A case study of the measurement of snowfall by radar: an assessment of accuracy

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SUMMARY

Radar measurements during a period of snowfall in a region of variable terrain are described. The accuracy of estimates of areal snow depth, using a calibrated radar, is shown to be similar to that achieved for areal rainfall using the same technique. This detailed case study supports similar conclusions made by other workers, who used more cases but fewer validating measurements. It is also shown that provided the variations in terrain height are not very large, compensation for the effects of melting over low terrain can be made in deriving the snow depth field by using two independent snow depth calibration measurements – one representative of upland areas, and the other of lowland areas.

1. INTRODUCTION

Radar measurements of precipitation are based on the relation between the radar reflectivity factor $Z$ and the precipitation rate $R$. This relationship has the form $Z = AR^B$ (see, for example, Battan 1973), where the coefficients $A$ and $B$ depend upon the particle size distribution, the particle phase, and the density of the particles. For rainfall, the literature contains a wide range of values for $A$ and $B$ (for a summary see Stout and Mueller 1968). There is an even larger range for snowfall (Ohtake and Henmi 1970). For aggregate snowflakes Gunn and Marshall (1958) give $Z = 2000R^{2.0}$, whereas Imai (1960) gives for ‘dry’ snow $Z = 540R^{2.10}$, and for ‘wet’ snow $Z = 2100R^{2.0}$. Instead of using a fixed $R:Z$ relationship for a particular type of rain or snow, Wilson (1970) suggested that a reference gauge could be used to calibrate the radar measurements. This technique was used successfully by Wilson for rainfall measurements, and was extended to assess the accuracy with which areal measurements of rainfall could be made using radar (Harrold et al. 1974; Collier et al. 1975; Wilson 1975).

Although much work has been done on the accuracy of radar measurements of rainfall, only a limited amount of data on the accuracy of radar measurements of snowfall has been obtained. Jatila (1973) examined the use of a reference gauge to calibrate radar reflectivity measurements of snow using an X-band (3 cm, 1.7° beamwidth) radar in Finland (see also Puhakka 1975). The radar was calibrated using the water equivalent of snow collected in one of four carefully sited raingauges. The calibrated-radar estimates for the other three gauge sites were compared with the water equivalent of the snow collected in the gauges over the duration of a number of storms. The distance of the gauge farthest from the radar was approximately 28 km, and the gauges were distributed roughly along a radial axis from the radar. It was found that about 68% of the snowfall amounts derived from radar measurements fell in the interval $-24\%$ to $+32\%$ of the daily amounts of snowfall measured by the gauges. However, the assessment of accuracy was based on a comparison with only a small number of gauge measurements over a very limited area.

Perhaps the most ambitious project to date has been the measurement of rainfall and snowfall over Lake Ontario and its watershed during 1972–1973, involving cooperation between groups in Canada and the USA (Pollock and Wilson 1972). This project made use of three radars (one C-band radar, 5.6 cm wavelength, 1.7° beamwidth, and two S-band

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radars, 10 cm wavelength, 2° beamwidth) and an extensive gauge network which included thirteen weighing recording precipitation gauges (Peck et al. 1973). The results of this project have been reported by Wilson (1975). Radar and gauge data were combined using the technique developed by Brandes (1975). The accuracy of radar measurements of snowfall was found to be similar to that reported by Jatila within about 40 km of the radar, but rapidly decreased at greater ranges. Such a degradation, as with radar rainfall measurements, might be expected because the echo originates higher in the atmosphere as the range increases, and is therefore perhaps less representative of surface conditions.

The accuracy of radar measurements of snowfall reported to date has related to comparatively flat terrain. Comparisons between radar and gauge measurements have been made for a small number of points, and have generally used the water equivalent of snow depth rather than the measured snow depth. Rain gauge measurements of the water equivalent of snowfall are known to be unreliable, depending critically upon the wind
speed at the gauge, which is dependent to some extent on the gauge exposure (Larson and Peck 1974). Moreover, it is not clear to what extent these data can be applied to areal measurements where the accuracy may strongly depend upon the representativeness of the calibration gauge for the given terrain. The purpose of the present paper is, therefore, to investigate the accuracy of areal snow depths determined by a calibrated radar, by comparing these determinations with a network of independent snow depth measurements augmented by raingauge data.
Knowledge of the accumulated snow depth or its water equivalent is required in order to estimate potential run-off within a river catchment when the snow subsequently melts, so that hydrologists may predict whether or not flood conditions may result (see for example Cole et al. 1975; Jackson 1977). In the British Isles the ground temperature is often slightly above freezing point as snow begins to fall, and drops soon after. Therefore initial snowfall often melts as it reaches the ground, and the depth of snow accumulated after a period of time will be somewhat less than that inferred from radar measurements made several hundred metres above the ground. It is demonstrated in what follows that, in a region where variations in terrain height are of order a few hundred metres, the surface melting may be allowed for by careful calibration using two snow depth measurements, one representative of high ground and the other of low ground. This enables estimates to be made of actual snow depth. The case study in this paper represents the first quantitative radar measurement of snowfall in the United Kingdom, and is perhaps the most detailed verification of snowfall measurement by radar over hilly terrain.

2. Data

The radar measurements of snowfall described in this paper are the most extensive measurements of snowfall made by radar during the Dee Weather Radar Project (see, for example, Collier 1977). They were made using a C-band radar with a 1° beamwidth rotating at approximately one revolution per minute, collecting data out to a range of 50 km in one degree azimuthal sectors. The data were processed and displayed in real-time as described by Taylor (1975).

An assessment of the accuracy of measurements of snowfall by radar requires an independent method of measurement. A very simple alternative to gauge measurements, used in this study, is the measurement of snow depth by a metre rule, which may be converted to water equivalent using a relationship found by measurement to be close to the normally assumed value of 10:1. Each volunteer observer made such measurements at three locations within an area of about 0.1 km² centred on the nominal measurement point. The measurements were made twice a day, at 09 and 17 GMT. To provide measurements of snowfall in areas where no measurements were made using metre rules, the existing gauge network of the Dee Weather Radar Project, augmented by other gauges existing outside the Dee catchment, was used. The number of gauges available was about 200 over an area of about 10000 km².

3. The case study: 23/24 January 1976

Radar data of the kind referred to in section 2 were integrated over a total of sixteen and a half hours in order to derive the field of total snow depth which accumulated during the period 09 GMT 23 January to 09 GMT 24 January 1976. This field was then calibrated after the event by comparing it with measurements of snow depth at a high-level site, 305 m above m.s.l., and a low-level site, 50 m above m.s.l., and applying the calibration factors derived for each site in turn to the rest of the radar field. In this way two separate radar fields were produced: Figs. 1(a) and (b). The effects of horizontal drift of snow between the radar beam and the calibration sites were avoided, as far as possible, by restricting the analysis to ranges within 50 km of the radar, and considering radar reflectivities over an area of about 16 km² around each site. Temperature records from Shawbury, Speke, Bala and Moel Eilio (Conway Valley) confirm that surface melting would have occurred below about 300 m throughout the day on the 23rd. It was assumed that any melting of snow over ground lower than ~300 m occurred at a constant rate everywhere,
and therefore that the time dependence of melting at all altitudes below ~300m could be represented by the low-level calibration derived at 50 m. This assumption was supported by temperature records of the stations referred to above. Fig. 1(c) has been prepared by combining the fields in Figs. 1(a) and (b) according to the altitude of the terrain. The demarcation between the two fields is complex, and consequently some parts of the combined picture are not obviously related to the individual fields from which they are derived.

Figure 1(c) may be compared with the field at 09 GMT 24 January shown in Fig. 1(d), which has been derived from the snow depth measurements and from raingauges, employing a ratio of snow depth to water equivalent of 10:1, in areas of sparse data. Such data as were available from comparable adjacent raingauge and snow depth measurements were consistent with this ratio.

The accuracy of the calibrated-radar measurements of snow depth was assessed by comparing the radar measurements with measurements made by the network of volunteer observers. For this comparison, average snow depths were derived from Figs. 1(c) and (d) for areas of 100 km². These areas were defined using a grid with grid length 10 km, used in several different positions relative to the radar site. This procedure increased the number of areal measurements which could be made (no areal measurements were derived in areas of sparse data), and prevented any undue bias arising from the positions of the calibration measurements relative to the areas for which measurements were made. The two sets of measurements are compared in Fig. 2. The mean error, regardless of sign, of

![Correlation Coefficient](image)

**Figure 2.** A comparison of the mean snow depth estimated by the calibrated radar ($S_m$) over areas of 100 km², with the snow depth measurements over the same areas derived from the measurements provided by the network of volunteer observers ($S_W$) augmented by existing raingauge measurements.

the radar measurements is 13%, and the correlation coefficient is +0.93, which is significant at better than the 0.1% level using Student's t-test. The value of the correlation coefficient is slightly lower than the range +0.94 to +0.97 given by Jatila for point comparisons.

In order to assess the dependence of the accuracy of the areal snow depth measurements, derived from the radar data, upon the height below which it is assumed that melting occurs, the data have been re-analysed using several heights delineating the areas for which the high- and low-level calibration values are used. The results are shown in
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Figure 3. The dependence of the mean percentage error, regardless of sign, of estimates of snow depth over areas of 100 km² derived from radar data, on the assumed height of the melting level.

Fig. 3. It can be seen that the accuracy of the areal snow depth measurements is not dependent on the assumed height of the level below which melting occurs, in the height range roughly 200 to 300 m, but that below about 200 m the accuracy rapidly decreases. This decrease of accuracy is also evident above about 300 m, but is not so rapid. Over the part of North Wales considered in this study the height of the melting level must be estimated to within about ±100 m of its actual height if the areal snow depth measurement error is not to increase significantly.

4. Conclusions

Radar measurements of areal snow depth over hilly terrain have been described which when integrated over the entire period of a snowfall have a mean error regardless of sign of 13%. This error is comparable with the errors of point measurements of snowfall water equivalent made by Jatila (1973), and areal measurements of rainfall described by Collier et al. (1975). If the snow settles without melting, then this accuracy may be achieved using an independent measure of the snow depth to calibrate the radar measurements. However, if surface melting occurs over lowland areas then it is necessary to use at least two snow depth measurements to calibrate the radar, one representative of upland areas and one representative of lowland areas. Routinely available synoptic data allow the height of the melting level to be derived with a mean error of about ±200 m. This allows radar measurements of snow depth to be made with percentage error of about 30–40%. To achieve the percentage error of 10–20% obtained for the case study described in this paper, knowledge of the time variations of surface temperature is required to enable the height of the melting level to be measured to an accuracy of about ±100 m. This could be obtained using measurements from a network of automatic weather stations. However the required density of surface temperature measurements is not known, as the spatial variability of the melting level has not yet been determined.

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REFERENCES


