The Relationship between Fractional Coverage of High Cloud and Rainfall Accumulations during GATE over the B-Scale Array

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ABSTRACT

A description is given of the relationship between 6 h averages of fractional coverage of cloud above various height and temperature thresholds, derived from infrared data from the Synchronous Meteorological Satellite 1 (SMS 1), and accumulated rainfall, derived from data obtained with a group of quantitative C-band digital radars. Comparisons are made over a hexagonal area extending from 22.25–24.75°W longitude and from 7–10°N latitude (the B-scale array) for each phase of the GARP Atlantic Tropical Experiment (GATE). Scattergrams of fractional coverage above 10 km, the altitude of maximum correlation, show a linear relationship for each phase, with correlations ranging from 0.81 to 0.89. Reanalysis of Phase I, omitting a single outlier, results in a very narrow range for the regression coefficients for all three phases. An analysis of the pooled data from all three phases, omitting the single outlier, shows that 75% of the variance in 6 h rainfall accumulations over the GATE B-scale array is explained by a linear function of the fraction of the array covered by cloud higher than 10 km.

1. Introduction

The GARP Atlantic Tropical Experiment (GATE) radar precipitation analysis (Hudlow and Patterson, 1979) provides a high-quality data set resolving the structure of convection over the eastern tropical Atlantic Ocean. This data set provides ideal "ground-truth" for comparison of the variability of rainfall on various space and time scales with the variations in the height and areal extent of cloudiness as observed by the infrared sensor on board the SMS 1 geosynchronous satellite. This report summarizes preliminary results of such a comparison for a single time and space scale.

The physical relationship between cloud top heights and rainfall is often variable and generally not well known. It has long been observed that areas of high convective cloud in satellite images are often associated with precipitation. Based on this and other empirical relationships, a number of techniques have been developed to estimate rainfall using satellite data. These methods, up to 1973, were reviewed by Martin and Scherer (1973). More recent work in this field includes that of Griffith *et al.* (1978), Scofield and Oliver (1977) and Stout *et al.* (1978).

The data now permit the derivation of empirical relationships for a tropical oceanic area from satellite and rainfall data more extensive in time and space than those previously available for this type of area. This paper provides preliminary results on the relationship between satellite parameters and rainfall when the comparison is made using coarse spatial and temporal resolution. This bulk approach has two important benefits. First, it vastly reduces the amount of computation necessary to carry out the study since there is no attempt to identify and track individual raining clouds during their life cycle. Second, the results should provide a type of benchmark from which the improvement achieved by more sophisticated methods of estimation can be measured.

The cloud-top data used in this study consist of frequency distributions of SMS 1 infrared brightness temperatures over a geometric area which approximates the GATE B-array, a hexagonal area extending from 22.25–24.75°W longitude and from 7–10°N latitude. They were obtained from data, in the form of frequency distributions of digital counts from each 0.5° × 0.5° area in the GATE A/B array, produced by Polifka and Cox (1977). Conversion to temperatures was done using an algorithm developed by Eric Smith of Colorado State University (R. Williams, National Climatic Center, Asheville, NC, personal communication). This algorithm removes the drift of the SMS 1 infrared sensor which took place during GATE, and corrects for the diurnal variation in sensitivity which began on 24 August. Where conversion from temperatures to heights was done, a GATE mean sounding supplied by R. Reeves,

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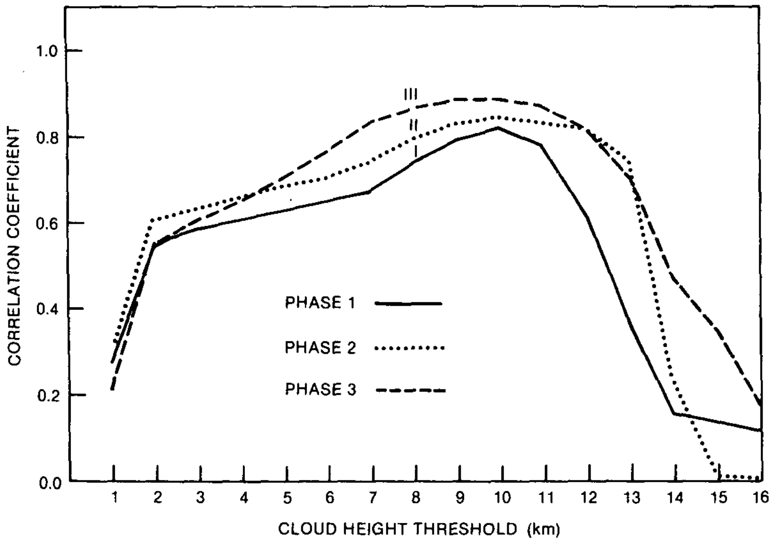


FIG. 1. Correlation between rainfall accumulation and fraction of B-scale area covered by clouds above various height thresholds.

Center for Environmental Assessment Services (personal communication) was used for the transformation.

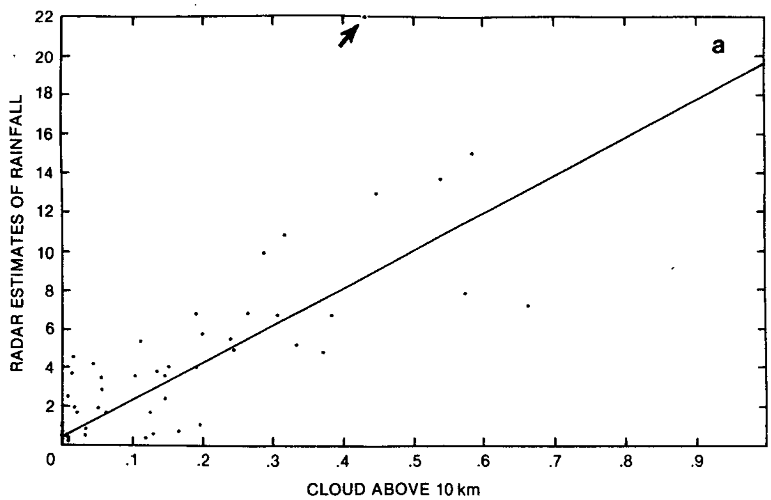
The rainfall data consist of 6 h mean accumulations over the GATE B-array as determined by the GATE C-band radars. Hudlow and Patterson (1979) discuss the sensors and processing involved in producing this data set.

The procedure of comparing satellite data of the form used here with radar estimates of rainfall over the B-scale array introduces two sources of error. The first is due to the difference in the shapes of the areas. The set of 0.5° × 0.5° boxes comprising the satellite data used here form an area whose border is between zero and 30 km from the border of the area used in computing the radar estimates. The total areas differ by less than 5%. The second source of error lies in the differing navigational procedures used with the two data sets. The algorithm used to navigate the satellite data was that described by Smith and Vonder Haar (1976). It is thought to have an error of less than 20 km (E. Smith, Colorado State University, personal communication). The error in navigation of the radar data is at most 4 km (Hudlow *et al.*, 1979). In the worst case, the total error should approximate 0.5° of latitude or the width of one of the satellite boxes. The most likely effect of such errors would be to very slightly decrease the observed correlations.

The satellite parameters are 6 h averages of the

TABLE 1. Lag correlations between 6 h means of fraction of B-scale area covered by cloud colder than various temperature thresholds and accumulated rainfall (for Phase III)

Temperature (K)	Lag (h)									
	−2	−1	0	+½	+1	+2	+3	+4	+5	+6
205	0.50	0.50	0.46	0.44	0.44	0.40	0.30	0.25	0.18	0.11
210	0.63	0.65	0.64	0.59	0.59	0.55	0.48	0.40	0.31	0.24
215	0.72	0.73	0.74	0.71	0.71	0.65	0.58	0.49	0.37	0.30
220	0.78	0.81	0.81	0.79	0.79	0.73	0.65	0.56	0.42	0.35
225	0.81	0.84	0.85	0.83	0.83	0.78	0.71	0.62	0.47	0.39
230	0.82	0.85	0.87	0.86	0.86	0.81	0.75	0.67	0.52	0.43
235	0.82	0.86	0.88	0.87	0.87	0.83	0.78	0.70	0.55	0.47
240	0.81	0.86	0.88	0.88	0.88	0.84	0.80	0.74	0.59	0.51
245	0.80	0.85	0.88	0.88	0.88	0.84	0.81	0.75	0.62	0.53
250	0.78	0.83	0.86	0.88	0.88	0.85	0.83	0.77	0.64	0.56
255	0.75	0.81	0.84	0.86	0.86	0.84	0.84	0.78	0.65	0.58
260	0.72	0.78	0.81	0.84	0.84	0.82	0.82	0.77	0.65	0.58
265	0.67	0.72	0.76	0.79	0.79	0.77	0.78	0.74	0.62	0.57
270	0.61	0.66	0.69	0.73	0.73	0.71	0.72	0.69	0.58	0.55
275	0.56	0.61	0.64	0.67	0.66	0.64	0.66	0.64	0.54	0.52
280	0.53	0.57	0.59	0.61	0.61	0.58	0.60	0.58	0.50	0.49



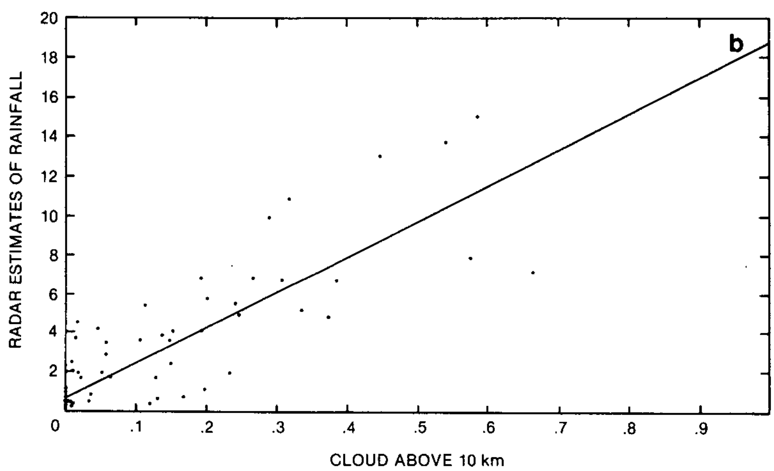


FIG. 2. Scatter diagram showing 6 h rainfall accumulations as a function of the fraction of B-scale area covered by cloud higher than 10 km for (a) Phase I, (b) Phase IA, (c) Phase II and (d) Phase III. Superimposed is linear least squares fit.

fraction of the B-array covered by cloud higher, or colder, than selected thresholds. Observation times with >10% of the points in the B-array missing were excluded. Thresholds at each kilometer from 1–16 km, and 5 K intervals from 205 to 280 K were used.

2. Analysis

a. Correlations

The linear correlation coefficients between 6 h rainfall accumulations and the fractional coverage of the B-array by cloud higher than heights from 1 to 16 km were computed separately for each phase of GATE. Fig. 1 shows how the correlation coefficient varies with fractional coverage above each height. The notable features are the similarity of the curves for the three individual phases with each reaching a maximum at 10 km, and the relatively high peak correlation coefficients (from 0.81 to 0.89).

Correlations were also computed between rainfall and fractional coverage for temperature thresholds at 5 K intervals between 205 and 280 K and lags ranging from −2 h (satellite leading) to +6 (radar leading). Table 1 shows the correlations for Phase III. For both Phases II and III, the peak correlations were found at zero lag and a temperature threshold of 235 K. The general area of high correlations was similar for Phase I, but the single highest value was found at 240 K and a lag of +1 h.

Stout *et al.* (1979) present a table of correlations between volumetric rain rate and infrared cloud area for various lags and thresholds. They were computed using individual cloud and echo entities observed during GATE. The total area and length of time included in their sample was considerably less than in this study, while their spatial and temporal resolution were much greater. They found a peak correlation at 175 digital counts (roughly 243 K) and a lag of +80 min (radar leading).

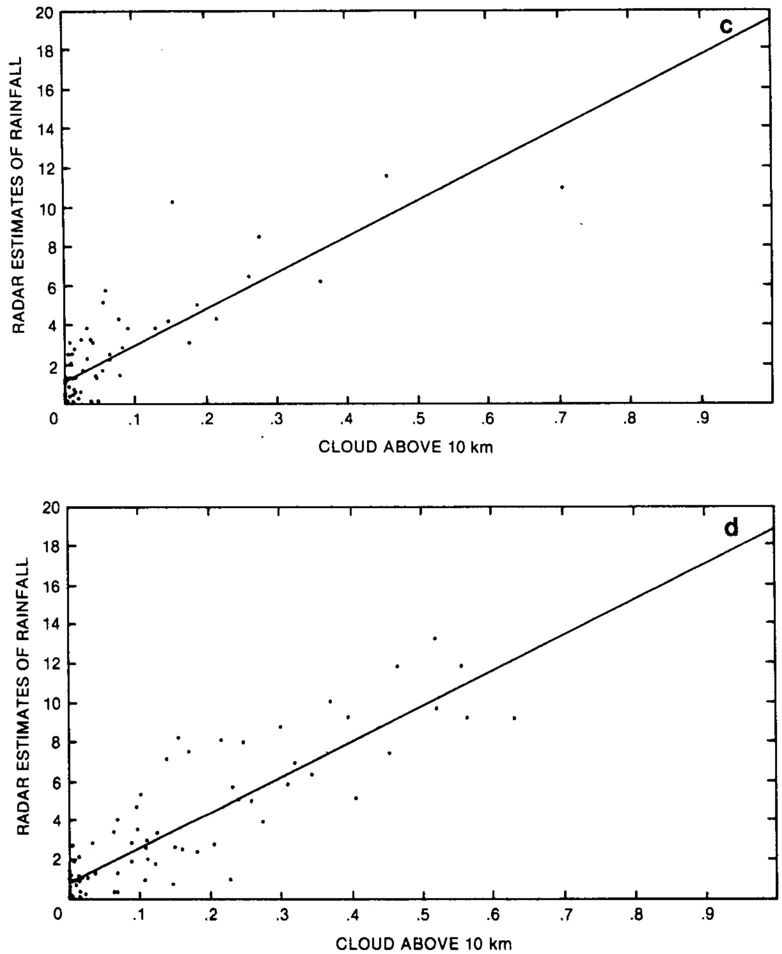


FIG. 2. (*Continued*)

During all three phases of GATE, the axis of highest correlations runs diagonally from 230 K at lag −2 h to 255 K at +5 h. This same tendency occurs in the results of Stout *et al.*, with the peak correlation at lag −80 min found at 205 digital counts (214 K) and at lag +5 h at 130 digital counts (265.5 K).

b. Linear regression

Figs. 2a, 2c and 2d show the scatter plots of the 6 h mean of the fraction of the B-array covered by cloud higher than 10 km versus the 6 h accumulated rainfall for Phases I, II and III. The data for each phase are well represented by linear regression lines.

The regression equations for Phases II and III are quite similar but differ from the regression line for Phase I (see Table 2). The slopes for Phases II and III differ by less than 5%, while the slope for Phase I differs from each of the others by more than 10%.

Examination of the data for Phase I revealed a single outlier for the 6 h period, 1200–1800 GMT 7 July 1974, with a relatively high rainfall for the observed high cloud that strongly affected the fit for Phase I (see arrow, Fig. 2a). This point represents a rare rainfall event; in fact, the rainfall accumulation over the B-array during this 6 h period was nearly 50% greater than that of any other 6 h period during GATE. Richards (personal communication) has also found that radar echo tops during this period were not as high as one might expect from the large rainfall accumulations.

TABLE 2. Coefficients and correlations for the linear least-squares fit between 6 h means of fractional coverage of the GATE B-scale array by cloud higher than 10 km and accumulated rainfall.

Period	Slope (mm)	Intercept (mm)	Correlation
Phase I	20.2	0.56	0.82
Phase II	18.2	1.07	0.84
Phase III	17.7	0.79	0.89
Phase IA	18.1	0.63	0.85
Pooled	17.8	0.84	0.86

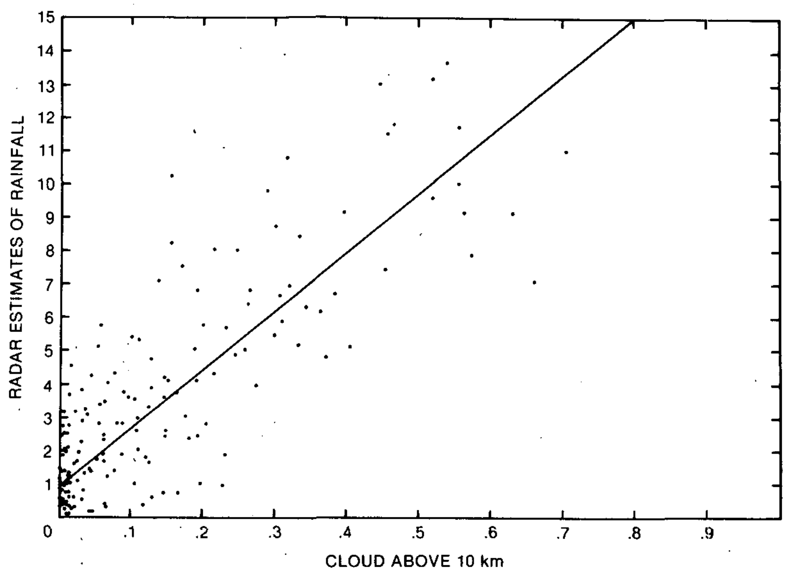


FIG. 3. As in Fig. 2 except for pooled data.

A reanalysis of data from Phase I, omitting the anomalous point (referred to as Phase IA), leads to a regression equation very similar to those obtained for Phases II and III (see Table 2). Correlations for various lags and threshold temperatures were again calculated: the largest correlation occurred at 235 K and zero lag, and the threshold temperature of highest correlation increased with increasing lag, as was found for Phases II and III. The scatter diagram (Fig. 2b) for Phase IA also was found very similar to Phases II and III.

c. Pooled data

The above results show that, with the exception of a single 6 h period, the statistical relationship between rainfall and areal extent of high (above 10 km) cloud was essentially the same for the three phases of GATE. A regression using the 10 km threshold and zero lag for all 6 h periods, except 1200–1800 GMT 7 July 1974, is shown on the scatter diagram for the pooled data (Fig. 3). Examination shows that a linear relationship is not unreasonable in that there appear to be no areas of systematic bias.

3. Summary and conclusions

A comparison of 6 h rainfall accumulations over the GATE B-scale array and fractional coverage of clouds above various threshold heights, or below threshold temperatures, as determined from SMS 1 infrared brightness frequency distributions, has shown relatively high correlations for a limited range of heights and temperatures. The maximum correlations, 0.84–0.88, were found at 10 km and 235 K for zero time lag.

The linear regression line for Phase I differed from that for Phases II and III because of a single anomalous 6 h value. Removal of this point gave results for Phase I very similar to those for Phases II and III. A correlation of 0.864 was found when data at the 10 km level from all three phases (except for the anomalous point) were pooled.

In spite of the phase-to-phase variability in factors such as average rainfall rate (Hudlow *et al.*, 1979) and the mean surface wind field (Seguin *et al.*, 1978), the relationship between rainfall and fractional IR coverage apparently remained the same throughout GATE. This suggests that the bulk spatial and temporal averaging employed minimized the importance of the details of the convection. Further work is underway to determine the effect of averaging over different time and space scales.

Finally, since many requirements for rainfall estimates over ocean areas (e.g., large-scale energy budgets, climatological statistics) will be satisfied by data of the time and space scale used here (6 h and ~2.5° × 3°), it is worth noting that 75% of the variance in the GATE rainfall on the B-scale as estimated from radar observations was explained by a linear function of the cloud area above 10 km. Since considerably more information is present in the infrared data than is used here, more elaborate statistical procedures and/or finer spatial and temporal resolution might achieve even greater accuracy. For example, a multiple-regression analysis using other satellite parameters, such as the change in cloud area at various heights, as well as fractional cloud cover, may yield improved estimates of bulk rainfall accumulations.

It should be kept in mind that this analysis is valid only for a single, limited area over the tropical ocean for a portion of one summer. Until similar, more extensive studies can be performed for other areas, it cannot be assumed that the relationship derived from the GATE data is generally applicable. Also, the observed relationship underestimates the largest single rainfall event of GATE by more than 150%. For some applications, this may be an important limitation for a rainfall estimation technique. Thus, this analysis, in itself, is not being proposed as the basis for a general technique of rainfall estimation from satellite data. Rather, the purpose has been a preliminary investigation of an already established empirical relationship between infrared cloud area and rainfall using a more extensive tropical oceanic data base than has previously been available. In the process, a benchmark accuracy has been established for the GATE region which may be exceeded by the use of more sophisticated techniques of rainfall estimation from satellite data.

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