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Wintertime Orographic Cloud Seeding—A Review

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ABSTRACT

This paper reviews research conducted over the last six decades to understand and quantify the efficacy of wintertime orographic cloud seeding to increase winter snowpack and water supplies within a mountain basin. The fundamental hypothesis underlying cloud seeding as a method to enhance precipitation from wintertime orographic cloud systems is that a cloud's natural precipitation efficiency can be enhanced by converting supercooled water to ice upstream and over a mountain range in such a manner that newly created ice particles can grow and fall to the ground as additional snow on a specified target area. The review summarizes the results of physical, statistical, and modeling studies aimed at evaluating this underlying hypothesis, with a focus on results from more recent experiments that take advantage of modern instrumentation and advanced computation capabilities. Recent advances in assessment and operations are also reviewed, and recommendations for future experiments, based on the successes and failures of experiments of the past, are given.

1. Introduction

The U.S. population more than doubled from 1950 to 2010 and shifted from rural to urban areas (U.S. Census Bureau 2010). Southern and western states experienced the greatest population increase, resulting in concurrent expansion of public water supply systems. In response to increased demands and limits on water supplies, western communities have sought additional water sources through technologies such as cloud seeding, and/or have instituted water-conservation measures to preserve existing supply (Kenny et al. 2009). Water will become an increasingly scarce resource as populations continue to grow and changes in climate over the coming decades threaten the water volume of snow reservoirs in the western mountains (Mote et al. 2005; Rasmussen et al. 2011).

Across the western United States during winter, precipitation falls as snow over higher elevations along coastal ranges, and at nearly all elevations over interior mountain ranges. The ensuing snowmelt in spring and summer then provides annual water supplies. As early as the 1950s, following the discoveries of Schaefer and Vonnegut concerning cloud seeding (Schaefer 1946; Vonnegut 1947), water resource managers recognized that seeding wintertime orographic cloud systems had the potential to increase water supplies in arid regions. Increasing winter snowpack through seeding was envisioned as a means to enhance the natural snow reservoir that supplies water to drainage basins throughout the melt season. Indeed, the demand for water drove pioneering scientists in the 1950s to develop projects to evaluate the scientific basis for weather modification as a tool to increase water supplies. The early studies of orographic cloud seeding, which progressed to include elaborate field investigations in the 1970s and 1980s, made some progress in understanding the conditions under which cloud seeding could enhance precipitation, but were unable to clearly establish the magnitude of that enhancement. In its 2003 report, the National Research Council (NRC 2003) stated that "there still is no convincing scientific proof of the efficacy of intentional weather modification efforts." Despite this uncertainty, operational winter orographic weather modification has continued in most western states of the United States

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FIG. 1. Operational cloud-seeding project target areas for enhancement of winter snowpack in the mountains of the western United States in 2015 (colored green). No projects occurred in the states that are colored blue. (Source: North American Weather Modification Council.)

(Fig. 1) and in other arid regions, a direct result of the increasing need for water, and the large potential cost benefit for production of additional water by cloud seeding.

The fundamental hypothesis underlying cloud seeding as a method to enhance precipitation from wintertime orographic cloud systems is that *a cloud's natural precipitation efficiency can be enhanced by converting supercooled water to ice upstream and over a mountain range in such a manner that newly created ice particles can grow and fall to the ground as additional snow on a specified target area*. Orographic clouds, in this context, refers to cloud systems over mountain ranges, whether isolated or components of frontal systems within extratropical cyclones. This *static-seeding* hypothesis has its roots in the physical principle that the equilibrium vapor pressure with respect to ice is less than that with respect to liquid water at the same subfreezing temperature. Thus, at temperatures below 0°C, a water-saturated cloud (relative humidity with respect to water $RH_w = 100\%$) will be supersaturated with respect to ice at a rate of about 1% per degree Celsius of supercooling (Pruppacher and Klett 2010). The consequence is that in an initially water-saturated cloud containing supercooled water, ice particles grow rapidly to precipitation size, whereas small and nonprecipitating supercooled cloud droplets are either growing in an updraft or evaporating, providing moisture for ice growth. Alfred Wegener first proposed this diffusional growth process for liquid-saturated clouds (Wegener 1911). It was later explained theoretically and demonstrated experimentally by T. Bergeron and W. Findeisen (Bergeron 1935; Findeisen 1938).

Scientific evaluation of the static-seeding hypothesis has been attempted over the last half century in a number of projects (Fig. 2) using observational process-oriented studies to understand natural cloud structure and effects of cloud seeding, statistical comparisons of surface precipitation between treated and untreated events, and numerical models to simulate both natural and seeded clouds. Past reviews at least partially focused on orographic weather systems and/or weather modification research to modify those cloud systems include those of Smith (1979), Elliott (1986), Rangno (1986), Reynolds (1988), Orville (1996), Bruintjes (1999), Long (2001), Garstang et al. (2005), Huggins (2008), Tessendorf et al. (2015), Reynolds (2015), Gultepe (2015), and Haupt et al. (2019). This paper provides a systematic assessment of our current understanding of the effectiveness of wintertime cloud seeding to enhance mountain snowpack, drawing extensively on results from recent studies not available to authors of past reviews, with a focus on results from new and advanced instrumentation, improved understanding of cloud dynamical and microphysical processes, and more sophisticated numerical modeling technologies. We note that many instrumentation platforms have been deployed in efforts to evaluate cloud seeding. It is beyond the scope of this paper to review their uses, accuracy, and effectiveness. The reader is referred to the American Meteorological Society monograph *Ice Formation and Evolution in Clouds and Precipitation: Measurement and Modeling Challenges* (McFarquhar et al. 2017) for a concise summary of issues related to measurements of ice and snow in clouds and to articles by Rasmussen et al. (2012), Gultepe et al. (2016) and Kochendorfer et al. (2017) for surface measurements of snow.

This paper reviews research related to glaciogenic seeding of winter orographic clouds using silver iodide (AgI), dispersed pyrotechnically from the ground or aircraft, specifically within clouds with cloud-top temperatures typically colder than from −6° to −8°C. Three different approaches to orographic cloud-seeding evaluations are discussed: physical experiments, statistical evaluations, and modeling studies. Section 2 reviews physical evaluations of the hypothesis, summarizing what has been learned about the thermal, kinematic, and microphysical structure of natural winter mountain cloud systems, the transport and dispersion of seeding plumes, and the microphysical chain of events that occurs when an orographic cloud is seeded. Section 3 examines statistical evaluations of the hypothesis, focusing

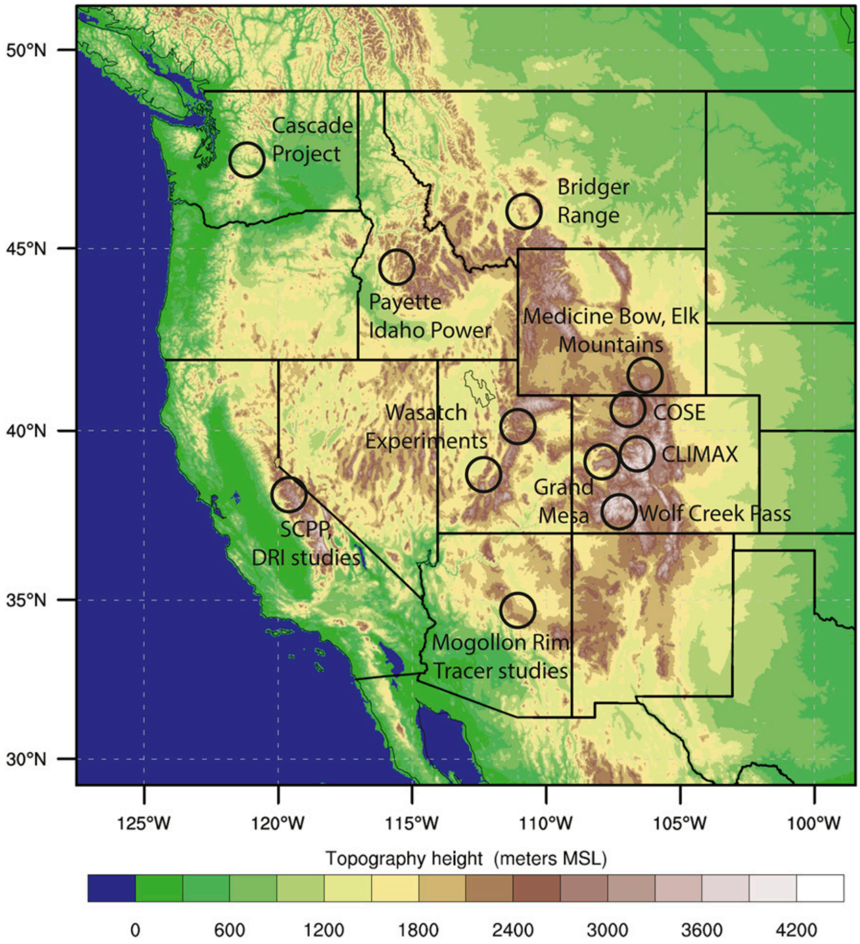

FIG. 2. Locations of major research projects in the western United States that were designed to evaluate the feasibility of orographic enhancement of snowpack through cloud seeding over the period 1960–2019.

on what has been learned by target/control and randomized evaluations of snowpack enhancement. Section 4 reviews modeling evaluations of the impacts of AgI seeding on orographic clouds. Section 5 considers recent advances in assessment and operations. The paper concludes with a summary of the state of the science and a look to the future.

2. Physical evaluations of the underlying hypothesis of orographic cloud seeding

Physical evaluations of the orographic cloud-seeding hypothesis follow four basic thrusts: 1) determining when and where supercooled liquid water (SLW) is present in clouds, 2) documenting natural precipitation processes and determining which orographic clouds are suitable for treatment with AgI, 3) determining conditions under which plumes of ground-released or airborne-released AgI reach clouds upstream and within target river basins, and 4) documenting the microphysical chain of events following seeding to determine whether it is consistent with the hypothesis and if the fallen snow contributes to snowpack enhancement.

a. Supercooled liquid water distribution

The first component of hypothesis evaluation has been to determine when and where SLW is present in orographic cloud systems. Mountain ranges were targeted in the first place because it was believed (correctly so) that SLW is commonly present in or near orographic updrafts. Understanding the SLW distribution in clouds was the focus of studies using aircraft, microwave radiometers, balloonborne instruments, and surface measurements conducted over California's Sierra Nevada (Reinking 1979; Heggli et al. 1983; Heggli and Rauber 1988; Demoz et al. 1993), Colorado's Park Range (Rauber et al. 1986; Rauber and Grant 1986, 1987), Utah's Wasatch (Hill and Woffinden 1980; Sassen et al. 1986, 1990), Idaho's Payette

Mountains (Tessendorf et al. 2019), Washington's Cascades (Hobbs 1975a; Ikeda et al. 2007), Wyoming's Medicine Bow Mountains (Politovich and Vali 1983; Jing and Geerts 2015; Rasmussen et al. 2018), Australia's Great Dividing Range and Snowy Mountains (Long and Carter 1996), and the central mountains of Japan (Kusunoki et al. 2004, 2005) [see also Reynolds and Dennis (1986), Rauber (1987), Hill (1980), Sassen and Zhao (1993), and Long and Huggins (1992) for additional information on field campaigns]. These studies, which produced consistent results, showed that SLW is most often found in clouds with sufficiently strong updrafts so that the condensate supply rate could be expected to exceed the diffusional growth rate of ice. Detailed measurements with various observation platforms, including airborne profiling W-, K-, and X-band Doppler radars, indicate that such updrafts can be found 1) along and over steep mountain slopes (Rauber et al. 1986); 2) in embedded convection, when it exists (Ikeda et al. 2007); 3) in cloud-top generating cells, particularly for cloud tops warmer than ~−25°C (Rauber and Tokay 1991; Morrison et al. 2013; Keeler et al. 2016a,b, 2017); 4) in updrafts associated with mountain-induced gravity waves (Reinking et al. 2000; Bruintjes et al. 1994); and 5) in turbulent eddies near the mountain surface induced by local terrain (Lee 1988; Geerts et al. 2011; Chu et al. 2018) or within Kelvin–Helmholtz billows and turbulence in shear zones upwind (Houze and Medina 2005; Medina and Houze 2015) or downwind (Geerts and Miao 2010; Barnes et al. 2018; Conrick et al. 2018) of terrain. Supercooled water has also been found 6) in shallow convection (coupled with surface) with cloud tops warmer than about −25°C (Heggli et al. 1983; Heggli and Rauber 1988); 7) in more laminar orographic clouds where cloud-top temperatures are greater than −15°C and ice processes are inefficient (Tessendorf et al. 2017); and 8) in orographic clouds with bases below melting level and terrain-forced ascent of cloud water through the 0°C level (Marwitz 1987; Rauber 1992; Ikeda et al. 2007).

b. *Natural precipitation processes*

A second component of hypothesis evaluation has been to document natural precipitation processes and to determine which orographic clouds, if any, are suitable for treatment with AgI to enhance precipitation. Again, numerous field campaigns have been conducted across mountain regions to study natural precipitation processes and evaluate the seedability of orographic clouds (e.g., Hobbs 1975a; Cooper and Saunders 1980; Cooper and Vali 1981; Marwitz 1987; Rauber 1987; Uttal et al. 1988; Sassen et al. 1990; Rauber 1992; Long and Carter 1996; Geerts et al. 2010; Ritzman et al. 2015; Rasmussen et al. 2018; Tessendorf et al. 2019). Together, these studies show that the microphysics of mountain cloud systems evolve in close relationship to their mesoscale dynamical structure, which in turn is associated with the approach and passage of surface and upper-tropospheric fronts and jet stream–related circulations. Deep orographic cloud systems, which often occur prior to frontal passage, are typically characterized by ice nucleation, primarily but not exclusively near cloud top within cloud-top generating cells or gravity waves, followed by diffusional growth and aggregation of ice particles during fallout to the surface. Studies in the Cascades of western North America (Hobbs 1975a; Stoelinga et al. 2003), northern Colorado Rockies (Rauber 1987), San Juan Mountains of Colorado (Cooper and Saunders 1980), and Australia's southern mountains (Long and Carter 1996) all support this basic microphysical evolution. Riming, when it occurs, is limited to areas where supercooled droplets are present, especially in strong updrafts. Shallow orographic clouds with cloud-top temperatures greater than −15°C can produce primary ice, but often in concentrations insufficient to consume supercooled water in the cloud, unless ice crystals are introduced from blowing snow near the ground (Geerts et al. 2011; Vali et al. 2012; Geerts et al. 2015b), or if cloud-top generating cells are present that produce plumes of ice particles (Plummer et al. 2014; Rosenow et al. 2014; Kumjian et al. 2014). The Hallett–Mossop ice multiplication mechanism (Hallett and Mossop 1974) can be active in more maritime clouds, such as over the Sierra Nevada and Cascades (Marwitz 1987; Rauber 1992), but it is rare inland because the cloud base is often too cold and few large droplets exist (Cooper and Saunders 1980; Rauber 1987). Shallow orographic clouds sometimes contain embedded convection, both over coastal ranges (e.g., Hobbs 1975a; Heggli et al. 1983; Rauber and Grant 1987; Rauber 1987; Ikeda et al. 2007) and in the interior (e.g., Kumjian et al. 2014; Geerts et al. 2015a). Some days these convective orographic clouds and precipitation can persist for hours as suggested by reflectivity profiles from airborne W-band cloud radar collected during the AgI Seeding Cloud Impact Investigation (ASCII) field program in Wyoming (Geerts et al. 2011; Geerts et al. 2013; Pokharel et al. 2014a; Chu et al. 2014) and the Seeded and Natural Orographic Wintertime clouds: The Idaho Experiment (SNOWIE) field campaign in southwestern Idaho (French et al. 2018; Tessendorf et al. 2019). Conditions on convective days are often marked by weak static stability (i.e., moist Brunt–Väisälä frequency is small) and a layer of potential instability (Kumjian et al. 2014; Geerts et al. 2015a; Pokharel and Geerts 2016).

c. *Transport and dispersion of aerosol plumes in complex terrain*

A third component of hypothesis evaluation has been to determine if ground-released and/or airborne-released

AgI plumes reach targeted mountain regions and sufficient altitudes above ground level, and what dynamical processes are important for the spread of the plumes. Two general frameworks, Lagrangian and Eulerian, are commonly used to simulate particle transport and dispersion in the atmosphere. Lagrangian particle trajectory and dispersion models are commonly used by the air quality modeling community. In the weather modification community, trajectory analysis (e.g., Hobbs 1975b; Holroyd et al. 1988) or simple trajectory models (e.g., Rauber et al. 1988) have been applied for cloud-seeding applications. More recently, sophisticated parcel trajectory models such as the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT; Stein et al. 2015) and plume dispersion models such as the Second-Order Closure Integrated Puff (SCIPUFF) model (Sykes and Gabruk 1997) have been used to investigate the dispersion of AgI emitted from ground-based generators in mountainous areas (Fig. 3). Their accuracy depends on the accuracy and resolution of the 4D numerical model driver dataset and the assumptions on instability and turbulence features applied by these models.

Simulations of AgI dispersion from ground generators have been difficult to validate with detailed observations because of safety considerations in flying research aircraft within plumes close to the surface near mountain peaks; airborne measurements within seeding plumes from ground generators have only been made under clear skies (Boe et al. 2014). Instead, the snowpack in the seeded region has been sampled during or after seeded events to detect anomalous concentrations of silver in snow (e.g., Fisher et al. 2016, 2018) or the ratio of silver to a nonnucleating, naturally covarying aerosol tracer, typically indium oxide (In_2O_3). Warburton et al. (1995) and Manton and Warren (2011), for example, examined the ratio of silver to Indium in snowfall during ground generator seeding events in the California Sierra Nevada and Australia's Snowy Range, respectively. The ratios of silver to indium showed clear evidence that AgI, acting as an ice nucleant, was selectively incorporated into ice crystals and deposited as snow on the mountains.

Early modeling studies by Super (1974) found that the plumes from AgI released from ground-based generators in a cloud-free and stable atmosphere were confined to the lowest 500 m above the terrain over the Bridger Range in Montana. Holroyd et al. (1988) showed that ground-released plumes over Colorado's Grand Mesa ascended upward at $\sim 2\,\mathrm{m\,s^{-1}}$ in cloudy environments, again confined within 500 m above the terrain. More detailed modeling studies of plume dispersion by Bruintjes et al. (1995) showed plumes remained lower than 800 m above maximum terrain height when released from an upwind ridge. This height corresponds with the typical turbulent planetary boundary layer (PBL) depth over a mountain in winter storms (Geerts et al. 2011).

Bruintjes et al. (1995) was the first study in the weather modification community that compared simulated gaseous tracer concentrations [sulfur hexafluoride (SF_6)] using a 3D Eulerian model with airborne in situ observations, demonstrating the capability of a model to qualitatively and quantitatively capture the dispersion of AgI in complex terrain. The interaction between the airflow and the topography was identified as the dominant factor in determining the transport and dispersion of the seeding agent. The modeling study suffered from relatively coarse grid spacing (2 km) so that only the largest turbulent eddies were resolved. In more recent years, large-eddy simulation (LES) models have been used to explicitly compute 3D turbulent motions at higher spatial resolutions on the order of 100 m enabling a better estimation of the 3D dispersion of particles. LES can reasonably reproduce the wind field and turbulent kinetic energy in complex terrain regions (Chow et al. 2006; Weigel et al. 2007). Using a 3D Eulerian model that simulates AgI seeding as part of the microphysical parameterization (Xue et al. 2013a), Xue et al. (2014) were able to demonstrate that the simulated dispersion of AgI particles from five ground-based generators matched airborne and ground-based measurements taken by Boe et al. (2014) over the Medicine Bow Mountains within 50% (see Fig. 4 for examples of AgI dispersion over complex terrain). They used LES with a horizontal grid spacing of 100 m and a stretched vertical coordinate (averaged grid spacing of 70 m below 2 km AGL) that resolved most energetic turbulent eddies induced by terrain. Based on their study, the terrain-induced wind shear generates 3D turbulent eddies that are responsible for the vertical dispersion of AgI. In cloudy conditions, both the buoyancy associated with cloud instability and shear induced by terrain were found to be responsible for the vertical dispersion of AgI (Xue et al. 2016). Lower-resolution non-LES simulations (on the order of 2-km grid spacing) using PBL schemes strongly underestimated the vertical dispersion of AgI (Xue et al. 2014). These results suggest that an appropriate and/or improved PBL scheme that incorporates effects of terrain-induced turbulence is needed for lower-resolution simulations (on the order of 2-km grid spacing) in complex terrain since it remains currently computationally impractical to run real-time and/or large numbers of simulations in LES mode.

d. *Physical observations of microphysical chain of events during seeding*

A fourth component of hypothesis evaluation has been to document ice formation and precipitation evolution from the point of releasing AgI from either ground

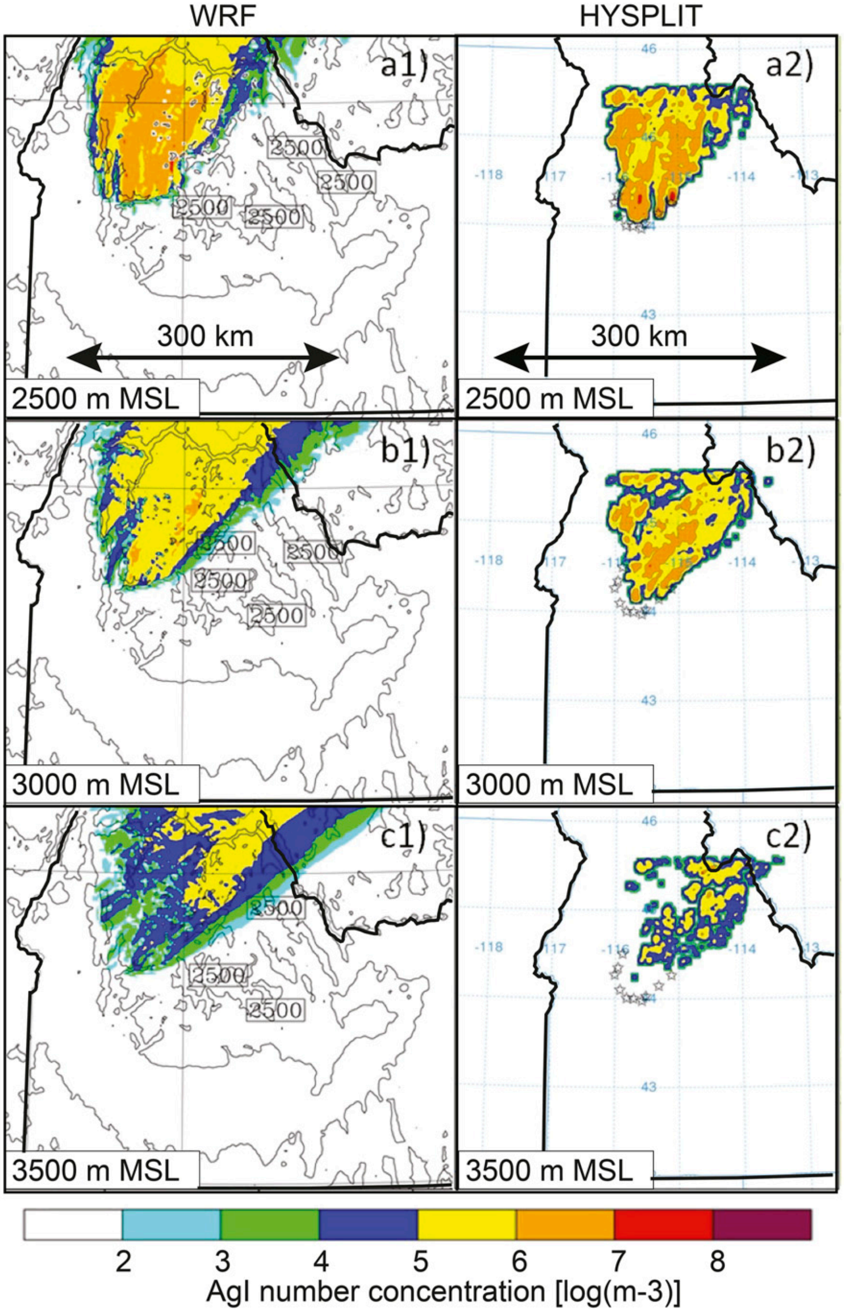

FIG. 3. Examples of (left) WRF-simulated and (right) HYSPLIT-simulated AgI number concentrations using a logarithmic scale [log(m^{-3})] at three vertical levels: (a) 2500, (b) 3000, and (c) 3500 m MSL. The ground-based AgI generators are at the southern edge of the plume indicated by the stars on the HYSPLIT maps. The WRF maps include terrain contours (1500 and 2500 m) and state lines for Idaho.

generators or an aircraft to precipitation reaching the ground. The most successful approaches have been to identify radar echoes corresponding in time and space to the calculated position of newly formed ice particles and precipitation based on advection speed of the AgI aerosol following the release of the seeding agent by an aircraft (referred to as seeding lines or seeding signatures), to document airborne microphysical measurements of anomalously high ice particle concentrations within the seeding lines, and to record any precipitation enhancement as ice particle plumes reach the surface. The primary limitation facing researchers has been extracting the signal

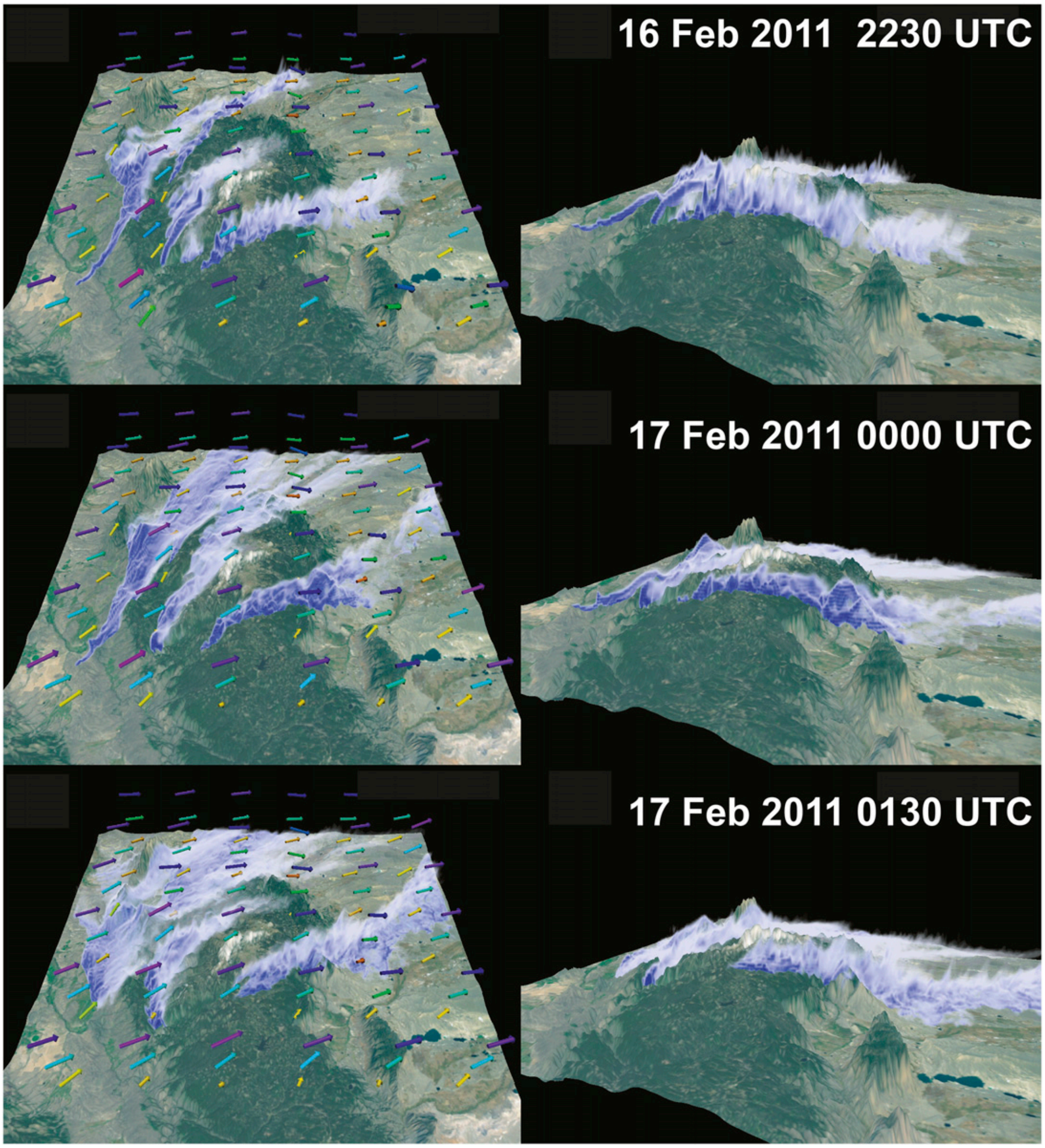

FIG. 4. Three-dimensional depictions of the topography of the Medicine Bow Range in Wyoming, AgI aerosol number concentration (>100 L^{-1} for visible plumes), and wind vectors at three levels [~2800 (yellow), ~3600 m (blue), and ~4400 (purple) m MSL] at three times separated by 90 min, shown as a (left) bird's-eye view from the south and (right) side views from the southeast. (Adapted from Xue et al. (2014).]

in cloud systems that are characterized by a high degree of natural variability (Gultepe et al. 2014). In general, the best, and clearest seeding signatures have been obtained in shallow orographic clouds containing supercooled water and few ice particles, since these clouds naturally produce weak or no radar echoes, even at short W- and K-band wavelengths, and ice particle concentrations within plumes created by seeding stand out well above background concentrations.

The first physical evidence of a seeding effect in an orographic environment was presented by Hobbs (1975b) in three case studies of airborne seeding of stratocumulus and cumulus clouds over the Cascades. In each case, enhanced in-cloud ice particle concentrations, transitions in ice particle habits, increases in silver concentrations in surface snow, and increases in snowfall rate were observed in space and time consistent with expectations based on ice particle plume trajectory calculations. Hobbs et al. (1981), Marwitz and Stewart (1981), Prasad et al. (1989), Deshler and Reynolds (1990), and Chu et al. (2017a) reported similar aircraft and/or radar observations. As part of the Sierra Cooperative Pilot

Project, Deshler et al. (1990) reported results from two experiments where in situ cloud microphysics and ground-based remote sensing platforms recorded seeding effects. Flying through areas affected by seeding, the research aircraft observed a high concentration, 50–100 L^{-1}, of small ice particles and rimed particles commencing 5–10 min after seeding. Otherwise nonechoing cloud regions produced $\mathrm{K_u}$-band radar echoes of 3–10 dBZ during passage of the seed lines. Seeding effects arrived downwind at the surface 35–60 min after seeding, as ice particle concentrations increased, habits changed to rimed particles, and precipitation rates increased by 0.1–1.0 mm h^{-1}.

Results from airborne seeding during the 2017 SNOWIE campaign in Idaho (French et al. 2018; Tessendorf et al. 2019) illustrate remarkably clear radar seeding signatures, appearing as zig-zag patterns of X-band radar reflectivity in low-elevation-angle horizontal scans (Fig. 5d), and as vertical plumes of W-band reflectivity observed by the airborne Wyoming Cloud Radar (WCR) at the expected location of seeding lines in vertical cross sections (Fig. 5c). The zigzag pattern in Fig. 5d resulted from the seeding aircraft flying repeated legs normal to the prevailing wind and the seeding material being transported downwind. The seeding aircraft burned AgI flares behind the aircraft wings resulting in semi-continuous horizontal lines and dropped AgI flares through the clouds resulting in discrete vertically oriented plumes. The initiation and growth of ice particles created by seeding were also documented in situ using aircraft probes on the University of Wyoming King Air aircraft. For the flight leg shown in Fig. 5a, hydrometeor size spectra collected at flight level showed that inside seed plume 1 aggregates and rimed ice particles up to 4 mm in diameter were present in concentrations of 3–20 L^{-1} (Fig. 5e black line and Fig. 5f right-hand image) while just upwind of seed plume 1 nearly all particles were liquid and had diameters less than 50 μm (Fig. 5e blue line and Fig. 5f left-hand image). French et al. (2018) show, from a different flight than the one presented here, the microphysical and radar evolution of similar seeded regions over seven flight legs as an ice-crystal plume evolved and the bottom of the plume reached the mountain surface.

Evidence of seeding effects has also been reported for ground-based seeding studies, however these studies have more sources of ambiguity than the results from airborne seeding during SNOWIE. Super and Boe (1988), Super and Heimbach (1988), and Huggins (2007) reported indications of ground-based AgI seeding in aircraft-measured ice particle concentrations and/or in precipitation at the ground in their studies of stable orographic clouds over Colorado's Grand Mesa, Montana's Bridger Range, and Utah's Wasatch Plateau. They observed, with aircraft, changes in cloud structure consistent with seeding, and enhanced precipitation rates (several times as large as outside the plumes but generally light—less than 1 mm h^{-1}) at the ground coincident with measured AgI plumes. However, the natural variability in ice particle concentrations and snowfall were more difficult to distinguish with certainty from changes in these parameters due to the ground-based seeding in these studies.

A similar technique was applied in ASCII to determine the times when ground-based seeding plumes impacted a downwind manned research station, equipped with a variety of probes including a disdrometer, a particle imaging probe, crystal photography, snow gauges, and a profiling K-band radar (Pokharel et al. 2014b, 2017). ASCII also deployed an X-band scanning radar on the ground and the WCR. Flight-level particle sizing and imaging data were collected as well, but except in a few cases, the flight level (chosen to be as low as permissible in cloudy conditions) was too high to sample ground-released AgI nuclei (Boe et al. 2014; Xue et al. 2014). In four cases with convective clouds in ASCII, the magnitude of the upward Doppler velocities observed by the WCR provided strong evidence that PBL air downstream of the AgI generators was lofted into clouds, and in situ cloud imaging probe data for University of Wyoming King Air (UWKA) interceptions of those clouds reveal more numerous but smaller ice crystals, compared to clouds over similar terrain on the sides of the AgI plumes, as well as compared to similar clouds over the same terrain before seeding started (Fig. 10 in Pokharel et al. 2017).

Most storms sampled in ASCII occurred in unblocked flow, were nonfrontal, and produced light natural snowfall from rather shallow clouds with little SLW contained in small droplets ($<$25 μm) (Pokharel and Geerts 2016; Pokharel et al. 2015). While the vertically integrated liquid water path (LWP) was less than 0.4 mm in ASCII clouds, the lack of stratification and the strong winds over the target mountains allowed effective in-cloud AgI mixing (Geerts et al. 2011; Aikins et al. 2016), especially in convective events (Chu et al. 2017b).

Most storms in ASCII were sampled for two hours under natural conditions, prior to a two-hour seeding period, enabling the examination of temporal differences. Comparisons were also made between the target region (within the assumed AgI plumes) and lateral and upstream control regions. A survey of all 25 ASCII cases found that the radar and snow gauge data agreed in that, in most individual cases and on average, the precipitation rate was higher during seeding, at least in terms of a double difference (i.e., where changes in the target region are compared to those in the control

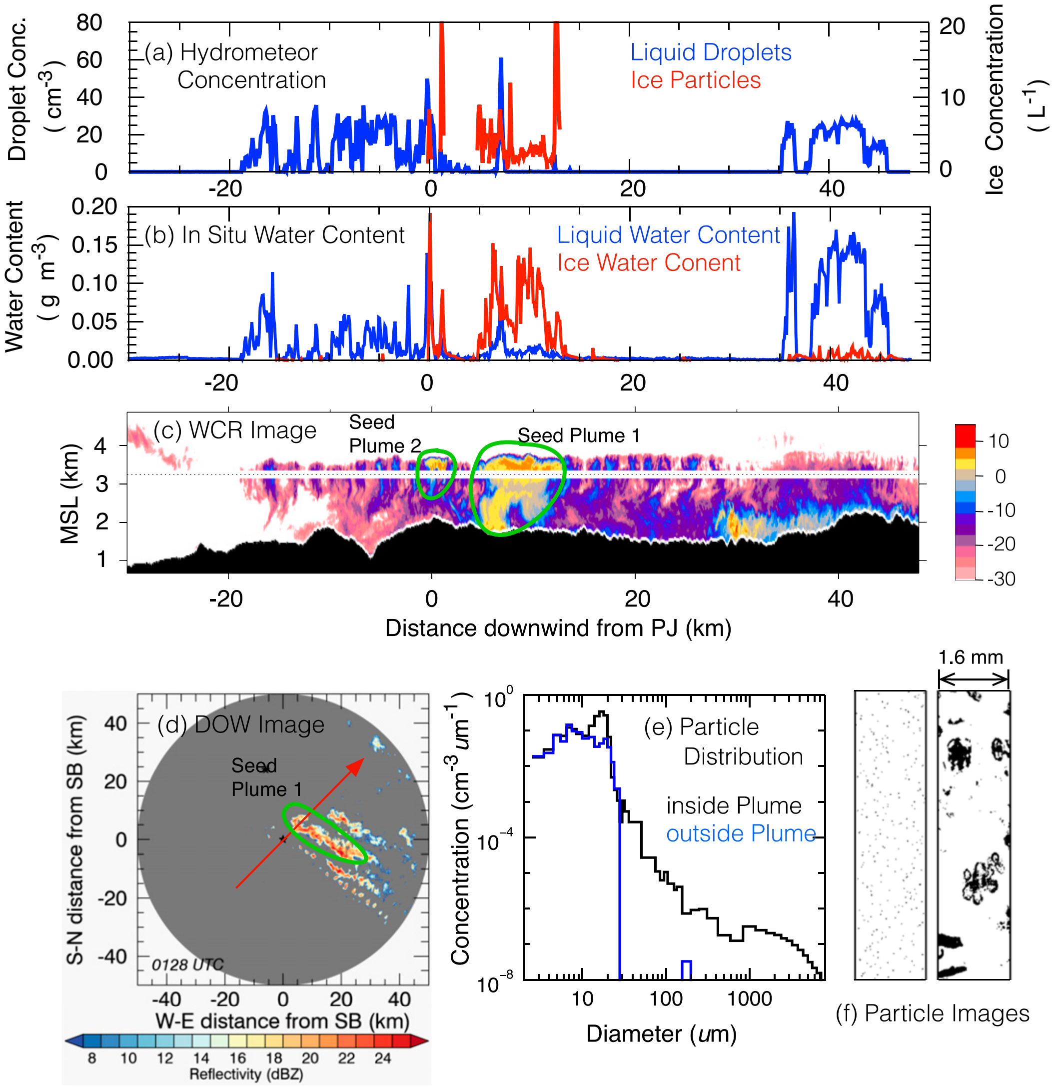

FIG. 5. Example of seeding lines observed during the 2017 SNOWIE campaign. Shown, from a single pass by the Wyoming King Air, are in situ measured (a) hydrometeor concentration for liquid droplets (blue; from Cloud Droplet Probe) and ice particles (red; only particles >50 μm in diameter, from 2DS probe) and (b) bulk condensed water content for liquid (blue) and ice (red), both from the deep-cone Nevzorov probe. (c) The vertical cross-section of W-band reflectivity during the same pass. The horizontal dotted line is the flight track. The locations of echoes resulting from seeding plumes are highlighted (green line). (d) A time-coincident 0.5° plan-position indicator scan using a ground-based X-band Doppler on Wheels, with the horizontal extent of the echo resulting from the seeding plume also highlighted. Also shown are 2DS probe particle size distributions (e) measured inside the plumes (black) and just upwind of the plumes (blue) and (f) corresponding two-dimensional hydrometeor shadows (left) outside the plumes and (right) inside the plumes.

regions; Pokharel et al. 2017, 2018). In some ASCII cases, especially those with few ice crystals during the untreated period, ice-crystal concentrations substantially increased during the cloud-seeding period (Pokharel et al. 2014a,b, 2015; Jing et al. 2015). The ASCII clouds, seeded from the ground, did not reveal the clear radar seeding signatures that were encountered in SNOWIE clouds (which were seeded from the air); the most apparent seeding impact was in a very shallow capped cloud that produced negligible natural snowfall (Chu et al. 2017a). This reflectivity increase, seen in WCR transects, was confirmed by an LES model simulation with the Xue et al. (2013a,b) seeding parameterization (see section 5). In Chu et al. (2017a), the simulated reflectivity was calculated for S-band wavelength. No Mie scattering was assumed for the corresponding W-band observations. The purpose was to compare the reflectivity trend before and during the seeding period

TABLE 1. Summary of the seven randomized seeding experiments studying the effect of winter orographic precipitation enhancement using silver iodide.

Project Name	Location	Years	Type of expt
Climax I; Climax II	Climax, CO	1960–65; 1966–70	Exploratory; confirmatory
Wolf Creek Pass	Wolf Creek Pass, CO	1964–70	Exploratory
Elko, NV	Northeast Nevada Range, NV	1961–67	Exploratory
Colorado River Basin Pilot Project (CRBPP)	San Juan Mountains, CO	1970–75	Exploratory
Bridger Range Experiment	Bridger Range, MT	1970–72	Exploratory
Wyoming Weather Modification Pilot Project (WWMPP)	Medicine Bow/Sierra Madre Ranges, WY	2008–13	Confirmatory
Snowy Precipitation Enhancement Research Project (SPERP1; SPERP2)	Snowy Mountains, Australia	1955–63; 2005–09; 2010–13	Exploratory; confirmatory; confirmatory

under the assumption that the W-band signals respond to the seeding in the same sense as the S-band signals. In Chu et al. (2017a, their Figs. 6 and 8), the >10-dBZ increase of observed reflectivity in the target from no-seed period to seed period was captured by the model-derived S-band reflectivity signal changes.

3. Statistical evaluations of the underlying hypothesis of orographic cloud seeding

Statistical evaluations of randomized cloud-seeding experiments are considered *exploratory* if the study considers a number of hypotheses/analyses, typically guided by understanding gained from physical studies. Evaluations are considered *confirmatory* if anticipated effects are stated ahead of time (a priori), and then proven at an acceptable level of statistical significance following the stated design of the experiment (Gabriel 1999; Silverman 2001, 2007). A variety of ratio statistics have been used in the design and evaluation of weather modification experiments and their significance has usually been estimated by rerandomization (Gabriel 1999). A result is deemed statistically significant when it is very unlikely to have occurred, given a null hypothesis that seeding had no effect. In cloud-seeding studies, this level of significance is typically at the 5% level, that is, the probability of an increase in precipitation due to seeding occurring by chance is less than 5%. The term *multiplicity* refers to the case in which tests are carried out following a failed exploratory or confirmatory experiment, beyond those tests stated a priori, in search of parameters that yield a statistically significant result.

There have been seven randomized scientifically based projects studying physical effects of cloud seeding for the purpose of increasing seasonal mountain snowpack (Table 1) All experiments employed ground-based seeding with AgI. Other randomized projects have been carried out targeting frontal rainbands in winter environments with the goal of increasing rainfall. These include Santa Barbara I and II (Neyman et al. 1960; Bradley et al. 1979), Tasmania I, II, and III (Ryan and King 1997; Morrison et al. 2009), and Israel I and II (Gagin and Neumann 1981; Silverman 2001). Projects targeting frontal rainbands to increase rainfall are not considered in this review.

The Climax and Colorado River basin Pilot Project (CRBPP) experiments had a single targeted area, randomly treated in 24-h seeded or unseeded intervals over the entire winter season (Mielke et al. 1970, 1971, 1981; Chappell et al. 1971; Elliott et al. 1978; Vardiman and Moore 1978; Rottner et al. 1980, Mielke 1995; Gabriel 1995). The Wolf Creek Pass Experiment, by contrast, seeded during three randomly chosen winter seasons, and left three other seasons untreated (Grant and Elliott 1974; Mielke et al. 1977). All three of these experiments were later shown to contain flaws in design (e.g., 24-h treatment units were too long), employ erroneous assumptions (e.g., the 500-hPa temperature was assumed to represent cloud-top temperature), or have errors in data handling that rendered their statistical results unreliable (Hobbs and Rangno 1979; Rangno 1979; Rangno and Hobbs 1980a,b, 1981, 1987, 1993; Gabriel 1995). The Elko experiment was briefly mentioned in Grant and Elliott (1974). Grant and Elliott claimed a seeding effect after segregating data by cloud-top temperature, estimated from 12-hourly rawinsondes. Their estimates did not take into account the high degree of variability of cloud-top temperature and their results should also be considered questionable.

The Bridger Range experiment exploratory analyses first used 24-h experimental units (Super and Heimbach 1983). In later analyses, these were subdivided into 6-h increments (Super 1986; Super and Heimbach 2009). A post hoc analysis using gauge data collected upwind of the seeding and crosswind (outside the target area) as a control yielded double-ratio estimates of 15% more precipitation due to seeding in the target area, provided temperatures were less than −9°C at levels about ridgetop, where AgI plumes from ground generators were confirmed to be present based on aircraft measurements (Super 1974). These results should be viewed with caution because of multiplicity.

In more recent times, a concerted effort has been undertaken to improve experimental design and statistical analysis to study natural and seeded cloud systems and to verify basic components of the hypothesis (e.g., Gabriel 1999; Manton et al. 2011; Breed et al. 2014). The primary method to evaluate the effect of cloud seeding on seasonal enhancement of the snowpack has been with precipitation gauge measurements using target/control statistics.

The exploratory Snowy Mountains experiment in Australia (1955–63, Ryan and King 1997) used two areas, one target and one control, and during any 10–15 day period a random process determined whether clouds over the target area should or should not be seeded. In some experiments, a crossover design was employed where a random process was used to select which area would be the target and which would be the control for each period. The results produced statistically significant evidence for precipitation increases over the entire experiment, with a 19% increase significant at the 5% level. In the confirmatory Snowy Mountains experiment (2005–09, Manton et al. 2011; Manton and Warren 2011), 107 experimental units were obtained, yielding a positive, but not statistically significant, precipitation impact. A post hoc analysis identified that a source of uncertainty was introduced by units where the seeding generators operated for relatively few hours. Reanalysis with only units where generators collectively burned for more than 45 h showed an increase in primary target area precipitation of 14% at the 8% significance level and in the larger overall target area of 14% at the 3% significance level. Restratification of data introduced a potential error because of multiplicity, that is, finding a positive result by accident and not design. To avoid multiplicity, a third experiment (Manton et al. 2017), was carried out between 2010 and 2013 that had a dual-target area, wherein criteria for seeding were further modified a priori based on additional analysis and subsequent restratification of the Manton et al. (2011) and Manton and Warren (2011) datasets. The start criteria for an experimental unit in the 2010–13 experiment were restricted to minimize the chance of a unit having low precipitation or low wind speed, situations that produced little seeding effect in the previous experiment. The calculated increase in precipitation in this confirmatory experiment under the revised criteria ranged from 12% to 16% in the two areas, significant at the 6% level in the south, and 3% level in the north target areas. The study concluded that there was strong evidence of a positive seeding impact across the overall target area of the Snowy Mountains.

The Wyoming Weather Modification Pilot Program (WWMPP) randomized confirmatory seeding experiment was conducted between 2008 and 2014 over two mountain ranges in southern Wyoming. This experiment was preceded by an exploratory experiment conducted by Weather Modification, Inc., from 2004 to 2005 (Weather Modification, Inc. 2005) that indicated there was potential for precipitation enhancement by orographic cloud seeding. To validate this result, a confirmatory experiment was designed and initiated in 2008 (Breed et al. 2014). The confirmatory WWMPP experiment collected 118 randomized statistical experiment (RSE) precipitation cases that met quality-control and seeding criteria over six years. The RSE included a crossover design between the two mountain ranges, whereas one served as the target and the other as the control, and the range to be targeted with seeding was chosen randomly (Breed et al. 2014). Each mountain range had a single target gauge site that served as a control site when the mountain barrier was not seeded, as well as two covariate sites. All gauge sites included three precipitation gauges to aid in the quality control process. The target gauges were located in forest clearings in which measured wind speeds were typically less than 2 m s^{-1}. Gauge undercatch due to wind becomes less than 15% at these wind speeds based on recent result from the WMO Solid Precipitation Intercomparison Project (SPICE) and other studies (Rasmussen et al. 2012), and thus no wind corrections were made.

The statistical results were inconclusive in that there was insufficient statistical evidence (p value of 0.28) to reject the null hypothesis that there was no effect of ground seeding after 118 randomized cases. The researchers concluded that it may be possible in their experiment to statistically reject the null hypothesis by collecting on the order of 1000 cases for a p value of 0.05 (i.e., a 5% chance that the precipitation change was not due to seeding), but that the time and expense required to collect such measurements made this prohibitive (Rasmussen et al. 2018).

Finally, statistical analyses of *operational* programs' impact on orographic snowpack enhancement appear both in nonreviewed reports and peer-reviewed articles. Authors have either been independent investigators (e.g., Silverman 2007, 2008, 2009), utilities sponsoring operations, or contractors doing the seeding (e.g., Henderson 1966, 2003a,b; Griffith and Solak 2002). Because of potential conflict of interest concerns, contractor assessments and utility self-assessments are not considered in this review. We focus only on independent evaluations.

The approach to evaluating the effectiveness of operational cloud seeding, where programs typically do not employ randomized seeding techniques, has been to use a target-control approach where one basin is seeded throughout a winter season, while a neighboring basin remains unseeded as the control. Assessments have been made using a variety of metrics from precipitation gauge data, snow-water equivalent measurements, or streamflow measurements. The foundation for this type of assessment is that the metric of choice in the target and control basins is highly correlated so that the control basin behavior can predict what the natural behavior would have been in the target basin. Silverman (2007, 2008, 2009), for example, conducted a posteriori evaluations of nonrandomized operational seeding programs conducted in the Kern River, Kings River, and San Joaquin River basins of California using this approach. Semiannual and annual integrated streamflow measurements in the seeded basin catchment were used, with a neighboring unseeded basin catchment as a control. He noted that streamflow measurements have the advantage of long records and high correlation across basins in unseeded years. For the Kern River, ratio statistic evaluation of water year streamflow for a specific streamflow gauge chosen a priori for evaluation indicated a + 12.2% increase in streamflow due to seeding with 90% confidence that the true effect of seeding was between +6.1% and +18.6%. The probability that the effect of seeding is equal to or greater than 0% and 1% (the estimated threshold of cost-effective operations) was 99.9. Similar results were obtained for the Kings River program, while weaker results suggesting an increase in precipitation were obtained in the San Joaquin operational program watershed. Silverman cautioned that his results should be taken as measures of the strength of the suggested seeding effect and not as measures of statistical significance. Simpler statistical approaches, for example applying traditional historical regression methods of comparing seasonal precipitation in seeded years with a regression line developed from data from target and control basins in nonseeded years, have also been used for operational programs. Such data must be viewed with caution, since the relationship between the target and control areas may have changed over time, or other meteorological factors, such as early snowmelt at selected measurement sites, may influence results (e.g., Super and Heimbach 2003).

4. Modeling evaluations of the underlying hypothesis of orographic cloud seeding

Evaluating seeding effects on orographic precipitation purely by observations and statistical analyses has always been challenging due to the unavailability of a control in nature, the difficulty in detecting the seeding signal and seeding effects on cloud and precipitation development, and the cost of conducting long term randomized seeding experiments. Thus, numerical models capable of simulating natural orographic cloud processes and cloud-seeding physics, and validated by observations, have become a useful tool to assess and quantify cloud-seeding effects.

a. Natural precipitation

Modeling studies of natural orographic clouds have developed in concert with physical process studies. Investigations of natural clouds have focused on aerosol/cloud microphysical controls on the distribution of precipitation across mountain ranges (Cotton et al. 1986; Colle and Zeng 2004a,b; Colle et al. 2005a,b; Lin and Colle 2009; Saleeby et al. 2009, 2011, 2013), terrain-induced local dynamics (Smith and Barstad 2004; Garvert et al. 2005a; Colle et al. 2008; Ikeda et al. 2010; Minder et al. 2008), and dynamical controls on precipitation estimation (Colle and Mass 2000; Garvert et al. 2005b). High-resolution studies of orographic precipitation (Ikeda et al. 2010; Rasmussen et al. 2011; Liu et al. 2017; Jing et al. 2017) have shown that cold-season natural precipitation in complex terrain can now be reasonably simulated with modern mesoscale models using the most advanced microphysical schemes, resulting in a seasonal precipitation dataset that can be superior to gridded gauge-based datasets for hydrological and other studies (e.g., Wrzesien et al. 2019). These studies show that natural seasonal snowfall over the mountain ranges of the western United States can be simulated to within 10% of SNOTEL observations if the model horizontal resolution is less than 6 km (Fig. 6). The success of these studies helped inspired the application of high-resolution model ensembles in the evaluation of recent orographic seeding programs (Rasmussen et al. 2018).

b. Seeded precipitation

Many numerical investigations on glaciogenic seeding effects in different cloud types have been performed (e.g., Reisin et al. 1996; Yin et al. 2000; Guo et al. 2006; Curic et al. 2007; Chen and Xiao 2010) using different AgI nucleation parameterizations and/or different model setups. Seeding effects on precipitation enhancement were found to be positive in most studies and seeding was shown to change the precipitation amount/distribution most of the time. However, most of these studies focused on deep-convective cloud-seeding scenarios. Few studies examined the sensitivities of seeding effects on wintertime orographic clouds to meteorological conditions and cloud microphysical properties in a

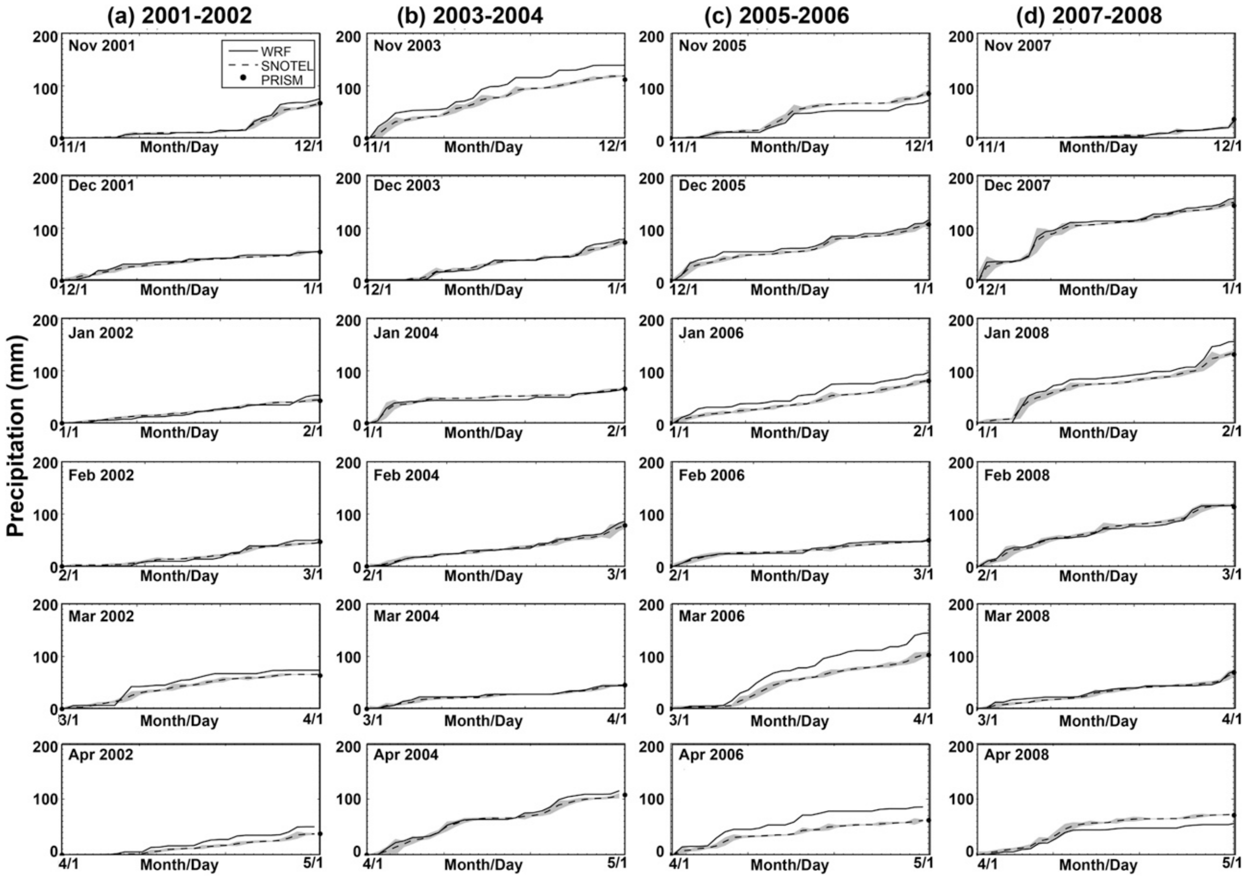

FIG. 6. Monthly time series of accumulative precipitation (mm) for (a) 2001–02, (b) 2003–04, (c) 2005–06, and (d) 2007–08. Solid line is simulated precipitation with the WRF Model at SNOTEL mountain site locations. Dashed lines are SNOTEL measurements, with gray shades representing 1 standard deviation from the average daily precipitation totals at SNOTEL sites. The dots are Parameter–Elevation Regressions on Independent Slopes Model (PRISM) monthly averaged snowfall estimates. [From Rasmussen et al. (2011).]

systematic way, Li and Pitter (1997) being the most thorough sensitivity study.

The laboratory observations of DeMott (1995) are the most complete data describing AgI accumulated nucleation rates as a function of temperature and saturation ratios with respect to ice and water for all four modes of nucleation (deposition, condensation freezing, immersion freezing, and contact freezing). Meyers et al. (1995) implemented an AgI nucleation parameterization based on DeMott (1995) into the Regional Atmospheric Modeling System and simulated an orographic cloud-seeding event from the Sierra Cooperative Pilot Project (Reynolds and Dennis 1986). Their results suggested that the model could simulate the microphysical interactions between AgI and cloud hydrometeors. Meyers et al. (1995) were the first to employ a 3D simulation of seeding effects in orographic clouds. Their study reproduced the primary results of the Sierra case study reported by Deshler et al. (1990). Meyers et al. (1995) also reviewed results of earlier 2D models examining seeding effects reported by Hobbs et al. (1973), Young (1974), Plooster and Fukuta (1975), and Blumenstein et al. (1987).

More recently, Xue et al. (2013a) developed a microphysical parameterization that simulates the physical processes associated with AgI seeding. This parameterization was initially built upon the Thompson et al. (2008) bulk microphysics scheme in the Weather Research and Forecasting (WRF) Model and includes (i) AgI particle dispersion over complex terrain, (ii) the coagulation of AgI particles after they are emitted from ground-based or airborne generators, (iii) wet deposition of AgI through scavenging, (iv) dry deposition of AgI through fallout and canopy interception, (v) water activation of AgI particles associated with any soluble portion of the aerosol, (vi) ice nucleation of AgI particles through different modes, and (vii) cloud processing of AgI and regeneration of AgI particles upon evaporation and sublimation of hydrometeors (Fig. 7). The critical physical processes that determine seeding impact to the first order are dispersion of AgI in complex

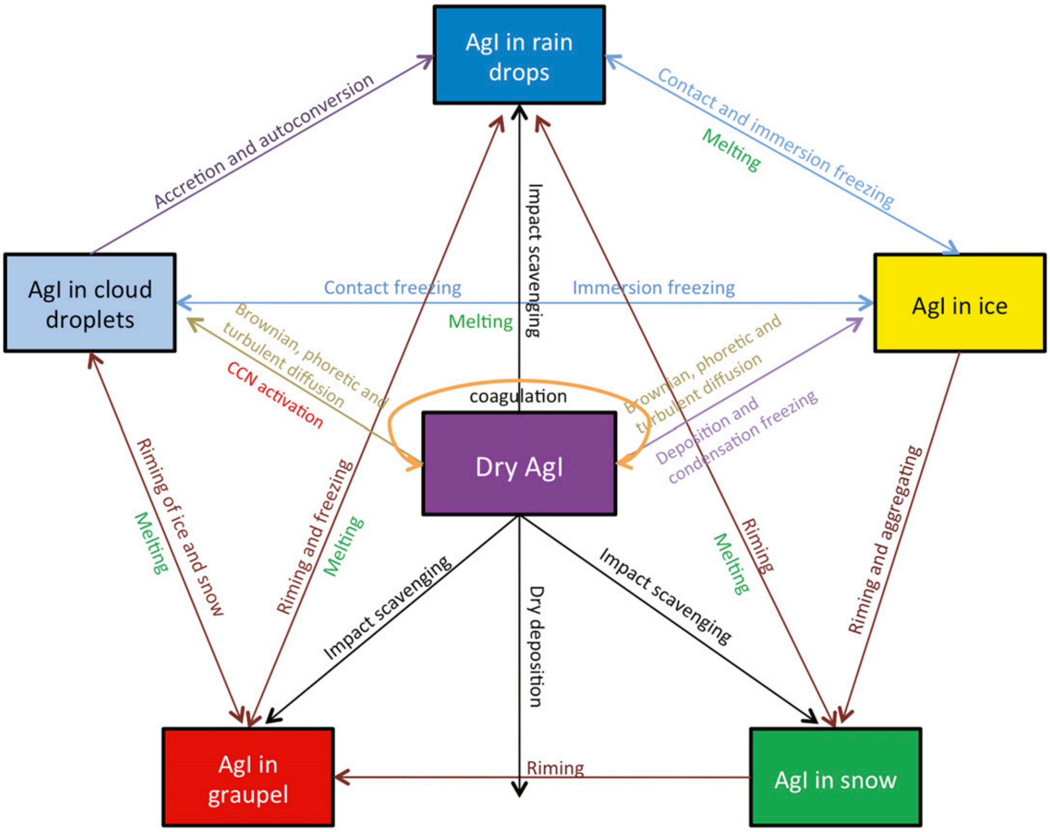

FIG. 7. Schematic of the AgI–cloud interactions that are simulated in the seeding parameterization. [Adapted from Xue et al. (2013a), with additional parameterizations now included in the scheme.]

terrain and cloud-seeding microphysics (processes in Fig. 7). Simulating all of these processes remains challenging both scientifically and computationally even with the most advanced, state-of-the-art numerical modeling frameworks.

Nonetheless, the examination of the chain of events associated with glaciogenic seeding of orographic clouds has recently become possible due to the emergence of such state-of-the-art cloud-seeding microphysics parameterizations incorporating these processes (Xue et al. 2013a,b; Geresdi et al. 2017), advances in microphysical schemes for numerical models (Thompson et al. 2008; Thompson and Eidhammer 2014; Morrison and Grabowski 2008; Geresdi et al. 2014; Sarkadi et al. 2016), and sufficient computing power to resolve large eddies. The Xue et al. (2013a) AgI cloud-seeding parameterization, which was built on a bulk cloud microphysics scheme, tracks the conserved AgI number and mass within different hydrometeors to determine AgI-produced precipitation. This bulk microphysics cloud-seeding modeling framework has been used to investigate the microphysical chain of events of glaciogenic seeding and its effect on wintertime orographic clouds under both idealized and realistic conditions (Xue et al. 2013a,b; Chu et al. 2014; Xue et al. 2016; Chu et al. 2017a,b; Xue et al. 2017). The scheme still requires validation, a primary driver for the recent SNOWIE field program (Tessendorf et al. 2019).

c. *Wyoming case study of orographic cloud seeding with observations and model*

During ASCII, a ground-based cloud-seeding event occurred on 18 February 2009 in the Medicine Bow Mountains of southern Wyoming. The event was thoroughly studied using observed soundings, liquid water path from radiometers, and vertical Doppler velocity and reflectivity-based cloud structures observed by the WCR. In addition, LES (100-m grid spacing) and non-LES simulations (900-m grid spacing) of this case were performed with and without the AgI cloud-seeding parameterization (Xue et al. 2013a,b, 2016). The 100-m LES was able to reproduce the thermodynamics and flow pattern, including boundary layer turbulence and a hydraulic jump in the lee. It also captured the spatial distribution of SLW and the cloud vertical structure, but had some difficulty simulating the cloud evolution from the untreated to the treated period (Chu et al. 2014; Xue et al. 2016). Model-simulated cloud-seeding impacts on clouds were found to occur primarily within the PBL (below 1 km AGL).

d. *Idaho case study of orographic cloud seeding with observation and model*

Four cloud-seeding cases in the Payette river basin of western Idaho were simulated from a snow trace chemistry field campaign that took place between 2003 and 2005 (Xue et al. 2017). Two ground-based and two airborne events were simulated by the WRF Model in LES mode with a grid spacing of 667 m. Testing indicated that grid spacings finer than 900 m were sufficient to resolve the most important turbulent scale that shapes the PBL structure. For all simulations performed for orographic clouds over complex terrain, the vertical coordinate had a grid spacing smaller than 100 m in the lowest 3 km AGL.

The 666-m LES results were compared with the observed soundings, precipitation from SNOTEL sites, and silver mass concentrations within the snow measured from snow samples by plasma mass spectrometers. The comparisons showed that the silver mass concentration accumulated in simulated snowfall had the same order of magnitude as the observations from all sample sites. Furthermore, the predicted spatial distributions of the silver mass concentrations agreed qualitatively well with the observations.

e. *Ensemble modeling approach*

LES is a useful modeling tool for the seeding simulation that resolves the AgI dispersion in complex terrain. However, the extremely high computational cost associated with LES prevents it from being used for large domains, long periods, or multiple cases simulations. As an alternative, non-LES simulations running PBL schemes have to be used in these situations. For example, to help understand and interpret the statistical results of the WWMPP (Rasmussen et al. 2018), numerical modeling simulations of the impact of cloud seeding were conducted for each of the 118 RSE cases.

Given the uncertainties associated with numerical modeling, an ensemble cloud-seeding simulation approach was designed to evaluate the WWMPP program using the WRF Model with the cloud-seeding parameterization (Rasmussen et al. 2018). The ensemble design was based upon varying numerous potential sources of uncertainty in simulating orographic clouds, precipitation, and associated seeding effects. These sources of uncertainty include: large-scale driving meteorological conditions, model physics for both natural clouds and seeding processes, background CCN and ice nuclei (IN) concentrations, and spatial/temporal distributions of precipitation. A 72-member ensemble was designed for each of the 118 RSE cases during the WWMPP (Rasmussen et al. 2018). The ensemble mean precipitation validated well against observations. The simulated seeding effects, defined as the difference of precipitation from simulations with and without seeding, indicated a median 5% enhancement of precipitation relative to seedable storms (those containing SLW) over a given winter season, with an inner quartile range of 3%–7% for the Sierra Madre and Medicine Bow Ranges in Wyoming based on about 9000 seeding case simulations. If one considers all storms during the six winter seasons, the median seeding effect was 1.5% increase in precipitation over that occurring naturally.

5. Recent advances in assessment and operations

a. *Advances in modeling*

A major advance in snowfall simulation in orographic environments has been the demonstration that *seasonal* natural orographic precipitation can now be realistically simulated within 10% of observations (Ikeda et al. 2010; Rasmussen et al. 2011; Liu et al. 2017). This presents potential opportunities for modeling the impacts of season-long operational or research-based orographic cloud seeding. Prior to this capability, uncertainty in model estimates of natural mountain precipitation largely prevented scientists from applying state of the art models to orographic cloud seeding. Although the sophistication of modern mesoscale models and cloud physics parameterizations (Rasmussen et al. 2011) has allowed implementation of cloud seeding directly into a model, convincing tests of the ability of the model to accurately assess seeding impacts in seasonal seeding operations still are required in future experiments.

Another advancement that allows use of models to evaluate cloud seeding is the increase by two–three orders of magnitude in computer speed over the past 10 years. This now permits simulations at very high resolution and the application of ensemble approaches to evaluate the impact of cloud seeding, providing a range of uncertainty for seeding effects. The ensemble approach also allows evaluation of aspects of the model initialization and physics that are known to be uncertain, providing better estimates of the likely range of seeding impact (Rasmussen et al. 2018). These novel modeling approaches in weather modification research require extensive testing and validation with observations, a goal for future projects, before their results can be accepted as convincing evidence of orographic precipitation enhancement.

b. *Advances in observing technologies*

The use of more sensitive, better resolved radars (such as airborne W-band radar or specially deployed X- and K-band radars) to investigate the physical effects of cloud seeding has made it possible to infer effects of ground-based seeding (Pokharel et al. 2017; Chu et al. 2017a) and directly detect plumes of ice particles created by airborne seeding (French et al. 2018). This, combined with specially deployed radiometers, rawinsondes, high-resolution precipitation gauges, and in situ airborne measurements in seeded clouds has opened new opportunities for tracing the seeding process from the AgI source to arrival of the precipitation at the ground (Tessendorf et al. 2019). A deficiency in cloud-seeding evaluations remains ground validation of seeding effects in target experiments. Although season-long precipitation impacts of seeding have been estimated in many experiments, the impact on precipitation of the passage of a single plume of ice particles generated from an airborne seeding line or a ground generator remains difficult to assess. There is often not a clear seeding signature on radar (except in cases where the initial radar reflectivity is dominated by SLW, as in French et al. 2018). This is compounded by the measurement uncertainty of snow gauges and difficulty of making measurements in snowstorms in remote mountainous terrain. Yet it is precisely these kind of case-study measurements that are needed to validate numerical simulations of seeding impacts. One possibility currently under exploration involves high-temporal-resolution (e.g., 30 min) snow sample collection for chemistry analysis, but results are not available at the time of this writing. A key challenge remains extrapolating obvious local effects observed with radar to the demonstration of more widespread and long-lasting impact on increasing snowfall across a target basin.

6. State of the science and a look to the future

Meteorological studies are continuing to advance our understanding of the distribution of supercooled water in orographic cloud systems, and the sources of vertical circulations that can lead to the production of that water. Unfortunately, a corresponding understanding of natural ice nucleation mechanisms in orographic clouds remains elusive. Future scientific studies in orographic environments should focus on this key issue. Our understanding of the growth and fallout of ice particles as precipitation over mountains has advanced considerably through detailed case studies. However, because cloud-seeding effects represent at best a small percentage increase in precipitation, it is essential that future efforts focus on ground-based measurements of precipitation intensity, type, and chemistry, and ground-based remote sensing of SLW. These measurements have always been challenging because of the difficulty of working in complex terrain in winter.

Models have improved in sophistication to the point that AgI plume dispersion and the growth and fallout of precipitation produced by AgI aerosol can be simulated; however, verification studies are required to validate model results before the models can be used to quantitatively predict seeding outcomes. For example, data are required to validate model predictions related to time scale for nucleation and fallout of ice particles versus the time scale for the aerosol/ice particles to be transported out of a target basin. Despite all the uncertainties, models are now being used operationally to estimate likely seeding opportunities based on short-term forecasts. For example, Idaho Power's orographic cloud-seeding operations are guided entirely by advanced WRF Model prediction of seeding windows, based on current understanding of seeding outcomes in various weather regimes.

Concerning seeding, clear physical evidence has been obtained that orographic clouds containing supercooled water, when seeded with AgI, produce plumes of ice particles that originate downwind of the seeding location and reach the ground through precipitation growth and fallout. The evidence, at present, comes from studies of clouds with sufficiently small concentrations of natural ice particles such that radar signals from ice particle plumes generated by seeding are not overwhelmed by background radar echoes from naturally occurring ice particle populations. Because sufficiently strong natural radar echoes are often produced by cloud systems that are deep and have cold cloud tops, clear physical evidence of seeding effects, at present, has been limited to shallow orographic clouds with warm (>-15°C) cloud-top temperatures; however, deep orographic clouds with strong radar echoes may still locally contain large amounts of SLW (section 2a).

A second independent line of evidence that cloud seeding has an impact on clouds has been the presence of trace silver concentrations in snow on the ground in the target area following seeding events. Experiments in which active ice-nucleating aerosol (AgI) and inert tracer aerosol (In_2O_3) were simultaneously released at collocated generators consistently demonstrate that trace silver in the snowpack following passage of a seeding event is due to ice nucleation rather than precipitation scavenging of aerosol. Experiments tying tracer detection in snow to model predictions of ice particle trajectories associated with seeding hold promise and should be further explored in future experiments.

Seven randomized statistical experiments have been conducted targeting orographic cloud systems. Unfortunately, four of them, all conducted in the 1960s–70s, had design flaws that rendered their findings questionable. Of the remaining three, two experiments, one in Australia's Snowy Mountains and the other in Wyoming, were confirmatory. The first, in Australia, reported statistically significant increases in precipitation. The second, in Wyoming's Medicine Bow Mountains, reported positive results but was unable to obtain statistical significance because of an insufficient number of events. Post hoc stratification analyses from the three valid experiments and from analyses of operational projects have consistently yielded positive, statistically significant precipitation increases. However, caution is necessary in interpreting these results, because the issue of multiplicity remains a concern when interpreting post hoc stratifications. Future statistical experiments should be closely coupled with observational studies employing the full suite of techniques now available for physical evaluations. Together, they hold promise for narrowing the uncertainty that has accompanied orographic cloud-seeding research over its long history.

The need for water for urban use, agriculture, and power generation in the western United States and other arid regions of the world where water resources depend on melting of winter snowpack in high mountain ranges will increase in the future as the human population increases and Earth's changing climate alters the extent of these snowpack reservoirs. As a result, operational cloud seeding will continue unabated, despite uncertainty in the outcome of the seeding. Significant progress has been made over nearly seven decades in understanding the natural structure of orographic clouds systems and the impact of seeding. At the same time, technological advances such as computer modeling, computer speed, and networking and advanced airborne radar systems have allowed scientists to explore orographic cloud seeding in ways that were only dreamed of 20 years ago.

It is societally important that this research continue. To make progress going into the future, it is necessary to carry out a confirmatory statistical experiment backed by comprehensive meteorological observations and physical studies employing all of the technologies now available to unambiguously extract the seeding signatures. It is clear, however, that obtaining statistically significant results will require a project extending over a sufficiently long time period. Obtaining commitments to conduct extended projects remains a challenge. The most feasible approach for future studies would likely involve a well-designed experiment that couples and coordinates observational, statistical, and modeling research with a long-term operational project similar to the recent WWMPP/ASCII and SNOWIE experiments (Pokharel and Geerts 2016; Rasmussen et al. 2018; Tessendorf et al. 2019). Water needs in the future may provide the impetus for these types of projects to be realized.

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