Large-Eddy Simulations of the Impact of Ground-Based Glaciogenic Seeding on Shallow Orographic Convection: A Case Study

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ABSTRACT

This study uses the WRF large-eddy simulation model at 100-m resolution to examine the impact of ground-based glaciogenic seeding on shallow (2 km deep), cold-based convection producing light snow showers over the Sierra Madre in southern Wyoming on 13 February 2012, as part of the AgI Seeding Cloud Impact Investigation (ASCII). Detailed observations confirm that simulation faithfully captures the orographic flow, convection, and natural snow production, especially on the upwind side. A comparison between treated and control simulations indicates that glaciogenic seeding effectively converts cloud water in convective updrafts to ice and snow in this case, resulting in increased surface precipitation. This comparison further shows that seeding enhances liquid water depletion by vapor deposition, and enhances buoyancy, updraft strength, and cloud-top height. This suggests that the dynamic seeding concept applies, notwithstanding the clouds’ low natural supercooled liquid water content. But the simulated cloud-top-height changes are benign (typically 100 m). This, combined with the fact that most natural and enhanced snow growth occurs in a temperature range in which the Bergeron diffusional growth process is effective, suggests that the modeled snowfall enhancement is largely due to static (microphysical) processes rather than dynamic ones.

1. Introduction

The most commonly used method to enhance precipitation from cold clouds is to seed them with glaciogenic nuclei, such as silver iodide (AgI) (e.g., National Research Council 2003). This method is used operationally in winter storms over various mountain ranges in the western United States and elsewhere.¹ Such seeding usually is conducted pyrotechnically from the ground, rather than from an aircraft, because ground-based seeding is less expensive and orographic clouds are often quite shallow (e.g., Reynolds 2015).

¹ Visit, for instance, the website of the North American Weather Modification Council (http://www.nawmc.org/).

Orographic winter storms in the western United States often are convective or contain convective cells embedded in stratiform precipitation (Marwitz 1980; Lee 1984; Shafer et al. 2006; Kumjian et al. 2014; Geerts et al. 2015). Convective clouds coupled to the surface may be more suitable for ground-based glaciogenic seeding than stratiform clouds of the same depth because the artificial ice nuclei can be mixed over the depth of the clouds: convective updrafts may carry these nuclei to higher levels, where they encounter lower temperatures, higher supersaturation values, and more supercooled liquid water (e.g., Bruintjes 1999). In addition, hydrometeor growth in convective clouds may be enhanced by the extra latent heat released by the freezing of liquid water, since this heat release can result in more buoyancy, a stronger updraft, and thus a deeper cloud, whereby more supercooled liquid water is converted into frozen hydrometeors by vapor diffusion (the Bergeron process) or by accretion, ultimately yielding more precipitation. This chain of effects is referred to as the “dynamic seeding” mechanism (Simpson et al. 1967; Woodley et al. 1982;
Bruintjes 1999; Gagin et al. 1985). The latter outcome of this dynamic seeding mechanism, that is, higher cloud tops, has been confirmed for warm-season cumuli with a relatively high cloud-base temperature (and thus a high liquid water content) and with relatively great depth [Cu congestus (Cb)] in several of the early cloud seeding studies (Simpson and Woodley 1971; Sax et al. 1979; Hallet 1981; Rosenfeld and Woodley 1989).

The supercooled liquid water content is much lower in cold-based convective clouds, that is, clouds with a base temperature below freezing. For these clouds, the dynamic seeding concept may be insignificant, and any increase in snow mixing ratio may be mainly due to microphysical processes, that is, by riming and/or vapor diffusion on ice crystals initiated by artificial ice nuclei in a temperature range where few natural ice nuclei exist (the “static seeding” mechanism). Several observational studies have addressed the impact of glaciogenic seeding of cold-based convective clouds on precipitation, for example, Gagin and Neumann (1981) and Freud et al. (2015) in Israel, Isaac et al. (1977, 1982) in Alberta, Vali et al. (1988) in Spain, Ryan and King (1997) in Australia, and Jing and Geerts (2015) in Wyoming, but they too focused on cloud-top height changes, lacking suitable observations to assess the chain of effects of the dynamic seeding mechanism.

Lack of adequate observations to evaluate dynamic seeding mechanism has motivated several numerical modeling studies (Orville 1996; Spiridonov et al. 2015; Guo et al. 2015). These studies, to our knowledge, have assumed highly idealized conditions and warm-based deep convective clouds only. Here we use numerical simulations to explore the impact of ground-based glaciogenic seeding on cloud processes and snow growth in cold-based convective clouds. These clouds were observed on 13 February 2012 over the Sierra Madre in Wyoming, as part of the AgI Seeding Cloud Impact Investigation (ASCII) campaign (Pokharel and Geerts 2016). Pokharel et al. (2014) analyzed these shallow convective clouds using an array of in situ and remote sensors. Using evidence from three complementary radar systems at different frequencies, each with their own control and target regions, they find that AgI seeding enhances low-level reflectivity. Pokharel et al. (2014) also find higher concentrations of ice crystals in the tops of shallow convective cells during seeding, according to aircraft in situ observations. But again the data collected were inadequate to discern seeding-related changes in vertical velocity and cloud-top height, making it impossible to evaluate the dynamic seeding concept.

The present study uses an AgI seeding parameterization within the Thompson microphysics scheme (Thompson et al. 2008). This parameterization was developed and evaluated by Xue et al. (2013a,b) for use in the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008). Here we used an improved version of this parameterization that accounts for precipitation scavenging of AgI particles, AgI self-coagulation, and dry deposition of AgI particles due to surface roughness and turbulence. A large-eddy simulation (LES) framework is needed to adequately capture the dispersion of the AgI nuclei from their point source (Xue et al. 2014). Similar studies have been conducted in recent years. For example, Chu et al. (2014) used the same glaciogenic seeding parameterization and LES framework to examine the impact of seeding on a stratiform, precipitating orographic cloud, observed on 18 February 2009 in Wyoming. Observations from a cloud physics research aircraft with a profiling Doppler radar and radiosonde data were used to validate the modeled natural storm structure, and also to evaluate the modeled impact of seeding. Chu et al. (2014) found good correspondence between the WRF LES (run at 100-m resolution) and observed vertical temperature, humidity, and wind profiles, as well as observed boundary layer turbulence and precipitation. Both the observations and the simulations indicate that seeding locally increases reflectivity in the target area (relative to an upstream control area). Model output further indicates that this increase was due primarily to an increase in ice particle concentration.

Chu et al. (2016, manuscript submitted to J. Appl. Meteor. Climatol.) used the same approach for a case study of an extremely shallow (<1 km), mostly blocked stratiform orographic cloud, on 13 February 2013 over the same mountain range in Wyoming, as part of ASCII. In this case the impact of seeding on snow growth was anticipated to be significant, in a relative sense, since liquid water was present and the cloud-top temperature was rather high (around −16°C), implying few natural ice nucleating particles. The WRF LES run for this case showed that seeding substantially increased the snow mixing ratio and snowfall within a narrow AgI plume (Chu et al. 2016, manuscript submitted to J. Appl. Meteor. Climatol.). This increase again was due to an increase in the number of ice particles, not their size.

The objectives of the present numerical study are to evaluate the ability of WRF LES to capture the structure and evolution of shallow orographic convection, to examine how artificial ice nucleating particles released near the ground affect snow growth, and to evaluate the dynamic seeding concept. If the model results reveal that snow growth in shallow, cold-based convective cells is enhanced by seeding without substantial increase in cloud buoyancy, updraft strength, and cloud-top height, then this enhancement is mainly due to microphysical processes rather than the dynamic seeding mechanism.
The experimental design and model setup are described in section 2. Section 3 uses observations to assess the ability of WRF LES to reproduce the (natural) storm structure. Section 4 uses model output to examine how seeding impacts cloud and precipitation and to evaluate the dynamic seeding concept. A discussion of this concept for cold-based convection is provided in section 5, followed by conclusions in section 6.

2. Data sources and model setup

This study focuses on the numerical simulation of shallow, lightly precipitating orographic cumuli, observed on 13 February 2012 over the Sierra Madre in Wyoming, as part of the ASCII experiment. A detailed description of the instruments used, the synoptic conditions, the observed upstream environment, and the cloud and precipitation structure for this case can be found in Pokharel et al. (2014).

a. Data sources

The ability of WRF LES to capture the upstream flow, stability, and humidity profiles, as well as the observed structure of orographic clouds and precipitation for this case will be validated using two datasets: data from radiosondes released from Dixon, upwind of the Sierra Madre (Fig. 1b), and Wyoming Cloud Radar (WCR) data. The WCR is a 95-GHz (W band, 3 mm) Doppler radar with nadir and zenith antennas, carried aboard the University of Wyoming King Air (UWKA). The UWKA flew a geographically fixed pattern consisting of five tracks (Fig. 1) at a fixed flight level, at 13 kft (3962 m) MSL, about 600 m above the highest terrain in the Sierra Madre. This pattern, referred to as a ladder pattern, was repeated four times during the flight on 13 February 2012, twice without any seeding (NOSEED), then twice while three AgI generators on the ground (Fig. 1) were in operation (SEED). An along-wind track (Fig. 1b) was flown before the two SEED ladder patterns were flown, in part to allow time for AgI nuclei to disperse.

We will compare WCR reflectivity and hydrometeor vertical velocity with time- and space-matched WRF LES output, in vertical transects along fixed flight tracks from near the ground to cloud top. Aside from the zenith and nadir antennas, the WCR also transmitted along a slant-forward antenna below the aircraft. The combination
of nadir and slant-forward antenna Doppler velocities allows derivation of the along-track wind below flight level (Geerts et al. 2006; Damiani and Haimov 2006). That wind component too will be compared with WRF LES output.

WCR reflectivity is dominated by ice crystals in mixed-phase clouds, rather than by (much smaller) cloud droplets, because of the sixth-order dependence on diameter for Rayleigh scattering. Ice particles may be large enough (larger than ~1 mm, smaller if particles are rimed) to backscatter less than expected from Rayleigh theory at W band. In effect, if a good fraction of ice particles is larger than ~1 mm, then the distribution of particle sizes scattering in the Rayleigh and Mie regimes will yield a lower reflectivity than that expected from Rayleigh theory. However, model reflectivity\(^2\) is computed from hydrometeor size distributions assuming Rayleigh scattering only. Therefore model reflectivity is expected to exceed WCR reflectivity, especially in convective cells.

Observations are used only to validate the simulated thermodynamic, kinematic, and precipitation structures. They are not used in this study to evaluate the simulated impact of AgI seeding on clouds and precipitation or to assess the dynamic seeding mechanism.

b. WRF LES configuration

The simulations evaluated in this study use WRF, version 3.4.1, with the Thompson bulk microphysics scheme (Thompson et al. 2008). This scheme is not aerosol aware, and ice initiation in cloud is temperature dependent only. We further use the Xue et al. (2013a) seeding parameterization built on top of the Thompson scheme. This parameterization captures four modes of ice nucleation (deposition, condensation freezing, contact freezing, and immersion freezing) as functions of temperature and the water vapor saturation ratios with respect to ice and water. Besides AgI-mediated ice initiation, the parameterization allows AgI particles to act as cloud condensation nuclei and AgI scavenging by drops and ice crystals.

The other WRF physics choices, listed in Table 1, are the same as in Chu et al. (2016, manuscript submitted to J. Appl. Meteor. Climatol.). Four nested domains are used (Fig. 1a), with 2700-, 900-, 300-, and 100-m grid spacings, respectively. The outer domain (d01) is driven by Climate Forecast System Reanalysis (CFSR) data, and is one-way nested with the next domain (d02). Both are non-LES. The d02 output fields then are processed to provide the initial and boundary conditions for domain d03, which is one-way nested with the inner domain d04, where terrain and flow are resolved down to 100 m. Both d03 and d04 use a WRF LES framework without PBL scheme (Table 1).

One important question regarding the validity of the LES runs and the dispersion of AgI nuclei released from the ground regards how well boundary layer (BL) turbulence is captured. A 100-m grid spacing in the domain of interest is chosen because it resolves the most energetic eddies: the resolved turbulent and terrain-driven eddies are responsible for the bulk of the turbulent kinetic energy (TKE), vertical transfer of momentum, heat, water vapor, hydrometeors, and AgI nuclei within the PBL and in convective cells (Xue et al. 2016). The residual subgrid-scale TKE is negligible relative to the resolved TKE. The domain d02 model output does not contain resolved TKE information, so TKE has to be generated from the upwind boundary in domain d03 (300-m LES). This occurs effectively through interaction with the complex terrain upwind of the area of interest (Xue et al. 2016). At 100-m resolution, the simulated AgI dispersion pattern

\[\text{Table 1. Model configuration.}\]

<table>
<thead>
<tr>
<th>Configurations/domains</th>
<th>d01: 2700-m non-LES</th>
<th>d02: 900-m non-LES</th>
<th>d03: 300-m LES</th>
<th>d04: 100-m LES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid points</td>
<td>360 × 720</td>
<td>210 × 420</td>
<td>540 × 330</td>
<td>810 × 810</td>
</tr>
<tr>
<td>Time step (s)</td>
<td>12</td>
<td>4</td>
<td>0.2</td>
<td>0.07</td>
</tr>
<tr>
<td>Nesting</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>61 layers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PBL</td>
<td>Mellor–Yamada–Janjič (MYJ)</td>
<td>CAM shortwave and longwave schemes</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microphysics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbulence</td>
<td>Horizontal Smagorinsky first-order closure</td>
<td>1.5-order TKE closure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^2\)Model reflectivity is calculated using an NCAR Command Language (NCL) build-in function that depends on temperature, pressure, and vapor, and mostly on the assumed size distribution and mixing ratios of all hydrometeor species. We use the NCL, version 6.3.0 (available from http://dx.doi.org/10.5065/D6WD3XH5).
matches observations within the uncertainty brackets of the measurements (Xue et al. 2014).

All simulations have a model top pressure of 20 mb, a damping-layer depth of 10 km, and 61 levels, most densely packed near the surface. The vertical grid spacing increases from \( \sim 20 \text{ m} \) near the surface to less than 200 m at 2000 m above ground level (AGL), which is near cloud-top level in this case. This implies a grid aspect ratio \((\delta z: \delta x)\) of less than 2 in the region of interest in the inner domain. This vertical resolution is sufficient to capture BL eddies and shallow convective cells. WRF, version 3.4.1, does not allow different vertical resolutions in nested domains, therefore the same high vertical resolution is used in all domains.

WRF LES 100-m resolution simulation is conducted with and without seeding by controlling the release of AgI in the seeding parameterization module from three generators in domain d04 (Fig. 1b). The seeding times in the “treated run” match the actual ones on this day (2015–2215 UTC). The “control run” is identical to the treated run (except that no seeding occurs) to isolate the impact of seeding on cloud and precipitation. Before we explore differences between treated and control runs, the 100-m LES model is validated against observations.

3. WRF LES validation

a. Upstream soundings

Three radiosondes were released during the UWKA flight period from Dixon, upwind of the AgI generators and the Sierra Madre (Fig. 1b). The first sounding was released just after UWKA started the first ladder pattern, the second one was launched during the UWKA along-wind flight leg, and the last was launched just before the UWKA finished ladder 4. The corresponding wind and equivalent potential temperature \( \theta_e \) profiles are shown in Fig. 2. As shown in Pokharel et al. (2014), the third sounding (2201 UTC) likely penetrated a convective cloud between 2.4 and 4.1 km MSL, and then experienced anomalous cooling due to the sublimation of accreted ice as the radiosonde exited the cloud. Therefore this sounding is less representative of the environment.

The first two radiosondes reveal some potential instability in the lowest 2 km AGL (\( u_e \) decreasing with height, Fig. 2c), although any convective available potential energy (CAPE) is insignificant (Pokharel et al. 2014). The WRF LES produces a slightly colder and drier environment in the lowest 2 km in comparison with the first two soundings, but a similar stratification, with some potential instability and CAPE. The atmosphere is slightly more capped near 4.0 km MSL than observed. Thus the model is likely to support shallow convection, as observed (shown below), although with the stronger capping near 4.0 km MSL, it may be slightly shallower than observed. Such convection likely is due to surface heating in the early-afternoon hours.

The wind speed below mountaintop level averaged \( 5 \text{ m s}^{-1} \). Given the weak low-level stratification, this is sufficient to yield a bulk Froude number \( \text{Fr} \) larger than one (Table 2), thus the flow is likely to ascend over the mountain rather than being blocked. The model Fr value is close to the observed one. The average WRF LES wind speed is higher below mountaintop level but lower between 3.4 and 5.0 km, relative to observations. The observed and modeled wind reveals rather little shear in the lowest 2 km AGL, facilitating the persistence of convective cells in the absence of significant

![Fig. 2. Profiles obtained from three radiosondes released from Dixon (Fig. 1b) (solid lines) and from time- and space-matched 100-m LES model output (dashed lines): (a) wind speed, (b) wind direction, and (c) equivalent potential temperature.](image-url)
The wind speed $U$ and the Froude number $F_r$ represent averages between the near surface (100 m AGL) and the height of the highest point in the Sierra Madre, Bridger Peak (3355 m). The Brunt–Väisälä frequency $N$ is the combination of the dry (moist) value of $N$ below (above) the cloud base [definied as the lifting condensation level (LCL)]. The Froude number is calculated as $U/(NH)$, where $H$ is the height difference between the sounding site in Dixon and Bridger Peak. The $T^*$ is the temperature at the LCL. All observations are averages from three radiosondes released in Dixon, except LWP, which is the average value recorded by a microwave radiometer placed on a hill in Dixon, pointing toward the Sierra Madre. The 100-m LES model output is time–space matched to these observations.

### Table 2: Evaluation of model performance in terms of upwind sounding parameters

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>Obs</th>
<th>100-m LES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$ (m s$^{-1}$)</td>
<td>5.1</td>
<td>6.7</td>
</tr>
<tr>
<td>Wind direction ($^\circ$)</td>
<td>249</td>
<td>250</td>
</tr>
<tr>
<td>$N$ (10$^{-2}$ s$^{-1}$)</td>
<td>0.32</td>
<td>0.45</td>
</tr>
<tr>
<td>$F_r$</td>
<td>1.61</td>
<td>1.31</td>
</tr>
<tr>
<td>LCL (km MSL)</td>
<td>2.42</td>
<td>2.57</td>
</tr>
<tr>
<td>$T^*$ (°C)</td>
<td>−4.2</td>
<td>−4.7</td>
</tr>
<tr>
<td>LWP (g m$^{-2}$)</td>
<td>26</td>
<td>17</td>
</tr>
</tbody>
</table>

CAPE. The low-level wind is from the southwest, about 22°/23° (observed/modelled) clockwise of the normal to the ladder tracks. Such small track-normal angle ensures that AgI nuclei are transported across tracks 2–5 (Fig. 1b), both in reality and in the model.

A passive microwave radiometer operated in Dixon, with its antenna pointing just above the horizon line toward the Sierra Madre. This probe was used to estimate the vertical liquid water path (LWP) in the orographic clouds. The mean radiometer LWP estimate of 26 g m$^{-2}$ (average between 1915 and 2115 UTC) is higher than the corresponding model estimate along the same slant path (Table 2). However, this estimate is uncertain because it is quite sensitive to the details of convective cells and their path and because radiometric LWP estimates are intrinsically uncertain (Crewell et al. 2009).

#### b. Along-wind vertical transect of storm structure

An along-wind track was flown following completion of the second ladder pattern (Fig. 1b). The WCR reflectivity transect (Fig. 3a) reveals cells of enhanced reflectivity embedded in weak (stratiform) echoes on both the windward and lee sides of the mountain. In terms of relative isolation and intensity, these cells appear convective (Steiner et al. 1995), although the peak reflectivity is rather low ($\sim$10 dBZ), and the cells are shallow, capped at $\sim$4.5 km MSL by a stable layer (Fig. 2c). In terms of vertical velocity, too, the cells appear convective. The towering echo in the lee ($34 < x < 42$ km), for instance, contains several flight-level updrafts exceeding 2 m s$^{-1}$, which probably lofts snow particles. An updraft strength exceeding the hydrometeor fall speed is one criterion used in defining convection (Houze 2014, chapter 6).

Note that the WCR hydrometeor vertical velocity, shown in Fig. 3b, is centered at $\sim$1 m s$^{-1}$ (white color band separating blue from red hues). This is intended to approximately account for the hydrometeor fall speed, which is about 1 m s$^{-1}$ for unrimed snow (Locatelli and Hobbs 1974; Mitchell 1996). Thus blue (red) hues generally imply updrafts (downdrafts). The gust probe vertical air velocity is shown at flight level, using the same color scheme, but centered at 0 m s$^{-1}$. The WCR and gust probe vertical velocity estimates (was as well as the fall speed) have a local uncertainty of $\sim$1 m s$^{-1}$. The first-order vertical velocity structure in Fig. 3b indicates rising (sinking) motion upwind (downwind) of the crest, but there is much variation on finer scales. The finescale vertical velocity variations near the ground are mostly shear-induced and terrain-driven PBL turbulent eddies (Geerts et al. 2011). The turbulence aloft, for instance in the convective tower in the lee ($34 < x < 42$ km), probably is buoyancy driven.

The along-track wind speed transect (Fig. 3c) reveals weak wind on the upwind side, downslope acceleration near the crest up to 15 m s$^{-1}$, and, near the surface, a sudden flow reversal in the lee ($x > 30$ km). Deep rising motion (Fig. 3b) occurs where the plunging jet decelerates and meets the weak reverse current (28 $< x < 30$ km). The confluent low-level flow and deep ascent are reminiscent of a hydraulic jump, which was observed frequently observed in ASCII, in the lee of the Sierra Madre and an adjacent mountain range (Jing et al. 2015; Geerts et al. 2015; French et al. 2015) under similar up-stream flow and stability conditions. Such deep ascent may trigger convective cells in the lee, such as the one observed farther east ($34 < x < 42$ km). The streamlines shown in Fig. 3e are tangential to the 2D hydrometeor velocity vectors. If the flow is steady, then these streamlines are trajectories, that is, they capture the actual movement of hydrometeors in this transect.

The “radar” reflectivity from hydrometeors in the 100-m resolution LES (Fig. 3d) clearly shows cells of enhanced values, similar to the observed convective cells. The relative isolation, aspect ratio, and echo top of these cells is similar to observed values. The maximum updrafts upwind of the Sierra Madre crest are $\sim$4 m s$^{-1}$ (Fig. 3e) and the maximum reflectivity $\sim$25 dBZ. The model’s ability to capture shallow convection embedded in stratiform clouds is a remarkable achievement, given the limited CAPE, the lack of information about snow cover and thus surface heat fluxes, and the rather coarse resolution of the driver dataset (CFSR) in the outer domain. The echo top is slightly lower than observed, consistent with the lower stable layer in the upwind sounding (Fig. 2c). The
convective cells are embedded in weaker precipitation, as observed. The model produces some high ice clouds in the lee (Fig. 3d). Such clouds are not observed at this time but are present in earlier WCR transects (not shown).

The along-track wind speed compares well to observations on the upwind side (Fig. 3f). The model also produces plunging flow across the crest, accelerating up to 15 m s$^{-1}$. But this jet extends farther downwind than observed, and a low-level reverse current is absent, possibly because the low-level upstream environment is slightly too stable (Fig. 2c). This may explain why in the model convective cells are found upwind of the crest only and decay rapidly in the lee. Nevertheless, the plunging flow does decelerate abruptly in some places, giving rise to some deep ascent plumes that are stronger than the buoyant or terrain-driven updrafts on the windward side (Fig. 3e). The model resolves turbulent eddies in the PBL (Fig. 3e); however, they are not as finescale as observed (Fig. 3b).

**FIG. 3.** Cross section from southwest to northeast along the along-wind flight track shown in Fig. 1b. (a) WCR reflectivity; (b) WCR-estimated hydrometeor vertical velocity and gust probe vertical air velocity at flight level; (c) WCR-derived along-track wind along with gust probe along-track wind at flight level. Time- and space-matched 100-m LES model output: (d) reflectivity, (e) vertical air velocity, and (f) along-track wind and isentropes. The dashed lines just below 4 km MSL in (a), (d), and (e) represent the flight level. The black contours in (c) and (f) are hydrometeor streamlines and moist isentropes, respectively. The moist isentropes in (f) are contoured from 290 to 300 K at a 2-K interval.
c. Storm evolution and seeding impact on reflectivity

1) OBSERVATIONS

We now analyze the reflectivity transects for four passes along track 3 to further evaluate the model under NOSEED conditions, and to examine the observed-modeled response of reflectivity to seeding, in the last two passes (Fig. 4). The distance between the three AgI generators and track 3, ~11 km along the direction of the mean low-level wind (Fig. 1b), is long enough for AgI nuclei to disperse into clouds and interact with water species, yet still upwind of the crest so clouds are not yet subject to plunging flow. The wind blows out of the transects in Fig. 4 (the reader is looking to the southwest), but there is a small wind component from right to left in the transects, because the wind is more westerly than the track-3 normal. Multiple convective cells are transected, both during NOSEED (Figs. 4a,b) and during SEED (Figs. 4c,d). Many cells reach flight level (4.0 km MSL). Some cirrus clouds are observed on the right (northwest) during the first pass (Fig. 4a); these are more pronounced farther downwind on tracks 4–5 at this time. Ignoring these clouds, the height of the WCR convective cells averages at about 4.5 km MSL, both during NOSEED and SEED. Some cells reach 5.0 km MSL (e.g., Fig. 4d), well above the interstitial more stratiform echoes.

The three asterisks in Figs. 4c and 4d are the projection of AgI-generator locations along the direction of the mean low-level wind. A strong, deep cell is present near the projected AgI plume of the leftmost generator during the last pass (Fig. 4d) but not near other projected plume locations. This could be natural: strong cells are present in the same area 1.5 h earlier, during pass 2 (NOSEED) (Fig. 4b). The simple linear projection based on estimated wind direction may not be very accurate. The actual location of the AgI plumes in this transect may be captured better by the WRF LES, given that the model replicates observed wind and atmospheric stability reasonably well (sections 3a and 3b). The modeled extent of the three AgI plumes is shown as white contours in Figs. 4g and 4h. 3 There is no clear

Fig. 4. Reflectivity transects along track 3 (Fig. 1b) for four UWKA passes, two during NOSEED and two during SEED. The southeast side of the track is on the left in all panels. (a)–(d) WCR reflectivity; the three white asterisks in (c) and (d) indicate the projected location of the three AgI plumes. Also shown is WRF LES output from the (e),(f) control and (g),(h) treated runs; the white lines in (g) and (h) delineate an AgI number concentration of 1 L⁻¹.

3 This includes dry AgI nuclei in the air as well as AgI in ice, snow, graupel, and cloud droplets.
evidence of enhanced WCR reflectivity in these three regions, including during the last pass.

2) SIMULATIONS

The WRF LES reproduces the observations well in terms of the intensity, size, and spacing between convective cells, and in terms of the presence of interstitial shallow stratiform precipitation (Figs. 4e–h). The simulated echo top is lower than observed. The echo cells tend to be collocated within the three AgI plumes in Figs. 4g,h. The possible reason is convective updrafts converge BL air including tracers such as AgI nuclei and mix them over a greater depth, and also produce precipitation and thus enhance reflectivity.

But it is possible that the AgI nuclei enhance snow growth (echo strength) and enhance the depth and strength of the convective updrafts (dynamic seeding concept). To examine this, we compare model reflectivity in the same transect (track 3) at the same time, but without seeding (control run) (Fig. 5). The 1 L$^{-1}$ contour of AgI concentration contours from the treated run are overlaid for reference only. During pass 3 (50 min after the AgI generators are switched on), the three convective cells seen in the treated run (Fig. 4g) remain present without seeding (Fig. 5a), but reflectivity is slightly enhanced in the treated run, especially in the rightmost cell. The reflectivity of cells within the AgI plumes is much increased during the fourth pass (Fig. 4h vs Fig. 5b), 90 min into the SEED period, by which time the model has dispersed more AgI along track 3 (not shown).

To increase reflectivity, a certain time period is required for AgI particles to be advected into cloud, activated as ice nuclei, and grow big enough to contribute to reflectivity. A careful analysis of the history of the leftmost convective cell in ladder 3 (near $x = 7$ km in Fig. 5a) shows that this cell is not intensified by seeding because 1) naturally this cell is already deep and mature enough that supercooled liquid water has been totally consumed by the time it moves over the AgI-enriched PBL, and 2) this cell is in its decay stage by the time it reaches track 3. But the elevated cell just to the right of this decaying cell (the one near $x = 16$ km in Fig. 5a) does contain much liquid water and thus seeding causes significant enhancement of snow mixing ratio (Fig. 4g vs Fig. 5a).

4. Modeled impact of glaciogenic seeding on cloud processes

Since the 100-m LES faithfully reproduces the upstream flow and stability profiles, as well as the convection embedded in stratiform clouds, we can use the model to explore how seeding affects the microphysics and dynamics of these orographic clouds.

a. AgI dispersal and impact on cloud and precipitation

The vertically integrated concentration of AgI nuclei at 2130 UTC, 75 min after the AgI generators were activated, is shown in Fig. 6. Note the logarithmic scale, which tends to emphasize the plume margins. The AgI plume cores remain separate over the Sierra Madre, and only merge downwind, where AgI nuclei are mixed over a great depth by transient hydraulic jumps (Fig. 7c). The downwind transport across the target mountain is somewhat uncertain, as the AgI seeding parameterization (Xue et al. 2013a) does not account for dry sedimentation, self-coagulation, and wet scavenging by precipitating hydrometeors, processes that decrease the AgI concentration at range. The surface wind barbs and AgI plumes shown in Fig. 6 suggest only slight flow diversion around the highest terrain, consistent with the rather high Fr value (Table 2). The wind barbs also confirm the flow acceleration across the terrain crest.

We now examine the model cloud structure along the middle AgI plume in a cross section across the Sierra Madre. Significant cloud water ($q_c$) is present in the tops of convective cells on the upwind side of the mountain in the control run, but hardly any snow ($q_s$) (Fig. 7a). This is because cloud tops are not colder than $-16^\circ$C and modeled natural ice nucleation rates are quite low at these temperatures. Simulated ice crystal concentrations in cloud are about 1 L$^{-1}$ at flight level in the control run, similar to observed values (0.5–5 L$^{-1}$), according to data from a cloud imaging probe aboard the UWKA (Pokharel et al. 2014). The ice crystal concentration
increases by two orders of magnitude at matching locations in the treated run, relative to the control run. The treated run shows a reduction of cloud water and a substantial increase in snow mixing ratio in the convective cloud tops and down to the ground (Fig. 7b). The conversion from $q_c$ to $q_s$ mostly takes place in the $-12^\circ$ to $-16^\circ$C temperature range, where the saturation vapor pressure difference between water and ice...
peaks and thus the Bergeron–Findeisen process (Bergeron 1935) operates optimally. The snow growth in the treated run is enabled by ice initiation mediated by AgI nuclei, which are transported upward by the convection (Fig. 7c). The virtual absence of AgI in areas of high $q_s$ is the result of the sedimentation of AgI in snow particles. A 3D view of cloud, snow, and AgI concentration at the same time is given in Fig. 8. The discrete, layered vertical structure is due to inadequate smoothing by the Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (VAPOR) software (Clyne et al. 2007) used to generate the 3D view, but it highlights the model vertical resolution. This view nicely illustrates the convective nature of clouds and precipitation. The convective cells are purely orographic and collapse when crossing the Sierra Madre crest, which disagrees with WCR observations (Fig. 3a) and visible satellite imagery (not shown). The liquid cloud phase dominates in the control run, with peak $q_s$ values below 0.3 g kg$^{-1}$ (the $q_s$ visibility threshold in Fig. 8) in most convective cells. Most cells attain this $q_s$ threshold within the AgI plumes in the treated run (Fig. 8b). The depth and location of AgI towers (Fig. 8c) matches that of the convective cells, indicating vertical transport of AgI nuclei by convection. The AgI nuclei are dispersed over a greater depth on the (dry) leeside by hydraulic jumps, although in smaller concentrations, relative to the upwind convective cells.

b. Changes in water content in all phases

To quantify the impact of glaciogenic seeding on the water cycle components over the Sierra Madre, we examine vertically integrated changes in cloud liquid water, solid phase water, and water vapor (Fig. 9), an approach taken also by Xue et al. (2016). Natural liquid water is present on the upwind side only where BL air is lifted and convective towers form, resulting in LWP values up to 180 g m$^{-2}$. More than 50% of this liquid water is depleted in the AgI plumes in the treated run (Fig. 9a). Some solid phase water is present far upwind of the Sierra Madre because of cirrus clouds and some shallow convective cells, with very little natural orographic enhancement of snow and ice over the Sierra Madre (Fig. 9b). The spatial pattern and amount of LWP depletion in the treated run matches those of ice water path (IWP) enhancement. The change in water vapor path (Fig. 9c) is negative in the lee of the Sierra Madre on account of the seeding-induced conversion of liquid water to snow and snow fallout, whereas in natural conditions most of the cloud liquid water evaporates in the subsiding flow in the lee. Natural precipitation upwind and over the Sierra Madre is very light (<0.5 mm in 2 h), concentrated in stripes following the moving convective cells. The seeding-induced augmentation of precipitation over the mountain (up to 1.1 mm in 2 h) is larger than the natural precipitation, and on average more than doubles the precipitation rate within the AgI plumes over the Sierra Madre.

c. Chain-of-effect evaluation of the dynamic seeding concept

One of the expectations of the dynamic seeding concept is an increase in convective cloud top (section 1).
The vertical extent of cloud in the control and treated runs and their difference are shown in Figs. 7d–f, along the same transect shown in Fig. 6. “Cloud” is defined here as where the sum of all mixing ratios of liquid and solid water species (cloud + snow + ice + graupel + rain) exceeds a low threshold (0.001 g kg$^{-1}$), which results in the inclusion of the lee cirrus clouds and some snow particles advected by the plunging flow in the lee.

The cloud top only slightly increases upwind of the Sierra Madre crest (Fig. 7f), by 65 m on average. This gives 0.47 K temperature decrease for a moist-adiabatic lapse rate of 7.3 K km$^{-1}$, which is representative of the observed temperature and pressure. Yet the temperature at cloud-top height ($H_c$) decreases by just 0.26 K in the treated run, relative to the control run over the same area upwind of the Sierra Madre. This implies additional latent heating due to AgI-induced freezing of 0.21 K, which is a plausible amount given the reduction in $q_c$ in the treated run relative to the control run (Figs. 7a,b). Thus the dynamic seeding concept appears to apply in this cross section. That does not mean this concept is significant in the simulated snowfall enhancement. In fact, the simulated relative changes in water paths and precipitation (Fig. 9) are far greater than that in $H_c$, suggesting that the dynamic seeding concept is relatively insignificant for cold-base orographic clouds.

To explore this further, we examine the differences in cloud liquid water $q_c$, temperature $T$, vertical velocity $w$, and cloud-top height $H_c$ between treated run and control run as a function of simulated reflectivity (Fig. 10). The treated versus control comparison is on the basis of individual grid points. Such an approach is warranted since the vertical displacement differences (between treated and control runs) typically are very small relative to the vertical grid spacing. Convective cells are characterized by a relative high reflectivity; that is, they are on the right side in the panels of Fig. 10). Other markers of convective activity could be used in lieu of reflectivity: convective cells are buoyant (positive temperature anomaly) at least sometime during their life cycle, and have a strong updraft and a high liquid water content. The dynamic seeding concept’s expectation is that convective cells have less liquid water, a higher temperature, more ascent, and a higher cloud top in the treated run. Here reflectivity is used as a measure of
convective intensity because it is less transient than some other parameters, and is more directly related to precipitation rate. Note that in the context of cloud-top height (Fig. 10d), reflectivity must be defined differently from that in the other panels of Fig. 10: rather than the local value, it is the column-average value within the boundary layer cloud layer (excluding the decoupled cirrus cloud layer aloft). The data used to generate Fig. 10 are all model grid points within an AgI plume (total AgI concentration $>1 \text{ L}^{-1}$) and within cloud (total hydrometeor mixing ratio greater than $0.001 \text{ g kg}^{-1}$ in both treated and control runs) between 2045 UTC (30 min after the start of seeding) and 2215 UTC. The domain is a rectangle over the Sierra Madre delineated by tracks 2 and 5 (Fig. 1b).

Seeding tends to deplete cloud water more in convective cells (Fig. 10a) or at least in grid points with higher reflectivity above $-8 \text{ dBZ}$. The mean difference between treated and control runs ($\Delta q_c$) increases with reflectivity. (Few points remain with reflectivity values over $-24 \text{ dBZ}$.) The depletion of cloud water is most pronounced in pockets with significant liquid water in the first place (Fig. 11a), and at lower temperatures where AgI nuclei are more likely to initiate ice (Fig. 11b). Both tendencies make sense intuitively.

Latent heat released through the freezing of supercooled liquid water in convective cells heats the air locally. Seeding does indeed tend to cause slight warming in grid cells with enhanced reflectivity (Fig. 10b). The warm anomaly is expected to dynamically force more rising motion. Indeed convective cells (or rather, strong echoes) tend to exhibit slight rising motion relative to weaker echo areas (Fig. 10c), but the average vertical velocity difference in convective cells ($>8 \text{ dBZ}$) is rather small ($2 \text{ cm s}^{-1}$). Finally, the extra ascent rate may result in a higher cloud top. There is no such signal in the cloud-top height difference (Fig. 10d). Seeding does tend to raise the cloud tops slightly on average, consistent with Fig. 7f, but mainly in weaker reflectivity regions. The likely reason for the more substantial $H_c$ increase in shallow, weak-echo regions is that the environment in which more shallow clouds (including young convective clouds with weak echoes) grow by seeding is better mixed, that is, closer to the moist-adiabatic lapse rate. Stronger, deeper echoes (usually older convective clouds) may be capped and may no longer contain the liquid water to benefit from the AgI boost. Note that $H_c$ tends to decrease in the weakest echoes (Fig. 10d), probably because of compensating subsidence.
In short, the chain of effects postulated by the dynamic seeding concept appears to be in effect, although conclusive evidence for the final step (regarding $H_c$) is lacking.

5. Discussion

The main weakness of this chain-of-effects analysis (section 4c) is that the postulated changes are not simultaneous but rather sequential. Certainly the increase in cloud-top height $H_c$ is delayed relative to the enhanced latent heat release. A second weakness is that reflectivity is not a perfect surrogate for convection: convective cells exhibit a life cycle in which the updraft precedes high reflectivity. A similar analysis to that in Fig. 10, but using control vertical velocity in lieu of reflectivity in the abscissa, yields similar results, confirming that seeding tends to deplete liquid water, increase buoyancy, and slightly increase average cloud-top height, mainly in weak updrafts (not shown). These weaknesses can be tackled by a nonsimultaneous trajectory-based analysis, whereby air parcels are described from the moment they enter a cloudy AgI plume until they exit it. Such more rigorous approach is beyond the scope of this study, but a time lapse (not shown) analysis of transects (Figs. 7a,b) and 3D views (Fig. 8) qualitatively shows that early-stage cells located within an AgI plume will grow more vigorously and deeper in the treated run than the control run, whereas mature cells are hardly affected by seeding. The dataset on which Fig. 10 is based is collected over a long period (1.5 h) relative to the typical life cycle of convection; thus all stages should be represented. But a more in-depth analysis of changes in $H_c$ (the key component of the dynamic seeding concept) requires a trajectory-based air parcel or hydrometeor analysis.

This study confirms the chain of effects postulated to occur according to the dynamic seeding concept: glaciogenic seeding depletes supercooled liquid water and generates pockets of enhanced buoyancy and convective ascent, resulting in higher cloud tops. But these changes are small in these cold-based, shallow clouds (average $\Delta H_c < 100$ m in Fig. 7f). The absence of more substantial changes in cloud-top height, combined with the fact that most snow growth occurs around $-14^\circ\text{C}$ where the ice water saturation vapor pressure difference is large, suggests that the modeled snowfall enhancement is largely due to static (microphysical) processes rather than dynamic ones.

6. Conclusions

This study uses WRF in a LES framework to examine shallow embedded convection observed on 13 February 2012 over the Sierra Madre in Wyoming (Pokharel et al. 2014) as part of ASCII. The convection in this case has a cloud-base temperature well below freezing, a cloud top around $-15^\circ\text{C}$, updrafts peaking around 3 m s$^{-1}$, and peak W-band radar reflectivity values around 10 dBZ. The AgI seeding module developed by Xue et al. (2013a,b), coupled to the Thompson microphysics scheme, is used to examine the impact of ground-based glaciogenic seeding on the microphysics and dynamics of this cold-based convection.

The key findings are as follows:

- Shallow orographic convection, including the depth, intensity, and spacing of convective cells, can be simulated faithfully using WRF LES at 100-m resolution. The model also reasonably captures the orographic flow field, including plunging flow in the lee.
- A comparison between treated and control simulations indicates that AgI seeding effectively converts cloud water to ice and snow in this case, resulting in increased surface precipitation. This conclusion, for convective clouds, is consistent with similar studies focused on stratiform clouds (Chu et al. 2014, 2016, manuscript...

- The model further shows that glaciogenic seeding depletes liquid water and enhances buoyancy, updraft strength, and cloud-top height, indicating that the dynamic seeding concept applies in these shallow, cold-based convective clouds. But the cloud-top-height change is very small (<100 m on average). The absence of more substantial changes in cloud-top height, combined with the fact that most natural and enhanced snow growth occurs in a temperature range where the Bergeron process is effective, suggests that the modeled snowfall enhancement is largely due to static (microphysical) processes rather than dynamic ones.

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**REFERENCES**


