Final Report

PRECIPITATION MEASUREMENT AND GROWTH MECHANISMS IN OROGRAPHIC WYOMING SNOWSTORMS

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Abstract

We review activities supported by our WWDC/USGS grant. The first is Jonathan Wolfe's assessment of data from the Cheyenne National Weather Service Radar, combined with surface measurement of snowrate, and his parameterization of a radar reflectivity / snowrate relationship. Wolfe's thesis was completed in 2007. The second is Binod Pokharel's study of airflow and cloud processes inferred using Wyoming King Air and Wyoming Cloud Radar measurements made in orographic clouds formed over the Medicine Bow Mountains. Pokharel's thesis was completed in 2009. The third is Bujidmaa Borkhuu's study of snowfall measurement made at the Glacier Lakes Environmental Experimental Site during the winters of 2007 and 2008. This work entails a comparison of snow accumulations made at one of the sites being used to evaluate the efficacy of the Wyoming Weather Modification Pilot Project. Borkhuu's thesis defense is planned for July 2009. Each of the theses presents significant findings; all three are being advanced to the level necessary for submission to a peer-review journal.

Proposal Objectives –

1) Contrast precipitation development in storms moving in from the west against those coming from the Great Plains.

With funding from WWDC, USGS and NASA seven University of Wyoming King Air flights were conducted in snowstorms with low-level westerly flow over the mountain ranges west of Laramie, and one flight in an "upslope" snowstorm over the Laramie Range, in which the low-level flow had an easterly component. The flight operations were conducted in January and February 2006. Profiles of Wyoming Cloud Radar reflectivity and Doppler velocity were collected on all flights. Storms of both types (low-level westerly and easterly flow) reveal strong turbulence in the lowest 500-1000 m above the ground along the slopes upwind of the crest. This boundary-layer turbulence is important in orographic precipitation generation; we are preparing a manuscript which reports that finding. In the one "upslope" storm we sampled, there was considerable wind shear in the layer between 1-2 km above ground level (AGL). This shear produced far less turbulence than inferred from analysis of the Doppler radar data acquired at lower altitude, suggesting that turbulence associated with snow generation occurred relatively close to the ground. Also with support from WWDC, USGS and NASA J.Wolfe collected Hotplate snowrate data on the ground, in both low-level westerly flow regimes, at the Glacier Lakes Environmental Experiment Site (GLEES) in the Medicine Bow Mountains, and in low-level easterly storms at a site east of the Laramie Range crest, near Cheyenne. A fair comparison of snowrate characteristics of the two storm types was not possible because of inaccurate measurements at the GLEES. The thesis work of J.Wolfe and B.Borkhuu address this inaccuracy, and is discussed below.

2) Acquire data by conducting flight transects across the Laramie Range and the Medicine Bow Mountains and to study how cloud depth, horizontal and vertical wind speed, thermal stability and properties of the aerosol ingested by winter orographic storms influence snow formation.

In the four WWDC/USGS/NASA cases analyzed by B.Pokharel in his thesis, a diverse combination of cloud depth and thermal stability was documented. This diversity, and the limited number of cases (B.Pokharel only analyzed cases which had aerosol measurements made up and downwind of the Medicine Bow Mountains), prohibits a climatological assessment. Consistency does emerge from Pokharel's analysis of the horizontal and vertical wind fields derived from the Doppler-capability of the Wyoming Cloud Radar. Specifically, Pokharel documents low-level vertical shear of the horizontal wind and localized regions of ascending air in association with ridges that run perpendicular to the prevailing (westerly) wind direction. Pokharel concludes that assessments of airflow through orographic clouds, based on conventional measurements of the wind magnitude and wind direction, can only provide rough estimates of time available for precipitation particle growth. In contrast, the two-dimensional wind field available form the Wyoming Cloud Radar was promoted as a better product for evaluating precipitation processes in orographic clouds and for developing understanding of the efficacy of cloud seeding. In spite of this new application for the Wyoming Cloud Radar, it has its own limitations. Details are discussed in the thesis of B.Pokharel and in a manuscript we are preparing for journal submission.

3) Refine the Z_e-to-S parameterization applied to Weather Surveillance Radar measurements of Z_e acquired in shallow winter upslope snow storms.

This aspect of the study was conducted by J.Wolfe. His analysis reveals that the reflectivity-to-snowrate (Z_e-to-S) parameterization is temperature dependent, in a manner consistent with the combined action of ice nucleation and snowflake aggregation on snowflake concentration. Data was collected over the temperature range -20 ^oC to 0 ^oC. Wolfe's temperature-dependent Z_e-to-S parameterization was found to produce snowrates that agreed well with those derived using the parameterization of Super and Holroyd (1998). This finding is significant because it indicates consistency among the data set utilized in the Wolfe thesis and by Super and Holroyd (1998). The result also points to a physical limitation in the use of radar measurements of reflectivity, or radar reflectivity combined with temperature, for making snowrate estimates. These limitations are discussed in more detail below. The significant advantage of radar-derived snowrates, versus those made with precipitation gauges, is that the radar-derived values are available for a broad area, extending out to as far as 100 km from the radar.

4) Intercompare snowrate measurements from two Hotplates to infer Hotplate measurement uncertainties.

In our Year-1 report we presented our decision to not collaborate with NCAR in this proposed intercomparison. Rather, we elected to calibrate our Hotplate sensor versus an accurate lab-based precipitation reference standard. In addition, the response of our Hotplate sensor to ventilation was also evaluated in the laboratory. Both of these effects were incorporated into the Wyoming Hotplate algorithm developed by thesis candidate B.Borkhuu. We elected this path after consultation with Dr. Roy Rasmussen, co-inventor of the Hotplate, and after obtaining legal permission to access the proprietary data necessary for developing the Wyoming Hotplate algorithm.

5) Evaluate consistency among Hotplate and Snotel snow accumulation measurements.

These results are in the B.Borkhuu thesis. She concludes that the Snotel measurements (made at the Brooklyn Lake NRCS site) are positively biased due to registration of wind-resuspended ice particles. As is discussed below, this positive bias may be as large as a factor of two.

6) Quantify orographic precipitation enhancement, in the Medicine Bow Mountains, over time intervals shorter than that measurable by Snotel.

It is our opinion that bias associated with snowrate measurement is profound and underappreciated, and that these complexities limit our ability to interpret snowrate measurements made at the GLEES. Having said this, we also recognize that a range of time response is available in the set of sensors operated at the GLEES (weekly to minute) and that there is merit to doing an examination of measurements from the fast-response snowrate sensors, especially after making an attempt to correct for snowrate bias. This analysis may be especially informative during study days that were modulated by cloud seeding. We have not attempted such an analysis, but will make the data available if a request is made.

Jon Wolfe Vitae –
Master of Science, Dept. of Atmospheric Science, University of Wyoming, May, 2007
Current Employment: National Weather Service, Portland, OR

Wolfe Manuscript Title and Abstract –

A Temperature Dependent Reflectivity/Snowrate Relationship for S-Band Radar

Jonathan P. Wolfe, Jefferson R. Snider and Bart Geerts

Weather radar offers a practical way of estimating snowfall rate with high spatial and temporal resolution. Such remotely-sensed snowrates are useful for weather advisory and hydrometeorology. In either application a relationship between equivalent radar reflectivity (Z_e) and water equivalent snowrate (S) is needed. In the Rayleigh scattering regime (radar wavelength much larger than snowflake diameter), the leading coefficient in the relationship $Z_e = \alpha \cdot S^{\beta}$ can be shown to vary with temperature-dependent properties of the snowflake size distribution. We describe measurements, and a statistical analysis, leading to a temperature dependence for α which can be applied to wintertime upslope storms occurring in southeastern Wyoming. This documented temperature-dependence for α is suggestive of the combined action primary ice nucleation and snowflake aggregation.

Wolfe Manuscript: Exemplary and Significant Findings -

24 hr Snow Water Equivalent Accumulation Comparisons

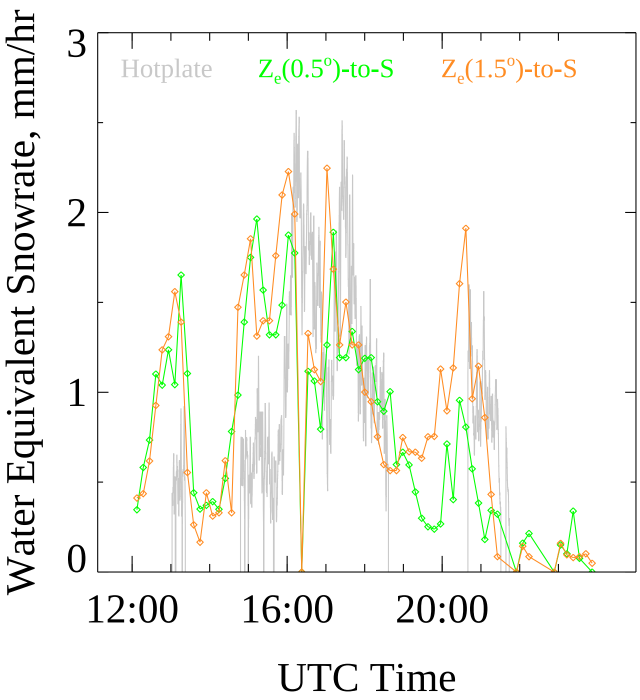
Start Time UTC [a]	Start Date	NWS Gauge [b] mm	Radar-derived [c] mm	Radar-derived (Super and Holroyd, 1998) [d] mm
07:00:00	Feb. 15, 2006	8.6	11.9	10.1
07:00:00	Mar. 8, 2006	7.9	11.1	9.3
07:00:00	Mar. 10, 2006	2.5	7.2	6.5
07:00:00	Mar. 11, 2006	5.8	>7.4	>5.5
07:00:00	Mar. 18, 2006	8.1	3.5	3.1
07:00:00	Mar. 19, 2006	13.7	8.3	6.6
07:00:00	Mar. 20, 2006	2.5	2.5	2.3

[a] Coordinated Universal Time

[b] Data from the precipitation gauge operated at the Cheyenne, WY National Weather Service Office

[c] Based on the temperature-dependent Z_e-to-S parameterization derived in Jon Wolfe's thesis

[d] Based on the parameterization derived by Super and Holroyd (1998)



Values of the Hotplate and radar-derived snowrate on March 8, 2006. For the radar-derived snowrates a radar reflectivity acquired at tilt angles 0.5° and 1.5° and the parameterization developed in Jon Wolfe's thesis were used. Radar reflectivities were acquired along the 299° radial connecting the Cheyenne National Weather Service Radar and the surface site where the Hotplate was located (25 km northwest of Cheyenne). The time lag apparent at ~15:00 and at ~17:00 UTC with maximum snowrate observed at 1.5°, next at 0.5° and finally at the Hotplate is attributed to the time it takes for snowflakes (fall speed ~ 1 m/s) to fall the 800 meter distance from the top of the 1.5° radar volume to the Hotplate. The plot also demonstrates that the radar is a more sensitive detector of snow, for example at ~14:00 UTC where the Hotplate reports no snowrate. It is also possible that this discrepancy is due to negative bias in the Hotplate's assessment of snowrate. This figure is from a manuscript in preparation for journal submission

Binod Pokharel Vitae –
Master of Science, Dept. of Atmospheric Science, University of Wyoming, May, 2009
Current Employment: Dept. of Atmospheric Science, Research Scientist, University of Wyoming

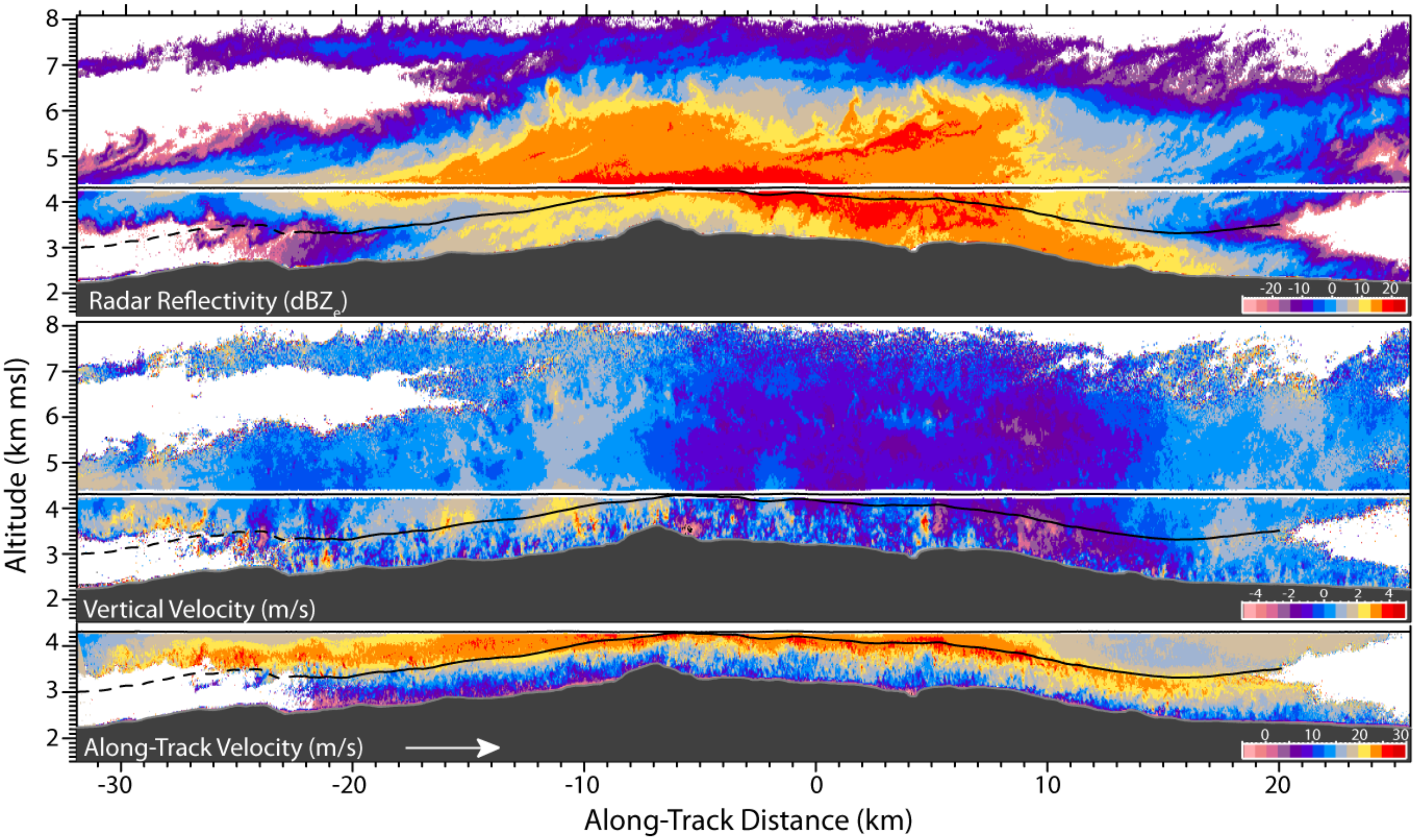
Pokharel Thesis Title and Abstract –
The Removal of Ultrafine Nuclei in Mountain Wave Clouds

The smallest detectable atmospheric aerosol particles - ultrafine nuclei (UFN) with diameter between 0.003 and 0.015 µm - were studied in association with mountain wave clouds formed over the Medicine Bow Mountains located in southeastern Wyoming. Aircraft measurements of the UFN were made upwind and downwind of the cloud and used to estimate the in-cloud removal of those particles. Also, an airborne Doppler cloud radar was used to measure the horizontal and vertical components of the wind. The study was conducted on four days: January 18, 2006, January 26, 2006, January 31, 2006 and February 2, 2006.

In model simulations, an air parcel trajectory obtained from the radar wind field and a cloud parcel model were used to simulate UFN removal in the cloud. The trajectory/parcel model was initialized with the measurements made upwind of the cloud and was validated with cloud property measurements made near the top of the trajectory and with measured values of the UFN removal.

The model simulates the time-dependent size distributions of cloud condensation nuclei, cloud droplets, and ice particles. Based on the model, and its comparison to the observations, four conclusions are reached: 1) Approximately 50% of the UFN entering the cloud are removed during in-cloud transport, 2) the UFN are too small to initiate cloud droplet formation, 3) the removal of the UFN is dominated by their Brownian attachment to cloud droplets, and 4) the Brownian attachment of the UFN to ice particles contributes less than 10% to their removal.

Pokharel Thesis: Exemplary and Significant Findings -



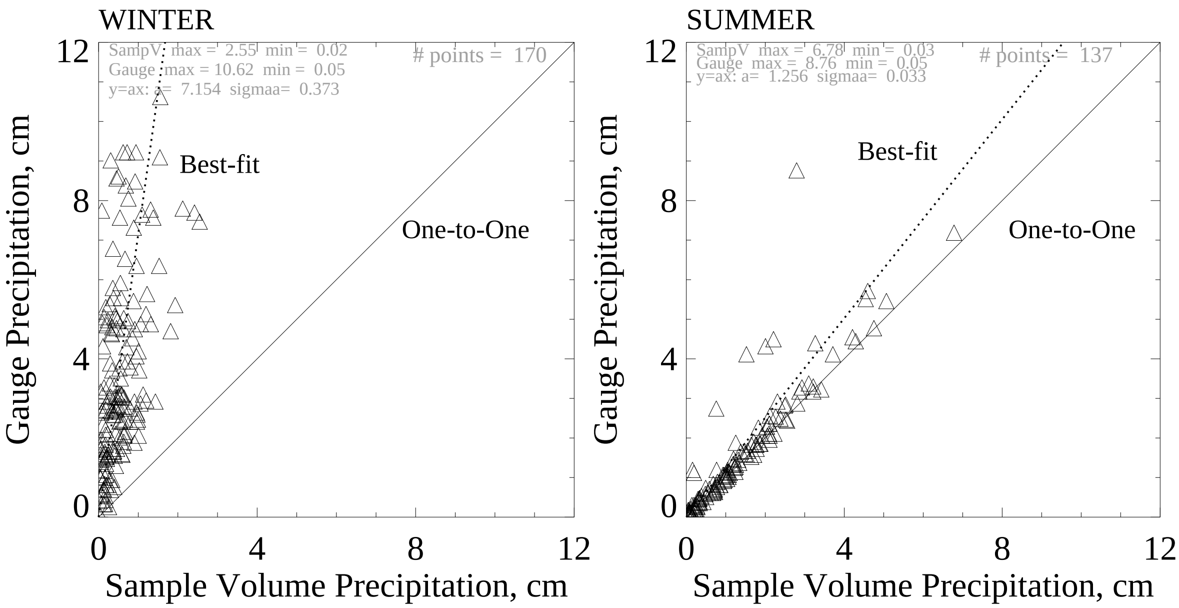
Wyoming Cloud Radar measurements made on 20060118 over the Medicine Bow Mountains. Top panel is the field of radar reflectivity (expressed as decibels, $dBZe = 10log_{10}Z_e$), the middle panel is the field of vertical-component Doppler velocity, and the bottom panel is the field of horizontal-component Doppler velocity (only available below the aircraft). Values presented in the middle panel were increased by 1.4 m s^{-1} to account the contribution of the particle fall speed to the vertical-component Doppler velocity. The top and middle panels show the flight track of the King Air at 4300 m, and all the three panels show the derived air parcel trajectory. The air parcel trajectory for this case, and trajectories derived for three other study days, were the basis for B.Pokharel's calculation of conditions experienced by an air parcel moving through the orographic cloud. The trajectory/parcel model is the basis for B.Pokharel's assessment of ultrafine aerosol particle scavenging due to their Brownian attachment to cloud droplets and ice crystals.

Bujidmaa Borkhuu Vitae –
Master of Science, Dept. of Atmospheric Science, University of Wyoming, August, 2009

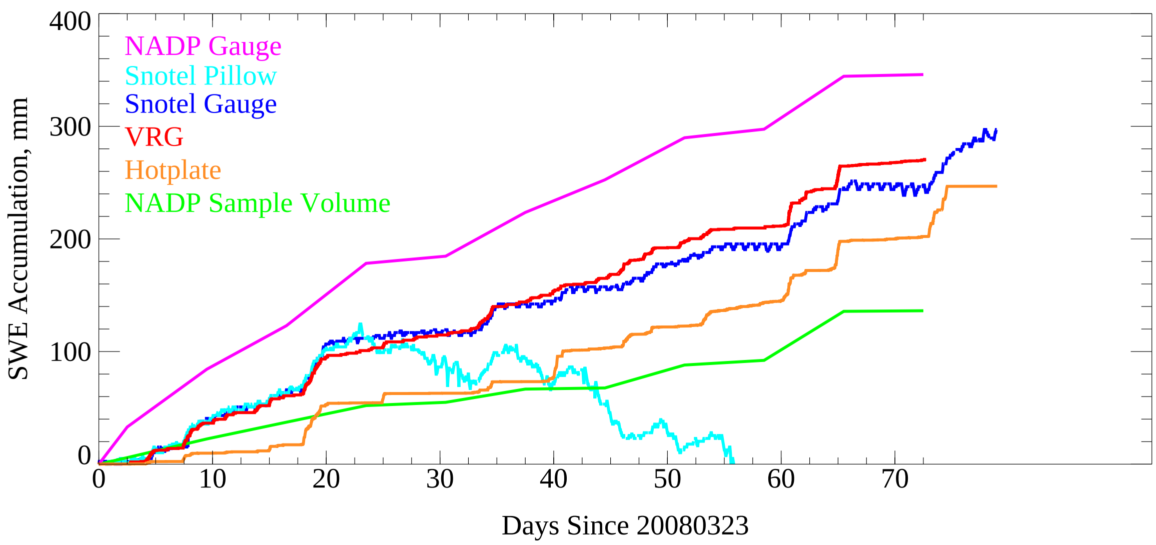
Borkhuu Thesis Abstract –
Snowfall at a High-elevation Site: A Comparison of Six Measurement Techniques

Diminishing annual snowpack in Rocky Mountain region is causing concern for water resource management and motivating improved techniques for wintertime (snow) precipitation measurement. At many high elevation sites in the Rocky Mountains the measurement of snow precipitation is confounded by wind. For example, at forested gauge sites both negative and positive wind-bias can occur, 1) due to the shadowing of a precipitation gage by trees (negative bias) and 2) due to the capture of wind-resuspended ice particles (positive bias). This work presents an analysis of data from six precipitation measurement systems operated near the forested Glacier Lakes Environmental Experiment Site (GLEES) located in the Medicine Bow Mountains of southeastern Wyoming. There are two objectives of the research: 1) to analyze the data sets for evidence of bias and 2) to recommend which of the systems is least affected by bias. The study demonstrates that gauge precipitation measurements made by the National Atmospheric Deposition Program at the GLEES are positively biased. The degree of this bias is a factor of two. Further, snowfall measurements made with the Yankee Environmental Systems Hotplate, and a comparison of that data to measurements made with three other measurement systems, show that all of the three (SNOTEL pillow, SNOTEL gauge and Vaisala VRG gauge) are biased positive relative to the Hotplate. Because the Hotplate measurement was made on a 30 meter tower, above the gauges, and also above the top of the forest canopy, this result indicates that a significant component of the accumulation recorded by surface gauges may be attributable to the inadvertent measurement of wind-resuspended ice particles.

Borkhuu Thesis: Exemplary and Significant Findings –



Comparison of weekly precipitation from the two sensors (gauge and sample volume) operated at the GLEES site by the National Atmospheric Deposition Program (NADP). Precipitation amounts less than 0.1 mm/week are eliminated from the analysis. Left panel is a comparison for winter months (December, January and February) and the right panel is the comparison for summer months (June, July and August). The poor agreement during winter is attributed to registration of wind-resuspended ice crystals by the NADP gauge.



Accumulation from the six sensors at the GLEES starting on 23 March 2008. The decrease of Snotel pillow accumulation at day 21 is because of snowpack melting - daily-averaged temperature in excess of 0 ^{o}C. Prior to day 21 the daily-averaged temperature was significantly smaller (~ -10 ^{o}C) and registration of wind-resuspended ice crystals by gauges other than the Hotplate is thought to explain the discrepancy in accumulation. The Hotplate was operated on a 30 m tower, 5 m above the tree tops and 30 m above the VRG gauge.

Published Conference Presentations –

B.Pokharel, J.R.Snider and D.Leon, Freshly-formed Aerosol Particles: Connections to Precipitation, In *Nucleation and Atmospheric Aerosols, 17th International Conference, Galway, Ireland*, 2007, Edited by C.D.Odowd and P.E.Wagner, pp.484-488, Springer

Conference Presentations with Abstracts –

Pokharel, B., J.R.Snider and T.Deshler, The removal of ultrafine nuclei in mountain wave clouds, Weather Modification Association Annual Meeting, Anaheim, CA, April, 2009

Borkhuu, B., J.R.Snider and T.Deshler, Snowfall at a high-elevation site: A comparison of six measurement techniques, Weather Modification Association Annual Meeting, Anaheim, CA, April, 2009

Geerts, B., J.R.Snider, G.Vali, and D.Leon, Orographic precipitation enhancement by boundary-layer turbulence: a vertically pointing airborne cloud radar view, 13th Conference on Mountain Meteorology, Whistler, British Columbia, 2008

Wolfe, J.P., J.R.Snider and B.Geerts, Development of a temperature-dependent radar reflectivity to snowrate relationship for the S-band, 15th International Conference on Clouds and Precipitation, Cancun, Mexico, 2008

Pokharel, B., J.R.Snider and D.Leon, Trajectories and microphysics within wintertime mountain wave clouds: Implications for the aerosol size distribution, 15th International Conference on Clouds and Precipitation, Cancun, Mexico, 2008

Geerts, B. and G. Vali, Impact of surface interaction and cloud seeding on orographic snowfall: A downlooking airborne cloud radar view. Oral presentation at the 17th AMS/WMA Symposium on Planned & Inadvertent Weather Modification, Westminster, CO, 2008

Geerts, B., Detailed vertical structure of orographic precipitation development in cold clouds. Oral presentation at the 16th Conf. on Mountain Meteorology, American Meteorological Society, Santa Fe, NM, August 2006

Wolfe, J., and J. Snider, Validation of radar-estimated upslope snowfall in Southeastern Wyoming, 32nd Conference on Radar Meteorology, Albuquerque, NM, October 2005

Presentations without Abstract –

Wolfe, J., Radar-estimated Upslope Snowfall Rates in Southeastern Wyoming, MS Thesis defense, 15 February 2007

Snider, J.R., Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms, Wyoming Weather Modification Technical Advisory Board, January 18, 2007

Snider, J.R. (for B.Geerts), Detecting the Signature of Cloud Seeding with the Wyoming Cloud Radar, Wyoming Weather Modification Technical Advisory Board, January 18, 2007

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, September 6, 2006

Snider, J.R., Aerosol scavenging in winter orographic clouds, presented at the Wyoming-NCAR RAL workshop in Boulder, CO, September 6, 2006

Wolfe, J., Temperature dependence of the Z-S relationship for upslope snowfall, presented at the Wyoming-NCAR RAL workshop in Boulder, CO, September 6, 2006

Students Supported by the Grant -

Wolfe, J.P., Radar-estimated Upslope Snowfall Rates in Southeastern Wyoming, MS thesis, Dept. of Atmospheric Science, University of Wyoming, 2007

Pokharel, B., The removal of ultrafine nuclei in mountain wave clouds, MS thesis, Dept. of Atmospheric Science, University of Wyoming, 2009

Borkhuu, B., Snowfall at a high-elevation site: A comparison of six measurement techniques, MS thesis, Dept. of Atmospheric Science, University of Wyoming, 2009

Casey, G., A comparison of observed vs. predicted snowfall amounts over the mountains of Southeastern Wyoming in Jan-Feb 2006. An undergraduate research term paper, Dept. of Atmospheric Science, University of Wyoming, 2006

Funding that was Complimentary to this WWDC/USGS Grant –
Grants from NASA and DEPSECoR were used to support two students (Wolfe and Pokharel) who are conducted analyses of the WWDC/USGS data set as part of their MS thesis research.

References –

Super, A. B., and E. W. Holroyd, Snow accumulation algorithm for the WSR-88D radar: Final Report. Bureau of Reclamation Report R-98-05, 1998