ERRORS IN THE WSR-88D ZS (SNOW) ALGORITHM

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ABSTRACT

The WSR-88D's ZS (snow) Algorithm gives current estimates of snow accumulations. However, underestimations from the radar beam overshooting the dendrite production zones and riming zones can occur. Overestimations can occur from bright banding and sub-beam evaporation/sublimation. This study seeks out a method for forecasting when and where these errors might occur and tests its accuracy.

Ground observations used as ground truths and corresponding radar data was collected for three snow events: Wisconsin for March 1-3, 2007, Pennsylvania for March 16-17, 2007, and Colorado for January 29-31, 2005. Comparing the ground truths to the radar's snow water equivalent (SWE) rate showed the ZS algorithm is inaccurate in its SWE estimates. A method for forecasting the sources of the previously mentioned errors was devised, but after analysis, it too was considered inaccurate. Regressions were then run on the data to see what factors would lead to better predictors of SWE rates. Out of all the data tested, it is believed that basing SWE rates off the distance between the bottom of the radar beam and the -3°C and -12°C layers. If better predictors could be found, improvements can be made to the ZS snow algorithm.

INTRODUCTION

Snowfall rates can affect the open/closing of schools and business, the spending of tax money on salt trucks, and can seriously affect travel conditions for both roads and airports. Many organizations make emergency decisions based on Snow Water Equivalent rates (SWE). For example, the decision on whether or not a plane can take off is based on SWE rates (Rasmussen et al. 2002). There is a lack of accurate observations of SWE rates available for use. There are numerous observation stations that record SWE rates, but many of them have difficulties reporting accurate data. Even if we had accurate ground station data, we still do not have adequate resolution to capture small-scale variations in SWE rates. The WSR-88D network can help to provide estimates of SWE rates through the application of the ZS (snow) algorithm with adequate spatial and temporal resolution (Super 1998). The ZS (snow) algorithm is currently in use for providing current SWE rates. According to Vasiloff 2001, studies have shown the algorithm's outputs can contain significant errors. If these errors can be anticipated, it could lead to more accurate snowfall rate forecasts. With that information, people could make better decisions when handling severe winter weather.

The goal of this project is to evaluate the performance of the snow algorithm and devise a method to anticipate its errors. First, some background information will be given about the WSR-88D's ZS (snow) algorithm. Reasons for error in the snow algorithm will be identified and discussed. Then a method for forecasting these errors will be described and analyzed. If a proper method cannot be found, further analysis of the algorithm's performance will be assessed. If errors in the snow algorithm can be anticipated from a forecaster's point of view, there can be better forecasts out there. Hopefully, those forecasts will lead to better decisions regarding winter weather.

2. BACKGROUND

Currently, the WSR-88D uses the ZS (snow) algorithm for nowcasting SWE rates. The algorithm is an equation in the form of $Z=aS^b$. Z is reflectivity ($mm^6\ m^{-3}$) and S is the liquid water (mm h^{-1}) equivalent (Super 1998). The "b" coefficient is 2, and the "a" coefficient depends on the region of the nation. There are eight different regions with adapted snow algorithms: Sierra Nevada: $Z=222S^2$, Intermountain West: $Z=40S^2$, High Plains: $Z=130S^2$, both the North Plains and Upper Midwest: $Z=180S^2$, Great Lakes: $Z=180S^2$, and Northeast: $Z=120S^2$. The Southeast region of the US uses the same equation as the Northeast because it did not receive enough snow cases in the Super 1998 study to develop its own reliable one. Beam blockage, ground clutter, and other spurious echoes are accounted for before snow accumulations are calculated. The algorithm includes SWE and snow depth for hourly, event total, and user selectable time periods. Each region contains its own static range correction factor to account for increasing distance away from the radar (Super 1998).

3. METHODOLOGY

Even though the snow algorithm was deemed accurate enough for use, errors do occur. Underestimates are hypothesized to occur when the radar beam overshoots the dendrite production zone and riming/needle production zones. Overestimates are hypothesized to occur from both bright banding and sub-beam sublimation and/or evaporation (Vasiloff, 2001). Horizontal advection of falling snow and snowflake shape also affect the ZS algorithm's accuracy but for this study, they will not be discussed. There is no operational ground truth that measures snowflake shape and/or size. Horizontal drift of falling snow provided minimal improvements to the accuracy of the ZS algorithm when it was constructed (Super 1998).

3.1 Underestimates Due to Beam Overshooting

The radar can produce underestimates when the radar beam overshoots the dendrite production zone. This region is a major producer of snow and exists approximately from -12° C to -18° C (Byers 1965). If the radar beam is above this region, it cannot accurately detect the snow falling below it. The moment that any part of the beam penetrates into the precipitation production zone, the beam is not completely sampling all of the precipitation. Therefore, we need to know the heights of the radar beam top, center, and bottom. If there is also saturated ascent at warmer temperatures, precipitation production can be significant due to other processes such as riming and needle production. Therefore we measure where the beam top, center, and bottom crosses the -3°C layer. For all cold precipitation to be sampled the beam must be completely below these production layers (LaDue 2007).

To forecast for underestimation due to beam overshooting, the heights of the radar beam top, center, and bottom were compared to the heights of the -3° and -12°C layers. If it appeared that any part of the beam overshot the -12° layer, the forecast was given a "yes" forecast. There was some subjectivity to this method. For example, say only the top of the radar beam overshot the -12° layer, but the entire beam overshot the -3° layer, then that case would receive a "yes" forecast. If the beam was below the –12º layer, but the top and bottom of the beam overshot the -3º layer the case would receive a "no" forecast.

3.2 Overestimation Due to Sub-beam Evaporation/Sublimation

The radar can produce overestimates of snowfall rates if evaporation and sublimation occur below the radar beam. Chances of this increase with dry air below 700mb (Vasiloff 2001). Snow detected by the radar may sublimate before it can be measured at the surface. Overestimation due to evaporation/sublimation is more common on down slope regions from the radar and increased distance from the radar. A January, 1999 case from Vasiloff's 2001 had gauge readings 0.11 inches below what the radar predicted for a site in the Wasatch Mountains. This site also had relative humidities between 50 and 80 percent (Vasiloff 2001a).

Forecasting for radar overestimation due to sub-beam evaporation/sublimation was the most difficult. The forecast for each case was mostly dependent on the sounding each particular case. If a dry layer (relative humidities close to 90 percent of less) was observed below 700mb, the case was given a "yes" forecast. If not, it was given a "no" forecast. Note that the forecasts for sublimation are fairly subjective.

3.3 Overestimation Due to Bright Banding

Bright banding can also lead to overestimates in the radar's results. It occurs at just below freezing to just above freezing temperatures. When the snowflakes reach these temperatures, the outer edges begin to melt. Water has a higher reflectivity factor than snow. In turn, the radar detects a greater amount than is actually there because it detects large raindrops instead of the actual snowflakes (Rinehart 1997).

When forecasting if bright banding would occur, one looked at the heights of the -1° layers and the heights of the radar beam sections. If the radar beam went through that temperature layer, that event was given a forecast of “yes”. If it overshot the layer, it was given a “no” forecast.

3.4 Data

The ground observation sites used in this study came from several organizations. SNOTEL (SNOwpack TELemetry) measures snow pack in the western mountain region of the US (NRCS 2007). CoCoRaHS (Community Collaborative Rain Hail and Snow network) measures precipitation and maps it (Colorado Climate Center 2007). All of the ground data came from Real-time Observation Monitor and Analysis Network (ROMAN) site. ROMAN contains data from different station types (RAWS, NWS/FAA, APRS/CWOP, and SNOTEL) and records current weather conditions usually used for reporting fire conditions. RAWS stations use a heated tipping bucket to measure precipitation (Zachariassen). This is the site where the hourly snowfall rates were gathered for ground observations. Plymouth State Websites and Southern Region Headquarters Precipitation Analysis site were used to determine large-scale snow events for certain time periods (Plymouth State 2007; NWS 2007).

Corresponding level II radar data were used in comparison with the data gained from the observation sites. It was obtained from the National Climatic Data Center (NCDC 2007). In order for the radar data to match the ground observations in location, the raw radar data came from KARX, KGRB, KCCX, and KPUX. After being run through the Radar Product Generator (RPG) and displayed on the Advanced Weather Interactive Processing System (AWIPS) program. The beam center height, the ground observation’s distance from the radar, and the radar’s one hour SWE were obtained. From that information, we could find the beam top, bottom, and beam width using a beam characteristics calculator (WDTB 2007).

The Eta Data Assimilation System (EDAS) soundings were obtained from the Air Resources Laboratory. It provides temperature, winds, surface pressure, specific humidity, and turbulent kinetic energy in non real time. The model begins twelve hours before the forecast starting time and assimilates data for every three hours (Black 1994). From the soundings, the heights of the +3, -1, -3, -12, and -18 degree temperature layers were gained (READY 2007).

This data was collected for three snow events: Wisconsin March 1-3, 2007, Pennsylvania March 16-17, 2007, and Colorado January 29-31, 2005. Each event contained several ground observations with corresponding radar data. Within each observation site were numerous three-hour accumulation observation cases.

3.5 Case Selection

Snow events had to meet certain criteria to be considered useable. The snow event had to be wide spread. This would ensure a large amount of ground observations near several radars in the area. The events also had to be low wind events. High wind events can decrease the efficiency of gauge catch, which can lead to incorrect snow gauge readings in the ground observations. According to Vasiloff 2001, the gauge can catch 20% less than actually falls with wind speeds of $4ms^{-1}$ (Vasiloff 2001b). Snow events for this study were to have winds near or less than $4.47\ ms^{-1}$ (ten mph).

We used CoCoRaHS (Community Collaborative Rain Hail and Snow network) sites to find significant snow events. These events were then researched on the RAWS website for ground observations with hourly snowfall rates. The Plymouth State Websites and Southern Region Headquarters were used to verify that the events were widespread snow events with low wind speeds. Table 1 shows case studies that met the criteria for this study.

After ground observations were found, hourly SWE rates were converted into three hourly SWE rates. This ensured us with higher SWE accumulations while still preserving the goal of verifying rates. Three hourly rates also matched better with the EDAS soundings.

4. RESULTS

The Wisconsin, Pennsylvania, and Colorado snow events examined yielded 115 individual three hourly accumulation cases. This section will discuss several topics and results from analyzing these cases. We will determine if there is a correlation between the ZS algorithms SWE rates and the ground truths. We will discuss the accuracy of this study’s method for predicting radar overestimation and underestimation. Finally, we will examine if there are any other predictors that can lead to better snow algorithm SWE rates.

Overall, cases in Wisconsin showed that the storm was a light snow event with light winds. Surface temperatures hovered from just below to just above freezing. The dew points were mostly close to the actual surface temperatures. The Pennsylvania event was another light snow event with light winds. The air was just under saturation with surface temperatures, around or below freezing. The Colorado event feature light winds too, but this case was a much larger snow event than the other two. The air was slightly sub saturated and the temperatures were well below freezing.

Figure 1 shows the radar's estimated SWE rates for each snow case compared to what

Figures 2, 3, and 4 show trend between the distance between the bottom of the radar beam and the –12ºC, -3ºC, and –1ºC layers. In figure 2 a weak negative linear trend is noticed. It implies that the further the radar beam bottom is below the -12ºC layer, the larger the overestimation in the radar's SWE rates. Although, this may not be the only contribution to the graph's trend. Notice that the cases from the Colorado observation sites generally lie vertically in the same area on the graph. This may indicate that something about the conditions of this event other than the distance between the beam bottom

Two-by-two contingency tables were created for underestimation due to beam overshooting, overestimation to due sub-beam evaporation/sublimation, overestimation due to bright banding, and general forecast of overestimation. The same two-by-two contingency tables were made again, but this time they were done only for cases with forecasts in which we had confidence. This means that we did not have one error source contributing to underestimation while another error source from the same case contributing to overestimation. An

After observing relatively low skill scores of dichotomous forecasting we decided to create a linear regression model between the predictors and observed SWE rates to determine which factors are better predictors. Then we wanted to

The best correlation came from predictors involving the height difference between the beam bottom height and the -12°C and -3°C layers and the initial radar ZS algorithm SWE rates. From Figure 5 the scatter plot between only observed and radar estimated SWE (marked by plotted triangles) indicate that there is no correlation. Its regression line is the dotted line on the graph.

A frequency histogram of the unadjusted radar-based SWE estimates errors shows a relatively large spread with numerous instances of large errors (Figure 6a). Where as the histogram of the regression model-adjusted predicted SWE residuals, shows a much smaller spread (Figure 6b). There are also a significantly greater amount

the ground stations observed. Out of the total 115 cases, the radar overestimated 15 more cases than it underestimated, and was only completely accurate six times. We shall note that it is not expected that the radar be exact on its SWE estimates. SWE estimates that are close to the ground observations would be considered accurate.

and -12ºC layer affect how much the radar overestimates or underestimates. Because the Colorado event had greater SWE rate amounts, it may in turn have had greater errors.

In both Figures 3 and 4 there are less data plotted. That is because there were some cases that were so cold they did not have these temperature layers in their soundings. Far more overestimations than underestimations are noticed in these plots than in Figure 2. This is regardless to whether the beam bottom is overshooting or undershooting the –3ºC and –1ºC layers.

example of the two-by-two tables can be seen in Table 2. From these tables, forecast statistics were calculated and shown in Table 3.

One can see from the tables that the accuracies and Heidke skill scores are not very high. Even after the statistics were recalculated on confident cases, if they increased, they did not increase by much. For Heidke skill scores, a "1" is perfect skill and a "0" is no skill. The low skill scores for Heidke sill scores could have resulted from a high FAR for underestimation due to beam overshooting forecasts (Table 3).

determine if a regression model of these factors could improve the performance of the snow algorithm. Table 4 displays correlations between different predictor sets. Notice the best fit lies in predictors from the -12°C and -3°C layers.

Notice that not only is it flat, but it is slightly negative and the R^2 value in Table 4 is nearly zero. The circles represent SWE estimations that are adjusted based on the distances between the bottom of the radar and the -3°C and -12°C layers. Its regression line is the solid line on the graph. Even though it is not a strong trend, it has the best correlation of all the predictors that were tested.

of adjusted SWE residuals closer to 0 cm than original residuals. Fewer adjusted SWE residuals lay on the extremes. This implies that the adjusted SWE predictors based on the differences between the radar beam and -12ºC and -3ºC layers are more accurate than the radar's original SWE rates based on this data set.

5. DISCUSSION

The ZS algorithm-based SWE rates showed almost no correlation with observed SWE rates (see figures 5 and 6). The negative regression line of the original radar SWE estimates versus observed SWE estimates shows that there is clearly no correlation (fig 5). This indicates the ZS algorithm by itself is not skillful in estimating SWE rates.

Is there any skill in anticipating the sign of the ZS algorithm errors? Based on the Heidke skill scores and accuracies for the error source forecasts, it can be said that this study's method for anticipating the ZS algorithm errors shows poor skill. In the confidence cases, the skill scores increased in some categories after being recalculated. However, they still showed poor skill.

A second question asked is whether or not a linear regression model can improve the ZS algorithm SWE rates using the predictors in this study? So far, it is believed the best predictors to adjust radar-based SWE rates is basing predictions off the distances between the radar beam bottom and the -3ºC and -12ºC degree Celsius layers. This is slightly unexpected. Recall earlier we hypothesized that errors of underestimation can occur the moment the top of the beam overshoots the bottom of precipitation production zones. Instead of basing sources for underestimation on the radar beam top overshooting the dendrite and riming production zones, it may be based on the radar bottom overshooting these zones.

There maybe several sources for error in the study that may have affected the results like this studies forecasting method. There was not diverse enough data gathered. Also, the ground observations themselves may have contained errors.

For the most part, the forecasting method was very repeatable and straightforward. The method for forecasting overestimation due to sub-beam evaporation and/or sublimation could be a little subjective. Different people can have different definitions of what is "dry" air below the 700mb level on the soundings. Forecasts for overestimation due to sub-beam sublimation should maybe be based on a quantitative measure of dry air. This study may have listed an air mass as saturated enough to withstand evaporation, while in reality it was not.

As in most cases the more data there is to work with, usually the more significant the results. Having not only too little data, but having one data set that dominated the rest may have affected the results. The best example of this would be the Colorado cases. The amount of SWE for each three-hour case was much greater than those of the Pennsylvania and Wisconsin cases. In turn, the Colorado cases' SWE rate errors were more likely to be greater and could have affected trends on the graphs.

The greatest factor that could have affected the results was the ground observation stations. Even though they were considered to be "true" in this study, and the best effort was made to find reliable stations, the gauges cannot always be 100% accurate. Some gauges' qualities are so poor that they may be completely unreliable. Even in light wind events, the gauge can still under catch. Snow can stick to the sides or just rest at the top of the gauge and fall in all at once later (Vasilhoff 2001b). If gauge observations were more accurate and reliable, more confidence could be placed in the results.

6. CONCLUSION

The WSR-88D uses the ZS (snow) algorithm in predicting SWE rates, which are used for winter weather forecasts. After comparing the ground observations in Wisconsin, Pennsylvania, and Colorado with their corresponding radar data, it is apparent that the algorithm is not an accurate tool in predicting SWE rates. We had tried to devise a plan to anticipate underestimation do to beam overshooting, overestimation due to sub-beam evaporation/sublimation, and overestimation due to bright banding. However, after testing our hypothesis, we came to the conclusion that the method showed poor skill using this dataset. Further testing of different SWE rate predictors through a linear regression model proved that the best way to anticipate SWE rates was by using predictors based on the difference between the radar beam bottom and the –12ºC and –3ºC layers. Hopefully, this knowledge can be used to improve the WSR-88D's ZS algorithms SWE rates. With that improvement, forecasters may be able to improve SWE rate predictions, and people can make better decisions regarding winter weather.

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APPENDIX

Event	Station Name, # of cases	Radar	Distance of station from radar (km)
Wisconsin March 1-3, 2007	CW1930 Kendall, 7	KARX	64.82
	Pardeeville, 7	KARX	151.864
	DeSoto, 7	KARX	44.448
	Rome (Saratoga), 7	KARX	120.38
	CW3882 Mauston, 6	KARX	88.896
	Keshena, 7	KGRB	153.716
	CW2106 Stevens Point, 2	KGRB	116.676
	CW4812 Sherwood, 8	KGRB	38.892
	CW2086 Waunakee, 2	KGRB	181.496
	CW5937 Sturgeon Bay, 2	KGRB	68.524
	CW1988 Brookfield, 7	KGRB	157.42
	Waupaca Municipal Airport, 5	KGRB	85.192
	Wausaukee, 8	KGRB	100.008
Pennsylvania March16-17, 2007	Harrisburg Capital City Airport, 2	KCCX	124.084
	Selinsgrove Penn Valley Airport, 1	KCCX	94.452
	Williamsport regional Airport, 1	KCCX	96.304
	Harrisburg International Airport, 2	KCCX	133.344
	Altoona-Blair County Airport, 2	KCCX	75.932
Colorado January 29-30, 2007	Trichera, 8	KPUX	155.568
	Culebra#2, 8	KPUX	166.68
	Apishapa, 8	KPUX	150.012
	Whiskey Creek, 8	KPUX	162.976

Table 1 Snow events, Observation Stations names and its corresponding radar, and distance between the two.

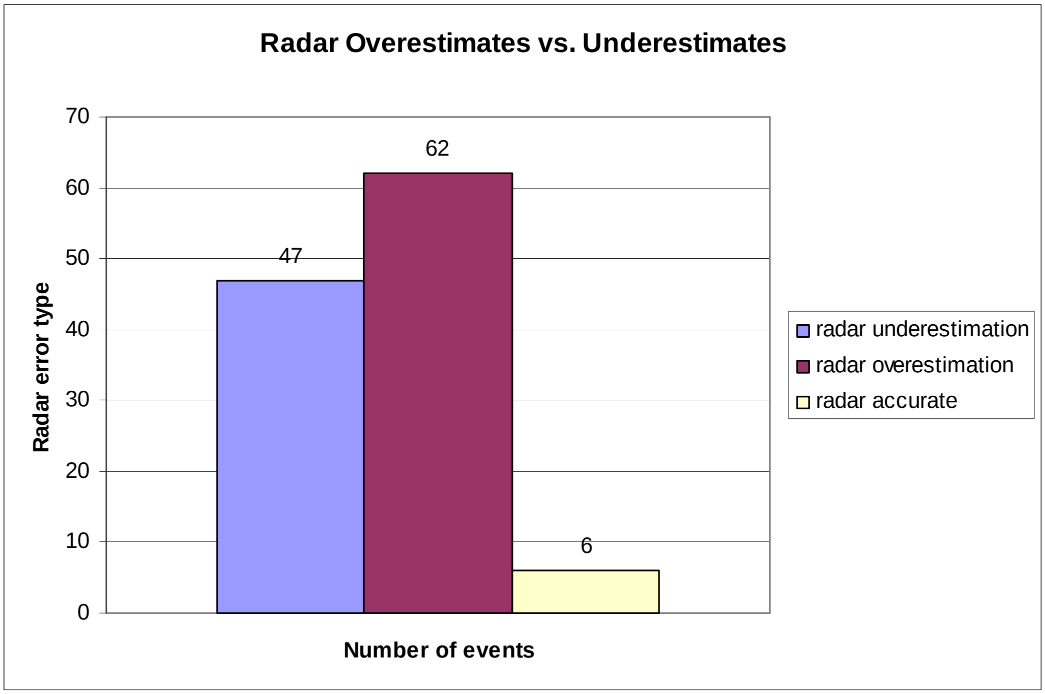

Figure 1 Bar Chart showing the number of each radar error type observed.

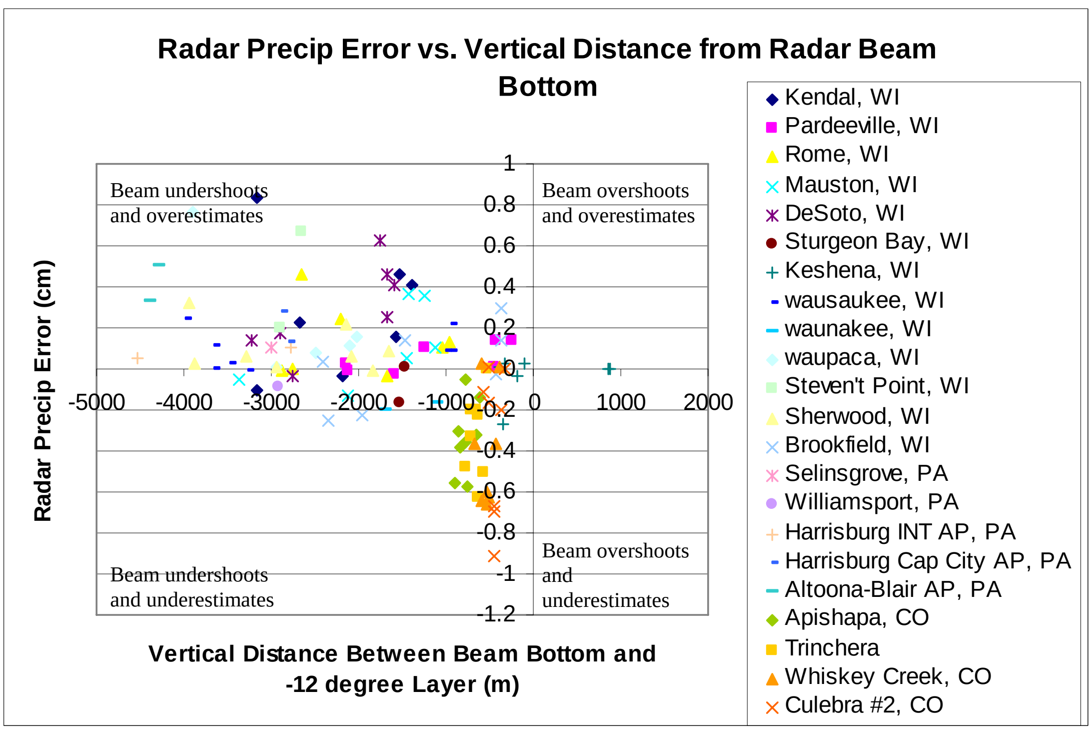

Figure 2 Scatter plot of the difference between radar's results and ground observations versus the distance of the radar beam bottom above or below the -12° layer.

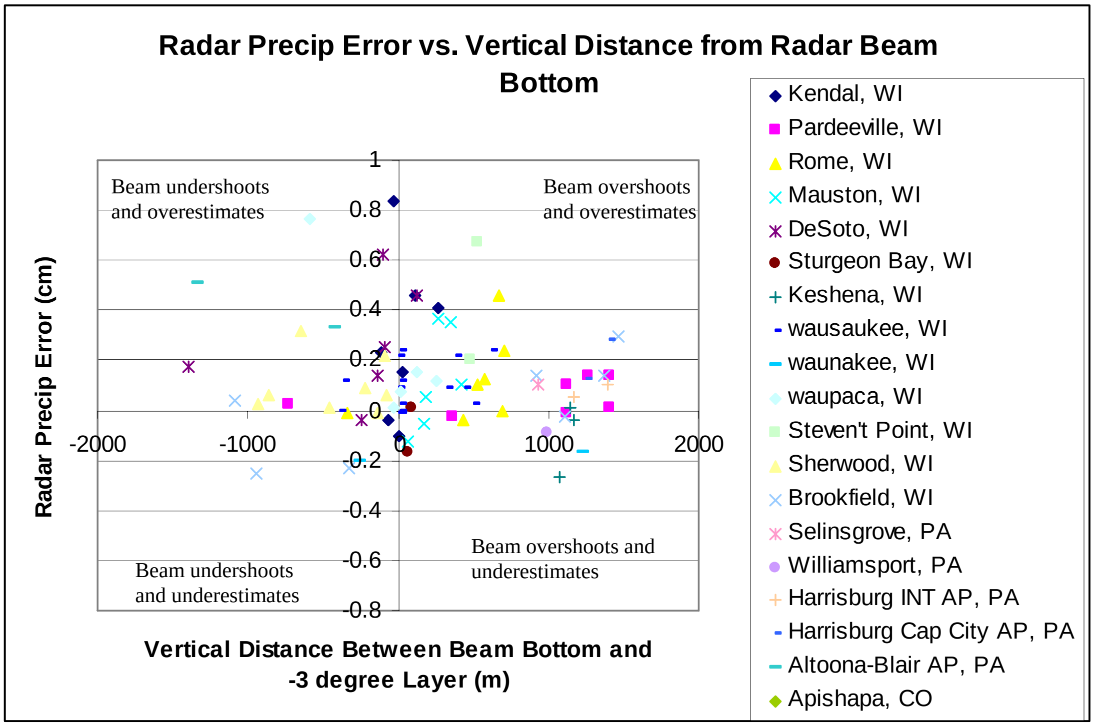

Figure 3 Scatter plot of the difference between radar's results and ground observations versus the distance of the radar beam bottom above or below the -3° layer.

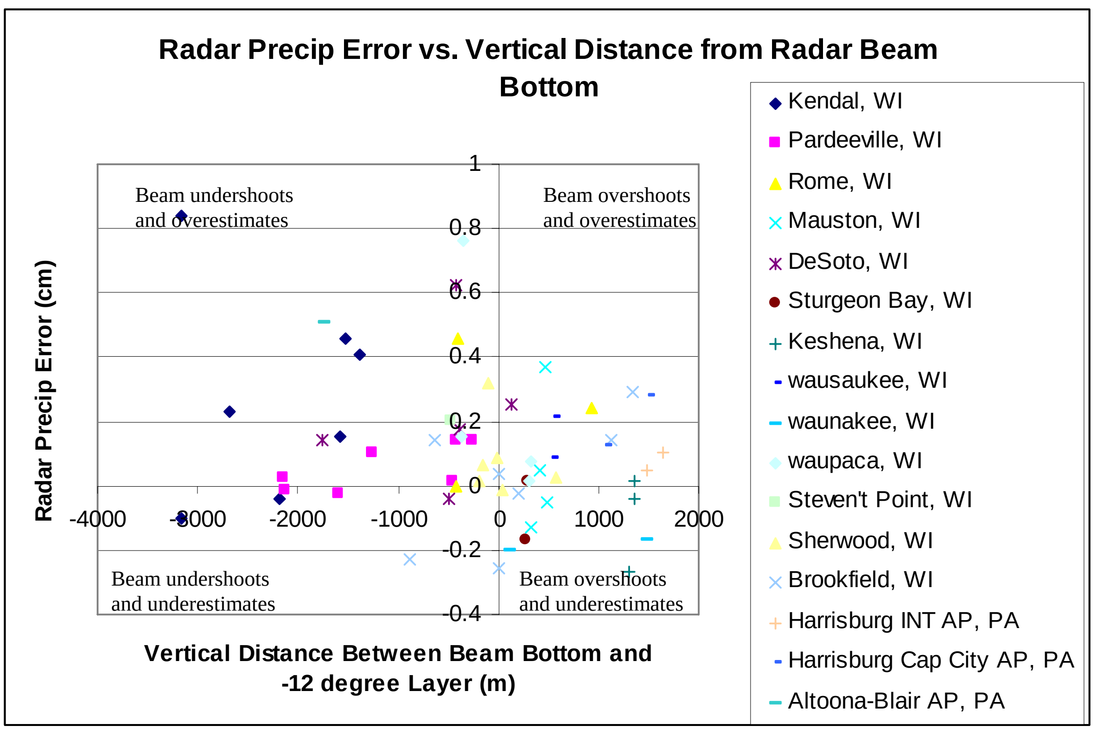

Figure 4 Scatter plot of the difference between radar's results and ground observations versus the distance of the radar beam bottom above or below the -1° layer.

	Underestimation		
	obs yes	obs no	total
Forecast yes	43	47	90
forecast no	4	21	25
total	47	68	115

Table 2 Sample 2X2 contingency table for underestimation due to beam overshooting. The rows are forecasts whether underestimation will "yes" occur or "no" will not. The columns are if underestimation was observed "yes" or observed "no".

	Accuracy	POD	FAR	Prob of False Detection	CSI	Heidke skill score
Underestimation due to Beam Overshooting	0.56	0.91	0.52	0.69	0.46	0.2
Confident Cases	0.52	0.95	0.45	0.73	0.53	0.24
Overestimation due to Sub-beam sublimation	0.46	0.13	0.5	0.15	0.11	-0.02
Confident Cases	0.55	0.05	0	0	0.05	-0.07
Overestimation due to Bright Banding	0.51	0.21	0.35	0.13	0.19	0.07
Confident Cases	0.57	0.14	0.25	0.05	0.13	-0.02
General Overestimation	0.51	0.37	0.49	0.36	0.27	0.02
Confident Cases	0.57	0.23	0.31	0.12	0.21	0.06

Table 3 Statistics obtained from 2X2 contingency tables. Confident cases occurred when the statistics were recalculated on confident radar error forecasts. These are cases that are believed not to have conflicting sources of error. General overestimation implies that a forecast was made for overestimation due to either source for error.

SWE Prediction based on regressions from	R^2
Radar SWE	0.0014
Radar SWE, T-(-12°), C-(-12°), B-(-12°)	0.09676
Radar SWE, T-(-3°), C-(-3°), B-(-3°)	0.1918
Radar SWE, T-(-12°), C-(-12°), B-(-12°), T-(-3°), C-(-3°), B-(-3°)	0.2266
Radar SWE, T-(-1°), C-(-1°), B-(-1°)	0.08548
Radar SWE, T-(-12°), C-(-12°), B-(-12°), T-(-1°), C-(-1°), B-(-1°)	0.1541
Radar SWE, T-(-12°), C-(-12°), B-(-12°), T-(-3°), C-(-3°), B-(-3°), T-(-1°), C-(-1°), B-(-1°)	0.2273
Radar SWE, T-(-3°), C-(-3°), B-(-3°), T-(-1°), C-(-1°), B-(-1°)	0.1933
Radar SWE, T-(-12°), C-(-12°), B-(-12°), T-(-3°), C-(-3°), B-(-3°), OS	0.2327
Radar SWE, T-(-12°), C-(-12°), B-(-12°), OS	0.1145
Radar SWE, T-(-12°), C-(-12°), B-(-12°), T-(-3°), C-(-3°)	0.2266

Table 4 Table of correlations (R^2) between the predictors and observed SWE. T=height of radar top, C=height of radar center, B=height of radar Bottom, temperatures represent heights of temperature layers in Celsius, OS= forecast for overestimation due to sub-beam evaporation/sublimation.

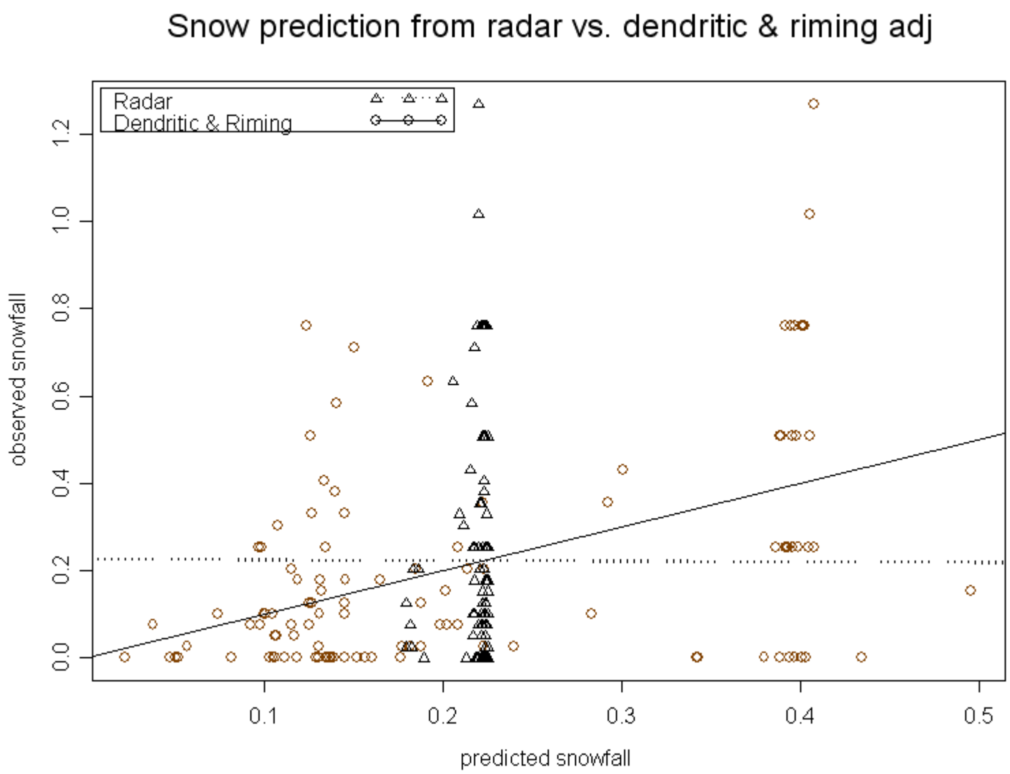

Figure 5 Scatter plot of radar SWE estimates (cm 3hr^{-1}). The triangles are unadjusted radar estimates and have the dotted regression line. The circles are adjusted predictions based on the distances between the bottom of the radar beam and the -3°C and -12°C layers.

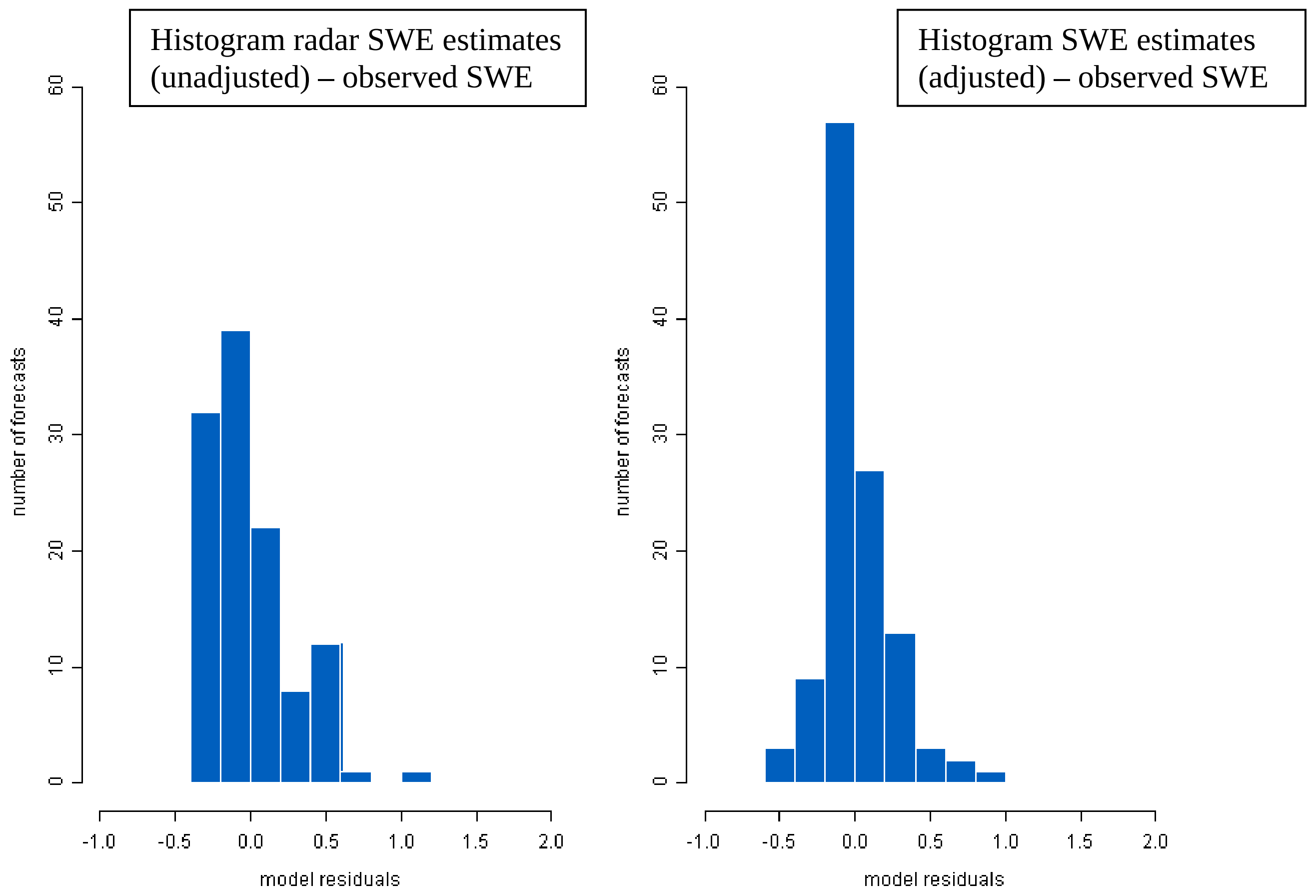

Figure 6 Comparison of histograms. A). The left histogram is of the Radar's original SWE estimates minus the observed SWE. B). The histogram on the right is of Predicted SWE adjusted by a regression model with the radar estimate SWE, and the distances between the radar beam bottom and the -12°C and -3°C layers.

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