A Comparison of Two Satellite Rainfall Estimates for GATE[1]

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ABSTRACT

Rainfall estimates obtained for the GATE experiment by two satellite rainfall estimation techniques are compared for different time and space scales. The Kilonsky-Ramage technique uses polar-orbiting satellites for 1° resolution rainfall estimates over the tropics. The Griffith-Woodley technique uses geostationary satellite data to generate much higher resolution estimates. There is good correspondence between the A scale isohyetal patterns and rainfall volumes estimated by both techniques for periods ranging from 1 to 80 days. Largest discrepancies appear over Africa and nearby ocean areas, where the Griffith-Woodley estimates are higher. Correlation coefficients between the two estimates are higher when only oceanic points are compared, ranging up to 0.92 for the entire GATE period. When continental areas of the A scale are included, correlation coefficients are lower, reaching 0.66 for phase 2. The large discrepancies over Africa and nearby ocean areas are seen to be associated with a nocturnal peak of rainfall which is not detected by the daytime passes of the polar orbiting satellite used in the Kilonsky-Ramage calculations.

Comparison of results of both techniques with shipboard radar ground-truth over the GATE B scale show that both techniques produce comparable rainfall volume estimates at this scale, generally within 15% of the radar estimates. Overall, results indicate that the Kilonsky-Ramage technique can produce low cost and fairly reliable estimates of rainfall over the tropical oceans.

1. Introduction

In recent years several techniques have been developed for estimating rainfall using satellite imagery. A comprehensive review of these was made by Martin and Scherer (1973). Griffith *et al.* (1978) recently developed what is the most sophisticated method of rainfall estimation by satellite now available, which makes use of high resolution infrared geostationary satellite imagery in computer automated procedures. Unfortunately, the large computer calculation requirements of this technique make it as yet unfeasible for routine use in deriving climatological rainfall estimates over large areas of the globe.

Kilonsky and Ramage (1976) devised a straightforward procedure of rainfall estimation based on the incidence of highly reflective clouds on daily picture mosaics obtained from polar orbiting satellites. This technique, although having much lower resolution than the Griffith-Woodley technique, has the advantage of producing rainfall estimates over large areas and long periods of time at much lower cost than the latter.

The intensive observational program conducted during the GATE experiment (27 June through 20 September 1974) afforded a rare opportunity to conduct a detailed comparison of these two rainfall estimation techniques over a wide area (the GATE A scale), and in turn to compare the results of both techniques with radar estimates of rainfall over a more limited area (the GATE B scale). Woodley *et al.* (1980) used the Griffith-Woodley technique to develop isohyetal maps and rainfall volume estimates for the A and B scales for time scales ranging from 6 hours to the full 85 day GATE period. The purpose of this paper is to report the rainfall estimate comparisons of the two techniques for the GATE experiment.

2. The Kilonsky-Ramage highly reflective cloud technique

Based on the assumption that most rainfall in the tropics is caused by organized convection (Riehl, 1954), Kilonsky and Ramage (1976, hereafter referred to as KR) developed a regression equation relating the observed monthly rainfall at Pacific coral island stations (with elevations under 30 m) to the number of days with highly reflective clouds appearing over the stations on satellite picture mosaics published by the National Environmental Satellite Service[3]. The shape, location and extent of highly

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[3] Conlan, E. F., 1973: Operational products from ITOS scanning radiometer data. NOAA Tech. Memo NESS 52, 57 pp.

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reflective clouds are subjectively analyzed by trained observers. Only clouds with radii over 2° in length are coded. Cloud centers are located to the nearest 1°. Manual intervention allows the identification of highly reflective clouds in areas of different background brightness. Also this intervention helps to discriminate true convective systems from spuriously bright clouds such as might appear by the interaction of the sun glint with a stratus deck. Over 820 station-months of data were considered in arriving at the regression equation

$$Y = 62.6 + 37.4X, \quad (1)$$

where Y is the estimated rainfall for the month (in mm) at an oceanic location and X is the number of days during the month with highly reflective clouds noted over that location, as seen in the satellite mosaics.

The regression equation rests on three hypotheses:

1) A linear relationship exists between the variables X and Y, for which the theory of least squares was used in fitting the regression to the data.

2) No relationship exists between successive pairs of observations.

3) Coral island rainfall is representative of open ocean rainfall. Correlation between the two variables was computed at 0.75, which was significant at the 1% level.

The y intercept value of 62.6 indicates that stations for which no highly reflective clouds are noted in the mosaics during a month still record an average of 62.6 mm of rainfall for the period. This residual rainfall may be due to one or more causes. Since the satellite mosaics are composed of pictures taken in the late morning local time, a station might come under the influence of areas of organized convection forming locally or drifting over the area at other times of the day. Some rainfall may also result from convective systems smaller than the 2° minimum radius considered by the technique. Finally, a significant amount of rain in the tropical oceans may fall from stratiform clouds that would not appear as highly reflective cloud masses in the satellite mosaics.

Since the KR regression equation was derived from monthly rainfall records, it should properly be used for monthly rainfall estimates only. Initially, the Griffith-Woodley rainfall estimates were available to us only for the entire 85 day GATE period and for the three phases, ranging in duration from 19 to 21 days. Since the y intercept of Eq. (1) is not equal to zero it became necessary to modify the equation in order to use it in deriving rainfall estimates for periods under one month. This was accomplished by changing the value of the y intercept in proportion to the length of period examined. For example, since the average month is 30.4 d long, the y intercept value of Eq. (1) when applied to a 21 d period (as in phase 3 of GATE) should be changed to $(21/30.4) \times 62.6$, or 43.2 mm. This procedure was followed in deriving rainfall estimates for time periods smaller than one month.

In order to obtain rainfall estimates for the entire GATE period, it was subdivided into three segments of roughly equal duration (periods A, B and C) of just under one month. The y intercept value was adjusted for the length of these periods and the three resulting estimates were then added to arrive at a cumulative estimate for the entire GATE period.

One further modification to the original KR regression equation was made by setting the rainfall estimate equal to zero for those grid squares having no highly reflective clouds overhead during an observation period. However, if adjacent squares (in the N–S or E–W direction) had at least one day of highly reflective clouds, then the modified y intercept value was retained as the rainfall estimate. This was done to keep from overestimating rainfall volumes, particularly in areas far removed from significant convection activity, where it would be unrealistic to expect significant rainfall accumulation.

3. The Griffith-Woodley (GW) technique

The basic premise of the Griffith-Woodley technique is that areas of active convection and rainfall in the tropics appear relatively bright on satellite imagery (both visual and infrared). This technique was developed by calibrating geostationary satellite imagery with 10 cm radar data over South Florida (Griffith *et al.*, 1978). The GW technique was used to produce rainfall estimates for the GATE experiment. Processing of 85 days of hourly full resolution data (4 km by 8 km) required the development of automated procedures, as well as a method of condensing the data to a more feasible resolution of ⅓° by ⅓°. Programs were created for navigating the satellite and decreasing spatial resolution, isolating and tracking raining convective clouds and calculating and mapping rainfall over user-specified regions.

Woodley *et al.* (1980) show isohyetal maps and rainfall volume estimates for both the GATE A scale (1.43×10^7 km^2) and for a 3° square enclosing the B scale (1.10×10^5 km^2) for the three phases of GATE. In addition data is available on magnetic tape for 6 h rainfall totals for the entire A scale at ⅓° resolution.

4. The KR-GW cumulative rainfall estimate intercomparisons for the A scale

To directly compare rainfall estimates for the GATE A scale using the two techniques, it was

TABLE 1. Dates of GATE experiment.

Period	Julian dates	Number of days duration	Calendar dates (1974)
Interphase	178	1	27 Jun
Phase 1[1]	179–197	17[1]	28 Jun–16 Jul
Interphase[2]	198–208	10[2]	17 Jul–27 Jul
Phase 2[3]	209–227	18[3]	28 Jul–15 Aug
Interphase[4]	228–241	13[4]	16 Aug–29 Aug
Phase 3[5]	242–262	20[5]	30 Aug–19 Sep
Interphase	263	1	20 Sep
Period A[1,2]	178–207	27[1,2]	27 Jun–26 Jul
Period B[3,4]	208–236	27[3,4]	27 Jul–24 Aug
Period C[5]	237–263	26[5]	25 Aug–20 Sep

[1] Jul 10 and 12 excluded from consideration due to lack of NOAA-2 satellite data over the GATE area.
[2] Jul 20 excluded, no NOAA-2 data.
[3] Jul 30 excluded, no NOAA-2 data.
[4] Aug 22 excluded, no geostationary satellite data.
[5] Sep 13 excluded, no NOAA-2 data.

necessary to further reduce the resolution of the GW estimates to 1° by 1°. The KR estimates were obtained for 1° squares centered at latitude-longitude intersections. Each KR square encompasses sixteen ⅓° GW squares in whole or in part. The corresponding 1° GW rainfall estimate was obtained by averaging the values of the sixteen ⅓° squares, each weighted in proportion to the fraction of the ⅓° square area falling within the boundaries of the KR square.

The 1° resolution GW and KR data sets used for intercomparison constituted 44 × 26 arrays, with each array element representing the estimated mean rainfall occurring over a 1° by 1° square centered at latitude-longitude intersections. The grid square centers were located between 6°W and 49°W and between 21°N and 4°S.

Intercomparisons of cumulative rainfall estimates for the two techniques were made for seven periods: the three phases of GATE, the entire GATE period and periods A, B and C, each lasting approximately one-third of the entire GATE experiment (see Table 1). A total of six days were excluded from consideration in deriving the cumulative rainfall estimates: five days during which there was either full or partial interruption of data from the NOAA-2 satellite over the GATE area, and one day for which there was no geostationary satellite data.

Approximately 18% of the GATE A area extends over West Africa and eastern South America. Since the KR technique was developed for oceanic locations, the 938 grid squares located exclusively over the Atlantic Ocean were considered separately in all the intercomparison calculations.

Figs. 1–4 show the isohyetal maps obtained using both techniques over oceanic locations for phases 1–3 and for the entire GATE period, respectively.

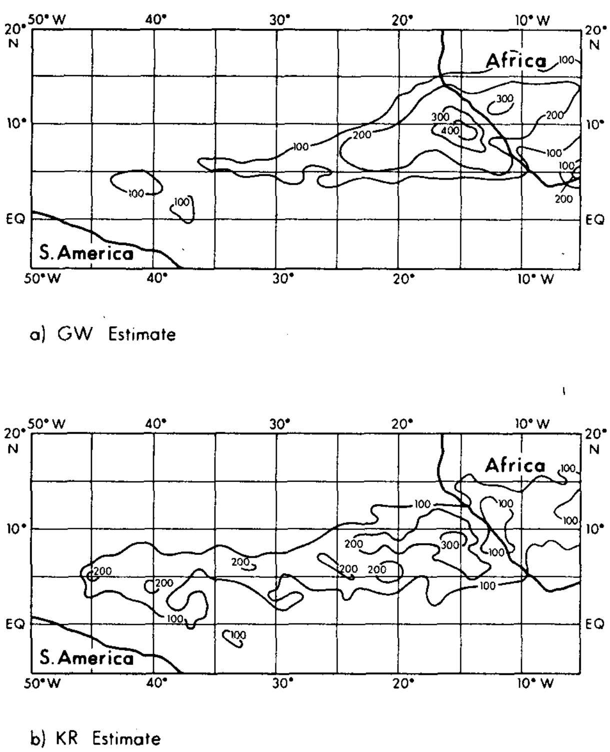

FIG. 1. Cumulative rainfall estimates (mm) for the GATE A scale during phase 1 (10 Jul and 12 Jul excluded from consideration).

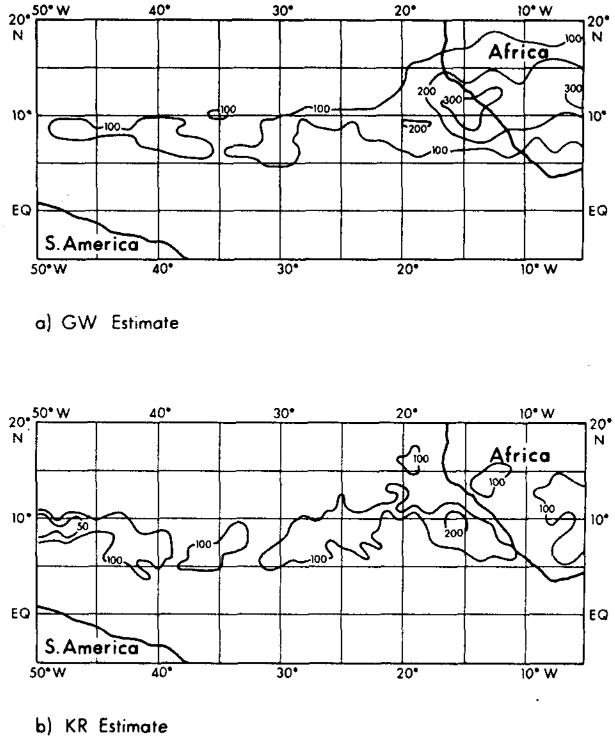

FIG. 2. As in Fig. 1, for phase 2 of GATE (30 Jul) excluded from consideration).

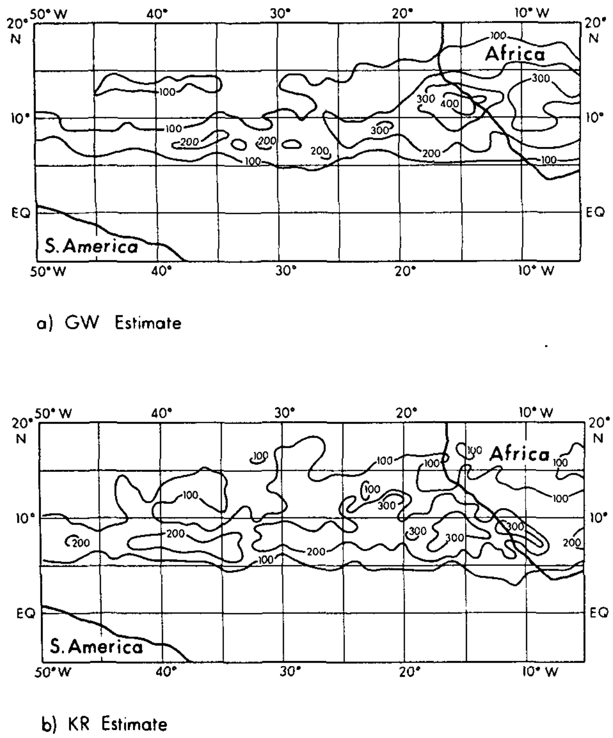

FIG. 3. As in Fig. 1, for phase 3 of GATE (13 Sep excluded from consideration).

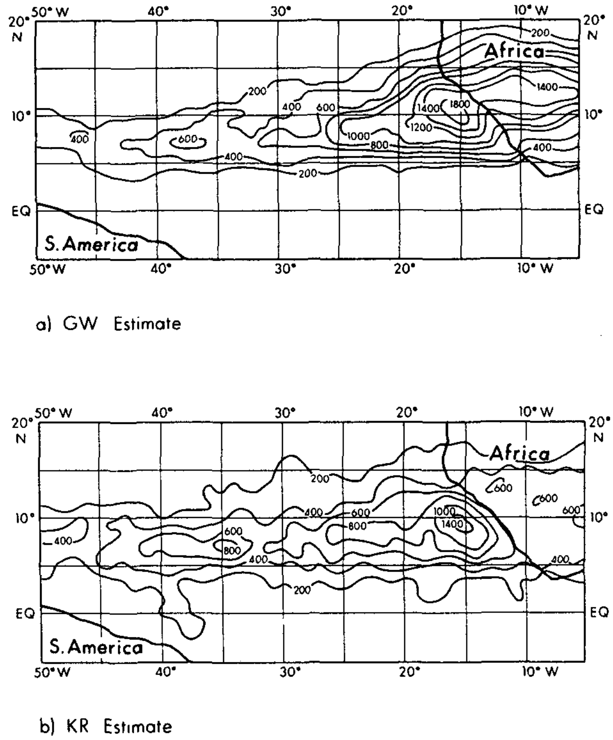

FIG. 4. As in Fig. 1, for 80 day period during GATE (see Table 1 for specific dates).

There is good correspondence in the isohyetal patterns and location of rainfall maxima in the figure pairs. The band of maximum precipitation drifts northward in both cases between phase 1, occurring in July and phase 3 in September. Both the GW and KR estimates indicate that the heaviest rainfalls take place in the eastern Atlantic and diminish westward. The largest differences between the two estimates occur near the African coast, where the GW values are significantly larger in all cases.

Scatter point diagrams were generated for all grid squares and oceanic grid squares for the pairs of estimates. Fig. 5 shows the scattergrams obtained for the cumulative rainfalls of the entire GATE period. The scatter is significantly higher for all the grid squares (both continental and oceanic) than for the oceanic squares alone. It can be seen that most of the KR rainfall estimates over continental areas are significantly smaller than the GW estimates; when these points are removed from consideration the scatter becomes smaller.

Correlation coefficients were calculated between the rainfall estimate pairs for all squares of the A scale array and for oceanic squares only. Table 2 shows the correlation coefficients obtained for the three phases of GATE, periods A, B and C, and the entire GATE period. In all cases the correlation coefficients were distinctly higher when only oceanic squares were considered. There is, overall,

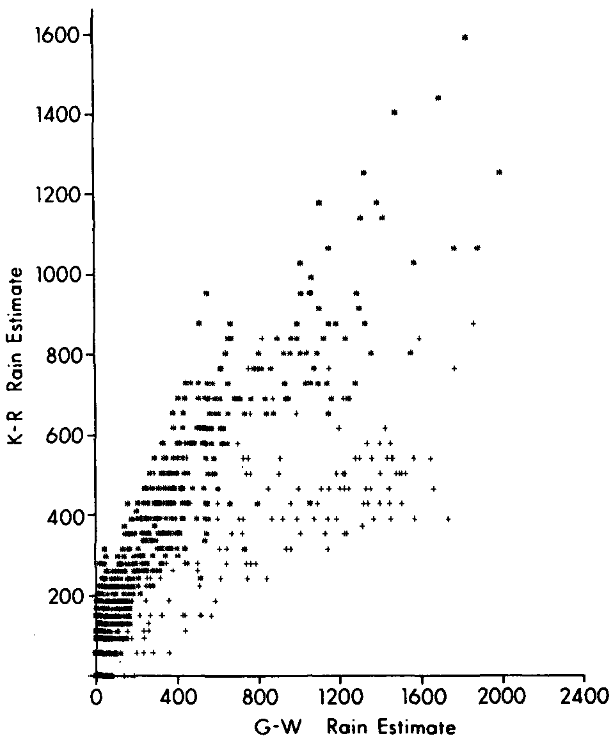

FIG. 5. Scattergram of cumulative rainfall estimates (mm) for 80-day period during GATE. Asterisks: oceanic grid squares; crosses: continental grid squares.

TABLE 2. Correlation coefficients between the cumulative rainfall estimates of the GW and KR techniques.

	All grid squares of the GATE A scale	Oceanic grid squares only
Phase 1	0.78	0.85
Phase 2	0.66	0.77
Phase 3	0.73	0.85
Period A	0.81	0.89
Period B	0.73	0.82
Period C	0.74	0.89
Entire GATE	0.81	0.92

a remarkably high correlation between the two techniques that tends to increase as the length of the period examined increases. This is particularly true for oceanic locations, where the highest correlation between the two techniques (0.92) was obtained for the full GATE period.

Total rainfall volume estimates for the two techniques were also obtained for the seven periods previously described. The ratios of the KR to the GW volume estimates are shown in Table 3. When the entire A scale area is considered, the volume estimates tend to fall within 10% of each other, with the exception of phase 2, where the KR estimates are only 75% of the GW estimates. For oceanic areas, the KR/GW volume is significantly larger.

5. The daily rainfall variability in the A scale

It is possible to analyze the two techniques in more detail by examining their respective daily rainfall volume estimates over different areas. Indirect estimates can be made of daily rainfall volumes over the A scale for each phase of GATE by apportioning the phase volume total to each day according to the daily areal coverage by highly reflective clouds (HRC) obtained using the KR technique. The GW daily rainfall estimates were available on tape.

Fig. 6 shows the daily pair of rainfall volume estimates for the A scale and oceanic areas during the three phases of GATE. There is a fair correspondence between the A scale volume estimates, with good agreement on the day to day tendencies. Significant disagreements occur on 7 and 8 August and during 9–12 September. Correlation between the two A scale time series is 0.53; if the 7–8 August and 9–12 September time periods are excluded the correlation rises to 0.72.

If only oceanic areas are considered the correspondence between the two sets of daily volume estimates is more apparent. Correlation between the two series is 0.73; it increases to 0.83 when the above mentioned six days are removed from consideration. In order to shed more light on the daily relationship between the two sets of estimates, especially on days with large discrepancies, maps of 1° resolution daily GW rainfall estimates were plotted using the same smoothing procedure employed in obtaining the cumulative rainfalls.

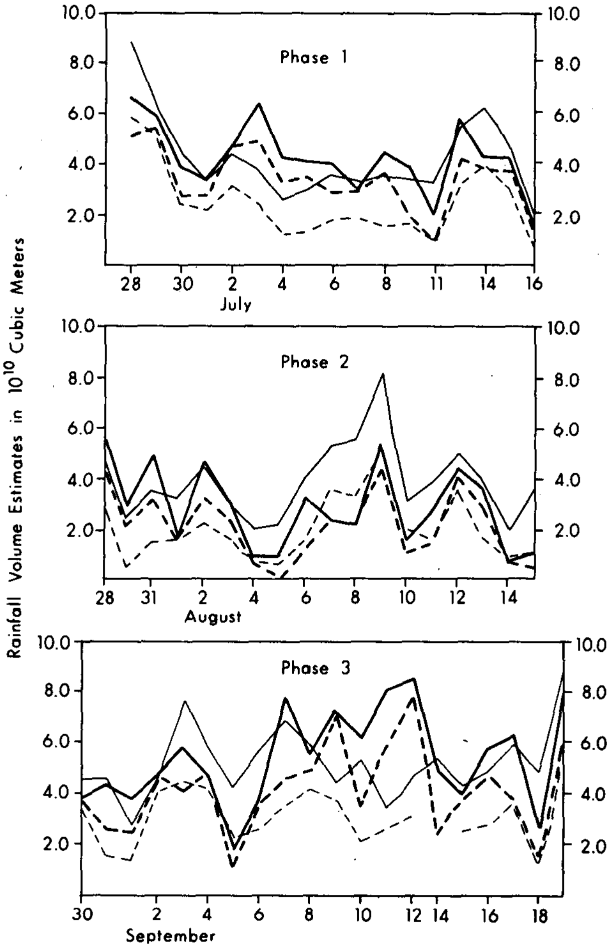

FIG. 6. Estimated daily rainfall volume for the three phases of GATE. Thick solid lines: KR estimates for entire A scale. Thick dashed lines: KR estimates for oceanic areas of GATE A scale; thin solid lines: GW estimates for entire A scale; thin dashed lines: GW estimates for oceanic areas of GATE A scale.

TABLE 3. Ratios of cumulative rainfall volume estimates (KR result/GW result).

	All grid squares of the GATE A scale	Oceanic grid squares only
Phase 1	1.02	1.33
Phase 2	0.75	1.07
Phase 3	1.05	1.33
Period A	0.98	1.27
Period B	0.81	1.16
Period C	0.90	1.15
Entire GATE	0.91	1.20

These maps were compared to the daily distribution of HRC obtained using the KR technique.

Fig. 7 shows three examples of this daily comparison where we arbitrarily define "significant precipitation" as 1° resolution GW estimated rainfall over 25 mm. One must, of course, keep in mind that HRC are measured once a day, while GW precipitation areas may be the result of events that occurred at other times of the day. August 30 was a typical day for which the estimated A scale rainfall volume total for both techniques was fairly close. There is good agreement on the location and extent of significant precipitation areas over the ocean, although the HRC area over the central Atlantic is somewhat larger than the corresponding area with GW estimated rainfall of over 25 mm. On the other hand, the KR technique failed to detect two rather small areas of heavy precipitation (>25 mm) over the African continent that were noted by the GW technique. Fig. 7b shows the results for 8 August, a day in which the GW estimates far exceeded the KR estimates. There is a reasonable match in the location of significant rainfall areas over the western Atlantic, but the KR technique shows no highly reflective clouds over the eastern Atlantic and Africa, where the bulk of the GW-estimated rainfall took place that day. Finally, Fig. 7c depicts an instance for which the KR estimated rainfall significantly exceeds the GW estimates. In this case (12 September) there is fairly good agreement over the ocean, although HRC extend over much larger areas than the GW heavy precipitation locations. This day has relatively light GW estimated precipitation over Africa (areas of ~20 mm), and a fairly rare instance of HRC over Africa without corresponding areas of precipitation over 25 mm in the GW map.

In general, the daily precipitation maps reveal a good correspondence between areas of significant precipitation over the ocean, even during days of large discrepancies in the overall estimated rainfall volumes. For oceanic areas, over two-thirds of all the GW areas with rainfall above 25 mm were at least partially overlapped by HRC. By contrast, more than half of the significant GW estimated rainfall areas over the continent were not detected by the KR technique.

6. The diurnal variation of precipitation during GATE

The most fundamental difference between the GW and KR techniques is that the former relies on data gathered around the clock, while the latter samples the clouds over an area once a day in the late morning, local time. To the extent that rainfall over an area occurs at night, the KR technique will be unable to produce reliable precipitation estimates.

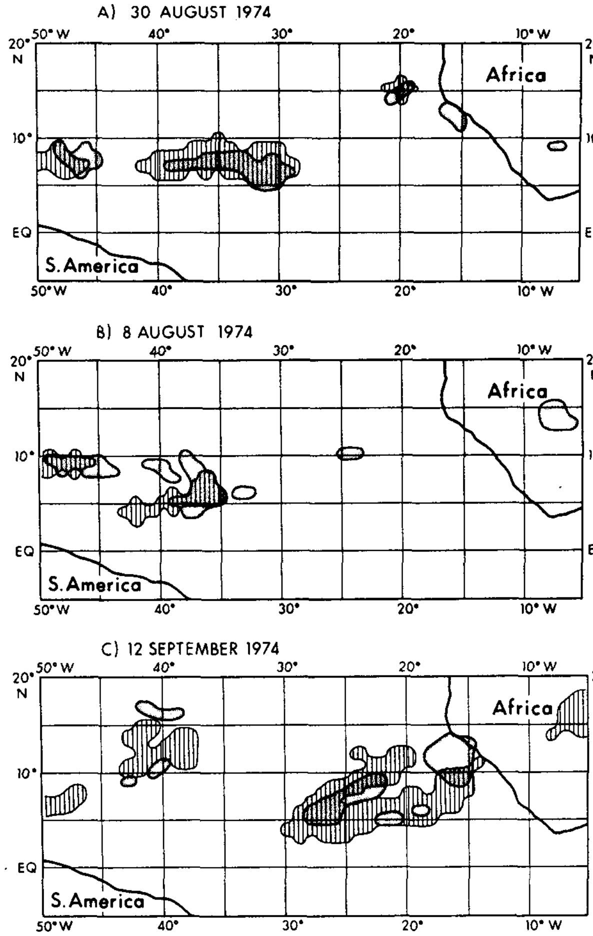

FIG. 7. Areas of significant rainfall detected by both techniques for three different days. Stippled areas: location of highly reflective clouds noted by the KR technique; shaded areas: location of areas with rainfall over 25 mm as estimated by the GW technique.

We have seen in various spatial and temporal scales (e.g., Figs. 1–4 and Fig. 7) that the most significant discrepancies between the two techniques tend to occur over the African continent and nearby ocean. The ratio of daytime to the total 24 h precipitation estimates obtained by the GW technique for the entire GATE period is shown in Fig. 8. It can be seen that the greatest proportion of nocturnal precipitation falls in precisely those areas where the greatest discrepancies occur between the estimates of the two techniques.

Correlation coefficients were calculated between the KR cumulative rainfall estimates for GATE and the GW cumulative estimates for each of the four six-hourly periods for which rainfall was calculated (Fig. 9). When the entire A scale area is considered, the correlation is highest (0.86) during period 2 (0600–1200 GMT), which includes the time of passage of the polar orbiting satellite. Lowest correlation (0.64) occurs for period 4 (1800–0000 GMT).

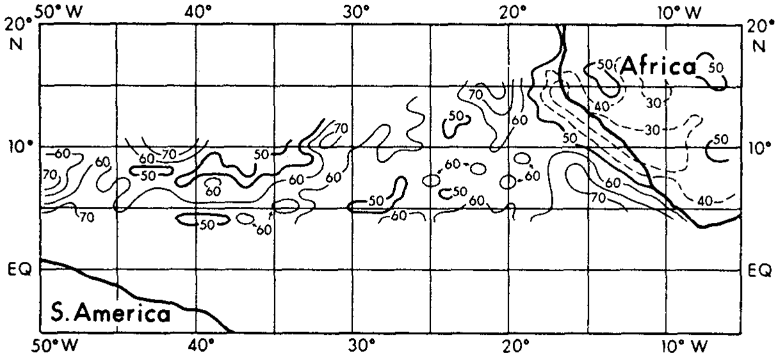

FIG. 8. Percentage of total precipitation that fell during the daytime (0600–1800 GMT) as estimated using the GW technique.

The corresponding correlation coefficients for oceanic areas show a consistently high value for the four time periods, apparently a reflection of the more even diurnal distribution of rainfall and of a tendency for greater persistence of convective systems over the ocean than over the continent.

7. The GW-KR radar intercomparisons for the B scale

The availability of radar estimated rainfall data for the B scale during GATE[3] make it possible to compare satellite estimates with radar-derived ground truth. Woodley *et al.* (1980) show a detailed comparison of GW and radar rainfall estimates during the three phases of GATE for a 3° square located between 7 and 10°N and 22 and 25°W, containing the B scale hexagon.

Comparing KR and radar rainfall estimates for the B scale square requires excluding from consideration dates that had a full or partial gap of radar data. These are 1 and 16 July during phase 1, 31 July–2 August during phase 2 and 19 September during phase 3. Since the KR estimates were obtained for 1° squares centered at latitude-longitude intersections, it is not possible to compare them directly with radar estimates for the B scale square. Sixteen KR grid squares fall wholly or partly within the B scale square; this includes four entirely within the larger square, eight with half their area within and four with one-quarter of their area within (Fig. 10). Assuming that rainfall was uniformly distributed within each square, the KR estimate for the B scale

[3] Hudlow, M. D., and V. L. Patterson, 1979: GATE radar rainfall atlas. NOAA Special Report, 155 pp.

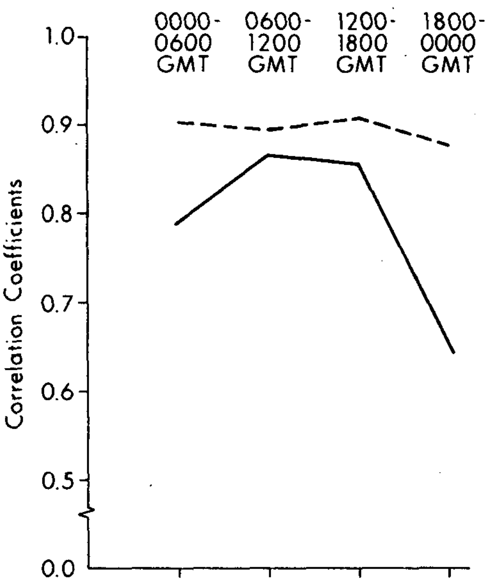

FIG. 9. Correlation between the cumulative KR estimates for the entire GATE period (80 days) and the four 6 h total estimates made by the GW technique. Solid line: entire A scale; dashed line: oceanic areas only.

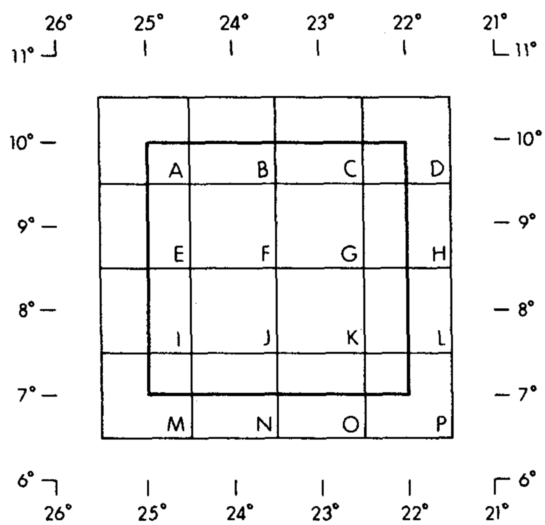

FIG. 10. Correspondence between 3° by 3° B scale square (heavy line) and 1° by 1° squares for which KR estimates were made (light lines).

square for any particular period was then taken as the rainfall volume of squares F, G, J, K plus one-half the rainfall volume of squares B, C, H, L, N, O, I, E plus one-quarter the rainfall volume of squares A, D, M, P (Fig. 10).

Table 4 shows the cumulative rainfall volume estimated to have fallen over the B scale square for the three phases. The *y* intercept of the KR regression equation was modified to apply to a reduced 15-day period for phases 1 and 2 and to a 19-day period for phase 3. In phase 1 both techniques estimated approximately the same rainfall volume. The large discrepancy of rainfall estimates between the GW technique and radar data for phase 2 (a ratio of 0.59) is absent from the KR results.

Augustine *et al.* (1981) have shown that the large discrepancy between the GW estimates and radar during phase 2 was due to the presence of shallow rain producing clouds which had cloud top temperatures too warm to be detected by the GW technique, but were apparently bright enough to appear as HRC in the visual range.

Daily KR rainfall volume estimates for the B scale were made in the same fashion as the A scale estimates of Section 5, and compared with the daily GW and radar estimates (Fig. 11). At this scale there is clearly a better correspondence between the GW and radar estimates (overall correlation for the three phases of 0.87) than between the KR and radar estimates (0.65 correlation). Nevertheless, the KR method agrees with radar in identifying the peak rainfall days. KR often indicated no rain on days with light to moderate radar and GW estimated rainfall, implying that on those days rain came from convective systems with radii smaller than the 2° minimum detected by the KR technique, or from convective systems occurring at night.

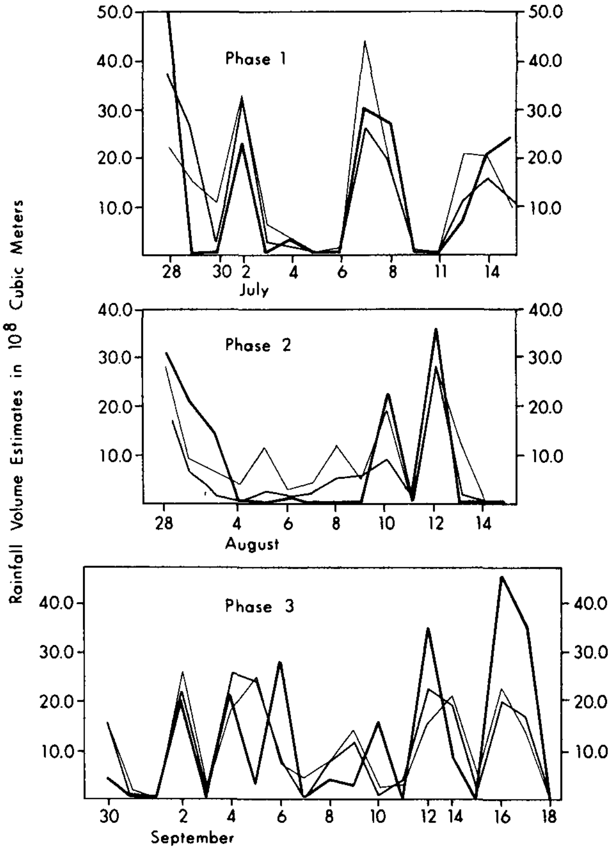

FIG. 11. Daily estimated rainfall volumes for the three phases of GATE within the B scale square. Thin lines: radar estimate; medium lines: GW estimate; heavy lines: KR estimate.

8. Conclusions

Comparison of the Kilosky-Ramage and the Griffith-Woodley rainfall estimation techniques has produced encouraging results. There was good correspondence between the isohyetal patterns produced by both techniques over the oceanic areas of the GATE A scale. Correlations of cumulative rainfall values for these areas ranged as high as 0.92 for the entire GATE period.

Substantial differences in both the daily patterns and in the cumulative estimates consistently appeared over Africa and the nearby ocean. Analysis of the diurnal variability of rainfall compiled by the GW technique revealed that the results of the two techniques diverged most where nocturnal rainfall predominated.

Comparison of rainfall volumes obtained by the two techniques over the B scale with radar-estimated ground truth showed that the KR technique can produce reliable rainfall volume estimates in this scale. Daily B scale rainfall volume estimates produced by the KR technique corresponded reasonably well with the GW and radar volume estimates, although the KR-derived isohyetal patterns within the B scale show only a rough correspondence with the much better resolution GW and radar results.

TABLE 4. Estimated rainfall volume within the 3° by 3° B scale square.

	Estimated rainfall volume in 10^8 m^3		
	Phase 1	Phase 2	Phase 3
Number of days.	15	15	19
GW estimate*	186.12 (0.89)	89.13 (0.59)	204.69 (0.96)
KR estimate*	186.79 (0.89)	129.82 (0.86)	224.20 (1.06)
Radar estimate	209.94	150.34	212.45

* Numbers in parentheses indicate ratio with respect to radar estimates.

It seems, therefore, that the KR technique can provide a low cost[4] and fairly reliable estimate of monthly rainfall over the tropical oceans. This technique can also be useful in identifying, on a daily basis, areas of significant rainfall and in estimating daily rainfall volumes over large areas. Our group at the University of Hawaii is producing a complete data set of KR estimates of rainfall over the global oceanic tropics from 1971 on.

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[4] It takes an average of 40 man-hours to identify, code and process one month of HRC data, worldwide for a cost of under $180, including computer processing.

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