Multi-frequency radar and precipitation probe analysis of the impact of glaciogenic cloud seeding on snow

Final Report
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UW Office of Water Programs
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Dr. Bart Geerts, PI
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1. Abstract

This proposal (referred to as Cloud Seeding III) called for the analysis of radar, aircraft, and ground-based datasets collected as part of the ASCII (AgI Seeding Cloud Impact Investigation) campaign over the Medicine Bow mountains and the Sierra Madre in Wyoming during the time of glaciogenic cloud seeding conducted as part of the multi-year Wyoming Weather Modification Pilot Project (WWMPP). The WWMPP is a randomized mountain-blind seeding experiment using a series of silver iodide (AgI) generators located in both mountain ranges.

Two previous UW Office of Water Programs grants (referred to as Cloud Seeding I and Cloud Seeding II) supported seven research flights over the Snowy Range. Analysis of these data led to a remarkable paper in the *J. Atmos. Sci.* (Geerts et al. 2010), which was important in the success of a proposal for the ASCII (AgI Seeding Cloud Impact Investigation) campaign, funded by the National Science Foundation [AGS-1058426: "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 2015]. The ASCII campaign was the first glaciogenic cloud seeding project sponsored by NSF in about 25 years. The two previous UW Office of Water Programs "seed" grants, the Geerts et al. (2010) paper, the NSF grant, and the ASCII campaign itself were all important in the 2012 National Institutes of Water Resources (NIWR) "IMPACT" Award to the PI (Dr. Geerts), a national recognition initiated by the UW Office of Water Programs.

The third UW Office of Water Programs grant (referred to as Cloud Seeding III) ran in parallel with ASCII. It complemented the NSF funds, especially allowing more graduate student participation. The mutual leveraging between federal and Office of Water Programs funds resulted in an accomplishment larger than the sum of the two grants. *The combined grants (which are truly inseparable) have enabled three MSc degrees and 2 PhD degrees, have led to the publication of no less than 18 peer-reviewed papers, and have supported numerous presentations at conferences and WWMPP meetings.*

2. Objectives and methodology

The key objective is to examine the impact of glaciogenic seeding of orographic clouds on cloud and precipitation. The methodology is described in Geerts et al. (2013) and Pokharel and Geerts (2014).

3. Summary of the field work and principal findings

Most of the 25 storms sampled in ASCII occurred in unblocked flow, were non-frontal and rather shallow, produced light natural snowfall (0.4-0.6 mm hr-1 on average), had rather cold cloud bases (-9°C on average), and had rather little SLW (<0.4 mm vertically integrated liquid in all cases). Several case studies emerged from ASCII. A study of a stratiform orographic cloud with few natural ice crystals (Pokharel et al. 2014a) revealed an increase in ice crystal concentration, according to disdrometer data in the target area, and an increase in low-level reflectivity, according to data from the ground-based and airborne radar systems, each with their own target and control regions. Of all studies ASCII cases, this case had the largest reflectivity increase in the target region, relative to the trend in the control region. This increase was ~4 dBZ for the DOW at low levels, corresponding to a near doubling of the precipitation rate.

Pokharel et al. (2014b) examined a case with small, shallow convective cells embedded in a larger weakly-precipitating, shallow stratiform snowfall emerging above a thin orographic stratiform cloud. Smaller but consistent increases in ice particle concentrations and near-surface reflectivity were observed, the latter mainly in the lee of the mountain in the target region. A consistent change in particle size distribution was observed at flight level, within the convective cells. . Pokharel et al. (2015a) examined the impact of seeding on an unusually "clean" shallow orographic cloud, confined between -5°C and 12°C, with large droplets (~35 μm) and few natural ice particles, most of them rimed. Small increases in reflectivity (1 dB) and ice particle concentrations (mainly of small particles) were observed in areas under cloud seeding compared to areas with no cloud seeding., without apparent change in the r Riming remained, which was the primary hydrometeor growth process during seeding. WCR reflectivity profiles suggest a strong seeding impact (at least in a relative sense), notwithstanding the very small liquid water path (<0.1 mm). This impact was confirmed by an LES model simulation with the Xue et al. (2013a,b) seeding parameterization (see next section).

Several ASCII-based composite studies have been conducted. Jing et al. (2015a) examined changes for six stratiform cases over the Sierra Madre, in terms of DOW polarization variables. They found evidence for increases in the concentration of unrimed dendritic ice crystals during seeding, and reflectivity which is consistent with the observed increase in differential reflectivity. Low-level reflectivity was higher on average and in all six individual cases, mainly at close range of the AgI generators, upwind of the mountain crest, which is about 18 km from the generators. Jing et al. (2015b) found that in three convective cases over the Sierra Madre, the seeding impact was more pronounced further downwind of the generators, i.e. in the lee, consistent with the convective case in Pokharel et al. (2014b).

Finally, a survey of all ASCII cases (Pokharel et al. 2015) shows that WCR, DOW, and snow gauge data all agree that, in most individual cases and on average, the precipitation rate was higher during seeding, at least in terms of a double difference (i.e., changes in the target region are compared to those in the control region) (**Fig. 1**). The average increase for all good cases (9-18 cases, depending on the instrument) ranges between 0.17-0.31 mm hr^{-1}, which is a significant fraction of the average natural precipitation rate. Pokharel et al. (2015) also examined the relationship between ambient and cloud conditions (such as cloud base and cloud top temperature, LWP, wind speed, and static stability) and affected seeding efficacy in ASCII reveals, but found no clear trends. This probably is due to a lack of cases and the noisiness of precipitation rate.

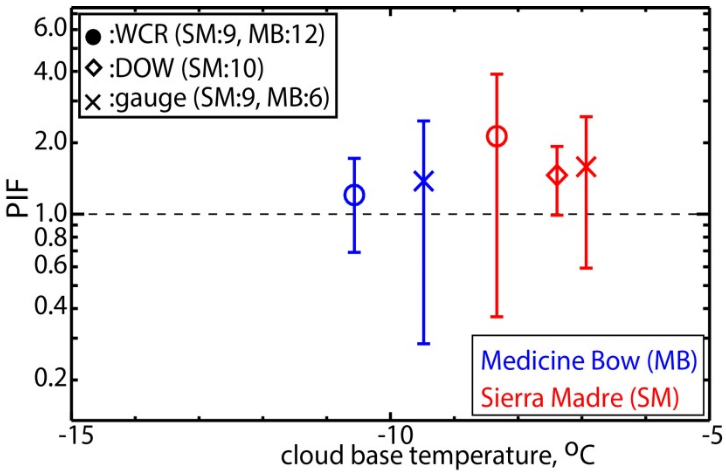

Fig. 1: Average change, ± one standard deviation, of precipitation rate during seeding, compared to an adjacent unseeded period, for all ASCII cases, based on three instruments. The precipitation impact factor (PIF) is a double ratio, defined as the seeded:unseeded ratio in the target area, compared to that in the control area. Here the PIF is plotted as a function of cloud base temperature. The number of cases for each instrument and each mountain range is shown between brackets.

All the ASCII case and composite studies highlight the challenge of signal detection within the highly variable, finely textured fields of cloud and precipitation particles. Not any single change reported in these studies can be attributed unambiguously to glaciogenic seeding. Signal detection remains the most significant challenge in observational weather modification research (see National Research Council 2003, Garstang et al. 2005).

4. Significance

Intellectual merit: A series of ASCII case studies (Pokharel et al. 2014a, b; Pokharel et al. 2015a, b; Chu et al. 2014) and composite observational studies (Geerts et al. 2013; Pokharel and Geerts 2014; Jing et al. 2015a; Jing and Geerts 2015; Pokharel et al. 2015b), mainly using the WCR and a DOW radar, consistently show an increase in radar reflectivity and (in most cases) in ice particle concentration at low levels downwind of AgI generators. Quantitative precipitation enhancement appears highly variable, remains difficult to measure, and is virtually impossible to predict based on environmental and cloud parameters alone. A separately funded collaborative effort, led by NCAR (Rasmussen, Xue et al.), reveals dramatic advances in the numerical modeling of artificial ice nucleation and cloud processes in mountain-scale large eddy simulations, which were tested in ASCII (Boe et al. 2014; Xue et al. 2014; Chu et al. 2014; Chu et al. 2015).

Broader Impact: Federal agencies including NSF extensively supported weather modification research in the 1960s-1980s. The ASCII campaign was the first glaciogenic cloud seeding project sponsored by NSF in about 25 years. The preponderance of evidence from an array of ASCII-supported publications (listed below) and separately funded collaborative modelling work supports the notion that glaciogenic seeding can significantly increase precipitation in shallow winter orographic clouds.

5. Peer-reviewed publications

The following 18 peer-reviewed papers were at least partly supported by this grant. As mentioned before, there is a significant overlap between this grant and the NSF ASCII grant, hence the statement "partly supported").

(1) An ASCII-12 overview paper can be found in Geerts et al. (2013).
(2) An ASCII-13 (plus pre-ASCII) overview paper can be found in Pokharel and Geerts (2014).
(3) Flight-level measurements of the impact of ground-based glaciogenic cloud seeding in plumes rising up to flight level are examined in Miao and Geerts (2013).
(4) Boe et al. (2014) and (5) Xue et al. (2014) examine the dispersion of AgI nuclei in the absence of clouds, using and acoustic ice nucleus counter and LES simulations respectively.
Binod Pokharel led three case study of the seeding impact on clouds and precipitation, i.e.,
(6) a shallow stratiform storm (21 Feb 2012 - Pokharel et al. 2014a),
(7) a shallow convective storm (13 Feb 2012- Pokharel et al. 2014b), and
(8) a stratiform cloud with large supercooled droplets (23 Feb 2012 – Pokharel et al. 2015a).
(9) a composite study of all ASCII cases, to examine how ambient and cloud conditions affect seeding efficacy in ASCII (Pokharel et al. 2015b).
A two-part paper in J. Appl. Meteor. Climat. explore numerical simulations of a stratified flow case under both seeded and natural conditions (18 Feb 2013):
(10) Chu et al. (2014) compare radar observations against WRF LES simulations; and
(11) Xue et al. (2015c) evaluate the microphysical changes due to seeding in model output.
(12) Geerts et al. (2015) examine snow growth, transport, and deposition patterns in both stratiform and convective orographic storms, using WCR profiling and dual-Doppler analyses for 15 storms over the Medicine Bow range.
(13) Jing et al. (2015) and (14) Jing and Geerts (2015) analyze the impact of seeding in stratiform and convective storms respectively, both over the Sierra Madre, and both using DOW reflectivity and dual-pol variables.
(15) Jing et al. (2015c) demonstrate a positive "downwind" (extra-area) effect, i.e. increased snowfall downwind of the target range.
(16) Chu et al. (2015) use WRF LES simulations to evaluate the seeding impact for a super-shallow layer cloud partially blocked by the terrain (13 Feb 2013).
(17) Geerts and Pokharel (2015) provide observational evidence for ice crystal generation by blowing snow in shallow orographic clouds.
(18) Rauber et al. (2015) survey historical progress in our understanding of the impact of glaciogenic seeding of orographic on precipitation, from the 1950s to ASCII.

Here are the full references:

Geerts, B. and co-authors, 2013: The AgI Seeding Cloud Impact Investigation (ASCII) campaign 2012: overview and preliminary results. *J. Wea. Mod.*, **45**, 24-43.

Miao, Q., and B. Geerts, 2013: Airborne measurements of the impact of ground-based glaciogenic cloud seeding on orographic precipitation. *Advances in Atmospheric Science*, **30**, 1025-1038. doi: 10.1007/s00376-012-2128-2. (link).

Boe, B., and co-authors, 2014: The dispersion of silver iodide particles from ground-based generators over complex terrain. Part I: Observations with acoustic ice nucleus counters. *J. Appl. Meteor. Climatol.*,**53**, 1325–1341.

Xue, L., X. Chu, R. Rasmussen, D. Breed, B. Boe, B. Geerts, 2014: The dispersion of silver iodide particles from ground-based. Part II: WRF Large-Eddy Simulations v.s. observations. *J. Appl. Meteor. Climatol.*, **53**, 940-958.

Pokharel, B., B. Geerts, and X. Jing, 2014a: The impact of ground-based glaciogenic seeding on orographic clouds and precipitation: a multi-sensor case study. *J. Appl. Meteor. Climat.*, **53**, 890-909. (21 Feb 2012 case study)

Pokharel, B., B. Geerts, X. Jing, K. Friedrich, J. Aikins, D. Breed, R. Rasmussen, and A. Huggins, 2014b: The impact of ground-based glaciogenic seeding on clouds and precipitation over mountains: a multi-sensor case study of shallow precipitating orographic cumuli. *Atmos. Res.*, **147**, 162-182. (13 Feb 2012 case study) http://dx.doi.org/10.1016/j.atmosres.2014.05.014

Pokharel, B., and B. Geerts, 2014: The impact of glaciogenic seeding on snowfall from shallow orographic clouds over the Medicine Bow Mountains in Wyoming. *J. Wea. Mod.* , **46**, 8-29. (link).

Chu, X., B. Geerts, L. Xue, and R. Rasmussen, 2014: Radar observations and WRF LES simulations of the impact of ground-based glaciogenic seeding effect on orographic clouds and precipitation: Part I: Observations and model validations. *J. Appl. Meteor. Climat.*, **53**, 2264-2286.

Geerts, B., Y. Yang, R. Rasmussen, S. Haimov, and B. Pokharel, 2015: Snow growth and transport patterns in orographic storms as estimated from airborne vertical-plane dual-Doppler radar data. *Mon. Wea. Rev.* , **143**, 644-665.

Jing, X., B. Geerts, K. Friedrich, and B. Pokharel, 2015: Dual-polarization radar data analysis of the impact of ground-based glaciogenic seeding on winter orographic clouds. Part I: mostly stratiform clouds *J. Appl. Meteor. Climat.*, accepted.

Pokharel, B., B. Geerts, and X. Jing, 2015a: The impact of ground-based glaciogenic seeding on clouds and precipitation over mountains: a case study of a shallow orographic cloud with large supercooled droplets. *J. Geophys. Res. Atmosphere*, accepted.

Jing, X., and B. Geerts, 2015: Dual-polarization radar data analysis of the impact of ground-based glaciogenic seeding on winter orographic clouds. Part II: convective clouds *J. Appl. Meteor. Climat.*, accepted.

Jing, X., B. Geerts, and B. Boe, 2015: The extra-area effect of orographic cloud seeding: observational evidence of precipitation enhancement downwind of the target mountain. *J. Appl. Meteor. Climat.*, in review.

Xue, L., X. Chu, R. Rasmussen, and D. Breed, and B. Geerts, 2015: A case study of radar observations and WRF LES simulations of the impact of ground-based glaciogenic seeding on orographic clouds and precipitation. Part II: AgI dispersion and seeding signals simulated by WRF. *J. Appl. Meteor. Climat.*, in review.

Pokharel, B., B. Geerts, X. Jing, K. Ikeda, and R. Rasmussen, 2015b: A multi-sensor study of the impact of ground-based glaciogenic seeding on clouds and precipitation over mountains in Wyoming in relation to ambient and cloud conditions. *J. Appl. Meteor. Climat.*, in preparation, submitted in early May.

Rauber, R. M., B. Geerts, L. Xue, J. French, K. Friedrich, R. Rasmussen, and S. Tessendorf, 2015: Wintertime orographic cloud seeding – a review. *J. Appl. Meteor. Climat.*, in preparation, submitted in early May.

Chu, X., B. Geerts, and L. Xue, 2015: A case study of radar observations and WRF LES simulations of the impact of ground-based glaciogenic seeding on a very shallow blocked orographic cloud. *J. Appl. Meteor. Climat.*, in preparation. (Presented at the AMS Annual meeting in Phoenix, Jan 2015)

Geerts, B. and B. Pokharel, 2015: Blowing snow as a natural glaciogenic cloud seeding mechanism. *Mon. Wea. Rev.*., in preparation (presented at the EGU meeting, Vienna, April 2015)

6. Presentations supported by the Grant

Dr. Geerts and his research group gave oral presentations at a series of meetings in all three years of the grant. These were partly funded by the NSF ASCII grant, partly by the UW Office of Water Programs grant.

a. Weather Modification Association meetings

2012: 44th Annual Meeting of the Weather Modification Association, in Las Vegas, 13-15 April 2012. Bart Geerts presented preliminary findings of the just-completed ASCII-12 campaign.

2013: 45th Annual Meeting of the Weather Modification Association, in San Antonio TX, 10-12 April 2013: Binod Pokharel presented an ASCII overview oral paper. Binod's trip was paid through an award he received (see below).

2014: 46th Annual Meeting of the Weather Modification Association, in Reno NV, 23-25 April 2014. Bart Geerts presented an ASCII overview oral paper, Binod Pokharel presented two posters (based on the papers Pokharel 2014a, and Pokharel et al. 2014b, listed above), and Xia Chu presented a poster based on Chu et al. (2014).

2015: 47th Annual Meeting of the Weather Modification Association, in Fargo ND, 22-24 April 2015. Bart Geerts presented the final ASCII overview (based on Pokharel et al. 2015b), Binod Pokharel presented a case study (3 March 2012), and Xia Chu presented a paper based on Chu et al. (2015).

b. AMS Planned and Inadvertent Weather Modification meetings, and other AMS meetings

- Bart Geerts gave a talk "The impact of AgI seeding on precipitation from orographic clouds: evidence from airborne profiling cloud radar data" at the 18th AMS Conference on Planned and Inadvertent Weather Modification, Seattle WA, 9-11 January 2011.
- A special session was devoted to ASCII at the American Meteorological Society 15th Conference on Mountain Meteorology in Steamboat Springs in Aug 2012 (**Fig. 2**) (http://ams.confex.com/ams/archives.cgi). Note that three oral presentations were given by graduate students funded by this grant and/or by the NSF ASCII grant, namely Binod Pokharel, Xia Chu, and Yang Yang.
- Xia Chu presented a poster "Validation of WRF and WRF LES Simulations of the Dispersal of Ground-generated AgI Nuclei" and Bart Geerts gave a talk "The ASCII 2012 campaign: overview and early results" at the 19th AMS Conference on Planned and Inadvertent Weather Modification, Austin, TX, 7-10 January 2013.
- Xia Chu presented a talk "case study of radar observations and WRF LES simulations of the impact of ground-based glaciogenic seeding on a very shallow blocked orographic cloud", Binod Pokharel gave a multi-sensor overview, and Bart Geerts gave a talk "The ASCII 2012 campaign: overview and lessons learned" at the 20th AMS Conference on Planned and Inadvertent Weather Modification, Phoenix AZ, 5-7 January 2015. We had two posters as well, one on DOW-based seeding impact assessment in ASCII (Xiaoqin Jing) and one on the 22 Feb 2012 case study (Binod Pokharel).
- Geerts was one of the panelists at a panel discussion on glaciogenic cloud seeding at the Phoenix AMS meeting. This discussion is summarized in a note in the *Bull. Amer. Meteor. Soc.* (Tessendorf et al., 2015)

3:45 PM-5:15 PM: Thursday, 23 August 2012

16 **Results from recent field campaigns: III**

Location: *Priest Creek C (The Steamboat Grand)*

Sponsor: ***15th Conference on Mountain Meteorology***

Papers:

3:45 PM 16.1 An overview of the ASCII 2012 (AgI Cloud Seeding Impact Investigation) campaign
Bart Geerts*, University of Wyoming, Laramie, WY; and K. Friedrich, T. Deshler, D. A. R. Kristovich, J. Wurman, L. D. Oolman, S. J. Haimov, Q. Miao, D. W. Breed, R. Rasmussen, and B. A. Boe*

4:00 PM 16.2 Effects of atmospheric conditions and cloud seeding on orographic snowfall characteristics during the Silver Iodide (AgI) Seeding of Clouds Impact Investigation (ASCII) experiment
Katja Friedrich*, University of Colorado at Boulder, Boulder, CO; and E. A. Kalina, B. Geerts, K. A. Kosiba, and J. M. Wurman*

4:15 PM 16.3 Using airborne vertical-plane dual-Doppler radar to analyze hydrometeor streamline patterns in orographic snow storms
Yang Yang*, University of Wyoming, Laramie, WY; and B. Geerts*

4:30 PM 16.4 Airborne Cloud Radar and Lidar Observations of Blowing Snow during the ASCII Project: a Possible Natural Cloud Seeding Mechanism
David A. R. Kristovich*, ISWS, Champaign, IL; and B. Geerts, Q. Miao, L. Stoecker, and J. M. Ritzman*

4:45 PM 16.5 Cold-season precipitation processes in shallow orographic clouds over a continental mountain range: impact of controlled ice nucleus injection
Binod Pokharel*, University of Wyoming, Laramie, WY; and B. Geerts, Q. Miao, and K. Friedrich*

5:00 PM 16.6 Comparison of model and airborne measurement of AgI plumes from ground-based generators
Lulin Xue, NCAR, Boulder, CO; and ***X. Chu*** *and B. Geerts*

Fig. 2: List of oral presentations in the ASCII session at the 15th Conference on Mountain Meteorology in Steamboat Springs CO.

c. Wyoming Weather Modification Pilot Project Technical Advisory Team meetings

Bart Geerts presented ASCII research update at the bi-annual WWMPP Technical Advisory Team meetings in 2012, 2013, and 2014 (usually in Pinedale in July, and in Cheyenne in January). Bart Geerts also presented at the November "ground schools" for the WWMPP.

d. Seminars

Bart Geerts gave the following invited seminars:

- 2013/5/6: Dept. of Atmospheric and Environmental Sci., University at Albany ("Glaciogenic seeding of orographic clouds revisited")
- 2013/6/4: invited talk at NCAR, Boulder CO: "ASCII overview, key findings, and lessons learned" (this was a planning meeting to prepare for a new, larger NSF proposal following up on ASCII)
- 2013/6/13: invited presentation at the National Institutes for Water Resources (NIWR) annual meeting, South Tahoe CA: "Impact of glaciogenic cloud seeding on mountain snowfall: an old question revisited."
- 2013/11/6: Cocorahs webinar on glaciogenic cloud seeding , total full-time attendees: 87 (available at http://youtu.be/Br8W0sf3bdM)

- 2014/4/16: Enhanced water recovery from clouds: is it possible? University of Wyoming Spring 2014 Faculty Senate Award Speech, in Laramie
- 2014/4/22: Enhanced water recovery from clouds: is it possible? University of Wyoming Spring 2014 Faculty Senate Award Speech, in Casper
- 2014/11/25: ASCII overview, results, and lessons learned: a presentation at the Denver office of the Bureau of Reclamation.

7. Media coverage

In Year 2 Geerts' research was covered in the Laramie Boomerang, the Casper Star Tribune, the Wyoming Business Chronicle, and the University of Wyoming News (http://www.uwyo.edu/uw/news/). The Associated Press had an article on 5/1/2014, and several news outlets carried the article, upon which Geerts was interviewed by ClimateWire in Washington, D.C. We were also part of the Weather Channel's "Hacking the Planet" series in early April 2013. The episode in which we are featured can be viewed at http://youtu.be/rVl_pjEOi9w (this is one of several episodes in the Hacking the Planet series). Note that this is an unlisted and unlinked video, i.e. it is *not* public – the only way to access it is through this link. The reason, of course, is copyright issues.

8. Dissertations/theses

Three MSc theses were partly or entirely funded by this grant:

- Ms. Yang Yang has been partly supported by the current and a previous UW Office of Water programs grant. She defended her thesis "Snow transport patterns in orographic storms as estimated from airborne vertical-plane dual-Doppler radar data" on 23 May 2013, and officially graduated in Fall 2013.
- Ms. Xia Chu defended her thesis "Cloud-resolving Large Eddy Simulations of the impact of AgI nuclei dispersed from the ground on orographic clouds and precipitation: model validation" on 6 June 2013, and officially graduated in Summer 2013.
- Ms. Xiaoqin Jing defended her thesis "Dual-polarization radar data analysis of the impact of ground-based glaciogenic seeding on winter orographic clouds" on 18 August 2014, and officially graduated in Summer 2014.

Two PhD dissertations were partly or entirely funded by this grant:

- Dr. Binod Pokharel (PhD) "A Multi-Sensor Study of the Impact of Ground-Based Glaciogenic Seeding on Orographic Clouds and Precipitation." (graduated in Dec 2014)
- Ms. Xia Chu (PhD) hopes to defend her dissertation by May 2016.

9. Awards

- Graduate student Binod Pokharel, who has been partly funded by this grant, received the 2012 North American Interstate Weather Modification Council Student Award. This is a $1000 fellowship plus all travel expenses to the WMA annual meeting, in 2013 in San Antonio TX, where Binod gave a presentation.

- Bart Geerts received the 2012 National Institutes of Water Resources (NIWR) "IMPACT" Award to the PI (Dr. Geerts), a national recognition initiated by the UW Office of Water Programs. He received the award at the NIWR meeting in Tahoe CA in June 2013.
- Graduate student Xia Chu received an NCAR Advanced Studies Program (ASP) doctoral fellowship (host: Lulin Xue), partially funded by the UW Office of Water Programs. She is spending the full year 2015 in Boulder CO.
- Bart Geerts received the Spring 2014 UW Faculty Senate Award. He gave presentations on weather modification at the UW campuses in Laramie and Casper WY, for which he received a $1000 honorarium.