Evaluation of Orographic Cloud Seeding Using a Bin Microphysics Scheme: Three-Dimensional Simulation of Real Cases

ISTVÁN GERESDI

University of Pécs, Faculty of Science, Pécs, Hungary

LULIN XUE

National Center for Atmospheric Research, Boulder, Colorado

NOÉMI SARKADI

University of Pécs, Faculty of Science, Pécs, Hungary

ROY RASMUSSEN

National Center for Atmospheric Research, Boulder, Colorado

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ABSTRACT

The University of Pécs and NCAR Bin (UPNB) microphysical scheme was implemented into the mesoscale Weather Research and Forecast (WRF) Model that was used to study the impact of silver iodide (AgI) seeding on precipitation formation in winter orographic clouds. Four different experimental units were chosen from the Wyoming Weather Modification Pilot Project to simulate the seeding effect. The results of the numerical experiments show the following: (i) Comparisons with the soundings, snow gauges, and microwave radiometer data indicate that the three-dimensional simulations with detailed microphysics reasonably represent both the dynamics and the microphysics of real clouds. (ii) The dispersion of the AgI particles from the simulated ground-based seeding was effective because of turbulent mixing. (iii) In the investigated cases (surface temperature is less than 0°C), surface precipitation and precipitation efficiency show low susceptibility to the concentrations of cloud condensation nuclei and natural ice nucleating particles. (iv) If the available liquid water content promotes the enhancement of the number of snowflakes by diffusional growth, the surface precipitation can be increased by more than 5%. A novel parameter relevant to orographic clouds, horizontally integrated liquid water path (LWP), was evaluated to find the relation between seeding efficiency and liquid water content. The impact of seeding is negligible if the horizontal LWP is less than 0.1 mm and is apparent if the horizontal LWP is larger than 1 mm, as based on the cases investigated in this study.

KEYWORDS: Cloud microphysics; Ice particles

1. Introduction

Since the discoveries in both the laboratory and the field in the 1950s of the impact of dry ice and silver iodide (AgI) on clouds (Schaefer 1946; Vonnegut 1947), artificial glaciogenic seeding (using AgI) of clouds, especially wintertime orographic clouds, became a viable

technology considered by water resource managers to potentially increase water supplies in arid and semi-arid regions. Efforts at evaluating the wintertime orographic cloud-seeding effects in a scientific way including comprehensive field investigations, statistical evaluation experiments, and numerical studies have been tried since the 1950s. Limitations in the fundamental understanding of cloud dynamics, microphysics, and seeding mechanisms; the capabilities of instruments to detect the key features and physical processes; and the model capability and computing resources in the early studies [see reviews from Smith (1979),

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Corresponding author: István Geresdi, geresdi@gamma.ttk.pte.hu

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Elliott (1986), Rangno and Hobbs (1987), Reynolds (1988), Orville (1996), Bruintjes (1999), Long (2001), Garstang et al. (2005), and Huggins (2008)] made the assessment of seeding efficacy inconclusive (National Research Council 2003). Despite the uncertain conclusions, progress was made in understanding the conditions under which glaciogenic seeding may increase orographic precipitation, and operational winter orographic weather modification programs have continued in the western United States and in other arid regions around the world given the potential large benefit-to-cost ratio of this technique.

Advances in theories on orographic clouds and precipitation; observational instrumentation; numerical model development, especially in the cloud microphysics parameterization and seeding-related parameterization; and computing infrastructure in recent decades significantly improved our scientific understanding of the natural cloud and cloud-seeding processes and provided great opportunities to quantify seeding impact with reduced uncertainties [see review paper by Rauber et al. (2019) for details].

Existence of supercooled liquid drops is crucial for efficient glaciogenic seeding. Detailed measurements from advanced remote sensing instruments and airborne in situ microphysics probes and sensors revealed that supercooled liquid water (SLW), an indicator of suitable conditions for glaciogenic seeding, is often found in strong updraft regions associated with steep terrain slope, embedded convection (Ikeda et al. 2007), in the cloud-generating cells (Morrison et al. 2013; Keeler et al. 2016a,b, 2017), and in turbulent eddies induced by waves and terrain–flow interactions (Houze and Medina 2005; Geerts and Miao 2010; Geerts et al. 2011; Medina and Houze 2015; Barnes et al. 2018; Chu et al. 2018; Conrick et al. 2018). Both field observations (e.g., Bühl et al. 2016) and numerical models (e.g., Geresdi et al. 2005) have proved that in the case of layer clouds the liquid water content is inversely related to the cloud-top temperature; therefore, clouds with warmer cloud-top temperatures should be more responsive to the seeding.

The transportation and dispersion of artificial ice nucleating particles (INP) determines where and when these seeding materials interact with SLW and is an important process to understand and quantify in order to assess the seeding impacts. Direct observations of the AgI dispersion features have been tried with airborne detection of coreleased trace gases (Bruintjes et al. 1995), airborne detection of AgI particles in clear conditions (Boe et al. 2014), and tracer chemistry analysis of snow samples (Warburton et al. 1995; Manton and Warren 2011; Fisher et al. 2016, 2018). Based on these observations limited in both space and time, only general dispersion

features such as the height above mountain peak and the horizontal dispersion speed were estimated. Only combined with fine-resolution model simulations, these data and model results revealed the dispersion mechanisms (both terrain-induced turbulence and buoyancy from clouds are responsible) and patterns in three dimensions in detail (Xue et al. 2014, 2016, 2017a).

It is extremely difficult to directly observe the microphysical processes associated with AgI seeding in real clouds using in situ and remote sensing instruments either on the ground or on aircraft. In fact, the rates of quantitative processes, such as AgI nucleation rates, in different modes have to be measured in a controlled laboratory environment (DeMott 1995). When these laboratory experiment–based quantitative relationships were implemented in numerical models (Xue et al. 2013a,b; Geresdi et al. 2017, hereinafter G17), uncertainties exist in terms of how reasonable these relationships work in the real cloud environment. Despite the uncertainties associated with these models, such a numerical tool is very useful in understanding the physical chain of events associated with AgI seeding through case studies (Xue et al. 2013b, 2014, 2016, 2017a; Chu et al. 2014, 2017a,b) and is useful in assessing the seeding effect over a target in multiple seasons through ensemble simulation approach (Rasmussen et al. 2018).

The AgI seeding parameterization implemented in the bulk microphysics scheme (Xue et al. 2013a) has inherent limitations that are due to the use of assumed hydrometeor size distributions and the prediction of only one or two moments of the distributions. As a result, uncertainties remain relatively high in such schemes to accurately simulate the impact of seeding with AgI, since the particles' evolution is only tracked in bulk. In contrast, the use of bin microphysical models, such as Geresdi and Rasmussen (2005) and Xue et al. (2010, 2012), provides explicit simulation of the evolution of individual species of hydrometeors and aerosol particles. This becomes especially important for cloud seeding with very small particles such as AgI, which typically has a mean diameter of $0.05\ \mu\text{m}$. Bulk schemes are challenged to span the hydrometeor size range from micrometers to millimeters because of the use of moments, whereas bin schemes are able to simulate this evolution explicitly by tracking individual size categories of particles but with a significant computational cost. Modern computer systems have made the simulation of clouds with bin models possible within reasonable amounts of computer time (Xue et al. 2017b), which led us to develop a new bin microphysical scheme to simulate cloud seeding with AgI (G17).

From previous results of 2D seeding simulations by the bin version of the AgI seeding parameterization (G17), the following hypotheses are made:

- 1) The stronger PBL turbulence caused by real topography and land surface properties, in comparison with the 2D simulation, impacts the simulated efficiency of ground-based seeding.
- 2) The ground-based seeding efficiency depends on and has a positive relationship with the amount of liquid water in the along-wind direction.
- 3) The efficiency of seeding is inversely proportional to the efficiency of precipitation formation in natural cases, and the efficiency of seeding has a strong correlation with enhanced diffusional growth of snowflakes resulting from the seeding.

In this study, these hypotheses will be tested for actual seeding cases that occurred during the Wyoming Weather Modification Pilot Project (WWMPP). The advantage of this approach is that each seeded case was accompanied by a nearby atmospheric sounding, radiometer data for liquid water path, and ground-based precipitation observations. [Section 2](#) describes the bin AgI cloud-seeding scheme, and [section 3](#) presents the results of simulations. Conclusions of the paper are given in [section 4](#).

2. Description of the model

A modified version of the University of Pécs and NCAR Bin (UPNB) microphysical scheme of [Geresdi \(1998\)](#) and [Geresdi et al. \(2014\)](#) was used to simulate AgI cloud seeding (see details in [G17](#); the scheme used in [G17](#) will be referred as UPNB-G17). The representation of the hydrometeor species in the seeded cloud in the UPNB-G17 scheme involves five categories: two types of water drops (one contains AgI particles and one does not), pristine ice crystals, snowflakes, and graupel particles. The drop category with AgI contains at least one AgI particle collected through either scavenging or activation. This approach allows us to track the AgI particles inside water drops and offers a more appropriate simulation of immersion nucleation and release of AgI after water drops evaporate. Artificial INP (dry AgI) is also defined as a new species with prognostic variables of mass and number concentration ([G17](#)). The UPNB-G17 scheme has been implemented into the Weather Research and Forecasting (WRF) Model, version 3.7.1 ([Skamarock et al. 2008](#)).

a. AgI physics in the model

Key AgI processes added by [G17](#) include 1) scavenging of AgI particles by water drops and ice crystals and 2) ice initiation by AgI particles. Four scavenging mechanisms of AgI by water drops and ice particles were added: Brownian diffusion, turbulent diffusion, phoretic effects, and gravitational collection. Four mechanisms to initiate ice by AgI were also added:

deposition, condensation freezing, contact nucleation, and immersion freezing. The activation of AgI nuclei was parameterized following [DeMott \(1995\)](#) and [Meyers et al. \(1995\)](#) [see more details in [Xue et al. \(2013a\)](#)]. Furthermore, AgI particles can act as CCN because of the water-soluble compound formed during the burning of seeding solution. The mass of embedded AgI particles inside the water drops is tracked for every mass bin. This way, the change of in-drop mass of AgI due to the collision-coalescence and scavenging processes is taken into account, and the regeneration of AgI particles after the evaporation of water drops also can be evaluated.

b. Model setup and experimental units

The goal of this study is to extend the 2D idealized simulations of seeding with UPNB-G17 to realistic three-dimensional cases that are fairly well documented. The WRF simulations used realistic topography of the Medicine Bow and Sierra Madre ranges of mountains located in southern Wyoming. To capture the irregularities of the topography, a horizontal grid spacing of 900 m was used. The domain size was about 210 km in the east–west direction (232 grid points) and about 160 km in the north–south, (180 grid points). In the vertical, 80 terrain following layers were used. The vertical extension of the domain was 23 km, with grid spacing changing from about 10 m at the lowest layer to about 1500 m at the highest level. The topography of the simulated area, generator locations, gauge sites, and the locations of the radiosounding station and microwave radiometer (MWR) are plotted in [Fig. 1](#). The model was integrated with a time step of 2 s.

The impact of seeding was investigated by numerical simulations of four cases from the WWMPP Randomized Seeding Experiment (RSE) [detailed descriptions of this project can be found in [Breed et al. \(2014\)](#) and [Rasmussen et al. \(2018\)](#)]. During the WWMPP, 154 randomized seeding experiments were performed between 2008 and 2013. [Rasmussen et al. \(2018\)](#) described a traditional statistical analysis of the data from this program as well as a modeling evaluation using a large ensemble of WRF simulations with the bulk seeding microphysics scheme in WRF ([Xue et al. 2013a,b](#)) for 118 quality-controlled 4-h seeding cases [called experimental units (EUs)].

This paper aims to examine four of these EUs using the more-detailed AgI seeding approach implemented in the bin model with WRF. The goal is to gain further understanding of the impact of AgI on the microphysical pathways to precipitation.

The four EU cases were selected from the results of [Rasmussen et al. \(2018\)](#) to represent the sufficiently large positive effect of seeding (RSE077), the average positive seeding effect (RSE114), the null case (RSE149), and the case with snow reduction by seeding (negative effect;

FIG. 1. Topography of the simulation domain. The western ridges are the SMM, and the eastern ridges are the MBM. Red triangles represent ground-based AgI generators. The blue circles indicate the snow gauge locations [Sand Stone (SS), Battle Pass (BP), Highway 47 (HY), Elk Ridge (ER), Barrett Ridge (BR), GLEES (GL), Towner Lake (TL), and Chimney Park (CP)]. The black plus sign shows the sounding location at Saratoga. The black square depicts the Cedar Creek radiometer location.

RSE023). These four cases were also chosen on the basis of the relatively small spread in the ensemble results (Rasmussen et al. 2018). Table 1 describes these four cases in detail including the model configuration and initial conditions. The common characteristics of the initial condition is that the Brunt–Väisälä frequency is close to zero and therefore weak embedded convective regions can evolve on the upslope side of the mountains. The characteristics of the initial vertical sounding profiles shows that, while in RSE077 EU the relative humidity was well above 90% near the surface, the lowest 150 hPa was dryer in the other three cases (Table 1 and Fig. 2).

For each set of numerical experiments, a control case without seeding (CTRL) and a seeding case (SEED) were simulated for 12 h starting 4 h before the onset of seeding. The initial and boundary conditions were taken from WRF simulations covering a larger domain with 2.7-km grid spacing that were driven by the ERA-Interim reanalysis (Rasmussen et al. 2018). The seeding period was 4 h in duration, matching the onset time and duration from the actual EU. The number, location,

and AgI emission rate of each of the seeding generators were accurately represented in the simulations as well (Table 1). The size distribution of the released AgI particles was assumed to be monodispersed with a diameter of $0.05 \mu\text{m}$, and the number release rate was 6.1×10^{13} per second per generator.

c. Sensitivity experiments for each EU

The precipitation formation in clean and polluted air masses was examined by changing the CCN activation curve in the bin model. Figure 3 (left panel) shows how the number concentration of activated condensation nuclei depends on the environmental conditions (clean vs polluted) and the supersaturation.

To examine the sensitivity to ice initiation, simulations with two different ice initiation parameterizations were conducted (Fig. 3, right panel). The first simulation was based on the Cooper (1986) approach derived from in situ observations of ice crystal concentrations (IN1). The second simulation is based on laboratory data as given by Meyers et al. (1995) (IN2). In both schemes, ice

TABLE 1. Summary of the model configuration, seeding generator AgI 4-h emission amount measured, and sounding data for each of the EUs.

	RSE023	RSE077	RSE114	RSE149
Date	16 Dec 2008	18 Feb 2010	16 Jan 2012	09 Jan 2014
	Seeding information			
Period (UTC) ^a	1100–1500	2220–0220	1800–2200	0330–0730
AgI (kg) ^b /no. of generators	6.5/8	3.25/4	4.88/6	4.07/5
Expected efficiency based on the bulk simulation	Negative	Positive	Regular	Null effect
	Model configurations			
Period (UTC) ^c	0700–1900	1800–0600	1400–0200	0000–1200
Radiation	Rapid Radiation Transfer Model for GCMs (RRTMG)			
PBL	Mellor–Yamada–Nakanishi–Niino (MYNN) 2.5-level TKE scheme			
Surface	MYNN with Noah MP land surface model			
Microphysics	UPNB			
Turbulence	Horizontal Smagorinsky first-order closure			
	Sounding information ^d			
Time (UTC)	0700	1800	1400	0000
U_{mean} (m s ⁻¹) ^e	12.5/15.0	3.0/5.5	16.0/18.0	2.5/5.0
$U_{\text{dir mean}}$ (°) ^e	237/253	313/266	233/240	226/268
N (10 ⁻² s ⁻¹)	—	0.005	0.006	0.003
Fr	—	—	1.2	2.0
Mean relative humidity ^f	0.72/0.69	0.97/0.85	0.62/0.80	0.65/0.78
Surface temperature (°C)	−10	−2	−5	0

^a Working period of the generator.^b Total mass of AgI released by the generators.^c Simulated time intervals.^d Sounding data were generated from model initial conditions at the location of Saratoga.^e Surface–1 km/surface–3 km.^f Layer of lowest 150 hPa/layer between the lowest 150 and lowest 300 hPa.

initiation via deposition and condensation–freezing is intended to be represented.

The sensitivity of the results to CCN and INP concentration was examined in cases of RSE077 and RSE114; furthermore, the sensitivity to the location of the ground-based generator was studied in the case of RSE149. Table 2 summarizes the sensitivity runs of four EUs cases in this study.

3. Results

a. Comparisons with observations

The simulation results are compared with a variety of observation data to verify that the model is performing in a reasonable manner.

Figure 2 compares sounding data with the simulations. The sounding from the simulation was taken at the closest grid point to Saratoga, Wyoming (the sounding location), at about the fourth hour of the simulation. The model soundings were extracted from CTRL simulations with CLNIN1 microphysical background. In each case, the modeled temperature profiles agree well with the observed temperature profiles. The simulated relative humidity in the lowest 300-hPa layer compares very well

(within a few percent error) to the observed sounding data in all EUs except for RSE023. This was the only EU where the simulation significantly underestimated the relative humidity near the surface. The wind direction and the wind speed were also very well simulated in most of the cases. The turning of the surface wind into the northern direction in the RSE077 EU was also well captured by the model. The simulated surface precipitation was compared in each case at all snow gauges in Fig. 4 except for TL because of the poor data quality at this site (see Fig. 1 for gauge locations). Both the observed and simulated data are given in water equivalent value in millimeters. The samples for the simulated data were from the adjacent five grid points in each direction relative to the exact location of the gauges. Furthermore, the variability caused by the different microphysical background is also included. In all cases except for the RSE114 EU, the simulated results agree well with the observed data (Fig. 4). For RSE114 EU, the model underestimated the observed values at five gauges regardless of the microphysical backgrounds.

b. Propagation of the AgI seeding plume

The 2D simulations in G17 showed that in the case of ground-based seeding, the AgI plumes remained

FIG. 2. Comparison of the observed (at Saratoga) and simulated (at the grid point nearest Saratoga) soundings at about the fourth hour of the simulation (the simulated sounding profiles were taken from the simulation of CLNIN1 cases for each EU). The solid lines denote the observed temperature and dewpoint temperature, and the dashed lines denote the simulated vertical profiles of these variables. The blue and black flags denote the observed and simulated wind profiles, respectively.

in a shallow layer close to the surface in the case of layer clouds. It was suspected that inefficient turbulent mixing was the reason for underdispersed plumes in the vertical direction in 2D simulations. Xue et al. (2014) asserted that complex topography and the involvement of boundary layer mixing resulted in a significant spreading of AgI seeding plume in both the horizontal and vertical directions. Figure 5 shows the plume at 1 h after the end of the seeding period in the RSE077CLNIN1 case. The horizontal mixing broadened the plume at least by a factor of 2 in 4 h. Furthermore, from vertical mixing, a significant number of AgI particles get into the region between altitudes of 3.5 and 4.5 km. Similar strong mixing of the AgI occurred in the other EUs as well.

c. Case studies

The efficiency of precipitation formation (PEFF) is defined by the following equation (e.g., Sui et al. 2007):

$$\text{PEFF} = P_{\text{surface}} / \text{TCOND}, \quad (1)$$

where TCOND represents the time- and domain-integrated amount of vapor condensed and deposited on the liquid and solid hydrometeors (evaporation and sublimation were not involved in this term), and P_{surface} is the accumulated surface precipitation. This definition is slightly different from the formula used in G17. In G17 the net accumulated condensation rate was in the numerator instead of the accumulated precipitation.

FIG. 3. Activation of CCN and natural INP: (left) number concentration of the activated condensation nuclei as a function of supersaturation in clean and polluted air masses, and (right) number concentration of the activated natural ice nuclei particles as a function of temperature. In the case of IN2, a water-saturated environment is assumed.

The results are quantitatively similar using these two definitions.

1) NATURAL CLOUD: RSE023 EU

The patterns of accumulated surface precipitation for CTRL cases were different in each EU (Figs. 6a,c,f,i). In the RSE023 case both the snow gauge data and the results of numerical simulation (cf. Fig. 4 and Fig. 6) show that the maximum of surface precipitation was in the northern part of the Sierra Madre (SMM), with much lower amounts of snow falling out in the Medicine Bow Mountains (MBM). Because, in the investigated EUs, the trajectory of snowflakes is typically horizontal, the available liquid water content was estimated by summing of the liquid drop mixing ratios horizontally (Fig. 7). Hereinafter, h-LWP is used for this parameter to distinguish it from the frequently applied LWP that is calculated or observed by summing the liquid water content vertically. Figure 7 shows the vertical profile of h-LWP in the different EUs. The summation of the liquid water content occurred in the prevailing wind direction. (These directions are indicated by black solid lines in Fig. 6.) The low h-LWP values in this EU are the consequence of the low surface temperature (-10°C at the sounding station). Because of the small liquid water content, the riming of snowflakes was negligible in this

EU. The dominance of aggregation processes in formation (aggregation of the pristine ice particles) and growth of snowflakes (collection of pristine ice by snow) is indicated in Table 3.

2) SEEDED CLOUD: RSE023 EU

The largest number of AgI particles was released in this EU relative to the other EUs (the locations of the eight generators are plotted in Fig. 6). Even though this case had the largest release of AgI among of the four EUs, impact of seeding was negligible. While the seeding could potentially impact precipitation formation over both mountains, significant effect occurred only on the northern part of MBM. The potentially impacted area is defined as the region where the AgI particles have dispersed from the start of seeding until the end of the simulation. The rectangles including these areas are denoted by solid black lines in Figs. 6b, 6d, 6g, and 6j. Hereinafter, these areas are called subdomains.

Figure 7a reveals that seeding had a negligible effect on supercooled liquid water content. This negligible effect is also supported by Table 3, which also shows the coincidence of subdomain-integrated production terms related to the CTRL and seeded case. It is important to note that while the data in Table 3 are for the

TABLE 2. Summary of the model simulations conducted.

	RSE023 EU	RSE077 EU	RSE114 EU	RSE149 EU
Clean CCN (CLN)	X	X	X	X
Polluted CCN (POL)	—	X	X	—
Cooper ice nuclei (IN1)	X	X	X	X
Meyers ice nuclei (IN2)	—	X	X	—
Change of location of the generators	—	—	—	X

FIG. 4. Observed precipitation vs simulated precipitation in the simulated cases at the end of the seeding (at the eighth hour of the model time). The different symbols denote the different RSE EUs, and the different colors represents the different stations. The vertical extension of the lines involves both the impact of different microphysical backgrounds and the variability of the simulated surface precipitation in the nearby grid points.

subdomains plotted in Fig. 6, the h-LWP represents a smaller cloud regions where the seeding effect was probably the most obvious. The slight increase of the aggregation and diffusional growth of pristine ice (Figs. 8g,h) can

be considered negligible comparing to the subdomain-integrated production terms (Table 3). The negligible effect of seeding in the case of low surface temperature was also found in our pervious results (G17). There are

FIG. 5. Spreading of the AgI particles in (left) horizontal and (right) vertical cross sections in the RSE077CLNIN1 case. The solid line in the left panel shows the location of the vertical cross section. The values related to the pixels in the left panel indicate the vertically integrated concentration. The plus signs denote the locations of the ground-based generators, and the red dots denote the locations of precipitation gauges.

FIG. 6. The impact of seeding on the surface precipitation. (a),(c),(f),(i) The accumulated surface precipitation in the CTRL cases at the end of the simulation. In the RSE077 and RSE114 cases, the microphysical backgrounds with clean-air CCN and IN1 ice nucleation are plotted. Also shown is the impact of the seeding (SEED – CTRL). In the RSE077 and RSE114 cases, the impact of seeding is represented by microphysical initiation (d),(g) with clean-air CCN and IN1 ice nucleation and (e),(h) with clean-air CCN and IN2 ice nucleation. The plus signs and red dots denote the locations of the generators and the locations of the snow gauges, respectively. The black-outlined boxes denote regions (SD1) where the impact of seeding was supposed. The dash-outlined boxes in the RSE077 EU show subdomain 2 (SD2). The solid black lines in (a), (c), (f), and (i) denote the direction along which the horizontally integrated liquid water contents (h-LWP) were calculated (Fig. 7, below). The G1 and G2 symbols denote cases to study the impact of the location of the generators, west of MBM (G1 case) and west of SMM (G2 case).

two factors that limit the impact of seeding if the surface temperature is less than -10°C : (i) As a result of the topography, the AgI concentration is small near the surface (Fig. 5), that is, in the region (from -10° to -20°C) where the activated AgI particles could efficiently enhance the ice crystal concentration. At higher elevation (where the temperature is less than -30°C), the concentration of the natural INP being activated is large enough to initiate efficient ice-phase microphysical processes, so the snow formation by aggregation was hardly enhanced by seeding in this case (Table 3 and Fig. 8g). (ii) The liquid water content is small in the seeded region (Fig. 7a).

The consequence of the seeding was the redistribution of accumulated precipitation between the upwind side

and the lee side of MBM. The increase and decrease of surface precipitation balanced each other so the net effect of seeding was close to zero. The occurrence of these opposite effects on the two sides of the mountains was also reported in G17.

3) NATURAL CLOUD: RSE077 EU

An interesting characteristic of the simulated precipitation pattern in the RSE077 case is that significant amounts of precipitation occurred on the east side of both mountains. Such precipitation distribution cannot be verified by the observations because no gauge was located in the heavy-precipitation area. This spatial distribution may be explained by the fact that a layer of air was moving from the north above

FIG. 7. Vertical profiles of the horizontally integrated liquid water contents (h-LWP) at the ninth hour of the simulation. The solid black curves denote the calculated h-LWP in the CTRL cases, the dashed red (and blue in the RSE149 EU) lines denote the seeded cases. In the cases of RSE077 EU and RSE114 EU, the results for the microphysical background of CLNIN1 are plotted. The G1 and G2 symbols denote cases to study the impact of the location of the generators, west of MBM (G1 case) and west of SMM (G2 case). The gray dashed lines show the altitude of the temperature levels of -20° and -10°C .

the surface during the simulation. The turning of wind direction was also supported by sounding data. Although at the initial time northerly wind was observed only near the surface (Table 1), the sounding data (both the observed and simulated wind profiles) at the fourth hour of the simulation time show that the depth of this layer increased to 1.5 km (Fig. 2b).

The dominant snow formation process was the aggregation of pristine ice particles; riming of pristine ice produced less snow. The mass of snowflakes was

mostly increased by diffusional growth; furthermore, the growth of snowflakes by riming was negligible. These characteristics of formation and growth of the snowflakes were common in the four investigated cases, independent of microphysical background. Furthermore, the change of microphysical background also resulted in a small impact on both surface precipitation and formation of liquid and solid hydrometeors. The increase of CCN (from clean to polluted) slightly reduced the growth of snow by riming. IN2 initiation

TABLE 3. The impact of seeding on precipitation formation. The second column gives the spatially integrated accumulated surface precipitation by the end of the simulation in the control cases. The third column contains the calculated efficiency of precipitation formation defined by Eq. (1). The next three columns and columns 8–10 are the domain- and time (until the end of the simulation)-integrated production terms for precipitation evolution in the CTRL and SEED cases, respectively). Column 7 contains the precipitation enhancement factor (PEHF), which shows the enhancement of surface precipitation due to the seeding. The parameters were evaluated over the subdomains plotted in (Fig. 6). The explanations for the case abbreviations are given in Table 2.

Case name	Precipitation (mm)	CTRL cases				Seeded cases			
		PEFF	Diffusional growth ^a (10 ¹⁰ kg) liquid/pristine ice/snow	Aggregation (10 ¹⁰ kg)	Riming ^b (10 ¹⁰ kg) total/snow	PEHF	Diffusional growth ^a (10 ¹⁰ kg) liquid/pristine ice/snow	Aggregation (10 ¹⁰ kg)	Riming ^b (10 ¹⁰ kg) total/snow
RSE023CLNIN1	35 243	0.49	0.01/1.15/0.66	0.79	0.15/0.00	1.00	0.00/1.17/0.66	0.79	0.15/0.00
RSE077CLNIN1	47 928	0.54	0.12/1.29/3.09	0.59	0.16/0.04	1.04	0.10/1.31/3.23	0.60	0.17/0.04
RSE077POLIN1	47 949	0.53	0.09/1.33/3.09	0.63	0.13/0.02	1.03	0.07/1.36/3.20	0.64	0.14/0.01
RSE077CLNIN2	49 422	0.57	0.10/1.22/3.29	0.59	0.19/0.04	1.02	0.08/1.26/3.36	0.60	0.20/0.04
RSE077POLIN2	49 289	0.57	0.08/1.28/3.25	0.63	0.16/0.01	1.02	0.03/1.36/3.30	0.64	0.17/0.01
RSE114CLNIN1	62 004	0.35	−0.10/1.95/2.46	1.18	0.47/0.07	1.01	−0.11/2.00/2.47	1.20	0.46/0.06
RSE114POLIN1	61 646	0.34	−0.16/2.29/2.17	1.43	0.43/0.02	1.01	−0.16/2.32/2.18	1.44	0.43/0.02
RSE114CLNIN2	63 521	0.37	−0.05/2.03/2.47	1.20	0.45/0.05	1.00	−0.05/2.08/2.45	1.22	0.45/0.04
RSE114POLIN2	63 116	0.37	−0.08/2.43/2.10	1.51	0.43/0.01	1.00	−0.08/2.45/2.09	1.52	0.43/0.01
RSE149CLNIN1_G1	18 795	0.25	0.05/0.54/0.64	0.31	0.07/0.02	1.02	0.05/0.53/0.66	0.31	0.07/0.02
RSE149CLNIN1_G2	18 795	0.25	0.05/0.54/0.64	0.31	0.07/0.02	1.07	0.03/0.54/0.76	0.31	0.08/0.03

^a The net diffusional growth of liquid, pristine ice, and snow; if the liquid is less than 0, the number of water drops decreases in the subdomain because of evaporation.

^b Total means riming of pristine ice and snow.

FIG. 8. Impact of seeding on the microphysical processes playing a role in snow formation and evolution. The plots represent the difference between the production terms related to the SEED and CTRL cases. These plots also show how the different INP initiations affect the results in a clean air mass. The terms denoted by solid lines were evaluated in subdomain SD1 in Fig. 6. Terms denoted by dashed lines are related to the RSE077_CLNIN1 case and were evaluated in subdomain SD2. The impact of seeding in the RSE023 EU was denoted by black lines in (g)–(i). Shown is how the seeding impacts the (a),(d),(g) aggregation of pristine ice, (b),(e),(h) riming of pristine ice, and (c),(f),(i) diffusional growth of snowflakes.

slightly increased the amount of vapor diffused on the snowflakes (Table 3).

4) SEEDED CLOUD: RSE077 EU

Figures 6c–e show how seeding impacted the surface precipitation in the CLNIN1 and CLNIN2 cases. The patterns for the other microphysics backgrounds were very similar. While the seeding potentially had an impact on precipitation formation in both SMM and MBM, the effect was obvious only in SMM. Although negative

effect (reduction of surface precipitation due to the seeding) can be also observed over a relatively large area, it remains small in magnitude, generally below the 10% of the maximum positive seeding effect. Considering the effect of the microphysical backgrounds, the difference between the largest and smallest precipitation efficiencies was about 3% (third column in Table 3), and, as was found in the 2D simulations, the seeding efficiency was inversely proportional to the precipitation efficiency in the CTRL cases (G17).

The impact of seeding on h-LWP was mostly confined to the regions above 3 km (Fig. 7b). The liquid water was significantly depleted between 3 and 4 km, and the liquid drops almost completely disappeared due to the seeding above the altitude of 4 km. The comparison of the time- and domain-integrated production terms related to the CTRL and SEED cases (Table 3) shows the following: (i) The aggregation remains the most dominant snow formation process, and it was only slightly impacted by seeding. (ii) The seeding enhanced the amount of solid particles due to the efficient depletion of vapor by solid particles. (iii) Although the snow formation by riming of pristine ice particles was increased by the seeding, the further growth of snowflakes was restricted by negligible changes in riming of snow induced by seeding. We suspect that the ice crystals formed as a result of the seeding might deplete the liquid drops to form snowflakes so efficiently that further riming of snowflakes is suppressed.

These statements above are supported by Figs. 8a–c. They show how the differences between the production terms (SEED – CTRL) change during the simulation. Only the results of RSE077_CLNIN1 and RSE077_CLNIN2 are presented because the seeding effect changed in a slightly wider interval when IN background concentration was changed and CCN background concentration was fixed, than the other way around (Table 3). Furthermore, dashed lines representing the RSE077_CLNIN1 case for the subdomain involve just the MBM (SD2 in Fig. 6). The impact of seeding became obvious about 1 h after the AgI emission was started. The enhancement of the INP concentration due to seeding promotes snow formation both by aggregation and riming of pristine ice. However, these differences caused by seeding are only a few percent of the domain-integrated production terms in CTRL cases (Table 3). This small effect was amplified by the diffusional growth significantly in the CLNIN1 case and less so in other cases (Table 3).

In the CLNIN1 case, the seeding impact on diffusional growth of snow was about 2 times that in the CLNIN2 case. The blue dashed lines (Fig. 8) show how the seeding impacts the investigated processes over MBM (see the area defined by SD2 in Fig. 6). In this region, because of the relatively low speed of propagation of the AgI plume (the wind speed was about 10 m s^{-1}) the impact of seeding can be observed about 2–3 h after the seeding started. If the plots after the eighth hour of the simulation are compared, it is found that positive impacts of seeding for snow formation either by aggregation or by riming of pristine ice are mostly confined to the cloud regions above the MBM. This is evident, because the concentration of the AgI particles started to decrease over the SMM and

increase over the MBM at this time. If the diffusional growth of snow is considered, the difference between the two curves is a factor of 2, which means that the impact of seeding on diffusional growth of snow remains strong over the SMM after the AgI plumes left the region. This prolonged effect over the SMM explains why the seeding effect was stronger in this region than over the MBM.

5) NATURAL CLOUD: RSE114 EU

In comparison with the other investigated EUs, the largest amount of surface snow was simulated and observed in the RSE114 EU (Table 3 and Fig. 4). Although this qualitative statement is supported by the snow gauge data, the quantitative agreement between the observed and simulated surface precipitation was the worst in this EU. While at the stations of Battle Pass and HY47 the simulated data fit well to the observed ones (seeded case), the model significantly underestimates the observed data at the other five other stations (Fig. 4). This discrepancy between the observed and simulated data cannot be explained by the uncertainty associated with the microphysical backgrounds. Although both CCN and INP concentrations were significantly modified, the differences still remain large. The impact of the microphysical backgrounds on the amount of surface precipitation was almost the same as in the RSE077 EU. Considering the calculated accumulated surface precipitation, the difference between the smallest and the largest values is about 2.5% (Table 3). The precipitation efficiency was also slightly impacted by using different microphysical backgrounds; it changes between 34% and 37%.

Table 3 shows that while the net increase of solid particles due to diffusion is positive, the net diffusional growth of liquid drops (condensation – evaporation) is negative over the subdomain. The dominance of the evaporation of water drops explains the low h-LWP values (Fig. 7c). Although the maximum of the h-LWP is significantly larger than in the RSE023 EU, it is smaller than 0.2 mm, and liquid drops can be found only in the region below 1 km. It is also important to note that, while the number of snowflakes formed by aggregation and riming of pristine ice was larger than the previous case, the diffusional growth of snowflakes was about 20%–30% less. This stems from the fact that loss of the mass of snowflakes due to the sublimation was significant in this EU (the domain-integrated production term of the snow sublimation shows that about 60% of the total snow mass was lost as a result of sublimation). The strong sublimation of ice particles and evaporation of water drops explain why the precipitation efficiency is smaller in the RSE114 EU than in the RSE077 EU. Similar to the RSE077, the impact of CCN on snow

formation is more obvious than that of INP. Data about the aggregation in Table 3 shows how the CCN concentration impacts the aggregation. Because in the POL case the mean size of the water drops is smaller than in the CLN case, snowflakes formation via riming of pristine ice is less efficient than via the aggregation of ice crystals. Therefore, about 20% more snow formed by aggregation in the polluted air mass (POL) than in the clean air mass (CLN).

6) SEEDED CLOUD: RSE114 EU

While the seeding potentially had an impact on precipitation formation in the northern part of both SMM and MBM, the seeding effect was confined to a relatively small area in the northern part of MBM (Figs. 6f–h). Furthermore, the amount of surface snow was enhanced over a relatively small area, so the impact of seeding was rather small, independent of the microphysical backgrounds. Not only the relative change of the accumulated precipitation due to seeding was smaller in this EU than in the RSE077 EU, but also the absolute change was significantly smaller. Considering the seeding effect on the microphysics, independent of the microphysical backgrounds, seeding hardly affected the total net diffusional growth of water drops, and similar to the RSE077 EU, it has negative or zero effect on the riming of snowflakes (Table 3). The injection of AgI particles contributed to the increase of snowflake formation by aggregation, but this effect was not amplified by the diffusional growth of the snowflakes (Figs. 8d–f). Even more in the CLNIN2 case (the precipitation efficiency in the CTRL was the largest in this case), the diffusional growth of snowflakes was reduced between 450 and 600 min. Similar to the RSE077 case, the seeding greatly reduced the liquid water content. The value of h-LWP was decreased by a factor of 2 between the altitude of 2.5 and 3.5 km, and the liquid drops were completely depleted above this layer (Fig. 7c).

7) NATURAL CLOUD: RSE149 EU

Both the observations and simulated data show that snow accumulated only on the upwind side of MBM and over the SMM. The areal average precipitation was only about 1 mm (Figs. 6i–k). While the accumulated surface precipitation and the precipitation efficiency were the smallest among the investigated EUs (Table 3), the maximum value of the liquid water content was the largest in this EU.

The low precipitation efficiency can be explained by the intense sublimation of the snowflakes (the domain-integrated production term of the snow sublimation shows that about 80% of the total snow mass was lost as a result of sublimation) and evaporation of water

FIG. 9. Comparison of the observed and simulated SLWP in the RSE149 EU. The solid line denotes the observed SLWP made by slanted MWR located at Cedar Creek (Fig. 1). The black dots, red squares, and blue diamonds show the simulated SLWPs related to the same slanted path as that on which the observation was made, as labeled. The time is given in real time (the seeding started at 0330 and finished at 0730).

drops at the lee side of both ridges (see the surface precipitation pattern in Fig. 6). However, the relatively warm low layer (surface temperature was the highest in this EU—close to 0°C) resulted in larger liquid water content locally.

Despite the relatively large liquid water content, similar to the other EUs, the aggregation of pristine ice crystals was the dominant snow formation process, and the riming of pristine ice played a less important role (Table 3).

8) SEEDED CLOUD: RSE149 EU

In the actual seeding case, the generators located on the upwind side of MBM (G1 in Fig. 6) were turned on, so the impact of seeding should be confined to the northern part of MBM (Figs. 6i–k). In this area the accumulated snow was increased by about 1 mm, which means about 2% augmentation of surface precipitation (Table 3). The simulated accumulated surface precipitation fits well to the data observed at most of the stations (Fig. 4). The model results are also partly confirmed by the MWR observation (Fig. 9). While in this case the slanted liquid water path (SLWP, related to the slanted paths, 8.1° elevation from the surface, and with an azimuth angle of 80°) was larger than 0.2 mm in a time period longer than 2 h, in the other EUs its value was significantly smaller (less than 0.1 mm) in most of the observing periods. To compare the observation with model data (red squares in Fig. 9), the liquid water content was integrated along this path from the model outputs. The observed and simulated maximum values are

about 0.35 and 0.30 mm, respectively. Both the observation and the simulation have two local maximums. If the time periods related to the $SLWP > 0.01$ m are compared, the model results underestimate it by 2 h (5 vs 7 h). This explains the 2–3-h delay of response to seeding (see the blue curves in Figs. 8g–i). Therefore, the model might have underestimated the seeding effect in the SEED_G1 case, because liquid water content was underestimated in the first half of the simulation. In the second half of the simulation (from the sixth hour) the simulated and observed data agree fairly well. The SLWP was also calculated for the CTRL case as well. The coincidence of the values related to the CTRL and the SEED_G1 case is in line with the content of Fig. 7d. The integration occurred along the path that is almost parallel to the MWR observation (Fig. 6), but it is about 3 times as long (see the h values at the bottom-left corners in Fig. 7).

A numerical experiment was accomplished by moving the generators to the upwind side of SMM (Figs. 6i–k). The relocation of generators resulted in increase of the precipitation enhancement from 2% to 7%. The effects of seeding on both riming process and the diffusional growth of snowflakes were more evident in this case than in any other cases (Table 3). Note, this is the only EU in which the seeding did not impact the aggregation process and the growth of snow by riming was enhanced (Table 3). The negligible effects of seeding on the domain-integrated production terms of aggregation of pristine ice and on the net diffusional growth of water drops are found. The large positive effect of seeding on the riming stems from the fact that the seeding effects are mostly confined to the temperature region warmer than -15°C in this case. In this temperature region, relatively fewer AgI particles were activated, so the seeding does not result in significant increase of the number concentration of pristine ice particles to enhance the aggregation (Fig. 8g). Because of the large amount of liquid drops, the formation of snow was more efficiently enhanced by riming of pristine ice than by the aggregation in the seeding region (Figs. 8g,h). Furthermore, while in the other EUs the riming of snowflakes was reduced by 0%–10% due to the seeding, the growth of snowflakes by riming was enhanced by about 5% in this case. The significant increase of precipitable snowflakes both by diffusional growth (Fig. 8i) and riming resulted in the largest precipitation enhancement factor among the investigated cases (Table 3).

4. Conclusions

Four different EUs were chosen from WWMPP to study the impact of glaciogenic cloud seeding on the precipitation formation in winter orographic clouds.

The comparison with the available observation data (soundings, surface precipitation, and MWR) shows that the numerical model reproduces both the dynamics and the microphysics of the real clouds reasonably well.

The conclusions of this research are summarized according to the hypotheses that were listed in the introduction:

a. Hypothesis 1: The stronger PBL turbulence caused by the real topography and land surface properties, in comparison with the 2D simulation, impacts the simulated efficiency of the ground-based seeding

Relative to the 2D idealized simulation (G17), the 3D topography significantly enhanced the spreading of the AgI particles released from ground-based generators both horizontally and vertically. This result indicates the limits of the application of 2D idealized mountains for the simulation of seeding effect. Another important aspect should be taken into consideration when the results of 2D and 3D simulations are compared. Because of the extra dimension for AgI particles dispersion, the concentration of AgI is about one order of magnitude less in the 3D simulations than in the 2D simulations if the release rates are the same.

b. Hypothesis 2: The seeding efficiency depends on and has a positive relationship with the amount of liquid water along the wind direction

The seeding impacted the ice initiation mostly through the deposition and condensation-freezing nucleation, the role of freezing of supercooled droplets initiated by the AgI particles was negligible. About five-orders-of-magnitude fewer ice particles were formed by freezing than by the two other nucleation mechanisms (see more details in G17).

Table 4 summarizes how the seeding impacts the microphysical processes that are important to the precipitation formation. To highlight the significant effects, plus or minus signs are used if the absolute value of seeding effect is larger than 5%. In all other cases the impact of seeding was considered to be negligible.

The impact of AgI seeding can be described as a chain of the following processes: (i) increase of the concentration of pristine ice crystals and the enhancement of vapor deposition on these crystals, (ii) advance of snow formation by aggregation and/or riming of pristine ice particles, (iii) enhancement of the amount of snowflakes due to the diffusional growth, and (iv) enhancement of the amount of snowflakes due to the riming. The first two processes

TABLE 4. Summary of the impact of seeding on the microphysical process. The impact is considered to be positive or negative if the seeding respectively increased or decreased the domain-integrated production terms by at least 5%. If the effect is smaller than 5%, it is denoted by 0. The cases in which the seeding effect on surface precipitation was larger than or near 5% are written in boldface type.

	Diffusional growth of liquid	Diffusional growth of snow	Aggregation	Riming of pristine ice/snow
RSE023CLNIN1	—	0	0	0/0
RSE077CLNIN1	—	+	0	+/-
RSE077POLIN1	—	0	0	+/-
RSE077CLNIN2	—	0	0	0/-
RSE077POLIN2	—	0	0	+/0
RSE114CLNIN1	0	0	0	0/-
RSE114POLIN1	0	0	0	0/-
RSE114CLNIN2	0	0	0	0/-
RSE114POLIN2	0	0	0	0/-
RSE149CLNIN1_G1	0	0	0	0/-
RSE149CLNIN1_G2	0	+	0	+/+

only slightly increase the amount of solid precipitation elements; they mostly increase the number concentration of them. Significant increase of the surface precipitation can happen only if the precipitation formation can proceed to steps iii and/or iv. If the h-LWP is small, the processes i and ii deplete the available liquid water content and there is little chance for the seeding-induced ice-phase particles to proceed to steps iii and iv. Our results show that the seeding effect is close to or larger than 5% if the maximum value of the h-LWP is above ~ 0.5 mm. The diffusional growth of snowflakes was significantly increased by seeding only in two cases in which maximum value of the h-LWP was larger than ~ 0.5 mm (RSE077_CLNIN1 and RSE149_CLININ1_G2). If the enhancement of snow riming is considered, positive effect can be found only at even larger h-LWP (in the RSE149_CLININ1_G2 case). In any other case, the riming of snow was reduced by seeding. The change of vertical profile of h-LWPs due to seeding reveals how the ice particles that formed on AgI particles deplete the available supercooled drops. The reagent was dispersed mostly at altitudes between 3 and 4.5 km (Fig. 5). In the case of the RSE023 EU, seeding occurred above the level of -20°C , so the concentration of activated AgI particles was negligible relative to the concentration of the natural INP, and the seeding effect is also negligible. In the RSE077 and RSE114 EUs the seeding occurs mostly between the temperature levels of -15° and -20°C . Because of the large difference between the water and ice saturation in this temperature range, the enhanced concentration of ice particles increases the depletion of vapor at the expense of water drops. The decrease of available supercooled drops reduces the riming of snow. In the RSE149_CLNIN1_G2 case, the seeding was confined to the region below the temperature level of -15°C . No seeding

effect was found above 4 km and below 3 km because of the small concentration of AgI particles and small concentration of activated AgI particles, respectively. The negligible depletion of liquid drops below the altitude of 3 km allows enhancement of riming of the descending snowflakes.

Of course, the four cases are not enough to perform a statistical analysis; however, it can be concluded that if the h-LWP is less than 0.1 mm then the seeding effect is negligible and if the h-LWP is larger than 1.0 mm then the seeding effect can be significant. The small precipitation enhancement efficiency in the RSE149 EU G1 case seems to contradict this statement. However, in this case the model underestimated the liquid water content over the northern part of MBM in the time period when the AgI particles reached this region from the nearby generators (Fig. 9).

c. Hypothesis 3: The efficiency of seeding is inversely proportional to the efficiency of precipitation formation in natural cases and that the efficiency of seeding has a strong correlation with enhanced diffusional growth of snowflakes due to the seeding

The relation between the precipitation efficiency of natural clouds and the precipitation enhancement factor was more ambiguous in this study (Fig. 10a) than was published in G17. This stems from the fact that, whereas in our previous study (G17) the soundings of the investigated cases were similar in many respects (e.g., initial relative humidity was 95% near the surface in each investigated case; the relation of wind direction to the mountain was the same), these conditions changed more significantly from case to case in this study. However, sensitivity tests in a specific case show that this relationship still holds in general.

Sensitivity test was used to investigate how the microphysical processes and the efficiency of precipitation

FIG. 10. Relation (a) between the seeding efficiency and precipitation efficiency of control simulations and (b) between the seeding efficiency and enhancement of the diffusional growth of snowflakes due to the seeding.

formation are impacted by microphysical backgrounds. We found that both the accumulated surface precipitation and the precipitation efficiency show low susceptibility to the microphysical background (Table 3). This result agrees with that published in Glassmeier and Lohmann (2018). They found that the change of aerosol concentration (both CCN and INP) is buffered in both warm- and mixed-phase clouds. However, in our previous study (G17; Xue et al. 2013a), we found that the susceptibility was higher if the surface temperature was warmer than in the current investigated cases, that is, above 0°C. In theory, the surface precipitation can be increased, if the amount of the precipitable snow was enhanced by diffusional growth and/or by riming. The results of our study show that the enhancement of diffusional growth of snowflakes due to seeding is strongly correlated with the efficiency of seeding (Fig. 10b). Seeding has a negative effect on the riming of snowflakes in most cases. Seeding enhanced the riming of snowflakes in only one case in which the maximum h-LWP was around 1.0 mm.

Although both our numerical results and observations (Tessendorf et al. 2019) show that the seeding can increase the number concentrations of ice crystals and aggregates, this enhancement does not necessarily result in the increase of surface precipitation. The enhancement of the ice crystal concentration due to seeding can increase surface precipitation only if the liquid water content is large enough to amplify diffusional growth of snowflakes.

Rauber et al. (2019) summarized the statistical analysis of field experiments about orographic winter cloud seeding. They showed that the efficiency of seeding was between 5% and 20% (in most of the cases at significance level of about 5%) in most of the field experiments. However, in the case of the WWMPP the results

of statistical analysis did not reject the null hypothesis, that there is no seeding effect. Our result shows that the seeding effect is between 0% and 4%, which does not contradict this conclusion.

The efficiency of seeding strongly depends on environmental conditions and cloud microphysical properties. Our results suggest that in the case of orographic winter clouds the h-LWP can be a reasonable parameter for estimation of the seedability. The WWMPP EUs simulated in this study were all ground-based AgI seeding cases in which it is hard to observe a seeding effect directly (Pokharel and Geerts 2016). The cloud could respond to seeding very differently if the AgI particles are released from an aircraft. The recently completed Seeded and Natural Orographic Wintertime Clouds: The Idaho Experiment (SNOWIE) field campaign collected a wealth of in situ and remote sensing measurements and observed clear seeding signals in clouds treated by aircraft seeding (French et al. 2018; Tessendorf et al. 2019; Friedrich et al. 2020), which provides great opportunities to validate and improve our model in the near future. The possible indication of seedability level by the novel h-LWP parameter will be tested in the SNOWIE cases.

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