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EXPERIMENTAL STUDY ON THE MEASUREMENT OF SNOWFALL BY RADAR

by

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Abstract

An X-band radar was used to estimate the total water equivalent of snow during 9 storms above 4 snow gauges. The radar measurements were calibrated by the daily amount of snowfall measured by each of the gauges in turn. All the time it was assumed that the exponent in the Z-R relationship is equal to 2.0. On the average the coefficient of correlation of the logarithms of the radar-derived and gauge-measured water equivalent of snow was 0.96. The standard error of estimate was 0.12, which indicates that 68 % of radar-derived estimates fall in the interval −24 % to + 32 % of the »true» daily value of the water equivalent. When the Gunn-Marshall relation ($Z = 2000\ R^{2.0}$) was applied to the data, the coefficient of correlation was 0.89 and the standard error 0.17 (corresponding to the interval −33 % to +49 % of the water equivalent).

1. *Introduction*

Of all the measurements of basic meteorological parameters, the determination of snowfall perhaps encounters the greatest difficulties. The horizontal distribution of snowfall is conventionally calculated from point values, which often contain great errors (Golubev [3], Rodda [12]), however, due to several reasons, the wind being the most important. Quite recently new methods have been developed to estimate the point values of snowfall (snow pillows, Tollan [14], Lemmelä [8]) or its areal distributions (measuring from a helicopter the attenuation of natural radiactive radiation by snow on the ground, Dahl and Ødegaard [2]). Radar has also been used to measure the snowfall intensities during the last two decades, with varying success.

The purpose of the present study is to show that radar is capable of giving a reliable estimate of snowfall, especially if the radar measurements are calibrated by a reference gauge on the ground.

As in the case of the measurements of rainfall by radar, snowfall measurements, too, are based on the relation between the radar reflectivity factor Z (measured by radar) and the precpitation rate R. Without exception, all radar meteorologists agree that the relationship between these quantities is of the form $Z = aR^b$, where a and b are coefficients. The main problem in the measurement of precipitation by radar is the variation in coefficients a and b with the variation in particle size distribution. If this is a difficult problem in the measurement of rainfall, it is far more difficult in the case of snowfall. This is caused by the fact that the reflection of electromagnetic radiation from solid hydrometeors is no longer a simple function of the size of the particles, as the shape and structure of the ice crystals affect the reflection. This was demonstrated by Ohtake and Henmi [11], who gave Z-R relationships for six main types of crystals as well as for graupel and hail. Their values for coefficient a (in the equation $Z = aR^b$) ranged from 330 to 3300 and the variation in exponent b was from 1.5 to 2.3. Their findings are of fundamental importance, but in practice the determination of the distribution of crystal types in snowfall is impossible in routine work.

Average Z-R relationships for aggregate snowflakes have been reported by a number of authors. Imai *et al.* [6] found that during a two hour storm coefficient a first changed from 600 to 2400 and then back to 1800. Exponent b was kept equal to 1.8 all the time. In a frequently referenced paper, Gunn and Marshall [4] gave the relationship $Z = 2000\,R^{2.0}$ for aggregate snowflakes. Imai [5] introduced $Z = 540\,R^{2.0}$ for »rather dry snow» and $Z = 2100\,R^{2.0}$ for »wet snow». Later Sekhon and Srivastava [13] reanalysed the data of Imai *et al.* [6], Magono [9], Gunn and Marshall [4] and Ohtake [10], giving as a combined result

$Z = 1780\,R^{2.21}$. The above examples show that even averaged Z-R relationships vary widely, depending on the material used.

In order to avoid the problem of finding out a proper Z-R relation which would be valid for certain types of precipitation, WILSON [15], [16] suggested the use of a reference gauge to calibrate the radar measurements. He successfully used the method for rainfall measurements by radar. As far as the author knows, no one has applied this idea to snowfall measurements. Hence it is worth trying to calibrate the radar to show an equal amount of snow above a reference gauge and then evaluate the Z-R relationship obtained outside the reference gauge.

2. *Data collection*

An X-band radar (Selenia Meteor RMT — 1L, for specifications see JATILA *et al.* [7]) was used to measure the values of the radar reflectivity factor. Measurements were carried out at time intervals of 5

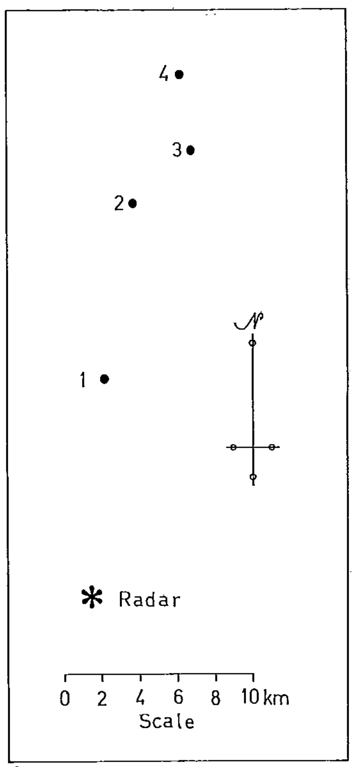

Fig. 1. The locations of the snow gauges and the radar.

minutes, changing the gain (6 dB steps) of the radar receiver manually and filming the scope for each gain value. From the radar pictures, the reflected power was read above each gauge. If the snowfall consists of showers the procedure will involve serious errors due to the wind shift. During the storms investigated here, the horizontal gradient of snowfall intensity was small, however, and hence it was assumed that nothing would have been gained if the shift had been taken into account.

To compare the radar-measured values with the snowfall amounts on the ground, four observation sites were established (Fig. 1). Snowfall amounts were gathered with normal nonrecording rain gauges (area of the orifice 500 sq. cm) with a Nipher shelter. Great care was paid to the locations of the gauges to minimize the error due to the wind. A typical place was an open area (diameter about 50 meters) inside a forest. Nothing was done to correct the observed amounts of melted snow.

The calibration of the radar was done in the following way. Such a value of coefficient a was sought (keeping exponent b equal to 2.0 all the time) which made the amount of radar-measured snowfall above the reference gauge the same as the snowfall amount measured by the gauge. This was done for each storm using each of the gauges as the reference gauge in turn. These values of a were then used to derive the radar-measured estimates of snowfall amount above the other three gauges. The Gunn-Marshall relationship $Z = 2000\,R^{2.0}$ was also applied to the data.

Table 1. Parameters characterizing each storm. The temperature is the mean temperature of the observations during each storm made by the Finnish Meteorological Institute, Helsinki Airport (located between gauges 1 and 2 in Fig. 1.). The mean water equivalent of snow (mmw) is the mean value of the measurements of all the gauges 1—4.

Date	Duration hours	Temperature °C	Mean water equivalent mmw
10 Dec. 1971	11.5	−1.5	3.65
14 Dec. 1971	6.9	−1.1	0.75
21 Dec. 1971	4.0	0.0	9.55
19 Jan. 1972	6.4	−11.5	0.77
31 Jan. 1972	1.2	−5.8	0.98
3 Feb. 1972	21.3	−6.5	5.10
8 Feb. 1972	4.8	−0.8	4.28
11 Feb. 1972	5.9	−3.0	2.88
3 Apr. 1972	5.0	0.0	1.50
Σ	67.0		29.46

Measurements were carried out during 9 storm of altogether 67 hours and containing 29.5 mm of melted snow. Table 1 shows some characteristic parameters of the storms.

3. *Results*

The calibration of the radar by a reference gauge led to values of coefficient *a* ranging between 360 and 6000 from one storm to another.

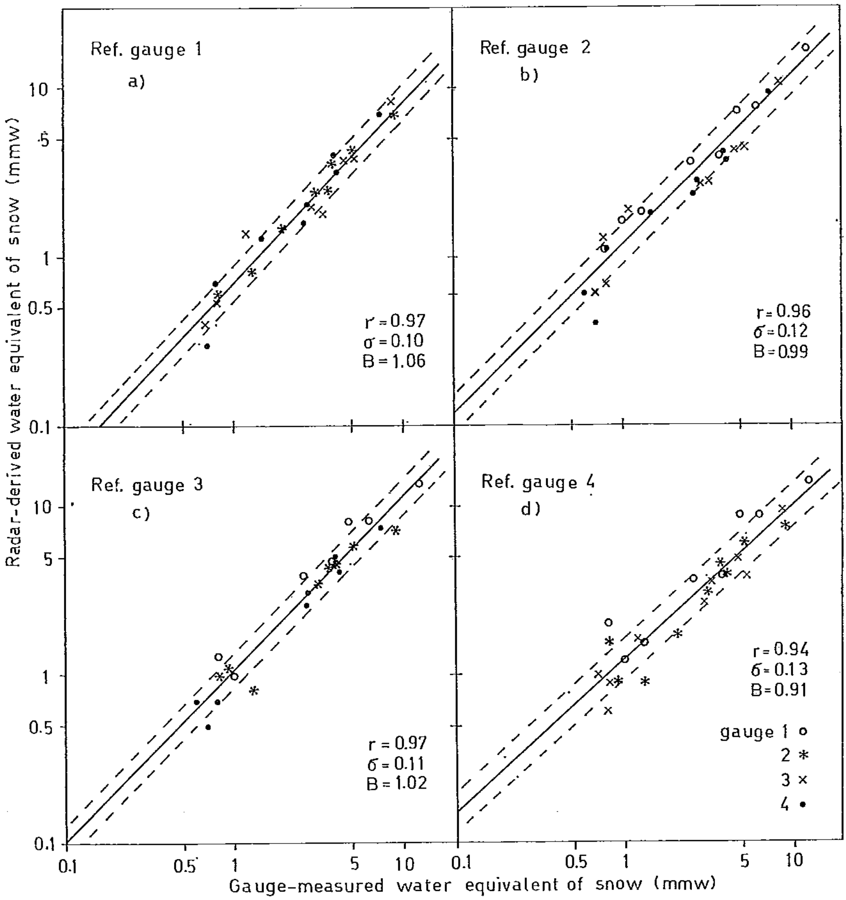

Fig. 2a-d. Radar-derived versus gauge-measured daily water equivalent of snow when the radar measurements were calibrated by the observations of a reference gauge. r = coefficient of correlation, σ = standard error of estimate, B = slope of the regression line.

In most cases, the value was between 1000 and 3000. Because no observations of the type of ice crystals were made, we tried to explain the variation of a with the aid of surface temperature. However this procedure did not give any interpretation for the variation in a. Perhaps the estimation of temperature at the level at which ice crystals were formed would have been more successful.

Figures 2a-d show the log-log plots of radar-derived vs gauge-measured values of the water equivalent of snow obtained by calibrating the radar with a reference gauge. Figure 2e shows the same, but applying the relation $Z = 2000\ R^{2.0}$. The logarithms of the values of water equivalent were used to get a better normal distribution.

Inside Figures 2a-e, the coefficient of correlation and the standard error of estimate*) of the logarithms of the radar-derived and gauge-measured values of water equivalent are given. Also the slope of the regression line has been marked to indicate the success of the square-law relationship between Z and R.

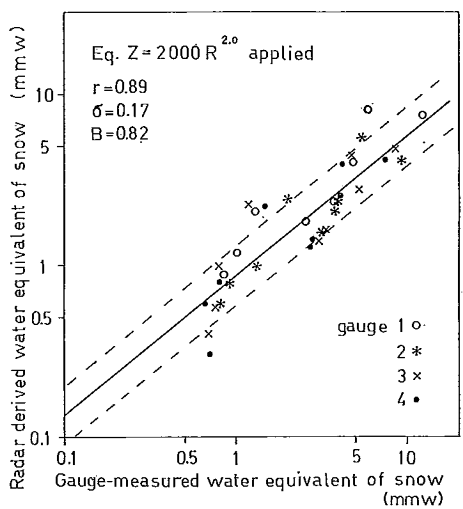

Fig. 2e. Similar to Fig. 2a-d, except the Gunn-Marshall relation applied to the radar data.

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*) The standard error of estimate was computed applying the equation $\sigma = \sqrt{\dfrac{\Sigma(\log Q_r - \log Q)^2}{n-2}}$, where Q_r is the radar-derived water equivalent and Q is the corresponding value obtained from the regression line.

The coefficient of correlation is high using any of the gauges as reference. It ranges from 0.94 to 0.97, giving the value 0.96 as the arithmetic mean. A somewhat lower value of $r = 0.89$ was obtained when the Gunn-Marshall relation was applied.

The standard error of estimate is on the average 0.12 when a reference gauge was used. This value indicates that roughly 68 % of radar observations of water equivalent fall in the interval -24 % to $+32$ %. The same interval is -33 % to $+49$ % with the value $\sigma = 0.17$ (obtained with the Gunn-Marshall coefficients).

The slope of the regression line depends on the exponent of the Z-R relationship. The square-law relation worked well using a reference gauge (the slope ranges from 0.91 to 1.06 with a mean value of 1.00), but the value $B = 0.82$ (Gunn-Marshall coefficients) indicates that the exponent was too high to interrelate the storms with high and low values of water equivalent.

4. *Discussion*

The method of using reference gauge together with radar observations of snowfall has been criticized by Carlson and Marshall [1]. They state that because the scattered power from snowfall is not constant to such great heights as in the case of rainfall, this limits the range to which the radar measurements are relevant to snowfall intensity on the surface. If we assume, however, that the mechanism producing most of the snow generally has a vertical extent at least up to a height of 3 km, a narrow beam radar will work under this height to a range of 40—60 km. During the storm investigated by Carlson and Marshall [1], the reflected power was almost constant under 3 km. If the temperature increases to above zero at some level, the rise of the bright band will cause serious errors in the radar snowfall estimates. Fortunately, in winter time the zero level rarely exists above the surface at high latitudes.

The standard error of estimate $\sigma = 0.12$ obtained in the present study using a reference gauge is identical to the standard error found by Carlson and Marshall [1] for their short range region (within 42 mi of the radar) during a storm. For longer ranges (up to 100 mi) they gave a standard error of 0.20.

For the data of Carlson and Marshall, the slope of the regression line of the logarithms of radar and gauge-measured snowfall amounts was 1.07. This presumes that a slightly higher exponent in the *Z-R* relation would have been better than the one they used ($b = 2.0$). Using the Gunn-Marshall relation ($Z = 2000\, R^{2.0}$) the slope B = 0.82 was obtained in the present material indicating the need for a lower value than 2.0 for the exponent.

In the present study it was not possible to investigate the maximum range to which the information from a reference gauge is applicable, because the distance between the extreme gauges (nos. 1 and 4) was only 16 km. The careful investigation of figures 2a-d, however, reveals that the scatter of the observations of the gauges farthest from the reference gauge is not essentially greater than the deviation of nearby observations. This indicates that a range of 15—20 km from a reference gauge is certainly acceptable for the method.
The use of a reference gauge has some obvious advantages. It releases the radar meteorologist from worrying about the actual type of crystals during a storm. Further, careful calibration of the radar equipment and continuous surveillance of the state of the transmitter and the receiver are no longer necessary. A change in radar parameters (causing a change in the radar coefficient) is compensated by the coefficient a (in *Z-R* relation) obtained with the aid of a reference gauge.

5. *Summary*

Daily snowfall amounts were measured by an X-band radar during 9 storms. Simultaneously 4 nonrecording snow gauges were used to obtain the daily values of the water equivalent of snow on the ground. These values were used to calibrate the radar measurements. Each of the gauges was used as a reference in turn. In the radar calibration it was assumed that the exponent in the *Z-R* relationship is always equal to 2.0.

The radar calibration by a snow gauge turned out to be successful. On the average, the correlation coefficient of the logarithms of the radar-derived and gauge-measured daily values of the water equivalent of snow was 0.96. The standard error of estimate was on the average 0,12, which indicates that about 68 % of radar-derived snowfall amount fell in the interval −24 % to +32 % of the gauge-measured daily amount of snowfall.

The Gunn-Marshall relationship $Z = 2000\, R^{2.0}$ was also applied to the radar data. In this case the correlation coefficient was 0.89 and

the standard error of estimate 0.17, which corresponds to the interval −33 % to +49 % of the water equivalent.

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