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The impact of ground-based glaciogenic seeding on clouds and precipitation over mountains: A multi-sensor case study of shallow precipitating orographic cumuli

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ABSTRACT

This paper examines reflectivity data from three different radar systems, as well as airborne and ground-based in situ particle imaging data, to study the impact of ground-based glaciogenic seeding on shallow, lightly precipitating orographic cumuli, observed on 13 February 2012, as part of the AgI Seeding Cloud Impact Investigation (ASCII) experiment in Wyoming. Three silver iodide (AgI) generators were used, located on the windward slopes of the target mountain. This case was chosen for several reasons: the AgI generators were near the lifting condensation level, where the temperature was about −6 °C; cloud droplets were present in the cumulus clouds, which were rooted in the boundary layer; and the airflow, although weak, ascended over the mountain. The target mountain pass site was almost certainly impacted by seeding, according to a trace element analysis of the falling snow.

Data from three radar systems were used in the analysis of the impact of seeding on precipitation: the airborne W-band (3 mm wavelength) profiling Wyoming Cloud Radar (WCR), two Ka-band (1.2 cm) profiling Micro-Rain Radars (MRR), and a X-band (3 cm) scanning Doppler-on-Wheels (DOW) radar. The WCR was onboard a research aircraft flying geographically fixed tracks, the DOW and one MRR were located at the target mountain pass, and another MRR was upstream of the AgI generators. Composite data from the three radar systems, each with their own target and upwind control regions, indicate that the observed changes in reflectivity profiles can be explained largely by the natural emergence of shallow cumuli. A comparison with lateral control regions (i.e., over the mountain, but to the side of the AgI plumes) suggests that seeding may have further enhanced snowfall, but the signal is weak.

Particle probes at flight level and at the mountain pass site show that the concentration of small ice crystals (<1 mm) was significantly larger downwind of the AgI generators during seeding. This too is consistent with the emergence of shallow convection, but a comparison between flight sections downwind of the AgI point sources and those to the side suggests that glaciogenic seeding increased the concentration of ice crystals of all sizes in the shallow convection.

Abbreviations: ZIP, reflectivity impact factor: $\text{ZIP} = \Delta\text{dBZ}_T - \Delta\text{dBZ}_U$ where $\Delta\text{dBZ} = \text{dBZ}_S - \text{dBZ}_N$, and subscript S (N) refers to SEED (NOSEED), while subscript T (U) refers to treated or target (untreated or control); PIF, precipitation impact factor; ASCII, AgI Seeding Cloud Impact Investigation; UWKA, University of Wyoming King Air; WCR, Wyoming Cloud Radar; WCL, Wyoming Cloud Lidar; MRR, Micro-Rain Radar; DOW, Doppler on Wheels.

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1. Introduction

Ice nuclei (IN) in the atmosphere are particles that can catalyze the freezing of supercooled cloud droplets, producing ice crystals that would not otherwise form (Creamean et al., 2013). IN are naturally scarce above −20 °C, thus more snow could grow in supercooled water clouds if IN were added to such clouds. This process is important to the climate system as it links precipitation to mineral and biological aerosols (e.g., Creamean et al., 2013; Wiacek et al., 2010); it is also the basis of intentional glaciogenic cloud seeding (e.g., Vonnegut, 1947; Mielke et al., 1970; Hobbs and Rangno, 1979).

The 2010 World Meteorological Organization (WMO) report on weather modification states "the glaciogenic seeding of mixed-phase clouds formed by air flowing over mountains offers good prospects for increasing precipitation in an economically-viable manner under suitable conditions" (WMO, 2010). But both actual seeding impact and suitable conditions remain poorly understood (National Research Council, 2003; Garstang et al., 2005). Much research has been conducted into the impact of glaciogenic cloud seeding of cold-season clouds over the mountains in the western United States and elsewhere, mostly using statistical techniques (e.g., Elliott et al., 1978; Mielke et al., 1981; Gabriel, 1995; Manton and Warren, 2011). Several case studies have reported a change in surface precipitation and/or in radar reflectivity following the injection of AgI nuclei (Hobbs et al., 1981; Super and Heimbach, 1988; Super and Boe, 1988; Deshler and Reynolds, 1990; Holroyd et al., 1995; Super, 1999; Huggins, 2007), although attribution is uncertain. Modeling work has shown that natural variability of precipitation can easily overwhelm the seeding effect (Seto et al., 2011; Chu et al., in review). The high variability of precipitation even at the finest spatial and temporal scales remains the biggest challenge in any attempt to observationally isolate a seeding signature (Garstang et al., 2005; Pokharel and Geerts, accepted for publication). The 2010 WMO report states that "if it were possible to predict precisely the precipitation from a cloud system, it would be a simple matter to detect the effect of artificial cloud seeding on that system".

The most recent research effort to reveal the efficacy of ground-based AgI seeding of orographic clouds is the 2008–2014 Wyoming Weather Modification Pilot Project (WWMPP) (Breed et al., 2014), which focuses on the Sierra Madre and Medicine Bow ranges in southern Wyoming. The 2012–13 AgI Seeding Cloud Impact Investigation (ASCII) project built on the WWMPP, with the specific aim to use new observational tools such as an airborne mm-wavelength radar (Geerts et al., 2013) and Large Eddy Simulations that resolve cloud processes including ice nucleation by AgI nuclei (Xue et al., 2013), to investigate the cloud-microphysical response to glaciogenic seeding.

Commonly used criteria for seeding wintertime orographic clouds with AgI nuclei relate to temperature, presence of supercooled liquid water, and wind direction (Vardiman and Moore, 1978; Breed et al., 2014). The suitable temperature range for AgI seeding in cloud is about −8 to −23 °C (Grant and Elliott, 1974). The lower temperature limit is variable and is dictated by the concentration of natural IN or large aerosol particles in the upstream air. The higher temperature limit varies somewhat as well, and relates to the temperature dependency of the AgI activation, measured as the number of crystals yielded per gram of AgI. This activation decreases by 2.5 orders of magnitude between −10 and −6 °C (DeMott, 1997). The success of AgI seeding may be affected also by the liquid water content (LWC) and drop size distribution, by the abundance of ice crystals, and by vertical cloud structure. For instance multi-layer clouds with ice crystals falling from aloft onto the shallow orographic cloud may not be suitable.

Natural production of ice crystals from the ground, mixed turbulently within the boundary layer (BL), may also affect the efficacy of ground-based glaciogenic seeding (Rogers and Vali, 1987; Geerts et al., 2011). Depending on the condition of the snow at the surface and in trees, ice crystals may be lofted and mixed into cloud when the wind is strong enough (Kristovich et al., 2012). On the one hand, the depth of the well-mixed BL is important for the mixing of ground-released AgI nuclei into cloud, and this depth is controlled by low-level wind speed and temperature lapse rate. A sufficiently strong cross-barrier wind and large lapse rate are important to avoid blocked flow. On the other hand, natural blowing snow may overwhelm any impact of ground-released AgI nuclei. Thus, relatively weak winds and some low-level potential instability, leading to shallow cumulus clouds, may be optimal, as it avoids blowing snow, ensures low-level flow over (rather than around) the mountain, and allows the mixing of ground-released AgI nuclei into cloud.

The present paper is the second ASCII case study, focusing on shallow orographic convection. The first ASCII case study (Pokharel et al., 2014, hereafter referred to as PGJ14) examines a precipitating stratiform cloud observed under much stronger wind on 21 February 2012 over the Sierra Madre. The cumulative evidence of three complementary radar systems, each with a (quasi-)simultaneous control and target region, indicates a measurable impact of seeding on low-level reflectivity in the PGJ14 case. The most convincing evidence in that case comes from the mapped change in average low-level reflectivity from a Doppler on Wheels (DOW) radar.

Many previous weather modification experiments have deployed one or more radars, as radar reflectivity is a reasonably good measure of precipitation rate. This paper is an observational case study that uses the same radars as the PGJ14 study. The objective of this paper is to detect an impact of ground-based seeding on snow in a shallow winter storm with cumulus convection. The experimental design and instruments are described in Section 2. The storm is described in Section 3. Reflectivity data from the various radars are explored in Section 4. Changes in snow size distribution at the surface and at flight level are described in Section 5. The findings are summarized in Section 6.

2. Experimental design and instrumentation

The ASCII-12 project is described in Geerts et al. (2013). The experiment was designed to measure clouds and precipitation initially during natural conditions, and later with three AgI generators in operation. Measurements were collected both upstream and downstream of these generators. The upstream measurements ("control") are essential in order to monitor the natural variations. The downstream