Distinct Change of Supercooled Liquid Cloud Properties by Aerosols From an Aircraft-Based Seeding Experiment

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Abstract Cloud plays essential roles to Earth’s energy balance and hydrological cycle. Its characteristics could be modified by human activities through cloud seeding. However, there is long-lasting debate whether the cloud seeding can modify the clouds to introduce or change precipitation effectively, due to the challenge that the effect of cloud seeding is difficult to be evaluated. Using the data from a cloud seeding experiment, this study investigates the differences of cloud properties between before and after the cloud seeding for a supercooled liquid cloud. It shows that before the cloud seeding, the clouds are supercooled liquid phase clouds. After cloud seeding, the observations from both the cloud particle images and cloud particle size distributions indicate the occurrence of large ice crystal particles and the broadening of particle size distribution. Thus, much larger and much more ice crystal particles occurred after the cloud seeding, which could further grow into precipitation particles through collision-coalescence process. Satellite image further shows the formation of precipitation clearly after the cloud seeding experiment. This study suggests that cloud seeding can work efficiently for supercooled liquid clouds.

1. Introduction

Cloud, as an essential part of atmospheric hydrological cycle, provides significant fresh water to the land ecology system via precipitation (Andreae & Rosenfeld, 2008; Li et al., 2016, 2019; Lohmann & Feichter, 2005; Tao et al., 2012; Zhao et al., 2020), while it also causes flooding through extreme precipitation (Alexander et al., 2006; Min et al., 2011; Rosenfeld et al., 2008; Zhai et al., 2005; Zhao, Lin, et al., 2018). With more clouds and precipitation in south China (Z. Yang et al., 2020; Zhao, Chen, et al., 2019), there are sufficient water supply making this region suitable for the growth of rice, along with the warm temperature. In contrast, with limited precipitation and clouds in North China (Sun et al., 2019; Zhao, Chen, et al., 2019), irrigation is often necessary for the growth of agriculture. Associated with this, people hope that we could modify the clouds and precipitation so that we can decrease the impacts of drought to human society.

Numerous studies have pointed out that aerosols could significantly change the cloud properties by serving as cloud condensation nuclei (CCN) during past few decades (Berg et al., 2011; Feingold et al., 2003; Garrett et al., 2004; Garrett & Zhao, 2006; Jiang et al., 2008; Kim et al., 2003; Qiu et al., 2017; Twomey, 1977; Wang et al., 2014; Y. C. Yang et al., 2019; Zhao et al., 2012; Zhao, Qiu, et al., 2018). Twomey (1977) proposed that aerosols could increase cloud albedo by increasing cloud droplet number concentration and decreasing cloud droplet effective radius ($r_e$), which is generally referred as cloud albedo effect or Twomey effect. Albrecht (1989) indicated that aerosols could enhance the cloud lifetime by decreasing the precipitation because there are less large cloud droplets when aerosol concentration is higher, which is referred as cloud lifetime effect. Garrett and Zhao (2006) further showed that aerosols could enhance thin cloud thermal emissivity by decreasing cloud droplet effective radius, which is referred as cloud thermal emissivity effect. Differently, recent studies also found controversial results. For example, Rosenfeld et al. (2008) proposed the invigoration effect of aerosols on strong convective clouds. Specifically, when the clouds develop strong enough to pass the freezing level at height, the more and smaller droplets due to aerosol effect freeze and release heat, making the convection stronger and precipitation heavier. This phenomenon has been found...
over various locations, such as Houston (Shepherd & Burian, 2003), the Gulf of Mexico and South China Sea (Yuan et al., 2008), and Yangtze River Delta (Wang et al., 2014).

When there are no strong convective clouds, is there a possibility for us to increase precipitation through human weather modification? For mixed-phase clouds, Bergeron (1935) suggested that the liquid droplets evaporate and water vapor gets deposited on ice particles. Based on this theory, we could add ice nuclei (INs) into supercooled liquid (or mixed with few ice particles) clouds to make them experience the Bergeron process to grow into large particles, which helps the formation of precipitation. In other words, by searching and identifying supercooled liquid or mixed-phase cloud, we could modify the cloud and potential precipitation associated with it by adding INs into it. This is one of the basic ideas for enhancement of precipitation, which we call as cloud seeding.

It is still on question whether the cloud seeding can help the formation of precipitation by changing cloud properties, since it is really challenging to evaluate the performance. Most existing studies evaluate the performance of cloud seeding by investigating the changes of cloud and precipitation characteristics after cloud seeding based on high time resolution observations from aircraft particle measurement system, satellite remote sensing, and ground radar reflectivity signals. Geerts et al. (2010) found an increase of Doppler radar reflectivity signals near surface after cloud seeding for an orography cloud over Wyoming in winter. There are also several similar evaluation studies in China. Cai et al. (2013) found that there are clear increases in cloud ice crystal size and concentration after cloud seeding for clouds with high supercooled liquid droplets. Zhu et al. (2015) found that the changes of cloud ice crystal shape, size, and concentration after cloud seeding vary with cloud top temperature and seeding location. Even with these studies, most field experiments cannot easily find direct evidence of increasing precipitation after cloud seeding due to the complicated cloud development process, which makes cloud seeding often in doubt. More evidences are highly demanded by the science community in order to fully understand the effects of cloud seeding on the precipitation. In this study, we investigate the performance of cloud seeding for a supercooled liquid cloud over Xingtai, China, on 22 January 2018 based on both aircraft and satellite observations.

The paper is organized as follows. Section 2 describes the data and method. Section 3 shows the analysis and results. A summary is provided in section 4.

2. Data and Method

2.1. Experiment

The aircraft-based experiment was carried out on 22 January 2018 over Xingtai, Hebei Province in China. Figure 1 shows the flight track of the aircraft on the experiment day. The aircraft got flight at 8:12 local time (LT) from the Zhengding station and then flew south horizontally at 2,100 m height from Zhengding to Xingtai, Hebei Province. When the aircraft arrived at Xingtai, it flew downward from 2,100 to 600 m to do the observation of vertical profiles of cloud properties at the time period from 8:53:38 to 8:58:19 LT. For this vertical profile observation, the horizontal observation radius is 10 km. After the vertical observations, it makes horizontal observations at three heights within clouds, which are 600, 900, and 1,200 m, also with a horizontal radius of 10 km. After observing the cloud properties, a cloud seeding experiment was carried out from 9:44 LT at the height of 1,200 m, with release of six silver iodide flames at 9:44 LT, five silver iodide flames at 9:49 LT, and three silver iodide flames at 9:53 LT. When the experiment was done, the aircraft went back to height 2,100 m and made further horizontal observations at 1,200, 900, and 600 m at the time period 10:21:45–10:52:10 LT in order to know the effects of cloud seeding.

During the experiment day, the observations from a new-generation geostationary satellite, Himawari-8, are also investigated to show the performance of cloud seeding. Himawari-8 was launched in January 2014 and located approximately 35,800 km above the equator at 140°E, which is operated by the Meteorological Satellite Center (MSC) of the Japan Meteorological Agency (JMA) (Bessho et al., 2016; Da, 2015; H. Letu et al., 2020). Advanced Himawari Imager (AHI) is one of the major instruments onboard Himawari-8 with a spatial resolution from 0.5 to 2.0 km and a temporal resolution from 2.5 to 10 min. With AHI, the cloud mask product (CMP) was developed based on the cloud mask algorithm of the NoWClouding (NWC) Satellite Application Facility (SAF) and the National Oceanic and Atmospheric Administration (NOAA)
National Environmental Satellite, Data, and Information Service (NESDIS). Details about the cloud mask identification can be obtained from Takahito and Ryo (2016). In addition, cloud microphysical properties were also estimated by previous studies (Iwabuchi et al., 2018; H. S. Letu et al., 2018). In this study, we took use of the cloud observations of brightness temperature in January 2018 by Himawari-8 to investigate the change of clouds by cloud seeding. The spatial and temporal resolutions of the Himawari-8 cloud product used in this study are 0.05° and 10 min, respectively.

Note that there are no additional cloud layers above the observed clouds, making the clouds observed by the passive satellite. There are also no sufficient natural INs at high levels of the atmosphere, making it possible for the existence of supercooled liquid clouds.

2.2. Instrument

The King-350 aircraft is used for the observation of clouds, which is operated by the Hebei Province human weather modification office. The instruments onboard the aircraft include the particle measurement system,

| Instrument | Variables detected                              | Measurement range     |
|------------|-------------------------------------------------|-----------------------|
| FCDP       | Droplet size distribution                       | 2–50 μm               |
| AIMMS-20   | Meteorology (temperature, humidity, and wind)   | —                     |
| 2DS        | Cloud particle size distribution                | 10–1,280 μm           |
| HVPS       | Precipitation particle size distribution        | 150–19,200 μm          |
| CPI        | Cloud particle image                            | 2–3,000 μm            |
| Hot wire   | Liquid water content and total water content    | 0.005–3 g/m³          |

Figure 1. The aircraft observation route on 22 January 2018.
Aircraft-Integrated Meteorological Measurement System at rates up to 20 Hz (AIMMS-20) meteorology monitoring system, Nevzorov hot wire, and Global Positioning System (GPS). The particle measurement system includes the Fast Cloud Droplet Probe (FCDP), two-dimensional spectrometer (2DS), High-Volume Precipitation Spectrometer (HVPS), and cloud particle imager (CPI). The FCDP measures the particles with diameters between 2 and 50 μm with an uncertainty of 20% (Faber et al., 2018; Lance et al., 2010). The 2DS measures the particles with diameters between 10 and 1,280 μm (Lawson, 2011). The HVPS measures the particles with diameters between 150 and 19,200 μm. The CPI imager can get the high-resolution image of cloud particles. The Nevzorov hot wire can provide the real-time liquid water content (LWC) and total water content (TWC) with an uncertainty of 15% (King et al., 1978). Table 1 lists the main instruments used in this experiment, along with their detection range of particles.

2.3. Process Method

We obtain the cloud droplet size spectrum based on the combination of observations from FCDP and 2DS with a diameter size range from 2 to 100 μm. For large particles, we use the 2DS observations with diameters between 100 and 1,000 μm so that the influence of small particles can be excluded. Similarly, we also study the large particles with diameters from 150 to 19,200 μm from HVPS. Note that most of the large particles with diameters larger than 100 μm are ice crystals. For simplicity, we assume that the particle concentration with diameters larger than 100 μm is for ice crystals and that with diameters no more than 100 μm is for liquid droplets. In order to better understand the change of cloud particle size distribution after cloud seeding, we use the observations with a temporal resolution of 1 s.

Based on the cloud particle size distribution, the cloud droplet effective radius ($r_e$) and droplet number concentration ($N_d$) are calculated as

$$r_e = \frac{\int r^2 n(r) dr}{\int r n(r) dr} = \frac{\sum N_{ir} r_i^2}{\sum N_{ir} r_i}$$  \hspace{1cm} (1)

$$N_d = \int n(r) dr = \sum N_{il}$$  \hspace{1cm} (2)
where \( n(r) \) is the droplet size distribution and \( N_c \) and \( r_i \) are droplet number concentration and size radius at the \( i \)th bin of the instrument, respectively. The same as the previous study (Y. C. Yang et al., 2019; Zhao, Zhao, et al., 2019), the first two bins from FCDP and the first four bins from 2DS are neglected due to the potential large uncertainties. By combining the observations from FCDP and 2DS, full-size spectra of cloud droplets from 2 to 1,280 \( \mu \)m can be obtained.

### 3. Analysis and Results

#### 3.1. Overview of Cloud Characteristics

In this study, we investigate the clouds on the evening of 22 January and examine the impacts of cloud seeding on cloud microphysical properties and the potential impacts on the formation of precipitation. Figure 2 shows the vertical profiles of temperature and relative humidity (RH) measured by AIMMS-20, and cloud particle concentration measured by FCDP, 2DS, and HVPS, which are for cloud droplet concentration, ice crystal concentration, and large precipitation (ice crystal) particle concentration. As indicated earlier, the aircraft flew within the height range between 600 and 2,100 m. It shows that the temperature was below the freezing level for the whole layer that the aircraft flew through. The temperature decreased quickly from \(-8.5^\circ C\) to \(-13^\circ C\) from 600 to 1,400 m and then increased quickly from \(-13^\circ C\) to \(-6.7^\circ C\) from 1,400 to 1,500 m forming a strong inversion layer. Above the inversion layer, there was a layer with almost constant temperature around \(-6.7^\circ C\) from 1,500 to 1,700 m. Above 1,700 m, the temperature decreased with height from \(-6.7^\circ C\) to \(-8.5^\circ C\). Different from the temperature, the RH was high at low altitudes and low at high altitudes. The RH was larger than 85% for altitudes below 1,200 m, indicating the likely existence of clouds within the layer below 1,200 m. It is clear that there were large cloud droplet concentrations below 1,200 m when RH was larger than 85%. The droplet \( N_c_FCDP \) roughly decreased with height, with the maximum value of 1,240 cm\(^{-3}\) at height around 750 m. Small concentration values of ice crystal particles from 2DS...
can be found at altitudes ranging from 600 to 1,800 m, and large ice crystal particles from HVPS can even be found at altitudes from 600 to 2,100 m. The ice crystal particle concentration with diameters larger than 100 μm was generally less than 0.5 per liter, implying that the ice crystal concentration in the cloud was very small. The HVPS shows even lower large precipitation (ice crystal) particle concentration with values below 0.03 per liter and with most particles concentrating at low altitudes. The vertical distributions of FCDP cloud droplet measurements also indicate the existence of multilayer clouds from 600 to 1,200 m. Note that a cloud layer is identified as a layer with $N_d$ no less than 10 cm$^{-3}$ for all heights within that layer. For example, there was a shallow cloud layer with depth of 160 m between 970 and 1,130 m, and the maximum cloud $N_d$ within this layer was around 590 cm$^{-3}$.

3.2. Intercomparison of Cloud Microphysical Properties Between Before and After Cloud Seeding

Figure 3 shows the time series of cloud droplet number concentration from FCDP, ice crystal concentrations from 2DS and HVPS, LWC, and ice water content (IWC) from Nevzrov hot wire for one case between 9:38 and 10:02 LT on 22 January 2018, including the time before and after the cloud seeding. The cloud seeding was carried out at around 09:44 LT, and the aircraft flew back to the cloud seeding location at around 09:56 LT. It is clear that there are high concentration of cloud $N_d$ from FCDP with values around 700 cm$^{-3}$ at 09:44, which are similar to that at time range between 09:43 and 09:49 LT. After cloud seeding, the cloud $N_d$ from FCDP decreases significantly to below 200 cm$^{-3}$ with a minimum value of 5 cm$^{-3}$ at time around 09:56 LT, while the cloud $N_d$ from FCDP is still larger than 500 cm$^{-3}$ at time range between 09:53 and 09:55 or between 09:57 and 09:58 LT. In contrast, there are no ice crystals at all time before cloud seeding. After cloud seeding, there is a sharp jump in the concentration of ice crystals, which are around 300 (262–613) per liter from 2DS and 60 (47–83) per liter from HVPS. Associated with the changes of cloud particles, there

![Figure 3](image_url)

Figure 3. The time series of cloud droplet number concentration from FCDP, ice crystal concentrations from 2DS and HVPS, LWC, and ice water content (IWC) from Nevzrov hot wire for one case between 9:38 and 10:02 LT on 22 January 2018, including the time before and after the cloud seeding. The cloud seeding was carried out at around 09:44 LT, and the aircraft flew back to the cloud seeding location at around 09:56 LT. It is clear that there are high concentration of cloud $N_d$ from FCDP with values around 700 cm$^{-3}$ at 09:44, which are similar to that at time range between 09:43 and 09:49 LT. After cloud seeding, the cloud $N_d$ from FCDP decreases significantly to below 200 cm$^{-3}$ with a minimum value of 5 cm$^{-3}$ at time around 09:56 LT, while the cloud $N_d$ from FCDP is still larger than 500 cm$^{-3}$ at time range between 09:53 and 09:55 or between 09:57 and 09:58 LT. In contrast, there are no ice crystals at all time before cloud seeding. After cloud seeding, there is a sharp jump in the concentration of ice crystals, which are around 300 (262–613) per liter from 2DS and 60 (47–83) per liter from HVPS. Associated with the changes of cloud particles, there

![Figure 4](image_url)

Figure 4. The comparison of cloud microphysical properties including the particle shape and particle size distribution between before and after cloud seeding. For the cloud particle size distribution, the black, red, and blue colors represent the cloud droplet size distribution from FCDP, the ice crystal size distribution from 2DS, and the ice crystal (precipitation) size distribution from HVPS, respectively.

![Figure 5](image_url)

Figure 5. The comparison of cloud microphysical properties including the particle shape and particle size distribution between before and after cloud seeding. For the cloud particle size distribution, the black, red, and blue colors represent the cloud droplet size distribution from FCDP, the ice crystal size distribution from 2DS, and the ice crystal (precipitation) size distribution from HVPS, respectively.
is a significant decrease in LWC and increase in IWC after cloud seeding. These indicate the strong changes of cloud microphysical properties by the cloud seeding. Figure 4 further shows the cloud droplet spectrum for time before and after cloud seeding, including the measurements from FCDP, 2DS, and HVPS, along with the cloud particle images at the time before and after cloud seeding for the case shown in Figure 3. It is clear that the cloud particles are spherical liquid droplets before cloud seeding. After the cloud seeding, a large amount of ice crystals occurred with shapes of needle, plate, and columns. Considering the collision-coalescence process between ice crystal particles and cloud droplets, precipitation is very likely to occur after cloud seeding. Figure 4 also shows the spectrum of cloud particles, in which the black, red, and blue colors represent the cloud droplet size distribution from FCDP, the ice crystal size distribution from 2DS, and the ice crystal size distribution from HVPS, respectively. It is clear that the cloud droplets with diameters below 100 μm had little change after cloud seeding, with the most frequent occurrence at 10 μm. However, the cloud \( N_d \) from FCDP decreased after the cloud seeding. Also, the spectrum of ice crystals became wider with the change of maximum size obtained by 2DS from 200 to 1,050 μm. Note that the ice crystals with diameters larger than 100 μm from 2DS are mainly between 120 and 140 μm. Similarly, there were significant increases in the sizes of ice crystals from HVPS with maximum values from 1,040 to 3,225 μm after cloud seeding, along with an obvious increase in ice crystal number concentration.

Figure 5 shows another case about the cloud properties with and without impacts of cloud seeding during the time period from 10:20 to 10:34 LT at altitude around 1,200 m. The time period from 10:21:45 to 10:22:44 LT is for clouds with the impacts of seeding, and the time period from 10:25:50 to 10:30:51 LT is for clouds without the impacts of seeding. Similarly, for the time period with the impacts of cloud seeding, a large number of ice crystals occur. The ice crystal number concentration with diameters larger than 100 μm from 2DS is 17.1 per liter on average, with a maximum value of 58.4 per liter. In contrast, the ice crystals with
Diameters larger than 100 μm from HVPS are 13.6 per liter on average, with a maximum value of 38.9 per liter. With the impacts of cloud seeding, the LWC is 0.04 gm⁻³ on average with a maximum value of 0.11 gm⁻³, and the TWC is 0.09 gm⁻³ with a maximum value of 0.23 gm⁻³. In other words, the IWC becomes about 0.05 gm⁻³ on average with the impacts of cloud seeding. These also indicate the strong changes in cloud microphysical properties by the cloud seeding. Figure 6 further shows that the cloud particles were spherical liquid droplets before cloud seeding and a large amount of ice crystals with different shapes appeared after the cloud seeding, the same as that shown in Figure 4. The ice crystal shapes shown here are similar as that shown by Heymsfield et al. (2010) for ice crystals at temperatures roughly between −12°C and −5°C.

Figure 7 shows the vertical variations about the cloud particle size spectrum at time before and after the cloud seeding at 1,200 m height as indicated in Figure 5. It is clear that with the cloud seeding, much more and larger cloud particles form, particularly at the layer between 1,200 and 1,450 m. Moreover, large precipitation particles form at almost all heights, particularly for heights between the lowest height (600 m) and 1,400 m, implying the potential formation of precipitation after cloud seeding.

### 3.3. Satellite-Based Cloud Brightness Temperature

Figure 8 shows the cloud-top brightness temperature images observed by the Himawari-8 at 17:50 LT before cloud seeding and at 18:20 LT after cloud seeding on 22 January 2018. Figure 1 has shown that the flight track with cloud seeding was a circle in shape. Correspondingly, Figure 8 shows that there was a clear increase in the cloud brightness temperature from below 249 to above 250 K along the cloud seeding circle, implying the potential formation of ice crystals or precipitation along the flight track after cloud seeding. As indicated earlier, the addition of AgI particles into the clouds makes the supercooled cloud droplets change...
to ice crystals, releasing extra energy to warm the clouds. Moreover, the appearance of ice crystals increases the collision-coalescence efficiency, forming large enough particles falling downward. The reduction of water from clouds makes the thermal radiation from ground surface transfer more through the clouds, increasing the satellite-observed cloud brightness temperature. Thus, the phenomenon shown in Figure 8 by the satellite further indicates the efficiency of cloud seeding in generating large ice crystals and potential precipitation for supercooled liquid clouds.

Figure 7. The vertical variations about the cloud particle size spectrum at time before (left) and after (right) the cloud seeding at 1,200 m height for the case indicted in Figure 5.

Figure 8. Himawari-8 cloud brightness temperature observation before seeding (17:50 LT) and after seeding (18:20 LT) on 22 January 2018. Note the unit of cloud temperature in this figure is 0.1 K.
4. Conclusions

Using the case observations of clouds from in situ aircraft and Himawari-8 satellite on 22 January 2018, this study investigates the impacts of cloud seeding on supercooled liquid cloud properties and potential precipitation. It shows significant changes in cloud microphysical properties and cloud brightness temperature, with the major findings as follows.

1. For clouds occurring in winter, if there are no additional cloud layers above the clouds, there are often no sufficient INs in the atmosphere, and the droplets within clouds grow even under cold temperatures forming supercooled liquid clouds.

2. With the cloud seeding, the supercooled liquid droplets freeze quickly into ice particles with different shapes. The Bergeron process within clouds after cloud seeding reduces the liquid droplet number concentration and increases the ice crystal particle concentration, making the particle size spectrum wider.

3. Satellite images show clearly that the cloud properties change abruptly with the cloud seeding, implying the potential formation of precipitation or drizzle below clouds.

While more general conclusion would require larger sample volumes, this study shows encouraging results regarding the cloud seeding. It can help guide the human weather modification actions in future.

Data Availability Statement

The aircraft and satellite data used in this study can be downloaded publicly online (from https://pan.bnu.edu.cn/l/1CH54zd; a zippered file with data and data description).

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