Case analysis of artificial snowfall enhancement by aircraft in Winter Olympic Games Area

W X Yang¹,², Z X Hu³, X B Dong¹,², Y Yang¹,² and L W Zhao¹,²

¹Hebei Artificial Weather Office, Shijiazhuang 050021, China
²Hebei Key Laboratory of Meteorology and Ecological Environment, Shijiazhuang 050021, China
³Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100082, China

E-mail: ywx418@163.com

Abstract. It was dry in Hebei Province in winter of 2017, with less snow. But on November 25, 2017, snowfall occurred in Zhangjiakou and Chengde areas of Hebei Province by the influence of low trough-cold front weather process. Hebei Artificial Weather Office used cloud physics model products issued by National Artificial Weather Office for timely and accurate early warning, and successfully implemented artificial snowfall enhancement operation by an aircraft. Aircraft was King of the Air 350, and carried series of cloud physics and environment detection instruments produced by SPEC Company. In this paper, the case was analyzed, and technical conditions for artificial snowfall enhancement were summarized from water content and vertical velocity in clouds by combining several rainfall processes from winter of 2017 to spring of 2018.

1. Introduction
In the 1930s, Bergeron-Findeison proposed Begeron-Fendeison cold cloud precipitation theory, and artificial rainfall enhancement test on this basis was carried out in the world. Since entered into the 21st century, improvement of various detection methods promoted overall development of cloud physics in the world. In 2001, Hu et al proposed that attention should be paid to the role of supercooled water vapor. They pointed out that artificial ice crystal made supercooled cloud water transform into rainfall via Begeron process and a part of the supersaturated water vapor on the ice surface converted into precipitation [1]. With the improvement of assimilation technology of observation data in recent years, observation and research on mechanism of artificial rainfall enhancement developed rapidly [2-7], but there were fewer studies on snowfall process. Since formation mechanism of rainfall in snowfall process is unique, it is necessary to explore and study snowfall enhancement technology by aircraft.

2. Weather system
It was low trough-cold front weather process, and high-altitude and ground weather situation was shown as figure 1. It was clear that weather system mainly affected north Hebei Province.
3. Methodology used: Forecast situation of numerical model
At 17:00 on November 24, 2017, forecast result of horizontal potential zone in the process by CPEFS mode of National Artificial Weather Office was shown as figure 2. Whole weather process moved from northwest to southeast, and water condensate cloud band affecting Hebei Province contained multiple large-value centers, and the maximum could reach 3 mm. Main influence period was 08:00-22:00 on May 25, 2018, and it was consistent with movement situation of weather system.
Figure 2. Horizontal movement situation of stratiform cloud belt during 08:00-22:00 on November 25, 2017 (unit: mm, 云带: cloud band).
Figure 3. Observation data of surface precipitation at national and regional stations in the weather process. (a) 08:00-14:00 on 25th; (b) 14:00-20:00 on 25th and (c) 20:00-24:00 on 25th.

Figure 3 showed observation data of surface precipitation at national and regional stations in the weather process. Compared with figure 2, rainfall range and period forecasted by CPEFS model were consistent with actual situation. Seen from figure 4, the content of supercooled water was very rich in the process, and supercooled water in heavy precipitation center of clouds appeared at 750-500 hPa (-20- -35°C), and concentration of natural ice crystal corresponding to supercooled water was higher (≥1/L). The maximum content of supercooled water reached 0.05 g/kg, and horizontal range of large-value zone was obviously larger than other snowfall cases, with better artificial snowfall enhancement potential. Therefore, two snowfall enhancement operations by aircraft on 25th were designed, and a sortie of snowfall enhancement was carried out in the afternoon, and it obtained more complete information.

![Figure 3](image1)

Note: Colouring shadow showed cloud water; red contour showed ice crystal; purple contour showed isotherm.

Figure 4. Vertical distribution of supercooled water at large-value center of moisture content of cloud band forecasted by MM5 model at 16:00-18:00 on November 25, 2017, (云水混合比: cloud water mixing ratio; 冰晶数浓度: number concentration of ice crystal; 温度: temperature)

4. Detection situation of aircraft
Hebei Artificial Weather Office implemented artificial snowfall enhancement by King of the Air 350 in northwest area of Hebei Province during 16:19:24-18:54:21, and the aircraft carried series of cloud physics detection instruments produced by SPEC Company. Measurement range of cloud physics
detection instrument was shown as Table 1, and horizontal and vertical routes of aircraft were shown as figure 5. At 16:37, aircraft entered into Laiyuan County of Baoding City. At this time, it was snowing on the ground, and aircraft started to fly horizontally and performed catalytic operation. At 17:00, aircraft entered into Yuxian of Zhangjiakou City. During 17:19-17:43, aircraft carried out vertical detection and spiral descent at 3 800-5 000 m of Chongli, and then flew horizontally and sowed artificial ice crystal in clouds. At 18:03, aircraft returned back to the south of Xuanhua District of Zhangjiakou City. At 18:29, aircraft started to descend after flew horizontally to Quyang of Baoding City, and returned back to Shijiazhuang. Therefore, main period of aircraft in cloud area was during 16:27-18:29.

Seen from figure 5(b), the flight mainly consisted of two level flights and one oblique landing process. There was a little vertical detection in Chongli, and relative humidity of cloud area was mainly 70%-90%, while temperature was between -35 and 0°C. It was basically consistent with model forecast result of figure 4.

**Figure 5.** Horizontal (a) and vertical tracks (b) of aircraft detection during 16:19:24-18:54:21 (海拔高度: altitude; 相对湿度: relative humidity; 温度: temperature)
Table 1. Cloud physics detection instruments produced by SPEC Company and their measurement ranges.

| Name of probe | Measurement range and interval |
|---------------|--------------------------------|
| FCDP          | 2-50 µm                        |
| 2D-S          | 10 µm*128=1.28 mm              |
| HVPS          | 150 µm*128=19.2 mm             |
| CPI           | 2.4 µm*1024*1024               |
| CCP           | 2-50 µm                        |
|               | 15 µm*62=930 µm                |
| PCASP         | 0.1-3.0 µm                     |
| AIRMS         | Environmental factors          |

5. Data analysis at level flight stage

Compared with PMS series instruments, cloud physics detection series instruments produced by SPEC Company are improved greatly, especially increasing detection of vertical airflow in clouds. At present, detection of vertical airflow only could be applied in level flight stage. When the aircraft has the speeds of ascending and descending, the detection values will be seriously distorted. The case had two stages of longer level flight data. As shown in figure 6, both two level flight stages occurred in snowfall region of Zhangjiakou. It was clear that content of supercooled water and large-value zone of relative humidity showed better positive correlation with vertical ascending velocity. The maximum vertical ascending velocity was 6 m/s, and corresponding peak of supercooled water content was 0.6 mg/m³. In the process, the maximum peak of supercooled water was 0.85 mg/m³, with rich content.
6. Analysis on vertical structure at descent stage

After aircraft flew horizontally to Quyang of Baoding City, it started to descend and returned back to Shijiazhuang at 18:29. Vertical structure at descent stage was shown as figure 7. Peak areas of relative humidity and supercooled water content existed at the height of 3 600 m, and there was a section of inversion zone of -10–15℃. After aircraft flew to Shijiazhuang, temperature started to decline, while relative humidity gradually rose. It needed considering that aircraft has left snowfall region after leaving Zhangjiakou City, and clouds did not have snowfall conditions.
7. Conclusions and discussion

Compared with artificial rainfall enhancement operation, there were fewer studies on artificial snowfall enhancement. The artificial snowfall enhancement by aircraft was successful, and it was scientific and reasonable from model forecast product, formulation of operation plan and acquisition of aircraft data. A significant feature of the case was that content of supercooled water was higher. Compared with other snowfall enhancement cases in Hebei Province in winter of 2017 and spring of 2018, content of supercooled water was higher, and its area was larger. Since ice and snow crystals are rich in snowfall process, content of supercooled water in clouds is a direct and reliable index for identifying artificial snowfall enhancement potential. When content of supercooled water in clouds is lower and close to zero, it needs considering contribution of supercooled water vapor, declining sowing quantity of artificial ice crystal, and selecting large-value zone of vertical updraft for sowing.

Acknowledgment

Supported by Hebei Science and Technology Plan Project (14227003D, 17227001D); the National Natural Science Foundation of China (41475121).

References

[1] Hu Z J 2001 Discussion on mechanisms, conditions and methods of precipitation enhancement in stratiform clouds *Quarterly J. Appl. Meteorol.* 12(5) 10-3 (in Chinese)
[2] Yang W X, Niu S J, Wei J G et al 2005 Airborne observation for microphysical structure of precipitation system of stratiform cloud in Hebei *Plateau Meteor.* 24 84-90 (in Chinese)
[3] Zhang D G, Guo X L, Gong D L et al 2011 The observational results of the clouds microphysical structure based on the data obtained by 23 sorties between 1989 and 2008 in Shandong Province *Acta Meteorol. Sin.* 69 195-207 (in Chinese)
[4] Hou T J, Hu Z X and Lei H C 2011 A study of the structure and microphysical processes of a precipitating stratiform cloud in Jilin *Acta Meteorol. Sin.* 69 508-20 (in Chinese)
[5] Hong Y C 2012 Research progress of stratiform cloud structure and precipitation mechanism and discussion on artificial precipitation problems *Climatic Environ. Res.* 17 937-50 (in Chinese)
[6] Yang W X, Zhou Y Q, Sun J et al 2014 Observational studies of distribution characteristics of supercooled cloud water during a westerly trough process *Acta Meteorol. Sin.* 69 583-95 (in Chinese)
[7] Sun J, Yang W X and Zhou Y Q 2015 Numerical simulations of cloud structure and seed ability of a precipitating stratiform in Hebei *Plateau Meteor.* 34 1699-710 (in Chinese)