [5] Su, H. L., Fei, X. C., Wang, F. (2020): Main characteristics of the northward tropical cyclone and its influence on Hebei. – Henan Science 38(6): 966-972. DOI:10.3969/j.ISSN. 1004-3918.2020.06.017.
- [6] Su, H. L., Yuan, L. W., Wang, M., Dong, G. H., Fei, X. C. (2021): Analysis of tropical cyclone characteristics and disaster disasters in China 1949-2019. Journal of Applied Oceanography 40(3): 382-387. DOI:10.3969/J.ISSN.2095-4972.2021.03.002.
- [7] Sun, J., Yang, W. X., Zhou, Y. Q. (2015): Simulation study of stratified cloud system structure and rainfall enhancement condition in Hebei. – Plateau Meteorology 34(6): 1699-1710.
- [8] Sun, K., Sun, B. L., Zhang, X. (2020): Brief analysis of warm cloud seeding artificial precipitation. Science and Wealth 25: 47-48.
- [9] Wang, H. P., Dong, L., Xu, Y. L. (2022): Analysis of the main characteristics and difficulties of path forecast. – Journal of Marine Meteorology 42(1): 83-91. DOI:10.19513/j.cnki.ISSN.2096-3599.2022.01.009.
- [10] Xing, F. H., Huang, F. T., Li, G. W., Huang, Q. M. (2023): Analysis of physical effect of warm cloud seeding artificial precipitation in central mountainous area of Hainan Island. – Journal of Arid Meteorology 41(1): 114-122. DOI:10.11755/j.ISSN.1006-7639(2023)-01-0114.

- [11] Yang, W. X., Zhao, L. P., Deng, Y. P. (2011): Analysis of the cloud structure and precipitation formation mechanism of the typhoon eye wall. – Meteor Mon 37(6): 1481-1488.
- [12] Yang, W. X. (2013): Research on the cloud structure and precipitation formation mechanism in the typhoon spiral rain belt. Meteor Mon 39(2): 194-202.
- [13] Yang, W. X., Hu, Z. X., Lei, H. C. (2020): Numerical Simulation Study on the Microphysical Processes of Typhoon Wipha Using a New Moisture Conditioning Method. – Journal of Coastal Research, Special Issue No. 104: 156-159.
- [14] You, L. G. (1994): Study of cloud physics processes and artificial precipitation conditions using particle measurement systems. – Research on cloud-precipitation physics and artificial precipitation enhancement technology, Beijing, China, Meteorological Press, pp. 236-249.
- [15] Zhao, J. H., Chen, L. J., Zhang, D. Q. (2022): Analysis of the characteristics and genesis of climate anomalies in China in the summer of 2021. – Meteor Mon 48(1): 107-121. DOI:10.7519/j.issn.1000-0526.2021.120201.