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A multi-sensor study of the impact of ground-based glaciogenic seeding on clouds and precipitation over mountains in Wyoming. Part I: Project description

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ABSTRACT

The AgI Seeding Cloud Impact Investigation (ASCII) campaign was conducted in early 2012 and 2013 over two mountain ranges in southern Wyoming to examine the impact of ground-based glaciogenic seeding on snow growth in winter orographic clouds. The campaign was supported by a network of ground-based instruments, including microwave radiometers, two profiling Ka-band Micro-Rain Radars (MRRs), a Doppler on Wheels (DOW) X-band radar, and a Parsivel disdrometer. The University of Wyoming King Air operated the profiling Wyoming Cloud Radar, the Wyoming Cloud Lidar, and in situ cloud and precipitation particle probes. The characteristics of the orographic clouds, flow field, and upstream stability profiles in 27 intensive observation periods (IOPs) are described here. A composite analysis of the impact of seeding on snow growth is presented in Part II of this study (Pokharel et al., 2017).

Clouds were stratiform in most IOPs, but in 10 IOPs convective clouds were present. Most clouds were shallow (~2 km deep), all had some liquid water but generally with a liquid water path <0.3 mm, and all were naturally precipitating but generally at a rate <1 mm h^{-1}.

1. Introduction

A significant amount of precipitation in arid mid-latitude regions such as the western USA falls as snow over mountains in winter. The resulting snowpack serves as a natural reservoir controlling the stream flow of some major rivers such as the Colorado River, which is the main source of water for the arid southwestern US. Therefore there has been much interest in methods to enhance the snowpack in this region. The most common method, used for more than half a century, is to seed orographic clouds glaciogenically, mostly using silver iodide (AgI).

Orographic clouds almost always contain supercooled liquid water (SLW) at temperatures above −20 °C and often colder (Huggins, 1995; Rauber and Grant, 1987; Politovich and Vali, 1983), because natural ice nuclei are rare and because the condensate supply rate tends to exceed the diffusional growth rate of ice. Glaciogenic seeding intends to rapidly convert this SLW into frozen hydrometeors. The timing, location and amount of SLW are quite sensitive to atmospheric conditions (Rauber and Tokay, 1991; Sassen et al., 1990), in particular cloud base temperature, cross-mountain wind speed and terrain steepness. Slight variations in wind direction can alter the location of the maximum liquid water content (LWC).

Over the interior mountains in the western US, e.g. in Colorado and Wyoming, the LWC typically is quite low in mixed-phase clouds. Reported maximum LWC values at flight level are around 0.3 g m^{-3} (Cooper and Vali, 1981; Rogers and Vali, 1987; Politovich and Vali, 1983). Typically the mode of the drop size distribution is about 10–15 μm of diameter in winter orographic clouds in this region (Politovich and Vali, 1983; Cooper and Vali, 1981). The lack of larger drops implies that most snow growth is by vapor diffusion and aggregation, rather than accretion, because larger droplets (diameter larger than 20–30 μm) are required for the snow growth by riming (Pruppacher and Klett, 1997; Wang and Ji, 2000).

The basic requirement for effective glaciogenic seeding of an orographic cloud containing SLW is that the seeding material (in this case AgI nuclei) effectively disperses in a cloud in a temperature window between about −20 and −5 °C (Grant and Elliott, 1974). The lower threshold is based on the fact that natural ice nuclei become more abundant below ~−20 °C, depending mainly on the concentration of a large aerosol in the upstream airmass (diameter > 0.5 μm, DeMott et al., 2010). The upper threshold, around −8 to −5 °C, is the maximum activation temperature of AgI (DeMott et al., 1983; DeMott, 1997).

The AgI Seeding Cloud Impact Investigation (ASCII) campaign was conducted in early 2012 and 2013 over two mountain ranges in southern Wyoming. Most ASCII intensive observation periods (IOPs)

Abbreviations: 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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were conducted in post-frontal synoptic conditions. Deep frontal systems producing widespread precipitation were not targeted in ASCII for two reasons. Firstly, deep baroclinic systems have low cloud top temperatures (often below −20 °C) and thus are characterized by ice nucleation near the cloud top, often within small generating cells (Plummer et al., 2014), followed by diffusional growth and aggregation of ice particles during fallout to the surface (the "seeder–feeder" process; Hobbs, 1975; Rauber, 1987; Long and Carter, 1996; Cooper and Saunders, 1980). Secondly, such systems are rarely steady. Steadiness of flow, stability, and cloud and precipitation structure is needed in ASCII as an untreated period is compared to a treated period. Shallow orographic clouds can persist long after deep frontal disturbances have passed. They produce persistent light snowfall over mountains even from air containing relatively little SLW (e.g., Rauber, 1987; Pokharel and Geerts, 2014). Because of their persistence, shallow orographic clouds serve as a good natural laboratory for controlled experiments. These clouds are also good targets for glaciogenic seeding since snow growth may be inefficient, due to a scarcity of natural ice nuclei (cloud top temperatures typically are above −20 °C) and strong, SLW-producing updrafts.

In ASCII, glaciogenic nuclei were injected into the orographic flow by means of propane-burning generators on the ground. Ground-based cloud seeding outcomes do not only depend on cloud temperature, liquid water, and wind direction, but also on (1) the ability for the underlying earth surface to initiate ice crystals into the cloud, potentially overwhelming the effect of AgI seeding, and (2) the presence of boundary layer turbulence to mix the seeding material into the cloud. These two processes are important and need to be considered in cloud seeding experiments. Regarding the first process, there is some evidence that ice crystals are naturally inserted into supercooled orographic clouds hugging the terrain (Rogers and Vali, 1987), through two mechanisms: the lofting of blowing snow (Geerts et al., 2015b), and ice multiplication by splintering as supercooled droplets impact rimed obstacles at the surface, such as trees (Geerts et al., 2011). Regarding the second process, boundary-layer turbulence is important not only to mix natural ground-initiated ice crystals or AgI nuclei into cloud, but possibly also to enhance snow growth in mixed-phase clouds (Geerts et al., 2011). Either process may explain why shallow orographic clouds coupled to the surface tend to be effective snow producers, more effective than elevated lenticular clouds over mountains for instance. Qualitative indicators are used in ASCII to judge the potential significance of these processes in ASCII: blowing snow requires fresh snow and strong surface winds, at least 10–12 m s^{-1} (Dery and Yau, 1999). The Hallett–Mossop ice multiplication process is rather sensitive to temperature ($-4 < T < -8$ °C between cloud base and mountain crest level) and droplet size (diameter > ~25 μm) (Harris-Hobbs and Cooper, 1987).

The concentration of a cloud-active aerosol (cloud condensation nuclei or ice nuclei) in the inflow can also affect the efficacy of orographic cloud seeding (e.g., Givati and Rosenfeld, 2005). That topic is beyond the scope of the ASCII objectives. No aerosol measurements were made in ASCII.

The objective of this study is to explore a seeding signal in the ASCII IOPs, in terms of ice crystal size distribution and mainly snowfall rate. This composite study complements a number of ASCII case studies (Pokharel et al., 2014a, b; Chu et al., 2014; Pokharel et al., 2015).

Before we can explore the impact of seeding, we first must describe the campaign design, and the flow, stability, and cloud characteristics during the ASCII IOPs. That is the topic of this paper (Part I). The ASCII experimental design and instruments are described in Section 2. The ambient atmospheric conditions observed in ASCII are described in Section 3. The radar-derived horizontal and vertical structure of ASCII storms is described in Section 4, and flight-level cloud and precipitation particles are characterized in Section 5. The correlation between control and target regions precipitation is discussed in Section 6 and a summary is given in Section 7. A companion paper (Pokharel et al., 2017, hereafter referred to as Part II) will explore the AgI seeding impact using radar and particle probe data.

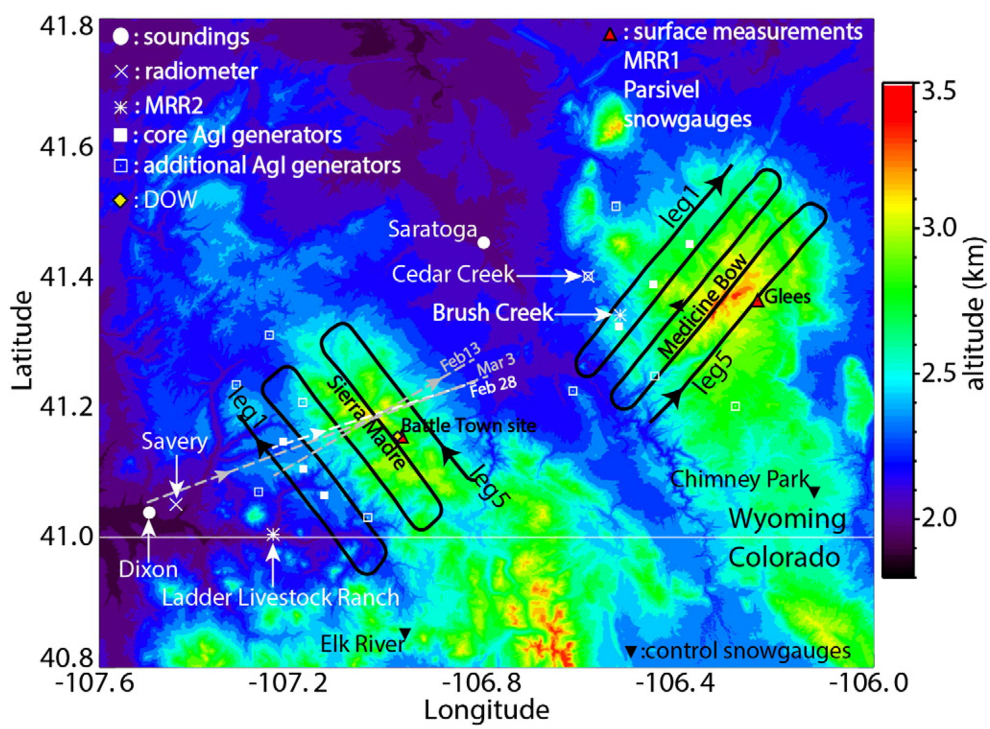

Fig. 1. ASCII experimental design map over the Sierra Madre (SM) and Medicine Bow (MB) mountains in southern Wyoming. The solid black lines show the UWKA flight tracks and square symbols show the ground-based AgI generators. The three most commonly used AgI generators are shown by the filled squares. Other symbols represent the various instrument locations. The dashed lines show the location of along-wind legs flown during three different IOPs. Data from these legs are shown below.