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TEST OF THE WSR-88D SNOW ACCUMULATION ALGORITHM AT WFO MISSOULA

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[Note: All figures appear only on the web page at http://www.wrh.noaa.gov/ under Technical Attachments.]

Introduction

During the winter of 1999-2000, the Missoula National Weather Service Forecast Office (WFO) was asked by the WSR-88D Operational Support Facility (OSF) to test a WSR-88D Snow Accumulation Algorithm (SAA). The snow algorithm estimates snow water equivalent (SWE) using a Reflectivity to Snow (Z-S) relationship similar to the way that rainfall is estimated in the warm season from a Reflectivity to Rainfall (Z-R) relationship. The algorithm has many configurable parameters, and it was hoped that a season-long test would provide guidance for future modifications of these parameters.

Algorithm

The algorithm has been tested in other parts of the country with some success. Table 1 shows the correlation between SAA storm total SWE estimates with observations at several other locations. While some tests with high elevation radars and complex terrain have been performed, the algorithm had not been tested in the Northern Rocky Mountain area. Also, it was hoped that a season-long test with a mountain-top radar in very complex terrain would provide helpful information for other radars where the algorithm may be implemented in the future.

Topography

Figure 1 shows the complex terrain of the Missoula WFO County Warning Forecast Area (CWFA). The diverse topography stretches from the Hells Canyon area of Idaho (bordering northeast Oregon), where elevations are less than 1000 feet, to the Bitterroot

Mountains of western Montana and the Glacier Region of northwest Montana, where mountain elevations near 10000 feet are located. The Missoula WSR-88D (KMSX) is a high elevation radar site (~8000 feet above sea level) located on top of Point Six Mountain, 6 miles north of Missoula. Much of this area is prone to heavy snow events which can occur as early as September and as late as May. Snowfall totals more than 175 inches per year are common over the mountainous terrain, while less than 30 inches typically fall in some of the lower valleys. Transportation corridors are a major concern during major winter storms. High mountain passes, on average, receive much more snowfall than nearby valleys, sometimes causing closures of high-volume transportation routes.

Configurable Parameters

To keep data analysis as simple as possible, the configurable parameters for the SAA were chosen as reasonably as possible, and kept constant throughout the study period. While certain parameters could reasonably be changed on a 'storm-by-storm' basis, keeping them constant in this fashion produced a large data set with which any consistent biases should be more readily apparent. The most significant parameters are the Z-S relationship, the snow-water ratio, and the range correction factor. The Z-S relationship was kept at a constant SWE=75Z2.0. The snow-water ratio was also kept constant at 13:1. Since this is a mountain-top radar site, it is likely that much of the precipitation producing part of winter storms will be below the lowest beam of the radar, leading to an under-estimation of snowfall. This under-estimation will become larger as distance from the radar increases since the radar beam gets farther above the ground, and more of the storms will not be sampled. The range correction factor artificially increases the SWE estimates by the equation:

SWE_final = SWE_raw * correction_factor

Where the correction factor is given by:

Correction Factor = 0.358 - 0.001953 * range + 0.000296*range*range

where range is in km. This correction factor is only applied at ranges beyond 50 km (27 nm). Figure 2 shows the correction factor as a function of range. Note that the correction factor is quite dramatic, doubling radar estimates of SWE at a range of 78 km (42 nm) and tripling the estimates at 97 km (52 nm).

Observation Network

Given the large forecast area of the Missoula WFO and the lack of surface observations, a special snow spotter network was developed across much of the CWFA. The network consisted of 111 volunteer spotters, all of whom were recruited from the existing weather spotter network. Snow measurement seminars were conducted at various locations throughout the CWA to give these volunteers instructions on making accurate snow measurements, and avoiding common problems such as compaction and drifting. The volunteers reported snowfall amounts and the specific time period over which the snowfall occurred.

To provide real-time results, and to help avoid problems with snowfall compaction, the volunteers were asked to give reports as frequently as possible during snowfall events. Some reports were as frequent as every hour, while some were over 24 hour periods. On average, about 3 hours between snowfall reports were common during precipitation events. In addition to the volunteer spotters, daily snowfall reports from 30 cooperative stations which utilize the "ROSA" telephone system were also used in the analysis. These stations report daily via a ROSA telephone system, and are denoted as "ROSA" stations in the analysis. Automated SWE data from 38 SNOTEL sites from the Natural Resources Conservation Service (NRCS) were also considered. These stations report SWE accumulations every 6, 12 or 24 hours at various high-elevation locations throughout the CWFA Snowfall observations from the Missoula WFO were also used in the analysis, but there were very few snowfall cases at this valley location during this particular winter season. The location of all stations used in the analysis are also shown in Fig. 1 , with the SNOTEL stations plotted in blue, the spotter locations in red, and cooperative stations plotted in green.

Due to the difficulty of getting volunteer spotters to accurately measure snow water equivalent (SWE) values, we decided to consider only actual snow amounts in the analysis. (Since the SNOTEL stations only report SWE values, we multiplied them by the same 13:1 snow-water ratio used in the SAA to come up with "observed" snow values at those locations as well). For each observation received, the SAA estimate of snowfall over the same time interval as the observed report was carefully calculated from the displays of the algorithm output and logged. From all snow events between December 1999 and April 2000, nearly 1600 reports were received where an observation and corresponding SAA estimate could be determined. Further quality control revealed several storms where all radar estimates were significantly in error at many locations. These reports were removed from the data set, leaving 1434 reports for analysis.

Results

Figure 3 shows a simple "scatter plot" of all the observed snowfall and corresponding SAA estimates (in inches). If the SAA were perfect, the points would all plot along the heavy black diagonal line on the plot. The correlation of all 1434 reports is only 0.392, and the linear "best-fit" line (shown in red on the graph) shows there is a very slight tendency for the algorithm to over-estimate snowfall amounts when snowfall is light, and under-estimate snowfall amounts when the snowfall is heavy. The different colored dots show the different observation types considered in the analysis. Many of the cases with large snowfall errors come from SNOTEL and ROSA observation sites.

Figure 4 shows the snowfall estimate error (radar estimate minus observed) as a function of distance from the radar. Once again, the different colors show the different types of observation sites. All cases at very distant ranges (i.e., beyond 110 nm) tend to have radar estimates that are "too low". Since the center of the lowest elevation radar beam is above 21000 feet at this range, it is likely that all of the precipitation producing part of storms is below the radar beam. Thus, it is not surprising that the SAA would estimate "too low" in these cases. However, it is encouraging that there is no obvious tendency to underestimate snowfall at shorter ranges, especially considering that the range correction factor is involved only at ranges beyond 27 nautical miles.

However, when considering individual observation types, there are subtle biases. The SNOTEL sites tend to have much larger errors than the other observation types, and further analysis shows that, on average, the radar estimates are too high at almost all SNOTEL sites, even at shorter ranges. SNOTEL sites are typically remote mountain sites with little shielding from the wind except for the effect of trees in the surrounding forest. Other studies have shown that without proper wind shielding, "under catch" of snowfall can be significant. Thus, it could certainly be that the SNOTEL observations are too low due to wind effects.

Careful examination of Fig. 4 also shows a tendency for ROSA observations to be lower than radar estimates, especially at short ranges. The cooperative observers who report via ROSA typically just call once a day with daily snowfall information. It is possible that compaction plays a role with these observations. When snowfall is measured several times over short intervals, a storm might produce a total of 6 inches of snow, but if only one observation is made at the end of the storm, compaction of the snow might make it look like only 4 inches of snow fell.

Due to these potential problems, and consistent differences with the radar estimates, the SNOTEL and ROSA observations were omitted from further analysis. In addition, the small number of observations from the Missoula WFO during the season were not enough to alter the results significantly, so they were also omitted. Figure 5 shows error versus distance for the remaining 560 cases from spotter reports. Beyond 80 nautical miles, the average error at all sites begins to fall below zero, probably due to large portions of the storms being below the lowest radar beam. The range correction factor seems to be doing a fine job of accounting for this problem at distances less than about 80 nm. When only reports from spotters within 80 nm of the radar are considered, there were 356 reports, and the errors from these reports are shown in Fig. 6 .

Figure 7 shows the errors for these same cases, but as a function of the height of the lowest radar beam above the topography. Most of the reports for sites where the lowest radar beam is within 6500 feet of the ground, have smaller errors than for those sites where the radar beam is higher. However, there are "outlier" cases of large errors for all sites, both those "close" (vertically) to the radar beam, and those more "distant" from the beam.

Figure 8 shows the errors plotted as a function of the duration of the snow observation. As stated earlier, these spotters were encouraged to call as often as possible during snowfall events, and they did a very good job. A few reports were for time periods beyond 12 hours, but these showed nearly the same error characteristics as observations over shorter time periods.

For each case, we looked at atmospheric conditions using temperature, dew point and wind measurements at an upstream upper-air observing site (Spokane, WA). We suspected that some of the cases with large errors might be related to cases with stronger winds. However, no obvious relationship was found between the errors and wind speed or direction at 850, 700 or 500mb. We did, however, find one weak relationship with stability as shown in Fig. 9. This shows the errors versus the temperature difference between 700 and 500mb at the upstream sounding. A dry adiabatic lapse rate between these two levels would be about 25 degrees, and at typical winter temperatures the moist adiabatic lapse would be about 18 degrees. Interestingly, the cases where the radar estimates were significantly too low tended to be during cases when the instability was large, whereas the cases where the radar estimates were significantly too high tended to be during more stable conditions.

Figure 10 shows the scatterplot of observed snowfall versus radar estimated snowfall for these 356 cases from spotter reports within 80 nm. The correlation of 0.64 is not great, but certainly better than the 0.39 for all reports shown in Fig. 3. The best "least-squares" line (shown in red) is also very close to the perfect line (shown in black) indicating that the Z-S relationship used here is fairly realistic in an overall sense. Figure 11 shows a histogram of errors for these reports. It is encouraging that 289 out of 356 estimates (81%) were within 1 inch of the observed amount.

One further factor that was considered was the effect of "storm total" observations. The higher correlations reported in earlier studies were for "storm total" observations, and it could be that the radar algorithm may slightly underestimate snowfall during the heavy snowfall "bursts" during a storm, but make up for it by slightly overestimating snowfall during the lighter periods of snowfall during the same storm. For cases where we received several reports during a storm, we combined them into a single "storm total" observation for that location and produced similar figures to those already shown. The impact was small, but positive - as shown in Fig. 12 where the scatterplot now shows a correlation of 0.66 for 233 "storm total" cases. The figure shows most of the improvement is in the cases of "light" precipitation where storm total accumulations of an inch or so are closer to the "perfect" line. However, large snowfall cases still have considerable errors.

Conclusions

The results from this study indicate that the Snow Accumulation Algorithm certainly has some skill at estimating snowfall even over rugged terrain and from a mountaintop radar site. The range correction factor appears to be realistically modifying the estimates, at least out to about 80 nm range. However, significant problems still remain. While most of the estimates were within 1 inch of what was reported, many of the cases of large errors were also during cases of heavy snowfall. From an operational perspective, this is very discouraging. There is often little need for accurate radar snowfall measurements for storms that produce 1 or 2 inches of snow and cause little more than a nuisance for most people. However, accurate estimates for large storms that produce 4 or more inches of snowfall can be critical for real-time updates of watches and warnings that have an impact on transportation managers and other concerns.

While over 100 spotters were recruited for this effort, it is clear that the algorithm can really only do well for distances less than about 80 nm. In this range, we only had 16 spotters that produced numerous observations consistently throughout the season. The results from these spotters is revealing, but these reports are mostly from "valley bottom" locations. As mentioned earlier, transportation problems with mountain passes can be the most dangerous part of winter storms in this area. These passes typically receive much more snowfall than nearby valleys, and accurate radar estimates in these area would be very beneficial. However, from the valley sites, indications are that the radar estimates have more difficulties with heavy snow cases, and these cases are more common in the mountains. Furthermore, getting high-quality snowfall observations in the mountains is very difficult, as seen in the SNOTEL measurements considered in this study.

It seems likely that the reason for higher snowfall amounts on mountain passes is due to the orographic effects of airflow over the mountains themselves. To "see" the enhanced reflectivity associated with these effects, the radar would likely have to "look down" into the air along the mountain slopes. This is not possible with current radar scanning strategies available on the WSR-88D system. Thus, while higher quality snowfall observations in these mountain locations would be revealing, we doubt that they would correlate well with the radar estimates, since the radar is unable to properly observe this phenomena.

The encouraging part of this study is that the radar estimates do as well as they do for valley locations far below the lowest radar beam. We have seen a few cases where the drift of snowfall due to wind in this layer can significantly displace "downstream" where the maximum snowfall is observed compared to radar estimates. However, over the entire season, this effect did not seem to be a serious issue.

Probably the most important benefit from this study was the development of a network of snow spotters. It is evident from the data that frequent observations from these highly trained spotters is of higher quality than less frequent measurements from other observers, and from other remote sensing platforms. While the radar algorithm has some benefit, the "ground truth" from observers still appears to be very valuable information.

References

Super, Arlin B and Edmond W. Holroyd, Snow Accumulation Algorithm For the WSR-88D Radar: Final Report, Bureau of Reclamation Report R-98-05.

Subject: **[Fwd: Possible TA...]**
Date: Tue, 14 Nov 2000 08:21:59 -0700
From: "Andy Edman" <Andy.Edman@noaa.gov>
Organization: NOAA/NWS/WR
To: Elaine Robinson <Elaine.Robinson@noaa.gov>

Subject: **Possible TA...**
Date: Tue, 31 Oct 2000 19:13:10 +0000
From: "Timothy Barker" <Timothy.Barker@noaa.gov>
Organization: NOAA/NWS/WR/BOI
To: Andy Edman <Andy.Edman@noaa.gov>

Andy,

On behalf of many other co-authors, I am submitting the attached TA on the performance of the NSSL Snow Algorithm that we tested in Missoula last winter. It has been reviewed by Keith Meier in Billings and also Mark Fresch at the OSF.

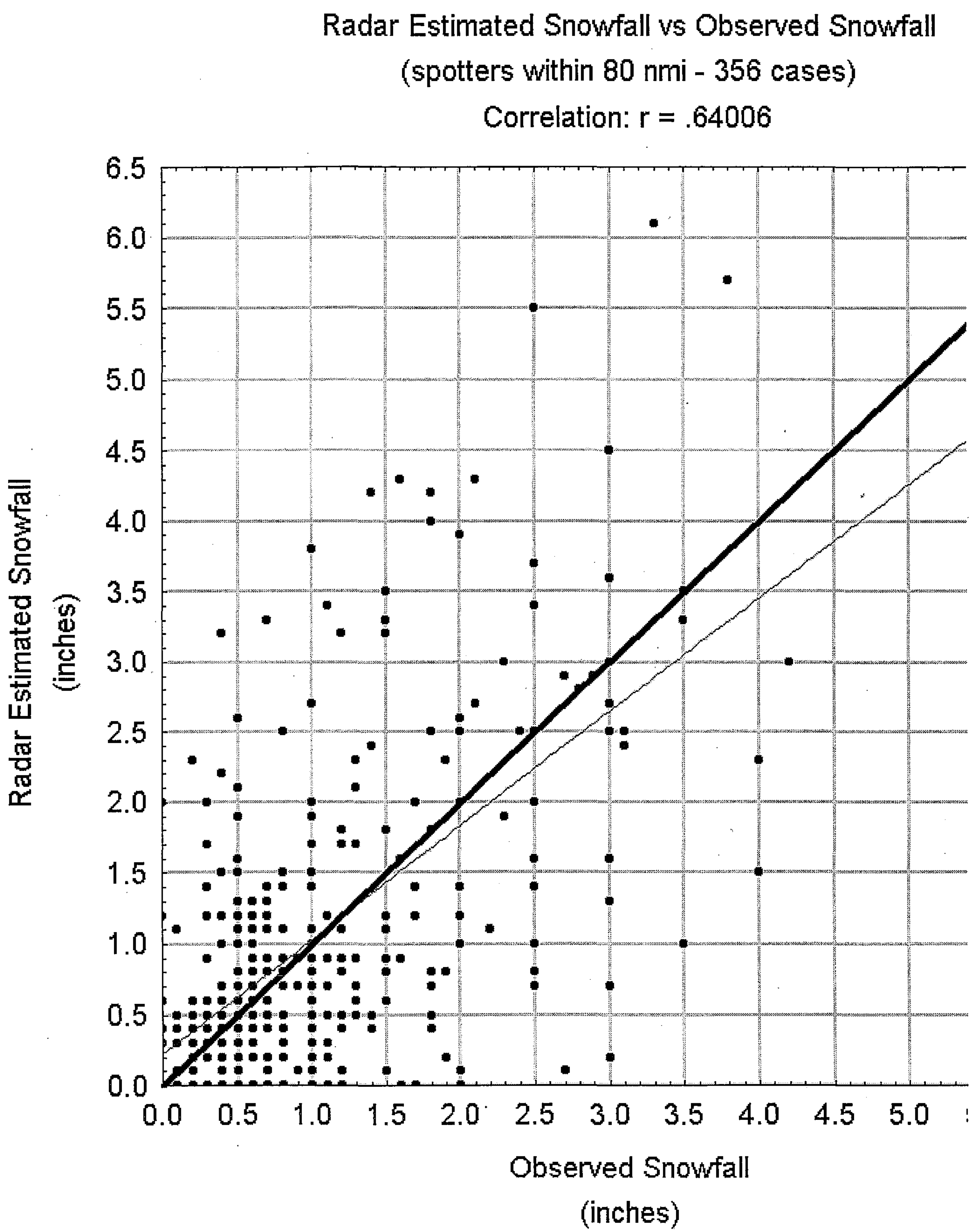
I have attached the text as a WordPerfect file (snow.wpd) and also as a html file (snow.htm). The figures are each in their own GIF, with a html "wrapper" around them (to put in the caption) and there is one table in html format as well. It is a bunch of files, but hopefully you have everything you need at this point (if not - let me know).

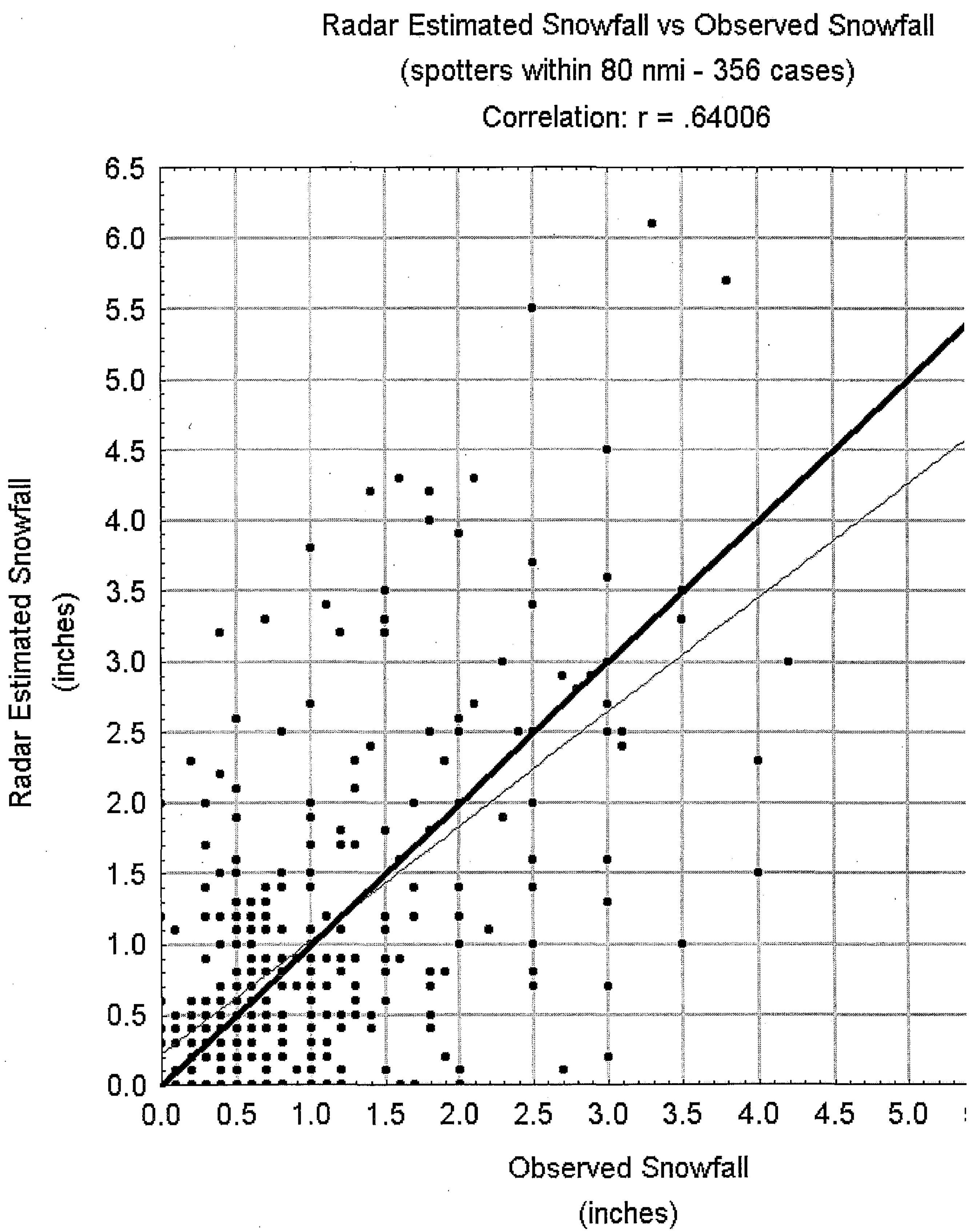
Let me know what you think.

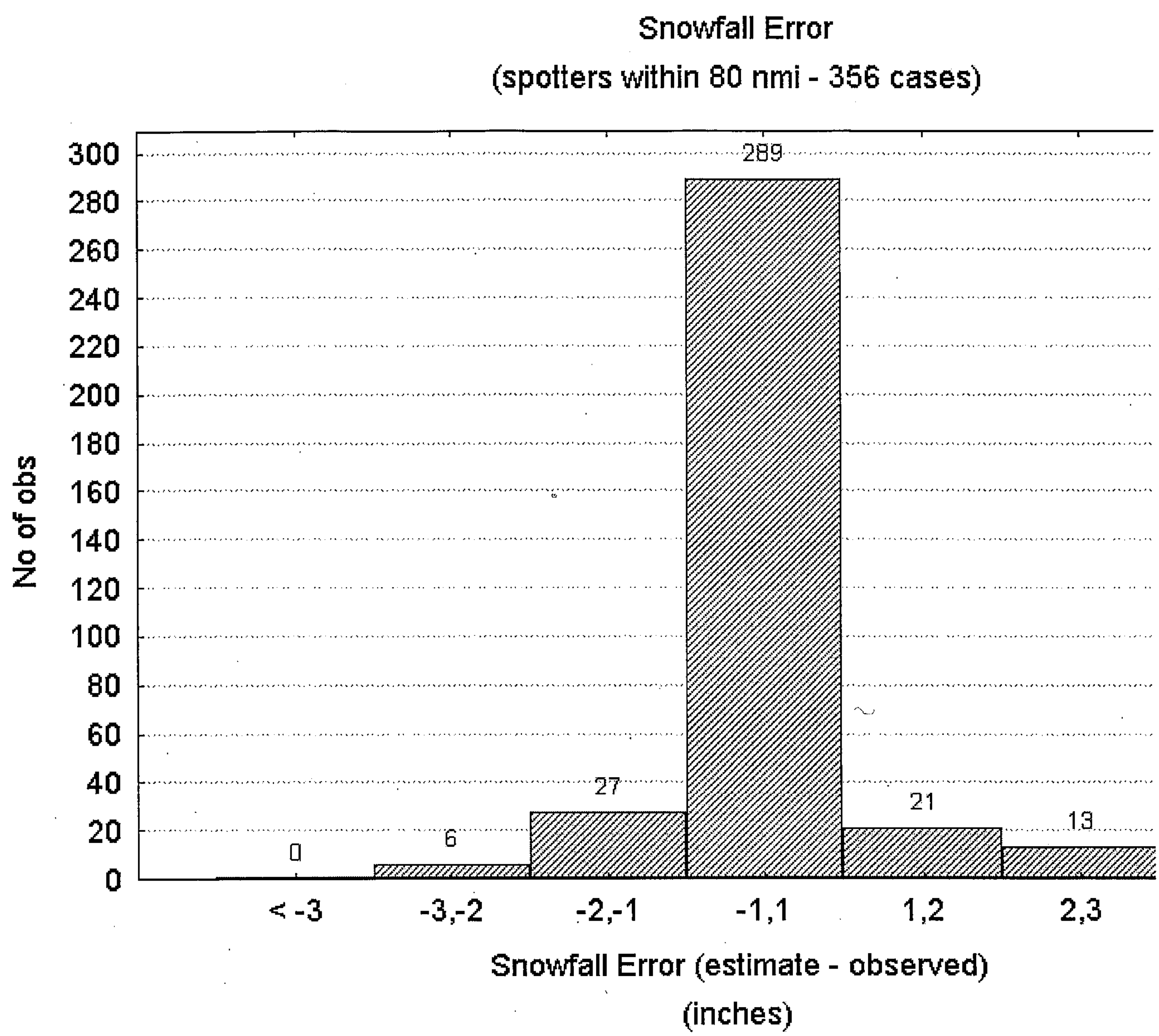
Tim Barker - SOO
National Weather Service - Boise, ID

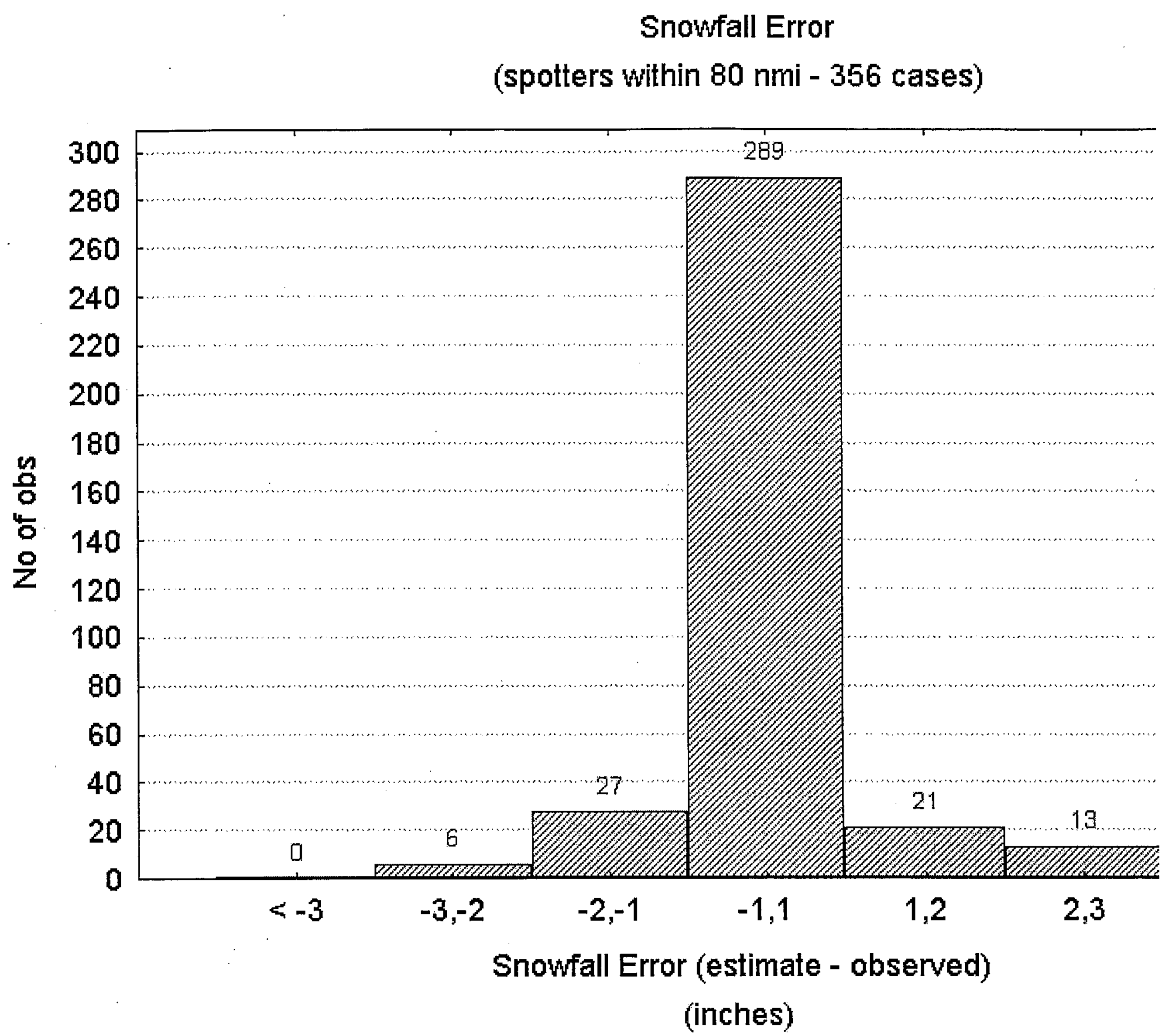
Table 1. Correlation coefficients between snow measurements and SAA storm total SWE estimates from development data sets (from Super and Holroyd 1998).

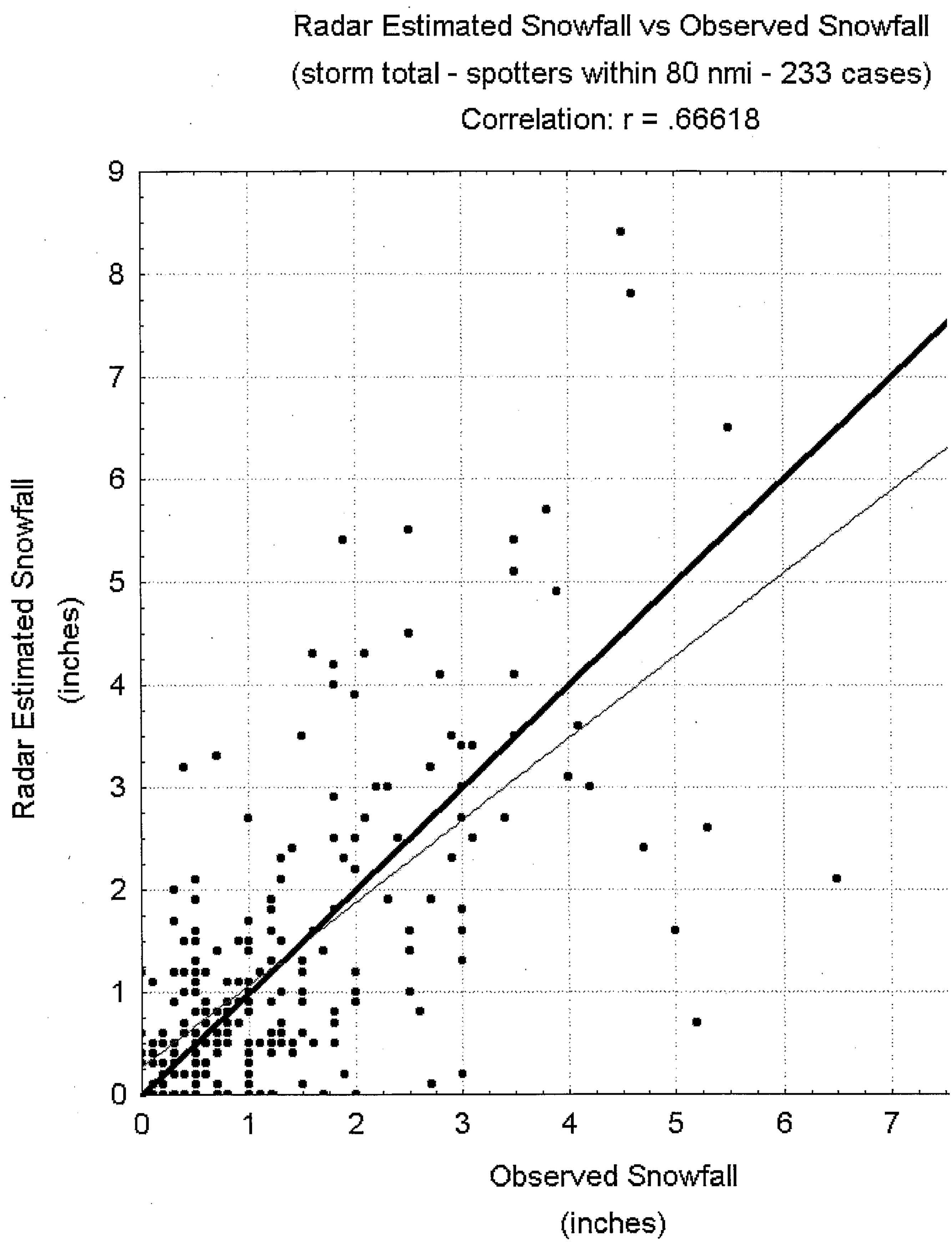
Site	Data Description	Sample Size	Correlation Coefficient
Albany, NY	storm total SWE	109	0.90
Cleveland, OH	storm total SWE	49	0.92
Denver, CO	storm total SWE	47	0.84
Grand Junction, CO	storm total SWE	94	0.96
Minneapolis, MN	storm total SWE	22	0.83

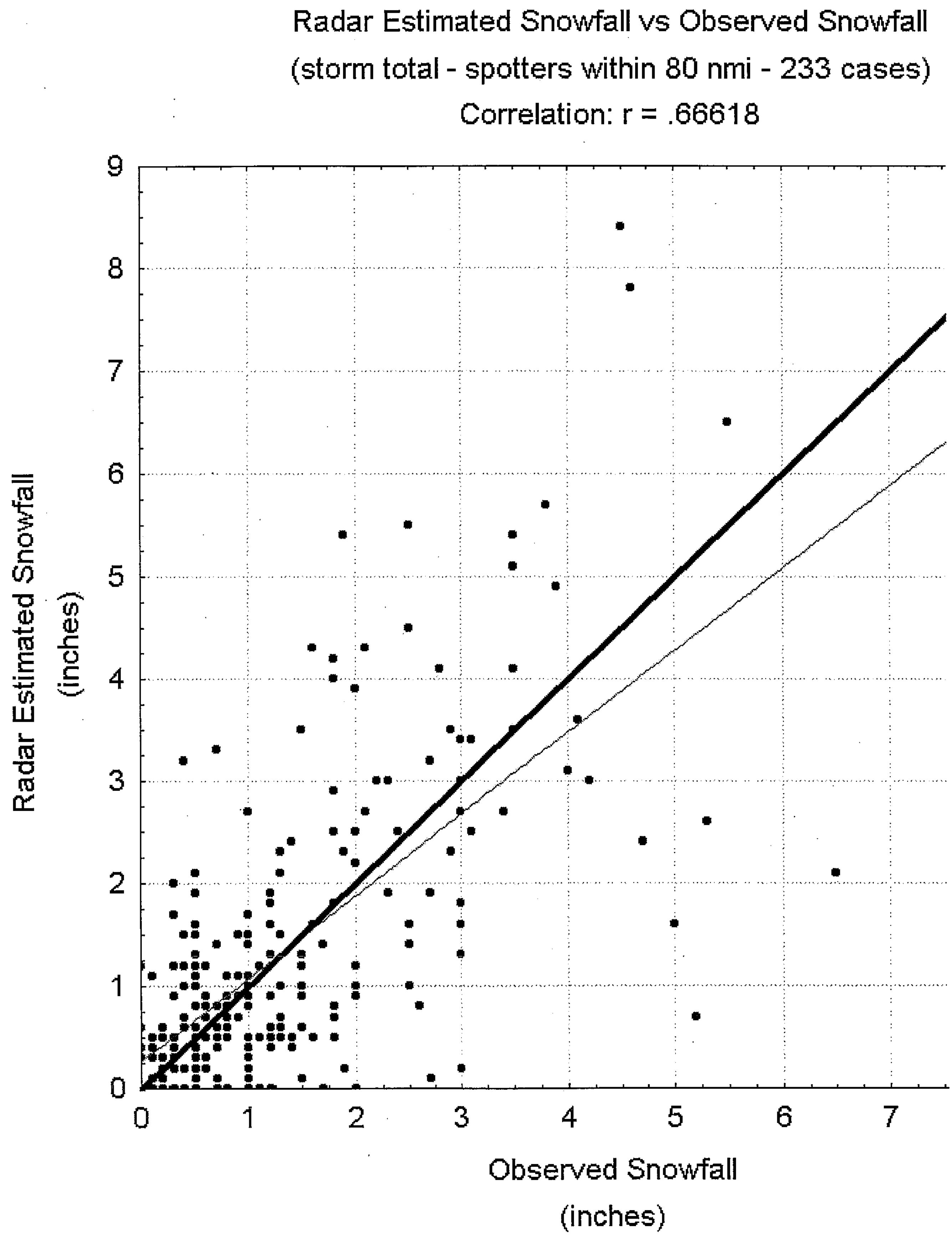

Radar Estimated Snowfall vs Observed Snowfall
(spotters within 80 nmi - 356 cases)
Correlation: r = .64006
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Radar Estimated Snowfall
(inches)
Observed Snowfall
(inches)

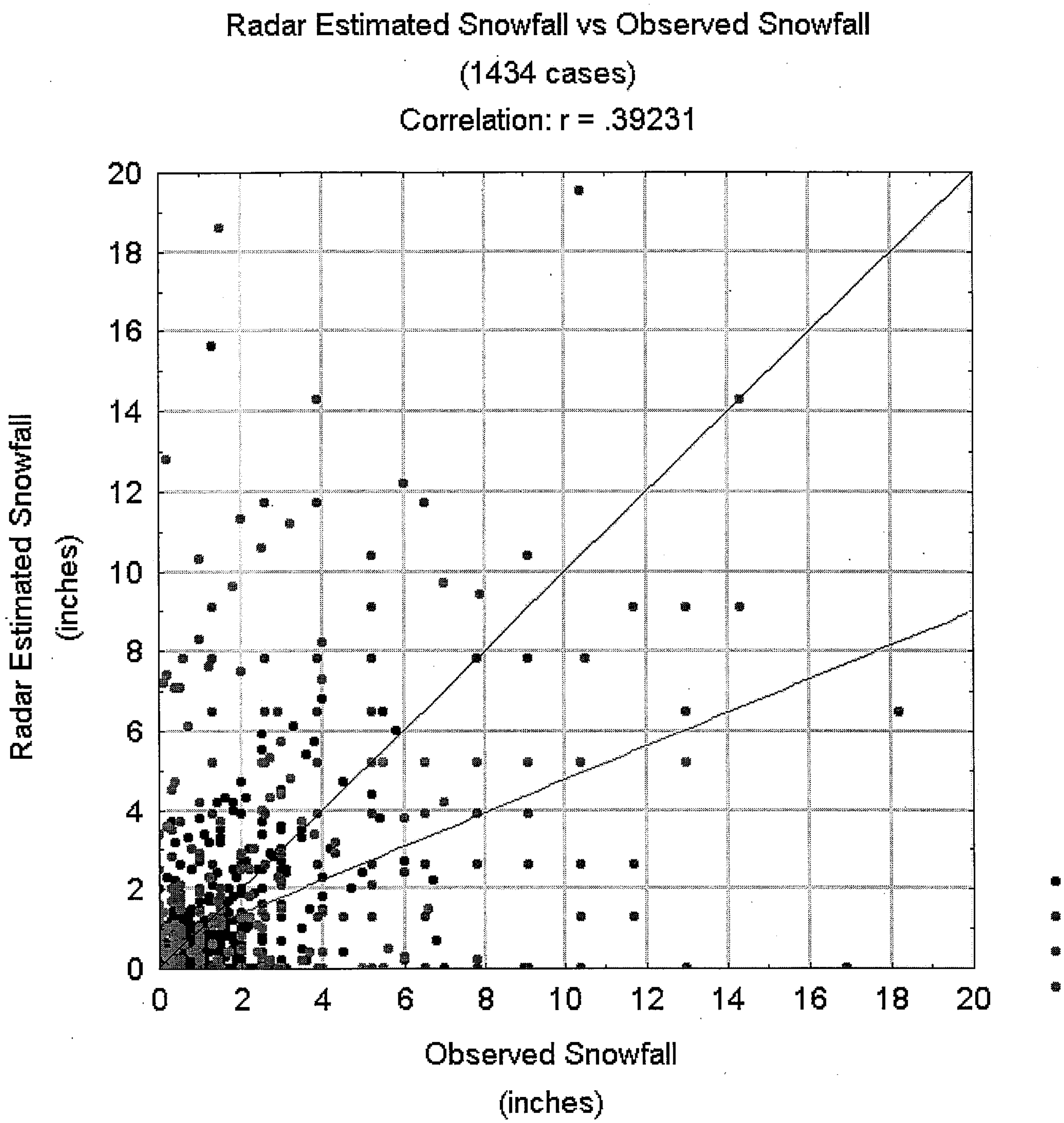

Radar Estimated Snowfall vs Observed Snowfall
(spotters within 80 nmi - 356 cases)
Correlation: r = .64006
Radar Estimated Snowfall (inches)
Observed Snowfall (inches)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

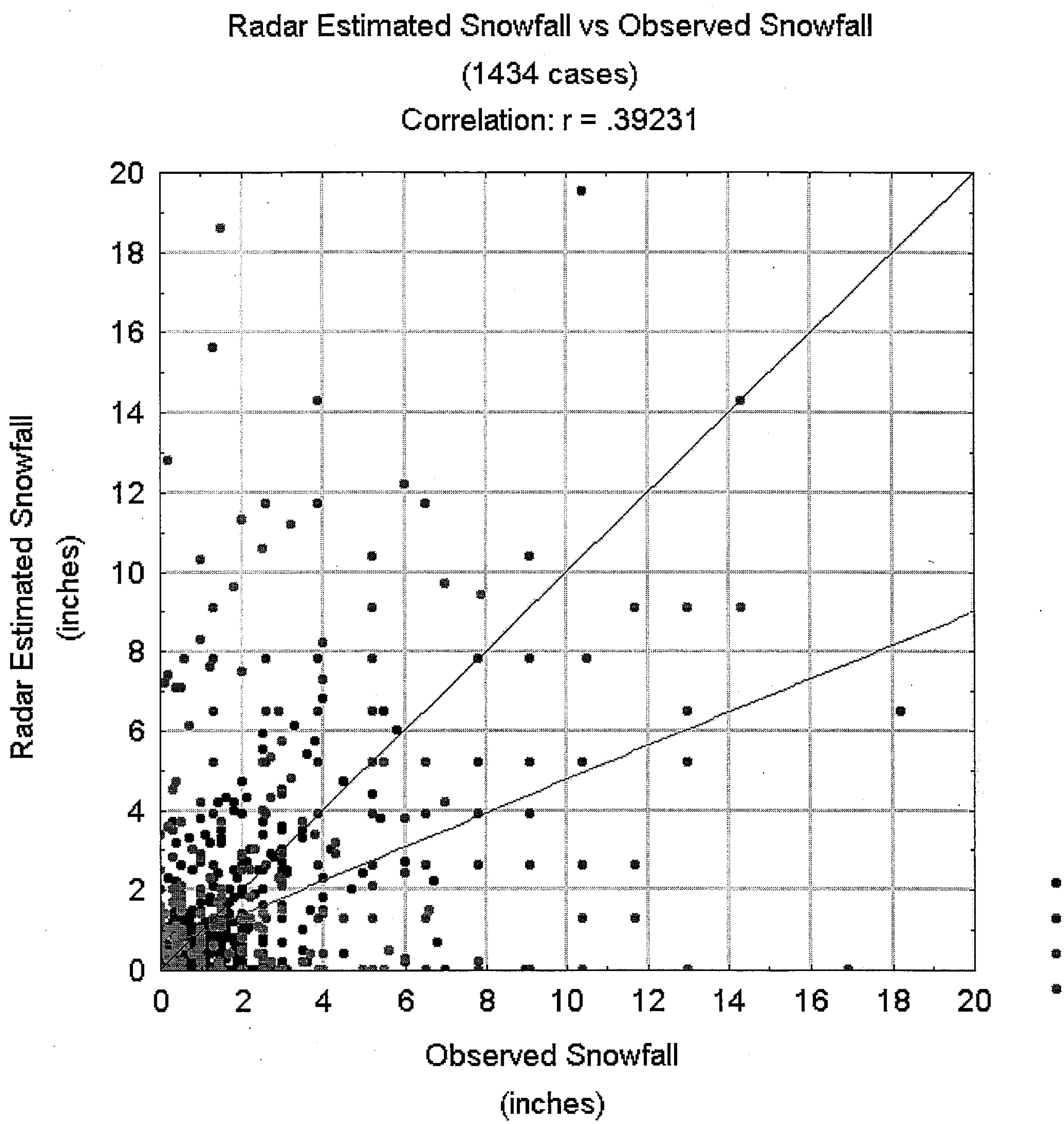

Snowfall Error
(spotters within 80 nmi - 356 cases)
No of obs
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
289
27
21
13
6
0
< -3
-3,-2
-2,-1
-1,1
1,2
2,3
Snowfall Error (estimate - observed)
(inches)

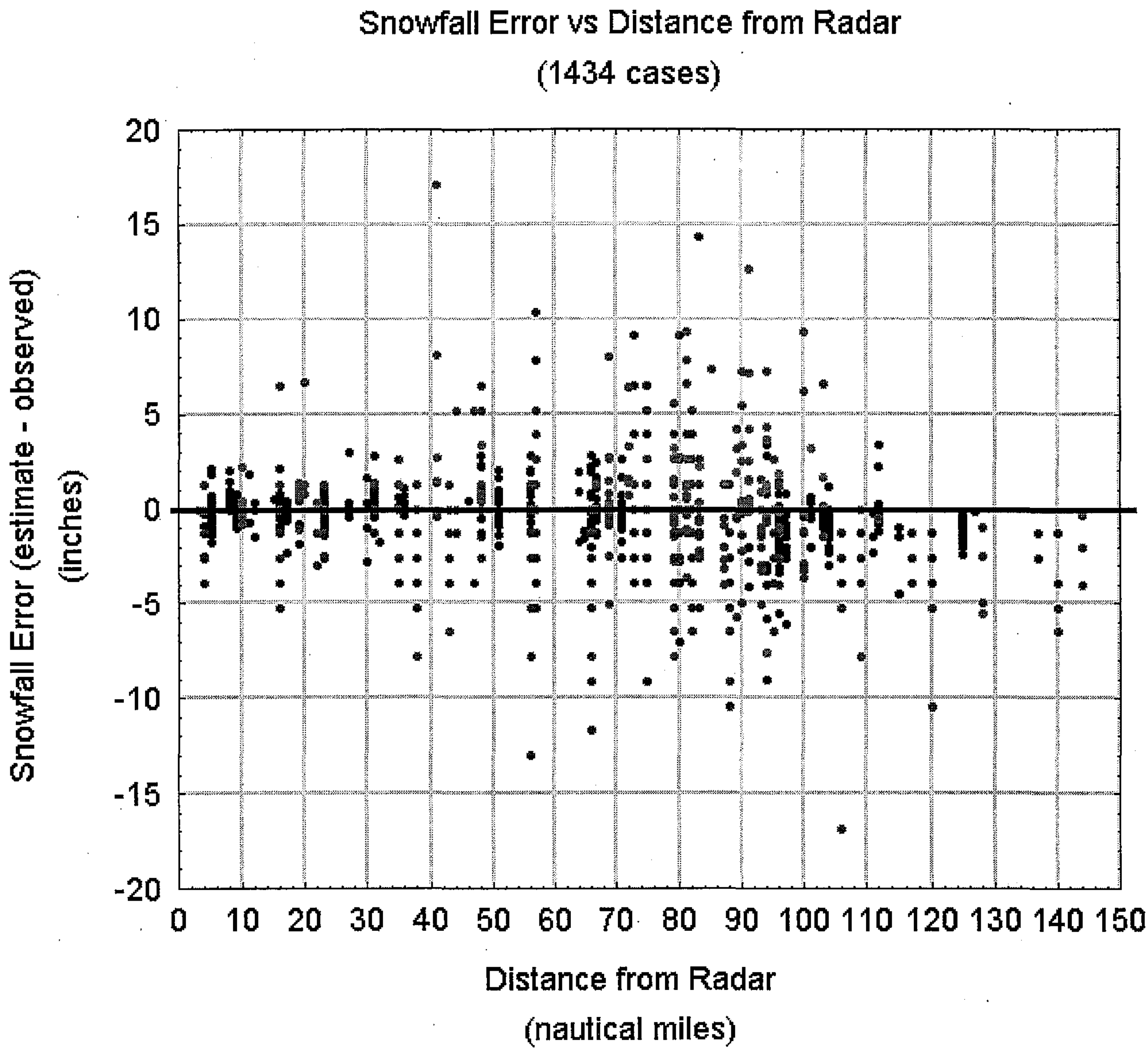

Snowfall Error
(spotters within 80 nmi - 356 cases)
No of obs
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
289
27
21
13
6
0
< -3
-3,-2
-2,-1
-1,1
1,2
2,3
Snowfall Error (estimate - observed)
(inches)

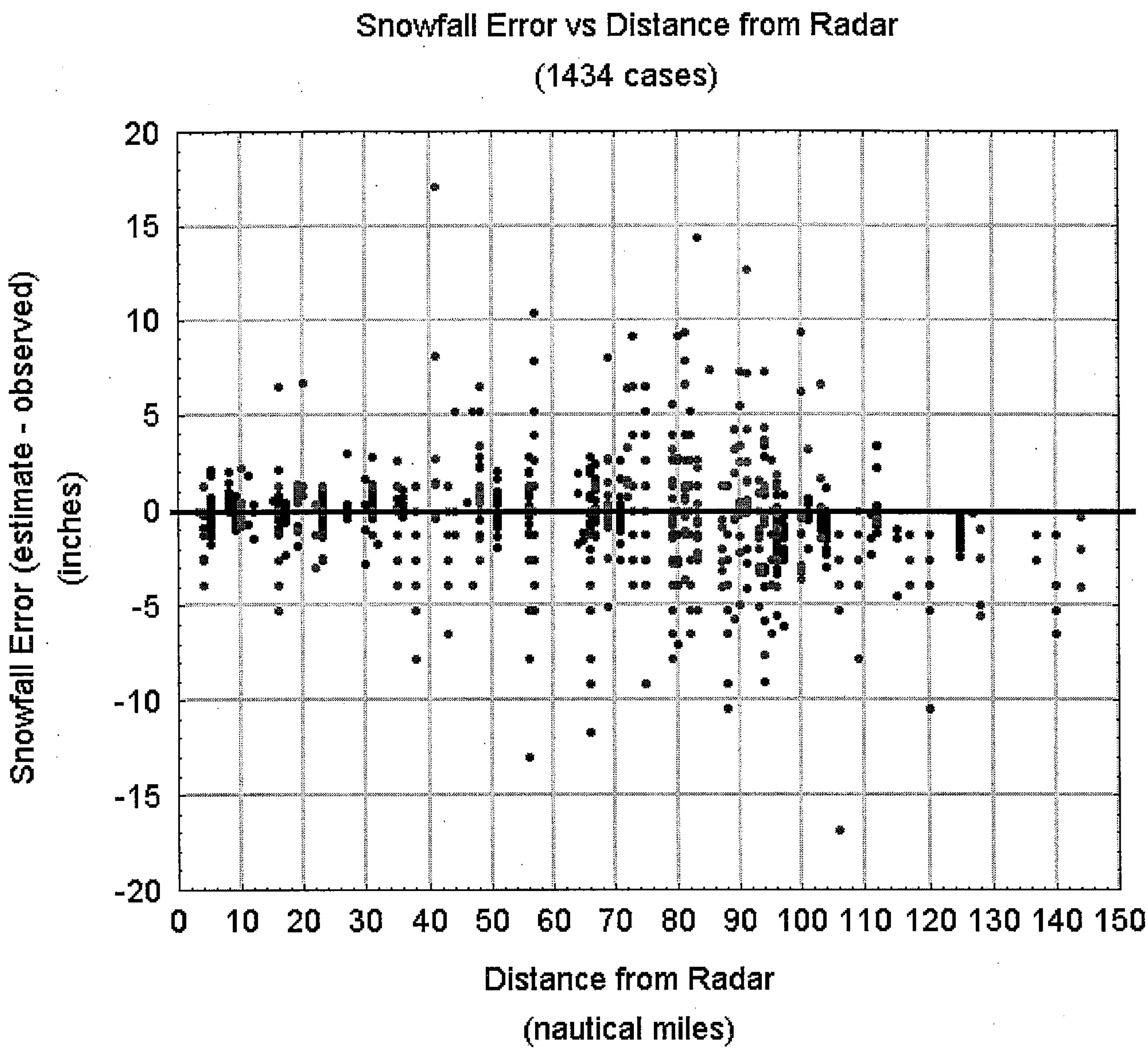

Radar Estimated Snowfall vs Observed Snowfall
(storm total - spotters within 80 nmi - 233 cases)
Correlation: r = .66618
Radar Estimated Snowfall
(inches)
Observed Snowfall
(inches)
0
1
2
3
4
5
6
7
8
9

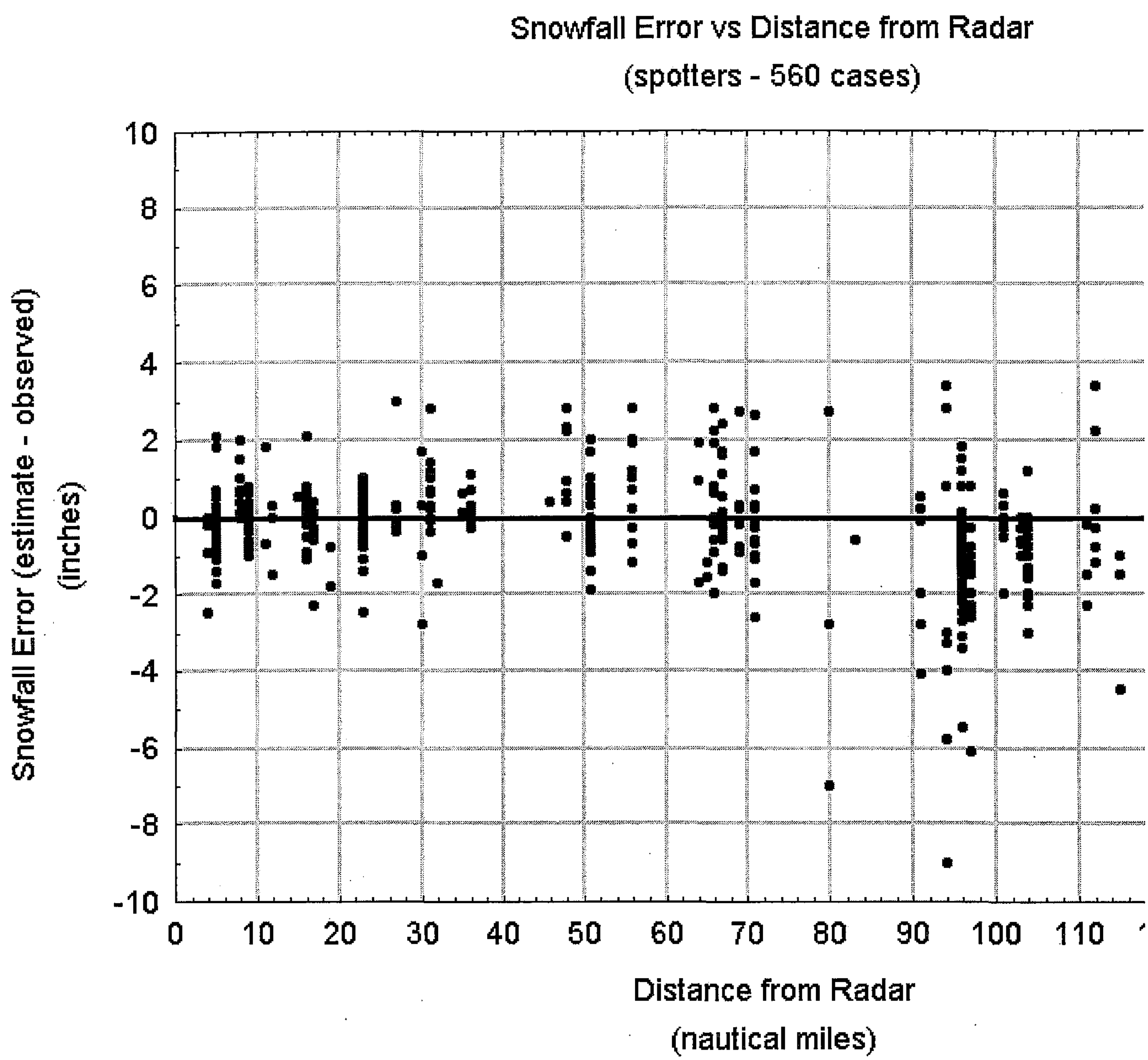

Radar Estimated Snowfall vs Observed Snowfall
(storm total - spotters within 80 nmi - 233 cases)
Correlation: r = .66618
Radar Estimated Snowfall
(inches)
Observed Snowfall
(inches)
0
1
2
3
4
5
6
7
8
9

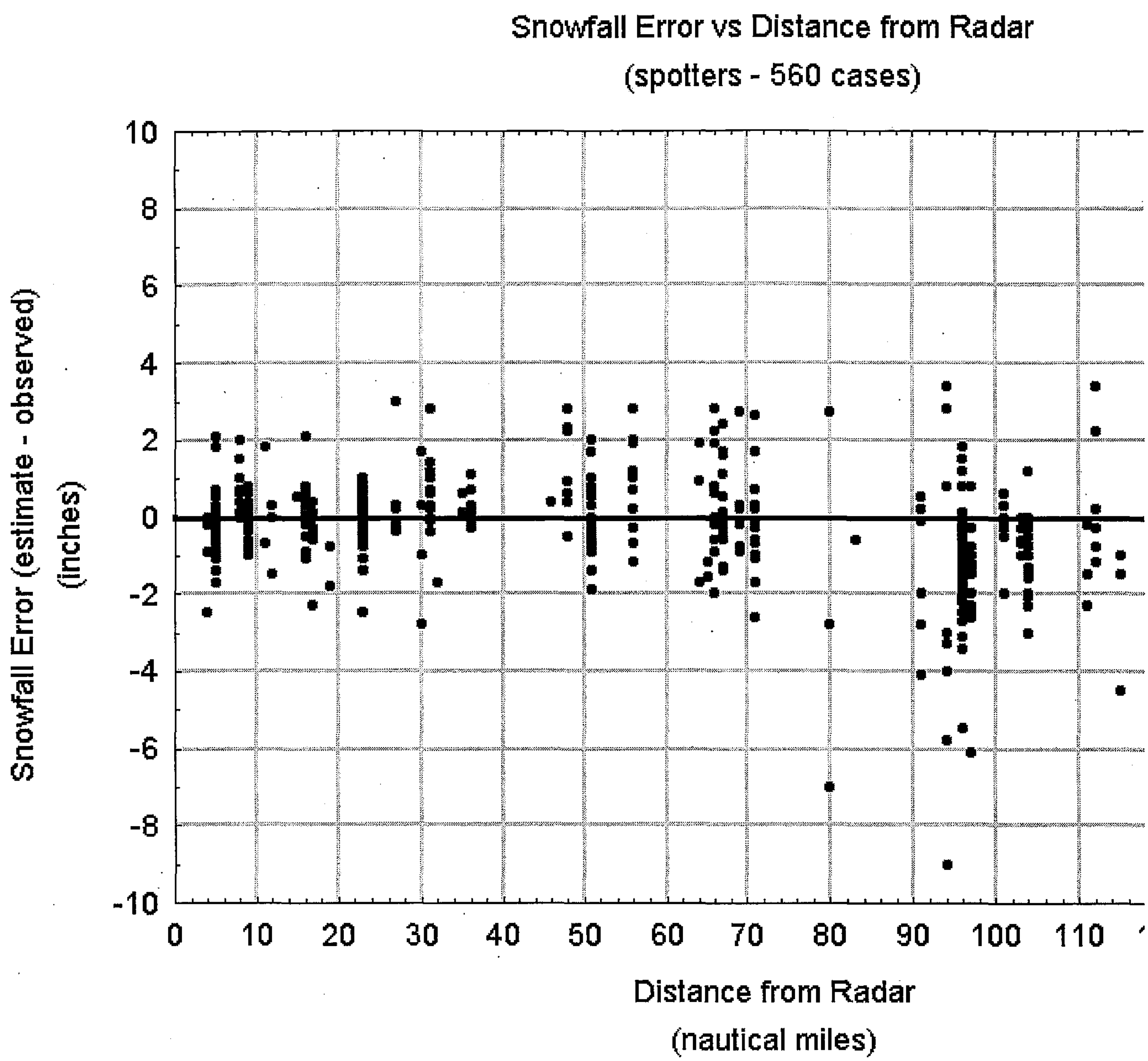

Radar Estimated Snowfall vs Observed Snowfall
(1434 cases)
Correlation: r = .39231
Radar Estimated Snowfall
(inches)
Observed Snowfall
(inches)
0
2
4
6
8
10
12
14
16
18
20

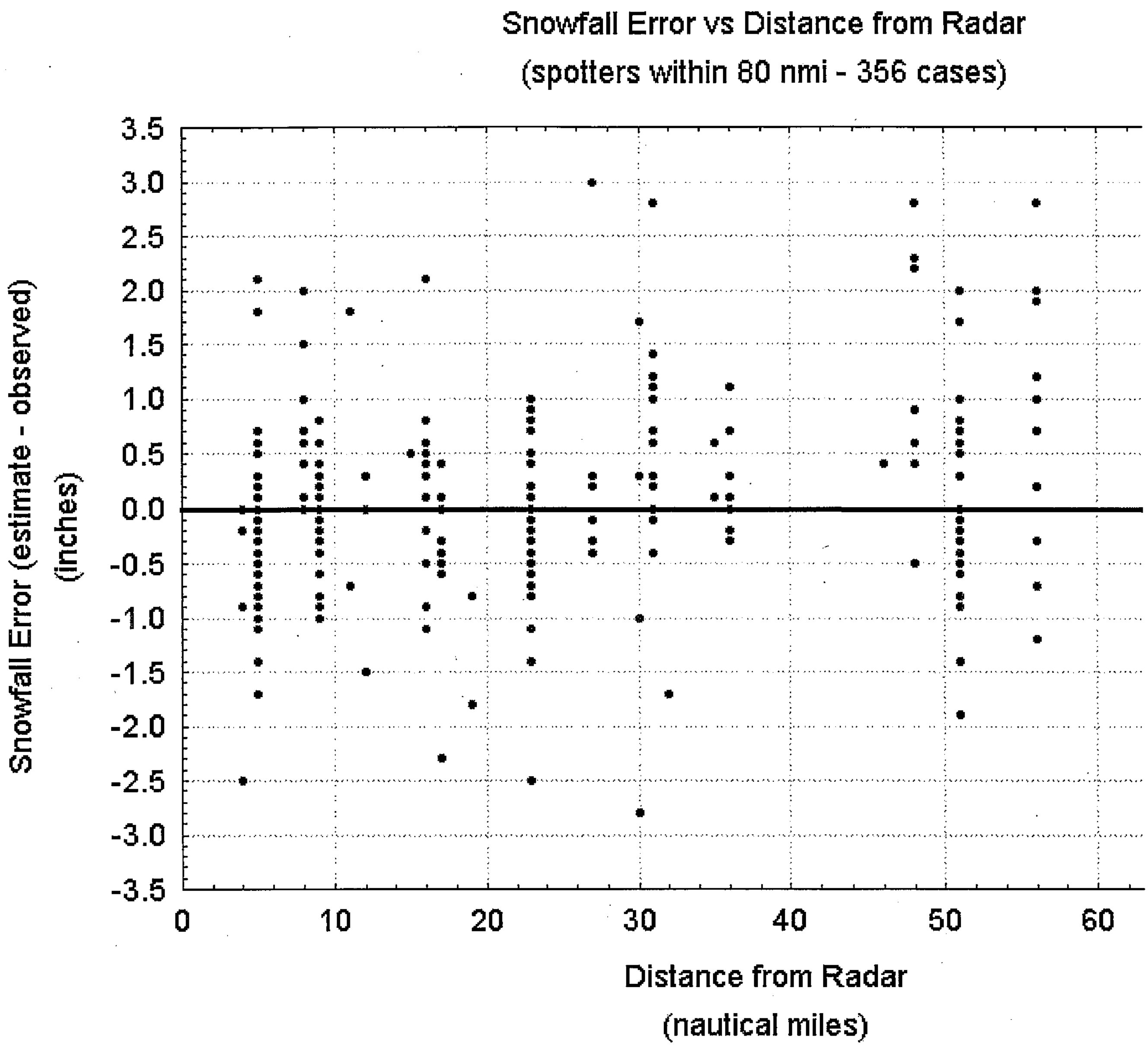

Radar Estimated Snowfall vs Observed Snowfall
(1434 cases)
Correlation: r = .39231
Radar Estimated Snowfall
(inches)
0
2
4
6
8
10
12
14
16
18
20
Observed Snowfall
(inches)

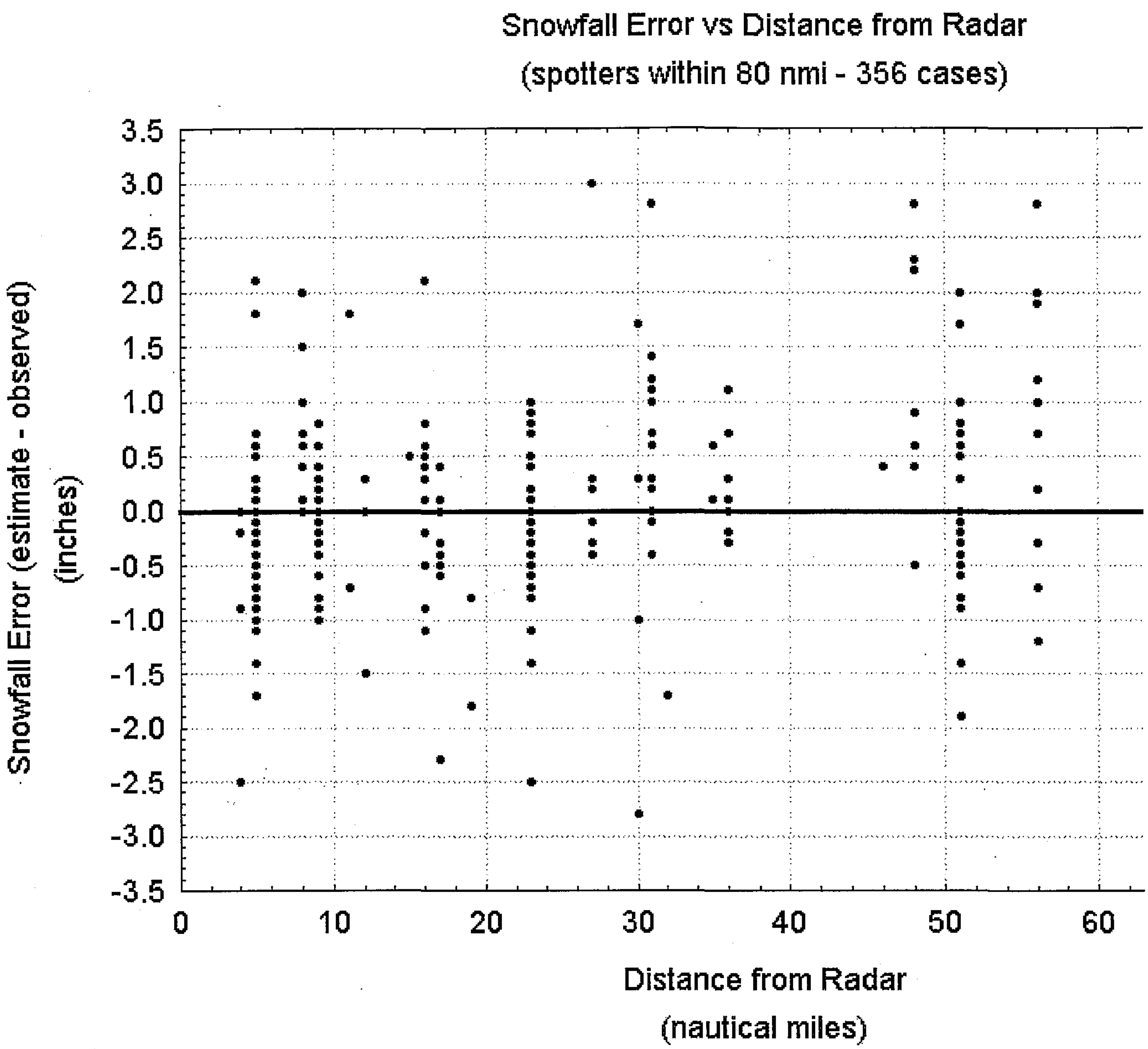

Snowfall Error vs Distance from Radar
(1434 cases)
Snowfall Error (estimate - observed)
(inches)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Distance from Radar
(nautical miles)

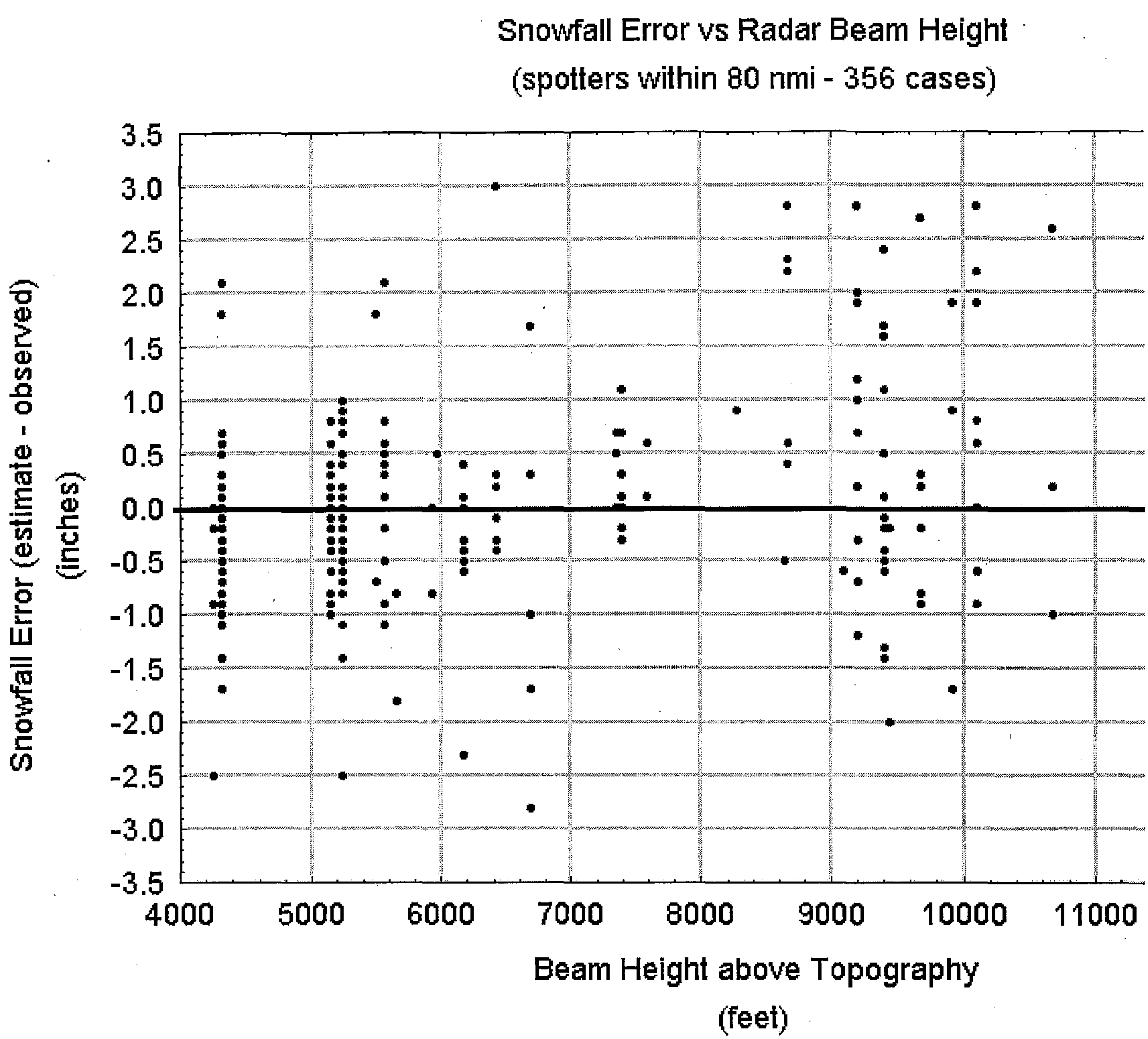

Snowfall Error vs Distance from Radar
(1434 cases)
Snowfall Error (estimate - observed)
(inches)
20
15
10
5
0
-5
-10
-15
-20
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Distance from Radar
(nautical miles)

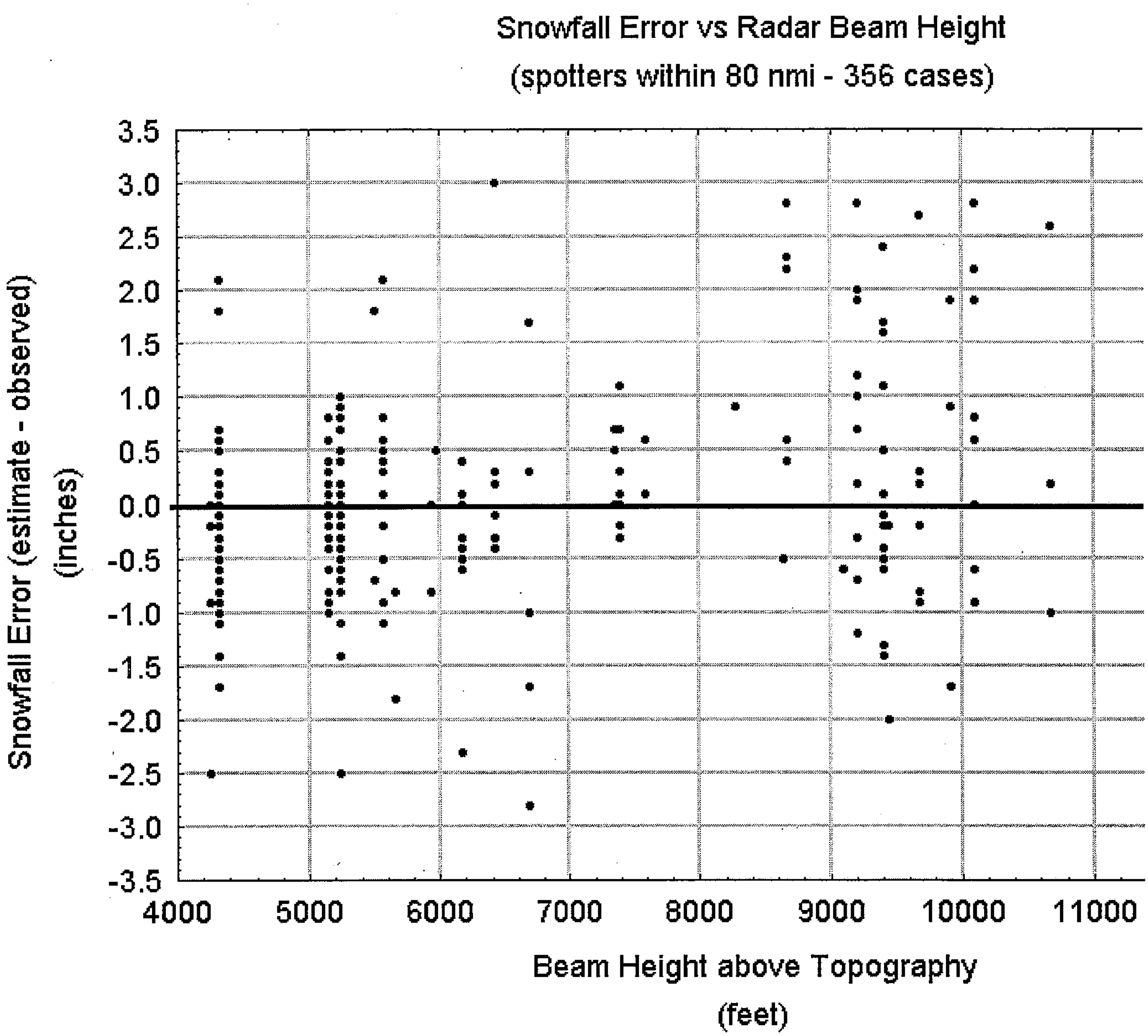

Snowfall Error vs Distance from Radar
(spotters - 560 cases)
Snowfall Error (estimate - observed)
(inches)
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
10
20
30
40
50
60
70
80
90
100
110
Distance from Radar
(nautical miles)

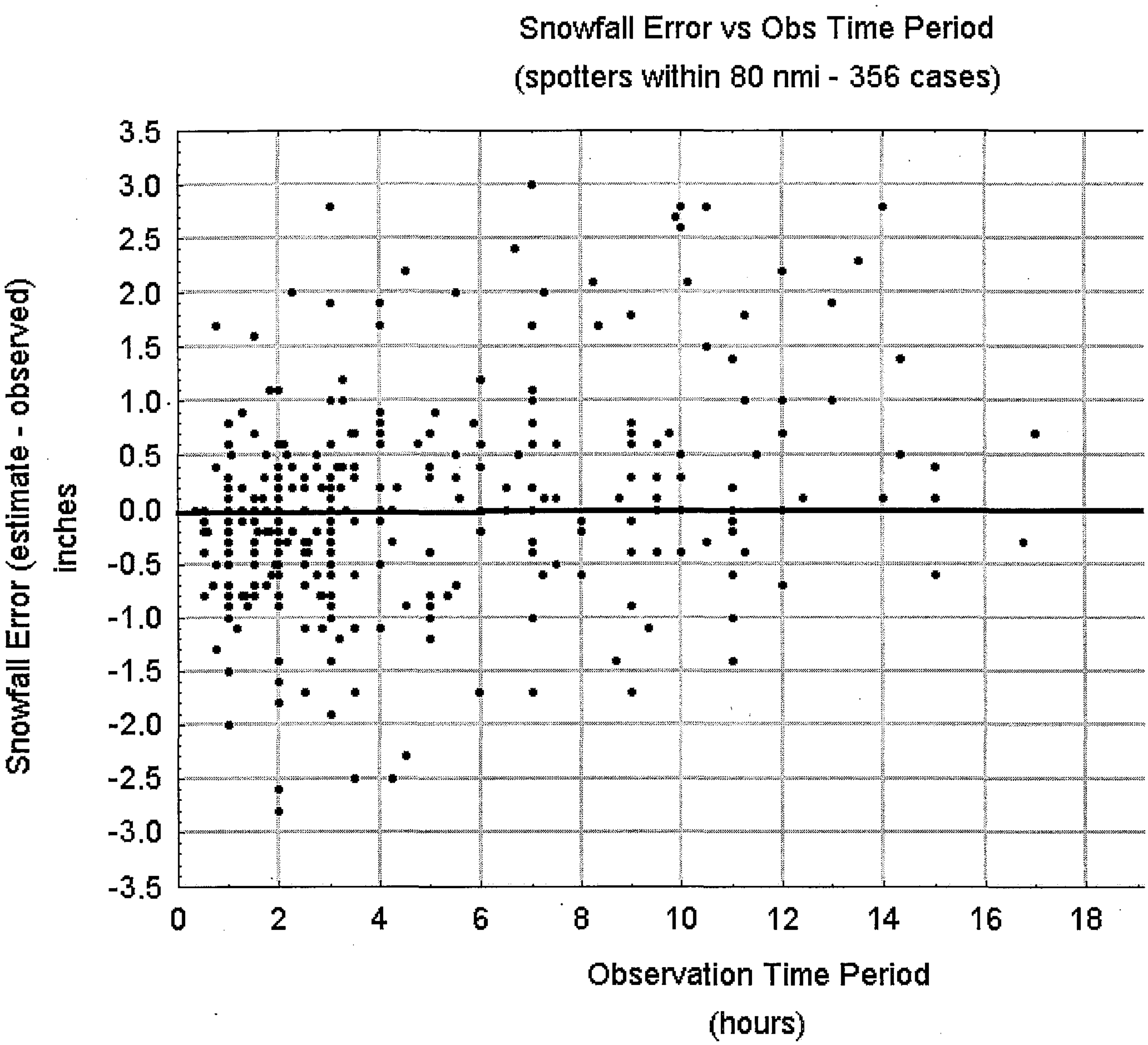

Snowfall Error vs Distance from Radar
(spotters - 560 cases)
Snowfall Error (estimate - observed)
(inches)
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
10
20
30
40
50
60
70
80
90
100
110
Distance from Radar
(nautical miles)

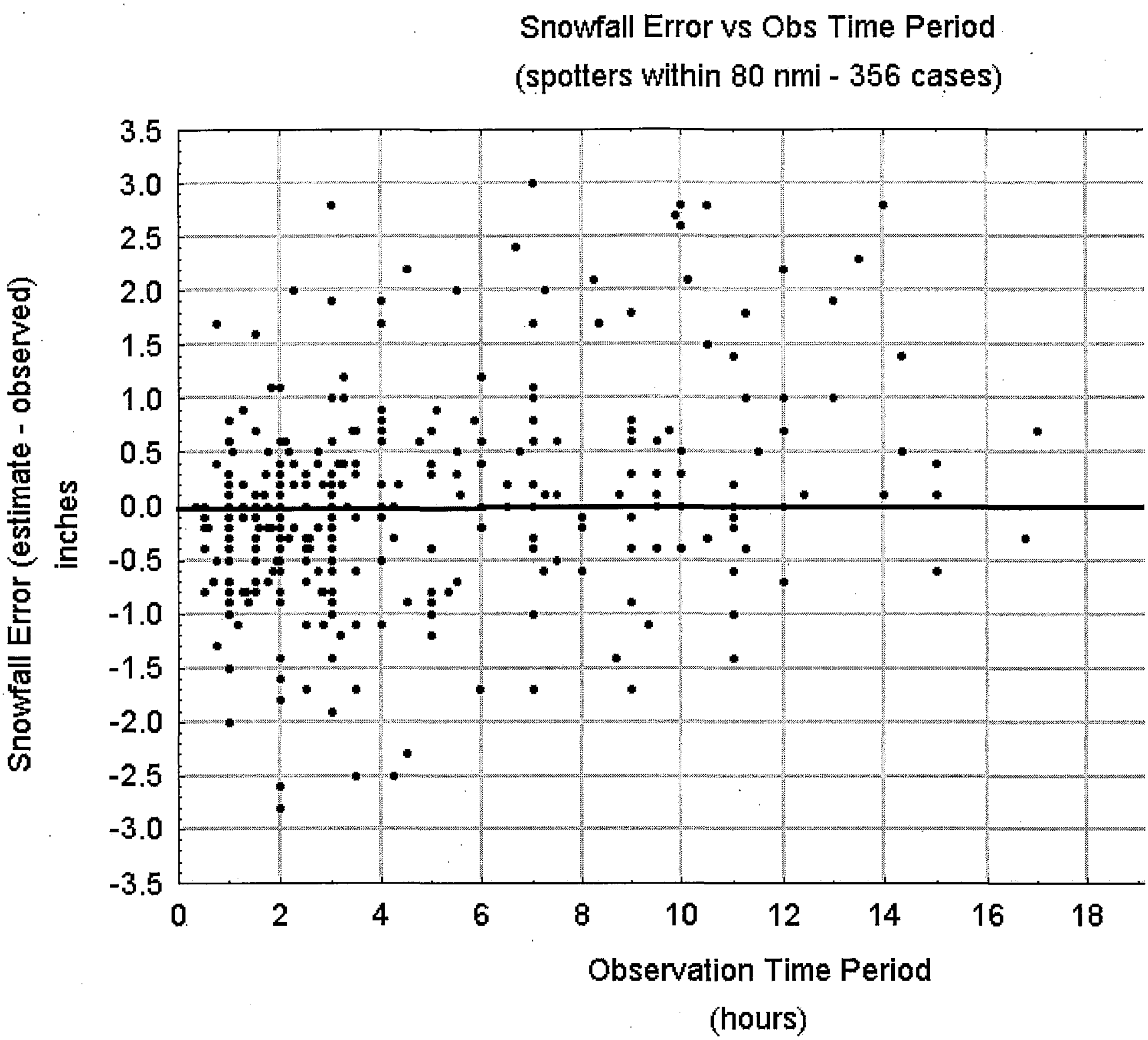

Snowfall Error vs Distance from Radar
(spotters within 80 nmi - 356 cases)
Snowfall Error (estimate - observed)
(inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0
10
20
30
40
50
60
Distance from Radar
(nautical miles)


Snowfall Error vs Distance from Radar
(spotters within 80 nmi - 356 cases)
Snowfall Error (estimate - observed)
(inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0
10
20
30
40
50
60
Distance from Radar
(nautical miles)


Snowfall Error vs Radar Beam Height
(spotters within 80 nmi - 356 cases)
Snowfall Error (estimate - observed)
(inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
4000
5000
6000
7000
8000
9000
10000
11000
Beam Height above Topography
(feet)


Snowfall Error vs Radar Beam Height
(spotters within 80 nmi - 356 cases)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
Snowfall Error (estimate - observed)
(inches)
4000
5000
6000
7000
8000
9000
10000
11000
Beam Height above Topography
(feet)


Snowfall Error vs Obs Time Period
(spotters within 80 nmi - 356 cases)
Snowfall Error (estimate - observed)
inches
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0
2
4
6
8
10
12
14
16
18
Observation Time Period
(hours)


Snowfall Error vs Obs Time Period
(spotters within 80 nmi - 356 cases)
Snowfall Error (estimate - observed)
inches
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0
2
4
6
8
10
12
14
16
18
Observation Time Period
(hours)