Atmospheric Research 214 (2018) 74–90

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

The impact of ground-based glaciogenic seeding on a shallow stratiform cloud over the Sierra Madre in Wyoming: A multi-sensor study of the 3 March 2012 case

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ARTICLE INFO

Keywords:
Glaciogenic seeding
orographic cloud and precipitation
radar reflectivity profiles
airborne measurements

ABSTRACT

A case study is presented of the impact of ground-based glaciogenic seeding on a shallow, lightly precipitating orographic storm with abundant supercooled cloud droplets, but few ice particles. The storm was observed on 3 March 2012 as part of the AgI (silver iodide) Seeding Cloud Impact Investigating (ASCII) experiment in Wyoming. The cloud base temperature was about −9 °C, and cloud tops were at about −16 °C. The high concentration of small droplets and low ice particle concentration lead to natural snow growth, mainly by vapor diffusion. The question addressed here is whether the injection of ice nucleating particles (AgI) enhanced snow growth and snowfall. The treated (seeded) period is compared with the preceding untreated (noseeded) period, and natural trends (observed in an adjacent control region) are removed. The main target site, located on a mountain pass at an elevation above cloud base, was impacted by AgI seeding, according to a trace chemistry analysis of freshly fallen snow.

Data from three radar systems were used: the Wyoming Cloud Radar, two Ka-band profiling Micro-Rain Radars, and a X-band scanning Doppler-on-Wheels (DOW) radar. Composite data from these radar systems and from gauges in the target area indicate an increase in low-level reflectivity and precipitation rate during seeding. This finding generally agrees with other published ASCII case studies. The increase in reflectivity during seeding in the target area appears to be due mainly to an increase in particle size (aggregation), not number concentration, as suggested by DOW differential reflectivity and by disdrometer and Cloud Particle Imager measurements on the ground.

1. Introduction

Cold-season snowfall over mountains is the main source of water in the western United States. Orographic clouds have been seeded to augment the snowpack over the western mountains for more than half a century. Orographic clouds often are suitable for glaciogenic seeding for several reasons: they are typically quite young and rich in supercooled liquid water (SLW) as air is lifted rapidly above the condensation level; and they are rather easy targets for ground-based seeding as they are often shallow and persistent. The efficacy of glaciogenic seeding remains poorly understood, notwithstanding many randomized experiments and field work focused on cloud microphysics (National Research Council, 2003; Garstang et al., 2005). This was the broader motivation for two recent field campaigns. The first one focused on ground-based seeding: the AgI (silver iodide) Seeding Cloud Impact Investigation (ASCII) was conducted over the Sierra Madre in southern Wyoming in early 2012 and 2013 (Pokharel and Geerts, 2016). The second one, the 2017 Seeded and Natural Orographic Wintertime clouds: the Idaho Experiment (SNOWIE-17) (Tessendorf et al., 2018), focused on airborne seeding. Both campaigns collected rich airborne and radar observations to study cloud-microphysical processes. The orographic clouds sampled in both campaigns all produced at least some natural snowfall, i.e. there were no ice-free orographic clouds, although a few orographic cloud layers with very few ice crystals ($\ll 1\ L^{-1}$) were detected in SNOWIE, and these proved to be quite seedable, at least from an aircraft (French et al., 2018). Only ground-based seeding was conducted in ASCII.

Cold-season orographic clouds are not always stratiform in nature.

Abbreviations: 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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https://doi.org/10.1016/j.atmosres.2018.07.013
Received 11 February 2018; Received in revised form 11 June 2018; Accepted 11 July 2018
Available online 12 July 2018
0169-8095/

Table 1
Comparison of cloud characteristics in this case study against two other ASCII-12 case studies of stratiform orographic clouds. The CIP and CDP data were collected at a flight level of 13 or 14 kft (~4.0 or 4.3 km MSL), during the NOSEED period only. The CIP concentration is in the 63–2000 μm size range only. It should be noted that the CDP data in IOP12 and IOP13 are based on limited cloud penetrations, because of instrument icing (in IOP13) and because of shallow clouds, mostly below flight level. The liquid water path (LWP) estimate is from the passive microwave radiometer at Savery (Fig. 1) and presents an IOP average.

IOP	12	13	17
date	21 February 2012	22 February 2012	3 March 2012
reference	Pokharel et al. (2014a)	Pokharel et al. (2015)	this study
CIP ice particle concentration (L^{-1})	30	17	8
CDP droplet number concentration (# cm^{-3})	86	31	125
CDP liquid water content ($g\ m^{-3}$)	0.15	0.52	0.13
LWP (mm)	0.22	0.31	0.08

Table 2
Definition of NOSEED and SEED periods for the 3 March 2012 IOP. Eight AgI generators were operating from 1930 to 2330 UTC ± a few minutes. The times are in UTC (HH:MM:SS). L refers to a ladder pattern, consisting of 5 tracks (T), as shown in Fig. 1. The UWKA flew two along-wind legs after completing two ladder patterns, thereby creating a buffer period between NOSEED and SEED (1932–2000 UTC). No such period is assumed for the instruments at Battle (MRR, Parsivel, DOW), but a ~25 min advection time between the AgI generators and Battle is applied. No DOW data is available after 22:30.

Instruments	Noseed		Seed	
	Start	Stop	Start	Stop
WCR/UWKA	18:16:28	19:32:00	20:00:52	21:16:00
UWKA cross-wind tracks	L1: T5-T1 L2:T5-T1		L3:T5-T1 L4:T5-T1	
MRR and Parsivel	17:30:00	19:56:00	19:57:00	22:50:00
DOW	17:30:00	19:56:00	19:57:00	22:30:00

In the presence of potential instability, the orographic lift may release that instability and give rise to embedded convective clouds (e.g., Rotunno and Houze, 2007). Sometimes, typically in post-frontal situations with significant cold-air advection, only shallow convective clouds are present over the mountains. The nature of clouds (stratiform vs. convective) affects both natural and artificially altered ice initiation, and snow growth processes, with depositional growth generally dominating in stratiform clouds and riming in convective clouds (Houze Jr, 2014). Most of the snowfall from stratiform clouds occurs on the windward side, while more snow may fall in the lee of the crest from convective clouds, especially if the instability is released rather late, close to the crest (Jing and Geerts, 2015). The seeding impact on the growth of hydrometeors is harder to isolate in convective clouds, because of natural variability, and may be found only downwind of the mountain, as shown in one ASCII-12 case study (Pokharel et al., 2014b).

Natural variability can be significant also in apparently steady stratiform clouds, as shown in two ASCII-12 case studies, making it difficult to isolate the seeding impact on stratiform precipitation also. These studies examined Intensive Operations Period #12 (IOP12) (Pokharel et al., 2014a) and IOP13 (Pokharel et al., 2015). The IOP12 and IOP13 case studies examined stratiform clouds containing high SLW content, with fewer droplets overall, but more large droplets (D > 20 μm), compared to most ASCII-12 stratiform cases. These two case studies (IOP12 and IOP13) were somewhat limited, either because of lack of flight-level particle data (as the probes became impacted by rime ice), or because the target cloud rarily reached flight level.

This paper presents a third case study of the impact of ground-based glaciogenic seeding on stratiform orographic clouds in ASCII-12. This is a study of the 3 March 2012 case (IOP17). This study is similar to IOP12 and IOP13 in that no embedded convection was present, the cloud was shallow, and it naturally produced light snowfall. This study differs from the previous studies in four important ways: firstly, this study utilizes a richer array of observations compared to the IOP12 and IOP13 case studies, and also compared to other ASCII case studies (Pokharel et al., 2014b; Chu et al., 2014; Chu et al., 2017b), which is important because it has proven difficult to tease out the seeding signal. One resource not used in the previous ASCII studies is the data from particle probes on an aircraft flying overhead, at a level corresponding with ~600 m above the mountain top. These in situ data are not expected to

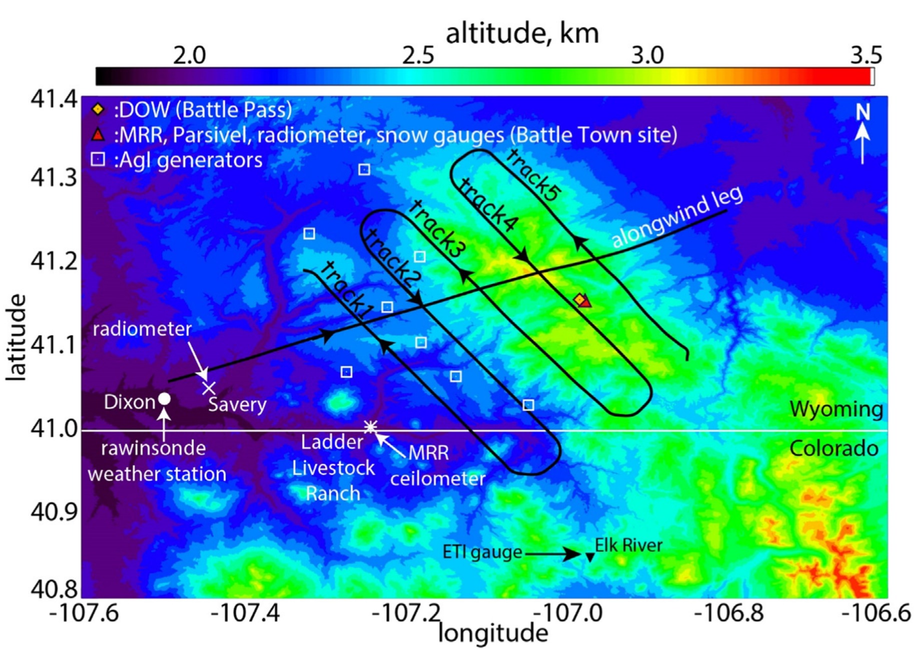

Fig. 1. ASCII-12 experimental design map, showing the location of AgI generators and instrument platforms, and UWKA flight tracks. The terrain elevation is shown in the background. The solid black lines show parts of the 3 March 2012 flight track, including the ladder pattern, with track labels (#1–5), and an along-wind leg.