

## Research Article

# Progressive and Prospective Technology for Cloud Seeding Experiment by Unmanned Aerial Vehicle and Atmospheric Research Aircraft in Korea

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This study applies a novel cloud seeding method using an unmanned aerial vehicle (UAV) and a research aircraft in Korea. For this experiment, the UAV sprayed a cloud seeding material (calcium chloride), and the aircraft monitored the clouds in the southern part of the Korean Peninsula on April 25, 2019. Cloud observation equipment in the aircraft indicated an increase in the number concentration and average particle size of large cloud particles after the seeding. Weather radar reflectivity increased by approximately 10 dBZ above the experimental area due to the development of clouds and precipitation systems. Rain was observed after seeding, and 0.5 mm was recorded, including natural and mixed precipitation from the cloud seeding. In addition, it showed that the rapid increase in the number of raindrops and vertical reflectivity was approximately 10 dBZ. Therefore, these results showed the possibility of cloud seeding using UAVs and atmospheric research aircraft. The effects of cloud seeding are indicated through the increased number concentration and size of cloud particles, radar reflectivity, and ground-based precipitation detection.

## 1. Introduction

Aerosols can act as cloud condensation nuclei or ice nuclei and affect cloud formation and lifetime. Understanding the microphysical effects of aerosols on clouds and precipitation is critical in understanding and predicting climate change [1]. In weather modification technology, cloud seeding materials corresponding to these aerosols act as cloud condensation or ice nuclei, thus affecting cloud and precipitation formation. Weather modification is an advanced scientific technique that is used in the meteorological field to enhance precipitation, suppress hail, and dissipate fog. It is an important method that can be used to alleviate water resource scarcity, drought relief, and forest-fire prevention.

For the future of atmospheric sciences, weather modification techniques are critical. Cloud seeding experiments have been performed using seeding materials that have been used since 1946 [2–5]. Weather modification is a technology in which cloud seeding materials artificially cause cloud condensation and precipitation development in areas of the atmosphere with insufficient cloud condensation or ice nuclei.

Weather modification techniques originated from the discovery that spraying artificial ice nuclei into supercooled clouds can increase the number concentration of ice crystals [2, 3]. The cloud seeding method depends on precipitation formation processes, which vary with cloud temperature. In cold clouds (below 0°C), precipitation is induced by spraying ice nuclei materials, such as silver iodide or dry ice, to

produce or strengthen ice. In warm clouds (above 0°C), precipitation is induced by spraying hygroscopic substances, such as sodium chloride or calcium chloride, which act as cloud condensation nuclei and promote the collision-coalescence process in the cloud. The seeding particles serve to increase the drop-size distribution, which accelerates the rain process [6, 7].

The World Meteorological Association (WMO) noted that the development of meteorological projects, such as weather modification activities, has grown significantly due to an increase in social-economic demand for drought relief, water resources, and fire forest prevention [8]. Weather modification has been proposed as a means to minimize environmental problems and secure water resources at a relatively low cost [9, 10]. Thus, cloud seeding experiments and analysis technologies are needed. Currently, weather modification projects are underway worldwide, including in the United States, China, Japan, the United Arab Emirates, and Russia [8]. Cloud seeding experiments using aircraft have been performed to gain meaningful results [6, 9, 11–26]. Furthermore, the method shows high success for rain enhancement [5, 6, 27–29]. The United States and Thailand are conducting cloud seeding experiments with aircraft to increase long-term precipitation; they suggested an increase in annual precipitation through cloud seeding [30–32]. Various other cloud seeding studies have been conducted using aircraft. An overview of these studies/experiments is provided in the following.

The Wyoming Weather Modification Pilot Project (WWMPP) was performed to statistically evaluate the effectiveness of cloud seeding with silver iodide in the Medicine Bow and Sierra Madre Ranges of south-central Wyoming [30]. The cloud seeding program over the Sierra Nevada mountains region resulted in six successful and five unsuccessful cases [33]. The Seeded and Natural Orographic Wintertime Cloud: the Idaho Experiment (SNOWIE) project was performed to verify the cloud seeding effect using meteorological radar and cloud droplet instrument [34]. The Queensland Cloud Seeding Research Program (QCSR) was carried out in Australia to investigate the cloud seeding effect on cloud and precipitation in a clean aerosol environment [35]. In South Africa, seeding with hygroscopic seeding flares from the wings of an aircraft resulted in an increase in radar-measured rain mass [20]. The cloud seeding experiments in Israel showed the precipitation enhancement over the target area with strong low pressure, precipitation, and wind of synoptic condition [36]. In India, cloud seeding from aircraft-based hygroscopic flares attributed an approximate 17% of the total rainfall. The growth rate was shown to be sensitively affected by aerosol size distribution, vertical velocity, pressure, temperature, and relative humidity [37]. These cloud seeding experiments have been attempted using various types of aircraft, such as helicopters, drones, rockets, and airplanes [8, 38].

In Korea, cloud seeding experiments using aircraft were first conducted in 1963 [39] and are still being used [40–47]. Since 2018, cloud seeding experiments and observations have been executed using atmospheric research aircraft [45, 46]. The available days for a cloud seeding experiment in

Korea are estimated to be between 40 and 91 per annum to cover all the focus areas, namely, water resources, drought relief, forest-fire prevention, and air quality improvement [47]. However, these experiments entail considerable costs associated with building and maintaining infrastructure (e.g., aircraft and equipment).

Recently, an unmanned aerial vehicle (UAV) has been proposed as an alternative, more cost-effective solution to expand weather modification technology. Thus, more recently, UAV systems have been tested for their use in various fields, including meteorology, environment, and its applications [48–52]. The UAV system is a useful tool for cloud seeding operations and efficiency analysis. In the United States, an unmanned aerial system platform was established to investigate the potential of UAVs in conducting cloud observation experiments [48, 50]. They tried to develop a framework to use autonomous unmanned aircraft systems for the operation and evaluation of cloud seeding activities. They found major advantages in using the UAV system for cloud seeding operations that enable the identification of the atmospheric environmental conditions for more effective implementation of cloud seeding. They further provided a context and guidance on using unmanned aircraft systems for the operation and implementation of cloud seeding. For the operation of cloud seeding, a large UAV system, including sensors and seeding material, is needed [48, 50]. The Lower Atmospheric Process Studies at Elevation-a Remotely Piloted Aircraft Team Experiment (LAPSE-RATE) campaign was conducted using an unmanned aerial system to observe the vertical profile of aerosol, carbon dioxide, water vapor, and other meteorological parameters [53]. Compared to manned aircraft, UAVs require less workforce and lower budgets and can fly during severe weather conditions.

This study introduces and analyzes the first cloud seeding experiment using both UAVs and atmospheric research aircraft in Korea. It further presents research direction for future cloud seeding experiments utilizing UAVs. Moreover, the experiment and observations considered the differences between the windward and leeward sides of the flight area and utilized diverse verification methods, such as satellites, radar, aircraft observation equipment, ground-based observation equipment, and numerical models.

## 2. Materials and Methods

In this study, cloud seeding experiments were conducted using a UAV and an atmospheric research aircraft. Figure 1 shows the aircraft and instruments in the (a) UAV and (b) Korea Meteorological Administration (KMA)/National Institute of Meteorological Sciences (NIMS) Atmospheric Research Aircraft (NARA). Table 1 provides the respective specifications. The UAV used in this study is a TR-60 practical tiltrotor UAV developed by the Korea Aerospace Research Institute, which can take off and land vertically and fly at high speeds. This is a next-generation UAV system that can perform reconnaissance and surveillance missions through a fast approach towards the target point [54–56]. It has a wing length of 3 m, maximum takeoff payload of 200 kg, maximum flight time of 5 h, and maximum ceiling altitude of 3 km. This

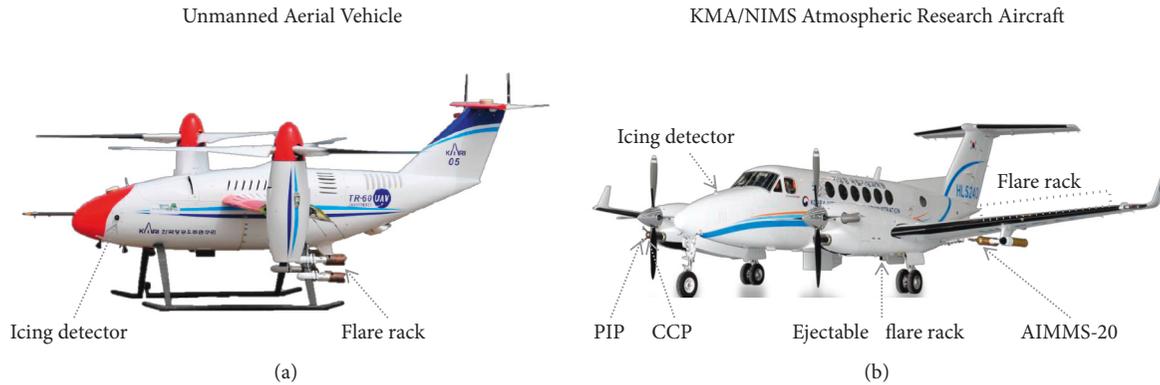


FIGURE 1: Aircraft and its instruments in (a) UAV and (b) NARA.

TABLE 1: Specification of UAV and NARA.

	Unmanned aerial vehicle (UAV)	KMA/NIMS Atmospheric Research Aircraft (NARA)
Type	TR60	King Air 350 HW
Manufacturer	Korea Aerospace Research Institute (Korea)	Beechcraft (USA)
Size (m)	Wing: 3	L/W/H: 14.22/17.65/4.37
Maximum ceiling (km)	3	10
Maximum speed (km/h)	240	578
Maximum takeoff payload (kg)	200	7,425
Maximum flight time (hour)	5	5.5
Maximum range (km)	240	2,871
Scientific instruments	Flare rack	Flare rack, CCNC, CIP, CDP, PIP, and WCM-2000

enables vertical takeoff and landing operations in narrow areas, high-speed flight, and high-efficiency reconnaissance and monitoring. To expand the utility of the UAV, it was developed to control a flare rack installed underneath it to conduct cloud seeding experiments. The flare rack is designed to be equipped with four to six flares.

The NARA used in this study was a King Air 350 HW model manufactured by Beechcraft in the United States in November 2017. The engine is a turbo-prop model in which two propellers operate, with a maximum ceiling of 10 km and a maximum flight time of 5.5 h. The NARA was equipped with a total of 25 types of meteorological observation instruments to conduct severe weather monitoring, environmental monitoring, greenhouse gas monitoring, cloud physics observations, and cloud seeding [57]. To conduct cloud seeding experiments, the NARA was equipped with a flare rack, cloud condensation nuclei counter (CCNC) for  $0.75\text{--}10\ \mu\text{m}$  cloud condensation nuclei observation, cloud imaging probe (CIP) for  $7.5\text{--}930\ \mu\text{m}$  cloud particle observation, cloud droplet probe (CDP) for  $2\text{--}50\ \mu\text{m}$  cloud particle observation, precipitation imaging probe for  $100\text{--}6,200\ \mu\text{m}$  precipitation particle observations, and multielement water content measurement (WCM-2000) for liquid water content. Cloud physics observations and cloud seeding experiments using NARAs have been actively conducted since 2018 and showed increases in cloud particle size and ground precipitation [45].

To conduct the cloud seeding experiment, the first in Korea to use both the UAV and NARA, an experimental design suitable for the purpose of each aircraft was prepared.

The experiment sprayed cloud seeding material using the UAV and observed the atmospheric conditions and cloud particles using NARA. To apply cloud seeding to warm clouds, the UAV was equipped with calcium chloride flares from the Ice Crystal Engineering company. To verify the experiment results, data from the CIP, CDP, weather radar, automatic weather system (AWS), micro rain radar, disdrometer, and a numerical model were analyzed.

Variations in the cloud particle microphysics were analyzed using cloud physics observation equipment mounted on the NARA. The C-band weather radar at the Korea Aerospace Research Institute was used to record reflectivity changes. Rainfall detection and amount data were collected from the ground-based observation network within the seeding particle diffusion range and time. In addition, the reflectivity before and after the experiment and the size distribution of the raindrops by field observations, such as by micro rain radar and disdrometer, were analyzed.

To verify the effectiveness of the cloud seeding experiment, a numerical simulation was performed using a weather research and forecasting (WRF) model. The Morrison microphysical scheme [58] of the WRF model was modified for the cloud seeding experiment, which was successfully simulated for orographic cloud in the winter [59].

### 3. Results and Discussion

*3.1. Description of Cloud Seeding Experiment.* Processes, such as weather forecast analysis, seeding scenario establishment, and licensing for aircraft operations, were conducted prior

to the cloud seeding experiment. The experiment was conducted by observing variations in atmospheric conditions and cloud particles using the NARA after spraying cloud seeding material using the UAV. This was conducted on April 25, 2019, during which the UAV flew from 0912 to 1037 local standard time (LST) (85 min) and the NARA flew from 0930 to 1254 LST (204 min). The UAV sprayed the cloud seeding material from 0917 to 1029 LST (72 min). The study area included Goheung and Boseong, Jeollanam-do. Figure 2 shows the target area and flight path of seeding by the UAV and the observation by the NARA over the southern part of the Korean peninsula. The UAV seeded the clouds using 12 calcium chloride flares at a height of 760 m on the windward side of the area; the NARA traveled straight at 1–2 km in height on the windward and leeward sides.

### 3.2. Weather Conditions during Cloud Seeding Experiment.

Investigating whether the weather conditions were suitable before the cloud seeding experiment was a major factor influencing its success. Moreover, the seeding material species are dependent on the threshold for atmospheric temperature. Thus, the threshold value and weather conditions were compared (Table 2). Table 2 provides the weather condition checklist for this experiment. The atmospheric conditions for cloud seeding experiments in warm clouds, as suggested by the NIMS, are a temperature above 0°C, a liquid water content over 0.1 g/m<sup>3</sup>, and a wind speed below 15 m/s at the seeding height. The NARA performed the atmospheric conditions at the seeding height to ensure the suitability of these conditions for seeding. The measured conditions were as follows: temperature of 10.1°C, liquid water content of 0.71 g/m<sup>3</sup>, and wind speed of 6.9 m/s.

Information on the prevailing synoptic conditions is useful to estimate the movement and characteristics of the cloud system for cloud seeding purposes. The synoptic weather conditions by Unified Model (UM) in KMA and satellite infrared satellite image during this experiment are provided in Figure 3. Figure 3 shows the (a) surface weather chart, (b) the gap between temperature and dew point temperature, dew point temperature, and wind at 850 hPa, (c) the weather chart at 850 hPa, and (d) the temperature at 850 hPa and vertical velocity at 700 hPa at 0900 LST on April 25, 2019. As shown in Figures 3(a) and 3(c), during the experiment, the middle and upper clouds, accompanied by an upper air pressure valley near Balhae Bay, were moving northeast, and the developed low and convective clouds behind them moved northeast to the northern Yellow Sea. As the southwest wind continued to blow from southern China, the dew point deficit in the target area increased from 0 to 1°C (Figure 3(b)), and the vertical velocity was –5 hPa/h, with a weak upward wind (Figure 3(d)). It was presumed that the seeding material sprayed in this moist atmosphere rose vertically and reacted with the cloud particles.

Vertical weather conditions were determined using the vertical sounding profile and (b) precipitable water in Heuksando at 0900 LST and 2100 LST on April 25, 2019. Figure 4 reflects (a) the vertical sounding profile and (b) precipitable water in Heuksando at 0900 LST and 2100 LST

on April 25, 2019. In the vertical profile of the atmospheric conditions, shown in Figure 4(a), the lifting condensation level was recorded at approximately 990 hPa, and the K-index increased by 9.2 after the cloud seeding, indicating the possibility of showers or thunderstorms. In Figure 4(b), the precipitable water increased in most areas from the lower to the upper layer. Moreover, the precipitable water at the surface was 0.65–0.76 mm, and the accumulated precipitable water was 1.70–2.39 m. From this vertical profile, it was observed that moisture and unstable cloud conditions were present, making it suitable for conducting cloud seeding experiments.

Information on the cloud characteristics was based on the data obtained from the Communication, Ocean, and Meteorological Satellite (COMS) and is presented in Figure 5. Figure 5 shows the horizontal distribution of the (a) cloud top height, (b) cloud type, (c) cloud top temperature, and (d) cloud optical depth at 1030 LST, as well as the (e) time series of cloud top height (grey), cloud thickness (green), observed height by the aircraft (black), cloud top temperature (red), liquid water path (blue), cloud base height (red triangle), and cloud type (character) on April 25, 2019. As shown in Figure 5, the cloud top height was 0.5–2 km (Figure 5(a)), and the cloud top temperature was 5–15°C (Figure 5(c)). The cloud optical thickness was 5–25 (Figure 5(d)), and the total liquid water content was 30–70 g/m<sup>2</sup> (Figure 5(e)). This indicates low stratocumulus clouds with liquid status (Figure 5(b)). This experiment was conducted with the NARA flight design that performed the entire cloud distribution from a cloud base of 0.1 km to a cloud top of 1.7 km. The cloud base height calculated from NARA and satellite data was similar to that from the ceilometer at the Boseong Weather Observatory (BSWO), indicating that stratus clouds with a cloud thickness of 0.2–0.3 km occurred.

### 3.3. Results of Cloud Seeding Experiment.

The results of the cloud seeding were determined using field observations and a numerical simulation.

To analyze the drop-size distribution in the cloud to determine the effect of cloud seeding, the information collected by NARA was utilized as shown in Figure 6, which depicts (a) the flight path map, (b) time series of flight height from 1030 to 1145 LST, and (c) average cloud size distribution at 1 km in height before (cyan) and after seeding (blue) on April 25, 2019. Considering the southeast wind and the spraying height during the cloud seeding (Figure 6(a)), the windward side (the section not affected by the cloud seeding material, shown in cyan) and the leeward side (the section affected by the cloud seeding material, shown in blue) were divided into three layers at 2.0, 1.5, and 1.0 km (Figure 6(b)). During the cloud observation flight, the points marked OB1-1 and OB1-2 were observed windward in the order of 2.0, 1.5, and 1.0 km in height, and the points OB3-1 and OB3-2 were observed leeward in the order of 1.0, 1.5, and 2.0 km in height. As shown in Figure 6(c), at 1 km cloud seeding height, the number concentration of the cloud particles below 10 μm in diameter was similar before and



FIGURE 2: Target area and flight path of seeding by the UAV (red) and observation by the NARA (blue) over the southern part of the Korean peninsula on April 25, 2019.

TABLE 2: The weather condition checklist for cloud seeding experiment on April 25, 2019.

	Threshold for warm cloud	Value at seeding height
Temperature ( $^{\circ}\text{C}$ )	Over 0.0	10.1
Liquid water content ( $\text{g}/\text{m}^3$ )	Over 0.1	0.71
Wind speed ( $\text{m}/\text{s}$ )	Below 15.0 for enough time for droplet growing	6.9

after seeding. However, the particle size of the cloud particles over  $10\ \mu\text{m}$  increased. Therefore, the maximum number concentration decreased, and a wide cloud particle spectrum appeared in  $10\text{--}100\ \mu\text{m}$  particles because of the competition effect and formation of precipitation by strengthening the collision-coalescence process in the cloud [14]. In addition, the cloud droplets showed a wide cloud particle spectrum in cloud particles over  $100\ \mu\text{m}$  through giant cloud condensation nuclei activity that appeared due to the tail effect, accelerating precipitation formation [6, 60]. Table 3 compares the average number concentration ( $\text{cm}^{-3}$ ) before and after cloud seeding at a height of 1 km on April 25, 2019. When comparing the result after seeding to those before the cloud seeding experiment, the cloud particles with diameters of  $2\text{--}50\ \mu\text{m}$ , as measured using the CDP, had similar number concentrations after the seeding, whereas those particles with diameters of  $60\text{--}500\ \mu\text{m}$  as measured using the CIP increased 1.52 times, from  $12.52\ \text{cm}^{-3}$  before to  $19.01\ \text{cm}^{-3}$  after cloud seeding, which was significant. The NARA observed an increase in the number concentration of cloud particles on the leeward side after the seeding, which is due to the growth of large cloud particles after cloud seeding.

The weather radar detected the sensitive fluctuation of precipitation in the cloud seeding experiment. The variation in the radar reflectivity to determine the effect of the cloud seeding is shown in Figure 7. Figure 7 shows the (a) horizontal distribution of reflectivity at 1100 LST and (b) time

series of reflectivity (red solid line with circles) and radar precipitation (blue dotted line with triangles) at BSWO (red point) from 0800 to 1400 LST on April 25, 2019. The pink line in the black box in Figure 7(a) is the area in which the UAV sprayed the cloud seeding material, and the red circle represents the BSWO. As shown in Figure 7, reflectivity near the target area was weak, at  $-10$  to  $-5$  dBZ. Figure 7(b) shows reflectivity near the BSWO, which was less than  $-10$  dBZ before the seeding and less than  $-15$  dBZ during the experiment. After the experiment, the reflectivity increased to  $-5$  dBZ due to the inflow of a weak cloud system. This indicates that the cloud seeding enhanced reflectivity as a result of the reaction of cloud seeding material and the growth of cloud particles. This echoes the result of the AgI Seeding Cloud Impact Investigation project conducted in Wyoming, USA, of an increase in reflectivity of approximately 10 dBZ after cloud seeding [23].

The BSWO data was further used to analyze the variation of rainfall on the surface to determine the effect of the cloud seeding (Figure 8). Figure 8 shows (a) the horizontal distribution of rain detection at 1130 LST, (b) the time series of relative humidity (blue), temperature (red), rain (black), and cloud top height (green), (c) the reflectivity, and (d) the number concentration (black) and diameter (red) of raindrops at BSWO from 0800 to 1500 LST on April 25, 2019. After the cloud seeding experiment, rainfall detection showed at the target Beolgyo (BG), Gwangyang-si (GYS), and Hadong

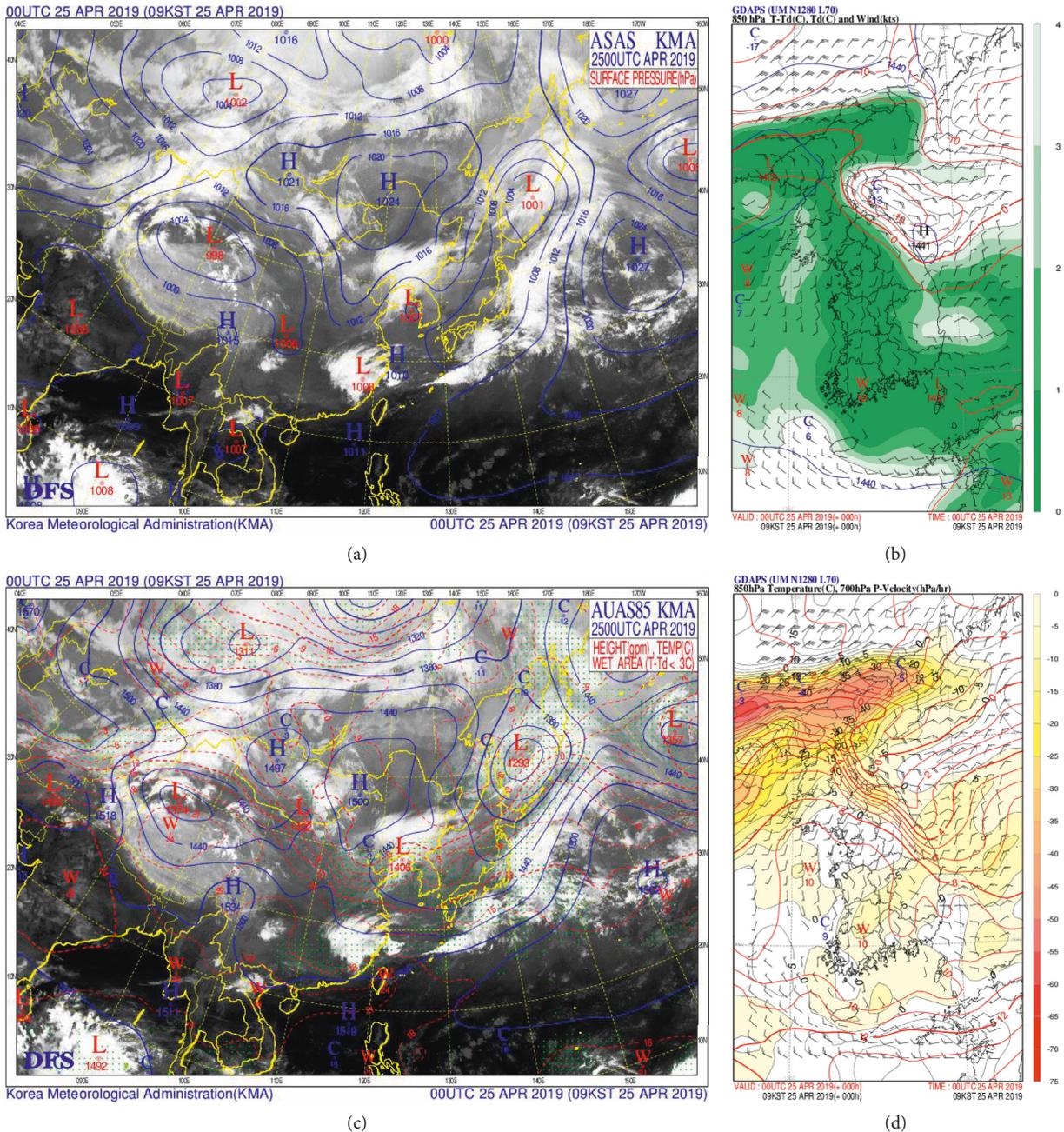


FIGURE 3: (a) Surface weather chart, (b) gap between temperature and dew point temperature, dew point temperature, wind at 850 hPa, (c) weather chart at 850 hPa, and (d) temperature at 850 hPa and vertical velocity at 700 hPa at 0900 LST on April 25, 2019.

(HD) AWS sites (Figure 8(a)). At the BSWO site (Figure 8), rain was detected but rainfall was not recorded after the cloud seeding experiment at 1023, 1036, 1045, 1050, or 1053 LST. In addition, these three sites recorded approximately 0.5 mm of precipitation, which was presumed to be a mix of natural precipitation and precipitation caused by seeding. At the BSWO, the relative humidity was 84–94% (humid conditions), and the temperature decreased by more than 1°C after the experiment (Figure 8(b)). In Figures 8(c) and 8(d), the cloud seeding time is shown in a red box, and the cloud seeding effect time is shown in a purple box. After cloud

seeding, the reflectivity increased by approximately 10 dBZ at 750 m in height at 1120 LST. Additionally, the average number concentration of the raindrop particles increased rapidly, and raindrops of approximately 0.2 mm were recorded from 1100 to 1135 LST. Although rainfall was not observed at the BSWO at 1100 LST, the effects of the seeding could be estimated through rainfall detection, increased reflectivity, and the increased number concentration and size of the raindrops.

A numerical model is a useful tool to estimate the dispersion of seeding material and the increase in rain

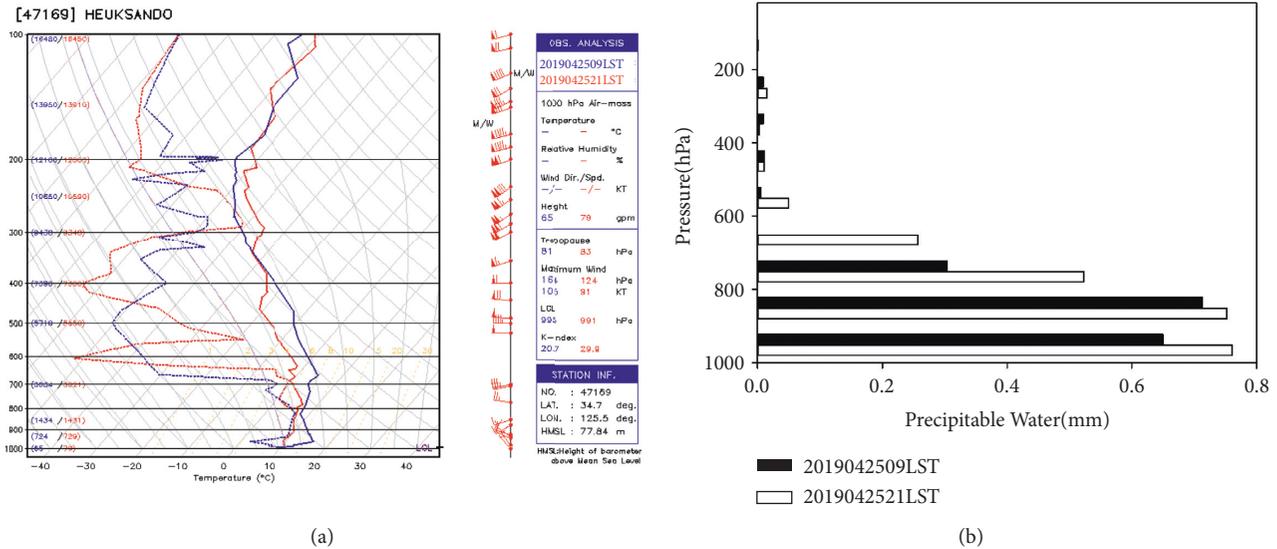


FIGURE 4: (a) Vertical sounding profile of sounding and (b) precipitable water in Heuksando at 0900 LST and 2100 LST on April 25, 2019.

during a cloud seeding experiment because the classification of natural and artificial (by cloud seeding effect) precipitation is complex. The modified numerical model simulation was used to verify the dispersion of seeding material during the cloud seeding experiment (Figure 9). Figure 9 shows the numerical simulation of the horizontal distribution of the seeding material dispersion (calcium chloride (CaCl<sub>2</sub>)) at (a) 0930, (b) 1030, and (c) 1130 LST as well as precipitation differences at (d) 0930–1030, (e) 1030–1130, and (f) 1130–1230 LST on April 25, 2019. Figure 9 shows a numerical simulation performed using the WRF model with Unified Model-Local Data Assimilation and Prediction System analysis data and global positioning system location information as input data [61]. In Figures 9(a)–9(c), the shaded area indicates the distribution of the number concentration of the seeding material (calcium chloride), and the vector represents the wind field at 0.75 height. The seeding material after being sprayed dispersed throughout the points of Boseong (BS), BSWO, BG, Gwangyang-eup (GYU), GYS, and Geumnam (GN). The cloud seeding material at seeding height spread to the BS, BSWO, BG, GYU, and GYS points due to the southeast wind but gradually spread northwest over time. In Figures 9(d)–9(f), the red and blue colors indicate an increase and decrease in precipitation, respectively. Figures 9(d)–9(f) show that the accumulated rain amount increased in the northwest portions of BS and BSWO, where the seeding material dispersed gradually. Three hours after the cloud seeding experiment, the accumulated rain amount increased to 5.1 mm at 1210 LST (not shown). This is a sufficient response time for calcium chloride, as a hygroscopic material, to react with clouds and precipitation; therefore, this was an effect of the cloud seeding experiment.

**3.4. Designing Cloud Seeding Experiments Using Two Vehicles.**  
 A successful cloud seeding experiment using two types of aircraft can be conducted to mitigate the disadvantages of atmospheric research aircraft. Atmospheric research aircraft have difficulty flying in low clouds. The UAV used for this study can fly in low clouds. Thus, the most important aspect of cloud seeding experiments using UAVs and atmospheric research aircraft is the experimental design. For the two aircraft to perform effectively and coordinated manner during cloud seeding experiments without safety concerns, the experiment must be designed considering temporal and spatial conditions. Figure 10 shows a schematic diagram of the cloud seeding experiment using the UAV (red) and the NARA (blue). As shown in Figure 10, the UAV should perform the cloud seeding first, and the atmospheric research aircraft should subsequently observe the meteorological conditions. Spatially, the experiment can be designed by dividing it into vertical and horizontal areas. Vertically, UAVs should fly in the lower regions of the clouds, and atmospheric research aircraft should fly in the middle and upper levels of the clouds, maintaining at least a hundred meters between the two aircraft to reduce safety problems and accidents. A previous study [50] emphasized maintaining a 100–300 m interval between the two aircraft; thus, this experiment was conducted with an interval of 240–1280 m. Horizontally, the atmospheric research aircraft must fly in a verification area where ground-based observation equipment is installed, and UAVs must fly in the seeding area of the target cloud. Cloud seeding experiments can be verified in various ways (ground-based and upper layers). Overall, when designing cloud seeding experiments using multiple aircraft, the UAV should spray cloud seeding material near the cloud base over the experimental area first, and atmospheric research aircraft should observe the

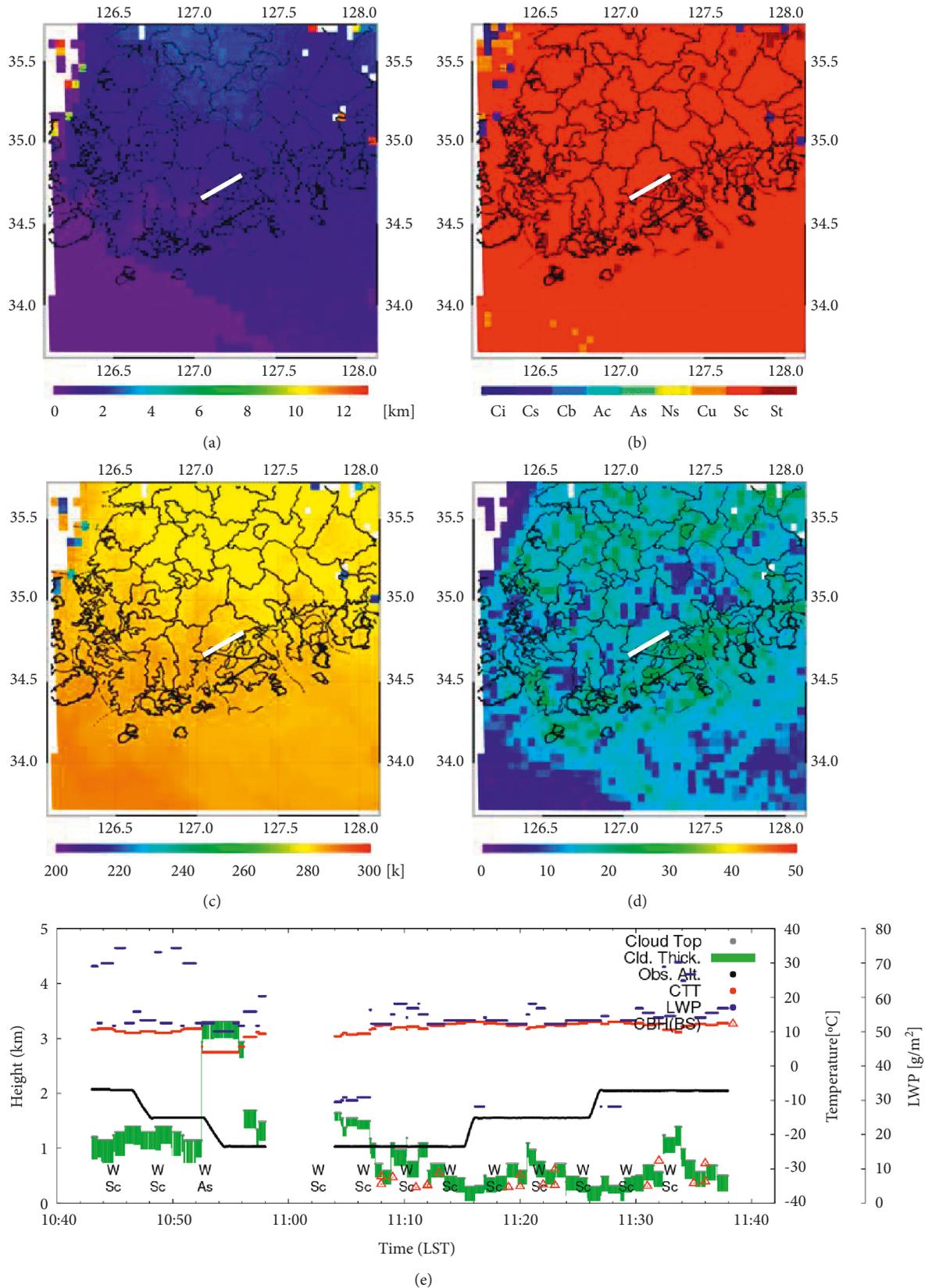


FIGURE 5: Horizontal distribution of (a) cloud top height, (b) cloud type, (c) cloud top temperature, (d) cloud optical depth at 1030 LST, and (e) time series of cloud top height (grey), cloud thickness (green), observed height by aircraft (black), cloud top temperature (red), liquid water path (blue), cloud base height (red triangle), and cloud type (character) on April 25, 2019.

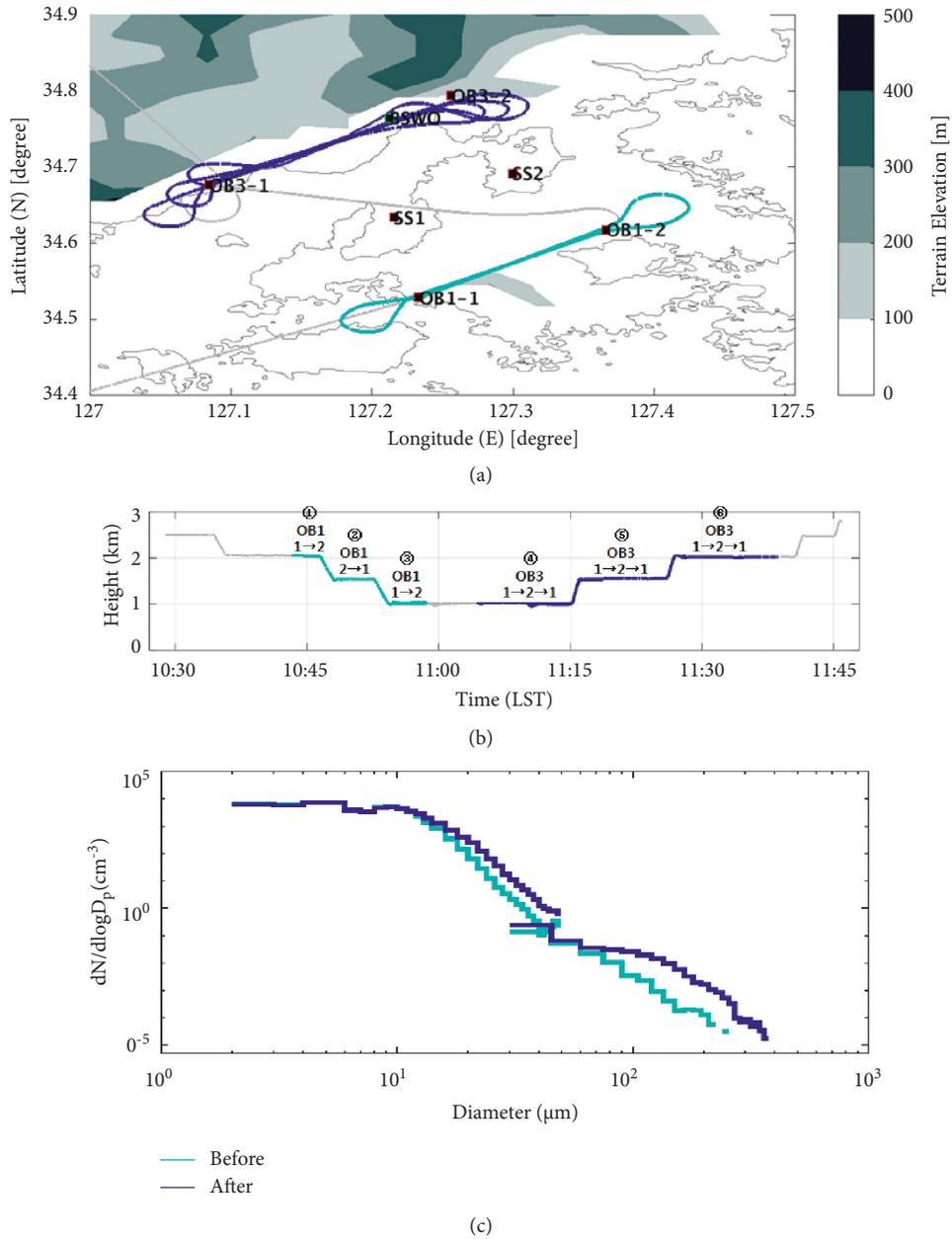
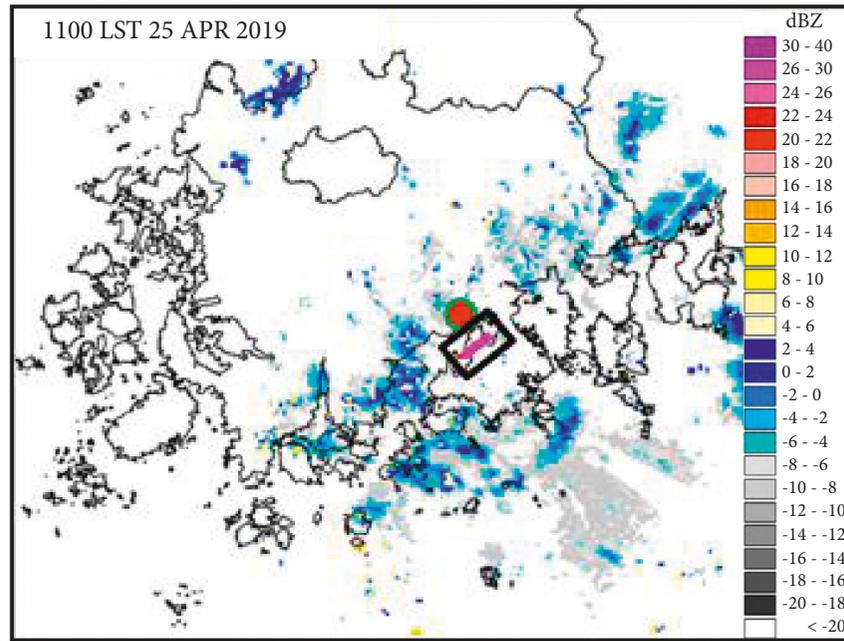


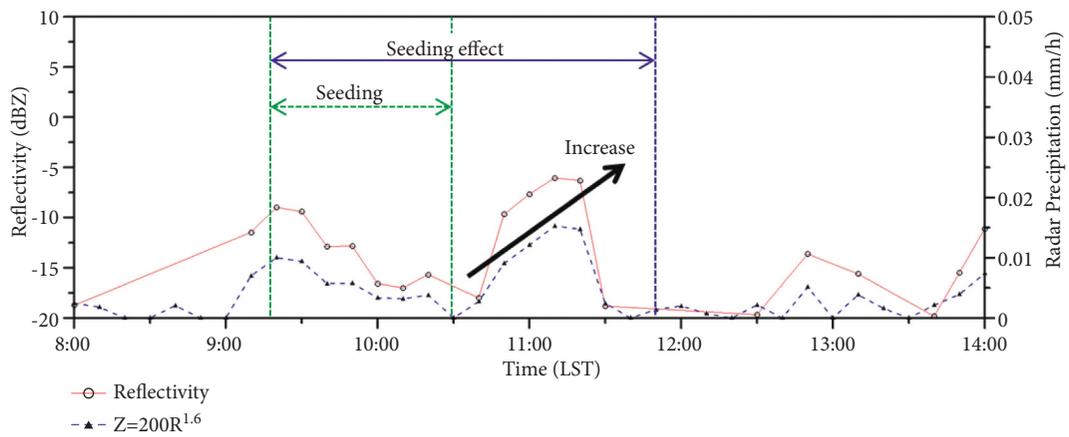
FIGURE 6: (a) Flight path map, (b) time series of flight height from 1030 to 1145 LST, and (c) average cloud size distribution at 1 km height before (cyan) and after seeding (blue) on April 25, 2019.

TABLE 3: Comparison of average cloud number concentration ( $\text{cm}^{-3}$ ) between before and after cloud seeding at 1 km height on April 25, 2019.

	Small cloud droplet (2~50 $\mu\text{m}$ )	Large cloud droplet (60~500 $\mu\text{m}$ )
Before cloud seeding ( $\text{cm}^{-3}$ )	4671.05	12.52
After cloud seeding ( $\text{cm}^{-3}$ )	4648.38	19.01
Variance	1.00 time	1.52 times

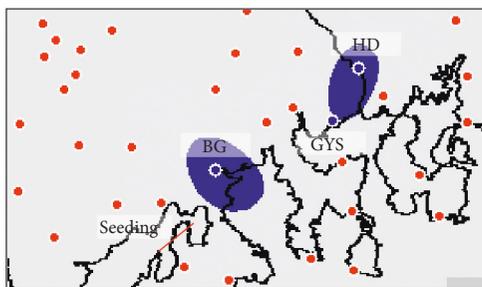


(a)

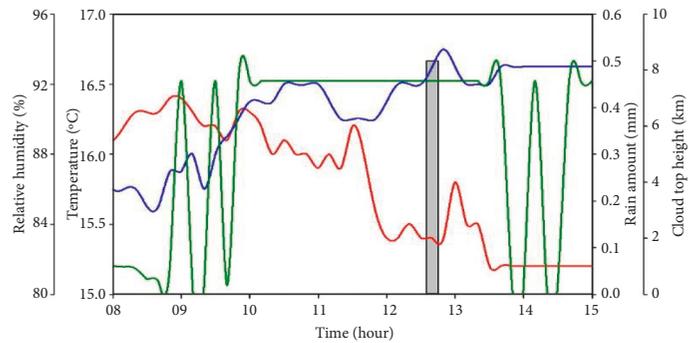


(b)

FIGURE 7: (a) Horizontal distribution of reflectivity at 1100 LST and (b) time series of reflectivity (red solid line with circle) and radar precipitation (blue dotted line with triangle) at BSWO (red point) from 0800 to 1400 LST on April 25, 2019.



(a)



(b)

FIGURE 8: Continued.

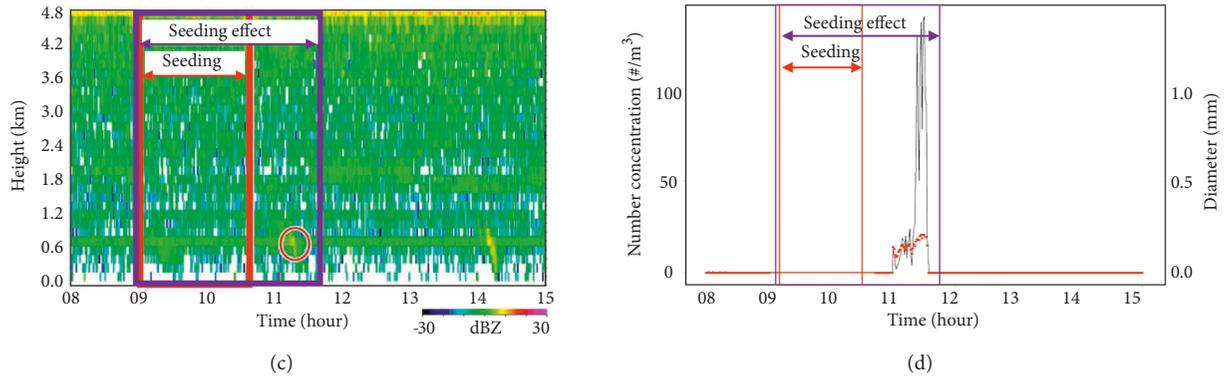


FIGURE 8: (a) Horizontal distribution of rain detection at 1130 LST, (b) time series of relative humidity (blue), temperature (red), rain (black), cloud top height (green), (c) reflectivity, and (d) number concentration (black) and diameter (red) of raindrop at BOWO from 0800 to 1500 LST on April 25, 2019.

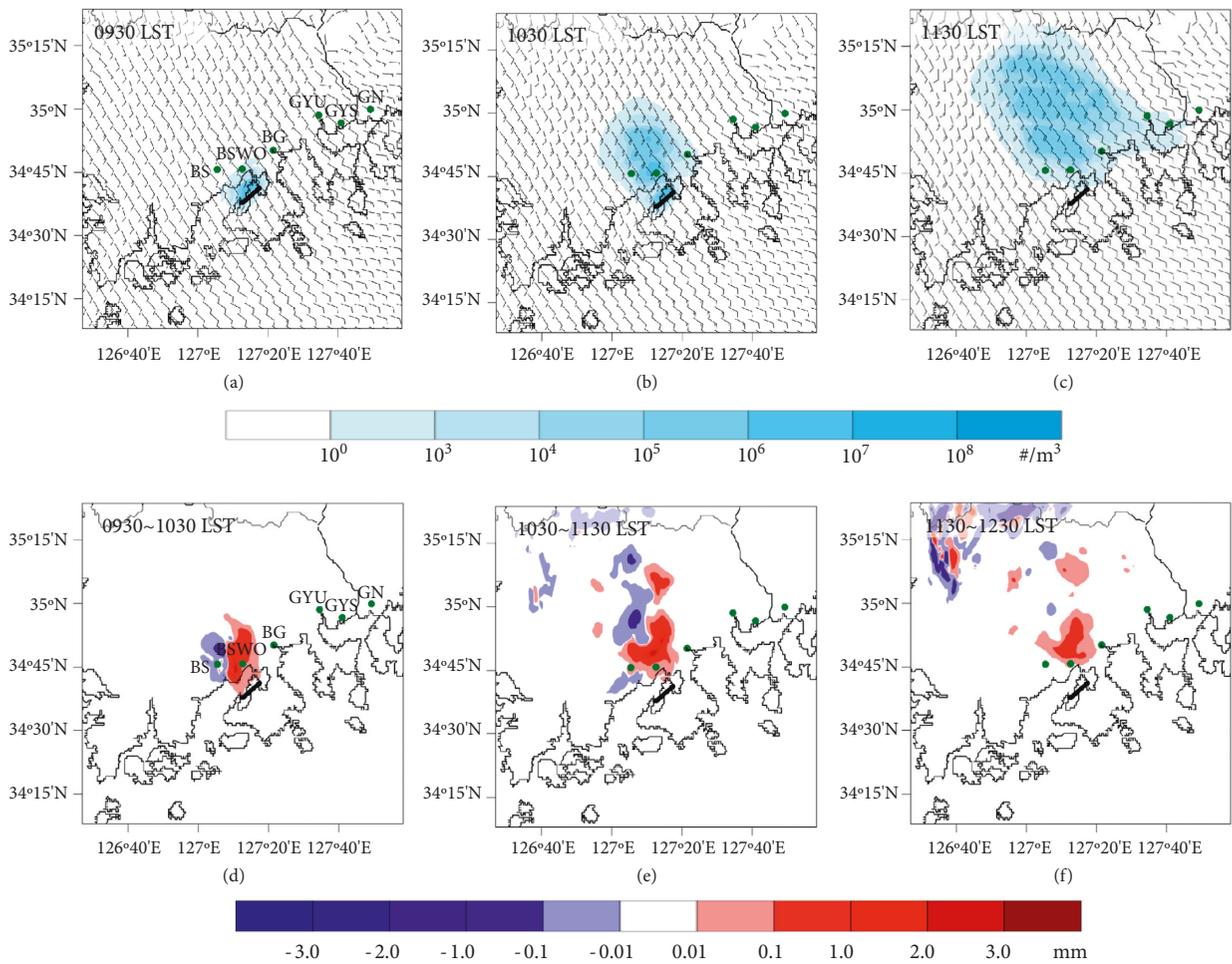


FIGURE 9: Horizontal distribution of seeding material dispersion (calcium chloride (CaCl<sub>2</sub>)) at (a) 0930, (b) 1030, and (c) 1130 LST and precipitation difference at (d) 0930-1030, (e) 1030-1130, and (f) 1130-1230 LST on April 25, 2019, by numerical simulation.

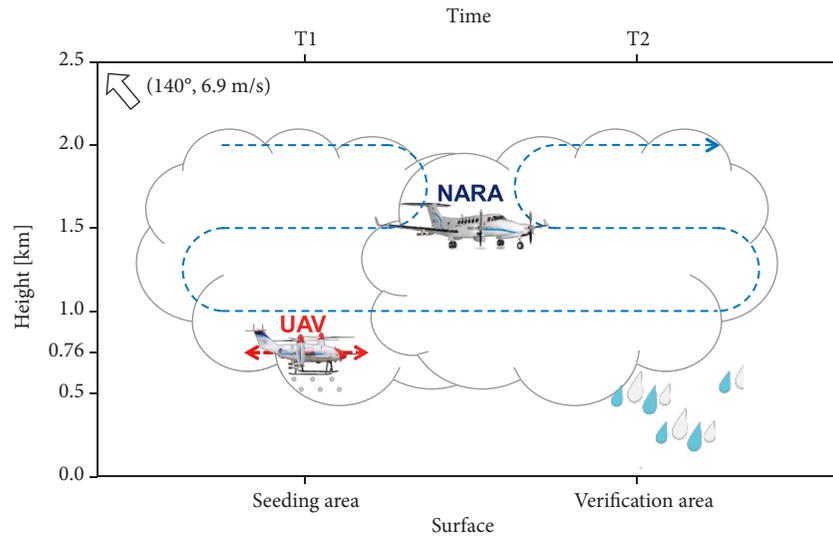


FIGURE 10: Schematic diagram of cloud seeding experiment by UAV (red) and NARA (blue).

atmospheric conditions in the middle and upper cloud layers over the verification area at a later stage. Effective and safe cloud seeding experiments and verification can therefore be conducted by using these two types of aircraft. This study (especially, Figure 10) will serve as a guideline for cloud seeding experiment using two or several aircraft.

#### 4. Conclusions

This study investigated for the first time in Korea the possibility of cloud seeding using crewed atmospheric research aircraft and UAVs. A thorough experimental design was prepared to spray cloud seeding material with the UAV and to observe the cloud physics by using the NARA. The meteorological conditions (temperature, liquid water content, and wind speed) on April 25, 2019, were suitable for cloud seeding experiments using calcium chloride as seed material. It showed that there were low clouds with liquid status, moist conditions, and a 0-1°C dew point deficit in the experimental area. Observations showed an increase in the number concentration of cloud particles over 10  $\mu\text{m}$  in diameter, an increase in radar reflectivity of over 10 dBZ, rainfall detection, and an increase in the number concentration and size of the raindrops. Moreover, a numerical simulation showed the dispersion of the cloud seeding material. Therefore, the growth of the clouds and raindrops was likely due to the cloud seeding experiment. The analysis criteria for cloud seeding effects proposed by the NIMS and KMA are increased surface precipitation, cloud particles, and radar reflectivity [45]; thus, this study shows suitable results.

Although increases in precipitation and clouds in the target area after the experiment were indicated, this may have been a natural increase. Therefore, statistical verification through more experiments is needed. Although this was the first cooperative experiment using UAVs and atmospheric research aircraft in Korea, we expect to see similar

experiments from other researchers and collaborative operators. Priority for investment to develop further weather modification technologies was analyzed using the 10 indicators for 16 technologies and noted that the development of new weather sensors for UAVs, spraying and diffusion of cloud seeding material, verification, numerical modelling, and ground-based experiments are required [62]. Therefore, the KMA will continue to strive for technology development in cloud seeding experiments using UAVs and atmospheric research aircraft. In the future, we plan to improve cloud seeding efficiency using UAVs through continued dual aircraft experiments.

#### Data Availability

The data that support the funding of this study are available from the corresponding author from NIMS, KMA, Korea.

#### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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