The Sources of Error in Rain Amount Estimating Schemes from GOES Visible and IR Satellite Data

S. LOVEJOY AND G. L. AUSTIN

Stormy Weather Group, McGill University, Montreal, Quebec, Canada H3A 2T8

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ABSTRACT

Recent work in GOES satellite rain amount estimation techniques suggests that these satellites primarily show skill in estimating areas of rain, rather than rain amounts directly. This hypothesis is quantitatively investigated by examining the errors in estimating rain areas from the satellite data separately from the errors involved in estimating the rain amount from known rain areas. These errors, when combined, are shown to be of the same magnitude as the errors obtained by direct rain amount estimation, giving firm support for techniques using independent rain area and amount estimation schemes. For Montreal, the rms error in hourly estimates produced by the rain area estimation technique was found to be 22% as compared to the 44% for estimating the rain amount from known rain areas. For independent processes, this yields an rms error of 49% for satellite rain amount estimation.

1. Introduction

The estimation of rain amount from satellite imagery is clearly a very important step in the operational exploitation of recent advances in remote sensing technology. This paper will concentrate on the use of GOES visible and IR data sets, since at present it is the only satellite (together with Meteosat and GMS) which offer sufficient temporal and spatial resolution to meet short-term operational requirements. The estimation of rain amounts necessarily depends on both the delineation of raining areas and the estimation of rainfall rates. We have separated these two problems and seek to address the extent to which the two parts contribute to the resulting errors in amount of rain estimated over time scales ranging from 1 to 15 h.

Early studies of satellite rain-estimating schemes have used people to subjectively classify the clouds (Barrett, 1970; Follansbee, 1973), then to estimate the amount of rain from the time that an area was covered by rain-producing clouds. This method has been refined by using climatological rain rates (Follansbee and Oliver, 1975; and Follansbee, 1976). Further development was done by Scofield and Oliver (1977a,b), who have used a sophisticated decision-tree method. This method, called a man-machine mix technique, enables a meteorologist to estimate point rainfall rates on the basis of the two preceding half-hour sets of GOES IR-visible data (at full resolution) and the synoptic charts. With some skill, the areas of more intense rain can be determined. Apparently good results are obtained after accumulation for time periods of about 6 h (Scofield and Oliver, 1977b). This technique has been largely oriented toward hydrological estimates from severe storm events. For comparison, the Follansbee and Oliver technique has been used mostly for estimating rainfall during periods from weeks to months.

There have been other attempts at relating satellite brightness measurements to rainfall rates (Blackmer, 1975; Cheng and Rodenhuis, 1977; Lovejoy, 1978). The latter two papers both arrived at the negative conclusion that single-image IR and visible data gave very little indication of the presence of intense rainfall. This conclusion can probably be explained on the basis of the fact that the visible and IR wavelengths predominantly respond to the relative abundance of cloud droplets and not to the precipitation-sized particles. This conclusion was further supported by Lovejoy and Austin (1979) by examining the IR-visible characteristics of light and heavy rain.

Microwave sensors (Wilheit *et al.*, 1977) do respond to hydrometers, but have poor resolution in time (once or twice daily) and have problems with surface emission (Rao *et al.*, 1976). Another serious problem is the low spatial resolution (~30 km) over which the assumption of uniform rain may be very poor (Smith and Kidder, 1978). Other techniques have been developed for estimating rain amounts by following the expansion of anvils (Sikdar, 1972; Stout *et al.*, 1979).

The objective of being able to estimate rain amounts from GOES satellite imagery came a step nearer fulfillment with the most recent paper using

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this technique by Griffith *et al.* (1978). Their technique defines a cloud area by using an IR or visible cutoff for a sequence of clouds. They argue quite plausibly that the flux of rain from convective clouds can be determined from a life history of the area of convective cloud. Analysis by Stout *et al.* (1979) and Wylie (1978), however, shows that when the life history is modelled by area and rate of change of area terms, the term involving the rate of change of area is on the average 1.7–1.8 times smaller, compared with the area term.

While Griffith *et al.* (1978) make it quite clear that they do not consider that their technique necessarily calls for the raining area of the cloud, the calculation of an equivalent radar echo area appears as an intermediate result of their calculation of the rain amounts.

Lovejoy and Austin (1979) describe a technique which determines the optimum contour in the visible/IR domain for separating raining from non-raining points as delineated by radar. This paper attempts to investigate the extent to which the errors in rain-estimation schemes are due to errors in the area-determining technique and to what extent they are due to the algorithm which determines the average rain rate.

2. Data base

The data used in this analysis consist of radar data from two radars, one located on CCGS (Canadian Coast Guard Ship) *Quadra*, as part of the GATE experiment, and one located at the McGill Radar Weather Observatory, near Montreal. The McGill radar operates at 10 cm wavelength, with a beamwidth of 0.8° with 148 range bins logarithmically spaced. The *Quadra* radar operates at 5.7 cm wavelength and a beamwidth of 1° with 200 linearly spaced range bins. The actual data used are in the form of digital CAPPI (Constant Altitude Plan Position Indicator) maps for Montreal, and PPI (Plan Position Indicator) maps for the lowest elevation angle for the *Quadra*, constructed from the polar data recorded on magnetic tapes. Such maps were made each 15 min for the duration of GATE and during the summers of 1976 and 1977 for Montreal. The maps covered a radius of 180 km ($=1.01 \times 10^5$ km^2). The GOES (Geostationary Operational Environmental Satellite) data were obtained as part of a joint research project with the University of Wisconsin through the good offices of Dr. Don Wylie, and consisted of digital visible and IR data for appropriate sectors (at resolutions of $\sim$1 and 8 km, respectively).

The radar data were used to estimate the total flux of rain, the area which was raining, and consequently the average rain rate for the raining areas. The satellite data were used to independently estimate the rain areas by means of the technique described in Lovejoy and Austin (1979).

3. Comparison of different rain area and amount estimating techniques

A major difficulty in evaluating different techniques for estimating rain areas and amounts is how to describe their accuracy statistically. Since there seems to be no generally accepted best statistic to characterize the errors, we have used several possible statistics giving indicators of the magnitude of the errors. In particular the bias (B) or mean ratio and the error factor (E_R) are the same as those used in Griffith *et al.* (1978), and the root mean square error ($E_{\rm rms}$) is the same as that used by Stout *et al.* (1979) and by Wylie (1978).

The bias is defined as the mean ratio of the satellite quantity to the radar quantity, and the error factor as the mean ratio of the same quantities such that the individual ratios are always greater than 1. The standard deviations of the bias and error factor (σ_B and σ_E, respectively), are the corresponding standard deviations. $E_{\rm rms}$ is defined as the root mean square of the deviation of the satellite quantity from the radar quantity divided by the mean radar quantity. For a perfect technique, $B = E_R = 1, E_{\rm rms} = 0$. We have also defined in the usual way a correlation coefficient for the rain area and amount (ρ_{VA}) and rain area and rain rate for raining areas (ρ_{RA}) when both of these quantities are radar determined.

All of these statistics may be accumulated for different time periods; thus, for example, satellite estimates made at 30 min or 1 h intervals over a period of hours to days may be summed and compared to the observed radar values summed over the same time periods. Obviously, the accumulated results are considerably smoothed with respect to the errors at individual times.

Table 1 shows the error statistics of several authors who have all used life-history approaches to estimate the rain amount for various regions. These figures are all derived from the papers referenced. Physically, we may roughly interpret B and E_R as giving indications of the performance of our algorithm weighted for small sized systems, since statistical fluctuations for small radar and satellite quantities give large fluctuations in the ratios of these quantities. Conversely, $E_{\rm rms}$ weights the cases with larger radar and satellite quantities more, since large contributions are unlikely for small values of the parameters. We thus favored the use of $E_{\rm rms}$ since we are mainly interested in errors in our algorithms for large rain area and amount cases, and since these give the largest contribution to the operationally significant rain areas and rain amounts. The significance of the bias was viewed sceptically since if the satellite estimated parameters were all multiplied

TABLE 1. Comparison of the error statistics obtained by various researchers in satellite rain amount estimation.

Author	Follansbee and Oliver (1975)*			Scofield and Oliver (1977b)**	Griffith *et al.* (1978)						Wylie (1978)†		Stout *et al.* (1979)			
Technique	Nephanalyses			History and synoptic data	Lifetime measurements						Expanding anvils		Expanding anvils			
Region	Alabama, Georgia, South Carolina			North Carolina	Florida						Montreal		GATE			
Size of area (km^2)	$\sim 10^5$			$\sim 10^5$	$\sim 10^4$		$\sim 10^5$				$\sim 10^4$		$\sim 6 \times 10^3$		$\sim 10^5$	
Number of sequences examined	255			1	8		5				5		2		4	
Number of data points used	255			4	53	8	37	43	5	5	35		219	329	62	8
Time of accumulation	"daily"			6 h	"hourly"	"daily"	"hourly"		"daily"		½ h		½ h		1 h	6 h
Type of data used	vis	IR	both	IR and vis	vis	vis	vis	IR	vis	IR	vis	IR	vis	IR	IR	IR
$E_{\rm rms}$	1.31	1.51	1.22	0.44	—	—	—	—	—	—	.58	.46	.62	.76	.32	.23
B	—	—	—	1.18	1.11	0.83	1.15	2.70	1.13	1.90	—	—	—	—	—	—
E_R	—	—	—	1.86	2.61	1.68	2.38	3.71	1.39	1.95	—	—	—	—	—	—

* The error figures have been computed from Follansbee and Oliver (1975, Tables 2, 3, 4).

** This column has been computed on the basis of the only rainfall amount statistics contained in either Scofield and Oliver (1977a or 1977b), that is, from Fig. 11 of Scofield and Oliver (1977b).

† These are the average $E_{\rm rms}$ figures for the five sequences, taken from Wylie (1978, Table 2).

by a suitable constant (which could be done since they are determined so as to best fit the radar parameters), the bias could always be set equal to 1. This is not true of any of the other parameters mentioned above. Furthermore, the statistics are independent, since it may be shown that only under certain conditions, not satisfied here (for example, $\mu_E \gg \sigma_E$ and $\mu_R \gg \sigma_R$ with $\mu_E \approx \mu_R$, where μ, σ indicate mean and standard deviation, respectively, and E, R indicate the estimated and radar parameters, respectively), then $\sigma_B \approx E_{\rm rms}$.

4. Estimating the rain amount when the rain area is known

Clearly, if the hypothesis we share with Griffith *et al.* (1978) is correct, the satellite data should be first used to estimate rain areas (or echo areas) and to estimate rain amounts from these by multiplying by a suitable average rain rate. This would enable the errors involved in each stage of the process to be calculated separately and compared. This would give us the information required to determine how much skill the satellite data show in rain area estimation and how much the data show in rain amount estimation once the area is known. This in turn would give us a much better physical understanding of the limitations in the use of the satellite data to estimate an amount and would also allow us to improve rain area and rain amount estimating techniques separately.

To this end, we decided to evaluate the errors involved in the following rain amount estimation technique. It was proposed that rain amounts be determined by multiplying the radar-determined rain area by a rain rate averaged over a long period of time. This radar-area-estimated rain amount would then be compared with the actual radar-determined amount, and the error statistics discussed in Section 3 determined. It is clear this is not intended as a reasonable operational technique.

This was done for the entire 20-day, Phase III of GATE for every radar PPI to the nearest hour on the hour recorded on the CCGS *Quadra* radar (328 PPI's with some rain). The results, accumulated for various time periods, are shown in Table 2. A similar table produced from 1233 CAPPI's was also drawn up for the near complete May–September CAPPI's

TABLE 2. Statistics determined by the *Quadra* radar for Phase III of GATE accumulated for various lengths of time.

Number of consecutive hours of data accumulated	1	2	4	7	10	15
Number of sequences of accumulated data	328	146	59	28	15	8
ρ_{VA}	0.91	0.91	0.91	0.91	0.94	0.93
ρ_{RA}	0.15	0.64	0.63	0.72	0.62	0.72
$E_{\rm rms}$	0.41	0.37	0.33	0.33	0.22	0.20
σ_B	1.02	0.79	0.71	0.66	0.39	0.40
B	1.53	1.41	1.35	1.34	1.17	1.16
E_R	1.74	1.56	1.49	1.47	1.29	1.29
σ_E	1.30	0.70	0.64	0.58	0.33	0.33

for 1976 and 1977 of the McGill weather radar in Montreal, shown in Table 3. It should be stressed that the column marked 1 h is based on a single radar image, and is not the accumulation of the 15 min images. Statistics were not accumulated every 30 min as the satellite data could be. Since consecutive 30 min images have meteorology which is highly correlated, accumulating two 30 min images for a 1 h estimate would not lower the errors significantly. This may be verified by comparing the slight change in errors when two 1 h images are accumulated for 2 h (GATE: $E_{\mathrm{rms}} = 0.44, 0.37$; Montreal: $E_{\mathrm{rms}} = 0.44$, 0.42, for 1 and 2 h, respectively).

Of great interest for the purposes of this paper are the correlation coefficients of rain area and rain rate (ρ_{RA}) and of the rain amount and area (ρ_{VA}). For Montreal and GATE, respectively, the rain areas and rain amounts are correlated with hourly coefficients of 0.88 and 0.91. However, we obtain 0.06 and 0.15, respectively, for the rate-area correlation.

These facts suggest the following: 1) given the rain area, the rain amount may be estimated to a fair degree of accuracy by multiplying the area by a constant; 2) knowledge of the area alone is insufficient to determine the variation of the rainfall rate about the long-term average value (since the area and rate are virtually uncorrelated). We believe that these two facts may account for the relative success of satellite rain amount estimation once rainfall area has been determined. It also suggests that rain area determination may be sufficient for reasonably accurate rainfall amount prediction. The meaning of the phrase "reasonably accurate" will be quantitatively specified in the sections which follow.

The other statistics presented in Tables 2 and 3 may be compared with those in Table 1. The hourly statistics may be compared with those of column 1 of Tables 2 and 3, for the appropriate region. It seems reasonable to assume that GATE statistics are not inappropriate to Florida cases, especially in view of the relatively small differences between the GATE and Montreal cases. It should also be noted that the area over which the estimates have been made are not always compatible. The statistics contained in Tables 2 and 3 are all for the radar-observed region ($\sim 10^5$ km^2). The areas used by the other authors are noted in Table 1 along with the number of data sources upon which the error estimates are based. When these differences are taken into account, we feel that the radar-area technique of rain amount estimation results in errors comparable with those obtained from the life-history techniques summarized in Table 1.

As expected, the error figures in Tables 2 and 3 are all reduced as the length of accumulation is increased with the bias, error factor and E_{rms} changing only slowly after about 10 h. We may expect this to be a good estimate of the "daily" error statistics of the type used by Griffith *et al.* (1978) indicated in Table 1. The errors would be slightly smaller if estimates were made every half-hour instead of every hour. The daily statistics also appear to give comparable errors for the radar-area estimation technique for rain amount estimation. This fact makes plausible the notion that the errors resulting from life-history techniques could be explained purely in terms of the errors involved in their area estimation ability combined with a meteorological variation of rain rates. It is interesting to compare the "daily" statistics with those derived from Follansbee and Oliver (1975). They produced nephanalyses based on IR or visible GOES imagery and multiplied the cumulonimbus cloud area by a climatologically determined rainfall rate. They accumulated these rain amounts over 24 h periods for Alabama, Georgia and South Carolina, and compared these with raingage estimates. We calculated E_{rms} from their data as shown in Table 1. Although the error is probably overestimated since raingages rather than radar were used as ground truth, the values so obtained ($E_{\mathrm{rms}} \approx 1.2$), when compared with the radar-area technique (which gives a value of 0.27 for 15 h), shows the large improvement effected by separating raining from non-raining clouds.

TABLE 3. Statistics determined by the McGill weather radar for Montreal summer weather in 1976–77.

Number of consecutive hours of data accumulated	1	2	4	7	10	15
Number of sequences of accumulated data	1233	585	266	128	70	27
ρ_{VA}	0.88	0.88	0.88	0.89	0.87	0.82
ρ_{RA}	0.06	0.06	0.05	0.10	0.17	−0.06
E_{rms}	0.44	0.42	0.39	0.34	0.32	0.27
σ_B	0.66	0.62	0.58	0.50	0.47	0.43
B	1.18	1.16	1.15	1.11	1.10	1.08
E_R	1.45	1.43	1.40	1.34	1.32	1.29
σ_R	0.40	0.37	0.32	0.27	0.25	0.20

It should be noted, that implicit in the statistics cited in Tables 2 and 3 is a perfectly accurate radar. However, radar is evidently subject to fairly large point-to-point fluctuations. For example, Woodley *et al.* (1975) cite an error factor of 1.39 for point-to-point radar-to-raingage comparisons. For GATE, Hudlow and Patterson (1978) found a value of 23% for the statistic determined by averaging point raingage-to-radar differences and dividing by the average raingage value for a 24 h period (this statistic is not unlike E_{rms}).

All of these statistics depend on the time and space scales employed. This is evident from a comparison of radar-determined point statistics and raingage determined values. If we compute the average rain rate, given that it is raining, from radar, we find values of 3.07, 2.46 and 2.76 mm h^{-1} for Montreal in 1976 and 1977 and GATE Phase III, respectively.

For 10 years of Montreal tipping bucket raingages, averaging over 1 min intervals, we obtain 3.66 mm h^{-1}. This value is higher than those determined by radar probably because the assumption of uniform rain over a 4 km × 4 km CAPPI resolution cell is not a very good one. Radar calibration and meteorological differences also contribute to the difference.

We may also calculate the errors in rain amount estimation for 1 min accumulations from the raingages, if the amount is estimated by assuming a constant rain rate. We obtained an E_{rms} of 2.35 (cf. with 0.44 for the radar for an entire CAPPI—see Table 3). The bias and error factor cannot be estimated from raingages for such small time intervals, since they depend crucially on the frequency of occurrence of rain rates between 0.01 and 0.1 mm h^{-1}, numbers which are extremely poorly estimated from tipping bucket raingages.

In the statistics compiled in Tables 2 and 3, however, the only significant numbers to be obtained from the radar CAPPI are the total rain area and total rain amount. Since each of these numbers represents an average of about 10^6 raw data points, statistical fluctuations of the kind probably responsible for large point-to-point errors are smoothed quite considerably. In fact, errors in the total rain area are dependent only on having a reasonably constant minimum detectable signal which even a poor radar is likely to have. The errors in amount are likely to be almost entirely due to radar calibration and Z-R relation changes. The best estimate we have for the Montreal radar calibration drift (Bellon and Austin (1977) is about 5% ($E_{\mathrm{rms}} = 0.045$) for a 12 h period, when ~80 gages are used to compare total gage amounts (summed over all gages) and total radar amounts integrated for the same location for 12 h. We may thus expect a smaller E_{rms} radar-to-gage variation for periods of less than 12 h. Since radar is used as ground truth in the satellite rain estimates used by other authors, we may expect a similar fraction of their errors to be attributable to radar calibration drift [the continuous recalibration procedure described in Griffith *et al.*, (1978) may reduce this source of error significantly in their case]. In any event, it seems likely that most of the variation in rainfall amounts documented in Tables 2 and 3 has meteorological origins. In what follows, we shall explicitly assume that compared to other sources of error in the techniques, the amount introduced by the radar is small. In this analysis we also use the radar to estimate the average rainfall rate which is then used to "predict" the total flux of rain. In this sense any radar error is cancelled out to the first order.

5. Results of rain amount and area estimation by two-dimensional pattern matching for Montreal and GATE

In order to illustrate how errors in area estimation combine with those of amount estimation, we have determined satellite rain areas and satellite rain amounts (by multiplying the satellite area by a constant rain rate), and compared these statistics to the radar-area determined rain amounts, for the sample studied, and with similar statistics for the long time period (taken from column 1, Table 2 and 3). The results are shown in Table 4, where the two-dimensional pattern matching technique was used for satellite rain-area determination.

This scheme may be roughly summarized as follows. The basis of the scheme is the determination of an optimum boundary in the two-dimensional IR-visible intensity plane, cleaving the plane into predominantly raining and non-raining parts, using radar ground truth. This scheme makes maximum use of single image IR and visible data, unlike the schemes based on life histories which normally use either IR or visible data separately.

The statistics in Table 4 for evaluating the rain area estimation technique, have been taken from Lovejoy and Austin (1979) for the half-hour statis-

TABLE 4. A comparison of the relative magnitudes of errors for satellite rain area and rain amount estimation.

Place	Montreal (1977)						GATE (Phase III)		
Period of time for which half-hour estimates have been accumulated	½ hour			2 hours			½ hour		
Number of data points	17			3			8		
Type of statistic	B	E_R	E_{rms}	B	E_R	E_{rms}	B	E_R	E_{rms}
Errors due to satellite area determination	1.13	1.26	0.22	0.99	1.26	0.22	1.21	1.41	0.25
Errors due to use of single rain date for the limited sample	1.19	1.32	0.28	1.08	1.15	0.12	1.47	1.59	0.23
Combined errors	1.39	1.59	0.39	1.12	1.44	0.33	1.85	1.93	0.21
Errors due to use of single rain rate for 1976 and 1977 (or Phase III GATE)	1.18	1.45	0.44	1.16	1.43	0.42	1.53	1.74	0.41

tics, and have been appropriately accumulated for the 2 h statistics (here, the 2 h statistics are based on accumulations of four consecutive half-hour estimates). As can be seen, $E_{\rm rms}$, bias and error factor for rain-area estimation may plausibly be combined with the radar-area rain amount determination statistics to yield the satellite rain amount error statistics. The latter should be compared for the appropriate place and accumulation period of Table 1. They are clearly of the same order of magnitude. The relative success of the two-dimensional pattern matching technique can only be attributed to its area determination capability, whereas the errors produced by the life-history techniques are of uncertain origin. However, as we hope the preceding has shown, the hypothesis that they predominantly reflect area determination skill could easily explain the magnitude of these errors.

Although it is admitted that the data base used in evaluating the area estimation scheme was limited, it is worth making two points. First, the data base used by other researchers was also limited (comparison of the number of data sequences and data points used can be made from the appropriate rows of Tables 1 and 4). Second, by evaluating the statistics obtained from the radar-area rain amount estimation scheme, over an exceedingly large number of cases, we can obtain a measure of how representative our sample was of the entire population. This can be done by comparing the rows of Table 4 marked "errors due to use of a single rain rate for the limited sample" and the row marked "errors due to the use of a single rain rate for 1976 and 1977 (or GATE Phase III)". In all cases, the variability (errors) of our sample appear to be slightly smaller than those of the long-term statistics.

Since all the Montreal sequences and all the GATE images (with some rain) at our disposal were used, it would appear that the only source of selection bias were the following: 1) only 1300 GMT data in GATE, and 1500–2030 GMT data in Montreal were used, so as to minimise the sun-angle normalisation problem; and 2) for the Montreal sequences, all the data were within a 28-day period. Each of these selection procedures presumably resulted in a sample with less meteorological variability than the long-term averages. They were also chosen so as to have both visible and IR images available. Clearly, for a complete 24 h sequence it would be necessary to use the optimum IR threshold technique. This IR only technique gives an $E_{\rm rms}$ of 0.71 compared with the 0.22 in Table 4 (Lovejoy and Austin, 1979).

While it is not obvious how biases and error factors for independent processes should be combined, $E_{\rm rms}$ may be expected, as a first approximation, to behave as a normal standard deviate quantity. If this is true, then the square of the total error for independent processes may be obtained by adding the squares of the individual contributions. We may use this fact to estimate $E_{\rm rms}$ for an operational satellite rain amount determination scheme. To do this we must include the 5% raingage-to-radar error—our best estimate of the satellite area determination scheme (22% for 1 h estimates)—and using the 1976–77 Montreal data on errors involved in estimating amounts from areas, another 44%. These combine to yield 49% for the whole process. This would be reduced for periods of accumulation greater than 1 h, or if consecutive half-hour images were used.

To investigate the effect of imperfect area determination schemes in a more rigorous way, we used a random number generator to give a random normally distributed error proportional to the area for each of the radar areas, and recomputed some of the error statistics. For 1 h accumulations for Montreal, the rms error increased from 0.44 for a perfect area determination scheme to 0.46, 0.54 and 0.73 for area schemes with rms area errors of 10, 25 and 50%, respectively. For 10 h, the error increases from 0.32 to 0.36 for a scheme with an hourly rms area error of 50%. If rain areas are randomly sampled and paired with rain amounts, we obtain an error of 1.21 for 1 h accumulations. This is the error when there is no skill whatsoever in area determination. These calculations show that even for 1 h accumulations, the error for the whole process depends very little on the rain area accuracy, as long as this is less than the rain amount accuracy. The area determination accuracy is even less important for periods of accumulation longer than 1 h. This makes plausible the notion that it is not the inaccuracies inherent in satellite area estimates which would limit the accuracy of such a satellite amount-estimating scheme, but rather the meteorological variations in rainfall rate about its long-term value.

Since the two-dimensional pattern matching scheme has been completely automated from the start, more cases could be analyzed should this prove necessary. However, we feel that the slight extra variability of the long-term statistics give a good indication that operational use of this method would give substantially similar results. In any event, we hope that the reader may be able to judge for himself on the basis of the data presented.

6. Conclusions

In agreement with other researchers, we have found that GOES infrared and visible imagery should be used both for rain area and amount estimation. By using data for long time periods in both GATE and Montreal, the variability of rain amount estimates from known areas of rain can be computed and, due to the high correlation between rain area and rain amount, this variability is shown to be of the same order of magnitude when compared to the errors involved in the existing satellite rain amount estimation techniques. When this variability is coupled with errors in the area estimation by two-dimensional pattern matching, reasonable accuracy for rain amount estimation is obtained. These facts support the hypothesis that GOES IR and visible data are good for determining rain areas, but poor for determining rain rates.

For Montreal, we may roughly estimate the contributions to E_{rms} from different sources as follows: 5% from the gage to radar measurement, 22% for radar area to satellite area and 44% for the satellite area to the satellite amount, yielding, for independent processes, 49% for the total process, for estimates based on single sets of IR and visible images.

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REFERENCES

Barrett, E., 1970: Estimation of monthly rainfall from satellite data. *Mon. Wea. Rev.*, **98**, 322–327.

Bellon, A., and G. L. Austin, 1977: The real time test and evaluation of SHARP. Report for AES(DSS) Contract OSZ5/0319, Stormy Weather Group Sci. Rep. MW-91, Physics Dept., McGill University, Montreal.

Blackmer, R., 1975: Correlation of cloud brightness and radiance with precipitation intensity. Final Report, Task B [NEPRF TR8-75 (SRI)]. Stanford Research Inst., Menlo Park, CA.

Cheng, N., and D. Rodenhuis, 1977: An intercomparison of satellite images and radar rainfall rates. Tech. Rep. 77-166, Meteorology Program, University of Maryland, 60 pp.

Follansbee, W. A., 1973: Estimation of average daily rainfall from satellite cloud photographs. Tech. Memo NESS 44, NOAA, Washington, DC, 39 pp.

——, 1976: Daily precipitation over China and USSR using satellite imagery. Tech. Memo NESS 81, NOAA, Washington, DC, 30 pp.

——, and V. J. Oliver, 1975: A comparison of infrared imagery and video pictures in the estimation of daily rainfall from satellite data. Tech. Memo. NESS 62, NOAA, Washington, DC, 14 pp.

Griffith, C. G., W. L. Woodley, P. G. Grube, D. W. Martin, J. Stout and D. N. Sikdar, 1978: Rain estimation from geosynchronous satellite imagery. *Mon. Wea. Rev.*, **106**, 1153–1171.

Hudlow, M. D., and V. L. Patterson, 1978: GATE radar rainfall atlas. Draft of Special Report, August 1978, NOAA, Washington, DC.

Lovejoy, S., 1978: The relationship between coarse resolution satellite data and area of rain. *Preprints Fourth Symp. Meteorological Observations and Instrumentation*. Denver, Amer. Meteor. Soc., 239–242.

Lovejoy, S., and G. L. Austin, 1979: The delineation of rain areas from visible and IR satellite data for GATE and midlatitudes. *Atmos.-Ocean*, **20**, 77–92.

Rao, M. S. V., W. Abbott III and J. S. Theon, 1976: Satellite derived global oceanic rainfall maps. *Preprints Sixth Conf. Weather Forecasting and Analysis*, Albany, Amer. Meteor. Soc., 121–123.

Scofield, R. A., and V. J. Oliver, 1977a: A scheme for estimating convective rainfall from satellite imagery. Tech. Memo. NESS 86, NOAA, Washington, DC, 47 pp.

——, and ——, 1977b: Using satellite imagery to estimate rainfall from two types of convective systems. *Preprints 11th Conf. Hurricanes and Tropical Meteorology*, Miami, Amer. Meteor. Soc., 204–211.

Sikdar, D. N., 1972: ATS-3 observed cloud brightness field related to a meso-synoptic scale rainfall pattern. *Tellus*, **24**, 400–413.

Smith, E. A., and S. Q. Kidder, 1978: A multispectral satellite approach to rainfall estimates. Dept. Atmos. Sci., Colorado State University, Fort Collins. (Preliminary draft.)

Stout, J., D. Martin and D. N. Sikdar, 1979: Estimating rain with geosynchronous satellite images. *Mon. Wea. Rev.*, **107**, 585–598.

Wilheit, T. T., A. T. C. Chang, M. S. V. Rao, E. B. Rodgers and J. S. Theon, 1977: A satellite technique for quantitatively mapping rainfall rates over the ocean. *J. Appl. Meteor.*, **16**, 551–560.

Woodley, W. L., A. R. Olsen, A. Hendon and V. Wiggert, 1975: Comparison of gage and radar methods of convective rain measurement. *J. Appl. Meteor.*, **14**, 909–928.

Wylie, D. P., 1978: An application of a geostationary satellite rain-estimation scheme to an extra-tropical area. Report to Dept. of Space Science, University of Wisconsin, Madison, 18 pp.