Report as of FY2009 for 2009WY46B: "Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements"

Publications

- Articles in Refereed Scientific Journals:
    - Geerts, B. and Q. Miao, 2010. Vertically-pointing airborne Doppler radar observations of Kelvin-Helmholtz billows, Monthly Weather Review, 138, 982-986.

Report Follows

Detecting the signature of glaciogenic cloud seeding in orographic snowstorms in Wyoming II: Further airborne cloud radar and lidar measurements

Year 1 report
for a three-year (Mar 2009 – Feb 2012)
U. S. Geological Survey and the Wyoming Water Development Commission grant
Dr. Bart Geerts, PI
4/30/2010

1. Abstract

This proposal (referred to as Cloud Seeding II) called for two research flights 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. The flights were conducted on 3/25 and 3/30 2009. A previous grant from the UW Office of Water programs, referred to as Cloud Seeding I, supported five WKA flights, flown in Feb 2008 and in Feb-Mar 2009. All seven flights (**Table 1**) were a success in terms of both the target weather conditions and instrument performance.

2. Summary of the field work

All seven flights listed in Table 1 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 four flights, we also collected data from the recently-purchased down-looking lidar.

No less than 4 graduate students participated in the field campaign (see Section 9), although only one graduate student (Yang Yang) is focusing her MSc research on the data from these five flights.

The seven cases have been used to construct composites of radar data and flight-level data, in order to tease out the effect of AgI seeding on cloud processes and snowfall. In all cases the static stability was rather low, and the wind speed strong, such that (a) boundary-layer turbulence effectively mixed tracers over a depth of at least 1 km, and sometimes above flight level (2,000 ft above the Med Bow Peak) up to cloud top, and (b) the Froude number exceeded one and thus the flow went over (rather than around) the mountain range (Table 1).

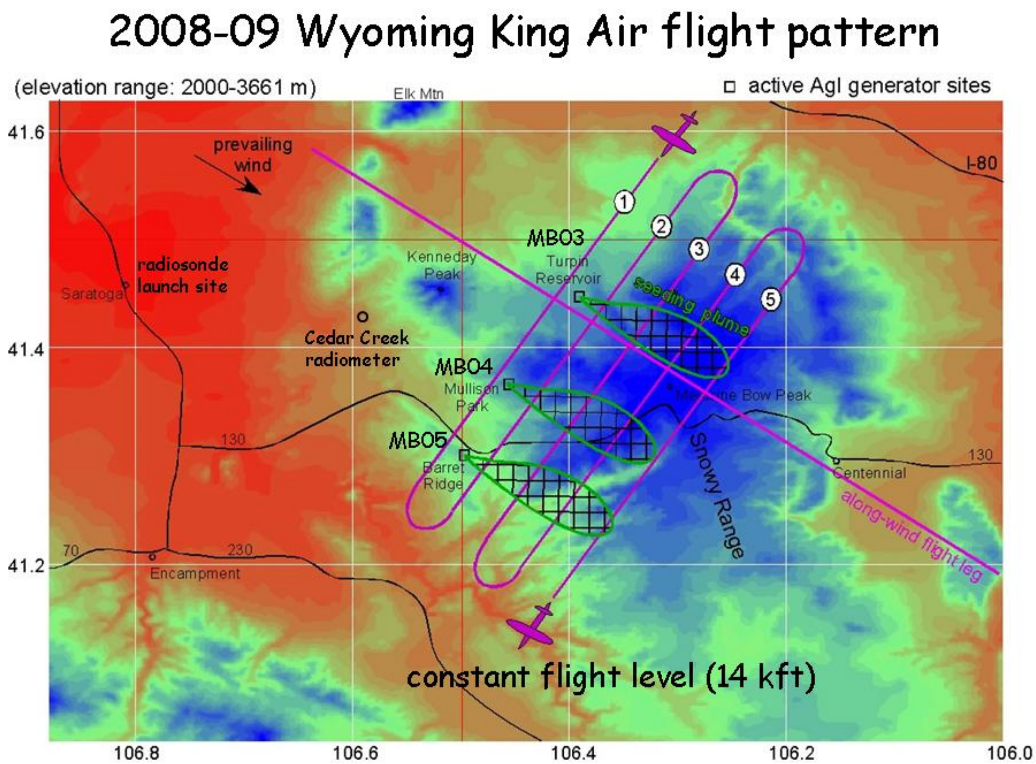

Fig. 1. A schematic of the WKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. On all flights the flight level was set at 4,276 m (14,000 ft) MSL. The prevailing 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.

3. Objectives and methodology

The key objective is to examine the impact of cloud seeding on radar reflectivity between the AgI generators and the slopes of the target mountain. To do this, a composite of reflectivity for seed and no-seed conditions for all downstream flight legs along the wind needs to be built. And it needs to be ascertained that the observed differences in composites is both statistically significant and not attributable to differences in vertical air velocity.

flight date	**11 Feb 2008**	**25 Feb 2008**	18 Feb 2009	20 Feb 2009	**10 Mar 2009**	**25 Mar 2009**	30 Mar 2009
start times (UTC, hh:mm)							
WKA take-off	**19:41**	**20:05**	16:22	21:30	**13:57**	**15:54**	17:04
Barrett Ridge generator	**21:28**	**21:55**	18:12	23:20	**14:54**	**16:45**	17:54
Mullison Park generator	**na**	**21:56**	18:15	na	**14:52**	**16:43**	17:52
Turpin Reservoir generator	**21:29**	**na**	18:09	23:19	**14:56**	**16:42**	17:50
flight pattern							
no-seeding leg sequence	**54321 54321**	**54321 54321**	54321 54321	54321 54321	**54321**	**54321**	54321
seeding leg sequence	**54321 54321**	**54321 54321**	54321 54321	54321	**5 times 543**	**5 times 543**	4 times 543
no-seed flight-level mean fallspeed (m s^{-1})	**1.19**	**0.99**	0.80	1.04	**0.91**	**1.02**	0.80
seed flight-level mean fallspeed (m s^{-1})	**1.04**	**0.93**	0.70	0.95	**0.78**	**0.80**	0.72
Saratoga sounding data							
mean wind speed (m s^{-1})	**15**	**12**	14	15	**21**	**14**	11
mean wind direction (°)	**317**	**293**	300	293	**272**	**265**	323
Brunt-Väisälä frequency (10^{-2} s^{-1})	**0.51**	**0.15**	0.78	0.76	**0.52**	**0.00**	0.61
Froude number	**1.9**	**5.0**	1.04	1.2	**2.6**	**∞**	1.1
Richardson number	**0.7**	**0.2**	8.1	2.4	**0.4**	**0.0**	3.5
lifting condensation level (m MSL)	**2719**	**2782**	2630	2314	**2896**	**2618**	2807
temperature at generator level (°C)	**-9**	**-7**	-10	-10	**-17**	**-8**	-15

Table 1: Summary of the seven flight days. The flight legs are numbered as shown in Fig. 1. The mean fallspeed of hydrometeors is based on a comparison between the air vertical velocity measured by the gust probe, and the mean WCR particle vertical motion measured at the nearest radar gate above and below the aircraft, at a range of ~120 m. The sounding data come from a radiosonde released upwind of the mountain. The numbers shown in the table represent averages between ground level and the elevation of Medicine Bow Peak. The Brunt-Väisälä frequency N is the dry (moist) value below (above) the cloud base. The Froude number is calculated as the wind speed divided by N and the height of Medicine Bow Peak above Saratoga. The Richardson number is N^2/S^2, where S is the magnitude of the shear between the mixed layer (50 hPa deep) and mountain top level. The elevation of the three generators ranges between 2752-2946 m. The direction normal to the five flight legs is 309°. The mean temperature at the elevation of the generators is estimated from the Saratoga sounding.

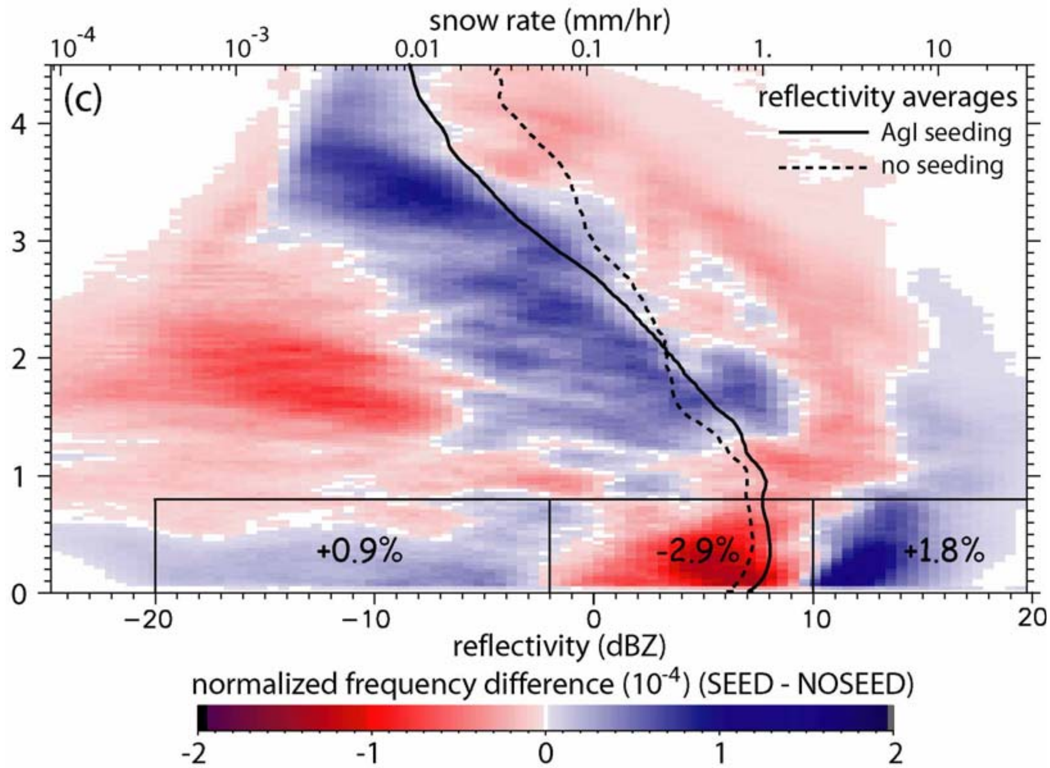

Fig. 2: Normalized frequency by altitude (FAD) of the difference in WCR reflectivity during seed and no-seed conditions. Also shown are cumulative normalized frequency differences (seed minus no-seed) in three boxes near the ground, expressed as a percentage, and the mean reflectivity profile during seed and no-seed conditions. The snow rate (S) shown in the upper abscissa is inferred from S=0.11 $Z^{1.25}$ (Matrosov 2007).

4. Principal findings

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, so we are confident that it will be accepted. 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.

Our ongoing study provides experimental evidence from vertically-pointing airborne radar data, collected on seven flights (Table 1), that ground-based <u>AgI seeding can significantly increase radar reflectivity within the PBL in shallow orographic snow storms</u>. Theory and a comparison between flight-level snow rate and near-flight-level radar reflectivity indicate <u>a ~25% increase in surface snow rate during seeding</u> (**Fig. 2**), notwithstanding slightly stronger updrafts found on average during no-seeding periods. The partitioning of the dataset based on atmospheric stability and proximity to the generators yields physically meaningful patterns and strengthens the evidence.

Firstly, the AgI seeding signature is stronger and occurs over a greater depth on the less stable days than on the three more stable days. Secondly, it is stronger for the two legs close to the generators than for the two distant legs. A random resampling of all flight passes irrespective of seeding action indicates that the observed enhancement of high reflectivity values (>10 dBZ) in the PBL during AgI seeding has a mere 2.2% probability of being entirely by chance (**Fig. 3**).

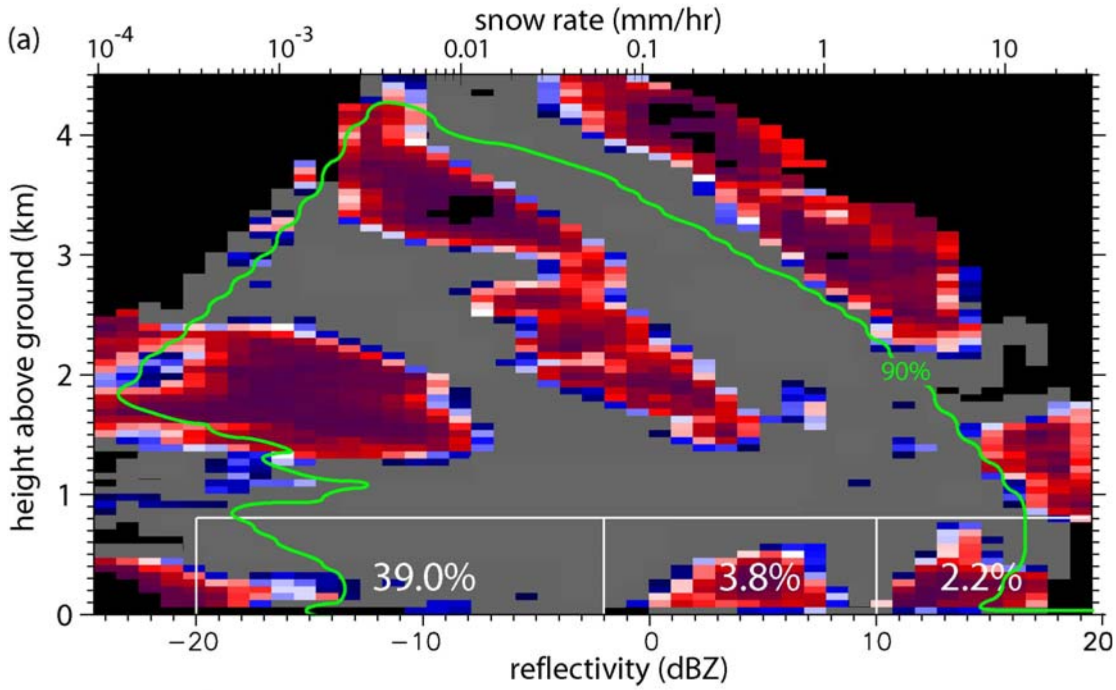

Fig. 3: Percentage of differences between randomly selected subgroups that exceeds the observed seed minus no-seed difference in WCR reflectivity (shown in Fig. 2). The white numbers show the same, not at the bin level but within the same boxes as in Fig. 2. In the grey areas there is a more than 10% probability that the seed minus no-seed difference is by chance. The green contour comprises 90% of the cumulative data frequency.

The results presented have limitations, mainly because just seven storms were sampled and these storms represent a rather narrow region in the spectrum of precipitation systems in terms of stability, wind speed, storm depth and cloud base temperature. While the analysis yields strong evidence for an increase in reflectivity near the surface, the quoted change in snowfall rate (25%) is unlikely to be broadly representative. It appears that PBL turbulence over elevated terrain is important in precipitation growth, both in natural and in seeded conditions, and thus the same results may not be obtained if the precipitation growth primarily occurs in the free troposphere. This work needs to be followed up with a longer field campaign under similar as well as more diverse weather conditions. Such campaign should include ground-based instruments, such as vertically pointing or scanning radars and particle sizing and imaging probes.

5. Further plans

So far we conducted seven flights over the Snowy Range, five funded under Cloud Seeding I and two under this grant (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 2011), and another paper further exploring seeded cloud properties with flight-level data (Yang et al. 2011).

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. If funded, then both winter and summer orographic precipitation will be studied, using experimental data and numerical simulations.

Second, Dr. Geerts is the PI in a proposal, known as ASCII (AgI Seeding of Cloud Impact Investigation). This proposal in preparation is a collaboration with NCAR, and is to be funded by NSF. If funded, ACII will 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.

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. and Q. Miao, 2010: Vertically-pointing airborne Doppler radar observations of Kelvin–Helmholtz billows. *Mon. Wea. Rev.* , **138**, 982–986.
- 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, 2011: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from vertical-plane airborne radar transects. *Mon. Wea. Rev*., in preparation.
- Yang, Y., B. Geerts and Q. Miao, 2011: The impact of glaciogenic cloud seeding on winter orographic clouds, based on vertically-pointing airborne Doppler radar data and flight-level data. *J. Appl. Meteor. Climat.*, in preparation.

8. Presentations

(a) <u>with abstracts</u>:

- 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) <u>without abstracts</u>:

- Geerts, B.: A series of progress reports presented at the Wyoming Cloud Seeding Pilot Project Advisory Team meetings in Cheyenne (Dec 09) or in Lander WY (Jul 09).

9. Students supported

Yang Yang is an MSc student. She 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 a visiting research scientist.

Finally, two other PhD students (Yonggang Wang and Mahesh Kovilakam) participated in the field campaign in early 2009. This participation has given them invaluable experience in airborne field research. In fact all four people listed above participated in the flight planning, the flight itself, the flight debriefing and the writing of the flight report.