Diurnal Oscillation of the Area of Cloudiness Associated with Tropical Storms

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ABSTRACT

An analysis of 16 days from eight Atlantic storms, two in 1974 and six in 1975, objectively quantified a suspected diurnal oscillation of tropical storm cirrus cloud cover. The oscillation shows a maximum area at approximately 1700 local mean solar time and a minimum area at 0300 local mean solar time. The average ratio of the maximum area to the minimum area is 1.65.

SMS infrared imagery was analyzed with a scanning false-color densitometer to obtain area measurements of the cloudiness associated with the storms. These measurements were made approximately every $1\frac{1}{2}$ h at three temperature thresholds: 253, 239 and 223 K.

Two tests were performed to rule out the possibility of the oscillation being due either to the satellite sensor or to image processing. Measurement of the ocean surface temperature was made with SMS-I to determine whether the sensor detected a constant ocean temperature. The second test compared simultaneous area measurements obtained by SMS-I and SMS-II. The results of these tests support the storm oscillation detected.

Two other related phenomena were also observed: 1) the amplitude of the area oscillation is apparently inversely proportional to the intensity of the storm, and 2) a time-dependent, shorter period oscillation is superimposed on the daily oscillation. Inferences of causality are made.

1. Introduction

Within the last year there has been widespread speculation and research on diurnal oscillations of cloudiness. The type of cloud systems being analyzed, the spectral regions of the data, the techniques and, consequently, the results have varied in detail. Holle and MacKay (1975) and Jacobson and Gray (1976) have studied the diurnal oscillation of oceanic cloudiness and convection with ground-based sensors. Gruber (1976), McGarry and Payne (1976) and Smith and Vonder Haar (1976) have used geosynchronous, infrared data to detect diurnal oscillations in the areal extent of oceanic cloudiness. All of these studies are Eulerian in that an entire field of clouds is described without any attempt to identify individual cloud masses and follow them in time.

We and others have noted an apparent diurnal oscillation in the areal coverage of the cloud canopies associated with tropical cyclones, although no one, to our knowledge, has actually described it. Because of the potential importance of such a study, we have objectively detected and quantified an oscillation in cloudiness associated with Atlantic tropical storms. Our approach is Lagrangian in that clouds within the envelope of each storm are followed in time and oscillations in coverage are noted. Tentative physical hypotheses for the oscillation are suggested.

[1] Part of this work was done when this author was a member of the Dade County (Florida) Community Laboratory Research Program.

2. Materials

The International Imaging System scanning microdensitometer, a false-color image enhancer, was used to make area measurements of the storm canopy at three temperature thresholds. The components of the densitometer include a light table, a photosensitive camera, a video processor, a monitor, electronics to measure density and an electronic planimeter. The light table emits light through the satellite transparency which is composed of various shades of gray. The camera senses these gradations, which are then channeled through the system video processor to the monitor where a false-color enhanced image of the transparency is displayed. The system can be used to make quantitative measurements of these shades of gray in terms of optical density units. For thermal infrared images, these density units can be converted to temperatures through an infrared sensor calibration. The last component, the electronic planimeter, measures the area of the color-coded information. Planimeter units can be converted to an absolute unit of measure, such as square kilometers, by using a known reference. [The reader is referred to Griffith *et al.* (1976) for details of the system.]

The imagery used in the analysis was from SMS-I, the geosynchronous satellite stationed at 45°W and the equator during the 1974 Atlantic hurricane season and at 75°W and the equator thereafter. The thermal infrared images are original, full-disc, 25-cm² negatives. The infrared sensor has a spatial resolution of 8 km at the satellite subpoint. Each image also contains a computer-generated step wedge (a stepwise progression of the shades of gray) on the top of the transparency. This step wedge covers the entire range of gray shades or temperatures on the image from 164 K (the first step) to 330 K (the last step). On board the SMS-I, a sensor calibration check is performed with a shutter whose temperature is monitored. The image was normalized, through the wedge steps, to remove changes caused by signal fluctuations or photographic processing, and then calibrated to determine temperature thresholds at which the area of the canopy was measured.

3. Procedures

To obtain reliable and informative data, it was necessary to establish three criteria to select a storm for study. First, there had to be a continuous sequence of satellite imagery. Second, the cloud system of interest had to be easily distinguishable from other systems nearby. This rule was imposed so that storms that merge with other cloud systems, thereby producing an artificial increase in cloud coverage, were not studied. Third, the storm had to be over water, because diurnal heating of the land enhances convection, which often produces spurious growth of the canopy of the storm. This rule was relaxed somewhat to study Caroline on 30 August 1975 and Carmen on 31 August and 1 September 1974. Both storms were near but not over land on these days.

The densitometer, in conjunction with the thermal infrared satellite imagery, was utilized to measure the area of storm cloudiness at three arbitrary temperature thresholds. To do this the first and last steps of the image step wedge were measured with the densitometer; the density units obtained were then corrected for densitometer fluctuations (see Griffith *et al.*, 1976). At the same time, the temperature thresholds, 253, 239 and 223 K, were converted to percent of gray scale by means of the relationship between temperature and percent of gray scale that was developed by NESS (Fig. 1). This relationship was checked in Florida by comparison of satellite-derived estimates of cumulonimbus top temperatures with those inferred from simultaneous radar measurements. The heights of echoes corresponding to clouds on the satellite images were converted into temperature by means of the atmospheric sounding nearest in space and time (Woodley and Griffith, 1975). Considering the uncertainties involved, the satellite and radar-derived estimates of cloud-top temperature agreed fairly well, particularly for temperatures less than 240 K.

In the calculation of density (d') on the image that corresponds to the desired temperature thresh-

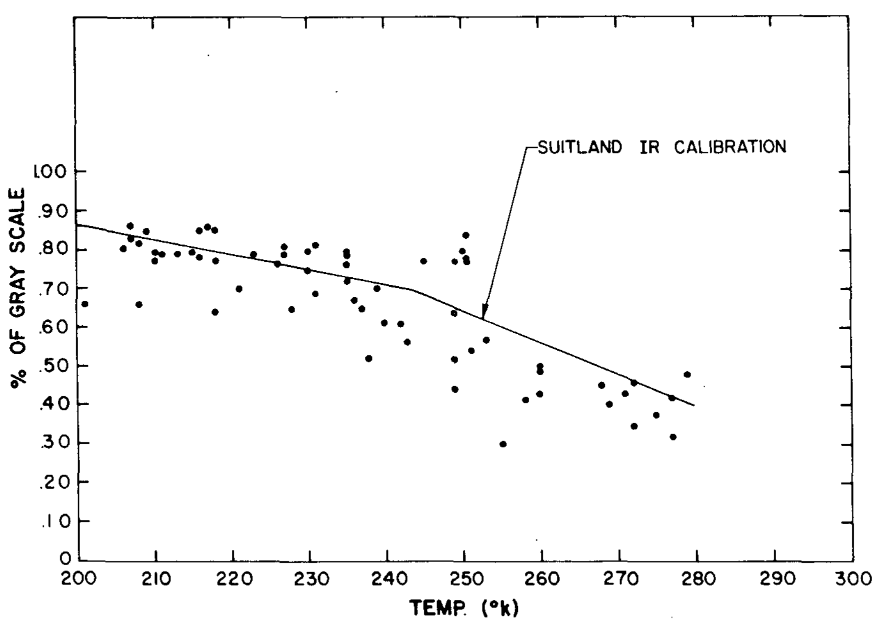

FIG. 1. The relationship between percent of gray scale and temperature. The solid line is the SMS-I relationship provided by the National Environmental Satellite Service, Suitland, Md. The plotted points were determined by NHEML personnel. SMS infrared observations of convective clouds (expressed as percent of gray scale) were related to simultaneous radar-derived top temperatures obtained by the conversion of echo height to temperature with the nearby atmospheric sounding.

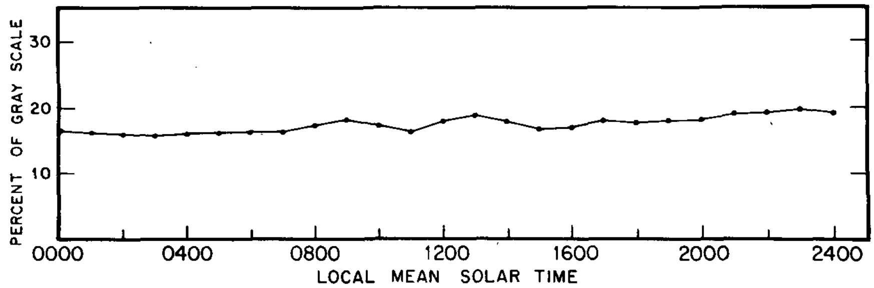

FIG. 2. A composite of six days of ocean surface temperature. One percent of gray scale is equal to approximately 1 K. The small variation in the temperature is within the accuracy of the systems and data used. See text for the definition of local mean solar time.

old (T), the following relationship was used:

$$\frac{d'_{\max}-d'_{\min}}{1.00}=\frac{d'-d'_{\min}}{T}, \tag{1}$$

where $d'_{\max}$ is the corrected density measurement of the last step on the image wedge, $d'_{\min}$ the corrected density measurement of the first step on the image wedge, d' the corrected density corresponding to a particular threshold T, and T the temperature threshold expressed in percent of gray scale. The equation, a linear apportionment scheme that was suggested by the National Environmental Satellite Service (P. Corbell, personal communication), was used to determine the optical density units of the film which corresponded to each of the three thresholds. The areas contained within each temperature threshold were then measured with the planimeter to determine the area of the storm cloudiness.

The areas of the storm canopy at temperatures equal to or less than each of the three thresholds were determined at intervals of $1\frac{1}{2}$ h and graphed as a function of local mean solar time (LMST). Local mean solar time is defined in the *Smithsonian Meteorological Tables* (List, 1958) as local standard time less 4 min for each degree of longitude that the location of interest is west of the standard meridian. The data were normalized to local mean solar time so that any possible influence of solar heating on convection and growth of the storm was comparable for the various longitudinal locations of the different storms. On each day all areas were also normalized to the maximum area within the 253 K threshold to facilitate the comparisons.

4. Tests of relative accuracy of area measurements

A comparison of SMS-I and SMS-II area measurements for a particular storm was made. Agreement provides little information about absolute accuracy because both satellites and IR sensors are of the same design, but agreement would indicate that any oscillation detected was not peculiar to the sensors aboard SMS-I. For this test, both satellites viewed eastern Pacific Hurricane Denise (which was at approximately 15°N, 109°W). The SMS-I observation was from 75°W and the equator and the SMS-II was from 115°W and the equator. Despite the rather large difference in storm viewing angle for the two satellites, the area measurements at a particular temperature agreed reasonably well. The mean ratio of SMS-I to SMS-II area measurements was 0.91 for 33 measurement pairs. Although not conclusive, this test supports the work reported here.

The second test examined the possibility that the oscillation detected was spurious and due only to an oscillation inherent in the sensor. To rule out this possibility, a point on the ocean surface with the lowest density value (presumably a cloudless point) was found within the area 20–30°N and 50–60°W on each SMS-I infrared image for six test days. The density measurements were converted to percent of gray scale, which is proportional to temperature, and graphed as a function of local mean solar time. The correction factor for atmospheric moisture was not applied to these measurements. This causes no problem in this instance because the moisture and, consequently, the correction should be relatively constant over the subtropical oceans. Because the actual temperature of the ocean is relatively constant within this area, no diurnal temperature oscillation was expected and none was found.

The results of this test are presented in Fig. 2. Each percent of gray scale corresponds to ~1 K. Therefore, the measured variation of the temperature of the ocean surface is about 4 K and shows no diurnal dependence, although there is a slight upward trend over the course of the day. These variations are definitely within the temperature resolution of the hard-copy data and within the accuracy of the equipment used to obtain the measurements. This test suggests that any oscillation in the temperature or in the temperature threshold of any other surface viewed by SMS-I is real and not due to the sensor itself.

5. Results

Six pictures of the display on the densitometer monitor of tropical storm Eloise on 16 September

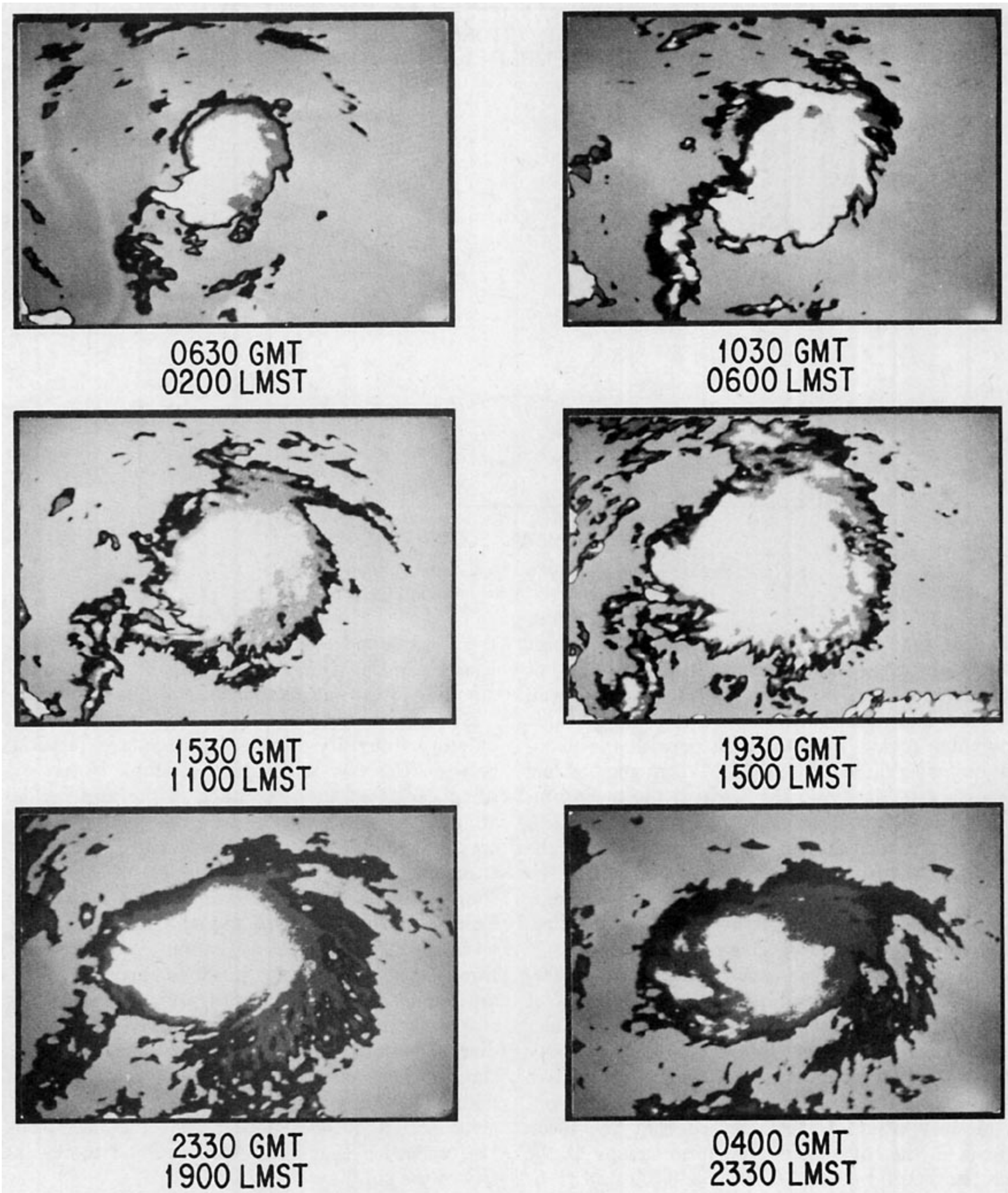

FIG. 3. A series of six pictures of the densitometer display of Tropical Storm Eloise, 16–17 September 1975. The black, gray and white contours correspond to the ~253, ~259, ~223 K isotherms, respectively. See Fig. 4 for a plot of these areas. See text for the definition of local mean solar time.

1975 are shown in Fig. 3. Each boundary of each gray shade represents a temperature threshold. Time histories of the areas contained within each temperature threshold are presented in Fig. 4. All the areas are normalized to the maximum area within the 253 K threshold, which occurs at 1630 LMST. An apparent oscillation is evident in this figure.

Examination of eight storms of 16 days (Fig. 5) reveals the same diurnal oscillation in the area covered by the storm canopy as was evident for Eloise. For this presentation, each area measurement at a particular temperature threshold was normalized to the maximum area attained by this threshold within the day. Compositing was done with respect to local

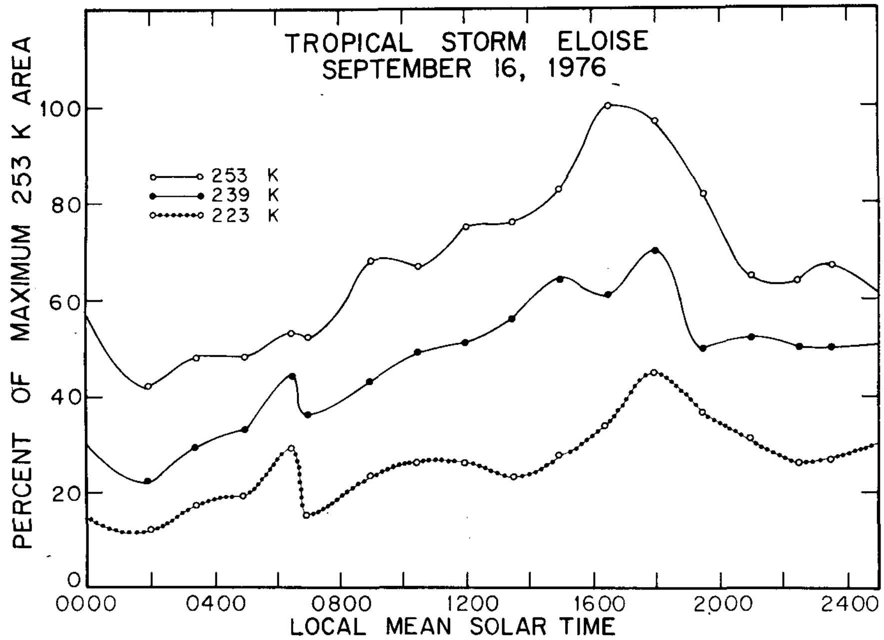

FIG. 4. A representative oscillation. Data are for Eloise, 16 September 1975, as shown in Fig. 3.

mean solar time as shown here and also with respect to the peak 253 K area independent of time (not shown). When compositing with respect to local mean solar time, the mean excursion from maximum area to minimum area is a factor of 1.65, with the maximum occurring at 1700 LMST. When compositing with respect to the peak 253 K area, the mean amplitude independent of time within the day is 2.39. The differences are caused by the variability of the time of minimum and maximum areas. Although the time of maximum area is 1700 LMST on the average, it may range from 1200 to 1800. Similarly, the time of the minimum areal coverage of the canopy is 0330 LMST in the mean with a range from 0000 to 0700. The variability as indicated by the plots of the 95% confidence intervals increases for the colder thresholds and makes it difficult to quantify any phase difference in times of occurrence of relative maxima among the three thresholds.

A Mann-Whitney U test showed that the mean difference in the coverage of the storm canopy at the 253 K isotherm between 0300 and 1700 LMST is significant at the 2% level. This supports our finding that the oscillation is a real time-dependent phenomenon.

A shorter period oscillation of approximately 4 h is apparent in the 16-day composite at the 223 K level, suggested in the 239 K level, and almost completely masked in the 253 K data. The average amplitude of the six cycles found on the 223 K level composite is a factor of 1.18. This oscillation has not been thoroughly studied in this analysis. It was observed as a by-product of the main analysis, but may be related to the short-period oscillation observed by Black (1976). Closer scrutiny is necessary to gain a better understanding of the nature and cause of this oscillation.

Stratification of the canopy oscillation as a function of storm intensity (Table 1) suggests a relationship between the two. Although the sample is very small, it appears that the magnitude of the area oscillation at the 253 K threshold decreases as the storm increases in intensity. The linear correlation between storm intensity as measured by maximum wind (hurricane, tropical storm, tropical depression, or predepression classification) and the magnitude of the measured 253 K area oscillation is 0.80 when the three days in which the storm is partially over land are omitted. The justification for omitting these storms is that land effects may have enhanced the diurnal oscillation. The correlation including these three days is only 0.46. Although a larger data set with a well-distributed population is necessary for confirmation, it does appear that the magnitude of the oscillation is inversely proportional to the intensity of the storm.

The variability of the oscillation within a particular storm is also of interest. By examining the measurements of the cloud canopies for storms in which there were data for two or more consecutive days, we obtained a measure of the constancy of the area oscillation. Results are presented in Table 2. Although it is apparent that the oscillation for a particular storm is variable from one day to the next, the times of minimum and maximum and the magnitude of the oscillation generally do not vary by more than 3 h and by more than 20%, respectively.

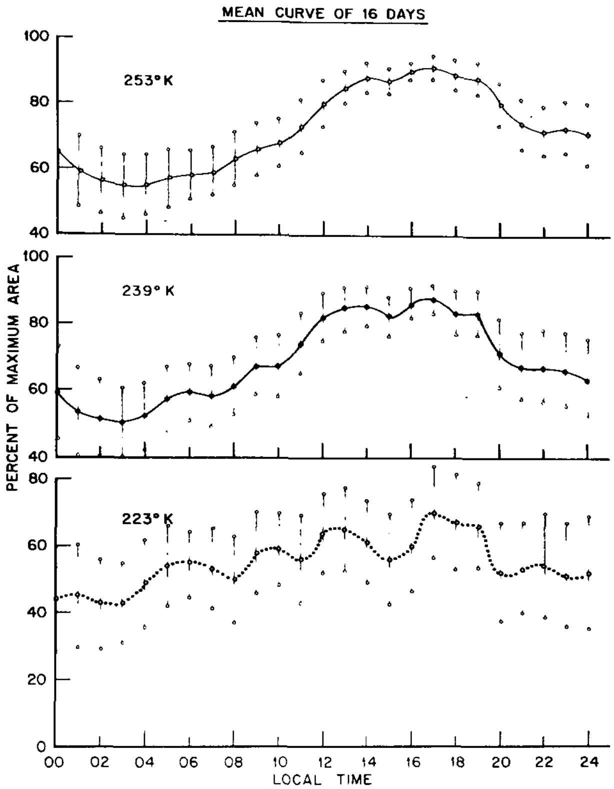

FIG. 5. A composite diurnal oscillation of eight storms on 16 days (see Table 1 for a list of the data used). Storm areas at each isotherm were normalized to the corresponding threshold maximum area for the day, composited according to local mean solar time (see text for definition) and then averaged. Ninety-five percent confidence intervals are shown. Due to the variability of the occurrence of the maximum areas from storm to storm, these curves do not pass through 100%.

6. Discussion

Once a diurnal oscillation and its general nature had been determined, we attempted to ascertain which clouds were oscillating in areal coverage. A simple test was carried out to gain an impression of the type and level of cloud that each temperature threshold represented. The test was a comparison of the false-color enhanced infrared image (displayed on the densitometer) with the concurrent visible image as shown in Fig. 6. The unenhanced infrared image was also used in the comparison.

It becomes apparent when one examines the image that the cloud cover within the 253 K contour is, for the most part, relatively thin cirrus with an emissivity that is probably less than unity. As a consequence, the actual temperature of the cirrus may be less than indicated because of modulation by the warm water which is sensed beneath the cirrus. We should also recognize an alternate possibility that the cirrus at the periphery of the storm is actually warmer than that near the core because of descent to a lower altitude in the subsiding outflow. Regardless of which interpretation is correct, it is the area of the cirrus canopy that has a diurnal oscillation as quantified here.

It is interesting to speculate on the cause of the diurnal oscillation of the cirrus canopy area of tropical storms. Dvorak (personal communication) used digital SMS-II infrared imagery to document that the coldest sensed temperatures in eastern Pacific tropical storms occurred at 0300 local time and the warmest at 1500 local time—or exactly out of phase with our area oscillation. Dvorak's findings and ours are not at all contradictory if one considers the work of Merritt and Wexler (1967). They determined that "cirrus generated at the eye wall and advected outward could produce, in 12 to 18 h, a canopy similar to those observed by meteorological satellites. If, in addition, generation occurs in the spiral arms, these times are shortened somewhat." Combining these studies with ours, we postulate that the tropical storm reaches a convective peak during the early morning hours with the debris from this convection

TABLE 1. Storm intensity versus magnitude of the diurnal area oscillation.

Stage of development	Name	Date	Magnitude	Average magnitude
1. Hurricane	Caroline	8/30/75	3.14*	2.09
	Eloise	9/17/75	1.65	
	Gladys	9/27/75	1.68	
	Gladys	9/29/75	1.19	
	Gladys	9/30/75	1.63	
	Gladys	10/ 1/75	1.53	
	Carmen	8/31/74	3.98*	
	Carmen	9/ 1/74	2.38*	
	Fifi	9/19/74	1.66	
2. Tropical storm	Amy	7/ 1/75	2.32	2.34
	Eloise	9/16/75	2.39	
	Faye	9/20/75	2.32	
3. Tropical depression	Blanche	7/24/75	3.99	3.03
	Blanche	7/25/75	1.54	
	Caroline	8/28/75	3.55	
4. Predepression	Blanche	7/23/75	3.31	3.31

* Storm partially over land. The overall correlation coefficient omitting these values was 0.80.

TABLE 2. Intra-storm variability of canopy oscillation (as measured by outer 253 K contour).

Storm	Day	Times for oscillation (LMST) Min	Max	Percentage change in area of canopy
Carmen	8/31/74	0530	1830	75
	9/ 1/74	0330	1900	59
Blanche	7/23/75	0430	1400	70
	7/24/75	0100	1430	75
	7/25/75	2330 (7/24/75)	1300	67
Eloise	9/16/75	0200	1630	78
	9/17/75	0400	1300	39
Gladys	9/29/75	0630	1200	16
	9/30/75	0300	1800	39
	10/ 1/75	0530	1700	35

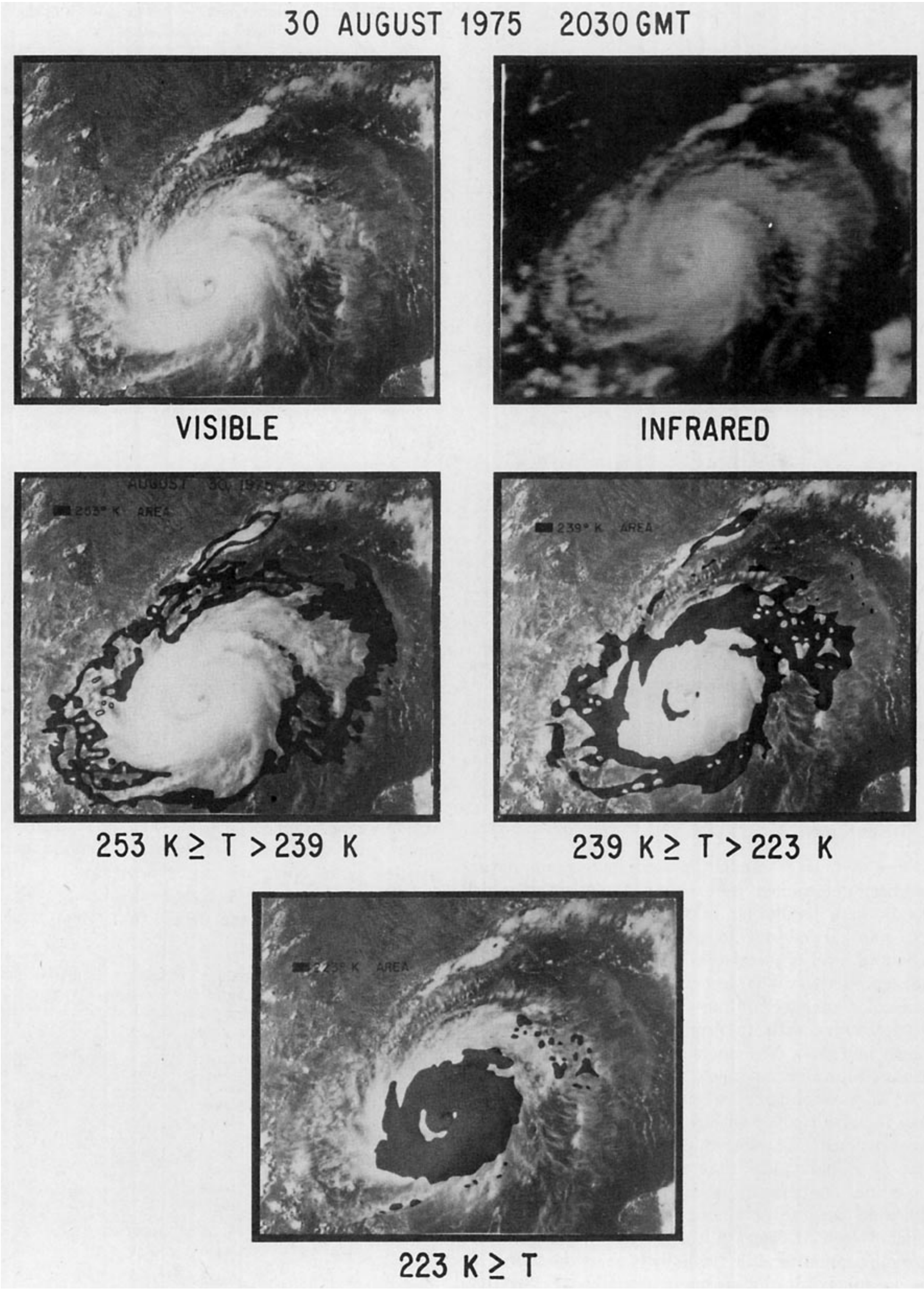

FIG. 6. A comparison of the concurrent visible and infrared views of Hurricane Caroline, 2030 GMT 30 August 1975. The top row shows the 1 km visible image (left) and the 4 km, unenhanced infrared image (right). The remaining three views are the three temperature contours of this study (determined from the infrared image with a scanning, false-color microdensitometer) overlaid on the visible image.

advected outward over a 12 h period as an expanding cirrus canopy.

Based on our work in Florida relating the infrared histories of convective cloud systems to rainfall reaching the ground (Grube *et al.*, 1977), the oscillation in the canopy area of a tropical storm implies an oscillation in storm rainfall. The relationship is not one-to-one, however. An oscillation of a factor of 2 in the canopy area implies a factor of 1.30 oscillation in the rain output from the storm. Gautier *et al.* (1976) have found a similar relationship over the tropical Atlantic Ocean.

Typically, the peak rain output from a cloud system viewed in the infrared is occurring when it has achieved 80% of its maximum size on the satellite image (Grube *et al.*, 1977). If this is valid for the tropical storm, the mean plots of Fig. 5 suggest that the peak rain production occurs approximately 3 h before the time that the storm reaches its maximum canopy area.

Little research is available on diurnal oscillations in rainfall from tropical storms over open ocean. After compositing rainfall observations from island stations in the western North Pacific, Frank (1976) detected a small diurnal variation in the rainfall from typhoons with a maximum in the late morning (1000–1200 local time) and a minimum in the late afternoon (1800). (Presumably the islands themselves did not alter the diurnal cycle of the rainfall.) Although this finding is consistent with our findings and speculations, it cannot be considered supportive until a diurnal oscillation in the canopy area of typhoons has been documented.

One might wonder whether the diurnal oscillation in the canopy area of tropical storms and hurricanes manifests itself as a diurnal oscillation in some other storm variable. In examining the intense hurricane, Sheets (1969, 1971) found that the afternoon soundings are typically warmer than the night soundings throughout the troposphere, but he could find no systematic diurnal oscillations in storm intensity as measured by minimum sea level pressure or maximum wind speed.

The apparent negative correlation between storm intensity and the amplitude of the canopy oscillation is also intriguing. It is possible that, as the storm becomes better organized, the area of subsidence becomes better defined and therefore circumscribes a tighter area within which the storm canopy may oscillate. Even if this is true, it does not necessarily mean that the convective oscillation diminishes as the storm intensifies; rather, it may mean that the external manifestation of the oscillation is not as obvious in the stronger storms.

7. Conclusions

The findings of this study are as follows:

1) The area of the canopy of tropical storms defined by three temperature thresholds exhibits a diurnal oscillation with an amplitude between 1.65 and 2.39, depending upon the reference for compositing; the average time of minimum area is 0300 LMST and of maximum area is 1700 LMST.

2) There is a smaller period oscillation superimposed on the diurnal oscillation that is apparent in the colder temperature thresholds.

3) The magnitude of the diurnal oscillation decreases as the storm intensifies.

4) The cirrus canopy is the oscillating component of the storm, although other cloud types may also be oscillating.

In the realm of speculation, these findings in conjunction with other research suggest the following:

1) The diurnal oscillation in the area of the storm canopy is probably a manifestation of a convective oscillation, but the timing has yet to be defined.

2) A better defined subsidence area may explain the apparent decrease in the magnitude of the canopy oscillation as the storm intensifies.

3) The canopy oscillation also implies an oscillation in storm rainfall.

The oscillation appears to be real; the other findings and explanations are considerably more tentative.

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