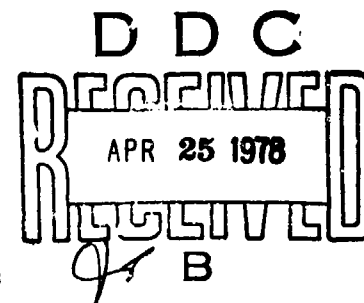


CORRELATION OF RADAR REFLECTIVITY AND SNOWFALL
RATE DURING MODERATE TO HEAVY SNOWRoland J. Boucher
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1. INTRODUCTION

An increasing number of radar measurements are becoming useful in operational applications such as determining expected run-off in watersheds by river forecast centers, Wilson (1970). The rainfall determined by radar measurements is not always precise, because radar reflectivity varies with the precipitation drop size spectra, yet, this mode supplies required information immediately for a sufficiently complete precipitation totalizer to provide a dependable streamflow forecast.

As might be expected, radar reflectivity is also related to snowfall rates. A few projects have used this relationship to determine snowfall over an area by using established Z-R relationships. Carlson and Marshall (1972) at McGill University and Wilson (1975) in the Eastern Great Lakes Area have used radar reflectivity to measure snowfall over a storm period or for an entire (winter) season.

In the Air Force Geophysics Laboratory (AFGL) Weather Radar Branch project being discussed here, the objective is to evaluate radar reflectivity as a means of determining snowfall rate on a short term basis and to ultimately revise snow accumulation forecasts during major snowstorms. The utility of such a successful technique would be to give immediate and continuous information on runway conditions at air bases or airports within the radar display area and to determine ground travel conditions based on snowfall rate and total depth accumulated. A second objective may permit accurate updates or revisions of snowfall forecasts at 1 to 2 hour intervals. Information of this nature, if reliable, would greatly serve military as well as civilian operations.

2. EXPERIMENTS

So far, three snowstorms have been observed by AFGL radars, two with the CPS-9, 3.2 cm, and one with both the CPS-9 and the Porcupine Doppler, 5.4 cm. Accurate snow accumulation measurements were made at different locations within a radius of 51 km from the radar site by as many as five observers. The snow accumulation measurements were ordinarily made at approximately half hour intervals. Unfortunately for this project, detailed observations of this nature are not normally routinely available. In addition to the snow increments, notes were kept by the observers regarding the type of snow crystals. The hourly air temperatures were also recorded, as well as the wind direction and estimated or measured wind speed. Some of the observers also were able to measure precipitation (water content) hourly.

3. RADAR OBSERVATIONS

The radar observations were mostly PPI at 0° elevation for the CPS-9 and 1° and 2° elevation for the Porcupine Doppler. The CPS-9 PPI's were processed on the Weather Radar Processor and Display and recorded at intervals ranging from 3 to no more than 10 minutes, Petrocchi (1976). This display, later photographed in 35 mm color, is presented in four colors, the range of which can be adjusted to cover the distribution of reflectivity values adequate for the particular storm. This range, even after recording, may again be readjusted if necessary. In the three storms analyzed to date, the effective radar reflectivity ranged from 10 to 30 dBZ. The CPS-9 observations were recorded at intervals of a few minutes (3 to 10 minutes). In comparison, the Porcupine Doppler observations available for this project were limited to antenna elevations of 1° or 2° taken at half hour intervals.

The Doppler radar equipment presents the current data on TV-type screens with 16 color-coded contours of three different parameters: a. logarithmic reflectivity; b. radial velocity; c. Doppler variance. These data are also recorded on multichannel tape which can be played back on the monitors for further study or measurements. Usually, in a case study, selected displays are photographed on 35 mm color film and the transparencies can then be easily used for reflectivity and/or wind measurements.

4. SNOWFALL RATE MEASUREMENT

The other equally important measurement is an accurate determination of the snow accumulation at an observation point during a half-hour period. Snow accumulation is defined as the depth of the snow that falls during the half-hour measuring interval. In order to obtain an accurate measurement of this variable element, several requirements must be met. First, the measuring surface needs to be a two foot square, thin board, such as plywood or masonite, or other non-metallic substance, to prevent any melting of the collected snow. Next, the measuring surface is positioned on the pre-existing snow surface at the same level as the surrounding snow. After every accumulation measurement, the measuring surface is completely cleaned and again reset level with the snow cover. Making the level of the measuring surface coincide with the surrounding snow eliminates the tendency for drifting of newly fallen snow into a depression or, off a surface higher than the surrounding undisturbed snow. This is a wise move because snowstorms are generally accompanied by moderate or even stronger winds and snow drifting frequently occurs and interferes with accurate snowfall rate

measurement. The drifting may either detract from or add snow to the amount which represents the true snowfall. In this respect, a good technique would be to select a sampling spot which, the observer has reason to expect, will be least susceptible to drifting. As the wind increases, this type of area becomes more difficult to find. So it may be advisable to use two sampling regions, and use the data from the region experiencing the least amount of drifting during the storm.

The AFGL experiment, so far, indicates that with snow accumulation rates of one inch or more per hour, half hourly snowfall measurements are highly desirable in order to correlate the snowfall rate variations and, the reflectivity changes, both of which vary substantially even in a period broadly referred to as "steady snow."

5. CORRELATION OF DBZ AND RATE OF SNOWFALL

By projecting the 35 mm color transparencies of the CPS-9 display onto a simple range map on which the snow observing points are indicated, reflectivity values are obtained at each snow observing point for each radar observation. There were two 1976-77 winter storms, 29 December 1976 and 7 January 1977 and a single storm in the previous winter, 16-17 March 1976. The 29 December and 7 January storms demonstrated emphatically the difference between a dry snow with excellent correlation between reflectivity and snowfall rate and a wet, sticky snow with no useful correlation. During the 29 December storm, the temperature, in the snow, ranged from 17° to 23°F. In the initial correlation, $r = 0.76$, the snow accumulation and the radar reflectivity were considered to be simultaneous events. In the final correlation $r = 0.85$, Fig. 1. This correlation improved when the half hour snowfall rate was correlated with the half hour reflectivity average which began 15 minutes before the snowfall measuring period. This time difference was used for all snow measuring points except at the radar site where both values were correlated simultaneously. Increasing the time difference to 30 minutes did not appreciably change the correlation at either Lexington or Bedford, but there was a substantial drop at Chelmsford and Reading.

In the second storm, 7 January, the snow was very wet as surface temperatures ranged from 32.3° to 34°F. Snow stuck in masses on tree branches; a number of limbs were seriously overloaded and cracked or broken off. The wet snow was difficult to plow, and snow stuck to the lower half of the radar antenna. At one of the measuring points, Hingham, rain fell for at least one hour. All of the measuring points reported the snow as wet, and there were many reports of conglomerate flakes and rimed crystals. The snow in the lower levels was quite definitely in the bright band area, i.e. the reflectivity was high but the snowfall rate was significantly lower. At Dedham, for example, reflectivity ranged from 14 to as high as 29 dBZ with the snowfall rate no higher than 0.47 in hr^{-1} . The correlation coefficient for this storm was consequently very low, $r = 0.345$, Fig. 2.

For wet snow, with a high bright band reflectivity, the snowfall rate cannot be reliably nor usefully determined from CPS-9 radar

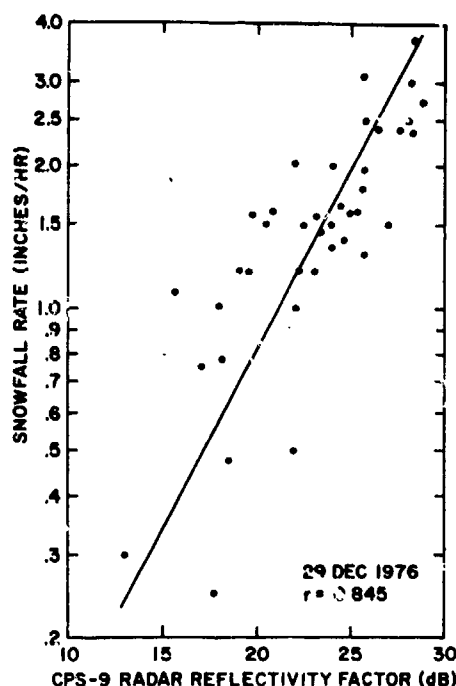


Fig. 1. Correlation of CPS-9 dBZ ($\text{dBZ} = 10 \log \text{ of } Z, Z \text{ mm}^6 \text{m}^{-3}$) and snowfall rate (inches hr^{-1}) for 29 December dry snow, surface temperature 17 to 23°F. Snow measurements at half-hourly intervals, reflectivity every 10 min.

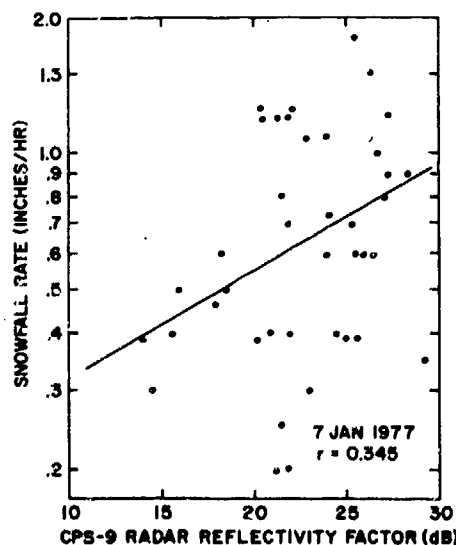


Fig. 2. Correlation of CPS-9 dBZ and snowfall rate for 7 January wet snow, surface temperature 32.3 to 34°F. Snow measurements at half-hourly intervals, reflectivity every 10 min.

reflectivity. In the 7 January case, the snowfall rate average, for the observed part of the storm, was 0.75 in hr^{-1} as compared to a nearly double

rate of 1.46 in hr⁻¹ for the 29 December storm. Reflectivity, however, for 7 January averaged 22.3 dBZ compared to a slightly lower average of 21.5 dBZ for 29 December. The wider range between reflectivity and snowfall rate on 7 January was no doubt due to higher reflectivity because of the wetness of the snow particles and, possibly to some extent, the riming of snow particles. One of the observers reported wet dendrites. This type of crystal has been reported by several researchers, notably Wilson (1975) and Ohtake and Henmi (1970), to give higher reflectivities than other crystal forms. These two storms, then, provide very contrasting results. The storm of 29 December was a case where reflectivity gave a very reliable index of snowfall rate, provided a 15 minute lag was used between the reflectivity and snowfall measurements. At the other extreme, the low level temperature in another important snowstorm on 7 January was high enough so that all the snow accumulation measurers reported wet snow. This factor increased the reflectivity to the point where the indicated snowfall rate was appreciably higher than on 29 December, and yet the actual snowfall rate was, on the average, half that of 29 December. In addition, changes in snowfall rate and reflectivity on 7 January exhibited no persistent correlation. On this occasion, radar reflectivity was therefore not usable as an index of snowfall rate.

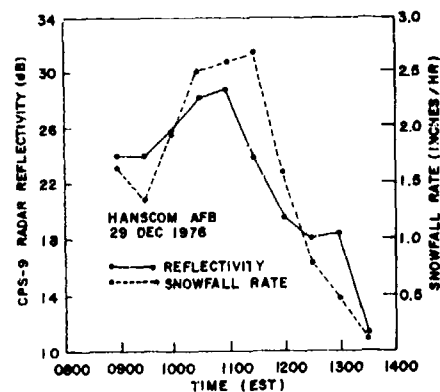


Fig. 3. Time diagram of dBZ over Hanscom AFB and snowfall rate at Hanscom for dry snow of 29 December showing good correlation.

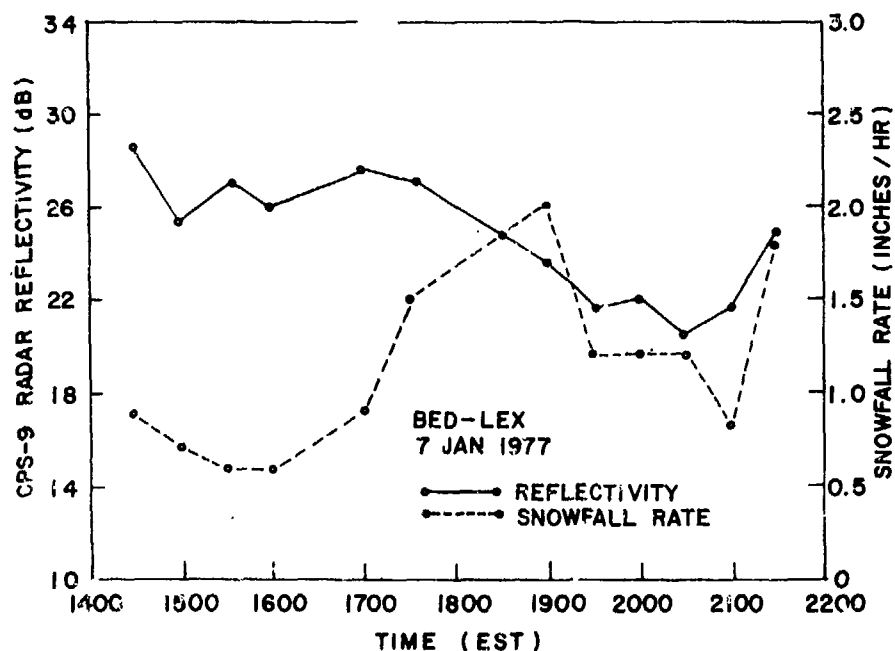


Fig. 4. Time diagram of dBZ over Hanscom-Lexington and snowfall rate at Hanscom-Lexington for wet snow of 7 January showing lack of correlation.

Fig. 3 is a joint plot for the Hanscom measuring point on 29 December. It gives the snowfall rate in inches per hour and radar reflectivity in dBZ. This diagram shows very close correlation between reflectivity and snowfall rate, accounting for the $r = 0.85$ in Fig. 1

Fig. 4, on the other hand, for 7 January shows the very poor correlation between reflectivity and snowfall rate in the case of wet snow. At the start, the reflectivity is as high as it was during the heaviest part of the 29 December storm, and yet, snowfall was less than 1 inch per hour. However, as the snowfall rate increased to between 1 and 2

inches, from 1730 and 2030, the reflectivity decreased. In brief, the lack of correlation between reflectivity and snowfall is quite obvious and the low correlation coefficient of $r = 0.345$ (Fig. 2) is not surprising.

A third sample, observed on 16 March 1976, was another major New England snowstorm, Fig. 5. Temperatures during this storm, while higher than on 29 December, ranged between 29° and 31°F at the radar site, or 3° to 5°F lower than on 7 January. Rain fell at Boston and points south, and even the observer at Lexington reported ice pellets (sleet) mixed with the snow at 1952 and 2030 EST. At 2001,

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during the period when the Lexington ice pellets were being reported, the reflectivity at 1° elevation on the Porcupine Doppler radar was 26 dBZ above Lexington, (equivalent to 1.3 in hr⁻¹ of snow), but the measured snowfall rate at Lexington during this period was only 0.47 in hr⁻¹. However, at 2° elevation, the reflectivity was down to 12 dBZ, (equivalent to 0.30 in hr⁻¹). This rapid change of reflectivity with elevation indicates that the much higher dBZ value at 1° elevation was most likely due to a temporary, shallow bright band effect.

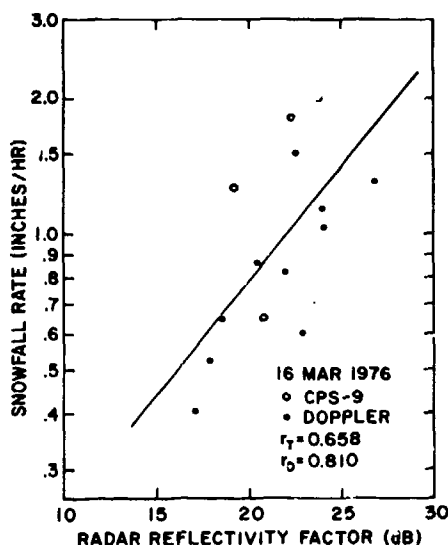


Fig. 5. Correlation of CPS-9 and Porcupine Doppler radar dBZ and snowfall rate for dry snow of 16 March.

The Porcupine Doppler PPI observations at 1° and 2° elevations were made only every half hour. Radar reflectivity at a stationary point in the atmosphere varies considerably and rapidly. In order to improve the reliability of radar derived snowfall rate estimates, more radar measurements at 10 minute intervals or less are necessary for adequate coverage.

Fig. 5 shows what appears as a good correlation between snowfall rate and reflectivity on 16 March 1976. For the ten Doppler radar points, $r = 0.81$. Using both the Doppler and four CPS-9 points together results in a correlation $r = 0.66$. It is not known whether this difference can be attributed to a lack of close agreement between the Doppler and the CPS-9 radars in the determination of the reflectivity values. In the 1977-78 snow season, simultaneous reflectivity measurements from both radars will be compared with snowfall rate measurement to establish a comparison.

6. CONCLUSION

The preliminary results from this study in the use of radar reflectivity to determine snowfall rate show very encouraging results in dry snow falling through sub-freezing temperatures. Snow, falling through the lower atmosphere with temperatures near or slightly above freezing, becomes wet, i.e. snow crystals are covered with small water drops. This modification process substantially increases the reflectivity of the snow

particles and the resulting "bright band" reflectivity will indicate snowfall rates in excess of the measured values.

Observations have, so far, been limited to three major snowstorms having differing degrees of snowfall wetness and snowfall rate determination accuracy. These variations warrant additional radar reflectivity and accurate snowfall rate measurements. A sufficient amount of such data will establish the consistency of the radar reflectivity vs. snowfall rate correlation i.e. to what extent a standard correlation can be established to determine the snowfall rate from the radar measurements. The long term objective of the project will be to utilize the radar estimated snowfall rate as a technique to update 1 - 2 hour snow accumulation forecasts for the area downwind of the radar site.

Acknowledgements The success of this project would not have been possible without the diligent and accurate measurements of snowfall rates by five volunteer observers: H. A. Brown, Chelmsford; J. H. Conover, Hanscom AFB and Dedham; R. E. Lautzenheiser, Reading; H. S. Muench, Hanscom AFB and Lexington; F. R. Skilling, Hingham and the author at the radar site.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER AFGL-TR-78-0079	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) CORRELATION OF RADAR REFLECTIVITY AND SNOWFALL RATE DURING MODERATE TO HEAVY SNOW		5. TYPE OF REPORT & PERIOD COVERED Scientific. Interim.	
7. AUTHOR(s) Roland J. Boucher		6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (LYW) Hanscom Air Force Base Massachusetts 01731		8. CONTRACT OR GRANT NUMBER(s) Interim rept.	
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (LYW) Hanscom Air Force Base Massachusetts 01731		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 6670701 1207 2101F	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 126p.		13. REPORT DATE 3 Apr 1978	
		12. NUMBER OF PAGES 4	
		15. SECURITY CLASS. (of this report) Unclassified	
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)			
18. SUPPLEMENTARY NOTES Reprinted from Preprint Volume: 18th Conference on Radar Meteorology, Mar. 28-31, 1978, Atlanta, Ga. Published by the American Meteorological Society, Boston, Mass., pp 328-331.			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Radar Reflectivity Snowfall Rate Dry Snow Wet Snow Nowcasting Snow			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Radar reflectivity in falling snow varies slightly with prevailing types of snow crystals. Experimental results in major New England snowstorms indicate that the most significant difference in determining the rate of snowfall by radar reflectivity occurs between wet and dry snow. In dry snow (surface temperature below freezing), the correlation coefficient between radar returns and snowfall rate runs as high as $r = 0.85$. However, in wet snow (surface temperature above freezing) with bright band characteristics, the correlation coefficient is very poor, as low as $\rightarrow$			

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$r = 0.35$. In spite of this anticipated problem, radar is a reliable means of determining dry snowfall rates and provides a potential technique for snowfall forecast improvement.

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