Insights into Errors of SMS-Inferred GATE Convective Rainfall

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ABSTRACT

In the mean the Griffith/Woodley rain estimation technique underestimated the radar-measured rain of each of the three phases (a total of 56 days) of GATE, to varying degrees, and the satellite-derived isohyets were generally too extensive relative to radar-measured patterns. Three possible error sources are investigated in the present paper: 1) the method of apportionment of satellite-derived rain at the surface; 2) resolution degradation of the digital satellite imagery; and 3) anomalous behavior of convective clouds in the tropical Atlantic relative to those of the Florida derivation data set.

To correct the satellite-derived rain patterns, a new method of apportionment was tested by recomputing the GATE satellite rain estimates. Better volumetric comparisons between radar and satellite estimates were observed for 24 h and phase periods, and comparisons of isohyetal patterns improved on all time scales.

The relative error caused by resolution degradation was quantified by comparing rain estimates produced from full resolution imagery to estimates derived from degraded imagery for an 8° latitude by 12° longitude area in the eastern tropical Pacific ocean over a 54 h period. Results showed that the volumetric rainfall estimates made at ⅓° spatial and 1 h temporal resolution would be on the order of 10% lower than estimates made with the full resolution data ($\frac{1}{15}$° and 30 min).

The remaining differences between the GATE satellite and radar estimates are attributable to different conditions prevailing in Florida and in GATE. These include significant rain from clouds that do not grow above the −20°C level ("warm rain") and very long-lived anvils.

1. Introduction

A precipitation atlas for the 85 days of the GARP Atlantic Tropical Experiment (GATE) (27 June–20 September, 1974) has been derived recently by Griffith *et al.* (1980)[1] from SMS-1 imagery for the tropical Atlantic Ocean (5°S–22°N and 5–50°W). For GATE's three phases (each 19–21 days in duration) both volumetric and isohyetal comparisons were made between satellite-derived rainfall, rain gages and radar-derived rainfall (Woodley *et al.*, 1980) over the B-scale area (7–10°N and 22–25°W) for several time periods ranging from 24 h to a composite of all phases. Daily volumetric comparisons showed overestimates as well as underestimates, but in the mean, a net underestimate was observed. For Phases I and III the satellite-derived rain volumes were within 10% of those measured by radar, but in Phase II the estimates were low relative to the radar by 42%. Over all phases the net disparity averaged to a 14% underestimate. Twenty-four-hour isohyetal patterns generated by the satellite technique were similar to those derived by radar and as the comparison period increased, the similarity between the satellite- and radar-derived patterns improved. Generally, however, the satellite-generated isohyets were low and covered larger areas relative to those measured by radar.

Because the GATE precipitation atlas was the first application of the objective rain estimation software, problems were expected. It is believed that observed shortcomings arise from three sources: 1) the method used to distribute the estimated rain volumes at the ground; 2) the degradation of the resolution of the satellite imagery, which was necessary in order to make rain estimates for such a large area over a 3-month period; and 3) anomalous behavior of convective clouds of the tropical Atlantic relative to those of south Florida, where the technique's empirical relationships were derived.

In this article these error sources are investigated and possible solutions are offered. To correct the rainfall distribution problem, a new, more reasonable method of apportionment, based on radar and

[1] Griffith, C. G., W. L. Woodley, J. S. Griffin and S. C. Stromatt, 1980: Satellite-derived precipitation atlas for GATE. NOAA, ERL, Boulder, 280 pp. [Govt. Printing Office: 1980 0-315-309].

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raingage observations of tropical rain patterns, is proposed and the GATE data set is its first independent test. Assessment of the errors resulting from degradation of the resolution of the input satellite imagery is addressed through sensitivity testing. Finally, satellite rainfall underestimates in the eastern tropical Atlantic are explained by differences in the behavior of clouds of the eastern Atlantic versus those in Florida, where the technique was derived.

2. Production of satellite-estimated isohyets for GATE

a. Background

The satellite rain-estimation technique is based on the finding that active convective regions of rainfall appear brighter and colder on satellite imagery than inactive regions (Griffith *et al.*, 1978). In its present form it is an empirical diagnostic technique in which time histories of convective clouds, at the −20°C threshold in the infrared imagery, are related to rainfall. The inferred rainfall is directly proportional to cloud area, inversely proportional to cloud-top temperature, and is a function of cloud lifecycle (more rain is inferred in the cloud's growing stages than in its decaying stages).

The technique's empirical relationships were developed in Florida by comparing concurrent hard copy satellite imagery to a combined system of raingage and radar ground measurements. Subsequent applications of these relationships permit the inference of rain from satellite imagery alone. Initially, rain estimates were made manually by compiling the necessary information from hard copy negatives, analyzed on a false-color densitometer. This was a tedious process and only gross measures of rain (total volumes or area averages) were possible. In 1977 the technique was automated. Rain estimates could then be achieved routinely over much larger areas by use of the digital imagery. Moreover, use of digital imagery made the derivation of isohyets feasible.

Because the technique uses satellite imagery alone, the production of isohyets, by the apportionment of estimated rain volumes, is based on the cloud-top temperature pattern. More rain is allotted to colder regions of the subject cloud's top than to its warmer regions. The physical basis for this procedure is simply that the most intense rain occurs ultimately in the region having the stronger upward ascent, an area usually marked by an overshooting top in the satellite image.

b. The whole cloud apportionment

The method developed to infer isohyets for GATE is referred to as the whole cloud apportionment. Rain volumes, computed per cloud, per time interval, are allotted to individually resolved (⅓° latitude × ⅓° longitude) bins of a cloud according to its cloud-top temperature pattern. Colder parts of the cloud receive more rain than warmer parts, but all of the cloud (as defined by the −20°C threshold) receives some rain.

Radar coverage over the GATE B-scale supplied ground estimates with which the satellite-derived isohyets could be compared. In most cases the satellite-derived rainfall patterns covered a larger area than those detected by radar, and the rainfall maxima were generally too low. To quantify this tendency, pairs of corresponding daily radar and satellite maxima were plotted. A linear regression of the resulting scatter diagram showed that, on the average, the radar rain maxima were on the order of 2½ times greater than the satellite-derived rain maxima (see Section 2c). These results prompted a search for an apportionment scheme which would produce more realistic isohyetal patterns.

c. An improved method of apportionment

A review of the literature reveals that the distribution of tropical convective rain is quite nonlinear. Higher order distributions of rainfall both in space and time are reported. Riehl (1954) and Garstang (1972) report that roughly 50% of convective rain falls in 10% of the time that rain is occurring. Woodley *et al.* (1975) reveal that this general rain-time relationship is transferable to a rain-area relationship. Their results show that the spatial distribution of rainfall from convective clouds also is highly nonlinear. For 24 h, 15–20% of the raining area of a cloud contains 50% of the rain volume and 50% of the raining area contains 90% of the total volume. Over longer periods (monthly), however, the spatial distribution of convective rainfall becomes more linear. These findings, of course, cannot be directly applied to the satellite technique because instantaneous cloud-top temperature patterns and temporally integrated radar rainfall are not related uniquely. However, a parallel approach can be used.

Based on the findings of Woodley *et al.* (1975), a new method of apportionment for satellite-derived rain volumes is hypothesized. According to the new method, half of the estimated rain volume is distributed over the coldest 10% of the cloud-top area and the remaining half over the next coldest 40% of the cloud top. Within each of these subareas the allotted rain volume is distributed according to temperature, just as in the whole-cloud method, because again, regions of strongest upward ascent should be given the most weight. This new algorithm is called the "10–50/40–50" apportionment.

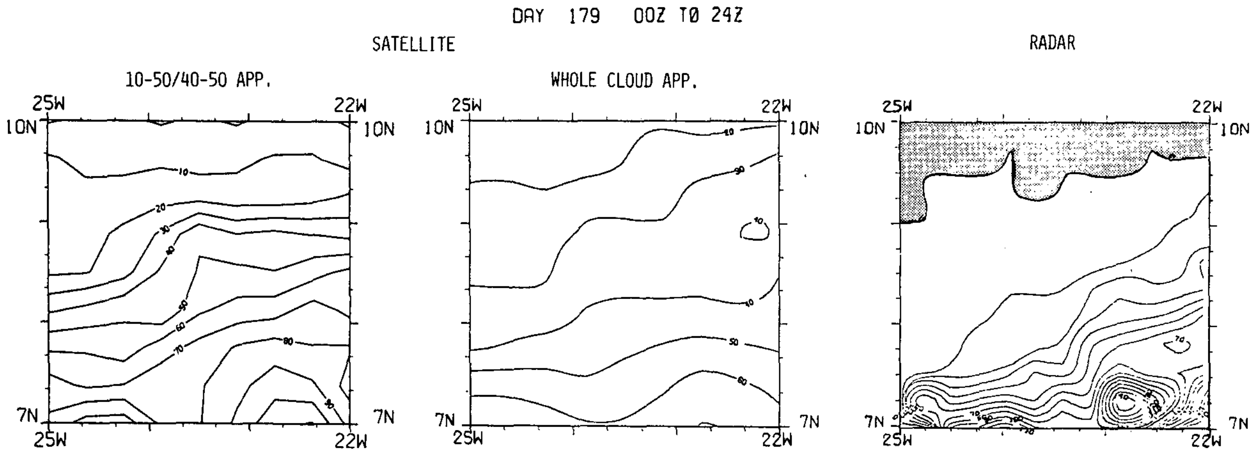

FIG. 1. Satellite-derived isohyets using the 10–50/40–50 apportionment (left), satellite-derived isohyets using the whole-cloud apportionment (middle) and the radar-derived isohyets (right) for the B scale, for 28 June 1974.

1) B-SCALE RESULTS USING THE NEW APPORTIONMENT

In order to test the 10–50/40–50 apportionment, rain estimates for the entire 85 days of GATE were recomputed using the new method. The radar-derived rainfall volumes and patterns over the B scale again provided the ground truth to assess the accuracy of the new products. To quantify the net improvement achieved by the new apportionment, identical analyses to those performed by Woodley *et al.* (1980) for results derived from use of the whole-cloud apportionment were carried out on the revised B-scale results. Results of these exercises were quite intriguing. Situations involving light rain from stratiform clouds or shallow convection did not improve significantly. However, where deep convection was predominant, resulting rain amounts and daily patterns substantially improved as can be seen in a representative example in Fig. 1.

The scatter diagrams for daily B-scale rain volumes as derived by the whole cloud and 10–50/40–50 apportionments versus radar-derived rain volumes are contrasted in Fig. 2. In comparing these two analyses, the linear fit of the B-scale daily rain volumes derived from the 10–50/40–50 method of apportionment shows a slight improvement over that of the whole-cloud apportionment; although the scatter and y intercepts are nearly identical, the slope of the linear fit changed from 0.87 to 0.97.

Since the 10–50/40–50 apportionment was designed to concentrate the satellite-estimated rainfall, the new daily rain core maxima were expected to exhibit improvement over those of the whole cloud method. The improvement was measured through a comparison of linear regression analyses of two scatter plots of satellite versus radar daily maxima—one for each method of apportionment. Results are given in Fig. 3. Although the correlation coefficients are nearly the same for the maxima generated from both methods of apportionment, the y intercept shifted from 6.29 to 0.38 mm and the slope improved from 0.37 to 0.63, with use of the 10–50/40–50 apportionment. It is clear from Fig. 3 that the

TABLE 1. Phase comparisons of radar (R) and satellite (S) rain estimates for the B-scale area.

	Radar	Satellite								
		Whole cloud apportionment				10–50/40–50 apportionment				
Period	Rain volume (10^8 m^3)	Rain volume (10^8 m^3)	R/S	S/R	Satellite under-estimate* (%)	Rain volume (10^8 m^3)	R/S	S/R	Satellite under-estimate* (%)	Number of cases
Phase I	218.6	200.0	1.09	0.92	9	201.2	1.09	0.92	8	19
Phase II	155.2	89.8	1.73	0.58	42	100.1	1.55	0.64	36	16
Phase III	246.1	241.3	1.01	0.99	2	234.5	1.05	0.95	5	21
All phases	619.9	531.1	1.17	0.86	14	535.8	1.16	0.86	14	56

* Satellite underestimate is defined as (R − S)/R × 100.

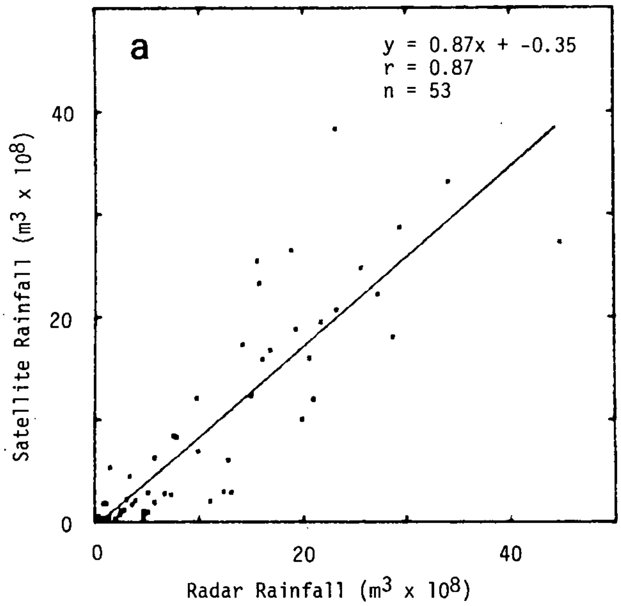

FIG. 2a. Scatter plot and linear regression of satellite- versus radar-derived daily rain volumes for all phases over the B scale for the whole-cloud apportionment.

heavy rain cases (maxima > 50 mm) are responsible for this improvement, as the low rain end of the diagram hardly changed.

Use of the new apportionment not only improved the daily comparisons to radar, but also improved the longer phase rain volumes and patterns. As reported in Table 1, the B-scale underestimates for Phase II improved with the new apportionment from an underestimate of 42% to an underestimate of 36%,

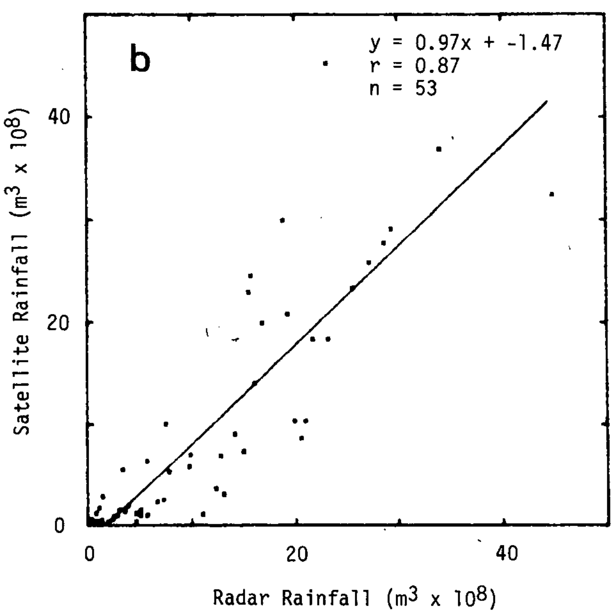

FIG. 2b. As in Fig. 2a except for the 10–50/40–50 apportionment.

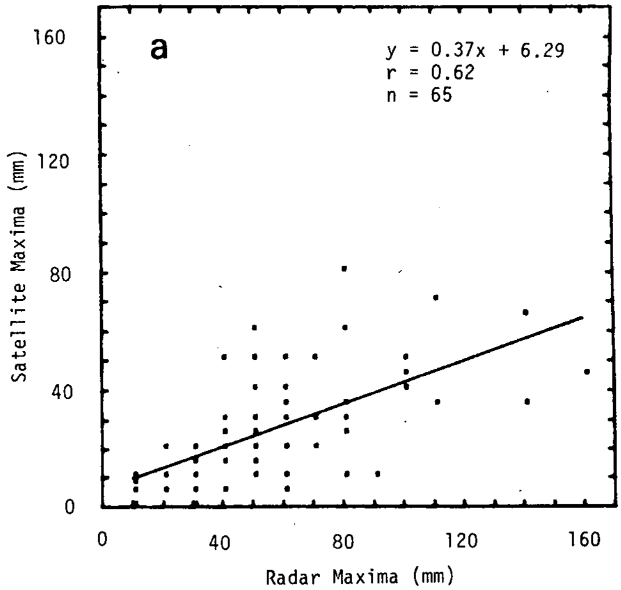

FIG. 3a. Scatter plot and linear regression of satellite- versus radar-derived rainfall maxima over the B scale for the whole-cloud apportionment.

whereas in Phases I and III much smaller changes of −1 and +3%, respectively, were observed.

Apparently, a portion of the error in the satellite rain estimates in Phase II described by Woodley *et al.* (1980) was due to the whole cloud method of apportionment. Table 1 results suggest that in Phase II most of the clouds' coldest tops were over the B-scale area and that the whole cloud apportionment had distributed too much of their inferred rainfall to warmer parts of the cloud top which lay outside the borders of the B scale. In contrast, a number of storms in Phase III had cold tops outside of the

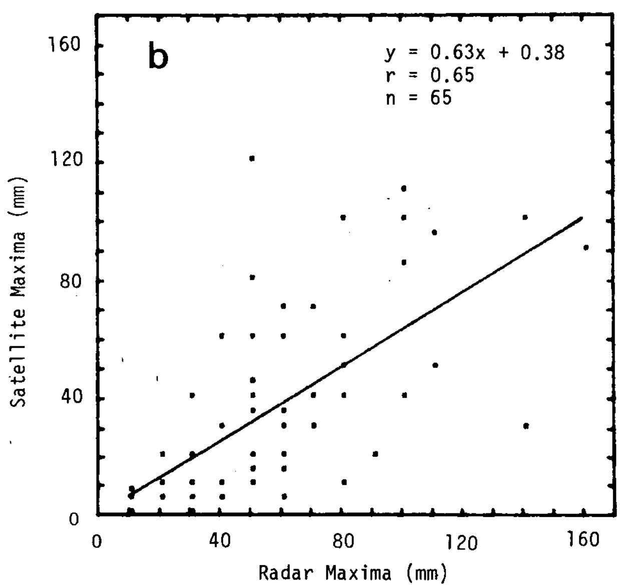

FIG. 3b. As in Fig. 3a except for the 10–50/40–50 apportionment.

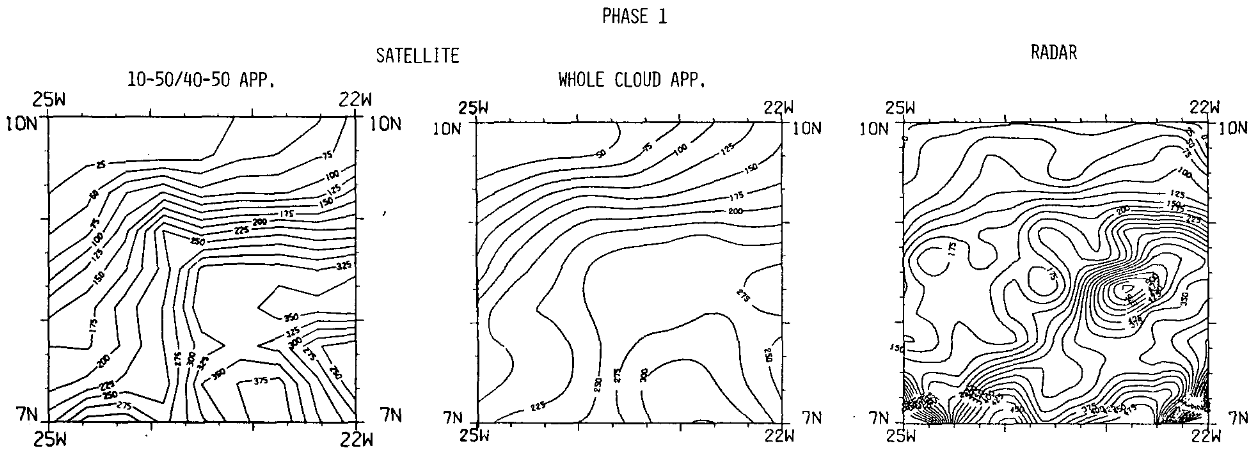

FIG. 4. Comparison of radar-derived isohyets (right) to satellite-derived isohyets from the whole cloud apportionment (middle) and the 10–50/40–50 apportionment (left) over the B scale for Phase I.

B-scale area, resulting in a decrease in B-scale rainfall when the concentrated apportionment was applied. For Phase I the cloud-top location versus rain apportionment differences nearly compensated each other, and only a 1% improvement was observed.

Figs. 4, 5 and 6 show the composited isohyetal patterns for the radar and the two satellite products for each of the three phases. In each phase a general improvement is observed in the satellite-derived rain pattern. Maxima and minima are better defined with respect to the radar, especially in Phase II. Although there still remains a problem with underestimation in Phase II, the isohyetal patterns and amounts based on the concentrated apportionment better simulate those of the radar and this is responsible for the 6% improvement in the volumetric comparison.

Over the longer "all phases" period (56 days) however, the effect of applying the 10–50/40–50 apportionment appears only in the isohyetal patterns. Volumetrically, each method of apportionment generates a 14% underestimate relative to the radar, of which the largest part is attributable to the poor performance of the technique in Phase II. On the other hand, Fig. 7 shows that the isohyetal pattern generated from the 10–50/40–50 apportionment for the 56-day period better simulates the radar-derived pattern than does the whole cloud result. Both the rain maxima and gradients are better defined in the 10–50/40–50 product. These results suggest that for long term rainfall (two months or greater), if only gross measures of precipitation such as total volume or area average depth is required, the two methods of apportionment are comparable. However, if accuracy in the positioning of the isohyets are of equal concern, use of the 10–50/40–50 method of apportionment is more desirable.

2) A-SCALE RESULTS USING THE NEW APPORTIONMENT

It was impossible to assess the accuracy of the larger A-scale rain estimates in the same manner

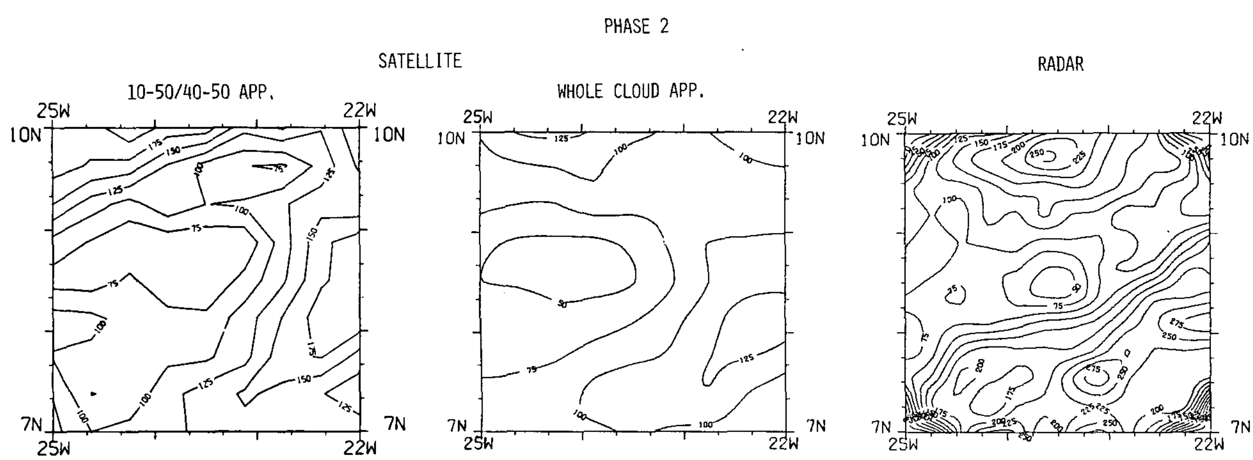

FIG. 5. As in Fig. 4 but for Phase II.

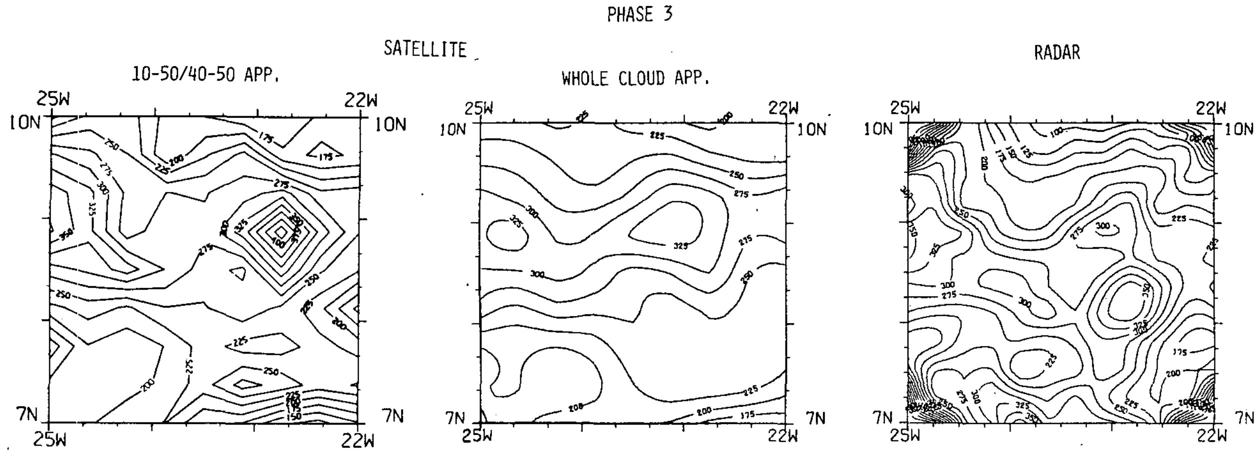

FIG. 6. As in Fig. 4 but for Phase III.

as the B-scale estimates because of the paucity of surface estimates. (There were gages on 18 GATE ships in the Atlantic Ocean). However, a discussion of the manner in which these large scale estimates were affected by the concentrated apportionment is warranted. Of course, the total rain volume did not change because the new apportionment only redistributed the rain, but rain rates and rain coverage did. Table 2 contrasts these parameters for the two methods of apportionment. For all of GATE the rain coverage over the *A* scale decreased from an average of 22% to an average of 16% and rain rates within the rain areas increased, on the average, from 1.4 to 1.9 cm day^{-1}. In contrast, Gray (1973) estimated areal coverage of daily rainfall over the tropics as a whole at 20%, and Williams and Gray (1973) estimate that 2.5 cm day^{-1} of rain falls in tropical clusters. However, because of differences in approach, data type, resolution and geographical locations, the differences between the satellite estimates and those of Williams and Gray may not be significant.

3. Spatial and temporal resolution degradation

Assuming that the 10–50/40–50 apportionment indeed accounted for errors accrued through use of the whole cloud method, there still remain the 8, 36 and 5% underestimates for the three phases yet to be accounted for from other sources. A portion of the remaining error in the phase rainfalls is presumed attributable to the degradation of temporal and spatial resolution of the digital imagery.

Because of computer time and core limitations, degradation of the temporal and spatial resolutions of the satellite imagery is necessary when making rain estimates over very large areas such as the GATE A scale. The effect of spatial resolution degradation is to slightly increase the average temperature of the cloud top and thus decrease the rainfall estimates. Reduction of the temporal resolution of satellite imagery also decreases estimated rainfall by omitting the contributions of short-lived clouds. In order to assess the relative error

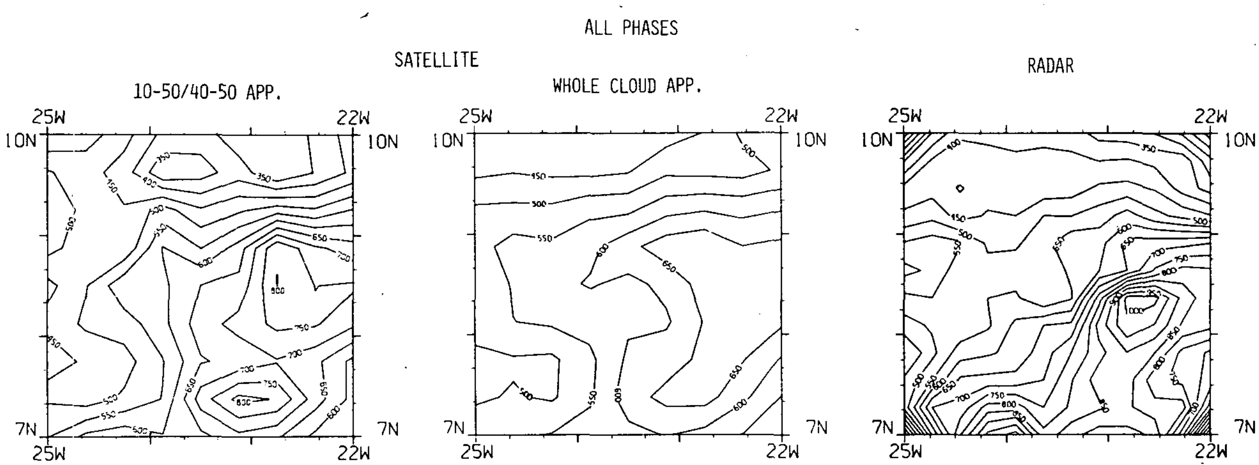

FIG. 7. As in Fig. 4 but for all phases.

TABLE 2. Mean rainfall in, and fractional coverage of satellite-derived rain areas over the A scale for the whole cloud and 10–50/40–50 apportionments.

Period	Mean A-scale rain rates (cm day^{-1}) Whole-cloud apportionment	Mean A-scale rain rates (cm day^{-1}) 10–50/40–50 apportionment	Mean A-scale rain coverage (%) Whole-cloud apportionment	Mean A-scale rain coverage (%) 10–50/40–50 apportionment
Phase I (days 179–197)	1.41	1.86	20	15
Interphase (days 198–208)	1.50	2.02	21	16
Phase II (days 209–227)	1.26	1.69	20	15
Interphase (days 228–241)	1.58	2.17	19	15
Phase III (days 242–262)	1.37	1.85	26	19
Phases I, II, III	1.35	1.80	22	17
All GATE	1.41	1.89	22	16

caused by resolution degradation, sensitivity tests were carried out on 54 h of imagery for an 8° × 12° area of the eastern Pacific. Both spatial and temporal resolutions were varied and the resulting rain volumes compared. Results, given in Table 3, show that as resolution is degraded, both in time and space, the total estimated rain volume decreases, although it appears that spatial resolution degradation has a greater effect than temporal resolution degradation.

For the GATE application the supplied temporal resolution was 1 h[2] and the spatial resolution was reduced from 1/15° to 1/3°. As indicated in Table 3, the degree of resolution degradation used in GATE might produce a relative error of 10% in the total rain volume. In a gross sense, this bias could be removed by increasing the 10–50/40–50 results by 10%. In doing this, the total rain volumes for Phases I and III show a 1% and 5% overestimation, respectively, but still, Phase II shows a substantial underestimate of 29%. To account for this remaining error meteorological considerations are investigated.

4. Anomalous behavior of convective clouds in GATE relative to Florida

Examination of the daily performance of the satellite technique versus the radar-estimated rainfalls over the B scale reveal that the frequency of under- and overestimation is nearly the same in all three phases. The poor performance in Phase II is therefore attributable to larger underestimates in Phase II than in Phases I and III—perhaps due to undetectable "warm rain" from shallow convective clouds.

Warm rain, in the context of this technique, can occur when an active cloud does not reach the −20°C threshold at which rain-producing clouds are defined. If this occurs, no rain is inferred. It may be possible to detect these events through use of lower infrared thresholds but this would entail a rederivation of the technique's empirical relationships. This is not only undesirable because of its expense, but it also may be counterproductive. The −20°C threshold was chosen statistically to maximize the number of clouds with rain and minimize the number of clouds without rain (Griffith *et al.*, 1978). Changing to a lower threshold may actually increase contamination by non-raining clouds, thereby worsening the problem.

In order to assess the magnitude of the warm rain problem in the GATE B scale, cloud-top and echo-top temperatures were compared in some representative cases. Comparisons were carried out at 1/3° resolution. To make the satellite and radar data sets compatible, the spatial resolution of the echo-top data[3] was reduced from 1/30° to 1/3° by simple averaging. Echo-top heights were converted to temperature by use of phase mean soundings.

After the echo-top and satellite data were made spatially compatible they were compared over the region of the B scale which had reported radar echoes at cloud base at the time of analysis. This area is hereafter referred to as the "rain area." Beginning with the coldest reported echo top, the percentage of the rain area covered by echo tops whose temperatures were less than or equal to a par-

[2] Smith, E. A., and T. H. Vonder Haar, 1976: Hourly Synchronous Meteorological Satellite-1 (SMS-1) data collected during the GARP Atlantic Tropical Experiment (GATE). Earth located edited data set. Dept. Atmos. Sci., Colorado State University, Ft. Collins, 174 pp.

[3] GATE NOAA radar echo top graphics data compiled by Michael D. Hudlow, NOAA. [Available from the Environmental Data Service, National Climatic Center, Federal Building, Asheville, NC 28801.]

TABLE 3. Cumulative rain volumes (m³ × 10⁹) over an 8° × 12° area in the eastern Pacific for a 54-h period as a function of the resolution of the input satellite imagery.

Spatial resolution	Temporal resolution ½ h	1 h	1½ h	3 h	6 h
1/15° × 1/15°	16.30	16.27	16.21	—	—
1/3° × 1/3°	15.53	14.71	15.05	14.05	13.40

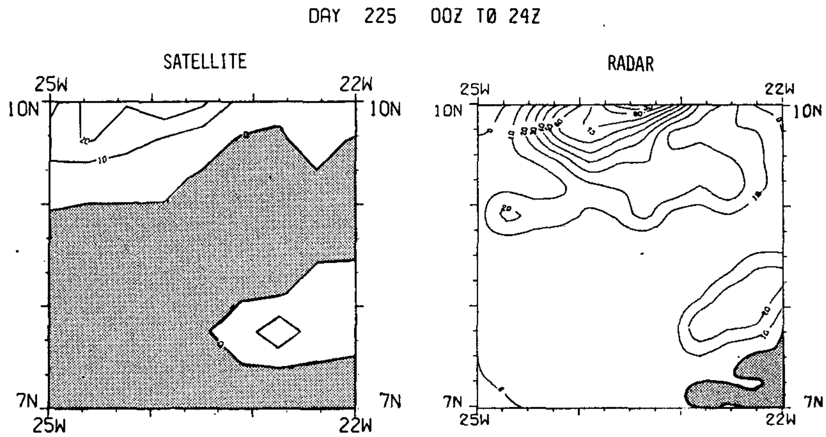

FIG. 8. Satellite-derived isohyets using the 10–50/40–50 apportionment (left) and radar-derived isohyets (right), for the B scale, for 13 August 1974 (day 225).

ticular temperature was computed. This calculation was made for the complete range of echo-top temperatures reported over the rain area. The computed percentage would be lowest for the coldest reported echo-top temperature and 100% for the warmest echo top, which defines the rain area. This calculation was repeated for the satellite-derived cloud-top temperature fields over the same radar-defined rain area.

Although the resultant echo-top and cloud-top temperature curves are computed identically, each has a different interpretation. The satellite cloud-top temperature analysis is designed to measure the relative amount of warm rain that occurred. The percentage computed for the −20°C level is the ratio of satellite detectable rain to undetectable (warm) rain. The echo top curve, on the other hand, gages the intensity of the convection. Relatively high echo tops indicate deep, intense convective activity, whereas low echo tops typify weak convection.

A typical example of the warm rain problem occurred on day 225. On this day the satellite technique underestimated the radar-derived rain volume over the B scale by a factor of 4.52. As observed in Fig. 8 the radar-derived rain pattern showed relative maxima in the north-central and southeast regions of the B scale. The maximum in the north exceeded 90 mm, whereas the maximum in the southeast was substantially less. Comparing the satellite to the radar product suggests that the satellite technique did recognize raining clouds but did not correctly identify the rain intensities, especially in the north.

Fig. 9 illustrates, for two representative periods on day 225, why the satellite method underestimated the radar-estimated rainfall. Fig. 9a shows that only 17.5% of the area recording precipitation was so detected by the satellite technique at 0513 GMT. The relatively low echo tops at this time indicate that the convective events were not very vigorous. Fig. 9b gives the same type of analysis for 1713 GMT for another significant rain period on day 225. During this time convective activity was most intense in the northern part of the B scale, where the heaviest rain was recorded that day. The radar data for this period show that of the area reporting echo tops, only 8% surpassed the −20°C level, again indicating relatively weak convection. Corresponding satellite temperatures for this area show that 30% of the clouds in the rain area were above the −20°C level, 20% above the −30°C level, and only 10% between −40 and −50°C. This suggests that, on this day, most of the rain in the B scale came from clouds that did not grow above the −20°C level.

In contrast to the warm rain cases, there were also instances when the satellite technique overestimated the radar-derived rain. As with the previous case, it is presumed that anomalous convective behavior relative to the Florida derivation data set was responsible for the overestimates. Day 179 (Fig. 10) is a good example of this type of error. On this day, the satellite technique overestimated the radar-derived rainfall by nearly a factor of two. The radar-derived pattern shows two strong maxima (>110 mm) along the southern border of the B scale and a sharp decrease in rainfall northward. The satellite product shows a similar pattern but the spatial distribution of the estimated rain is much too extensive.

Diagrams in Fig. 11, which represent a heavy rain period for this case (1003–1103 GMT), show that between 40% and 50% of the echo tops (averaged over 1/3° squares) in the rain area were measured at heights above the −20°C level. The full resolution data (not plotted) indicated that between 60 and 80% of the echo tops were above the −20°C level, of which the highest were reported at heights of 12 km—an indication of vigorous convective activity.

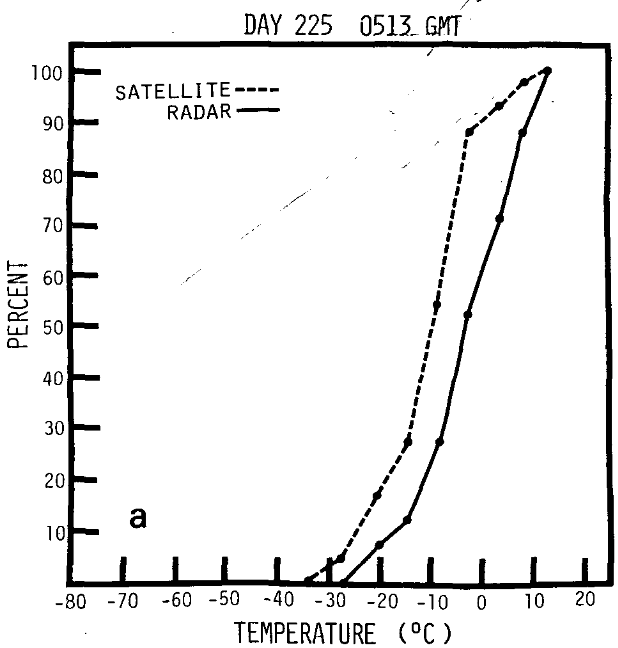

FIG. 9a. Percentage of radar-inferred rain area covered by radar echo tops and satellite-derived cloud tops as cold or colder than the indicated temperature for 0513 GMT 13 August 1974.

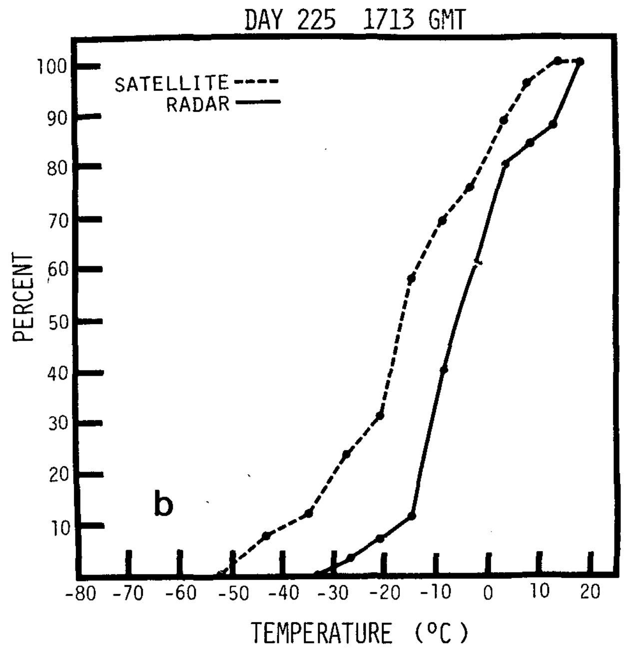

FIG. 9b. As in Fig. 9a except for 1713 GMT.

Satellite-derived cloud-top temperatures were even colder. In fact, all of the clouds over the area reporting precipitation had tops at least as cold as −60°C (Fig. 11). It is postulated that anvils from very deep convective storms probably persisted for longer periods than had anvils in the Florida derivation data, and as a result the rainfall was overestimated. Moreover, the estimated rain volume was dispersed over the very large and cold anvil area, thus misrepresenting the more restricted actual rain pattern, even after the 10–50/40–50 apportionment had been applied.

The two previous examples were obvious under- and overestimation errors. On day 209 these types of errors balanced resulting in a very good volumetric comparison between the radar and satellite 24 h products. There were two distinct areas of precipitation on this day (Fig. 12), a broad area extending over the southern half of the B scale which peaked at 0400 GMT, and a line of convective activity extending from the west-central to the northeast corner which occurred about 2000 GMT. A comparison of radar- and satellite-derived products shows that the earlier, more intense event was better simulated by the satellite technique than the later event. However, the 24 h volumetric comparison over the entire *B* scale showed only a 3% net underestimate by the satellite technique.

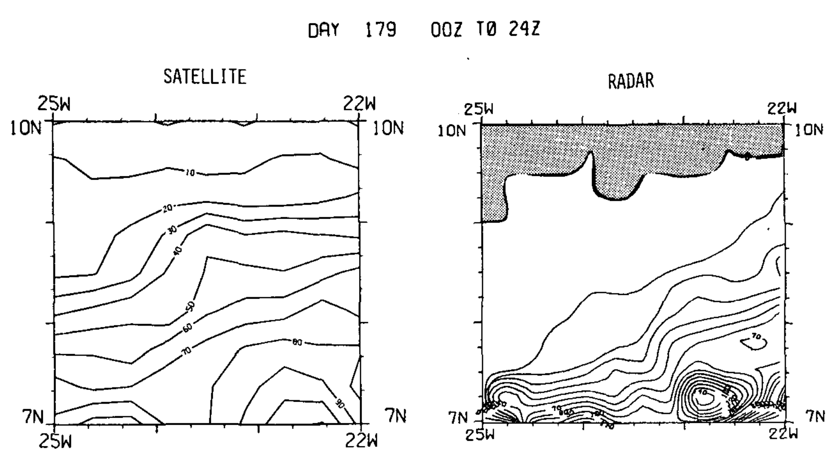

FIG. 10. Satellite-derived isohyets using the 10–50/40–50 apportionment (left) and radar-derived isohyets (right) for the B scale, for 28 June 1974.

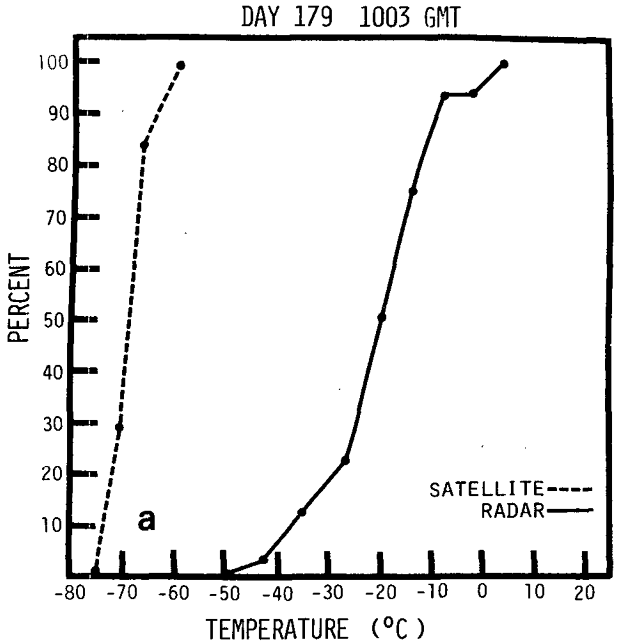

FIG. 11a. Percentage of radar-inferred rain area covered by radar echo tops and satellite-derived cloud tops as cold or colder than the indicated temperature for 1003 GMT 28 June 1974.

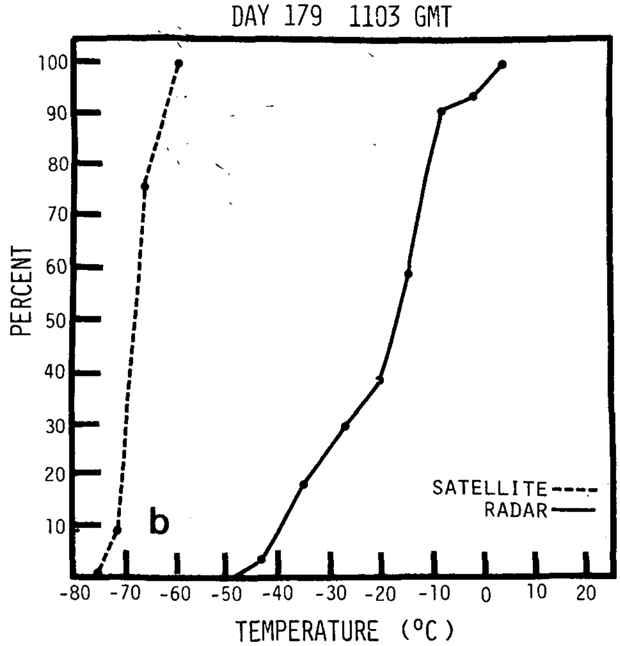

FIG. 11b. As in Fig. 11a except for 1103 GMT.

Examination of the echo top analyses (Fig. 13) provides insights into the performance of the satellite technique on this day. Fig. 13a represents the deep convection that was in the southern part of the B scale. The cloud top temperature curve shows that most of the clouds over the rain area were very cold with over 90% of the clouds colder than −20°C. The echo top curve suggests that the convective activity producing the observed rainfall was rather intense with hydrometeors observed up to the −50°C level. Fig. 13b, on the other hand, is the cumulative plot of echo-top and cloud-top temperatures for 2000 GMT, when the line of convective activity, for which the rain was underestimated, was most active. The two profiles of Fig. 13b suggest rather shallow clouds, in that only 6% of the echo-top and 21% of the cloud-top temperatures within the rain area were colder than −20°C. These differences explain the differential performance of the technique on this day.

Collectively these three case studies suggest that for any given day the errors resulting from meteorological factors are difficult to quantify. Warm rain and anvil contamination effects compensate each other on a varying basis from day to day; an anvil-produced overestimate on one day is offset by a warm rain underestimate on another. Therefore, as the period of rain estimation increases, the satellite

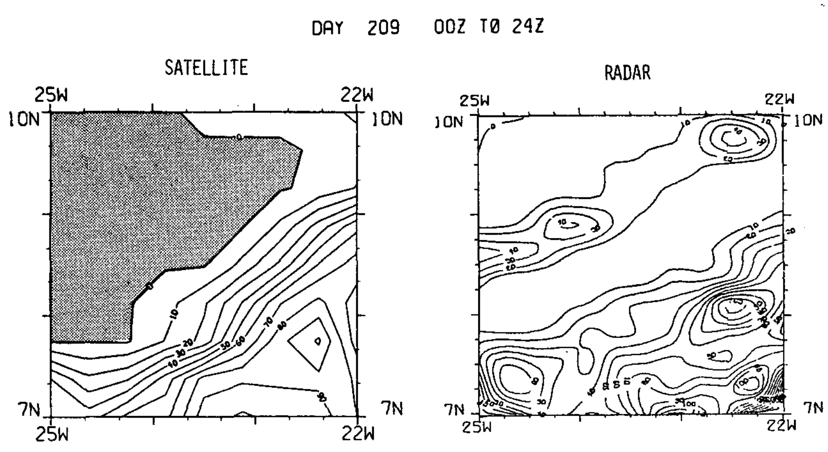

FIG. 12. Satellite-derived isohyets using the 10–50/40–50 apportionment (left) and radar-derived isohyets (right) for the B scale, for 28 July 1974 (day 209).

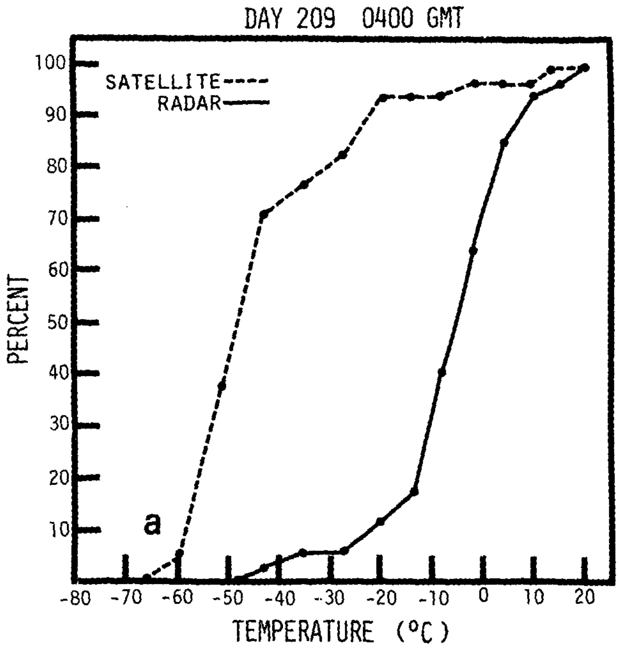

FIG. 13a. Percentage of radar-inferred rain area covered by radar echo tops and satellite-derived cloud tops as cold or colder than the indicated temperature for 0400 GMT 28 July 1974.

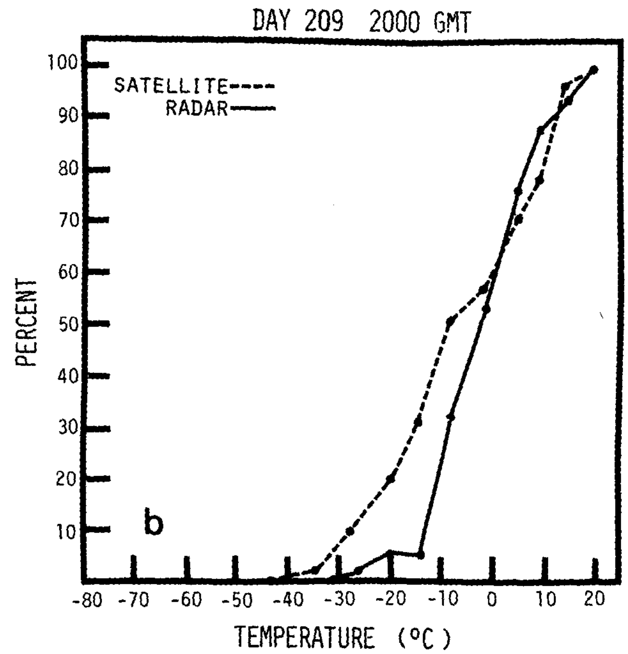

FIG. 13b. As in Fig. 13a except for 2000 GMT.

estimates should converge to the ground-based estimate.

Cumulative results for Phases I and III are good examples of warm rain-anvil rain compensation. Although comparisons between satellite and radar vary from day to day, the overall phase results compare favorably to radar. For Phase II, however, the daily satellite rainfalls are generally less than the radar-derived rain, and over the whole phase the satellite technique underestimates the radar by 29%, after accounting for the spatial and temporal resolution degradation errors.

Finally, similar analyses, composited for Phases I and II show that, on the average, rain producing storms of Phase II were more shallow than those of Phase I. Specifically, average cloud coverage at the −20°C threshold for Phase II was 18% lower than that for Phase I. On the basis of this result and the cases presented in this section, it appears that there were more warm rain events (i.e., rain from clouds warmer than −20°C) and fewer or less intense deep cloud rain events in Phase II than in Phases I and III.

5. Conclusions

Several analyses have been employed to gain insights into the satellite rainfall underestimates produced by the Griffith/Woodley technique in GATE. A new rainfall apportionment scheme has been applied to the SMS inferred GATE rainfalls, which improves the *B*-scale satellite and radar 24 h rainfall comparisons. The revised satellite-inferred isohyets show a decrease in spatial extent and an increase in the values of rain maxima, both of which better approximate the radar results. The linear fit to the comparisons between satellite and radar daily volumetric rainfall show a smaller underestimation bias. Phase volume results indicate that the new apportionment produced relatively small changes in satellite-radar comparisons for Phases I and III (−1 and +3% change, respectively), but a 6% improvement was achieved for Phase II. Over the period encompassed by all three phases however, there is no difference between results from the two apportionments as each is low relative to the radar by 14%.

Over the A scale, total rain coverage decreased from 22 to 16% and the average rain rate increased from 1.4 to 1.9 cm day^{-1} with implementation of the new apportionment. These results are encouraging because they are similar to independent calculations made by Gray (1973) and Williams and Gray (1973) who employed a much different approach.

In addition to the errors associated with the rainfall apportionment scheme, errors arising from resolution degradation of the satellite data and from meteorological conditions were investigated. Tests have suggested that this satellite rain estimation technique is more sensitive to spatial degradation than to temporal degradation, and that for the space and time scales used in the GATE application, on the order of a 10% reduction in the inferred rainfalls is expected.

Significant rain from clouds whose tops do not reach the −20°C level ("warm rain") appears to have contributed to satellite rain underestimates of radar-derived results of all phases of GATE. In this case, the satellite rain estimates are low compared to ground measurements because raining clouds are not identified as such. An opposing effect, perhaps due to long-lived anvils, produces overestimates for very deep convective storms. If both conditions exist during a given period, they may compensate. Accordingly, it appears that there were more warm rain events and fewer compensating events in Phase II than in Phases I and III, thus explaining the net underestimation in Phase II.

Recognition of a warm rain event cannot be determined solely from the infrared imagery. Therefore, no general correction has been made, as is possible with the resolution degradation error. None is possible over any time period without access to additional information, such as, visible geosynchronous imagery, which is available only during the daylight hours.

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