Research Article

Case Study of Ground-Based Glaciogenic Seeding of Clouds over the Pyeongchang Region

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Ground-based glaciogenic seeding experiments were conducted at the Daegwallyeong Cloud Physics Observation Site (CPOS) from 2012 to 2015 for the target area Yongpyeong, which lies 9 km away. The preseeding (NOSEED) and seeding (SEED) periods were defined based on the simulation results of AgI concentration ($>10 \text{ L}^{-1}$) in the Weather Research and Forecast (WRF) model with the modified Morrison scheme in microphysics. It was difficult to determine whether snow enhancement via seeding occurred over the entire target area due to uncertainties associated with limitations such as observations and numerical model based on only two points (seeding and target sites). However, in three of four cases, the vertical reflectivity from micro rain radar, total concentration, and average size of snow particles observed at PARSIVEL and precipitation increased in the seeding effect time. In two of four cases, the simulated increased precipitation during the seeding effect time was also observed. In one case that did not show changes after seeding, it is analyzed that a sufficient cloud depth was not supplied to the seeding region due to the blocking effect of the Taebaek Mountains.

1. Introduction

Clouds in the atmosphere are potential water resources; however, only a small proportion of clouds fall as precipitation. To secure water resources, cloud seeding can be used to enhance precipitation and accelerate precipitation efficiency by injecting artificial ice nuclei (IN) or cloud condensation nuclei into targeted clouds [1]. Many studies have been conducted since the first successful field experiment by Schaefer [2]. Experiments on winter snow enhancement through glaciogenic seeding from the upwind side of mountainous areas have shown a high probability of success [3, 4].

It is difficult to distinguish between the orographic increase in precipitation and precipitation increased by seeding. Microphysical studies through direct observations using airborne or surface observation may be essential for the verification of the seeding effect. Super and Heimbach

[5] and Super and Boe [6] performed aircraft sampling above the target area after ground-based inserting IN into mountain clouds during winter in the Rocky Mountains. They have shown that ice particle concentration increased in seeded zones compared to control zones. Direct evidences for the changes in precipitation rate, ice crystal habits, and concentration after seeding were confirmed on the ground.

In the silver iodide (AgI) Seeding Cloud Impact Investigation (ASCII) pilot project, Geerts et al. [7] confirmed an increase in radar reflectivity at the boundary layer (0.5–1.0 km) of mountainous areas during seeding. Pokharel et al. [8] separated upstream (control) and downstream (target) regions based on the location of the AgI generator and defined the preseeding (NOSEED) and seeding (SEED) periods. They confirmed an increase in the radar reflectivity during SEED compared with the NOSEED period.

Ground-based snow enhancement experiments at the Daegwallyeong Cloud Physics Observation Site (CPOS) in

FIGURE 1: The model domain and topography of the experimental region. The triangle, circle, and square indicate the locations of the Yongpyeong observatory (YP), Cloud Physics Observation Site (CPOS), and Gangwon Regional Office of Meteorology (GN), respectively. The dashed line from A to B represents the horizontal cross section passing through YP, CPOS, and GN.

South Korea have been conducted continuously since 2006, targeting Yongpyeong, where the alpine skiing competition of the 2018 Winter Olympics was held. Lee et al. [9] verified an increase in snowfall at CPOS after ground-based AgI seeding in 2006. However, they examined the change in snowfall via rapidly forced condensation processes (~ 1 min) at the seeding site CPOS and did not analyze the seeding effects in the downwind target area to show the extension of the seeding effect.

In this study, we examined changes in clouds and precipitation in the downwind target area after ground-based AgI seeding, following the methods of Geerts et al. [7] and Pokharel et al. [8]. But, by the modified WRF (Weather, Research and Forecast) model, the simulated AgI dispersion was used to distinguish the periods unaffected (NOSEED) and affected (SEED) by seeding in the target region. For four seeding experiments, the observed and simulated changes of cloud and surface precipitation during the period between NOSEED and SEED were examined.

2. Methods

2.1. Experimental Design. Figure 1 shows the topography of the experimental area and the model domain. The domain for numerical simulations was set to the Korean Peninsula (domain 1, D1) and Gangwon (domain 2, D2), using a two-way grid nesting procedure to simulate D2 more precisely. The CPOS ($37^{\circ}41'N$, $128^{\circ}45'E$, 843 m MSL), which was used as the seeding site, is located on the ridge of the Taebaek Mountain Ranges about 13 km southwest from the Gangwon

Regional Office of Meteorology (GN, $37^{\circ}45'N$, $128^{\circ}53'E$, 26 m MSL). The Yongpyeong observatory (YP, $37^{\circ}38'N$, $128^{\circ}40'E$, 772 m MSL) is about 9 km southwest from the CPOS. A-B in model domain 2 (D2) stands for a horizontal path of cross section, passing YP, CPOS, and GN. To minimize the possibility of orographic cloud and precipitation enhancement, the target area at YP was designed to be lower than the seeding point CPOS with an altitude difference of ~ 70 m.

Ground-based AgI seeding experiments were performed at CPOS from 2012 to 2015 by burning the 2% AgI- NH_4I -acetone solution, converting supercooled liquid water into ice crystals. In general, AgI is activated as IN at temperatures of $-5^{\circ}C$ or lower [10]. However, Blair [11] suggested that the AgI- NH_4I -acetone solution is activated as IN at warmer temperatures ($-3^{\circ}C$) through a cloud chamber-wind tunnel experiment. Four experimental cases were selected in which, at a low temperature ($< -3.5^{\circ}C$) and under the influence of northeasterly wind at CPOS, the AgI seeding amount was 0.63 g min^{-1} , the average liquid water content (1 h before experiment until the end of the experiment) was above 0.1 g m^{-3} (0.5–1 km) at GN. The observed meteorological information is listed in Table 1. Except for the missing EXP1 data, the average liquid water content at GN (1 h before seeding to the start of seeding) was $0.10\text{--}0.29 \text{ g m}^{-3}$. The height peak CPOS is 843 m MSL, and thus the LWC of incoming cloud is estimated in the vertical range of 500–1000 m. Stratiform clouds with sufficient liquid water content moved toward CPOS. Easterly winds of 5 m s^{-1} or lower flowed into CPOS during the seeding period, and AgI particles injected

TABLE 1: Summary of the ground-based glaciogenic seeding experiments during 2012–2015.

Exp. number	Location		GN	Burning period (LST)	Temp. ³ (°C)	CPOS		WD ³ (deg)	Visibility ³ (m)	NOSEED (LST)	YP ⁴		Post-SEED (LST)	Enhanced rainfall ⁵ (mm)	MRR ⁶	Results	
	Date	LWC ¹ (g m ⁻³)				Cloud type ²	WS ³ (m s ⁻¹)				WS ³ (m s ⁻¹)	SEED (LST)				SEED (LST)	Total conc. (L ⁻¹)
EXP1	2012.02.25	N/A	StNs	1425–1455	–5	3.6	3.6	52	233	1345–1435	1435–1525	1525–1655	Yes (0.5)	Yes	Yes	N/A	N/A
EXP2	2013.03.13	0.29	StNs	1800–1900	–5.3	1.3	1.3	55	186	1705–1815	1815–1925	1925–2015	Yes (0.5)	Yes	Yes	2.3 → 4.5	0.63 → 0.72
EXP3	2014.01.04	0.28	St	1530–1600	–4.8	1	1	45	151	1455–1550	1550–1645	1645–1735	-	No	No	N/A	N/A
EXP4	2015.04.07	0.10	StAs	1510–1610	–3.7	N/A	N/A	64	123	1405–1520	1520–1635	1635–1725	Yes (0.5)	Yes	Yes	6.9 → 8.3	0.61 → 0.70

¹ Average liquid water content between 500 m and 1000 m MSL during the period from 1 h before turning the generator on to turning it off. ² Cloud type based on human-eye observations during the period from 1 h before turning the generator on to turning it off. ³ Average weather conditions during the burning period. ⁴ SEED is the period during which more than 10⁻¹ L of AgI in the WRF simulation exist on the surface at YP. The NOSEED and SEED periods are equally long, whereas the post-SEED is the 50 min period after SEED as estimated by the SNPS at CPOS. ⁵ The enhanced precipitation by seeding is calculated as the difference between NOSEED and Tot-SEED (SEED + post-SEED). ⁶ “Yes” represents MRR reflectivity increased during Tot-SEED compared with that during NOSEED. ⁷ Variation in the average total concentration and diameter during NOSEED and Tot-SEED.

TABLE 2: Summary of model configurations.

	EXP1	EXP2	EXP3	EXP4
Date	25 Feb. 2012	13 Mar. 2013	4 Jan. 2014	7 Apr. 2015
Period (LST)	0900-2100	1200-0000	0900-2100	0900-2100
Domain	Domain 1 (D1)		Domain 2 (D2)	
Horizontal spacing	5 km		1 km	
Dimension (x, y, z)	$170 \times 170 \times 40$		$121 \times 106 \times 40$	
Time step (s)	15		5	
Model top	50 hPa			
Grid nesting	Two-way			
Initial & boundary layer	KLAPS (1 hour, $5 \text{ km} \times 5 \text{ km}$)			
Microphysics	Morrison scheme			
Planetary boundary layer	YSU PBL			
Land-surface model	Thermal diffusion scheme			
Land use data	USGS (e.g., topo_30s, soiltype_top_30s)			
Longwave radiation scheme	Rapid Radiative Transfer Model (RRTM)			
Shortwave radiation scheme	Goddard shortwave			

directly in the lower clouds (cold fog) with a visibility of ≤ 200 m at CPOS.

Numerical simulations of the four cases were conducted using the WRF mesoscale model, version 3.4, which is a fully compressible, nonhydrostatic, and primitive equation model [12]. The model configuration is listed in Table 2. The domain D2, used for the analyses of all the experiments, consists of 121×106 horizontal grid points with a grid spacing of 1 km and 40 vertical layers. Initial and boundary conditions for hindcast were set using 1 h Korea Local Analysis and Prediction System (KLAPS) data with a 5 km resolution. In this model, the Morrison microphysics scheme was modified to include the actual AgI release at a chosen surface point and ice nucleation process. A detailed description of the ice nucleation process is provided by Kim et al. [13] and Chae et al. [14].

2.2. Instruments. Several instruments were used both upwind and downwind of CPOS. Lee et al. [9] mentioned the importance of humidity in the upwind area as a factor influencing the seeding effect at CPOS. To examine the upwind weather conditions before the seeding, wind profiler (PCL1300, Degreane Horizon) and microwave radiometer (MWR; RPG-HATPRO, Radiometer Physics GmbH) data at GN were used. The wind profiler observes the upper-air wind speed and direction with high vertical resolutions by performing observations every 10 min [15]. The MWR receives microwave signals in 14 frequency bands from the atmosphere and represents measurements of brightness temperature. It may produce the sounding of temperature, humidity, water vapor amount, and liquid water content data.

At the seeding point CPOS, changes in weather conditions and aerosol due to seeding were observed with an automatic weather station (AWS, Vaisala) at 15 m above ground level and a scanning nanoparticle spectrometer

(SNPS; HCTm), respectively, throughout the experiment. The SNPS is connected to a differential mobility analyzer and condensation particle counter and measures the size distribution of 7–282 nm particles. At YP, which is in the downwind area, observation data from the micro rain radar (MRR; Metek) and a PARSIVEL disdrometer (PARSIVEL; OTT Hydromet) were used. Snow depth was not observed during the experimental period; therefore, the precipitation data obtained using a 0.5 mm tipping-bucket rain gauge (JY100097-2; Jinyang) were used for verification. The rain gauge for measuring the snowfall has a time delay of around 20 min due to internal heating (communication with GN). The PARSIVEL is a laser-based optical sensor used for the simultaneous measurement of liquid and solid precipitation particles [16, 17]. The MRR retrieves quantitative rain rate, drop size distribution, radar reflectivity, fall velocity of hydrometeors, and other rain parameters simultaneously on vertical profiles up to several kilometers above the radar [18]. To use the MRR data for snow observations, Maahn and Kollias [19] regarded the main signals from the Doppler power spectrum of raw data as the Doppler speed by snow and calculated the equivalent reflectivity after noise removal and dealiasing. In this study, we analyzed the reproduced data following their proposed MRR processing method.

3. Results

3.1. Description of Cases. Figure 2 shows the synoptic weather situation of the four cases from the Korea Meteorological Administration (KMA) website. At CPOS, air parcels in the seeding experiments move from the East Sea and frequent low clouds and fog occur because it is close to the east coast and there are steep slopes to the east [20]. When the synoptic chart over the Korean Peninsula is of a northern high

FIGURE 2: Synoptic weather charts for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4. The red box indicates the experimental region shown in Figure 1.

and southern low type, the long period of fog (low clouds) often occurs in the Daegwallyeong area due to the northeast airflow. This fog is effective for experiments of direct seeding into clouds because it moves upward via advection along the steep mountain of the Taebaek Mountain Ranges and flows into Daegwallyeong in a supercooled condition [21–23].

The EXP1 case exhibits a cold advection pattern (CA) with a typical high-west-low-east pressure pattern due to the effects of the migratory anticyclone in China and the trough in the Yeongdong region, South Korea, and northeasterly wind flows into the Yeongdong region (Figure 2(a)). Lee [24] confirmed that, in CA, the cold advection via northeasterly winds results in precipitation in the Yeongdong region in general. The EXP2, EXP3, and EXP4 cases exhibit the low-pressure patterns (LPs) that passed along the Japanese islands resulting in easterly airflow into the Taebaek mountains (Figures 2(b)–2(d)). In the LPs, an easterly wind with high

humidity lasting for 1–2 days produced easterly orographic low clouds in the Daegwallyeong region.

3.2. Simulated Results. We compared the simulated and observed precipitation to verify the performance of the WRF model. Figure 3 illustrates the 12 h accumulated simulated and observed precipitation over the simulation period of each case. In most cases, the simulated precipitation is slightly underestimated in the coastal area, overestimated in the mountainous area. However, the simulated precipitation pattern was reasonably consistent with the observations.

Figure 4 shows vertical cross sections of the AgI particle concentration, cloud water mixing ratio, temperature, and wind vectors at the 30 min after the AgI generator was turned on. AgI diffuses toward YP in all simulations. Cloud water mixing ratio more than 0.1 g kg^{-1} was simulated above CPOS for all the cases, and northeasterly winds of $7\text{--}10 \text{ m s}^{-1}$ from CPOS to $1.5\text{--}2.0 \text{ km}$ MSL were simulated from the CPOS

FIGURE 3: The 12 h accumulated precipitation (mm) of nonseeded simulation and rain gauges for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4. The simulated precipitation is color shaded, overlaid by the rain gauge precipitation in color-filled circles. The cross indicates the location of CPOS.

to YP in EXP1, EXP2, and EXP4. In EXP3, the relatively low wind speed of 5 m s^{-1} was simulated. The 9 h simulated vertical wind by this model for 1.5–2.0 km MSL at CPOS showed agreement with the observed wind by radiosonde at 1800 LST, 13 March 2013 [20]. Compared with the simulated mean wind speed for 1.5–2.0 km MSL at CPOS, the observed surface wind speed appears to be relatively very weak (Table 1) due to the roughness of mountain forests.

Under natural conditions, IN exists less than 1 L^{-1} [7]. The SEED period was defined in accordance with the simulation

results of the AgI concentration ($>10 \text{ L}^{-1}$) at the surface of YP. This value was arbitrarily chosen value in the seeding simulation to induce some difference from the natural value. A period of the same duration as the SEED period before seeding was defined as NOSEED. Figure 5 shows the temporal behavior and residue of aerosol particles after seeding at CPOS. During the background measurements at CPOS, the accumulation mode was predominant, with a mean particle size of 110 nm. After the AgI generator was turned on at 1510 LST, aerosols of 10–100 nm were generated, and the total

FIGURE 4: Vertical cross sections of the AgI particle number concentration (color shaded, m^{-3}), cloud water mixing ratio (blue solid line, g kg^{-1}), temperature (grey solid line, $^{\circ}\text{C}$), and wind vectors at 30 min after seeding simulated by the WRF model. The A-B line is the same as shown in Figure 1.

concentration of aerosols increased to $22,000 \text{ cm}^{-3}$, reaching a maximum for particles around 40 nm . According to the results of Vali et al. [25], the dry $\text{AgI-NH}_4\text{I}$ solution has a size range of $0.01\text{--}10 \mu\text{m}$, and most aerosols exist in the range of $5\text{--}50 \text{ nm}$. Therefore, most of the aerosols observed after seeding seems to be the AgI particles. The particle concentrations steadily decreased after the generator was turned off and then returned to a similar state as the preseeding state at approximately 50 min after the end of seeding. The residue time (post-SEED) after the end of seeding was assumed as 50 min for all the experimental cases. It was assumed that the air mass moving toward YP was affected because the seeding material at CPOS exerted an influence until 50 min after the end of seeding (Figure 5). Therefore, 50 min after the SEED period was defined as the post-SEED period, and the total section affected by seeding was defined as Tot-SEED (SEED + post-SEED).

3.3. Vertical Reflectivity and Precipitation. Figure 6 shows the 10 min accumulated precipitation from the 0.5 mm tipping-bucket rain gauge and the vertical reflectivity from the MRR at YP. The quality control method proposed by Maahn and Kollias [19] removes noise up to the second observation bin (400 m). In Figure 6, the increase in vertical reflectivity was well shown in Tot-SEED compared with that in NOSEED especially for EXP1, EXP2, and EXP4. During NOSEED ($\sim 1400 \text{ LST}$), the reflectivity of $0\text{--}5 \text{ dBZ}$ appeared intermittently at altitudes below 1 km (Figure 6(a)). However, in Tot-SEED, the reflectivity of $5\text{--}15 \text{ dBZ}$ appeared homogeneously from the ground up to around 1.5 km . In the cases of EXP2 and EXP4, no reflectivity was detected via MRR for NOSEED, but reflectivity was observed for Tot-SEED.

In the cases of EXP1 and EXP4, a 0.5 mm increase in precipitation was observed during post-SEED. However, in the case of EXP3, vertical reflectivity showed no significant

FIGURE 5: Distribution of the (a) particle number concentrations with geometric size and (b) time series of the geometric mean (dotted) and total particle number concentrations (solid) of aerosols measured by SNPS at CPOS on 7 Apr. 2015. The dashed lines represent the seeding period.

changes and no precipitation was observed in NOSEED and Tot-SEED. In addition, there was a difference in the reaction time of the seeding effect at YP that corresponded to the downwind side depending on the wind speed at CPOS (Figure 6). For example, the surface wind speeds at CPOS for EXP1 and EXP2 were 3.6 m s^{-1} and 1.3 m s^{-1} , respectively. Therefore, EXP1 is believed to show more rapid precipitation enhancement more rapidly than the other cases. We assumed that the starting time of snowfall at YP was earlier than the detection of precipitation due to the delay in the snow melting time (estimated as about 20 min) in the rain gauge. In Figures 6(a) and 6(d), we believe that the precipitation appears later than the reflectivity due to this delay. On the other hand, in the case of EXP3, the vertical reflectivity showed no significant changes and no precipitation was observed in NOSEED or Tot-SEED (Figure 6(c)).

In the cases of EXP2, the precipitation of 0.5 mm occurred during post-SEED, but the increased reflective was smaller than other cases. For the EXP1 and EXP2, the difference of the seeded and nonseeded simulated precipitations was well appeared near the YP target area (Figure 7). In case of EXP4, an increase in reflectivity and precipitation was observed, but the increase in precipitation in the model by seeding was not shown. Figure 4(d) shows that the simulated temperature near the minimum optimal concentration for ice nucleation ($\sim 10^{-5} \text{ m}^{-3}$), proposed by Xue et al. [26], in the middle between YP and CPOS is about -2.5°C , which is lower than the minimum temperature for ice nucleation (-4°C).

Therefore, we guess that the condition for the ice nucleation is insufficient in the simulation for EXP4 (Figure 7(d)).

To examine the vertical cloud changes before and after seeding, the difference in the frequency-by-altitude diagram (FAD) was calculated following the methods of Yuter and Houze [27] and Pokharel et al. [28]. These diagrams show the normalized frequency of vertical reflectivity by height. The difference FAD for the MRR vertical reflectivity composited during Tot-SEED and NOSEED is shown in Figure 8. The FAD difference analysis was not performed for EXP2 and EXP4 because no reflectivity was observed in NOSEED. In the case of EXP1, the reflectivity increased up to around 1.5 km and about 2 dBZ on the ground (Figure 8(a)). However, in the case of EXP3, the average reflectivity change between NOSEED and Tot-SEED is very small, lower than 0.5 dBZ, indicating that seeding had no significant effect (Figure 8(b)).

Figure 9 shows the vertical wind field observed by the wind profiler at GN. The dashed line indicates the height of wind change from east ($0-135^\circ$) to west ($225-360^\circ$). The altitudes at which the wind field changed one hour before the start of seeding in EXP1, EXP2, EXP3, and EXP4 were 1.6 km, 1.3 km, 0.9 km, and 1.2 km, respectively. In EXP3 (Figure 9(c)), in which there was no increase in precipitation at YP, the thickness of the cloud layer flowing to the seeding point appeared to be relatively thinner because the mountain (the height of peak is about 840 m) blocked the supply of sufficient liquid water (by simple calculation, the easterly cloud

FIGURE 6: Time series of vertical reflectivity measured by micro rain radar (MRR, color shaded) and 10 min accumulated precipitation (grey bar) from the rain gauge at YP for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4.

thickness may be estimated as 60 m, the difference between the height of mountain peak and changed wind field).

To investigate whether the inflow of natural precipitation into YP was the cause of the increased reflectivity of Tot-SEED, 1 h averaged radar reflectivity of PPI0 after the start of seeding was examined (Figure 10). Radar reflectivity was not shown in the target area during the Tot-SEED period for EXP2, EXP 3, and EXP4. For the EXP1, the reflectivity at YP is small (-2 – 0 dBZ).

3.4. Changes in Snow Particles. We investigated microphysical changes such as number concentration and particle size

before and after seeding using PARSIVEL data as in the ASCII study [28–30]. PARSIVEL observes snow particles between 0.062 mm and 25.5 mm with 32 size bins. Figure 11 shows the total snow concentration and mean diameter for EXP2 and EXP4 from PARSIVEL at YP. EXP1 and EXP3 were excluded from this analysis because of missing measurements. In EXP2 (Figure 11(a)), the snow particle number concentration rapidly increased from 1810 LST to 1830 LST. Although the average snow particle number concentration observed by PARSIVEL from 1630 LST to 1750 LST at CPOS (the seeding point) was below 5 L^{-1} , it increased sharply to over 15 L^{-1} from 1750 LST to 1820 LST before the start of seeding (not

FIGURE 7: Differences between the accumulated seeded and nonseeded precipitation (mm) during the period from the start of seeding to the end of post-SEED. The triangle and cross indicate the locations of YP and CPOS, respectively.

shown). Therefore, the period from 1810 LST to 1830 LST when the number concentration at YP increased sharply was excluded from this analysis, considering that the change was not caused by seeding but by a temporary inflow of natural precipitation from CPOS. In the case of EXP2 (Table 1), the mean diameter of Tot-SEED increased from 0.63 mm to 0.72 mm compared to NOSEED, and the total snow particle concentration increased by 1.9 times from 2.3 L^{-1} to 4.5 L^{-1} . In EXP4 (Figure 11(b)), the average particle size

increased from 0.61 mm to 0.70 mm and the particle number concentration increased by 1.2 times from 6.9 L^{-1} to 8.3 L^{-1} in Tot-SEED compared to NOSEED.

In the ASCII project, the total snow concentration was below 0.5 L^{-1} during NOSEED but increased to $2\text{--}15 \text{ L}^{-1}$ during SEED, and a high particle number concentration was maintained even in the post-SEED period. The project suggested that the continuous increase in snow particles during the post-SEED period was caused by a delayed impact

FIGURE 8: Normalized frequency difference from the MRR between NOSEED (dashed) and Tot-SEED (solid) at YP for (a) EXP1 and (b) EXP3.

due to the slow mixing of AgI nuclei in the clouds, the low transport speed, and the slow nucleation rate following the AgI nuclei seeding at the 300 m cloud base. This study also showed that the mean diameter and particle number concentration increased during post-SEED compared to SEED. The simulated AgI dispersion was faster than the wind speed at the same altitude observed with the wind profiler at GN. The relatively large increase of snow particles during the post-SEED appears to be partially due to the earlier simulated end time of SEED.

The particle size distribution data from PARSIVEL are grouped into two parts corresponding with the NOSEED and Tot-SEED. Figure 12 shows differences in the normalized frequency-by-diameter displays for NOSEED and Tot-SEED at YP based on the method of Pokharel et al. [28]. Compared with NOSEED, both large and small particles increased markedly during Tot-SEED. This indicates the effect of seeding, similar to the results of previous studies [30–32].

4. Conclusions and Discussions

In this study, experimental cases from 2012 to 2015 were analyzed to investigate the effects of ground-based AgI seeding on clouds over Pyeongchang region. At YP, the target area downwind of the seeding site (i.e., CPOS), the vertical reflectivity based on MRR increased at altitudes below 1 km during the Tot-SEED period, when the cloud thickness was sufficient. In those cases, the total snow particle number concentration and mean size measured by PARSIVEL also increased after seeding. In all the cases, the 1 h averaged composite reflectivity of grounded scanning radar was absent

or negligible after seeding, and thus the inflow of natural precipitation into YP appeared to be low. As a result, the precipitation increase in Tot-SEED could be attributed to the seeding effect in EXP1, EXP2, and EXP4. The precipitation enhancement is well shown in the simulation by the WRF with the modified Morrison scheme in microphysics seeding effect, especially for EXP1 and EXP2. In the case (EXP3) without any change after seeding, the cloud layer was thinner than the other cases, sufficient liquid water content was not supplied to the seeding area. This is due to the small vertical extent of the easterly wind field, thus showing almost no seeding effect.

There were uncertainties associated with the results. First, the simulated dispersion time of AgI used to define the NOSEED and SEED periods was slightly (below 30 min) faster than the time estimated by the advection with the observed wind speed from wind profiler at GN. However, because we used the same numerical model as that used by Kim et al. [13], it was assumed that the dispersion time of the seeding material was valid in this study.

Second, the inflow of natural precipitation was uncertain. Only the 1 h averaged PPI0 of the composite reflectivity data was used to determine the inflow of natural precipitation. Therefore, the inflow of natural precipitation could not be excluded completely in each case, especially below 1.5 km. Consequently, the increases in reflectivity, precipitation particle size, and particle number concentration that appeared after seeding could not be clearly attributed to the seeding effect. Furthermore, it is difficult to assert that the snow enhancement due to seeding existed in the entire Yongpyeong area due to uncertainties in the observations and numerical model. However, there were many seeding effects such as the

FIGURE 9: Time series of horizontal wind and the signal-to-noise ratio (SNR) of the wind profiler at GN for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4. The vertical solid lines mark the period of AgI generator operation at CPOS. The dashed line indicates the height of wind change. The details of each experiment are listed in Table 1.

microphysical and precipitation difference between NOSEED and Tot-SEED at YP after seeding. Finally, there was no snow depth measurement sensor that could be used to observe the actual snow accumulation before and after seeding at YP. The 0.5 mm tipping-bucket rain gauge used in this study only measured the snow melted by heating, and so the starting time of the increase in precipitation may be delayed. In addition, the actual ending time of the precipitation increase

and the exact precipitation between 0.5 and 1.0 mm could not be determined due to the observational resolution of 0.5 mm. However, if delayed, the appearance of precipitation increase at YP was within the Tot-SEED period.

To reduce the above-mentioned uncertainties, a snow depth meter was installed at YP in May 2015. Furthermore, a precipitation collector was developed to build a system for the analysis of the chemical composition of precipitation at

FIGURE 10: The 1h averaged composite reflectivity of PPI0 after the start of seeding from the Korea Meteorological Administration ground-based operating radars for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4. The red dot indicates the automatic weather station (AWS).

YP in March 2017. Many studies (e.g., [30–32]) have already addressed chemical verification for snow accumulation observed at the target region after seeding. In future experiments, more reliable verifications will be made by analyzing chemical changes in snow and precipitation. To complement these results, an intensive observation and seeding study will be carried out between November 2017 and January 2018 before the Winter Olympics in Pyeongchang.

Disclosure

An earlier version of this work was presented as a poster at Geophysical Research Abstracts Vol. 20, EGU2018-5930,

2018, EGU General Assembly 2018, and Korean Meteorological Society Fall Meeting, 2017.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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(a)

(b)

FIGURE 11: Time series of snow size distribution obtained from the PARSIVEL at YP for (a) EXP2 and (b) EXP4. The dotted and solid lines indicate the mean diameter and total particle number concentrations of snow particles, respectively.

FIGURE 12: Normalized frequency difference from the PARSIVEL between NOSEED (dashed) and Tot-SEED (solid) at YP for (a) EXP2 and (b) EXP4.

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