Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming Using the Wyoming Cloud Radar

Final report for a three-year (Mar 2007 – Feb 2010)
U. S. Geological Survey and the Wyoming Water Development Commission grant

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1. Abstract

This proposal called for 20 research flight hours of the University of Wyoming King Air (WKA) over the Snowy Range (Medicine Bow) mountains in Wyoming during the time of glaciogenic cloud seeding conducted as part of the five-year Wyoming Weather Modification Pilot Project (WWMPP). This pilot project, administered by WWDC and contracted to the National Center for Atmospheric research (NCAR) and Weather Modification Inc (WMI), involved seeding from a series of silver iodide (AgI) generators located in the Snowy Range. In Feb 2008 we conducted two WKA flights (8 flight hours). The remaining three flights were conducted in early 2009 (18 and 20 February and 10 March). Thus we have flown all flight hours (20) supported by this award. All five flights were a success in terms of both the target weather conditions and instrument performance.

2. Summary of the field work

All five flights in this campaign (referred to as WWDC Cloud Seeding) followed the general flight pattern shown in **Fig. 1**. We targeted west- to northwesterly wind, because in such flow the Snowy Range forms the first obstacle following a long fetch over relatively flat terrain (the Red Desert), because three generators (Barret Ridge, Mullison Park, and Turpin Reservoir) are aligned with the cross-wind flight legs (Fig. 1), and because this flow pattern does not interfere with NCAR's randomized experiment. This is because under such flow the seed generators are upwind of both the target and the control snow gauges. Aside from the along-wind leg (whose orientation depends on the prevailing wind, pivoting around GLEES), there are five fixed tracks roughly aligned across the wind. The NW-most of these five tracks is upwind of the three generators, and the 2nd, 3rd, 4th, and 5th tracks are about 2, 6, 9, and 13 km downwind of the generators. The first four legs are on the upwind side, while the 5th one (tracking over GLEES) is mostly on the downwind side.

The pattern shown in Fig. 1 was repeated four times on several flights: the first two patterns had the seed generators off, and the last two patterns were flown with the seed generators on. On other flights we concentrated on the three most-downwind legs, and the number of patterns with seeding was increased at the expense of flight time without seeding (**Table 1**).

On all flights the Wyoming Cloud Radar (WCR) operated flawlessly, with three antennas (up, down, and forward-of-nadir). We recently discovered a small (0.60 m s^{-1}) downward bias in the Doppler vertical velocity from the up-looking antenna, on all flights. This correction was found after extensive comparisons with the down-looking antenna and with flight-level vertical wind data. On all flights we also had the up-looking lidar (Wyoming Cloud Lidar, WCL). On the last two flights, we also collected data from the recently-purchased down-looking lidar.

No less than 4 graduate students participated in the field campaign (Table 1), although only one graduate student (Yang Yang) is focusing her MSc research on the data from these five flights.

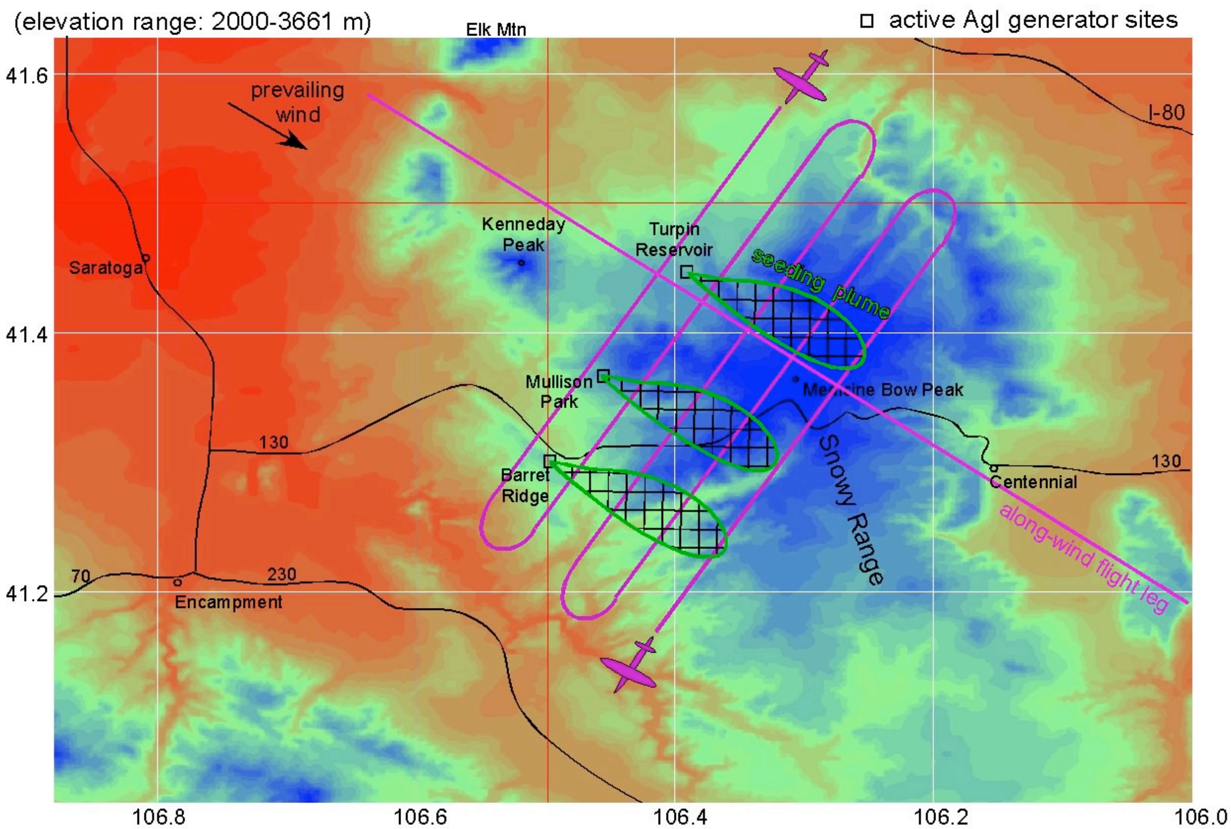

Fig. 1. A schematic of the WKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. On all flights the flight level was set at 4,276 m (14,000 ft) MSL, the minimum permissible flight level over the terrain. The prevailing wind was from the NW. One flight leg was across the terrain (along the wind), the other 5 flight legs were roughly across the winds at various distances downstream of the three active AgI sources.

Table 1: Summary of the five WKA flights

date	flight scientist	nadir WCL?	# across-wind legs without seeding	# across-wind legs with seeding	14 kft wind direction (deg. from)	14 kft temperature (°C)
2/11/08	Bart Geerts	N	10	10	290°	-19
2/25/08	Qun Miao	N	10	10	293°	-18
2/18/09	Yonggang Wang	N	10	10	294°	-20
2/20/09	Yang Yang	Y	10	5	298°	-17
3/10/09	Mahesh Kovilakam	Y	5	15	280°	-23

List of graduate student participants

The following students participated in the flight planning, the flight itself, the flight debriefing and the writing of the flight report:

- Qun Miao, PhD student, advisor: Dr. Geerts: field training opportunity (he is currently a post-doc in the group)
- Yonggang Wang, PhD student, advisor: Dr. Geerts: field training opportunity
- Yang Yang, MSc student, advisor: Dr. Geerts: both essential to her research, and a field training opportunity (Yang Yang is partly funded by this WWDC/USGS grant)
- Mahesh Kovilakam, PhD student, advisor: Dr. Deshler: field training opportunity

3. Objectives and methodology

1. Document the planetary boundary layer (PBL) turbulence and natural precipitation enhancement on the upslope side of the Medicine Bow mountains. This work has been conducted mainly by Miao Qun, a post-doc in our group. This research has these elements:
    a. Conduct a spectral analysis of WCR vertical velocity near the ground, to see whether the turbulence is consistent with theoretical expectations in the inertial subrange.
    b. Generate colored frequency-by-altitude diagrams (CFADs) showing vertical velocity variance over all depths including above flight level.
    c. Stratify these CFADs as a function of ambient wind speed, maybe stability, using radiosonde data in WWDC Cloud Seeding.
    d. In order to determine whether streamers rise from the ground, estimate snow crystal trajectories from vertical-plane dual-Doppler analysis, which includes the actual fall speed.
    e. Isolate flight sections where WKA is in the PBL layer, and contrast these sections to upstream in-cloud sections (above the PBL), and
        i. in these sections, relate updrafts to LWC and ice crystal concentration;
        ii. also look at riming & aggregation using 2D-C, 2D-P data.
    f. Develop a composite reflectivity (and vertical velocity) structure across the mountain (following the method in Kusunoki et al., 2005, in MWR). The following steps are needed:
        i. obtain a typical terrain profile;
        ii. assign coordinates to reflectivity (and vertical velocity) from each cross-section (x,z), with x=distance from crest, z=height above ground;
        iii. compute average reflectivity (Z) and vertical velocity for each (x,z) and plot this over typical terrain profile;
2. Examine the impact of cloud seeding on reflectivity. This has been Yang Yang's MSc thesis research. She developed a composite reflectivity as function of distance from the seeder in each of the 4 downstream flight legs along the wind.

4. Principal findings

Preliminary results of the first two flights were presented at the joint 17th joint American Meteorological Society - Weather Modification Association Symposium on Planned & Inadvertent Weather Modification in Westminster CO (Geerts 2008). In Feb 2010 a paper was submitted to *J. Atmos. Sci*. (Geerts et al. 2010), the most prestigious journal in its field. This paper is still in review, but the reviewers' comments are relatively minor. And in April 2010, Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM. In that talk, he presented the main findings of the *J. Atmos. Sci*. paper.

Here are the main results from the five flights conducted under this grant:

1. With so much natural variability it is very difficult to detect a seeding signature. Nearly 50% of the flights were in unseeded conditions (Table 1), and the 1st of 5 across-wind legs was upstream of the mountain (Fig. 1). These choices were made to detect a seeding signature by contrasting seeding to no-seeding patterns. Clearly the actual location of the plumes is uncertain. We do have excellent wind profile data from VAD analyses in the turns between across-wind legs. Still, the plumes may meander considerably in time. Visual inspection of WCR data along each leg indicates that there is no apparent change in radar reflectivity downwind of the AgI generators. Some boundary-layer eddies make it up to flight level, especially along the 4th leg going over the highest peaks. In these eddies, there appears to be no reduction in supercooled liquid water content nor a increase in number of ice crystals in areas downwind of the AgI plumes, compared to eddies in similar locations but clearly away from the AgI generators, or collected before the generators were turned on.
2. Deep PBL turbulence along the upslope section of the mountain was present on all days. The depth of PBL mixing was about 1 km, ranging from 600 m on more stable days to 1300 m and beyond on the less stable days. This turbulence effectively mixes the AgI aerosol released from ground generators into an orographic cloud where most of the supercooled water naturally resides, in other words, ground-based seeding of orographic clouds is more effective than airborne seeding. Since this turbulence occurs within cloud, precipitation growth though riming is likely in turbulent eddies whose updraft speed far exceeds the average ascent rate over the terrain. In fact this growth is suggested by the increase of the WCR reflectivity along the upwind slope of the Snowy Range, near the surface, in a layer that is sometimes disconnected from the snow layer aloft. The flight-level data were usually collected above the BL, but in some sections we were low enough to collect cloud microphysics data within the PBL, and they show large ice crystal concentrations and evidence of riming. Note that PBL turbulence would also mix ice particles generated near the ground into cloud (natural cloud seeding). Such ice particles could result from blowing snow or from the splintering of supercooled water along rimed surfaces on the ground. The main evidence for this is the increase in reflectivity along the upwind slope, above cloud base, in the PBL, by local growth of ice crystals (Vali et al., 2008). This needs to be examined further.
3. We flew two additional flights in March 2009, funded by a follow-up WWDC/USGS grant (referred to as Cloud Seeding II). On the last of these flights, on 3/25/09, there is a hint of a "seeding signature" downwind of mainly the middle generator (Mullison Park, see Fig. 1). This signature includes reduced flight-level liquid water and increased concentration of ice crystals (**Fig. 2**). It also includes increased radar reflectivity below flight level, and more rapid attenuation of the nadir lidar backscatter power. The high depolarization ratio indicates

that this attenuation in the high-reflectivity plume is due to ice crystals. Three other passages along the same flight leg shows repeatability, that is, the seeding signature is present in four successive legs during seeding, but absent on the first passage, before the AgI generators were turned on.

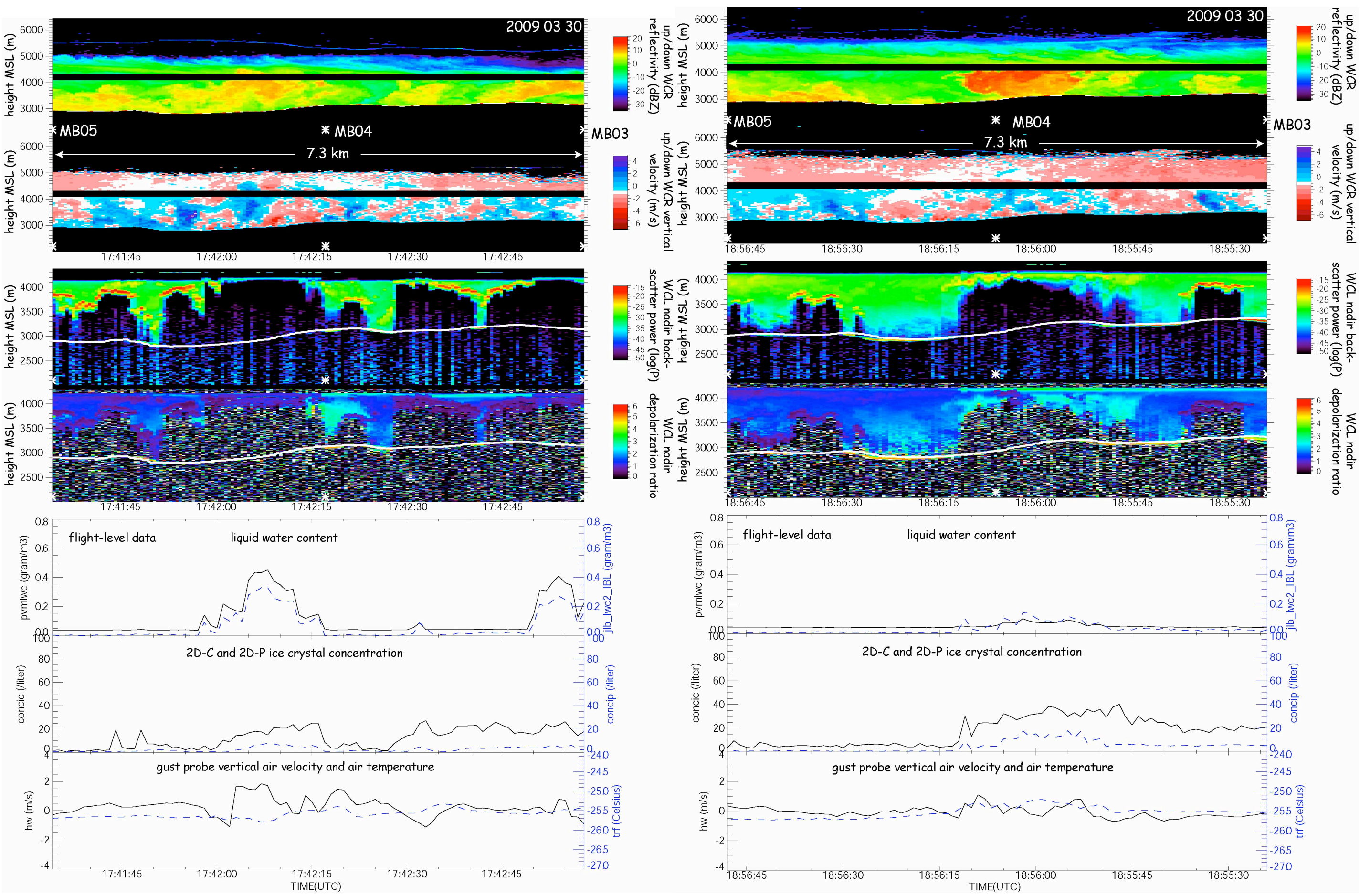

Fig. 2: Comparison of flight-level and remote-sensing data along flight leg #3, located 6 km downwind of the AgI generators (Fig. 1), on 3/25/2009. The AgI generators were off during WKA passage on the left, and on for the flight leg on the right. The top two panels show WCR reflectivity and vertical velocity, above and below the aircraft. The black stripe in the middle is the flight level, and the ground is evident as the sloping surface below flight level. The next two panels give nadir WCL backscatter power and depolarization ratio. The bottom three panels show flight-level data.

5. Further plans

So far we conducted seven flights over the Snowy Range, five funded under the present project and two under Cloud Seeding II. Following the review of the *J. Atmos Sci.* paper (Geerts et al. 2010), we are preparing a paper dealing with the importance of PBL turbulence on orographic precipitation (Geerts and Miao 2010), and another paper further exploring seeded cloud properties with flight-level data (Yang et al. 2010).

We also have two other orographic precipitation studies planned. First, Dr. Geerts is the PI of the SOLPIN component of the current University of Wyoming NSF EPSCoR proposal, called “Earth System Interactions in Complex Terrain”. The SOLPIN (Simulations and Observations of Land-Precipitation Interactions) component is worth about $6 million, plus $2 million in UW matching. Both winter and summer orographic precipitation will be studied, using experimental data and numerical simulations. Second, Dr. Geerts is the PI in a large, collaborative proposal, known as ASCII (AgI Seeding of Cloud Impact Investigation). This proposal in preparation is to be funded by NSF and, if funded, to be conducted in the Medicine Bow Mountains in the winter of 2011-12, as part of the WWMPP. The emphasis here is on the cloud microphysical effects of glaciogenic seeding in cold orographic clouds.

The following new elements will be included in these proposal(s):

a. fly on a windy clear-sky day (following a snow storm) to look at the vertical distribution of blowing snow mixed into the PBL;
b. fly a mission downwind of seed generators under conditions unsuitable for ice particle generation near the ground, but suitable for seeding;
c. include crystal habit / riming measurements at the ground, preferably on the upwind side of the mountains
d. examine diurnal variation of PBL turbulence, and changes in stability & cloud depth in association with the passage of a frontal disturbance;
e. examine a broader parameter space, in terms of cloud depth and ambient temperature by including snowstorms advected from the southwest.

6. Significance

Our findings are believed to be very significant. Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM in April 2010. At that meeting, Arlen Huggins, a veteran researcher in weather modification, mentioned our work as one of the most significant achievements in glaciogenic seeding efficacy research in the past decade.

7. Publications

- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: The impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. *J. Atmos. Sci*., in review.
- Geerts, B., and Q. Miao, 2010: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from vertical-plane airborne radar transects. *Mon. Wea. Rev*., in preparation.

8. Presentations

(a) with abstracts:

- Andretta, T., and B. Geerts, 2008: Snowfall in mountain lee convergence zones: a case study. 13th Conference on Mountain Meteorology, Whistler, BC, 11–15 August 2008. [Thomas Andretta is a PhD student under Dr. Geerts]
- Geerts, B., 2008: Impact of surface interaction and cloud seeding on orographic snowfall: A downlooking airborne cloud radar view. Oral presentation at the 17th joint American Meteorological Society - Weather Modification Association Symposium on Planned & Inadvertent Weather Modification, Westminster, CO, April 21-25, 2008.

- Geerts, B., J. Snider, G. Vali, and D. Leon, 2008: Orographic precipitation enhancement by boundary-layer turbulence: a vertically pointing airborne cloud radar view. 13th Conference on Mountain Meteorology, Whistler, BC, 11–15 August 2008.
- Vali, G., B. Geerts, J. Snider, and D. Leon, 2008: Surface source of ice particles in mountain clouds. 15th International Conference on Clouds and Precipitation (ICCP), 7-11 July 2008, Cancun, Mexico.
- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: Vertically-pointing airborne radar observations of the impact of glaciogenic cloud seeding on snowfall from orographic clouds. Weather Modification Association meeting, Santa Fe NM, 21-23 April.

(b) without abstracts

- Geerts, B.: A series of progress reports presented at the Wyoming Cloud Seeding Pilot Project Advisory Team meetings in Cheyenne or Lander WY (May 07, Oct 07, Feb 08, Dec 08, Jul 09, and Dec 09).
- McIntyre, H.: NASA06 observations of orographic precipitation types over the Snowy Range under different stability and flow regimes, UW-NCAR RAL workshop in Boulder, CO, March 6, 2007.

9. Students supported

Three graduate students have been supported by this grant:

Heather McIntyre (MSc student) was supported by this grant in Spring semester 2007, but she failed to maintain a 3.0 GPA and left the program in May 2007.

Thomas Andretta started in late August 2007, although coursework and PhD Qualifying Exam were his main pre-occupations until May 2008. He participated in the February 2008 cloud seeding validation field experiment. Unfortunately, in June 2008 he decided to switch research topics and focus on natural snowfall processes in mountain lee convergence zones. His project was funded by a UW NASA Space Grant Consortium fellowship between Aug 2009-May 2010.

Yang Yang (MSc student) joined us from China in August 2008, and was supported by this grant. Her father and grandfather have been involved in cloud seeding research in China, and she has strong credentials, so we are pretty excited to bring her on-board. She is expected to graduate in May 2011.

One post-doctoral scientist, Dr. Qun Miao, has also been partly supported by this grant. He was essential in the data analysis leading to the *J. Atmos. Sci.* paper (Geerts et al. 2010). He left the group in Jan 2010 to assume a faculty position in Ningbo University. He will be back in summer as visiting research scientist.

Finally, two other PhD students (Yonggang Wang and Mahesh Kovilakam) participated in the field campaign in early 2009 (see Table 1). This participation has given them invaluable experience in airborne field research.