The Area–Time Integral as an Indicator for Convective Rain Volumes

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ABSTRACT

Digital radar data are used to investigate further a simple technique for estimating rainfall amounts on the basis of area coverage information. The basis of the technique is the existence of a strong correlation between a measure of the rain area coverage and duration called the Area–Time Integral (ATI) and the rain volume. This strong correlation is again demonstrated using echo cluster data from the North Dakota Cloud Modification Project 5 cm radars.

Integration on a scan-by-scan basis proved to be superior for determining ATI values to the hour-by-hour integration used previously. A 25 dB(z) reflectivity threshold was found suitable for the ATI calculation. The correlation coefficient on log-log plots of cluster rain volume versus ATI is approximately 0.98, indicating a power-law relationship between the variables. The exponent of that relationship is just a little higher than one, which indicates that the cluster average rainfall rate is almost independent of the storm size and duration.

A test of the relationship derived from one set of data (1980) against an independent set (1981) showed it to be consistent. Using the 1980 relationship to estimate the 1981 cluster rain volume for a given ATI, the uncertainty of the rain volume estimates was found to be −31%, +46%.

1. Introduction

A recently developed technique for estimating rainfall amounts on the basis of time-resolved area coverage information is described in Doneaud *et al.* (1981). The technique provides a means for estimating the volumes of convective rains over areas of the order of 1000–100 000 km^2. An interesting aspect of the technique is that it permits such estimates to be developed from radar data without using a Z-R relationship. The basis of the method is the existence of a strong correlation between a measure of rainfall area coverage and duration called the Area–Time Integral (ATI) and the rain volume.

Byers (1948) was apparently the first author to emphasize the close relationship between the amount of rain falling from a shower and its size and duration. From time to time, various authors (e.g., Estoque and Fernandez-Partagas, 1974; Dennis *et al.*, 1975; Gagin, 1980) have taken note of correlations between storm area, storm height, or other geometric variables and the rainfall produced. The existence of such correlations is important for methods of estimating rainfall amounts from satellite data (e.g., Griffith *et al.*, 1978, 1981; Lovejoy and Austin, 1979; Woodley *et al.*, 1980).

The ideas in Doneaud *et al.* (1981) have been further developed and tested using radar data from the North Dakota Cloud Modification Project (NDCMP). The NDCMP is a cloud seeding operation with dual objectives of rain enhancement and hail suppression. The purpose of this paper is to summarize the results of this more recent work. The area–time integral concept is developed more clearly, and application of the concept to new sets of data substantiates the validity of the general approach.

2. The Area–Time Integral concept

The area–time integral (ATI) concept may be illustrated as follows. The rain volume V over an area A during the time T is given by

$$V = \int_T \int_A R da dt, \qquad (1)$$

where R is the rainfall rate. If the rainfall rate were a constant R_c, Eq. (1) could be written as

$$V = R_c \int_T \int_A da dt. \qquad (2)$$

The ATI refers to the double integral in (2), which is usually approximated in our work by a sum, i.e.,

$$\text{ATI} = \int_T \int_A da dt \approx \sum_i A_i \Delta t_i. \qquad (3)$$

Here, A_i is the area over which rain was detected during the i^{th} observing period and Δt_i is the time interval between observations.

Above, R was taken as a constant to illustrate the area–time integral concept. However, in the process of data analysis, values of the ATI can be calculated from (3) without making any assumption about the values of R. The ATI calculations can be made for

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fixed areas on the ground, as in the work reported in Doneaud *et al.* (1981), or for moving storm systems, as in the present work.

The ratio of the rain volume to the resulting ATI gives an average rainfall rate $\bar{R}$ *over the area and time period with rain.* If the rain volume is expressed in km^2 mm (1 km^2 mm = 10^3 m^3 = 0.81 acre-foot) and the ATI in km^2 h, the quotient gives the average rainfall rate in mm h^{-1}.

The ATI concept is useful because it incorporates, in a simple way, information about both the areal extent and the duration of the precipitation events. Byers (1948) related shower rain volumes to an area–time integral calculated from radar data. Area–time integrals have also been related to the kinetic energy of hailfalls (Waldvogel and Schmid, 1982).

3. Data base for present study

The present study is based on C-band radar data collected during the summers of 1980 and 1981 in western North Dakota in conjunction with NDCMP. The data were collected at two radar sites, Bowman (District 1) and Parshall (District 2). Fig. 1 illustrates the geographic locations of the two radar sites. The radars used were Enterprise Electronics Corporation WR-100 5.4 cm systems with nominal 2° antenna beamwidths. Each system was equipped with a digital video integrator and processor and a magnetic tape recorder.

Data were recorded whenever there was convective activity within about 150 km range at either site. One volume scan up to 15° elevation angle, using 1° increments, was recorded roughly every 10 min. The first 20 km of range were blanked out to eliminate most of the ground clutter echoes. Radar receiver calibration data were recorded before and after each period of recording convective activity. The data tapes were processed following procedures similar to those described by Schroeder and Klazura (1978).

Digital printouts of the Z-values at low tilt angles (using data from 1° elevation outside 50 km range, and from 3° between 20 and 50 km) were prepared. From these products, individual radar echo clusters were identified by drawing a "box" around each cluster for each scan. These clusters are similar to the small mesoscale areas of Austin and Houze (1972) or the convective complexes described by Super and Heimbach (1980). Sometimes clusters so identified later merged; in such cases the merged entity was given a new cluster designation for this analysis.

The coordinates of the boxes were entered into a computer program that calculated the cluster echo areas for different reflectivity thresholds (20, 25, 30 dB(z), etc.) and the corresponding area–time integrals. For the present work, the rain area coverages were obtained from the radar data because no time-resolved gage data were available for NDCMP. The ATI values were computed using the low-tilt data and a scan-by-scan integration procedure over the whole cluster duration. The rain volume for each cluster was computed using an optimized Z-R relationship $Z = 155R^{1.88}$ (Smith *et al.*, 1975) based on data from this region.

The summer of 1980 was very dry in the NDCMP

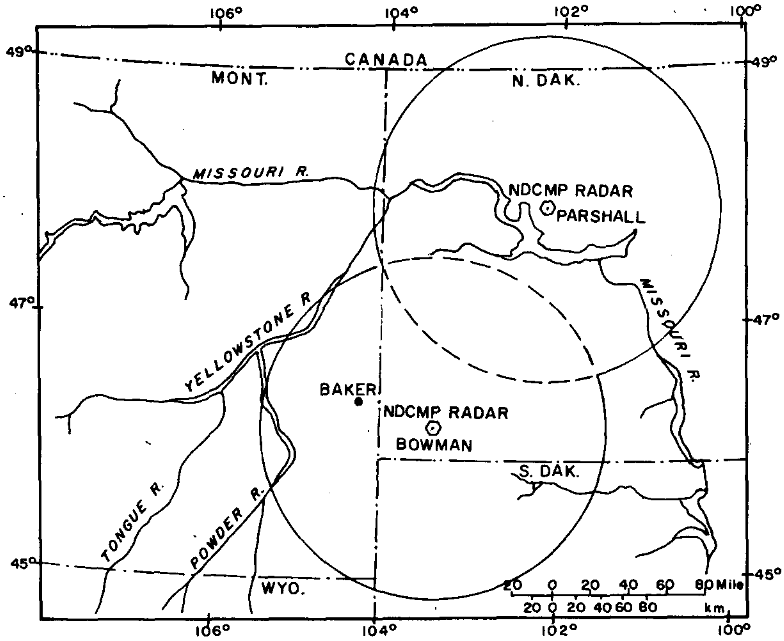

FIG. 1. Map showing the locations and 150 km range coverages of the NDCMP District 1 (Bowman) and District 2 (Parshall) radars.

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region and data recording problems limited the usable data set to the period 26 July–29 August. Consequently, only 163 echo clusters were identified in the 1980 data from both radar sites, of which only eight clusters were seeded. In the wetter summer of 1981, 583 clusters were identified in the Bowman data alone (11 June–21 August), of which 75 were seeded. For the 1980 data, the median observed cluster duration was a little over 1 hour and the longest cluster duration was a little over 4 hours. The overall durations for the wetter 1981 summer were somewhat longer.

Frequency distributions of the area–time integrals and the radar-estimated rain volumes for the echo clusters show those quantities to be roughly log-normally distributed (e.g., Fig. 2). Lopez (1977) found that various cumulus cloud characteristics are similarly distributed. The median ATI value for the sample in Fig. 2 was about 80 km^2 h, while the median rain volume was about 400 km^2 mm. The median rain volume for the 1980 echo clusters was only 250 km^2 mm, which may reflect the generally drier conditions in the summer of 1980.

4. Choice of reflectivity threshold for ATI computations

The value of the echo area at any given time depends strongly upon the reflectivity factor threshold employed, so the ATI values have a similar dependence. On the other hand, the amounts of rain associated with regions of low reflectivity are relatively small, so the rain volumes are much less sensitive to the Z threshold. The choice of the most appropriate reflectivity threshold for calculating the area–time integrals is partly subjective, but some objective factors are involved:

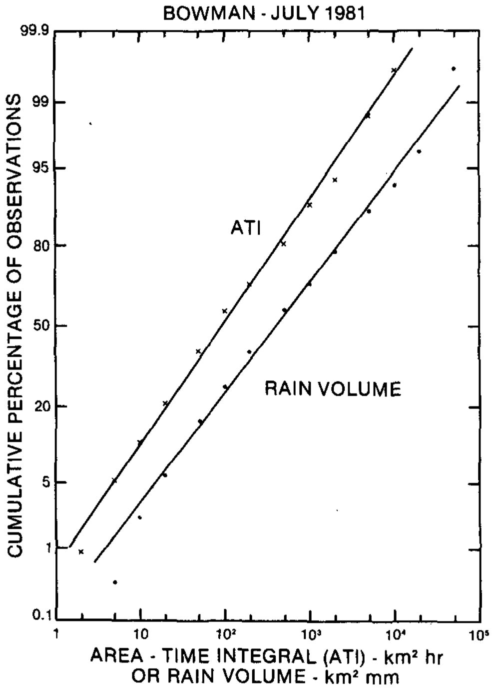

FIG. 2. Cumulative frequencies of the 25 dB(z) area–time integral (ATI) and radar estimated rain volume (RERV) for July 1981, Bowman data.

1) The correlation between rain volume and ATI on a log-log plot decreases, and the standard error of estimate increases, as the reflectivity threshold is raised from 20 to 30 dB(z) (see the NDCMP 1980 data in Table 1). The decrease in the correlation coefficient is related partly to a reduction in the range of values of the variables involved.

2) If the threshold is set too high, echo area that is significant in terms of the precipitation produced may be excluded. That is especially true for the smaller clusters, with maximum reflectivity factors not far above the threshold chosen. In dry summers, such small clusters occur often in the northern High Plains.

3) If the threshold is set too low, much echo area will be included that is not likely to be associated with any significant amount of precipitation. Also the decreasing radar sensitivity with range favors weaker echoes closer to the radar.

The relationship implied by the strong correlation between rain volume and ATI on a log-log scatter plot can be expressed in a power-law relationship of the general form

$$V = K(\mathrm{ATI})^b. \tag{4}$$

Table 1 gives values of the coefficient K and exponent b for different sets of data, with rain volumes in km^2 mm and ATI values in km^2 h. As mentioned in Section 2, the average rainfall rate $\bar{R}$ for a cluster is given by the ratio of the rain volume to the area–time integral:

$$\bar{R} = V/(\mathrm{ATI}). \tag{5}$$

Substituting (4) into (5), we obtain

$$\bar{R} = K(\mathrm{ATI})^{b-1}. \tag{6}$$

If $b < 1$, this result indicates that the average rainfall rate would tend to decrease as the area–time integral increases. In other words, larger, longer-lasting storms would give lower average rainfall rates. That does not agree with intuitive impressions about the behavior of convective precipitation.

According to Table 1, the value of b with a 30 dB(z) threshold is 0.88, which suggests that such a threshold is too high. In confirmation of this, calculations of the average rainfall rates using the 30 dB(z) ATI values in (5) gave the highest average rates for the echo clusters with the smallest ATI values. That is caused partly by the fact that all of the echo area from a cluster was counted in computing the rain volume; no threshold was employed there. If the maximum reflectivity factor of a cluster substantially exceeds the threshold used in determining the ATI, the amount of rain contributed

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TABLE 1. Rain volume versus ATI regression parameters for different sets of data.

	NDCMP 1980 Data (Composite July–August)			NDCMP 1981 Bowman Data (25 dB(z) threshold)				NDPP 1972 Data composite*
	20 dB(z)	25 dB(z)	30 dB(z)	June	July	August	Composite	
Number of analyzed clusters	163	149	117	72	391	120	583	—
Coefficient K	1.25	3.68	19.95	4.15	3.08	2.79	3.07	2.62
Exponent b	1.09	1.01	0.88	0.99	1.08	1.12	1.08	1.09
Correlation coefficient	0.99	0.98	0.97	0.98	0.98	0.99	0.98	0.97
Logarithmic standard error of estimate	0.16	0.17	0.19	0.15	0.16	0.17	0.16	0.16

* No threshold was used in the ATI calculations, and the cases analyzed were not echo clusters, but daily echo coverages over a fixed area on the ground.

by echo area below the chosen threshold would be of minor significance. If not, however, the apparent average rainfall rate can be unrepresentatively high, as frequently occurred with the 30 dB(z) threshold.

After considering these and related matters, we settled upon a 25 dB(z) threshold for determining the area–time integrals from radar data, at least for the semiarid type of climate of the northern High Plains. That avoids the difficulties discussed in the preceding paragraphs. A reflectivity factor of 25 dB(z) can be detected with the radars used, even for clusters at the maximum range of 150 km from the radar location, and will generally be associated with precipitation reaching the ground. The use of a 25 dB(z) threshold causes a loss of less than 10% of the total sample of clusters. It is clear that valid reasons may be offered for preferring a different threshold under other circumstances.

5. Rain volume versus area–time integral relationships

Figure 3 illustrates the fact that scatter plots comparing the cluster rain volumes and area–time integral values expressed on logarithmic scales show strong correlation. Table 1 presents values of the regression parameters K and b of the resulting power-law relationship (4), for different sets of NDCMP data. The parameters of a relationship derived for the 1972 North Dakota Pilot Project (NDPP) data discussed in Doneaud *et al.* (1981) are included for comparison.

The correlation coefficient for the 1972 NDPP data is slightly lower than those obtained for the 1980–1981 NDCMP data. In the former case the area–time integral values were calculated using *hourly* area coverages, with $\Delta t_i = 1$ h. That was done mainly to permit comparisons of values obtained from radar and recording gage data, where the gage data were reduced for 1 h time increments. It seems reasonable that the scan-by-scan ATI computation used with the NDCMP data should yield better results.

The values of the exponent b are generally a little greater than unity, implying that the rain volume increases slightly faster than the area–time integral. The differences from unity, while not large, are generally statistically significant; for example, 95% confidence intervals for the exponent b in the July 1981 relationship are 1.06–1.10. The smaller exponent for June 1981 is probably related to the stratiform precipitation more frequently encountered during that month (June of 1981 was generally cold and wet in North Dakota, with considerable stratiform precipitation). The fact that the summer of 1980, particularly the months of July and August for which data were available, was dry may account for the slight differences in the parameters between 1980 and 1981. These differences

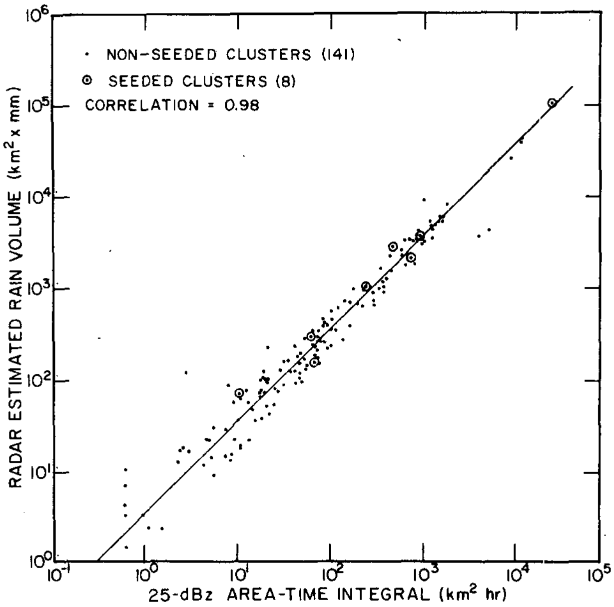

FIG. 3. Scatter plot of the echo cluster rain volumes versus the 25 dB(z) area–time integrals, for the 1980 (July and August) NDCMP radar data. The regression line shown is for points having ATI > 1 km² h.

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may indicate that the rain volume versus ATI relationship depends somewhat upon synoptic conditions and that more than a single year of data is needed to develop a climatologically representative relationship.

To a first approximation, we may consider $b = 1$, which, according to (6), would mean that the average rainfall rate is independent of the area–time integral and numerically equal to the coefficient K. According to Table 1, then, for the semiarid climate of the northern High Plains, the average rain rate is suggested to be ~4 mm h^{-1}. The numerical value of K, of course, depends upon the reflectivity threshold employed. If a constant rain rate K were assumed, the rain volume would be somewhat underestimated for large ATI and overestimated for small ATI because, with $b > 1$, the average rainfall rate increases with the ATI. Most of the values of b in Table 1 are slightly greater than unity, suggesting a tendency for such an increase in $\bar{R}$ with ATI.

The correlation coefficients and the logarithmic standard errors of estimate are roughly 0.98 and 0.16, respectively, for the data in Table 1. That indicates a consistent strong correlation between V and the ATI. The logarithmic standard error of 0.16 implies a one-standard-deviation scatter in the rain volume estimates of a factor 1.45 (= antilog 0.16). In percentage terms, the corresponding range is between +45 and −31%. That is comparable to the uncertainties which typically occur in rain volume estimates obtained from radar data in the usual manner, employing Z-R conversion followed by space and time integration (e.g., Atlas, 1964).

In Fig. 3, the rain volume versus 25 dB(z) ATI scatter diagram for the 1980 NDCMP data, the points for seeded echo clusters have been circled. The scatter of the data points about the least-squares-fit line seems to increase at the low end of the plot. Consequently, several regression equations were determined after various groups of points at the low end had been discarded; Table 2 summarizes the results. They indicate a slight increase in the exponent of the rain volume–ATI relationship, a decrease in the logarithmic standard error of estimate, and no significant change in correlation coefficient as the points with larger scatter at the low end of the plot are deleted.

TABLE 2. Regression parameters computed for NDCMP 1980 data using different cutoff thresholds for the smallest 25 dB(z) ATI considered.

Cutoff threshold ATI (km^2 h)	None	1	10	25
Number of clusters in the sample	163	152	132	107
Correlation coefficient	0.98	0.98	0.98	0.98
Coefficient K	4.27	3.68	3.55	3.34
Exponent b	0.98	1.01	1.02	1.03
Logarithmic standard error of estimate	0.180	0.166	0.149	0.126

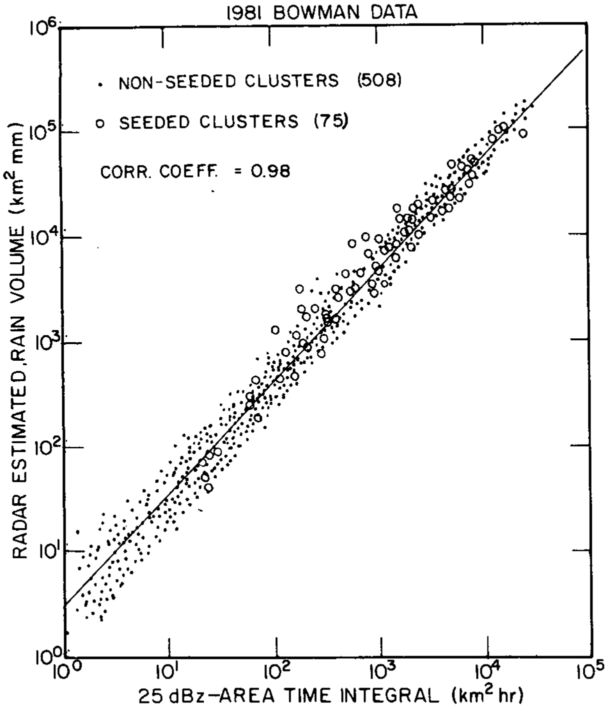

FIG. 4. Scatter plot of the echo cluster rain volumes versus 25 dB(z) ATI and regression line; for June–August 1981, Bowman data.

Figure 4 shows a similar scatter diagram for the 1981 Bowman data. Again, the points for seeded clusters have been circled. One evident difference between the seeded and nonseeded clusters is that the former tend to be concentrated toward the upper part of the plot (higher ATI and rain volume values). That is due largely to a "selection bias" inherent in the NDCMP operations, where first priority is given to seeding the larger storms for hail suppression.

6. Test of the V–ATI relationship against independent data

To test the consistency of the rain volume versus area–time integral relationship, the formula derived from the 1980 NDCMP data was applied to the 1981 echo cluster ATI values to estimate the corresponding rain volumes. The formula employed is

$$\text{Estimated rain volume} = 3.68\,(\text{ATI})^{1.01} \qquad (7)$$

Those estimates were then compared with the radar-estimated rain volumes computed in the usual way, using a Z-R relationship to obtain the rainfall rates followed by space and time integration.

Figure 5 illustrates the results for a sample of the 1981 echo clusters. If the two rain volume values agreed perfectly, all the points would fall exactly on the $y = x$ (solid) line. The actual agreement is fairly good, but the least-squares line (dashed) is inclined slightly

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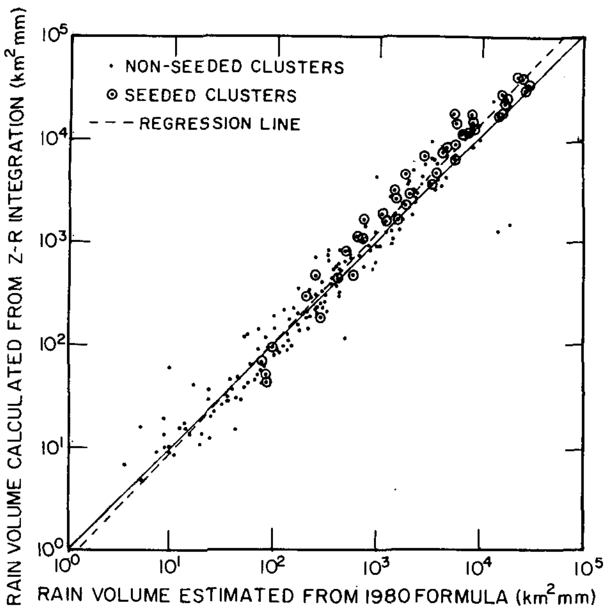

FIG. 5. Comparison of echo cluster rain volumes computed from *Z-R* conversion and integration with corresponding volumes estimated from the 1980 rain volume versus 25 dB(z) ATI formula. Data from Bowman radar, July 1981. The solid line is the $y = x$ reference line indicating perfect agreement, while the dashed line is the regression line. Points are shown for all seeded clusters, but only every other nonseeded cluster.

to the $y = x$ line. The dashed line, therefore, indicates a slight tendency for the 1980 formula to overestimate the 1981 rain volumes for small ATI values and underestimate them for large ATI values. That may be caused in part by the different weather conditions in the project area between 1980 and 1981.

Another possible explanation for the difference is that most of the underestimates are for seeded clusters. The 1980 data included very few seeded cases, so formula (7) can be considered as essentially one for unseeded clusters. The fact that it underestimates the rain volumes for the 1981 seeded clusters could then be taken to suggest a positive effect of the seeding upon the rain volumes.

The difference between the 1981 radar estimated rain volume and the rain volume estimated from the 1980 formula is indicated for each cluster by the residual difference (horizontal or vertical) between the corresponding point on the scatter diagram and the $y = x$ line. That residual is just the logarithm of the ratio of the two volumes; that is, on Fig. 5,

$$r = y - x$$

$$= \log\left[\frac{V \text{ for cluster using } Z\text{-}R \text{ relationship}}{V \text{ estimated from 1980 formula}}\right]. \qquad (8)$$

For the entire set of 1981 Bowman data (583 clusters), the mean value of those (logarithmic) residuals was -0.0154; the antilogarithm of that number is 0.965, indicating that (in the mean) the 1980 formula underestimated the cluster rain volume by ~3.5%. The root-mean-square residual value was 0.163; its antilogarithm is 1.46, indicating that the "factor of difference" was 1.46 or less about two-thirds of the time. (A factor of 1.46 is equivalent to a difference of +46% or −31%).

A similar test was made using the 1972 NDPP rain volume–ATI relationship,

$$\text{Estimated rain volume} = 2.62\,(\text{ATI})^{1.09}, \qquad (9)$$

in place of the 1980 formula to estimate the cluster rain volumes from the area–time integrals. The results were quite similar (mean logarithmic residual −0.0446 and root-mean-square residual 0.165), which is to be expected because the parameters in the formulas are quite similar. In fact, the least-squares line based on values from the 1972 formula was closer to the $y = x$ line. However, the root-mean-square logarithmic residual was slightly larger. That is not surprising, because the 1972 NDPP data were obtained with a different, 10 cm radar system. Moreover, no reflectivity threshold was employed and the area–time integrals were calculated on an hourly (instead of scan-by-scan) basis. In view of these differences, the agreement can be considered remarkably good.

Consequently, when tested on independent data from the same climate, the rain volume versus area–time integral relationship proves to be consistent. In other words, once determined the regression equation can be used to estimate the rain volume for an echo cluster of given ATI with results of acceptable accuracy.

7. Conclusions

Radar data from the 1980 and 1981 NDCMP were used to investigate further the relationship between convective rain volumes and area–time integrals. The following conclusions resulted:

1) The existence of a strong correlation between the rain volume (V) and the Area–Time Integral (ATI) was again demonstrated, this time for "floating-target" radar echo clusters. Computation of the ATI using echo area coverages integrated over the echo cluster lifetime on a scan-by-scan basis was found to be better than the hour-by-hour calculation used in Doneaud *et al.* (1981).

2) The use of a 25 dB(z) reflectivity threshold for computing the ATI values proved to be a suitable compromise.

3) The relationship between rain volume and ATI can be expressed as a power law. With the 25 dB(z) threshold the exponent of the relationship tended to be close to unity, but usually remained a little higher. This indicates that the cluster average rainfall rate is nearly independent of the area–time integral, but slightly increases with the ATI.

4) Estimates of rain volumes based on the ATI have

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uncertainties (as indicated by the root-mean-square differences) that are comparable to those found when the volumes are estimated through the usual *Z-R* approach. This substantiates the viewpoint, expressed in Doneaud *et al.* (1981), that the ATI method could be a useful alternative approach for determining rainfall amounts. The main advantage lies in the ease of computing the ATI values.

The tests with independent data in Section 6 show that, once determined, the rain volume versus ATI regression equation can be used to estimate rain volumes by simply calculating the ATI for each storm. A fixed average rainfall rate may also be used, but the actual average tends to increase slightly with the ATI so the rain volume would be underestimated for large ATI and overestimated for small ATI. Logarithmic standard errors of around 0.16 [(antilog 0.16 = 1.45) were obtained for the rain volume versus 25 dB(z) ATI plots. Thus, 68% of the points should fall within this range about the regression line. These errors are not small, but they are comparable to those encountered using standard methods of estimating rain volumes from radar data.

Evidence indicates that the rain volume versus area-time integral relationship may vary from one geographical region to another, depending upon the precipitation characteristics of each region (Doneaud *et al.*, 1981). Consequently, similar analyses of data from other regions would be quite useful. Further evaluation of the accuracy of rain volume estimates determined from ATI values by comparison with rain-gage data is also needed.[1]

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[1] While this paper was undergoing revision, a paper by Lopez *et al.* (1983) presented at the 21st Conference on Radar Meteorology gave such comparisons for Florida data and provided further confirmation of the ATI-rain volume correlation.

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