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Preliminary Results of the Ground-Based Orographic Snow Enhancement Experiment for the Easterly Cold Fog (Cloud) at Daegwallyeong during the 2006 Winter

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ABSTRACT

The snow enhancement experiments, carried out by injecting AgI and water vapor into orographically enhanced clouds (fog), have been conducted to confirm Li and Pitter's forced condensation process in a natural situation. Nine ground-based experiments have been conducted at Daegwallyeong in the Taebaek Mountains for the easterly foggy days from January–February 2006. We then obtained the optimized conditions for the Daegwallyeong region as follows: the small seeding rate (1.04 g min^{-1}) of AgI for the easterly cold fog with the high humidity of Gangneung. Additional experiments are needed to statistically estimate the snowfall increment caused by the small AgI seeding into the orographical fog (cloud) over the Taebaek Mountains.

Key words: snow enhancement experiment, cold cloud modification, forced condensation, AgI seeding, orographical supersaturation

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1. Introduction

The major objective of cold cloud seeding is to enhance the precipitation (snowfall) falling to the ground and to accelerate the precipitation efficiency by inputting artificial AgI particles into the seeding experiment target area. There is much experimental evidence for snowfall enhancement by AgI seeding in the laboratory (Blumenstein et al., 1987; Demott, 1988) and the field (Hill, 1980; Holroyd et al., 1987; Super and Boe, 1988; Rauber et al., 1987), based on the contact freezing process of ice crystallization. However, in these field experiments it is not easy to verify the AgI snowfall enhancement effect because of the difficulty of tracking the AgI particles because of the long (about 1 hour) processing time of contact freezing.

There has been a lot of research related to observation and seeding experiments for orographically produced clouds (Rottner et al., 1975; Hobbs, 1975; Deshler et al., 1989; Li and Pitter, 1996; Kusunoki et al., 2003). Kusunoki et al. (2003) have shown that the ice and supercooled liquid water in orographic snow clouds may grow under weak cold advection at the windward slopes of the Mikumi Mountains. Rottner et al. (1975) have obtained the results that a lower seeding rate gives a much stronger positive effect than a

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Fig. 1. (a) Location and (b) orography (m) of Gangneung, and Daegwallyeong in the Taebaek Mountains.

higher seeding rate in the several airborne and ground-based AgI seeding experiments over the Rocky Mountains.

Li and Pitter (1996) suggested a new ice formation mechanism, the forced condensation freezing process, which has a rapid ($\sim$1 min) process time compared with the contact freezing processing time. This process has been verified in the laboratory (Blumenstein et al., 1987), but needs more confirmation in the field. If the rapid process is obvious and efficient in a natural situation, then it should become very useful in further targeted snowfall enhancement experiments.

In this work, we try to confirm Li and Pitter's forced condensation process in a small-scale (the injection and observation points are 40 m away to verify the rapid process of ice crystallization) open chamber at the Daegwallyeong site by directly injecting AgI or water vapor into the orographically enhanced, almost supersaturated, cold cloud (fog). We have tested three experimental methods: large and small AgI seeding injections and water vapor injection into the steadily drifting cold fog. Nine burning experiments have been conducted and analyzed for the proper weather situation, i.e., the easterly cold fog at Daegwallyeong during the period of January–February 2006.

2. Experimental design

2.1 *Location and condition of experiment*

The Daegwallyeong site, located at 37°41′N, 128°45′E and 842 m from mean sea level, has the Cloud Physics Observation System (CPOS; http://weamod.metri.re.kr; Chang et al., 2007). Figure 1 shows the location of the Daegwallyeong site and the surrounding topography. The ground-based instruments were deployed at the Daegwallyeong site located near the ridge of the Taebaek Mountains.

Figure 2 shows the typical synoptic surface weather chart that may give the relatively long (1–2 days) easterly cold fog at the Daegwallyeong region. A low pressure system in southeast Korea is somewhat blocked by a cP (continental Polar) high pressure system which expanded in the East Sea of Korea, and then moved slowly to the northeast. The low pressure, blocked by the cP high, has generally stayed stationary over the past 1–2 days in southwest Korea, and has lead to the easterly wind near the Daegwallyeong site. Kim et al. (2005) and Lee (1999) have shown that this synoptic condition generally yields the easterly wind and sometimes the heavy snowfall in the Daegwallyeong region. Under this weather condition, the 1–2 days of the easterly wind along with the high humidity of Gangneung, have produced an easterly orographical, probably supersaturated, fog (cloud) at the Daegwallyeong site (Fig. 3).

2.2 *Experimental design*

Burning experiments, which burn the liquefied AgI by propane, by the four ground-based AgI generators, have been conducted at the Daegwallyeong site on the easterly cold foggy days, following the synoptic weather conditions of Fig. 2, from 18 January–19 February 2006. The instruments of CPOS employed for the experiments are the Particulate Matter 10 (PM_{10}), that measures the particulate mass concentration of aerosol below 10 μm, the Automated Weather System (AWS), which measures the atmospheric variables (air temperature of the surface vicinity, wind velocity, wind direction, and relative humidity), and the Ultrasonic snow depth meter, that measures the snow depth.

Figure 4 shows the schematic diagram of the win-

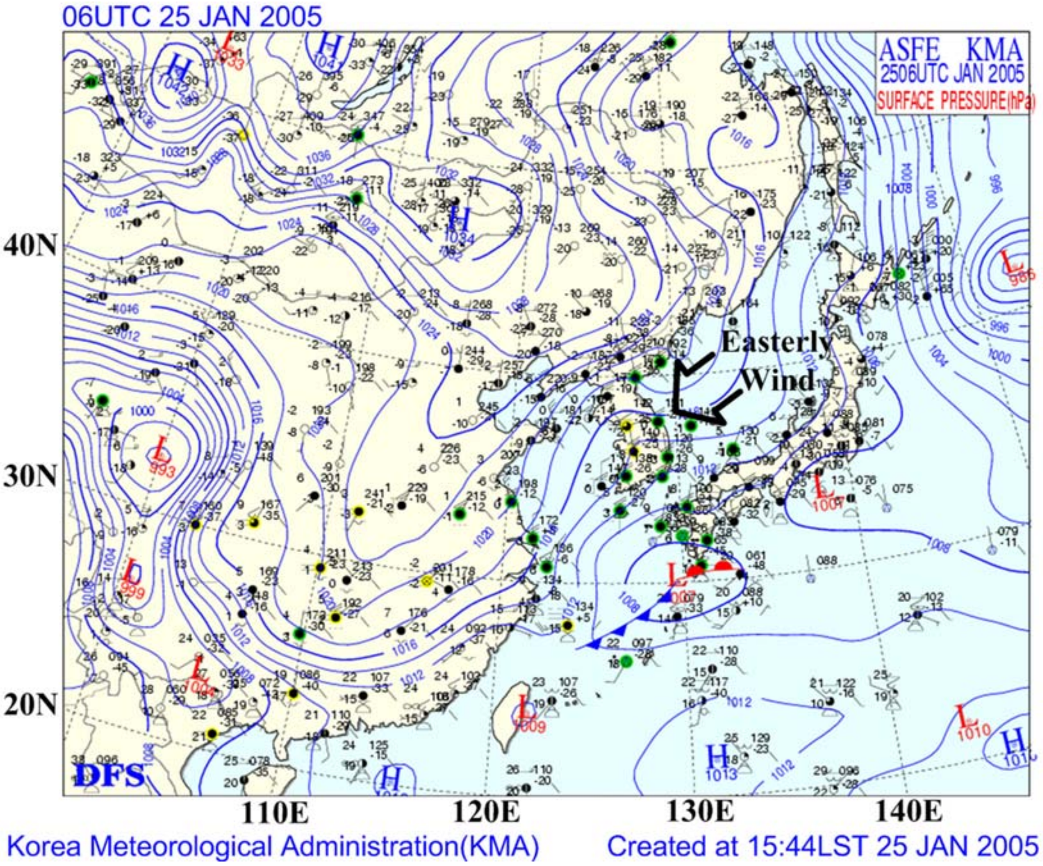

Fig. 2. Typical synoptic weather conditions for the 1–2 days of an easterly wind in winter time at the Daegwallyeong site.

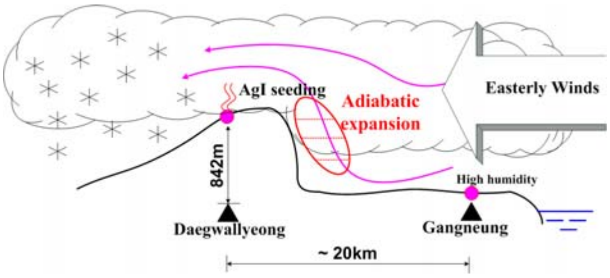

Fig. 3. Schematic diagram of the orographic snow enhancement experiments using the easterly enhanced cloud coming into the Daegwallyeong site.

tertime snow enhancement experiment, which we will use to prove Li and Pitter (1996) rapid forced condensation process at the supersaturated state for snow enhancement at the Daegwallyeong site. The experimental weather conditions pertaining of the easterly, humid wind flow from Gangneung is likely to orographically produce a supersaturated fog (cloud) at the Daegwallyeong site, as shown in Figs. 2–3.

Nine ground-based burning experiments for the easterly cold fog below about 5 m s^{-1} wind speed and near -5°C at the Daegwallyeong site, have been conducted during a 30-min period as follows: four burnings with a small AgI rate (1.04 g min^{-1} per AgI generator), three burnings with a large AgI rate (2.08 g min^{-1} per generator), and two propane combustions. Since we did not know the AgI pluming ratio appropriate to the snowfall enhancement in this region, the two (large and small) ratios of AgI pluming have also been tested. Also, since the propane combustion, which provided the great amount of water vapor into the cold fog (cloud), may contribute to the growth of the snowflake, the propane burning method is considered. The ultrasonic snow depth meter and the PM_{10} are placed about 40 m away from the burning locations to confirm the effect of the rapid (∼1 min) forced condensation process for the slowly moving cloud.

3. Experimental results

Figure 5 shows a time series of the meteorological variables, the hourly snowfall increment, and the PM_{10} concentration for the experiments. In Fig. 5a, the meteorological variables during the experiments maintain an easterly cold fog from 2°C to -6°C in a relative hu-

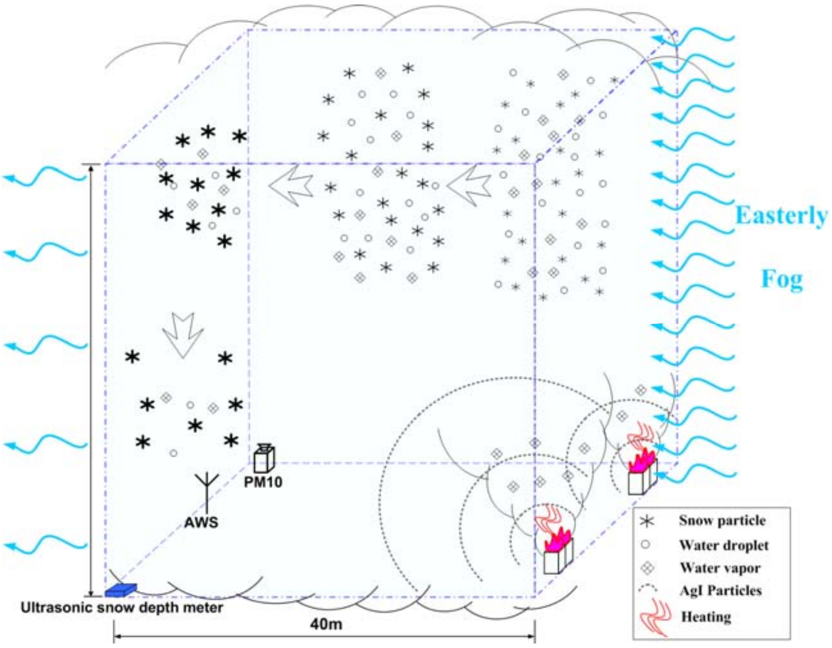

Fig. 4. Schematic diagram of the small-scale cloud seeding experiments at the Daegwallyeong site.

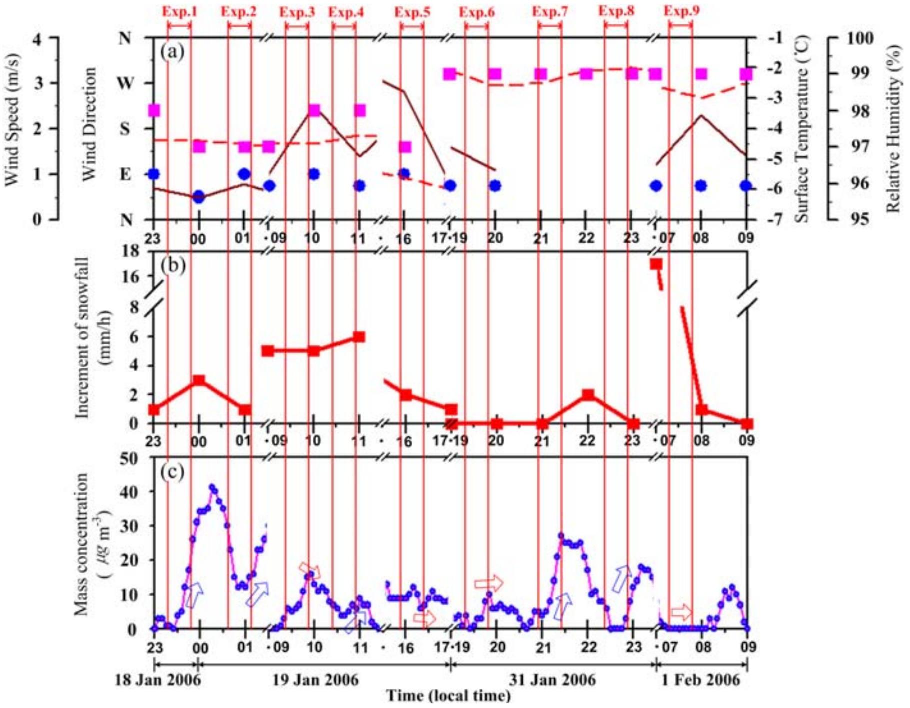

Fig. 5. Time series of the meteorological variables and the measurement of Particulate matter 10 for nine burning experiments: (a) meteorological variables (solid line: wind speed, dashed line: surface temperature, circle: wind direction, square: relative humidity), (b) the 1-h accumulated snowfall increment measured by the ultrasonic snow depth meter, and (c) the mass concentration by the PM_{10}. The arrows denote the trend of the PM_{10} mass concentration.

Table 1. Summary of the snow enhancement experiments.

			Initial condition					Summarized results	
			Daegwallyeong[a]		Gangeung[b]				
No. of Expt.	Date	Burning period (LST)	Surface temperature (°C)	Wind direction/ wind speed (m s^{-1})	Visibility/cloud base height (km)	Relative humidity (%)	Burning method	Trend of PM$_{10}$ mass concentration[c]	Increment of snowfall (mm)[d]
1	2006–01–18	2323–2347	−4.4	NE/0.5	1.2/0.5	94	Small AgI	+	1→3
2	2006–01–19	0038–0108	−4.5	E/0.8	1.2/0.5	95	Large AgI	+	Not shown
3	2006–01–19	0924–0958	−4.5	E/2.5	1.2/0.5	96	Small AgI	+	Not shown
4	2006–01–19	1028–1058	−4.2	ENE/1.4	2/0.5	95	Small AgI	+	5→6
5	2006–01–19	1556–1627	−5.8	NNE/0.8	3/0.5	83	Small AgI	−	Not shown
6	2006–01–31	1922–1952	−2.6	ENE/1.1	6/0.5	93	Only Propane		Not shown
7	2006–01–31	2057–2127	−2.4		6/0.5	94	Small AgI	+	0→2
8	2006–01–31	2227–2257	−2.0		6/0.5	95	Large AgI	+	Not shown
9	2006–02–01	0720–0750	−3.0	ENE/2.3	3/0.5	95	Only Propane		Not shown

Note: [a]These are the averaged values during the processing period defined as one hour after the start of burning. [b] These are the averaged values for 3 hours before the start of burning. [c] + and − denote the increment and decrement during the processing period, respectively. [d] These are the variation between the 30-min period before the start of burning and the processing period.

midity above 96%. Figure 5b shows that the increment of snowfall increases or decreases during the processing period, which is defined as one hour from the 30-min start of burning. During the processing period, the trend of the mass concentration measured by PM_{10} shows an increment except in Expts. 5, 6, and 9.

Table 1 gives the initial conditions, method, and results of the conducted snow enhancement experiments. As shown in Table 1, all the experiments have similar initial atmospheric conditions: the cold cloud flowing into the site with an easterly weak horizontal wind speed. It may be inferred from the visibility and cloud-base height at Gangneung in the easterly wind situation, that the fog in Daegwallyeong is coming from the cloud with the orographic fog, as described in Fig. 3. It is observed to be fully cloudy (stratus) at the Gangnung site (KMA weather station) 3 hours before each experiment. The 30-min averaged liquid water content, measured by FSSP-100 at Daegwallyeong before the start of burning, is 0.10–0.84 g m^{-3} except in Expts. 7–9, which is within the range observed in clouds by many researchers (Dong et al., 2005; Heymsfield and Miloshevich, 1989; Rauber and Grant, 1986). The enhancement of snowfall after the experiment is observed only in three experiments (Expts. 1, 4, and 7). The increment of snowfall only appears in the small AgI seeding method except in Expts. 3 and 5 which agree with Rottner et al.'s results (1975).

In Expt. 3, the wind speed was strongest among all the experiments. We guess that the fast wind did not give sufficient processing time for the forced condensation, as shown in Blumenstein et al. (1987). In fact, a particle drifting with the 2.5 m s^{-1} wind velocity takes 16 seconds to move 40 m, the distance between the burning and observing positions, and then it is a somewhat insufficient time for the forced co ndensation process to occur. In Expt. 5, we think the Gangneung's low humidity is likely the reason that the supersaturated fog (cloud) didn't form, which is necessary for the forced condensation process, in the Daegwallyeong region, as shown in Fig. 3. Another possibility is the decreased trend of the PM_{10} concentration, probably due to the strong upper wind during the processing period, as shown in Fig. 5.

Let's consider the large AgI and water vapor injection experiments that did not give the snowfall increment. It may be supposed in Expts. 2 and 8 that the large AgI injection excessively supplies the ice nuclei in the cloud, and then is likely to make the relatively large-concentrated small-sized ice flakes, insufficient for fall down. The experimental results of the propane combustion suggest the importance of the existence of ice nuclei for snowfall enhancement.

There are many uncertainties for these snow enhancement experiments using the forced condensation process. The experimental results are not based on the direct observation of the ice crystallization process, which measures the spatial and temporal variation of ice flake particles, and it needs to be further developed, such as the instrument consistently measuring the distribution of cloud droplets. Compared with Blumenstein et al.'s (1987) laboratory experimental results for the forced condensation process, our experimental study shows the potential to apply the forced condensation process to the natural situation for snow enhancement. However, further experiments are needed to statistically estimate the degree of the effect of the forced condensation method in the natural state. Contrary to the long-term (~1 hour) contact freezing process that has been generally considered by weather modification workers, the forced condensation process may make it possible to meet the targeted snowfall enhancement due to the rapid processing time.

4. Conclusion

We have conducted snow enhancement experiments by injecting AgI and water vapor into orographically enhanced drifting clouds, and then confirmed the possibility of Li and Pitter's forced condensation process in a natural situation. The nine ground-based experiments, conducted at Daegwallyeong in the Taebaek Mountains for the easterly cloudy days during January–February 2006, give the optimized conditions for snow enhancement in the region as follows: the small AgI burning (1.04 g min^{-1}) for the easterly cold cloud days with the Gangneung's high humidity. Applying this method over all the regions along the Taebaek Mountains, it may contribute to developing water resources over the internal region of the Korean Peninsula.

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