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Mean Rainfall Patterns for the Three Phases of GATE

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ABSTRACT

As a part of the GARP Atlantic Tropical Experiment (GATE), quantitative precipitation measurements were made during the summer of 1974 with four C-band digital radars complemented by shipboard raingages. Isohyetal maps covering a 125 000 km² array centered at 8°30'N, 23°30'W are presented for each of three, approximately 20-day observational phases of GATE. Large mean rain rates exist for all three phases, with the largest ones corresponding to accumulations exceeding 500 mm for some of the maximum isohyets during Phase I. The mean rainfall rate averaged over the B-scale array for all three phases, 11.3 mm day⁻¹, is apparently not significantly different from pre-GATE rainfall climatology. Another striking characteristic of the phase-mean precipitation patterns is the large spatial gradients; e.g., gradients as large as 200 mm in 16 km are observed.

Latitude shifts in the zone of maximum confluence (intertropical convergence zone) and in the tracks of the synoptic disturbances are reflected by interphase changes in the precipitation patterns. Also presented is a time-latitude rain cross section constructed from hourly precipitation amounts, which shows that the significant precipitating convection occurred most frequently in the vicinity of the troughs of African wave disturbances during Phase III.

1. Introduction

As a part of the GARP Atlantic Tropical Experiment (GATE), quantitative precipitation measurements, for an array centered at 8°30'N, 23°30'W, were made during the summer of 1974 with four C-band digital radars complemented by shipboard raingages. This paper presents selected results from the precipitation analysis project, which is an ongoing project within the GATE Convection Subprogram. Fulfillment of the central objectives of GATE, which have been described by Kuettner *et al.* (1974) and Austin (1975), requires an accurate evaluation of the quantity and morphology of rainfall. To address the question of scale interactions, this evaluation is needed for a range of space and time scales. The shortest time and space scales presented here are 3 h and 16 km, respectively. However, rainfall data for finer resolutions, as described by Hudlow (1975) and Hudlow and Patterson (1979), are available elsewhere.

The accuracy of radar precipitation rates is critically dependent on the quality of the radar electronic calibrations and on the accuracy of the transfer functions that relate the power measurements to rainfall rates. The electronic calibrations of the GATE

radars were established before the GATE field operations and were routinely checked throughout the experiment in the summer of 1974. A major subtask of the precipitation analysis project has been the evaluation of the radar calibrations. This has been achieved through a variety of comparative analyses, which have included comparisons of radar measurements from two or more radars in regions of overlapping coverage and comparisons of radar-rainfall estimates with shipboard raingage measurements (Hudlow *et al.*, 1976; 1979; Hudlow and Patterson, 1979). A summary of the expected errors in the radar rainfall estimates is presented in Section 4.

2. Data systems and processing

The GATE operations were divided into three observational periods: Phase I, 28 June–16 July; Phase II, 28 July–15 August; Phase III, 30 August–19 September. Table 1 lists the ships equipped with C-band digital radar systems and their locations within the B-scale array illustrated in Fig. 1. Also given in Table 1 are the countries and organizations responsible for collecting and processing the digital reflectivity data from the individual radars. Table 2 summarizes the technical characteristics of the radars. For additional details on the individual radars, see Hudlow (1975), Silver and Geotis (1976), Arkell and Hudlow (1977), Patterson *et al.* (1979) and Hudlow *et al.* (1979). The last reference also describes in detail the techniques used for calibrating and comparing

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TABLE 1. C-band radar ships, their locations, and principal organizations responsible for the data collection and processing.

Country	Organization	Ship	Nominal location (N latitude, W longitude)	
			Phases I & II	Phase III
Canada	McGill University	<i>Quadra</i>	9°15', 22°12'	9°00', 22°40'
USA	Massachusetts Institute of Technology	<i>Gilliss</i>	9°15', 24°48'	9°15', 24°48'
USA	NOAA	<i>Oceanographer</i>	8°30', 23°30'	7°45', 22°12'
USA	NOAA	<i>Researcher</i>	7°00', 23°30'	7°00', 23°30'

the radars and the manner in which various biases were determined and removed before the data from the individual radars were merged. The systematic biases were less than 3 dB for all of the individual radar data sets, which indicates that the hardware calibrations for the GATE radars were very accurate and consistent. Furthermore, comparisons between the final merged radar-rainfall estimates and the shipboard raingages justify expectations of very accurate "absolute" rain estimates (Section 4).

Based on agreement by the parties processing the reflectivity data from the individual radars (Table 1), it was decided that low-altitude data sets should be produced for all four radars in a format that would make it easier to merge data from two or more radars. A Cartesian data array with the elemental data bin sizes equal to 4 km × 4 km was adopted. The radius of coverage by the individual radars varied from 210 to 260 km.

The data input to the primary precipitation software system consisted of the Cartesian arrays of calibrated and validated reflectivity data from individual radars. These data were normally available each 15 min. The output from the primary precipitation software was hourly accumulated rainfall maps for a master array covering a circle 204 km in radius navigated to an origin at 8°30'N, 23°30'W (Fig. 1). A basic spatial resolution of 4 km × 4 km was retained for the hourly maps. Each ¼° latitude × ¼° longitude square (illustrated in Fig. 1) contained 49 of the 4 km × 4 km elemental data bins. For Phases I and II of GATE, only the radar data sets from the *Oceanographer* and *Researcher* were used to derive the hourly precipitation maps. The decision to use only NOAA radar data for Phases I and II was based largely on considerations of data availability and on the fact that the *Oceanographer* radar covered the complete master array during the first two phases, when the ship was stationed at the center of the array (Table 1). Also, as shown by Fig. 2, the *Oceanographer* radar data exhibited superior range performance characteristics. These range performance curves were determined by averaging the precipitation values, which had been corrected for atmospheric attenuation, for all azimuths and for 20 km range increments. The relative mean-rainfall intensity, as defined by the ordinate labels,

was then plotted as a function of range; R_{40} and R_r are the rainfall rates at 40 km and the other ranges on the abscissa, respectively. A range of 40 km was selected for normalization, since it was assumed that beam-filling problems would not seriously degrade the quantitative estimates out to at least this range. By averaging over long periods, this method gives, to a first approximation, the degradation of the radar measurements as a function of range. Of course, real rainfall variations with range, which remain in the phase averages, will have some influence on the shape of the range performance curves.

Comparisons between the radar estimates and the

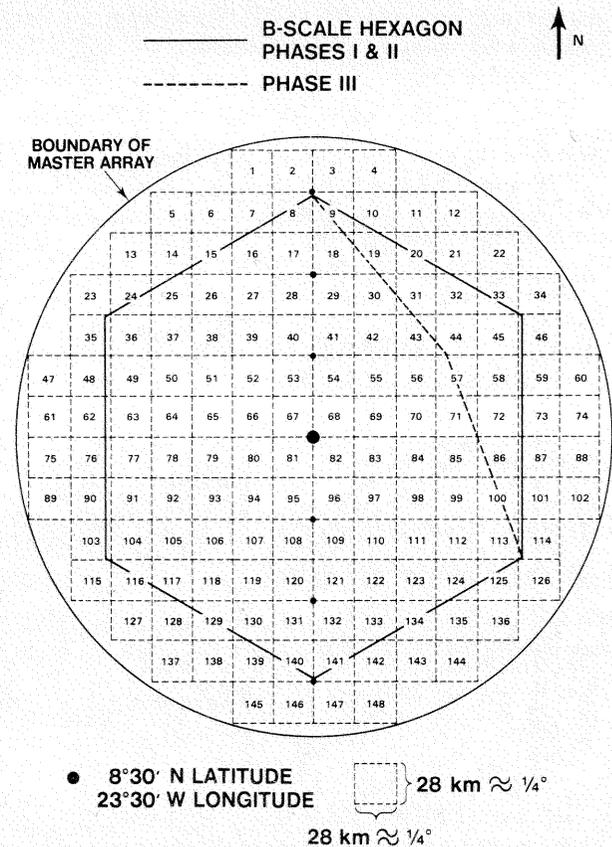


FIG. 1. Schematic of the master precipitation array, B-scale array and the network of ¼° × ¼° latitude-longitude squares within the master array.

TABLE 2. Characteristics and specifications of the C-band digital radar systems

Characteristics	Ships			
	<i>Oceanographer</i>	<i>Researcher</i>	<i>Gilliss</i>	<i>Quadra</i>
Wavelength (cm)	5.3	5.3	5.3	5.3
Peak power transmitted (kw)	215	225	250	1000
Pulse length (km)	0.57	0.60	0.60	0.30
Minimum detectable signal (dBm)	-100	-100	-100	-90
Antenna gain (referenced to directional coupler) (dB)	39.9	35.0	39.0	43.5
Pulse repetition frequency (Hz)	259	250	250	320
Polarization	Horizontal	Horizontal	Horizontal	Vertical
Beam width (deg)	1.5	2.0	1.5	1.0
Base elevation tilt-angle (deg)	0.6	0.5	0.5	0.6
Radome	Yes	No	Yes	Yes

remote shipboard gage catches give results that are in general agreement with the curves in Fig. 2 (Hudlow *et al.*, 1979). Both analyses indicate that the *Oceanographer* radar data remain, in the mean, within ~ 1 dB for ranges out to 175 km; while the radar-gage analysis indicates that the range degradation for the other three radars is somewhat less than the curves in Fig. 2 suggest, leading to the conclusion that the mean deterioration for them probably remains within 2 dB out to 150 km. To cover the master array during Phase III, data from all four radars were merged when available.

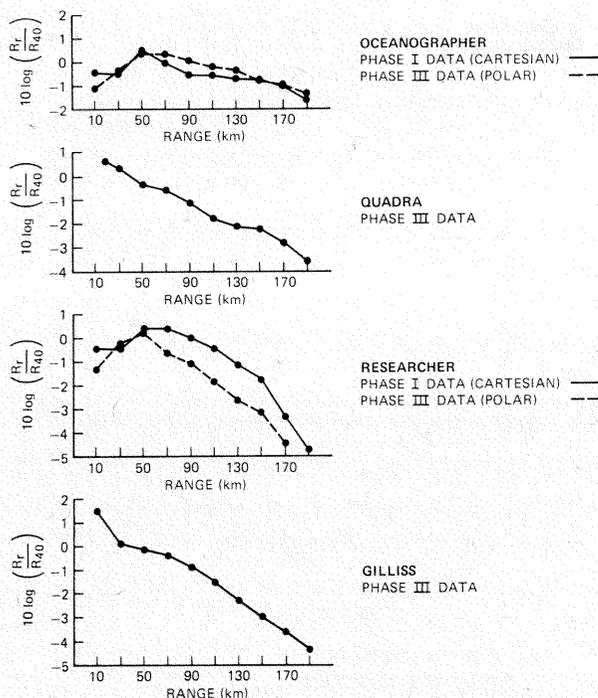


FIG. 2. The variation with range of the phase-mean relative rainfall as derived from data collected with the four GATE C-band radar systems, which gives, to a first approximation, an assessment of the range performance of the various radars.

In many respects, the precipitation processing for Phases I and II was analogous to that for Phase III. Only the significant differences will be briefly mentioned here. For Phases I and II, the *Oceanographer* data were corrected for atmospheric, wet radome and intervening rainfall attenuation, while for Phase III only atmospheric attenuation corrections were applied to the four radar data sets. Rainfall attenuation corrections were not considered as significant for Phase III, because data were merged from more radars, each of which viewed the precipitation lying in the interior of the array from different directions. Regardless, intervening rainfall attenuation was normally not significant at C-band frequencies for GATE convection, except for very small localized areas (Patterson *et al.*, 1979). As shown by Fig. 3, the combined effect of wet radome and intervening rainfall attenuation corrections on the Phase I and II mean rainfall rates is small; therefore, the lack of these corrections for Phase III should not seriously affect the interpretation of the Phase III mean rainfall patterns or the comparison of them with those from the first two phases. Patterson *et al.* (1979) describe in some detail the attenuation correction procedures.

Also, the merging process was somewhat different for Phase III than for Phases I and II (Patterson *et al.*, 1979). For Phase III, the nonzero rainfall amounts, for the common data bins falling inside the master array from the various radars, were averaged. For Phases I and II, all nonzero rainfall rates from the *Oceanographer* were taken alone as the best estimate. *Researcher* estimates were substituted only for common data bins within the master array where the *Oceanographer* values were zero and the *Researcher* estimates were nonzero. This merging process recovered data that were missed by the *Oceanographer* radar in a sector forward of the ship that resulted from obstruction of the radar beam by the ship's superstructure. The *Oceanographer's* obstructed sector was normally located in areas covered by the *Researcher* radar.

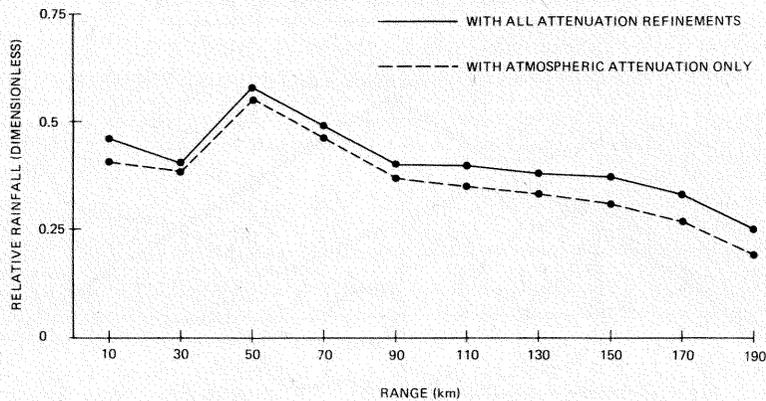


FIG. 3. Plots of phase-mean relative rainfall versus range, for Phases I and II combined, as derived from the *Oceanographer* radar data, including all attenuation corrections (solid) and with atmospheric attenuation corrections only (dashed).

The set of hourly Cartesian precipitation maps, derived using the precipitation processing system briefly described above, is the data base used for the analyses presented in the next section.

3. Analyses and results

Mean isohyetal maps for the three phases were derived, and a time-latitude cross section of rain amounts was constructed for Phase III. The isohyetal maps are important as background information for comparison with the mean fields of other meteorological and oceanographic parameters, for studying the mean variations of the intertropical convergence zone (ITCZ), and for relating the precipitation climatology during GATE to other times and locations. As pointed out by Sadler (1975), ITCZ is a blanket term used with profusion in the literature on tropical meteorology. Sadler further illustrates that the term may mean different things to different people. In this paper the term is used loosely to mean a maximum precipitation and/or cloud zone in the *region* of confluence between Southern and Northern Hemisphere air masses.

The time-latitude cross section of precipitation is a useful means for examining the synoptic-scale cycles. The accompanying wave phase diagram shows the relationship between the significant precipitation events and the passage of atmospheric wave disturbances during Phase III.

a. Phase-mean isohyetal maps

Figs. 4–6 are isohyetal maps of the phase-mean rainfall rates (mm h^{-1}) for the three phases. These maps were derived by 1) integrating the hourly Cartesian rainfall data (see Section 2); 2) dividing the totals by the number of hours of observation; 3) spatially averaging 4×4 data bins ($16 \text{ km} \times 16 \text{ km}$) and 4) contouring the resulting array of values.

Estimates of the total amount of rain falling during each phase can be obtained by multiplying the number of hours in the phase by the mean hourly rate of rain given by the contour values; there are ~ 450 h in Phases I and II and 500 h in Phase III. The largest totals occurred in Phase I with several peaks exceeding 500 mm in the south and east portions of the array.

Except for the 69 consecutive hours of data that were missed during Phase II when the *Oceanographer* was off station for a medical evacuation, missing data periods are infrequent and only a few hours in duration. Therefore, with the possible exception of this 69 h period, the phase-mean maps would be virtually unaffected by missing data. The 69 h gap during Phase II could partly explain the valley of low rainfall amounts stretching from west-southwest to east-northeast through the center of the array in Fig. 5. However, based on an analysis of all shipboard rain gauge data and on analysis of satellite data by Hudlow and Patterson (1979) and by other investigators (e.g., Martin, 1975), it seems likely that the basic features in the Phase II chart would remain very similar if the 69 h of missing data could be included. Satellite cloud trajectories presented by Martin (1975) show fewer trajectories through the center of the array for this period than to the south and north.

Comparison of Fig. 4 with Figs. 5 and 6 suggests that the mean location of the ITCZ was further north during Phases II and III than during Phase I. This agrees with the findings by Martin (1975) and Nicholson (1975), who based their conclusions on satellite cloud data, and with Holle (1977) who used cloud photographs collected with all-sky cameras aboard four GATE ships. Holle gives a mean position of 7°N for Phase I and 8°N for Phases II and III. Martin's mean positions are about $\frac{1}{2}^\circ$ north of Holle's.

PHASE I ISOHYETAL MAP (June 28 - July 16)

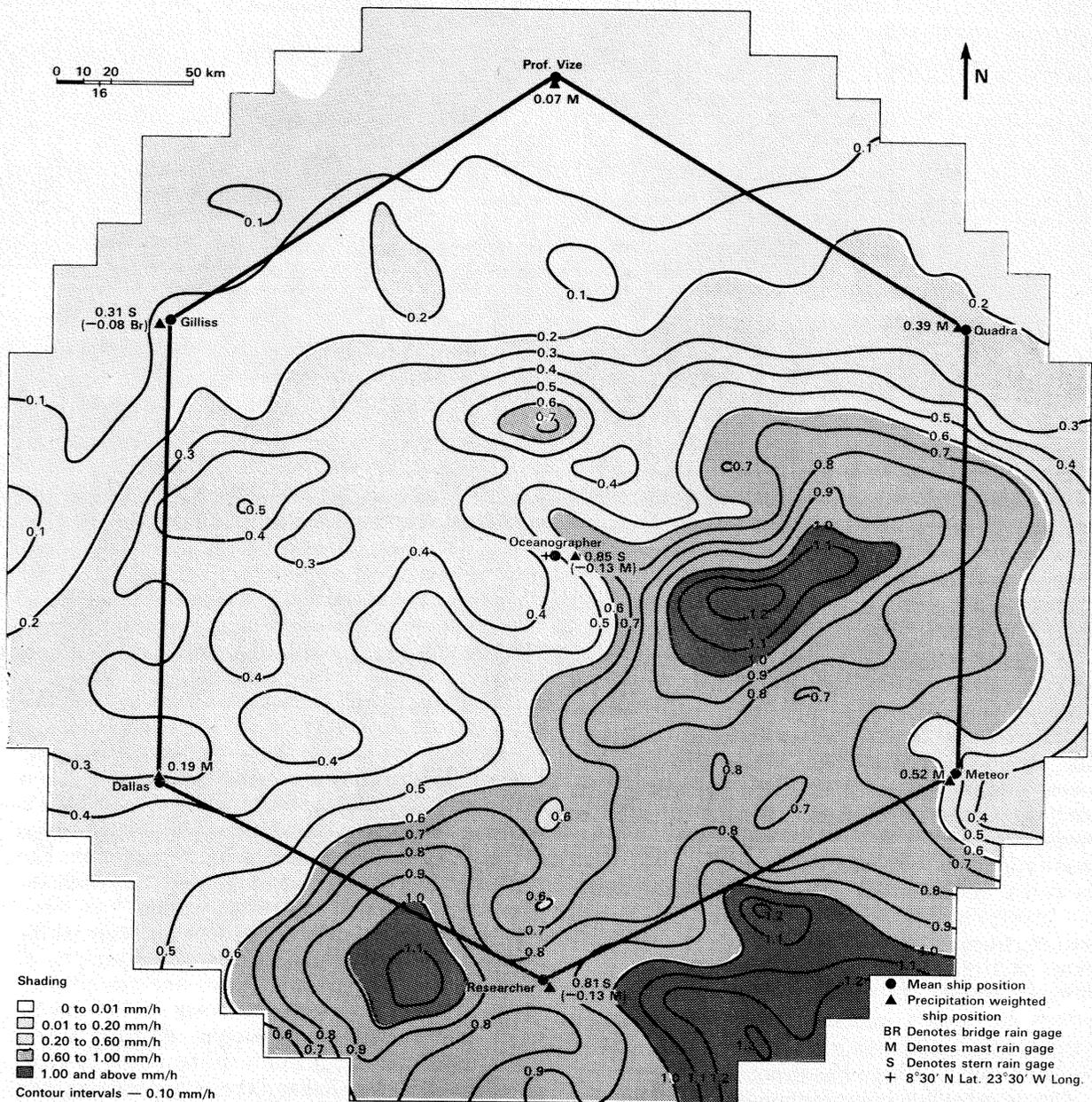


FIG. 4. Phase I isohyetal chart; the isopleths give the phase-mean rainfall rates (mm h^{-1}).

One of the striking characteristics of the isohyetal maps for all three phases is the amount of structure and large gradients that persist for averaging periods of approximately 20 days. For example, mean rain-rate gradients corresponding to accumulation gradients as large as 200 mm in 16 km are observed. Not only are the rain totals larger during Phase I, as mentioned above, but large rain gradients occur at more locations on the Phase I map than on the charts for Phases II and III. These findings are in accordance with the surface streamlines and the satellite

cloud trajectories shown by Martin (1975). A high percentage of the cloud trajectories are concentrated in the southern part of the array during Phase I, but comparable frequencies are observed in the north and south during Phases II and III.

Fig. 7 is a streamline chart constructed from the mean surface wind directions for Phase I. The wind directions used were not corrected for sensor biases. Although some biases have been identified by various intercomparison analysis techniques (Kidwell and Seguin, 1978), their magnitudes should have

PHASE II ISOHYETAL MAP (July 28 - August 15)
(Excluding GMT July 30 2200—GMT August 2 1900)

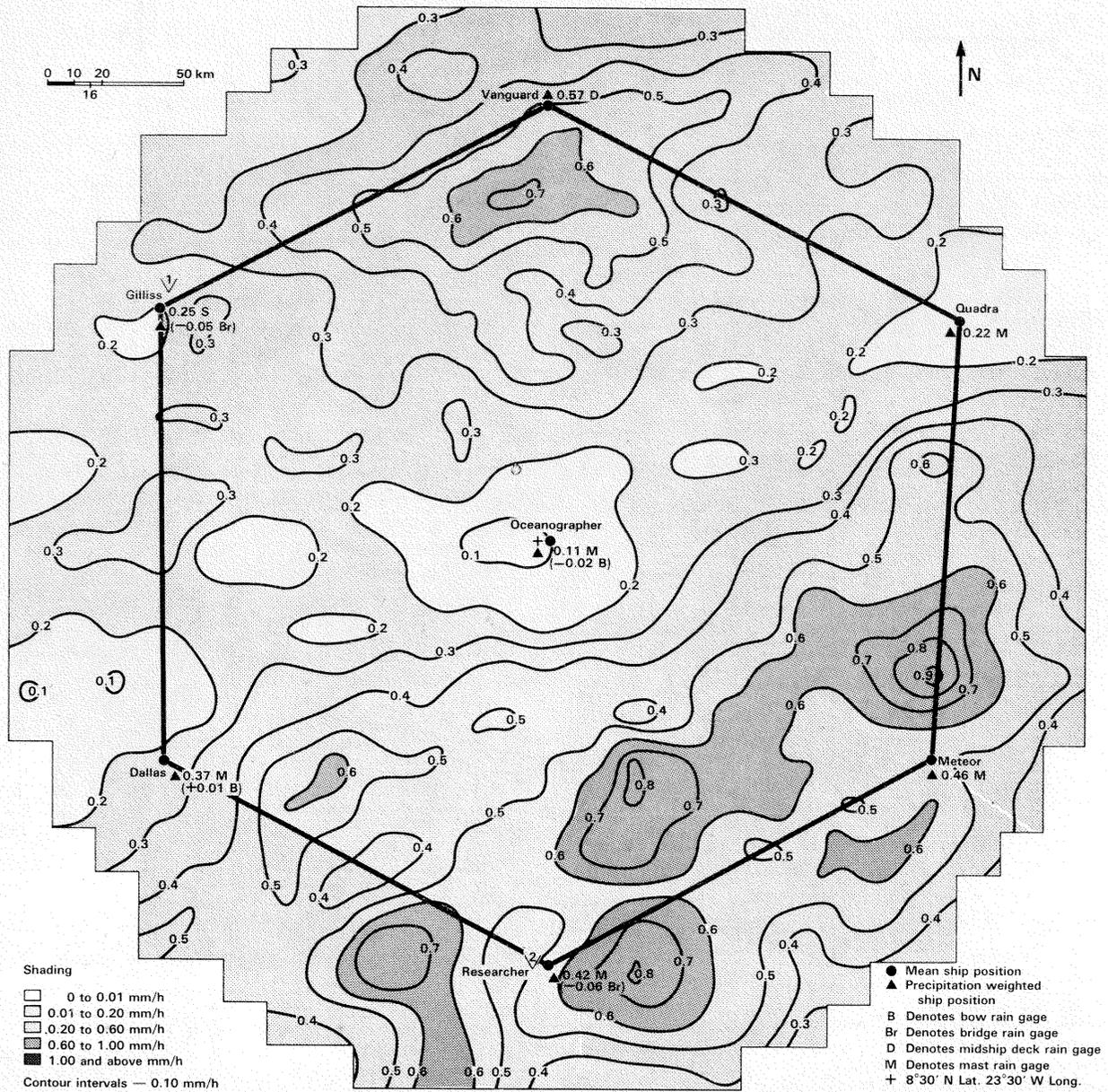


FIG. 5. Phase II isohyetal chart excluding the period from 2200 GMT 30 July–1900 GMT 2 August; the isopleths give the phase-mean rainfall rates (mm h^{-1}).

little effect on the Phase I mean streamline pattern, which shows strong confluence in the south and east portions of the array. For Phases II and III, the mean streamlines (see Seguin *et al.*, 1978) show nearly parallel southwest monsoonal flow over the entire B-scale array. No close correspondence is apparent between the rainfall patterns and the mean streamlines during Phases II and III, except that the average orientation of the isohyets roughly corresponds to that of the streamlines. Also, the smaller

rainfall gradients do seem consistent with the more nearly parallel flow during these latter phases. Also plotted on the isohyetal charts are the mean rainfall rates calculated from the shipboard raingage catches for ship stations in the B-scale array. The letter following the rainfall values denotes the approximate location of the gage aboard the ship (see legend, Fig. 4). Data were available from two or more gages for some ships. For these cases, the (maximum) deviation between the plotted gage and

PHASE III ISOHYETAL MAP (August 30 - September 19)

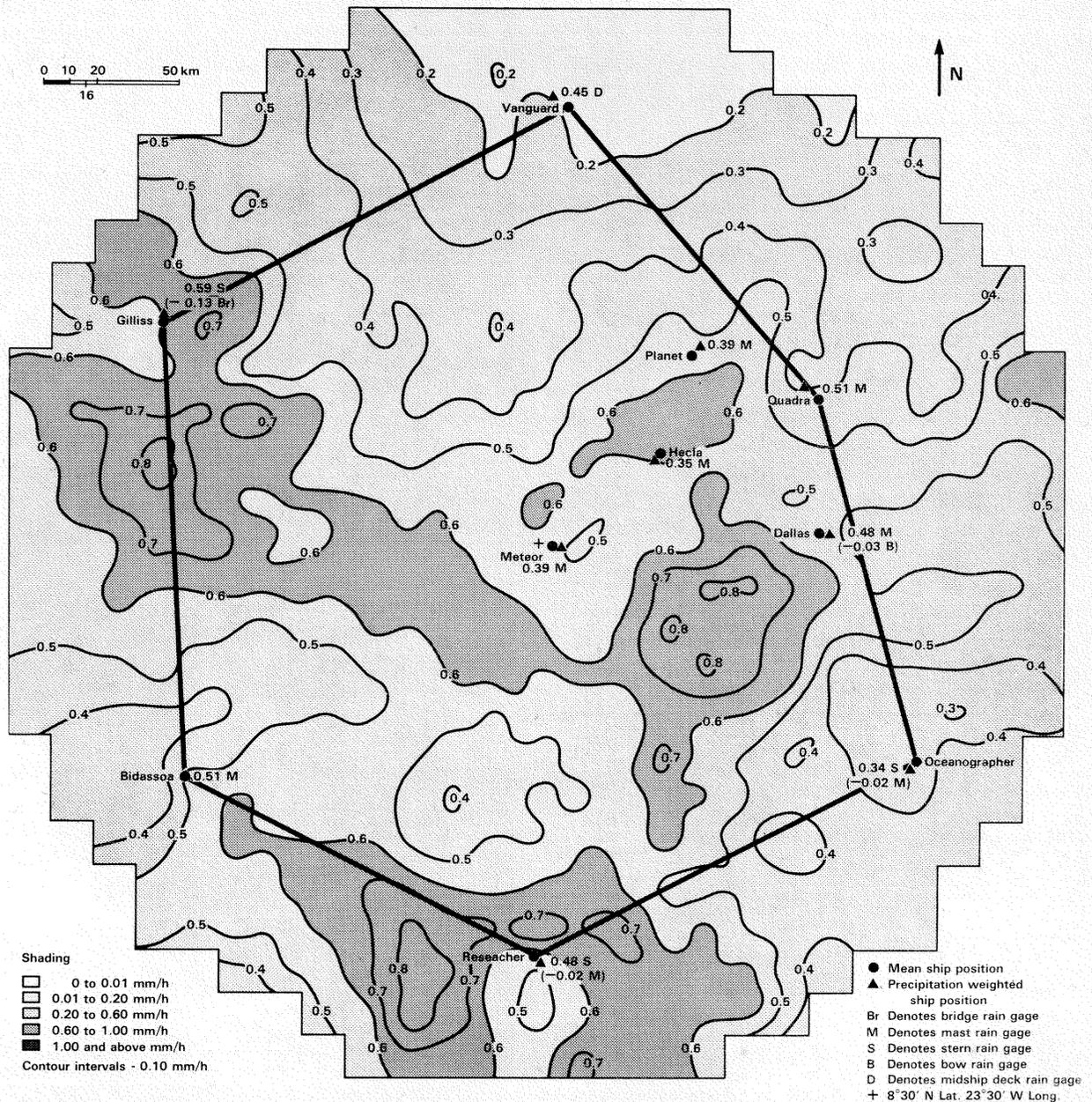


FIG. 6. Phase III isohyetal chart; the isopleths give the phase-mean rainfall rates (mm h^{-1}).

the other gage(s) is shown in parentheses. A negative deviation indicates that the plotted gage received the largest catch. The triangles mark the navigated gage positions, which are averages calculated by weighting the mean hourly ship positions by the hourly rainfall amounts. In most cases the difference between the rain-weighted position and the straight average position is small, and the gage-to-radar correspondence is not affected significantly. There are some notable exceptions, for example, the *Oceanographer* for Phase I.

The overall agreement between the radar and gage values is quite good. A few gage catches are suspiciously out of line, for example, the *Dallas* in Phase I and the *Vanguard* in Phase III. There is a possibility that the radar estimates are somewhat low in the northern portion of the array, since coverage over the north by multiple radars was limited (Section 2). However, there is little indication of this on the Phase II chart. It seems almost certain that the radar estimates in the vicinity of the *Vanguard* for Phase III cannot be low by the amount the gage

implies. Additional radar and raingage comparisons are presented in Section 4.

A comparison was also made between the mean GATE rainfall rate and that obtained from climatological rainfall maps. Few climatological rainfall rate, or accumulation, charts exist on a seasonal basis for the tropical oceans. However, annual isohyetal maps have been prepared by several authors [e.g., Drozdov, 1953; Rudolf Geiger (see Rao *et al.*, 1976)], and seasonal and monthly charts of precipitation frequency do exist (Lamb, 1977; Meserve, 1974). The Geiger and Drozdov maps give ~2200 mm annual rainfall for the GATE B-scale area. If we assume that this 2200 mm is distributed during the year in direct proportion to the precipitation frequency, then we find using Meserve's frequencies, which agree closely with those of Lamb, that 1200 mm of rain would normally fall in the B-scale during the three-month period, July–September.

The mean rainfall averaged over the B-scale array for all three GATE Phases is estimated from the radar analysis to be 11.3 mm day⁻¹. If we assume that this rate applies for the entire July through September period, then the rain accumulation for the 92 days was 11.3 × 92 = 1040 mm, which is within about 10% of the climatological value estimated above. Considering the uncertainties in both estimates, it is concluded that the 1974 GATE period was probably not an abnormally wet season.

b. Latitude-time precipitation cross section

The upper part of Fig. 8 is the Phase III latitude-time rain cross section for a 1/2° wide strip centered at 23.5°W longitude. The rain values for the diagram were derived by first averaging the hourly rainfall

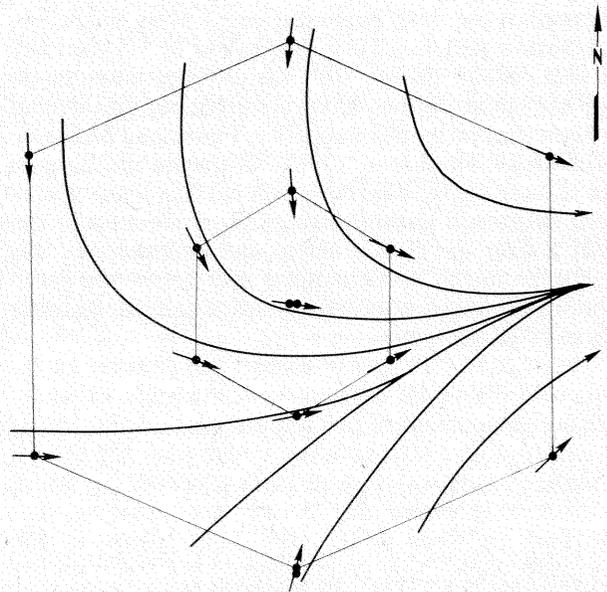


FIG. 7. Phase I surface streamlines, drawn from phase-mean wind directions, covering the B-scale array (inner hexagon) and the A/B scale array (outer hexagon). Figure courtesy of Ward R. Seguin.

values over 1/2° × 1/2° latitude-longitude squares. These spatially averaged values were then temporally averaged for 3 h periods. This gave rain values each 3 h for seven equally spaced latitude points in the master array (Fig. 1). The total set of 1162 points (7 latitudes times 166 3-h periods) were then contoured.

The cross section shows that five distinct synoptic-scale precipitation events occurred during Phase III, and parts of two other events were ob-

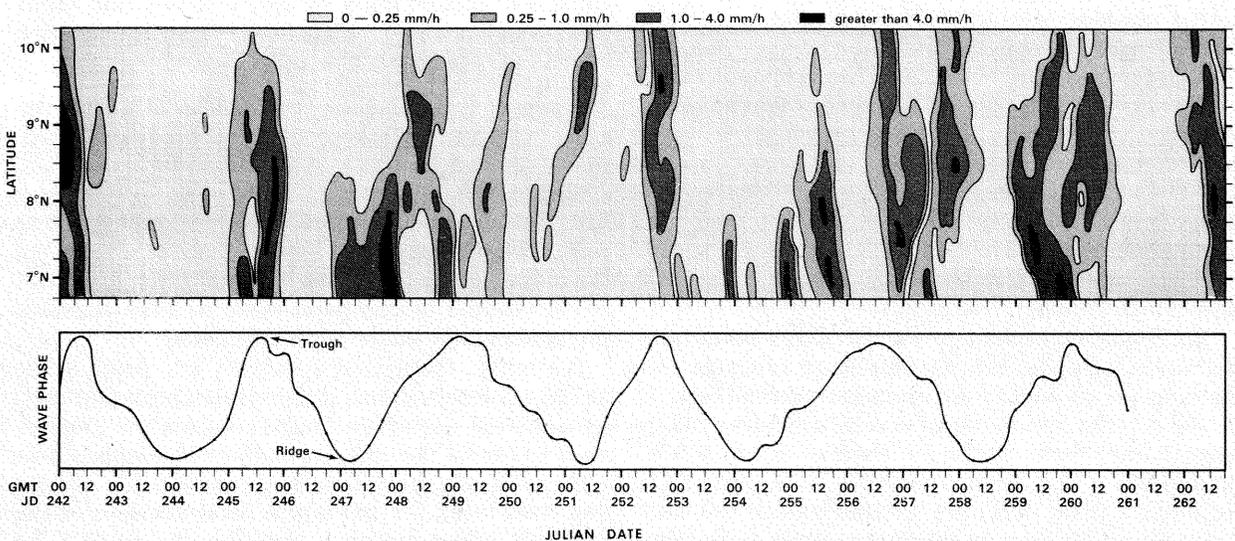


FIG. 8. Phase III time-latitude rain cross section through center of master array (upper) and time series of the phase of African waves at 8°30'N, 23°30'W (lower). The contoured rainfall rates were drawn from 3 h averages over 1/2° × 1/2° latitude-longitude squares.

served at the very beginning and ending of the observation period. This averages out to 3.5 days per event, which agrees with the average wavelength of the atmospheric wave disturbances of African origin studied by Burpee (1975), Payne and McGarry (1977) and Reed *et al.* (1977). If we use ITCZ again in a loose sense, Burpee points out that these waves are important in modulating the convection in the ITCZ near the GATE ships, and he illustrates this with the use of satellite cloud time series and satellite cloud data composited relative to eight discrete phases of the wave.

Reed *et al.* (1977), also using a compositing analysis with Phase III data, present evidence of three-fold enhancement of precipitating convection in the vicinity of the African wave trough over the GATE region. Using wave phase lines provided by Reed, which were based on 700 mb wind analyses described by Reed *et al.* (1977), the phase of the African waves was determined at 6 h intervals for the center of the array (23°30'W, 8°30'N). The lower portion of Fig. 8 is the time series of the wave phase. A positive relationship between the significant precipitating convection and wave phases in the vicinity of the troughs clearly exists for Phase III.

4. Radar-gage comparative analyses and summary of expected accuracies

Because of the large spatial and temporal gradients, it is always difficult to establish the absolute accuracy of convective rainfall measurements, even over land areas. At sea it becomes more difficult, since adequate independent "ground truth" measurements are usually not available, especially for the smaller space and shorter time scales. Most radar hydrologists accept that comparisons made against a dense raingage network, within optimum range of a land-based radar, often provide the best information for assessing the accuracy of, and for calibrating, radar rainfall estimates. However, it would not have been logistically feasible, if possible at all, to erect and maintain a dense network of buoys, instrumented with raingages, in the GATE B-scale area. Since a dense raingage network was not available, even greater emphasis had to be placed on careful comparisons between the radar estimates and the individual shipboard raingages.

As described in Section 3a, the phase-mean rainfall rates from the B-scale shipboard raingage collections are plotted on the isohyetal charts (Figs. 4, 5 and 6). The results from several objective radar-gage comparisons made by Hudlow *et al.* (1979) and Hudlow and Patterson (1979), using the 4 km resolution radar data, are summarized in this section. Based on knowledge of the spatial variability characteristic of convective rainfall, and on an assessment of the expected uncertainties in navi-

gating the gage data to "absolute" positions relative to the radar fields, Hudlow and Patterson concluded that matching the gage and radar values could best be done by minimizing the difference between the gage value and a radar estimate selected from a small set of radar data bins comprised of the one containing the mean gage position and the closest adjoining data bins. A summary of the uncertainties and the resultant methodology selected by them to match the gage and radar data also is included in this section.

The large spatial variabilities inherent in convective rainfall contribute significantly to the difficulty (error) in relating areal rainfall estimates from radar to point estimates from single raingages. Some other factors that potentially limited the precision with which the shipboard raingages could be absolutely positioned in the radar fields, and which led to the decision by Hudlow *et al.* to allow for positional uncertainty when relating the radar and gage data, are as follows:

- 1) Uncertainties in the ships' estimated positions were sometimes 1–2 km.
- 2) Small, time-variant antenna azimuth errors may have occasionally become significant.
- 3) Data resolution prevented navigation of individual radar fields to an accuracy better than 2 km.
- 4) The navigation accuracy could further deteriorate for parts of the master array subsequent to the merging of fields from two or more radars.
- 5) Areas that were obstructed by the ships' superstructures in the individual NOAA radar scans sometimes were filled by data from the same radar, 15 min removed (Richards and Hudlow, 1977), or from another radar as part of the merging process.
- 6) Wind between beam level and the surface could cause the precipitation to drift laterally and reach the surface a significant distance from the location of the radar observation.

None of the above six factors would have a significant impact on the accuracy of the rainfall estimates, except on those applications requiring very accurate absolute location of the radar and/or gage data; for example, "point" estimates are needed to make comparisons between radar observations and the individual gage catches. "Point" radar estimates in the context of this paper refer to the values for the elemental 4 km × 4 km data bins.

Normally, the spatial variability and some of the positional errors should decrease for increasing averaging period. However, for the comparative analyses used to obtain the error estimates presented below, only mean ship positions for the period of comparison were used for the initial determination of the data bin within which a gage was located. If the ship drifted from its assigned position during the period long enough to enter another data bin, this

contributed to an additional smearing of the positional relationship between the two data types.

Considering the large spatial variability and the data location uncertainties enumerated above that affected the precision with which the rain gages could be positioned relative to the radar fields, Hudlow and Patterson (1979) concluded that the effective positional error could be as large as 4 km for the phase duration. They also concluded, primarily because of the even larger spatial gradients existing in the daily isohyetal maps compared to the phase maps, that the effective location uncertainties would be somewhat greater for the daily scale. Based on these estimates of positional uncertainty, Hudlow and Patterson adopted the rationale of selecting the data bin value in closest agreement with the gage from small data bin sets, as opposed to simply using the value for the bin within which the mean ship (gage) position was estimated to fall. The bin sets they used for the radar-gage comparisons were comprised as follows: *phase*—set of four, 4 km × 4 km data bins consisting of the one containing the phase-mean ship position plus the three nearest neighboring bins to the gage and *daily*—set of nine, 4 km × 4 km data bins consisting of the one containing the daily-mean ship position plus the eight surrounding bins. Examples of the data bin sets and gage locations are schematically illustrated in Fig. 9.

Because the raingage observations can be in error and since, as discussed above, significant variability (error) is encountered in relating the point measurements from the gages to the much larger volume measurements from the radar, it is difficult to assess the absolute errors in the radar estimates from comparisons with the individual shipboard raingage catches. However, it is useful to summarize the observed differences between the radar and gage esti-

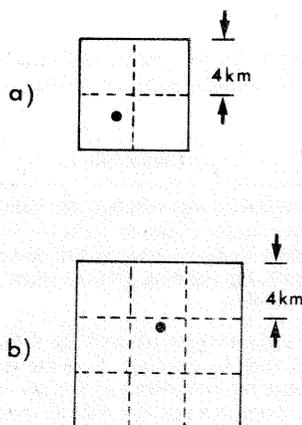


FIG. 9. Illustration of the radar data bin sets from which the radar estimates were selected to compare to the raingage catches for phase duration (a) and daily duration (b). For this example the estimated mean positions of the shipboard raingage are shown by dots.

TABLE 3. Residual systematic bias evaluation between shipboard gages and radar "point" measurements.

Observation period	Percent differences*
Phase I	+5%
Phase II	+6%
Phase III	-4%
All GATE	+2%

* Plus values indicate radar < gage; minus values, radar > gage.

mates, and if one assumes to a first approximation that the gage measurements represent "ground truth" at the point of observation and that the effective data positional uncertainties are largely eliminated by using the radar value in closest agreement with the gage from the data bin sets as described above, then these observed differences can be interpreted as estimates of the expected error for the radar "point" measurements.

An evaluation of any residual systematic biases in the radar estimates can be obtained by computing the following statistic for each phase:

$$\frac{[\sum(\text{Gage})_i - \sum(\text{Radar})_i]}{\sum(\text{Gage})_i} \times 100,$$

where the sum is for all B-scale ship stations (i). The phase-mean ship positions are shown on the isohyetal maps (Figs. 4–6). The results from this computation are given in Table 3.

The estimated systematic biases (Table 3) for the three phases are probably not statistically significant from zero when one considers the uncertainties that may accompany the estimates from both sensors. Although the estimated magnitudes of the biases are small, and possibly not significantly different from zero, the change in sign of the bias for Phase III may be real, and could be explained by remembering that the data from the individual radars were merged differently during Phase III (Section 2). Specifically, if systematic underestimates exist in the radar fields during Phases I and II, they probably are most significant over the northernmost part of the array since the estimates over this area were derived using the data coverage of only the *Oceanographer* radar. This was normally not a serious limitation because of 1) the *Oceanographer's* central position in the array, 2) the superior range performance characteristics of the *Oceanographer* radar (Fig. 2), and 3) the smaller amounts of rain occurring in the northern part of the array.

It should be emphasized that the raingage records could contain systematic biases, which are not reflected in the percent differences given in Table 3. In fact, most potential errors in shipboard raingage measurements tend to result in deficit catches

(WMO, 1962). Laevastu *et al.* (1969) and Reed and Elliot (1977) suggest that the approximate magnitude of these deficits would be less than 10% for suitable shipboard installations. For those GATE ships that were equipped with two or more gages, the maximum gage value was normally selected for comparison with the radar estimate. This tended to minimize the effect of gage underestimates, resulting from bad gage exposure, in the assessment of systematic biases in the radar estimates (Table 3). The difference between minimum and maximum gage values was frequently significant. For example, the maximum deviation between gages was observed on the *Gilliss*, where there was consistently about a 20% greater phase catch in one of the stern gages than in the bow gage (see gage values and deviations plotted on the phase isohyetal maps). Also, the stern gages on the GATE ships generally collected more rain than the mast gage. This was probably due to the sheltering effect provided by the stern exposure. The standard operating procedure for the GATE ships was a drift and slow recovery mode, with the bow maintained into the wind when possible.

The rationale for selecting the maximum gage value for comparison with the radar estimates is supported by referring, for example, to the work of Larson and Peck (1974). They point out that the effects of wind on gage catch is almost always the primary source of error in rainfall measurements with raingages, and this source of error as well as most other ones such as evaporation and tilt of the gage orifice, result in deficit catches. Optimal siting requires that the gage be suitably sheltered from the wind to prevent laterally introduced momentum and turbulence near the gage catchment. This has led to the recommendation that gages over land preferably should be sited so that the orifice of the gage is at or below ground level. This minimizes or

eliminates problems of wind effects. Although such optimal exposures were not possible for the GATE shipboard raingage installations, it is reasonable to assume when considering the standard operating procedures employed for the GATE ships that the stern gage sites were, on the average, better sheltered from the wind than any of the other gage sites. The fact that the maximum values were collected most frequently by stern gages supports this supposition, and selection of the maximum gage value, for those ships equipped with two or more gages, should provide an estimate that is closer to the truth. Also, such an approach would never give overestimates unless sea conditions were so rough that sea spray was deposited in the gage, or the gage was positioned where rainwater could drip or splash into the gage from nearby structures. This was not the case with the stern mounted gages for the sea conditions encountered during GATE.

Assuming no systematic biases exist in the gage records, an estimate of the expected errors in the radar point rainfall estimates, for daily and phase periods, is given by the mean absolute percent difference between the gage and radar values, i.e.,

$$\sum \sum \left| \frac{(\text{Gage}_{ij} - \text{Radar}_{ij})}{\text{Gage}_{ij}} \right| \times 100/N,$$

where the sums are for all B-scale stations (i) used in the analysis and for all phases (j), or days (j), during GATE; N is the total number of gage-radar pairs. The first two rows in Table 4 give this error statistic for the phase and daily periods.

Several analyses were performed to evaluate the sensitivity of the results from the radar-gage comparative error analyses, presented in Table 3 and the first two rows of Table 4, to the approach adopted for relating the two types of measurements. Hudlow

TABLE 4. Summary of mean absolute percent differences between radar and shipboard raingage measurements.

Time scale	Space scale	Mean absolute percent difference (error)	Comments
Phase	16 km ²	14%	Each radar estimate was taken as the value in closest agreement with the raingage, from the set of four, 4 km × 4 km data bins consisting of the one containing the phase-mean ship position plus the three nearest neighboring bins.
Daily	16 km ²	23%	Each radar estimate was taken as the value in closest agreement with the raingage, from the set of nine, 4 km × 4 km data bins consisting of the one containing the daily-mean ship position plus the eight surrounding bins.
1-3 h	1-5 × 10 ³ km ²	23%	Based on expected range of space scales over which the 4 km radar estimates must be averaged for time scales of 1-3 h, to obtain an accuracy equivalent to the daily point estimates.

and Patterson (1979) present scatter plots (their Figs. 10, 11 and 13) for the phase and daily durations that illustrate the increase in scatter when, for example, the average of the values from the four bins making up the four-bin sets are used as the estimates for the phase duration and when the daily radar estimates were taken as the values from the data bins containing the daily-mean ship (gage) positions. Other techniques also were compared, including, for the phase duration, interpolation to obtain the point estimates from the contoured isohyetal maps (Figs. 4–6). All techniques of relating the radar and gage measurements produced virtually identical results for the bias evaluation (Table 3), but the greater scatter with the other approaches increased the mean absolute percent differences over those given in Table 4 by roughly a factor of 2. For example, the percent difference for the phase duration increased to 25% when the interpolated values from the contoured maps were used, and to 28.5% with the four-bin averages.

Hudlow and Patterson also show a radar scatter plot (their Fig. 14) of the maximum and minimum bin values versus the central bin values, from the nine-bin sets used for the daily radar-gage comparisons, which illustrates that the spatial variability in the rainfall over 4 km distances is roughly equivalent to the scatter remaining between the radar and gage estimates when the radar estimates are taken from the bin value in closest agreement with the gage. This further supports the rationale of using the bin value in closest agreement with the gage, when one considers that the positional uncertainties in the radar data alone can be as much as 2–4 km.

Because of the very large variability (scatter) observed in relating the *hourly* gage and radar values (Hudlow and Patterson, 1979), it is not feasible to use their comparisons directly to assess the expected error for *hourly* point radar estimates. However, an hourly scatter plot presented by Hudlow and Patterson (their Fig. 12) shows that no significant systematic biases exist between the radar and gage values throughout the dynamic range of the hourly rain rates.

The error estimate for the 1–3 h time scale (third row, Table 4) was semi-objectively determined by assuming that, although error from such sources as variability in the Z - R relationship are locally correlated, for large enough space and time scales, the errors would behave as random. Therefore, by averaging over more area, an equivalent accuracy to that for the point daily estimates can be achieved for the shorter (1–3 h) time scale. Hudlow and Arkell (1978) experimentally show that potential error resulting from variability in the exponent of the Z - R relationship would monotonically decrease, for a given time scale, with increasing averaging area (their Fig. 6). They also arrive at similar results for

another source of error: inadequate temporal sampling (their Fig. 5). Their results show that averaging over areas as large as, say, 1000 km² ($\sim 1/4^\circ \times 1/4^\circ$) for the 3 h scale and 5000 km² for the 1 h scale should reduce the combined potential errors from these two sources to levels significantly below that given for the point daily scale in Table 4. It is reasonable to assume that other sources of error would behave similarly, and therefore it is logical to expect that accuracies equivalent to those for the daily point scale should be achieved for the 1–3 h time scales by averaging over 1000–5000 km² areas.

If the errors in the elemental data bin values were truly randomly and normally distributed, as was assumed by Stout *et al.* (1979) in assessing the probable error in the GATE radar rainfall estimates for the purpose of comparison with their satellite rainfall estimates, then the mean error would reduce even faster with increasing averaging area or time than indicated in Table 4. This is not the case because, as mentioned above, some sources of error are locally correlated. An estimate of error made by Stout *et al.* (1979) for the radar ground-truth rainfall corresponding to a 5000 km² satellite cloud image is significantly greater than that indicated in Table 4. The reason for Stout's *et al.* larger error estimate (50% probable error), in spite of their assumption of randomly distributed errors, can be explained by the following two factors: 1) they began with an estimate for the phase point error of 25% instead of the 14% based on the approach described above for making radar-gage comparative analysis and 2) they assumed only 10% of the *thresholded* satellite image area contained rain, which seems too low for active rain periods.

The conversion of reflectivity to rainfall was based on the GATE relationship

$$R = 0.013Z_e^{0.8},$$

where R is the rainfall rate (mm h⁻¹) and Z_e the equivalent reflectivity factor (mm⁶ m⁻³). This is a mean relationship based on the pooling of the disdrometer data collected during GATE from all platforms and periods (Austin *et al.*, 1976). Subsequent analyses by Cunning and Sax (1977) and Austin and Geotis (1979) resulted in somewhat conflicting relationships, but the final relationship recommended by Austin and Geotis (1979) gives rainfall estimates only slightly different from the one used here and originally recommended by Austin *et al.* (1976).

Hudlow and Arkell (1978) experimentally show, using observed GATE reflectivity distributions, that variations in the exponent of the R - Z relationship, over a range from 0.625 to 0.8, would not seriously affect the accuracy of the rainfall estimates for the space and time scales being considered for atmospheric budget studies (≥ 3 h, ≥ 4000 km²), if the systematic bias introduced by changes in the

R-Z relationship are first removed. This range of exponents encompasses all those proposed by the aforementioned investigators including the lowest exponent of 0.658 recommended by Cuning and Sax (1977).

Analogous arguments to those made above for the scales covered in Table 4 can be made with regard to error estimates for other time and space scales. For example, if the errors in the phase point estimates decorrelate with relatively short spatial separations, then averaging in space would reduce the 14% expected point error. In fact, if the gage phase totals, used as standards, contain no systematic biases, then the error in the phase-mean radar estimates should approach zero as the estimates are averaged over areas approaching the size of the total B-scale array. As described previously, however, there could be systematic deficits in the gage collections, averaging as much as 10%.

In conclusion, it is encouraging to note that both Lord (1978) and Thompson *et al.* (1979) have found excellent agreement between the radar rainfall estimates and those based on B-scale moisture budget analyses. Lord has further demonstrated that the rainfall rates estimated from the Arakawa-Schubert convective parameterization model are also in excellent agreement with the radar estimates. These findings are extremely significant, since they reveal that the quality of the principal GATE data sets should be adequate to achieve the central objectives of the experiment.

5. Concluding remarks

Using digital radar data from four C-band radars, the mean precipitation regime for GATE has been studied. The rainfall analysis products used were mean isohyetal maps for each of the three observational phases and a time-latitude rain cross section for Phase III. Some of the more important findings are as follows:

1) Large rain accumulations were observed for all three phases, with the largest totals exceeding 500 mm, corresponding to some of the maximum rain-rate isohyets during Phase I. The GATE period apparently was not an abnormally rainy period, since the mean rainfall rate averaged over the B-scale array for all three Phases, 11.3 mm day^{-1} , was not found to be significantly different from inferred pre-GATE climatology. As is apparent from the magnitude of the precipitation rates, tropical ocean areas such as GATE, which lie within regions influenced by the ITCZ, significantly affect the global water and energy balances.

2) One of the striking characteristics of the isohyetal maps for all three phases is the large spatial gradients; e.g., mean rain-rate gradients corresponding to accumulation gradients as large as 200 mm in 16 km are observed. The large gradients persisting

in the phase-mean rain patterns raise the question of inhomogeneity in other meteorological and oceanographic parameters, especially for shorter time scales.

3) The mean location of the ITCZ, as defined in this study, was about 1° farther north during Phases II and III than during Phase I.

4) The time-latitude rain cross section showed that the significant precipitating convection accompanying several synoptic-scale events during Phase III was positively related to wave phases in the vicinity of the troughs of African wave disturbances.

5) Considering the results from the radar-gage comparative analyses presented in Section 4 and the excellent agreement found by other investigators between the radar rainfall estimates and those based on B-scale moisture budget analyses, it can be concluded that the quality of the principal GATE data sets is adequate to achieve the central objectives of the experiment.

The results derived from this study represent only a miniscule part of the information contained in the GATE radar data sets. All of the primary data sets, including the hourly precipitation maps, both on magnetic tapes and microfilm graphics, are available from the GATE World Data Center A, National Climatic Center, Federal Building, Asheville, North Carolina 28801. Also, radar rainfall estimates for several time scales and geometric areas are available in the *GATE Radar Rainfall Atlas* (Hudlow and Patterson, 1979).

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