Cloud-Coverage Characteristics during Phase III of GATE as Derived from Satellite and Ship Data

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ABSTRACT

The spatial and temporal characteristics of cloud coverage during the 21-day GATE Phase III period were studied using SMS-1 infrared hourly digitized data and standard hourly meteorological surface observations taken on 18 ships positioned within the A/B and C scale regions. Results were obtained for the entire sample and for portions stratified according to enhanced (E) or depressed (D) convective activity. Separate areal analyses based on ship data and on satellite data were obtained for total coverage, low-cloud amount including cumulonimbus, middle-cloud amount and high-cloud amount. Both the satellite and the ship data indicate that the average coverage for the GATE A/B array area during Phase III is close to 80%. The zone of maximum cloudiness exhibits a basic east-west orientation and is centered near 8°N.

Analysis of hourly variations yields a nighttime maximum of total coverage near 0300 GMT on D days while on E days the maximum occurs in late afternoon or early evening. Analysis of low clouds showed a double maxima at 0400 and 1500 GMT. The early afternoon maximum predominates on E days while only the nighttime maximum is present on D days. On days of significant activity, the high cloud maximum occurs in the late afternoon (1900 GMT), ~4 h later than the low-cloud maximum. The results of this study emphasize that generalizations about the diurnal variations of clouds, convective activity and precipitation over tropical oceans must be carefully evaluated in terms of regional location and prevalent degree of convective activity.

1. Introduction

The GARP Atlantic Tropical Experiment (GATE) was an international field effort conducted off the west coast of Africa during the summer of 1974. Two major objectives as stated by Kuettner (1974) were 1) to estimate the effects of smaller-scale tropical systems on large-scale circulations and 2) to advance the development of numerical modeling and prediction methods. Numerical models must include spatial averages of radiative heating for realistic simulations of the atmosphere. As part of a study assessing various methods of computing radiation fields and heating functions during Phase III of GATE (30 August–19 September 1974), gridded analyses of the horizontal and vertical distribution of clouds, temperature and specific humidity were prepared. As clouds are the major modulators of radiation fields, the parameterization of cloud coverage is of particular importance in computing a radiation budget. This paper is concerned with describing the results of hourly layered cloud analyses obtained from Synchronous Meteorological Satellite (SMS)-1 data and GATE ship observations during Phase III. The results will be compared with previous studies of cloudiness over tropical oceans including studies of the GATE data.

The sparsity of observations and the vast distances involved have long placed severe limits on our knowledge of the time and space variations of meteorological parameters over the ocean, especially in the tropics. Utilization of data from meteorological satellites, both polar-orbiting and geostationary, greatly increases the information available, but restrictions on detail and resolution and problems in interpretation remain. It was pointed out by Young (1967) rather early in the use of satellite data that significant variability occurs in the estimation of cloud cover from satellite pictures by different analysts. Further, a variety of techniques (see, e.g., Harris and Barrett, 1978; Parikh, 1977) have been proposed and evaluated to accomplish an objective classification or analysis of cloud-amount and cloud-type information. However, the lack of a standard, commonly accepted technique for objectively analyzing cloud data increases the difficulty of interpreting and using satellite results in constructing climatological models of cloudiness over oceans. There remains also the difficulty of comparing and integrating satellite cloud data with more conventional surface observations of clouds. Conventional surface meteorological observations, of course, are point or small area estimates of cloudiness in contrast to the

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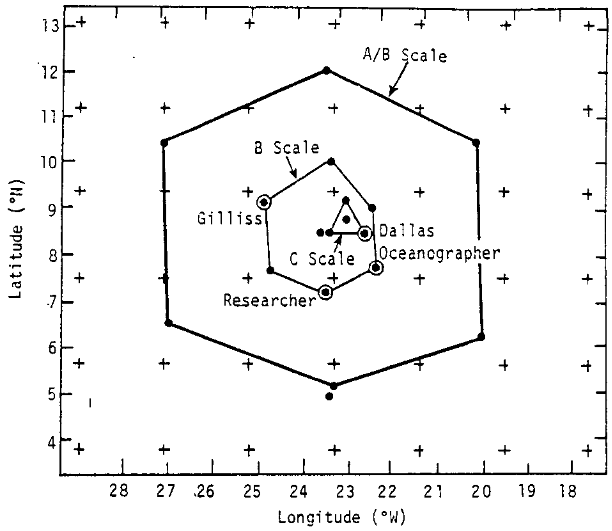

FIG. 1. Subset of modified GFDL grid used for cloud analyses, together with GATE A/B, B and C scale ship locations during Phase III.

large areal distributions obtainable from satellites. Problems such as differences in scale and perspective in making use of results from the two sources have been discussed by Court (1978) and Hoyt (1978). An additional problem in this study is the comparison of visible ship-observed clouds with clouds defined by the SMS-1 infrared data.

Gray and Jacobson (1977) have summarized the evidence for the diurnal variation of deep cumulus convection over both land and ocean regions. They assert that the evidence on the whole indicates a significant diurnal cycle of maximum oceanic tropical deep cumulus convection in the morning and a minimum occurring in the early evening. It is noted that the maximum occurrence of heavy rainfall during GATE is 6–7 h later than in most other ocean regions. The authors also state that the diurnal variations of low-level layered and total cloudiness show a much smaller range with early morning and late afternoon maxima separated by relative minima.

A number of studies have investigated cloudiness during all or part of the three phases of GATE. The high degree of cloudiness in the period June–September 1974 especially over the A/B ship array (approximately 5–12°N latitude and 19–27°W longitude) is a consistent result of all investigations. In a study employing SMS-1 infrared (IR) data, Gruber (1976) found an average cloudiness of 71% over the A/B array for all three phases. The technique employed in arriving at this average excluded some low-level stratocumulus clouds which are found frequently in the northern portion of the array. Gruber found a single diurnal maximum of both total cloudiness and upper level cloudiness at 1800 GMT (1630 LT) on convectively disturbed days. However, on undisturbed days total cloudiness showed a broad nighttime maximum centered at 0000 GMT.

Holle *et al.* (1979) analyzed over 2500 hourly, whole-sky camera photographs from four U.S. ships on the B scale (7–10°N latitude and 22–25°W longitude) to determine total and layered cloudiness during all phases of GATE. Average daytime total cloudiness was 77% during all phases and 79% during Phase III at the four ships. Low clouds averaged 36% overall, while upper clouds averaged 44%. A comparison with ocean cloudiness in the western Atlantic derived from whole-sky cameras in the Barbados experiment (Holle and MacKay, 1975) showed that there was nearly twice as much total and upper cloudiness in GATE and nearly three times as much low clouds. Cox and Griffith (1979) have recently estimated radiative divergence profiles on the B scale during Phase III of GATE. Their studies determine less upper tropospheric radiative divergence and more middle-level divergence than earlier climatological studies estimated. These differences are attributed primarily to the extensive middle and upper tropospheric cloudiness in the GATE area.

2. GATE data and analysis techniques

a. Data sets

The two data sets used to derive cloud analyses during Phase III of GATE are 1) SMS-1 IR hourly digitized data and 2) standard hourly meteorological surface observations taken on 18 GATE ships positioned on the A/B and C scales as shown in Fig. 1.

The satellite data set used in this study was prepared from original SMS-1 IR digitized data sets by Colorado State University (Smith and Vonder Haar, 1976).[1] The earth-located edited data set consists of approximately hourly data covering the geographic region from 22°N to 5°S and 50 to 5°W from 27 June to 20 September 1974. The field of view of a single infrared sensor is approximately 7 km × 7 km at the subsatellite point (45°W during GATE). Each IR data element consists of a brightness count that ranges from zero (dark) to 250 (white) and corresponds to warm to cold temperatures. The portion of the data set extracted for analysis in the study consisted of hourly Phase III data (30 August–19 September 1974) between ~5–12°N and 19–27°W.

[1] Smith, E. A., and T. H. Vonder Haar, 1976: Hourly Synchronous Meteorological Satellite-1 (SMS-1) data collected during the GARP Atlantic Tropical Experiment (GATE). Earth located edited data set. Res. Rep., Dept. of Atmospheric Science, Colorado State University. [Available from World Data Center (A GATE Data Catalogue), National Climatic Center, Asheville, NC 28801.]

Standard hourly meteorological data were obtained from validated surface observations taken at 18 ships located within the A/B array during Phase III. The cloud information consisted of reports of total cloud amount, cloud amount in the lowest layer (either low or middle clouds), height of the base of lowest cloud, low-cloud type, middle-cloud type and high-cloud type. Other parameters that could be of potential interest in deriving or assessing cloud information are present weather, past weather, visibility and the GATE convective cloud code. In some contrast to the satellite data, ship observations are concentrated in the region from 7–10°N latitude and 22–25°W longitude, with seven ships outside the central B and C scale locations.

b. Satellite data analysis technique

A detailed description of the development and evaluation of the technique to analyze SMS-1 IR data is given by Parikh and Ball (1980). The analyses initially consist of two parts: a cloud type analysis and a cloud amount analysis. The information from the two separate analyses are then combined by means of an algorithm to obtain layered cloud amounts.

The cloud type analysis uses a maximum-likelihood classification technique described by Parikh (1977). The classification technique was designed to differentiate the following five cloud type classes:

Class 1 Low clouds only
Class 2 Middle clouds with no significant high clouds
Class 3 High clouds with no significant lower clouds
Class 4 High clouds with significant lower clouds
Class 5 Cumulonimbus.

The cloud type class at a particular location was obtained by a discriminant analysis technique using spectral and textural features.

The cloud amount analysis uses a two-threshold weighted histogram technique to define three cloud amount categories:

Category 1 No clouds (0% cloud coverage assumed)
Category 2 Partially cloud-filled (50% cloud coverage assumed)
Category 3 Completely cloud-filled (100% cloud coverage assumed).

The two thresholds were selected from hourly histograms of IR counts in the GATE A/B area. The first threshold separates categories 1 and 2 and corresponds to the peak IR count associated with the clear area. The second threshold is defined as the IR count associated with the warmest overcast cloud area peak and separates categories 2 and 3. The two-threshold method has been described and applied by Shenk and Salomonson (1972).

TABLE 1. Algorithm used to determine layered cloud amount.

Cloud type class	Fractional multiplier of total cloud coverage		
	Low clouds	Middle clouds	High clouds
1	1.0	0.15	0.15
2	0.5	1.0	0.15
3	0.25	0.25	1.0
4	0.5	0.5	1.0
5	1.0	—	—

A cloud-type classification and a total cloud amount coverage is obtained for each 1° latitude-longitude location in the following manner. A 5×5 array of location points of 7 km interval is centered on each 1° latitude-longitude location. A cloud type class and a cloud amount category is determined for each point in the 5×5 array. The cloud type classification assigned to the 1° latitude-longitude location at the center of the array is simply the cloud-type class that occurs most frequently in the array. The total cloud coverage at the center of the array is computed as the average of all 25 points.

The final step in the satellite analysis determines layered cloud amounts at each 1° latitude-longitude location. Estimates of low-cloud amount, middle-cloud amount and high-cloud amount are made using the algorithm based on total cloud coverage and cloud class given in Table 1. Low clouds have bases below 2 km, while high clouds have bases above 6 km; middle clouds have bases between 2 and 8 km. The coefficient multipliers of total cloud amount used to derive each layer cloud amount reflect average layered cloudiness in each cloud type class as determined from selected unambiguous ship observations which comprised the training sample used in the development of the satellite cloud type maximum-likelihood classification technique (Parikh and Ball, 1980). The above algorithm obviously is dependent on cloud type class definitions and statistical averages of cloud amount associated with each class. The degree of uncertainty is greatest for low clouds and least for high clouds.

c. Ship cloud observation layering technique

The derivation of cloud information from standard meteorological surface observations presents a number of problems apart from the basic questions of the accuracy of the observers cloud estimates and the representativeness of the observation for a larger area. Total cloud coverage and low cloud amount can be obtained directly from the surface observation. However, middle and high cloud amount can be obtained directly from the observation only if there is not a lower cloud layer. Basically, there are three frequently encountered situations that pose difficulties in the estimation of upper clouds from surface observations:

- Low-cloud amount is overcast or near-overcast with no information about upper clouds (middle and high cloud type are unknown). Analogous to this is the situation where middle cloud layers or middle plus low cloud layers are overcast such that information on high clouds is lacking.
- Low clouds are present but not overcast and middle *or* high cloud layers are reported (middle or high cloud type is coded 1–9).
- Low clouds are present but not overcast and middle *and* high cloud layers are reported (middle and high cloud type is coded 1–9).

In the situation of overcast low clouds a limited number of estimates of middle cloud amount can be made indirectly from a present weather observation of precipitation. Otherwise, in the majority of cases upper clouds must be considered indeterminate or unknown. The second and third type of problem mentioned above depict situations with partial information. Many methods have been suggested to assign values for the upper cloud layers. After testing, an empirical objective cloud-layering scheme for surface observations was developed supplemented with data on present weather and middle and high cloud type. While the accuracy of the cloud-layering scheme cannot be stated, it is felt that the procedures followed have been conservative and it is quite likely that high cloud amount is underestimated.

d. Objective analysis of cloud amounts

Objective gridded analyses of total, low, middle and high cloud amount were prepared using a subset of the modified Geophysical Fluid Dynamics Laboratory (GFDL) grid shown in Fig. 1. The grid which was modified such that both the longitudinal and latitudinal grid intervals are 1.875° or are ~200 km is being used in various aspects of the GATE Phase III radiation studies.

A simple objective analysis technique called the weighted-average analysis method (WAAM) is used to compute cloud amount ϕ at a grid point from n observations of ϕ_i as follows:

$$\phi = \frac{\sum_{i=1}^{n} W_i \phi_i}{\sum_{i=1}^{n} W_i}, \qquad (2.1)$$

where W, the appropriate weight for each observation, is determined by

$$W = \frac{1}{1 + (ad^2)^b}, \qquad (2.2)$$

where a and b are constants specified by the analyst, and d is the distance of the observation from the grid point (Davis, 1962).[2]

e. Classification of GATE Phase III days

While overall cloud statistics and distributions representing all days of Phase III are useful, previous studies clearly indicate that additional understanding and insight into cloud characteristics can be obtained when the period is stratified according to days in which convective cloud activity is extensive or limited. In this study, convective cloud activity is classified by using the GATE convective code developed by Garstang and Aspliden (1974). The 21 days of the GATE Phase III sample were classified based on the frequencies of the hourly reports of convective code at the 18 ships within the A/B scale, with over 300 reports available on most days of Phase III. Each day is classified according to overall degree of convective activity as depressed (D), weak (W) or enhanced (E), with seven days being in each category.

3. Areal distribution of cloudiness

Sets of layered-cloud analyses were prepared from ship observations and from satellite data according to the procedures described in Section 2. The composite analyses for total, high and low cloud amount for all hours of Phase III (504 h) are given in Fig. 2 which contains the cloud analyses based on ship observations and the comparable analyses from satellite data.

Before making detailed comparisons a few overall remarks are appropriate. Generally, the cloud patterns are more clearly defined and coherent in the analyses based on satellite data, especially for total and high cloud amount. The basic east-west orientation of the major cloud maximum is consistent with a previous study by Sadler (1975) of climatological cloudiness in the GATE region and the results of Holle *et al.* (1979) who developed cloud analyses from analyses of whole-sky camera pictures at four ships within the B array.

The composite analysis of total cloud amount based on ship observations shows weak gradients, a diffuse pattern, and lack of a clear east-west orientation in total coverage. Coverage is a maxi-

[2] Davis, E. L., 1962: Objective techniques for the analysis of clouds and ceilings. TRC Tech. Rep. 7044-35, Hartford, CT, 51 pp. [Available from the Center for the Environment and Man, Hartford, CT 06120.]

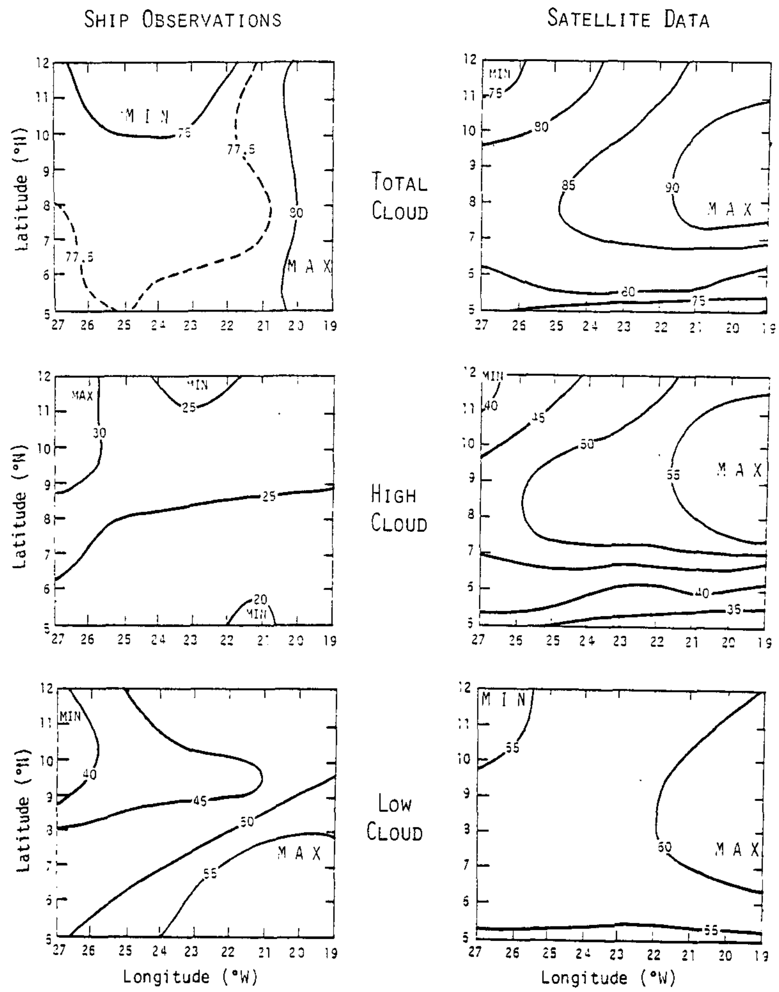

FIG. 2. Analyses of total cloud amount, high-cloud amount and low-cloud amount (%) based on ship observations and satellite IR data.

mum with ~80% in the eastern part of the region (19°W) and a minimum slightly under 75% in the northern part of the region (11°N). In marked contrast to this, the analyses based on satellite data shows a distinct east-west maximum near 7.5°N with values above 90% in the eastern end. This is consistent with other studies. McGarry and Reed (1978) determined that the maximum in convective cloud cover was stronger in the eastern part of the A/B array. Sadler (1975) found the climatological mean position of the maximum cloud zone in the GATE area to be near 8°N in August and 7°N in September. The zone of maximum cloudiness narrows and decreases to near 80% at the western end (27°W) of the GATE A/B region. Cloud amounts decline sharply to 70% to the south and more gradually to 70% to the northwest.

The analysis of low clouds based on ships and the analysis based on satellite data (Fig. 2) yield fairly similar results in that the maximum cloudiness is near 7.5°N, 19°W. Holle *et al.* (1979) found the zone of maximum rainfall and low clouds to be near 8°N. The ship maximum is slightly over 55% compared with a satellite maximum slightly over 60%. The satellite analysis shows a moderate decrease to near 50% to the south with small gradients elsewhere. The ship analysis by contrast yields a much more significant decrease in low cloudiness to the northwest reaching just over 35% near 12°N, 27°W. The relatively weak patterns for low-cloud amount in the composite satellite analysis is perhaps to be expected because of uncertainties in deriving this parameter from satellite data.

The composite analyses of middle cloud amount based on ship observations and satellite data (not shown) are in fairly good agreement. Both analyses show maxima near about 9°N, 20°W within 3% of ~45% coverage. The band of maximum cloudiness extends to the west and southwest in both analyses with maximum values maintained near 45% in the

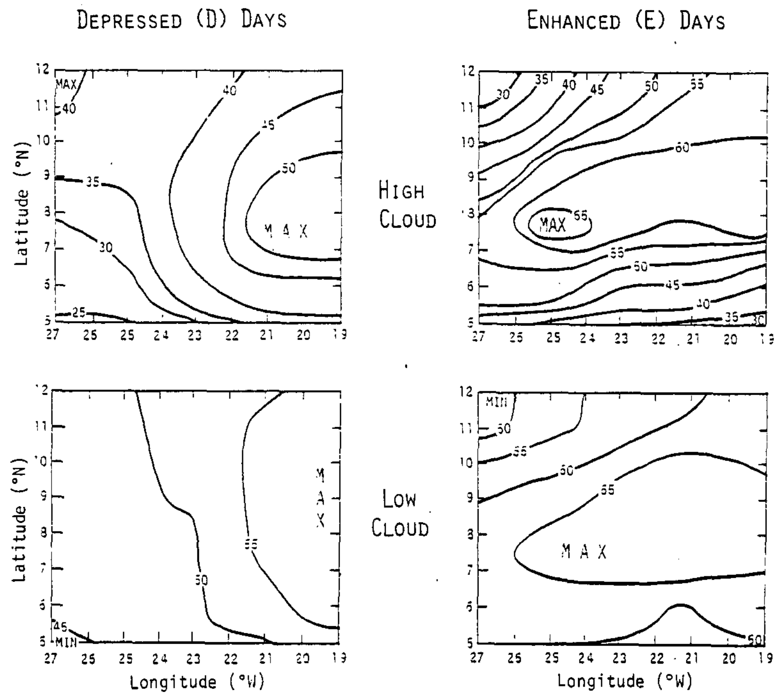

FIG. 3. Analyses of high-cloud amount and low-cloud amount (%) on enhanced (E) days and depressed (D) days based on satellite IR data.

ship analysis, but declining to 35–40% in the satellite analysis.

The composite analysis of high-cloud amount based on ship observations (Fig. 2) is poorly defined other than a general indication for slightly higher coverage (25–30%) in the northern half of the region compared with the southern half (20–25%). This weak pattern might be expected since high cloudiness is the least certain of the cloud parameters derived from ship observations. In sharp contrast, the satellite composite analysis shows a broad pronounced zone of maximum cloudiness in excess of 55% centered at 9°N, 19°W; the zone extends west-southwesterly to 7.5°N, 27°W and decreases to about 45%. High clouds decrease sharply to the south to under 30%.

The analyses shown above were based on all days and hours during Phase III. Some interesting differences in cloud analyses can be seen if the sample is stratified according to enhanced (E) and depressed (D) days. Resultant composite analyses of low and high cloud amount are shown in Fig. 3 for D and E days based on satellite data. On D days the analysis of low clouds is poorly defined. On E days the familiar elongated east-west maxima is present together with decreasing coverage both to the south and northwest. Within the zone of maximum low clouds, amounts are 5–20% greater on E days than D days.

Significant differences are also seen for high cloud amount. On D days, the primary cloud maximum zone extends only to ~7.5°N, 22°W and an area of weak maximum cloud is present in the northwest corner of the area in place of the usual minimum coverage. On E days, the band of maximum clouds extends west-southwestward over the entire region and has the greatest coverage of 65% near 7.5°N, 25°W, which is 30% greater than on D days. Minimum coverage under 30% is found in extreme northwestern and southwestern parts of the region. The more clearly defined and dramatic cloud patterns for both low and high clouds on convectively active days is consistent with intuitive reasoning that cloud systems would be better organized and region-specific than on days with convectively depressed conditions.

The cloud coverage values for all days and D and E days are given for the ship and satellite analyses in Table 2. The cloud coverage values are obtained by averaging the values at all grid points (as shown in Fig. 1).

Considering the entire sample (all convective conditions), the mean total coverage obtained from ship observations and satellite data is within 2%. The differences in the mean values obtained for low and middle clouds are less than 10%. There is a large difference for high clouds (19%) and it is believed that this results from underestimation of high cloud amount from ship observations.

The value of 78–80% for total coverage can be compared with other results. Gruber (1976) obtained an average cloudiness of 71% over the A/B array for all three phases of GATE. Holle *et al.* (1979) derived an average daytime cloudiness of 79% for the B array during Phase III from hourly whole-sky camera photography at four U.S. ships. The daytime mean estimates of total coverage from ship and satellite data in the present study were in the 78–82% range. Obviously, these comparisons are not exact but they do emphasize the high degree of cloudiness that characterized the GATE region and the caution that must be employed in generalizing results from the GATE to other tropic ocean regions. One final observation from the results in Table 2 is the similar mean cloud coverages for W and E days.

TABLE 2. Mean cloud coverage values (%) for GATE Phase III A/B array area based on ship observations and satellite data.

Convective condition classification	Cloud amount	Mean cloud ship observations (%)	Coverage satellite data (%)
All	total	78	80
	low	49	56
	middle	44	35
	high	25	44
Depressed (D)	total	71	73
	low	44	51
	middle	37	31
	high	22	38
Weak (W)	total	82	84
	low	50	58
	middle	48	38
	high	26	48
Enhanced (E)	total	80	84
	low	53	60
	middle	46	36
	high	28	46

4. Diurnal variations of cloudiness

There has been considerable interest and uncertainty about the diurnal variations of cloudiness over oceans, especially in the tropics. The diurnal variations of clouds during Phase III of GATE were studied by averaging cloud amount values at all grid points for each hour for all days and for E and D days only. This was done for the cloud analyses based on ship observations and also for the analyses based on the satellite data. A comparison of the results from the two sources showed many similarities as well as some distinct differences. One overriding factor was obvious lower estimates of cloudiness at night from ship observations. Cloud amounts are considerably lower before 0800 and after 1900 GMT, especially for total coverage and high cloud amount. It seems likely that this effect, to a degree, is due to the inability of observers to see high thin cloudiness at night.

The questionable estimates of high cloudiness at night from ship observations also affect the pattern of the hourly variation of total coverage as seen in Fig. 4 and suggest that primary reliance be placed on satellite data for studying hourly variations of total cloud amount.

The hourly variations as determined by satellite data given in Fig. 4 show significant differences for all days, D days and E days. When all days or only D days are considered, the maximum is near 0300 or 0400 GMT. Gruber (1976) found a broad nighttime maximum for undisturbed conditions centered near 0000 GMT. The minimum for all days of Phase III is at 1200 GMT while on D days a later minimum at 1700 GMT occurs. Gruber (1976) found minima at 1200 GMT for all days and 1500 GMT for undisturbed days. In marked contrast to the above, on E days the satellite data yield high values of total coverage from 1600–2300 GMT and the ship data indicate a maximum between 1600 and 2000 GMT. The two data sources suggest that on E days the time of maximum coverage may be ~2000 GMT. Gruber found a primary afternoon maximum on disturbed days at 1800 GMT.

The clearest evidence for the existence of a double set of maxima and minima exists for low-cloud amount especially as seen from ship observations in Fig. 5. When all days are considered about equally, significant maxima occur at 0400 and 1500 GMT separated by minima at 1100 and 2200 GMT. The early afternoon maximum in low-level cloudiness becomes a secondary maximum on D days when convective activity is suppressed and at nighttime more stratoform low-level clouds tend to dominate. On E days, when enhanced convective activity is present, the afternoon maximum is very strong and the nighttime maximum is not found. The early-to-mid-afternoon maximum in strong convective activity in the GATE region does not agree with the overall evidence presented by Gray and Jacobson (1977) for a maximum in deep oceanic tropical convection in the morning in most ocean regions. McGarry and Reed (1978), however, employing harmonic analysis on data from Phases II and III, note that a rainfall maximum for the A/B ship array as a whole is found in the early afternoon at 1530 GMT. They also obtained a noontime or early afternoon maximum from their analysis of convective clouds from SMS-1 IR photographs.

Both the satellite data and ship observations indicate a significant difference for middle cloud coverage between D and E days. On D days there is a predawn maximum at 0700 GMT and an afternoon minimum at about 1600 GMT. The pattern is considerably different for E days with an early evening maximum at 2100 and a predawn minimum near 0600 GMT suggested by the data. Certainly it must be kept in mind that considerable uncertainty exists in the derivation of middle cloud amount from both ship observations and satellite data.

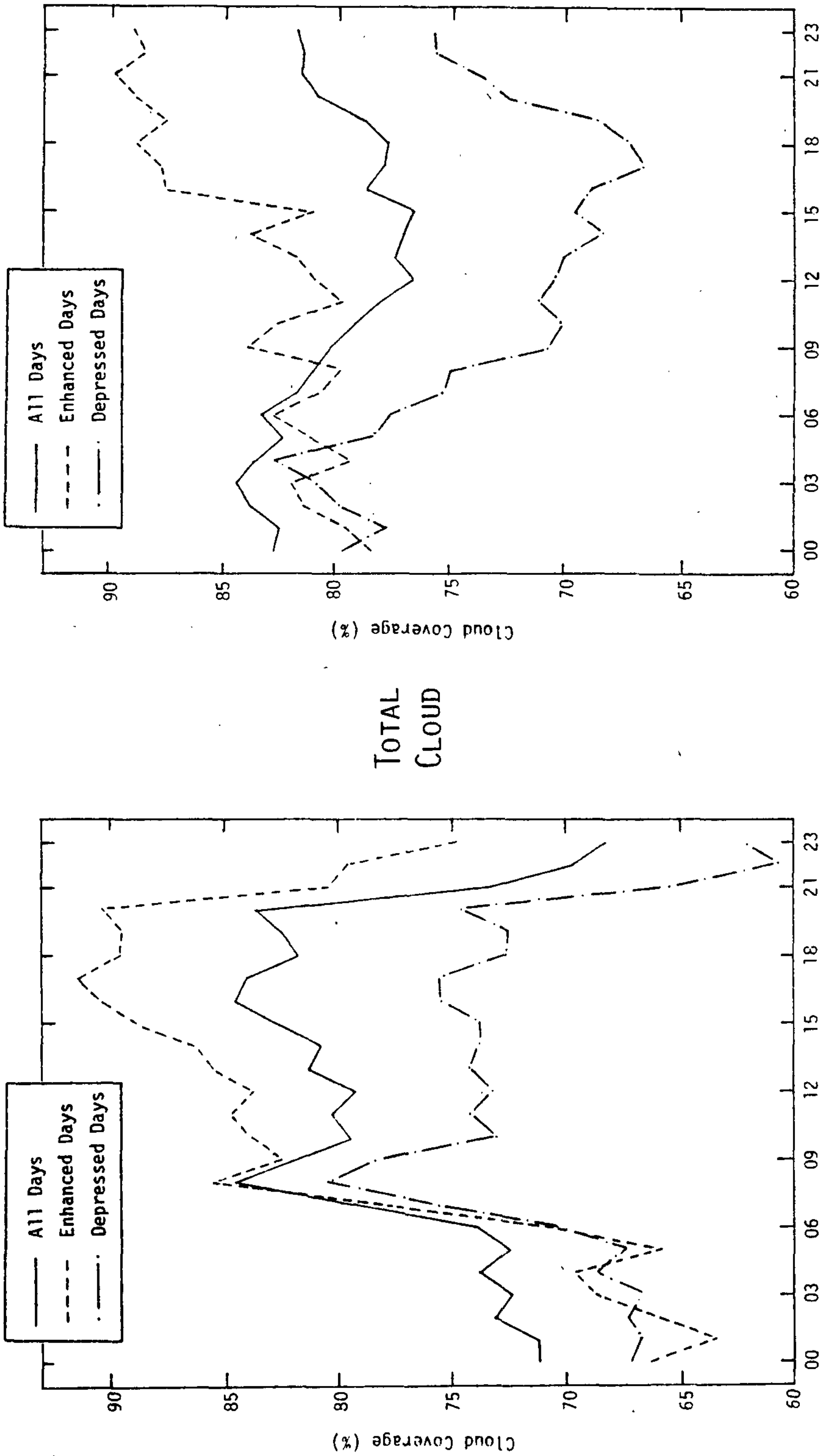

FIG. 4. Hourly variations of total-cloud amount based on ship observations (left) and satellite IR data (right).

Based on satellite data (Fig. 6), high-cloud coverage is a maximum at 1900 GMT and a minimum at 1100 GMT when all days are considered. Gruber (1976) found a clear maximum at 1800 GMT for upper cloudiness. The maximum is sharpened on E days and is contained in the 1800–2100 GMT period. Thus on days of significant convective activity, the maximum high cloudiness occurs ~4 h later than the low cloud maximum, indicating perhaps the later development of extensive cirrus and cirrostratus cloud layers following significant buildup of cumulonimbus clouds. It is also noted that under depressed convective conditions on D days, there is very little variation of high clouds beyond a gradual decline from the 0000 GMT value. This does not agree with the results of Gruber (1976) who had found a weak maximum in upper clouds at 1800 GMT under undisturbed conditions.

The observational evidence for the occurrence of maximum and minimum cloudiness based on ship observations and satellite IR data is summarized in Table 3. It is to be emphasized that the best estimates concerning variations in total and high cloud amount are based primarily on satellite data while variations in low cloud amount are derived mainly from ship observations. There are considerable uncertainties in estimating middle cloud variations from both data sources.

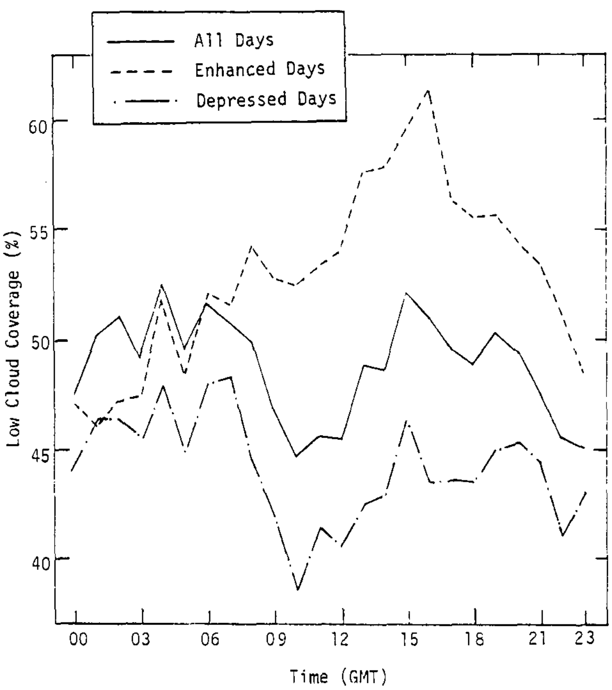

FIG. 5. Hourly variations of low-cloud amount based on ship observations.

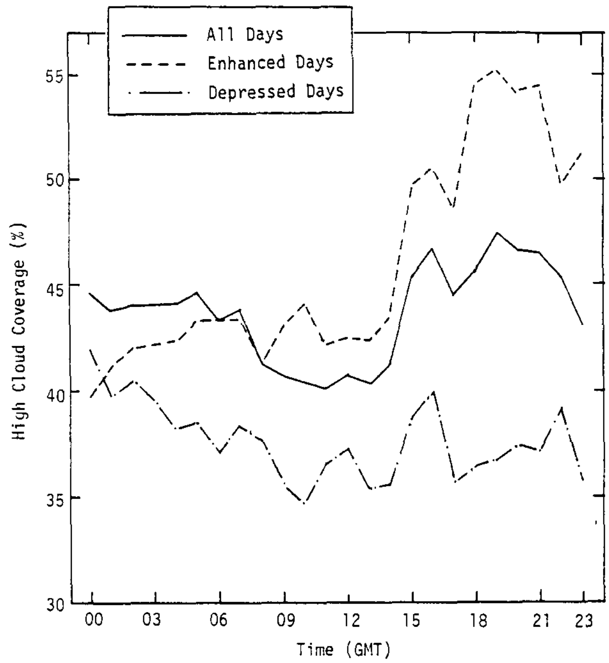

FIG. 6. Hourly variations of high-cloud amount based on satellite IR data.

5. Conclusions

It is possible to establish a coherent description of the spatial and temporal variations of cloudiness in GATE Phase III through a judicious and selective utilization of cloud information obtained from hourly ship observations and from SMS-1 IR hourly digitized data. The satellite data was emphasized for the analysis of total coverage and high cloud amount, while the ship observations were emphasized for data about low clouds. Both data sources provide only limited information on middle cloud amount.

Both satellite and ship data indicate that the average total coverage for the GATE A/B array area during Phase III is 78–80%. The close agreement does not imply, of course, that the methods of analyzing the ship observations and satellite IR data are equivalent. The predominantly cloudy conditions may contribute to the close agreement and a more comprehensive comparison of the two methods would require application to periods of reduced cloudiness.

The zone of maximum cloudiness is centered near 8°N latitude and exhibits a basic east-west orientation, with greatest amounts generally in the eastern part of the A/B scale region near 19°W. The composite analyses of both low and high clouds show a much more clearly defined pattern on convectively active days, when one would expect better organized and region-specific cloud systems.

TABLE 3. Summary of results on the hourly variation of cloudiness. Hours in parentheses indicate secondary maximum or secondary minimum.

Cloud amount	Convective cloud condition	Ship data Hour (GMT)		Satellite data Hour (GMT)		Best estimate Hour (GMT)		Comment
		Max	Min	Max	Min	Max	Min	
Total	All	1600–1700 (0800)	2200–0600 (1200)	2000–0400	1200–1500	0300	1200	Primary reliance placed on satellite data as total coverage may be underestimated by surface observer at night.
	D	0800–0900	2100–0600	0400	1700–1800	0400	1700	
	E	1600–2000	0000–0600	1600–2300	0000–1100	2000	0500	
Low	All	0400 1500	1000–1200 2200–2300	0200–0400	1200	0400 1500	1100 2200	Generally good agreement between ship and satellite results, but greatest reliance placed on ship observations.
	D	0400–0700 (1500)	1000 (2200)	0400	0900–1700	0400 (1500)	1000 (2200)	
	E	1600	2300–0300	1600–1800	0200	1600	0200	
Middle	All	0800 2000	2200–0600 1500	2100–0300	1400	2100	1400	Generally good agreement between ship and satellite results, but uncertainty in both sources.
	D	0700–1100	1500–1600	0000–0600	1400–1900	0700	1600	
	E	1800–2100	0000–0600	2100	1300	2100	0600	
High	All	1300–2000	2300–0600	1900–2100 (1600)	0900–1300	1900	1100	Estimates of high cloud amount from ship observations are of little value.
	D	1700	2100–0600	0000 (1600)	1000	0000 (1700)	1000	
	E	1600–2000	0000–0600	1800–2100	0000	1900	0000	

The hourly variations of total coverage and layered clouds yield clearly defined maxima and minima that differ for all days of Phase III, D days (depressed convection) and E days (enhanced convection). When all days or only D days are considered a nighttime total coverage maximum near 0300 or 0400 GMT is found. In marked contrast to this, on E days a late afternoon or early evening maximum near 2000 GMT occurs.

The most convincing evidence for a double set of maxima and minima exists for low clouds. For all days, clearly defined maxima occur at 0400 and 1500 GMT separated by minima at 1100 and 2200 GMT. The early afternoon convective-cloud maximum predominates on E days while only the nighttime presumably more stratoform cloud maximum is present on D days.

On days of significant convective activity, the high-cloud maximum occurs in the late afternoon (1900 GMT), ~4 h later than the low-cloud maximum, consistent with the later development of extensive cirrus layers following the buildup of cumulonimbus clouds. Little variation of high cloud amount is noted on D days other than a gradual decline in coverage throughout the day.

The results indicate that previous concepts emphasizing a nighttime maximum in both clouds and precipitation over tropical ocean regions must be evaluated in terms of regional applicablity and degree of convective activity. Further, it has been pointed out by several investigators that the results obtained from analyses of clouds, convective activity and precipitation may be strongly related to the location of the GATE region and any attempt to generalize these results for application to other ocean areas must take this factor into account.

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