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

Final Report
for a three-year (Mar 2009 – Feb 2012)
UW Office of Water Programs
U. S. Geological Survey and the Wyoming Water Development Commission grant
Dr. Bart Geerts, PI
5/1/2012

1. Abstract

This proposal (referred to as Cloud Seeding II) called for two research flights of the University of Wyoming King Air (UWKA) over the Medicine Bow mountains (aka the Snowy Range) in Wyoming during the time of glaciogenic cloud seeding conducted as part of the multi-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), involves 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 UWKA flights, flown in Feb 2008 and in Feb-Mar 2009. All seven flights were a remarkable success in terms of both the target weather conditions and instrument performance. The key findings from these seven flights led to a remarkable paper in the *J. Atmos. Sci*. (Geerts et al. 2010), and apparently national recognition in the form of a National Institutes of Water Resources (NIWR) "IMPACT" Award.

2. Summary of the field work

All seven flights 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.

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, 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.

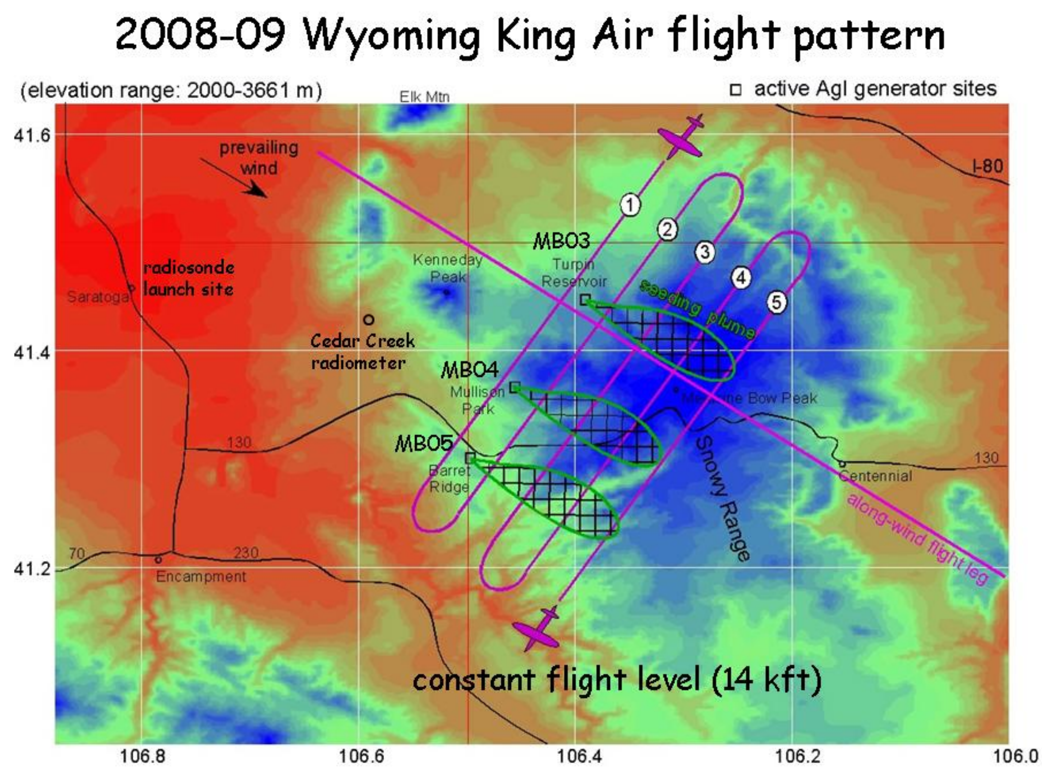

Fig. 1. A schematic of the UWKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. On all flights the flight level was set at 4,276 m (14,000 ft) MSL. The prevailing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

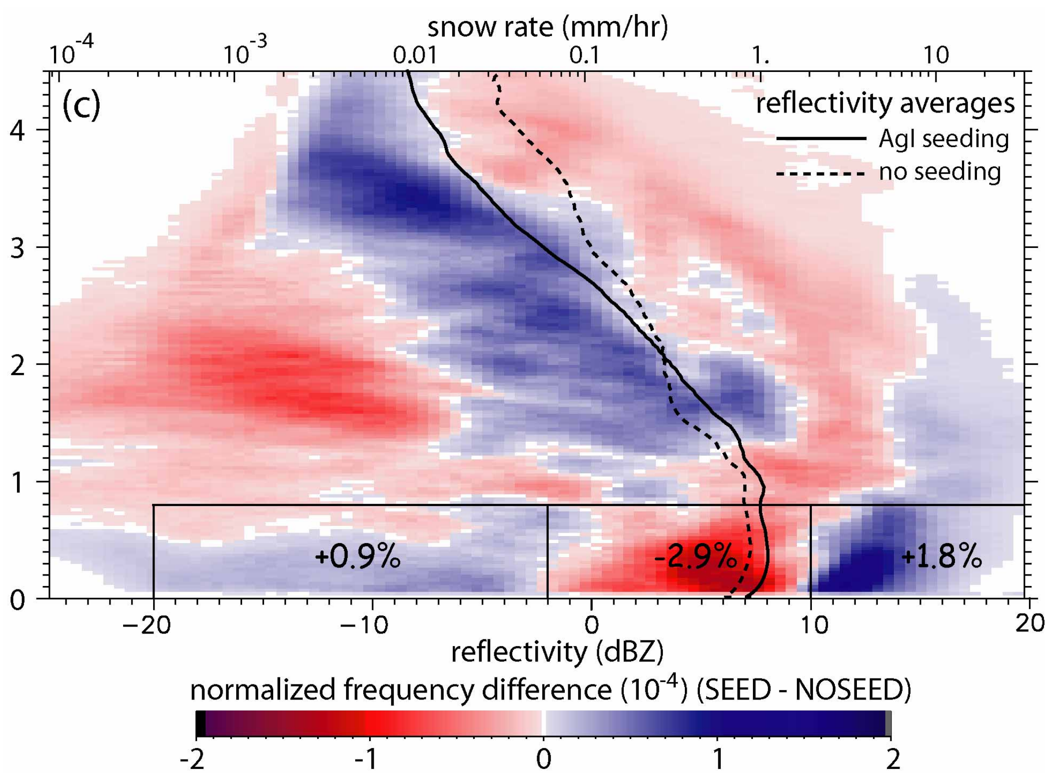

Fig. 2: Normalized frequency by altitude (FAD) of the difference in WCR reflectivity during seed and no-seed conditions. Also shown are cumulative normalized frequency differences (seed minus no-seed) in three boxes near the ground, expressed as a percentage, and the mean reflectivity profile during 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. 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 AgI seeding can significantly increase radar reflectivity within the PBL in shallow orographic snow storms. Theory and a comparison between flight-level snow rate and near-flight-level radar reflectivity indicate a ~25% increase in surface snow rate during seeding (**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**).

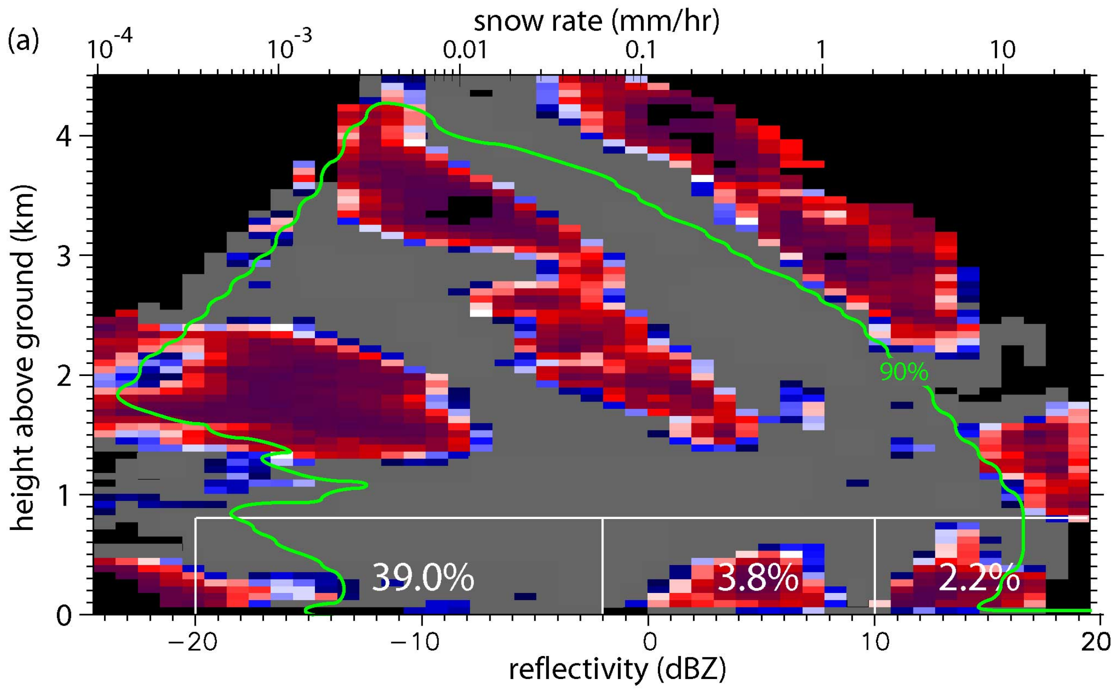

Fig. 3: Percentage of differences between randomly selected subgroups that exceeds the observed seed minus no-seed difference in WCR reflectivity (shown in Fig. 2). The white numbers show the same, not at the bin level but within the same boxes as in Fig. 2. In the grey areas there is a more than 10% 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 wrote a paper dealing with the importance of PBL turbulence on orographic precipitation (Geerts et al. 2011), and another paper further exploring seeded cloud properties with flight-level data (Miao et al. 2012).

The seven flights and follow-up publications, esp. Geerts et al. (2010), have served as a pilot effort for a much larger research project, known as ASCII (AgI Seeding Cloud Impact Investigation), funded by the National Science Foundation. This grant is a collaboration between Dr. Geerts' team and several NCAR scientists (Rasmussen, Breed, Xue). The USGS/WWDC-funded field work and data analysis (esp. Geerts et al. 2010, in *J. Atmos. Sci.*) were instrumental in the success of this $569,097 grant entitled "The cloud microphysical effects of ground-based glaciogenic seeding of orographic clouds: new observational and modeling tools to study an old problem" (Aug 2011 – Jul 2014; reference: AGS-1058426). The emphasis of ASCII is on the cloud microphysical effects of glaciogenic seeding in cold orographic clouds, but ASCII examines glaciogenic seeding in the context of natural snow growth processes. The ASCII research grant is the first time in nearly three decades that NSF (or any federal agency) has supported weather modification research.

The first ASCII field phase was conducted in the Sierra Madre (**Fig. 4**) between 4 Jan and 4 March 2012, and it deployed the UWKA, a MGAUS sounding system, an automated weather station, and a Doppler on Wheels (DOW) radar, all funded directly by NSF at an additional cost of about $500K. The DOW was positioned on Battle Pass, and often encountered hostile conditions during ASCII. Hidden in the trees about 600 m downwind of the pass, a scaffold was erected to make measurements with an array of instruments characterizing snow at the surface and overhead (Fig. 4b). ASCII-phase 1 involved 17 intensive observation periods, and is regarded a success, notwithstanding several technical challenges and a relatively warm, dry winter.

The second ASCII field phase will be conducted in Jan-Feb 2013, and will again be focused on the Medicine Bow Range. The NSF funding supports 10 UWKA research flights. We may also be able to deploy a series of snow probes at GLEES. Both ASCII campaigns are conducted in the context of the WWMPP, which conducts the ground-based glaciogenic seeding.

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.

Dr. Geerts has been informed that this project was selected along with the Wyoming Institute, for the 2012 National Institutes of Water Resources (NIWR) "IMPACT" Award. At the time of writing, this NIWR Impact Award was not officially presented, but if confirmed, this award confirms the significance of the present work in terms of the greatest potential impact on water supply enhancement. Three equally-weighted criteria have been used to select the winner of this award, i.e. magnitude, timing, and confidence. The award is national, following a regional selection process, and then a selection amongst the 8 NIWR regions nationwide. It will officially be presented at the NIWR annual conference held in Santa Fe, NM in July 2012, where Dr. Geerts will deliver a presentation.

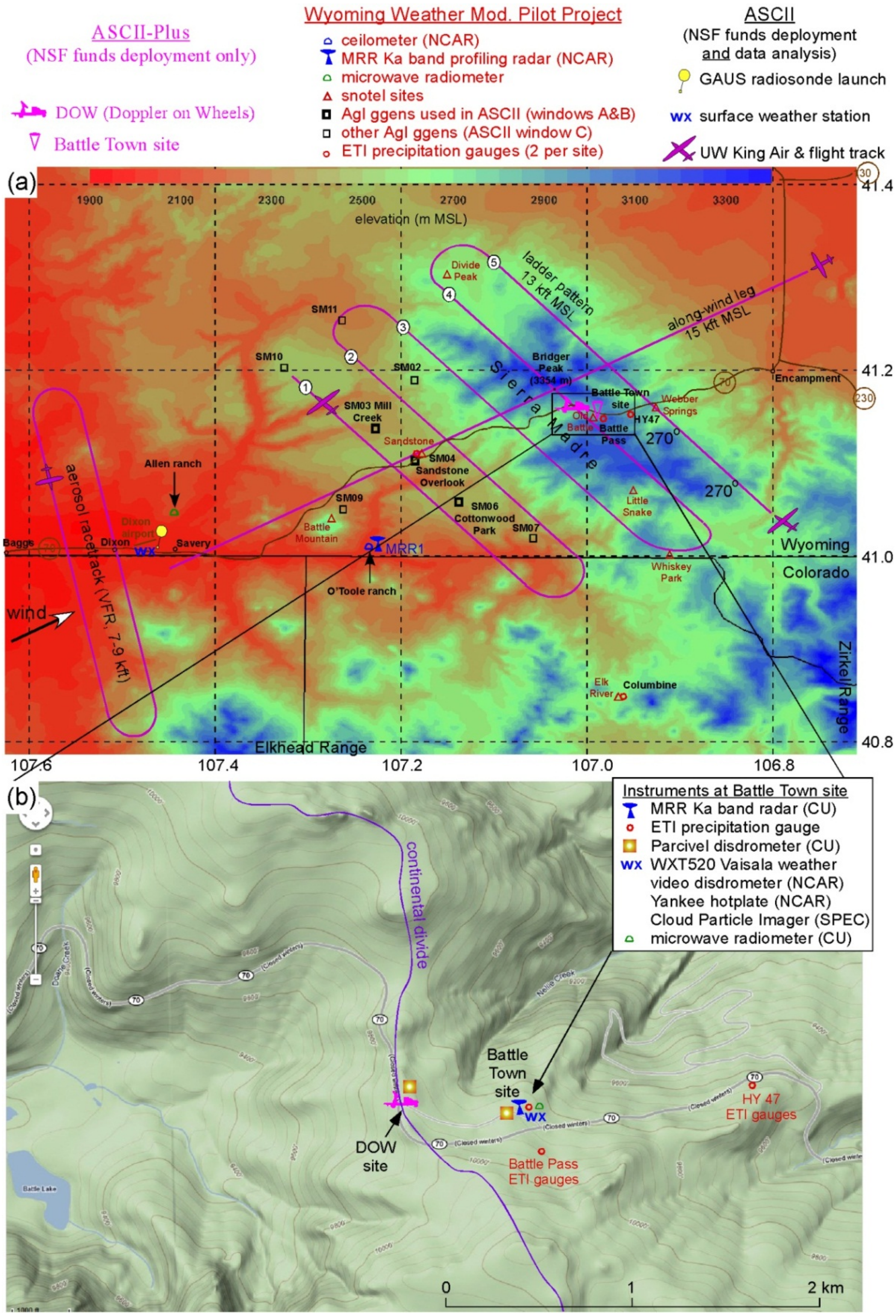

Fig. 4: ASCII/WWMPP experimental design map, showing UWKA flight tracks and ground-based instruments. The terrain is shown in the background, in color in (a) and using contours in (b). The highways are shown as well. Panel (b) is a zoom-in of (a) around Battle Pass. The scale in (a) can be derived from the latitude/longitude values.

7. Peer-reviewed publications

The following papers directly resulted from the research in this grant and (where possible) were paid for by this grant:

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: An airborne profiling radar study of the impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. *J. Atmos. Sci.*, **67**, 3286–3302.

Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: The impact of glaciogenic seeding on orographic cloud processes: preliminary results from the Wyoming Weather Modification Pilot Project. *J. Weather Mod.*, **42**, 105-107.

Geerts, B., Q. Miao, and Y. Yang, 2011: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from profiling airborne radar data. *J. Atmos. Sci.*, **68**, 2344-2365.

Miao, Q., B. Geerts, and Y. Yang 2011: The impact of ground-based glaciogenic cloud seeding on orographic precipitation: new insights from an airborne down-looking radar. *Advances in Atmospheric Science*, accepted.

Yang, Y. and B. Geerts, 2012: Observations of hydrometeor trajectories in winter orographic clouds. *Mon. Wea. Rev.*, in review.

8. Presentations supported by the Grant

Cloud seeding: Dr. Geerts gave oral presentations at the following meetings:

- 2010 Annual Meeting of the Weather Modification Association and the North American Interstate Weather Modification Council, Santa Fe, NM, 21-23 April 2010;
- 18th AMS Conference on Planned and Inadvertent Weather Modification, Seattle, 23–27 January 2011;
- 2012 Annual Meeting of the Weather Modification Association, Las Vegas, 25-27 April 2012.

Dr. Geerts and/or his graduate students also gave regular research updates at the WWMPP Technical Advisory Team (TAT) meetings, in Lander (typically in July) and in Cheyenne (typically in January), at the WWMPP Ground School (typically in November), and in 2011 also at the WWMPP seasonal debriefing meeting in mid-April. And we have provided the WWMPP team with material for use in their presentations at meetings of the Select Water Committee, a group of Wyoming state senators and representatives, in the context of updates and further funding requests.

PBL turbulence, blowing snow, and orographic precipitation: Dr. Geerts gave talks on the importance of PBL turbulence on the growth of snow particles over mountains at the 19th AMS Conf. on Boundary Layer Processes and Turbulence, Keystone CO (2-6 August 2010), the 10th Annual Meeting of the European Meteorological Society, Zurich, Switzerland (13-17 Sept), and the UW Department of Atmospheric Science seminar on 11/23/2010. Dr. Miao presented updated work at the orographic precipitation workshop hosted by Dr. Roy Rasmussen in Boulder 17-19 March 2012.

9. Dissertations/theses

No graduate students funded by this grant have graduated yet, but we are close: Ms. Yang Yang (MSc) has been supported by this grant during its 3-year period, and she will defend her thesis in July 2012. Binod Pokharel (PhD), and Xia Chu (MSc), both supported by the follow-up NSF "ASCII" grant, are in their first year. A new PhD student is starting in summer 2012, to be funded by a follow-up grant from the UW Office of Water Programs. So while we have been slow graduating professional students supported by this grant, the prospect for graduate student participation and graduation is good.

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 in China. His research on this grant was essential to his success assuming a faculty position. Dr. Miao is now on his way to become a leading scientist on weather modification in China. He was back in summer 2010 and during the NSF-supported ASCII field campaign as a visiting research scientist, and he continuous to work with us from China, as is evident in the list of publications (Section 7).