The Diurnal Variation of Large-Scale Inferred Rainfall over the Tropical Pacific Ocean during August 1979

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ABSTRACT

Average diurnal variation of satellite-inferred rainfall for August 1979 was examined for five 15° longitudinal slices of the tropical Pacific Ocean. Over each area, averages were computed for each hour of the day over 30 days and examined in time series. The results illustrate the character of maritime convective rain over very large tropical areas and do not reflect the behavior of individual cumuli.

Time series over four of the five areas exhibited dual maxima, one near dawn and the other in midafternoon. The remaining area's time series showed the greatest amount of rainfall in the morning. Harmonic analysis showed that the first harmonic (24-hour period), which peaked in the early afternoon over four of the areas, accounted for most of the variance in the data over all areas. The second harmonic (12-hour period) significantly contributed to the variance, peaking near dawn and dusk over all areas, but, in most cases, was of secondary importance. Higher frequency harmonics were unimportant. With the exception of the first harmonic of one area, the phase angles for the first two harmonics were coherent, suggesting that the same physical process (or processes) was at work.

1. Introduction

The inability to measure oceanic rainfall by conventional means has invoked many questions about the behavior of marine precipitation. A very basic question concerns how ocean rainfall varies over the period of a day. This work addresses this problem as it relates to large-scale tropical ocean rainfall.

Previous observational investigations, carried out over various time and space scales, have painted a complex picture of the diurnal variation of oceanic rainfall. In an extensive survey, Gray and Jacobson (1977) concluded that deep tropical convection exhibits a single nighttime maximum. However, as an exception, they also cite an afternoon maximum over the eastern tropical Atlantic during the GATE period. Kraus (1963) offers support for the nocturnal maximum for middle-latitude storms of both the Atlantic and Pacific Oceans, but he is inconclusive on the diurnal variation of tropical convective rainfall. Others, such as Lavoie (1963), support the existence of a nocturnal maximum over the tropical oceans. However, Riehl (1954) warns:

> . . . reports of nocturnal rainfall maxima also must be received with caution . . . [W]e have seen that at least in some areas the low-level wind speed increases at night and that the trade-wind inversion lowers appreciably. Such a lowering implies a decreased vertical thickness of trade cumuli at night, a trend not easy to reconcile with an increase in precipitation.

A number of other observational studies have documented an afternoon maximum in tropical cloudiness and rainfall. Wexler (1983) found a daytime maximum for cold summertime cloud clusters within the tropical belts of both the Atlantic and Pacific Oceans. Similarly, Reed (1983) observed a daytime maximum in the occurrence of cold cloud, at a temperature threshold highly correlated with surface rainfall, for the tropical Pacific during January 1979; and Holle and MacKay (1975) show an afternoon peak in high and middle cloudiness for the western Atlantic ocean near Barbados.

McGarry and Reed (1978), Woodley *et al.* (1980), and others show agreement with Gray and Jacobson (1977) over the GATE B-scale area of the eastern Atlantic in reporting a predominance of an afternoon rainfall maximum. The satellite-derived rainfall data (Woodley *et al.*), stratified by 6-hour periods, show a rain maximum between 1200 and 1800 GMT (1000 to 1600 LST), when 35% of the total daily rain occurred. Using a relatively simple technique that relates fractional cloud cover to 6-h area rainfall, Richards and Arkin (1981) found a similar daily rainfall variation over the same area, as did Holle *et al.* (1979) for high and middle clouds. These results are in general agreement with budget, photogrammetric and raingage studies over the same area but in contrast with the gage-derived average diurnal variations in the western Pacific published by Gray and Jacobson (1977). However, McGarry and Reed

(1978) point out that the afternoon maximum in the GATE area may be attributable to the passage of easterly waves at a preferred time of day.

Finally, evidence of a semidiurnal variation has been reported. Using long-term records from Batavia and Wake Islands in the western Pacific, Brier and Simpson (1969) isolated a semidiurnal variation in tropical cloudiness and rainfall with maxima near sunrise and sunset, and minima near noon and midnight. They link the dual maxima to the dynamic influence of the semidiurnal pressure wave.

The varied results of the referenced observational studies indicate that the diurnal variation of precipitation over the oceans, especially in the tropics, is a complex matter which is not well understood. It is not the intent of this paper to hypothesize a unifying theory, but rather to report on diurnal variations of satellite-inferred rainfall over a large area of the tropical Pacific for the month of August 1979. The use of satellite data enabled this study to be carried out over a very large oceanic area using data free of island-influenced rain measurements (Malkus, 1955), and of continental influences (as in Houze *et al.*, 1981; Ramage, 1971).

2. The rain estimation technique

The Convective Infrared Satellite Technique (CIST) developed by Griffith and Woodley was used to generate the satellite-derived rain estimates for this work. Its physical basis and initial verification results are described in detail in Griffith *et al.* (1978). The methodology is based on the findings that areas of convective activity appear brighter (or colder) on satellite imagery, and that the relationship between brightness (or temperature) and rain amount is time dependent. The significance of time dependence lies in the observation that a growing convective cloud is a more efficient rain producer. The technique also compensates for the large cirrus anvil that occurs during the dying stages of convective processes. Its empirical relationships were derived by calibrating thermal infrared satellite images with gage-adjusted radar data over south Florida. Inferred rain volume is directly proportional to cloud area (defined by the 253 K threshold), inversely proportional to cloud top temperature, and a function of the growth stage of the cloud.

In 1977, automation of the technique allowed computation of estimates for large time and space scales. Moreover, the use of digital imagery also provided the means by which the inferred rain volumes could be transformed to isohyets. The scheme now in use to apportion estimated rain volumes at the surface for tropical applications, the 10–50/40–50 apportionment, is described in detail in Augustine *et al.*, (1981). It is physically based on results of Woodley *et al.* (1975) who show that the spatial distribution of rainfall in tropical convective storms is highly nonuniform.

After its derivation and automation, the technique was tested on convective rainfall events in several climatological settings ranging from the tropical Atlantic (Woodley *et al.*, 1980) to the High Plains of the United States (Griffith *et al.*, 1981). Outside of the Florida environment the most favorable results were achieved over the tropical Atlantic where storms are generally organized in large mesoscale clusters. There, estimated rain volumes and patterns compared well to surface measurements, except for a few cases where warm rain processes were at work (Augustine *et al.*, 1981). In support of this result, Leary and Houze (1979) have shown that the tropical mesoscale systems which they studied within the GATE area underwent a longer but similar life cycle as that of individual cumuli, after which the rain estimation technique was modeled. Specifically, they showed that the most intense rainfall occurs in the clusters' growth stage and the lightest rains fall as "anvil rain" in the longer dying stage. It was assumed that the convective processes within the equatorial troughs of both Atlantic and Pacific Oceans are similar and therefore the same empirical relationships which worked well in the tropical Atlantic were transportable to the tropical Pacific without modification or rederivation. In support of the use of satellite data for this work, Reed (1983) cites others who have successfully used infrared satellite data to examine the diurnal variation of tropical cloudiness and rainfall in many different areas, including both the Atlantic and Pacific Oceans.

3. Data

The SMS-2 infrared digital imagery, obtained from the archives of the University of Wisconsin's Space Science and Engineering Center, was used in making the rainfall estimates for August 1979. The SMS-2 platform is geostationary and is positioned over the equator at 135°W. At subpoint the spatial resolution of its infrared imagery is nominally 8 km; the temporal frequency of its imagery is half hourly. Thermal sensitivity of the infrared sensor is 0.5 K for surfaces warmer than 242 K and 1 K for temperatures colder than that threshold.

The area over which the rain estimates were made ranged from 168°E to 112°W and 20°N to 20°S. Because of the enormity of the area and the monthly time span, it was impossible to use all of the satellite data available at full resolution. Therefore, before the rain estimates were made, the resolution of the digital satellite imagery was reduced. The temporal resolution was cut by half, using every other image, and the spatial resolution was reduced from 8 km ($\frac{1}{15}$°) to 40 km ($\frac{1}{3}$°) by simple arithmetic averaging of the satellite pixels. Rain was estimated over the analysis area, using the degraded data set; however, no adjustments were applied to the technique, empirical relationships, the apportionment scheme, or after-the-fact to the estimates.

It is important to note that the degree of spatial averaging applied to the SMS digital data does not permit the isolation of individual cumulus towers. For example, a few full-resolution infrared pixels identifying a small but cold cloud top in the raw data, summed with adjacent warmer cloud-free pixels will produce an average temperature corresponding to a lesser (if not zero) rain rate than that which would have been associated with the original cumulus tower. However, for more widespread mesoscale cloud clusters, which Gray (1973) identified as accounting for most of the total tropical rainfall, the impact of the pixel averaging on the final rain estimates is reduced. For example, the cold structure of a cluster's top is conserved when summing several cold pixels over a large overshooting top region; thus the estimated rain rates for large mesoscale systems are not adversely affected by spatial averaging as severely as those of smaller clouds. The results presented in this work, therefore, are representative of the behavior of large maritime-tropical cloud clusters that reach, at minimum, the cloud definition threshold of 253 K, which, according to Jordan (1958), lies between the 400 and 350 mb levels.

4. Results

a. The inferred tropical rain pattern for August 1979

A composite of the satellite-derived rainfall for August 1979 is given in Fig. 1. The dominant feature is a split intertropical convergence zone (ITCZ) which is climatologically normal for the tropical Pacific in August (Hubert *et al.*, 1969). The northern branch of the ITCZ dominates with a core of maximum rainfall extending zonally across the entire area at approximately 10°N. It is most active to the west of 180° where maxima exceeding 750 mm are achieved. East of 180° the northern branch slopes northward slightly, narrows, and reaches a minimum between 160 and 165°W. Eastward from there, the rainfall increases until reaching another maximum exceeding 750 mm near the eastern border. In contrast the equatorial zone is relatively inactive. South of the equator the southern branch of the ITCZ, notably weaker than its counterpart to the north, shows an axis of maximum rainfall extending from the western border of the area to about 145°W. To the south and east of this branch, there is little rainfall activity.

b. Computation of the average diurnal rain profiles

Before the data were analyzed, the analysis area was subdivided, by time zone, into five 15°-wide regions so that the question of diurnal rainfall variation could be addressed. These areas were centered on the longitudes of 180, 165, 150, 135, and 120°W, and bounded meridionally by 20°N and 20°S. Each region encompassed an area of approximately 7.41 $\times 10^6$ km^2. Average rainfall volumes were computed over the entire area of each time zone for each hour of the day, over 30 of the 31 days of August 1979, and plotted in time series. Results for 14 August were excluded because of an 11 h gap in the digital satellite imagery on that day. Each series was plotted according to local standard time, beginning at 0000 LST. Because these curves were both normalized to local standard time and represent areas of equal size, the results could be compared directly.

c. The average diurnal rainfall variations for August 1979

Diurnal time series of average hourly rain volumes for each of the five areas are presented in Fig. 2. A subjective examination of each suggests that over all

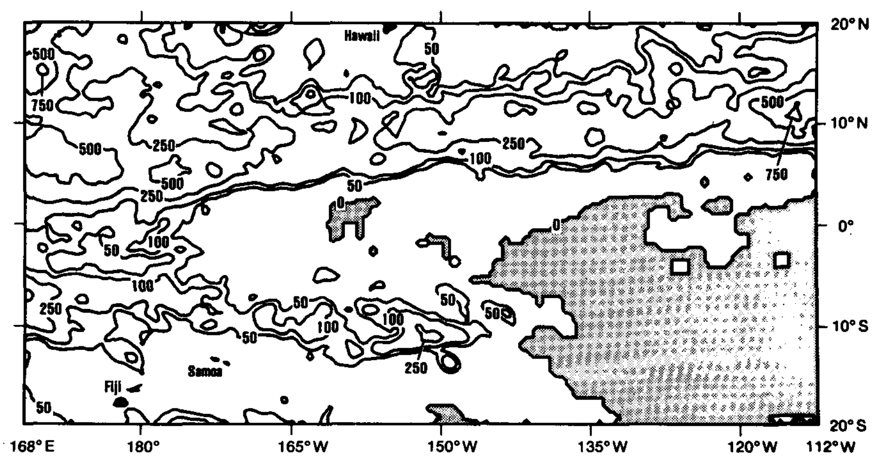

FIG. 1. Satellite-derived isohyets (mm) for August 1979 for the tropical Pacific Ocean.

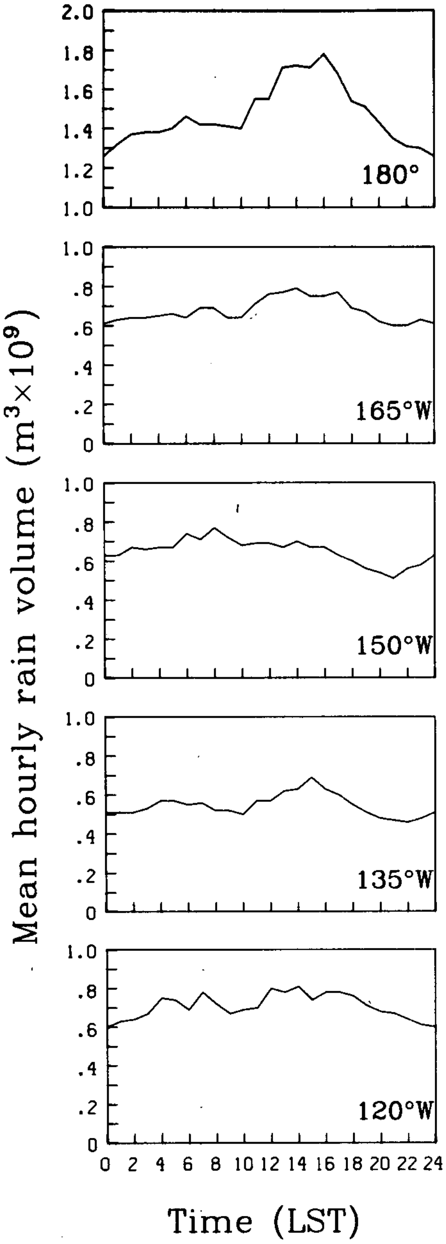

FIG. 2. Time series of hour averages of satellite-estimated rain volume computed over 30 days of August 1979 for the time zones indicated. The time zone areas are bounded meridionally by 20°N and 20°S.

areas except at 150°W, the variation of rainfall over the course of a day is characterized by a primary maximum in midafternoon and a secondary maximum near dawn, local time. Minima occur approximately two hours before local noon and between 2200 and midnight. The dual-maximum profile is most obvious at 180° where a large afternoon maximum dominates and a secondary peak is observed at 0600 LST. At 135 and 165°W the same major features emerge but the amplitudes are significantly reduced. (Note the different scaling of the ordinate for 180°.) More importantly, however, the relative differences between the afternoon and morning peaks for these three areas are similar, suggesting that the daily variations of rainfall within them are similar. Afternoon maxima are 22, 14 and 21% greater than the morning maxima for the areas at 180, 165 and 135°W, respectively. At 120°W the morning and afternoon maxima are split by single-point minima at 0600 and 1600 LST, respectively, and the amplitudes are again small. Finally, at 150°W only a diurnal variation is evident with a split maximum in the morning (similar to those at 120°W), a nearly level trend in the afternoon and a minimum at 2100 LST.

Although the dual-maximum daily pattern detected in the satellite rain estimates is better defined in some areas than in others, the systematic tendencies of the hourly averages, combined with the ability of the technique to distinguish light from heavy rain periods (Griffith *et al.*, 1981), lend much credence to its existence. However, with the exception of the pattern at 180°, the signals are not very strong. This is partially because, as shown in Table 1, the average hourly rain volume over the area at 180° is more than twice that over the other four areas. To remove this spatial variation in rain volume among the five areas, each time series was normalized by its maximum value. Each was then objectively analyzed for inherent periodicities using harmonic analysis.

TABLE 1. Average hourly rain volume ($m^3 \times 10^9$).

Area				
180°	165°W	150°W	135°W	120°W
1.47	0.68	0.65	0.55	0.71

d. Harmonic analysis

Harmonic analysis is the finite analog to Fourier analysis. The mathematical details of this technique are discussed in Panofsky and Brier (1968). It was applied to each of the series in Fig. 2 in order to determine which component frequencies (or harmonics) accounted for most of the variance in the data and possibly could be related to some physical source. Among the information supplied by the harmonic analysis were fractional variances, amplitudes, and phase angles of all 12 possible harmonics mathematically recoverable from the 24-hour time series. The fractional variance determines the relative importance among the recoverable frequencies, the amplitude is a measure of the strength of the signals and the phase angles describe the position of each harmonic's first maximum.

TABLE 2. Fractional variances from the harmonic analysis.

	Area				
Harmonic	180°	165°W	150°W	135°W	120°W
First	0.74	0.66	0.80	0.42	0.53
Second	0.22	0.22	0.06	0.47	0.25
First and second	0.96	0.88	0.86	0.89	0.78

The fractional variances, given in Table 2, show that the first harmonic (diurnal component) accounts for most of the variance in the individual time series, except at 135°W where the diurnal and semidiurnal cycles share nearly equal weight. The second harmonic (semidiurnal component) is of a secondary yet significant importance except at 150°W where it accounts for only 6% of the total variance. However, regardless of the relative importance of the first two harmonics, their summed fractional variance explains nearly all of the daily rainfall variability in each of the areas. The greatest is 96% at 180°, and the lowest is 78% at 120°W. The domination of the total variance by the first two harmonics supports the conclusion that no other important periodicities are contained in these series, and that the other ten higher mathematically achievable frequencies could be considered noise.

Table 3 shows that phase angles of the first two harmonics among all areas except that at 150°W are temporally consistent. At 180, 165, 135 and 120°W the diurnal signal shows its maximum consistently in the early afternoon between 1330 and 1530 LST, and the semidiurnal signal exhibits maxima just before dawn and before sunset. The coherency of these patterns is a strong indication that the same physical process (or processes) is responsible for the observed variation. At 150°W the first harmonic lags the positions of the others' first harmonic by as much as five and one-half hours, whereas the much weaker second harmonic is in phase with that of the others. It is noteworthy that the phase of the semidiurnal component is consistent among all five areas and is in near agreement with the results of Brier and Simpson (1969), who claim that the semidiurnal pressure wave could be responsible for increases in cloudiness and rainfall in the tropics near dawn and sunset. The physical source of the stronger diurnal component has not been addressed in the literature.

TABLE 3. Phase angles (h) for the first two harmonics.

	Area				
Harmonic	180°	165°W	150°W	135°W	120°W
First	15.2	14.4	9.7	13.8	13.8
Second	4.7	4.1	4.3	4.4	5.6

In Table 4, the relative magnitudes of the normalized amplitude coefficients between the first two harmonics, like the fractional variances, show the diurnal cycle as dominant. This similarity is not surprising because the variances are computed from these coefficients. Except for the area at 135°W where the amplitudes of the first two harmonics are nearly the same, the diurnal component's amplitude is greater than that of the semidiurnal component. At 180 and 165°W, the diurnal component is almost twice as strong as the semidiurnal component, and at 120°W this difference is in the same direction, only weaker. Finally, as expected, the amplitude of the first harmonic at 150°W is much greater than that of the second harmonic.

TABLE 4. Normalized amplitudes of the first two harmonics.

	Area				
Harmonic	180°	165°W	150°W	135°W	120°W
First	0.100	0.085	0.104	0.075	0.077
Second	0.055	0.048	0.029	0.079	0.053

It is beneficial to show the graphic addition of the first two harmonics of the normalized data, as it depicts the manner in which the diurnal and semidiurnal cycles interact in the absence of noise. These composites are shown in Fig. 3. With the exception of the area at 150°W, the sum of the first two harmonics exhibits a primary maximum in midafternoon and a secondary dawn maximum. The position and low amplitude of the morning maximum suggests that its source lies mainly in the semidiurnal component. The strength and position of the midafternoon peak in those areas indicate that it results from constructive interference of the diurnal and semidiurnal signals, with the diurnal component dominating. The graphic sum of the first two harmonics for the area at 150°W shows only one broad low amplitude maximum extending from early morning through midafternoon, reflecting the dominance of the first harmonic in that area.

5. Summary and conclusions

Satellite-derived rain estimates over an 80° longitude by 40° latitude area of the tropical Pacific were used to investigate the diurnal variation of large-scale tropical ocean rainfall for August 1979. It was impossible to verify the rain estimates with surface measurements over such a large area of open ocean. However, infrared satellite data have been successfully used as a rain index over the tropical oceans, on scales less than daily, by others such as Richards and Arkin (1981), Woodley *et al.*, 1980 and Reed (1983). In addition, these along with Houze *et al.*, 1981, have shown that GOES infrared data are useful in deter-

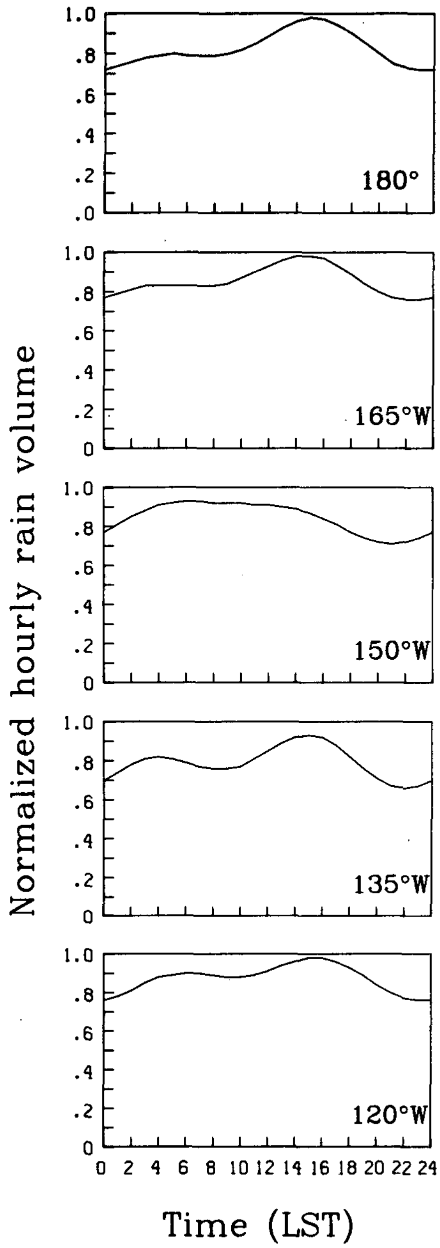

FIG. 3. Sum of the first two harmonics for the time series of Fig. 2 normalized by their maximum value.

mining diurnal variations of tropical rainfall. Therefore the variations demonstrated here are considered real and an important contribution to the documentation of the diurnal variation of rainfall in the tropics.

To standardize the results with respect to the daily path of the sun, the five time zones within this area at 180, 165, 150, 135 and 120°W were analyzed separately. Average daily time series were computed for each. Although these profiles represented only a one-month sample, the results were nonetheless intriguing. Four of the five time zones displayed a rainfall variation over the course of the day characterized by a small maximum near dawn and a larger maximum in midafternoon. This pattern was most evident in the area at 180° where the heaviest rain fell. The outlier signal at 150°W exhibited a morning maximum and only a level trend in the afternoon.

Harmonic analysis supported subjective observations. Results showed that most of the variance in the time series could be accounted for by frequencies at 24 and 12 h (the first two harmonics), except at 150°W where only the first harmonic contributed significantly to the total variance. Higher frequencies were unimportant and considered noise. Generally the diurnal component was strongest, peaking in early afternoon for all areas except that at 150°W, whereas the semidiurnal component was weaker but more consistent with peaks near dawn and sunset in all areas. The sum of the first two harmonics over each of the areas, except at 150°W, exhibited two maxima—a primary maximum in midafternoon and a secondary maximum near dawn. The realizations that the outlier signal at 150°W showed only a diurnal variation, and that there were differences in the relative strengths of the two maxima in the other four areas may be reflective of the small sample size from which the averages were computed.

Points of interest to evolve from the data and analyses presented are the dominance of the afternoon rainfall maximum, and the coherency of the component periodicities extracted from the average daily time series. The occurrence of an afternoon maximum is in contrast to the results and conclusions of Gray and Jacobson (1977), whose work was partially carried out over a region that included part of the 180° time zone area analyzed in the present study, but on a much smaller spatial scale. However, an afternoon rain maximum has been documented in several other observational studies conducted in the tropical belts of both the Pacific and Atlantic Oceans (i.e., Reed, 1983; Woodley *et al.*, 1980; Wexler, 1983; Holle and MacKay, 1975). The results of the harmonic analysis suggest that this strong afternoon maximum results from constructive interference of the large diurnal and weak semidiurnal periodicities. The source of the diurnal component has not been addressed in the literature and is left to speculation. However, the source of the weaker semidiurnal signal, which seems to be responsible for the small morning maximum, may be the semidiurnal pressure wave which, as suggested by Brier and Simpson (1969), may be triggering a very sensitive tropical atmosphere near dawn and sunset. Furthermore, phase angles computed for the semidiurnal component of the time series are in agreement with results of Brier and Simpson.

Intriguing results such as the coherency of the daily variations presented and their resemblance to findings of others warrant an expanded study of the behavior of large-scale oceanic precipitation. The phenomenon of the diurnal variation of pure oceanic rainfall should be documented over all tropical oceans for several years to find if there is a common variability. Also, if found to be persistent, the physical basis of the strong diurnal signal needs to be addressed. A composite of several years of satellite estimated rainfall or even a long term satellite-based cloud climatology using a carefully chosen temperature threshold could supply the answer.

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