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"A Quantitative Method for Estimating Cloud Cover over Tropical Cyclones from Satellite Data"

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A quantitative method for estimating cloud cover over tropical cyclones from satellite data

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ABSTRACT

A photometric method for quantifying cloud cover over tropical cyclones as observed from satellite photographs is presented.

Two gridded photographs of tropical cyclones are analyzed by this method. On each photograph, nine concentric circles are drawn. The observed or reported centre of the cyclones is used as the centre for each set of concentric circles. Photometric estimates of cloud cover are made along the nine concentric circles. The principle of harmonic analysis is applied to the cloud cover estimates along the circumference of the circles. The distribution of cloud cover estimates N (measured in tenths) and the orientation and development of the cloud patterns are quantitatively described by certain parameters and also by the phase angles of the harmonic components considered. These quantities are computed as functions of radial distances. The parameters allow for the process of symmetricalization of tropical cyclones to be studied as the cyclones develop and also provide an objective means of studying the changes in the areal extent of the cloud cover of the cyclones. The first two harmonic components are found to account for most of the cloud cover estimates along the circles. The curves joining the phase positions along the nine circles, for the first two components for each cloud pattern analyzed, provide a means for studying the changes in the orientation of the cloud structures.

By using conventional data to investigate the vertical structure of a tropical cyclone and by comparing the results with those from cloud analysis of the same cyclone, it is demonstrated that the cloud patterns of tropical cyclones often reflect the thermodynamic processes going on beneath the cloud patterns.

1. Introduction

Photographs of cloud systems of weather phenomena taken from meteorological satellite platforms give more detailed cloud patterns of the phenomena than observation of the cloud patterns from the ground. The problem has always been how to quantify the information given by the photographs for use in the study of the weather systems. Earlier researchers have either employed the methods of neph analysis or the procedure of averaging and compositing digital representation of brightness of clouds (reflected visible radiation from cloud tops) to estimate the amount and extent of cloud systems associated with large and planetary scale weather systems. The methods are especially useful when cloud climatology over specific areas is desired. The method of neph-analysis requires manual (or visual) interpretation of satellite cloud pictures to produce a neph-analysis and then interpretation of the neph-analysis to estimate cloud amounts over the area of interest. With this procedure (Clapp, 1964, 1968) has made estimates of Northern Hemisphere cloud cover from neph-analysis from TIROS (Television and Infra-red Observation Satellites) photographs for selected seasons. Sadler (1968) also used variations of satellite-derived total cloud amount in specified longitude–latitude squares as indicators of processes in the large scale general circulation over ocean areas. As regards the second method Kornfield et al. (1967) Booth & Taylor (1969), Herbert et al. (1969) and others have made contributions. These methods are, however, not very suitable for studying weather systems like tropical cyclones. Because there is a need to quantify the cloud changes of such systems a method is presented here that not only quantifies the variations in the cloud structure as observed from satellite photographs but also gives some insight into the distribution of clouds in such systems.

Many problems must be overcome to be able to obtain quantitative information from satellite photographs. Although the recognition of cloud features from satellite photographs and the gridding of the photographs can present enormous problems, the problem of quantitatively determining the cloud cover from the photographs is of a higher order of magnitude. Two major problems arise when visual estimation of clouds is made in a designated area (for example 1° × 1° latitude longitude area) on a satellite photograph. First, it is not always possible to distinguish between a high cloud and a low cloud within the area. Secondly, it is usually difficult to assign a single cloud estimate to a designated area if the area is totally covered by clouds of varying degree of brightness. One must also distinguish the case in which the area is totally covered by a thick convective cloud, from that case in which the area is totally covered by a thin cirrus cloud. The situation is further complicated if the area is partly covered by one type of cloud and partly covered by another type of cloud. It is noted that the variations in the reflection of solar energy from any cloud area may be due to several causes and very bright areas may not necessarily indicate an area of thick and well developed clouds.

In this investigation, the first problem is solved by avoiding it. There is no distinction made between high clouds and low clouds. It is assumed that all the cloud elements that make up the tropical cloud pattern result from integrated motions in the system. The study of the entire pattern, therefore, is assumed to be capable of revealing some characteristics of the tropical cyclone system. Errors in the determination of the cloud cover due to the second problem are reduced by careful treatment of the photographic data and

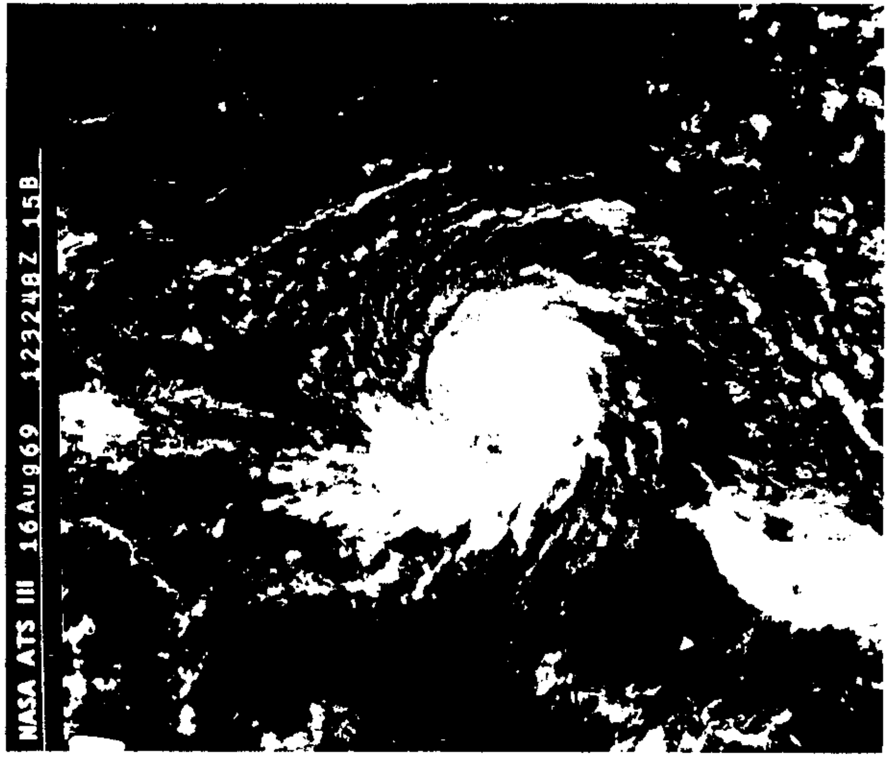


Fig. 1. Application technological satellite (ATS III) photograph of hurricane Debbie at 1233Z on August 16, 1969.

by the use of the objective method presented in this paper which takes into account the spatial variation in the estimation of the cloud cover over an area. The photograph of hurricane Debbie, August 16 1969 (see Fig. 1) and that of hurricane Abby, June 3, 1968, (see Fig. 10) are the two photographs analyzed by the method presented in this paper.

2. General procedure

The measuring device used to estimate the cloud cover of tropical cyclones from satellite photographs consisted essentially of a light meter, a 45° prism, a 100-watt light bulb and a variable auto-transformer. These components were assembled as shown schematically in Fig. 2. The 100-watt bulb was enclosed in a wooden box which had a hole, covered by ground glass to act as a diffuser, at its upper part to allow a beam of light to pass through to the outside. A sheet of plexiglass was placed on top of the box in such a way as to allow a satellite photograph to slide freely between the top of the box and the glass sheet. The light meter and the 45° prism were arranged on the glass sheet so that diffused light from the hole could be totally internally reflected and be recorded by the light meter. The light meter was secured on its sides, except on the side that contained the window to prevent its movement during cloud cover estimation. The 45° prism was held down by black adhesive tape so that each of its perpendicular sides faced very closely the window of the light meter and the hole on top of the box. The black adhesive tape also served to prevent light rays from the surrounding area from vitiating the reading of the light meter. The 100-watt bulb was connected to an auto-transformer so that the intensity of light from the bulb could be varied as desired.

To make cloud cover estimates over a desired area of a satellite photograph, the photograph was moved in the space between the top of the box and the plexiglass so that the area was brought over the hole on the top of the box. The area was then illuminated by diffused light from the ground glass. The light transmitted by the area of the photo-

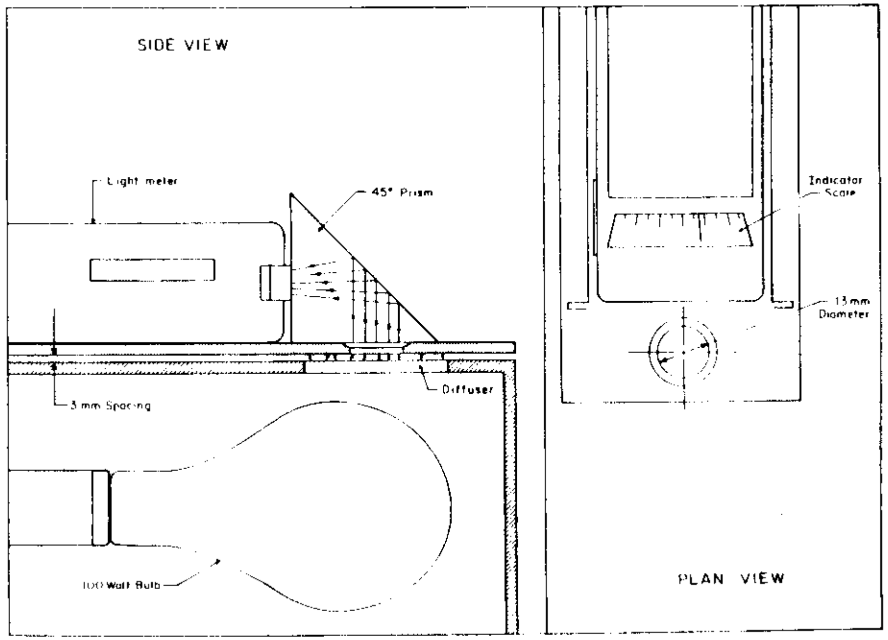


Fig. 2. Photometer arrangement.

graph underwent a total internal reflection in the prism and was recorded by the light meter. The light meter recorded the resultant of the transmitted light from the different parts of the illuminated area of the photograph. The recorded light depended not only on the degree of whiteness of the cloud but also on the percentage of area covered by the clouds. That was an advantage over the visually determined cloud cover. The reading on the light meter was converted into percentage of cloud cover by a procedure to be explained later in this section. The cloud cover estimates over the area by the present procedure therefore reflected both the intensity and the spatial distribution of the cloud over the area.

The light meter used had a photo conductive cell which changed its conductivity in the presence of light. The indicator needle which showed those changes was deflected by a system of small mechanical levers and gears powered by tiny mercury batteries. The data provided by the manufacturers of the light meter indicated that the amount of light recorded in foot lamberts by the light meter was related to the indicator scale by the exponential relation, $L = K2^s$ where

L the amount of light recorded by the light meter in foot-lamberts

s Indicator scale reading; and

K Constant with the value 0.00105.

The curve $L = k2^s$ was plotted on a linear scale and used as the calibration curve for the determination of cloud cover (see Fig. 4).

Step One: A single frame of an Application Technological satellite photograph of hurricane Debbie was reproduced on a special non stretching photographic paper. An appropriate one degree by one degree grid (made up of longitude and latitude lines) was imposed on the photograph. In the case of hurricane Abby, an ESSA (Environmental Satellite Survey) photographic mosaic on a mercator projection was used. The grid in each case was adjusted so that the observed or estimated centre of the cyclone was at the grid point.

Step Two: Each photograph was inspected for the darkest areas usually cloudless ocean areas and for the brightest areas, usually areas with well developed cumulonimbus clouds with glaciated tops. Each photograph was illuminated in the device as described earlier. For each photograph indicator readings s_1 for the darkest area and s_2 for the brightest area were recorded. For a properly processed set of photographs of the tropical cyclone, the variation in the s_2 readings and the variations in the s_1 readings did not exceed one tenth. It was possible then to use a single calibration curve for many sets of photographs of tropical cyclones taken over the oceans. The light from the 100 watt bulb was kept constant during a pair of s_1 and s_2 readings. The transmitted light by the photograph in each case is related to the corresponding amount of light L_1 and L_2 given in foot lamberts by the expressions

$$L_1 = K2^{s_1}$$
$$L_2 = K2^{s_2}$$

The difference in transmitted light from these two areas is therefore

$$L_1 - L_2 = K(2^{s_1} - 2^{s_2})$$

The dark area with a reading corresponding to L_1 was assigned zero tenths cloud cover and the bright area with reading L_2 was assigned ten-tenths cloud cover. Once these extreme values were established

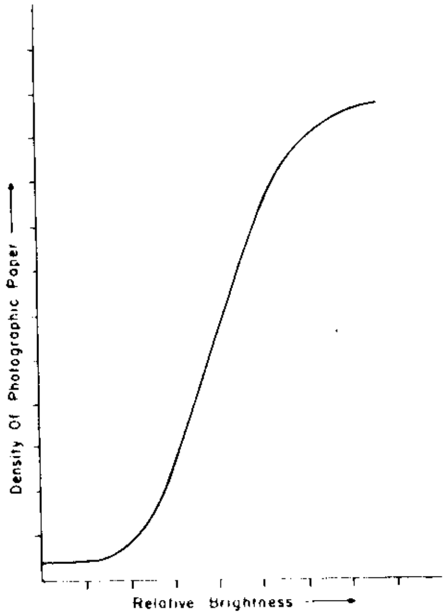


Fig. 3. Curve illustrating the relationship between relative brightness and density of the photographic paper.

then values for areas with intermediate brightness could also be established. However, caution was taken in assigning values to the areas where the light meter reading fell between the two extremes. The following points were put into consideration when values were being assigned to those areas. First, the density of the photographic paper prints, that is, the amount of the chemicals deposited during the exposure of the paper to light, varied from one area of the paper to the other. The relationship between the density of the paper and the relative brightness of areas on the paper often follows the general pattern of the curve shown in Fig. 3. From the curve it is observed that initially

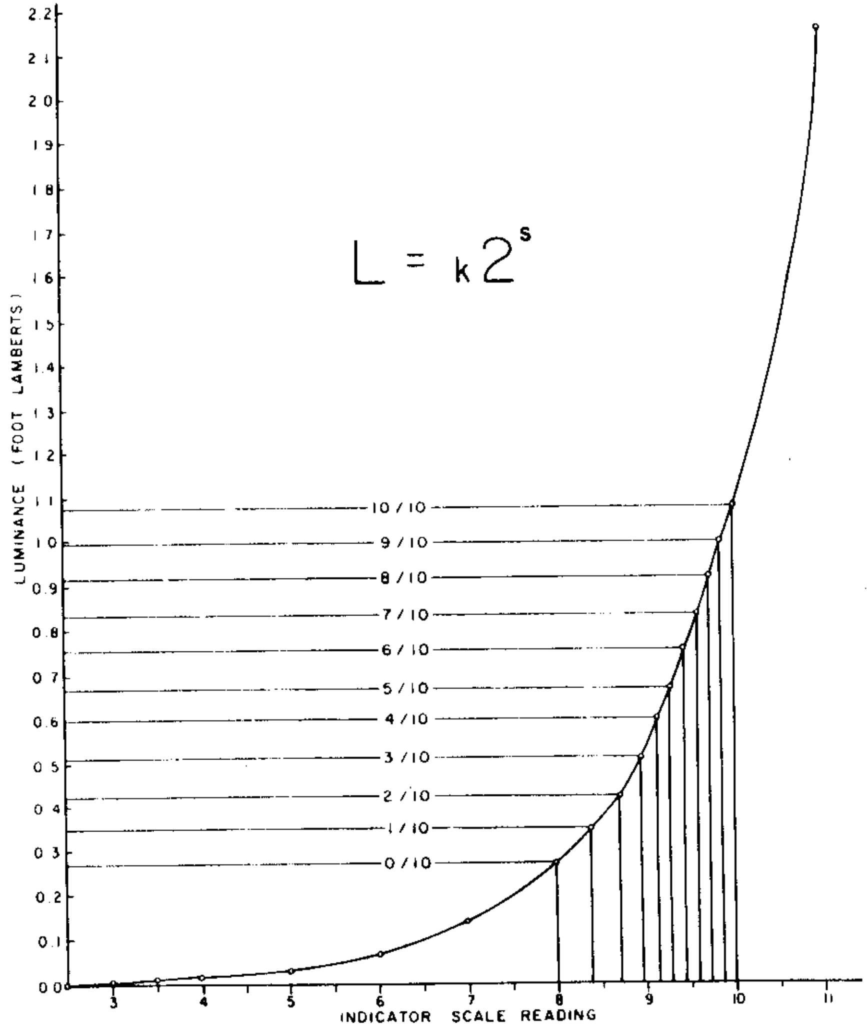


Fig. 4. Calibration curve for the determination of satellite observed cloud cover.

the density does not increase directly as very dark areas become progressively brighter. Then the density increases directly as the areas of the photograph become brighter and continues to be so until a saturation point is reached. At that point, the density no longer increases as areas in the photograph become excessively bright (saturation). An approximately linear relationship therefore exists between the density and the brightness on a straight line portion of the graph. Most of the measurements made lie on the straight line portion of the graph, as the extreme cases of zero tenths cloud cover and ten tenths cloud cover were much fewer than the cases in which the amount of cloud cover recorded lie between the extreme values. The second point to be emphasized was that a controllable source of light was used to illuminate the photographs. It was possible to adjust the source of light until a steady reading was obtained for the dark areas. After proper adjustment, the amount of light recorded on the light meter increased almost directly as the cloud amount increased. The assumption of a linear relationship between the density of the paper and the brightness of the cloud features facilitated the estimation of the cloud cover.

Step Three: The quantity $L_2 - L_1$ in foot lamberts was divided into ten parts of identical fractional illumination that is $(L_2 - L_1)/10 = \Delta L$. In a specific case s_1 the indicator scale reading and the corresponding measurement of light transmitted L_1 were 8.0 and 0.2688 foot lamberts respectively. For the same case s_2 and L_2 were found to be 10.0 and 1.0748 foot lamberts respectively. ΔL was then calculated to be 0.806 foot-lamberts. The cloud cover for any area on the photograph was then determined by measuring the light transmitted by the area and then converting the reading on the indicator scale to the appropriate cloud cover by using the calibration curve $L = K2^s$. For example the light transmitted by an area in a picture gave an indicator reading of 9.2. The amount of light transmitted was estimated to be 0.5912. From Fig. 4 the cloud cover was estimated to be four tenths.

3. Analysis of cloud estimates over the tropical cyclones

In the case of hurricane Debbie, cloud cover amounts estimated within each 1° × 1° grid were transferred to a mercator grid before analysis. The mercator grid was used in order to facilitate computation. The mercator grid was used as a square grid since a unit square of the projection at 30° latitude is only 15% larger than the area of a unit square at the equator. The center of the hurricane was approximately on latitude 15° at the time of analysis. In the case of hurricane Abby, the photographic product was already on a mercator grid.

With the observed or estimated center of the cyclone as center, concentric circles of radius 1°, 2°, ..., 9° latitude were drawn on the photograph for which cloud cover has been determined. From the same center, radial lines were drawn at an azimuthal interval of 10° so that the radial lines intersect each circle at 36 equally spaced points (see Fig. 5). All azimuthal distances were measured from the north in a clockwise manner. Each of the 36 points was made the center of a square with the length of each side equal to six grid lengths. The cloud cover at each point in question was then determined by considering the contribution to the cloud cover of points within the square. The contribution from each grid point was weighted by a factor $e^{-\sigma y_i}$ where y_i, the distance of a grid point from the point where the cloud cover estimate was being determined was less than or equal to two grid lengths and was a factor determined by assuming that $e^{-\sigma y_i}$ had a value 0.1 at $y = 2°$. From that assumption, the value of σ was found to be 1.15. The specification of six grid length square was for computational convenience. The weighted cloud cover estimate N at each of the 36 grid points on each of the circles was then computed from the expression

$$N = \frac{N_i e^{-\sigma y_i}}{e^{-\sigma y_i}}$$

where N_i was the satellite observed cloud cover estimate at distance y_i within the square box. The cloud cover was thus determined for all the 36 points on each circle. The computation involved in this procedure was accomplished by the use of IBM computer system at the University of Chicago Computation Center. The choice of 0.1 for $e^{-\sigma y_i}$ at two grid lengths away was based on the assumption that a grid point value at that distance from the center of the square should not contribute more than one tenth of its value to the cloud cover value at the center of the square. N is henceforth

referred to as satellite observed cloud cover or simply, cloud cover. Figs. 6 and 7 show the results of the estimates from the ATS photograph of hurricane Debbie on 16 August 1969.

4. Harmonic analysis of estimated cloud cover

In this study, estimate of cloud amount at 36 equally spaced points along a circle is approximated by a function $N_{(\theta_i)}$. It is assumed that $N_{(\theta_i)}$ is a well behaved function of the azimuthal distances and can be represented in terms of azimuthal mean plus a fourier series of sinusoidal components

$$N_{(\theta_i)} = \overline{N_{(\theta_i)}} + \sum_{n=1}^{l} A_n \sin K_n\theta_i + B_n \cos K_n\theta_i \quad (1)$$

where

$N_{(\theta_i)}$ = function expressing distribution of estimated cloud cover along a circle

K_n = $2\pi n/l$ is the azimuthal wave number

l = the distance around a circle

n = the number of harmonics around a circle. It identifies the harmonic of $N_{(\theta_i)}$

θ_i = Azimuthal distance from the north, in degrees.

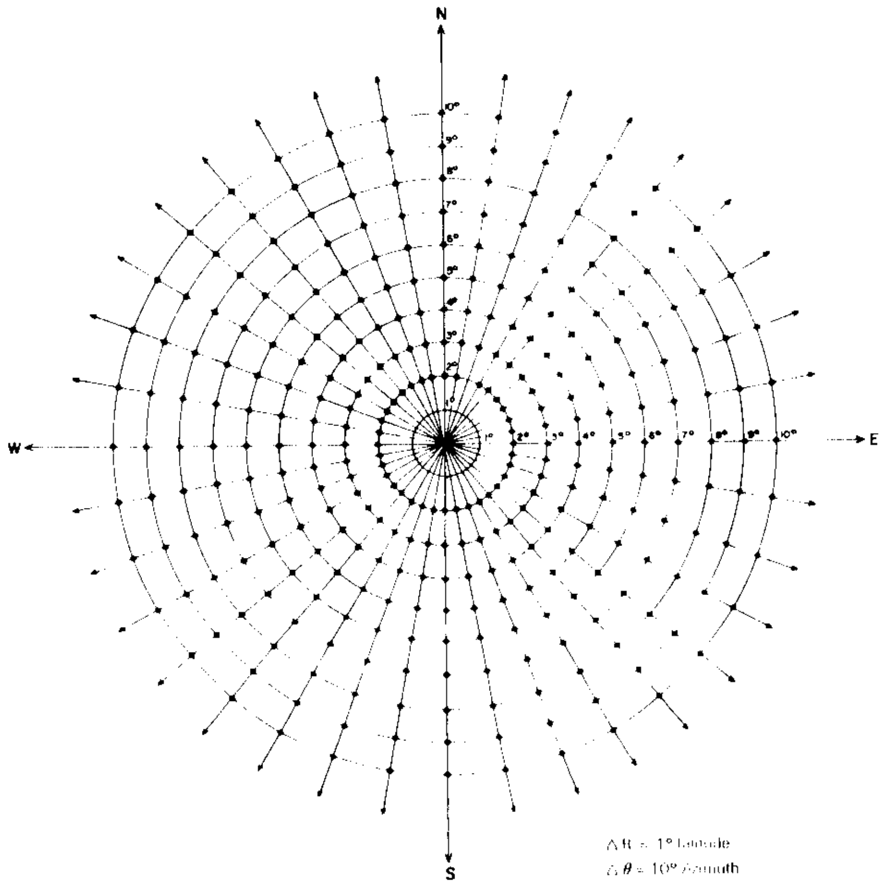


Fig. 5. Polar grid for the determination of satellite observed cloud cover.

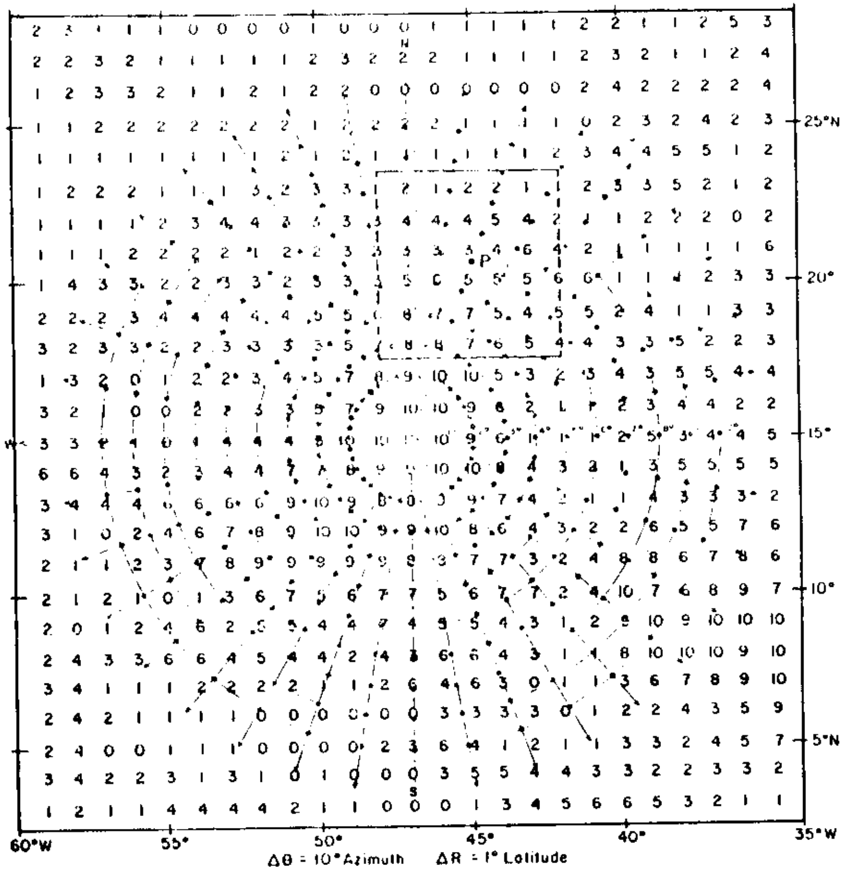


Fig. 6. An example of photometric computation of satellite observed cloud cover. Hurricane Debbie, August 16, 1969 (1232Z).

Fig. 7. Weighted cloud cover estimated at 36 data points along the circle $R = 6°$ latitude in Fig. 6.

The coefficients A_n and B_n are calculated by multiplying both sides of (1) by $\sin 2\pi m\theta_t/l_t$ and integrating along a circle. From orthogonality relationships,

$$\int_0^{l_t} \frac{\sin 2\pi n\theta_t}{l_t} \frac{\sin 2\pi m\theta_t}{l_t} = \begin{cases} 0 \text{ for } n \neq m \\ l_t/2 \text{ for } n = m \end{cases} \quad (2)$$

we obtain, using summation notation since discrete values are considered, $(l_t - 1)/2$

$$A_n = \frac{2}{l} \sum_{n=1}^{(l_t-1)/2} N_{(\theta_t)} \sin\left(\frac{360}{l} n\theta_t\right) \quad (3)$$

and

$$B_n = \frac{2}{l} \sum_{n=1}^{(l_t-1)/2} N_{(\theta_t)} \cos\left(\frac{360}{l} n\theta_t\right) \quad (4)$$

The expression in (1) can be rewritten in the form,

$$N_{(\theta_t)} = \overline{N_{(\theta_t)}} + \sum_{n=1}^{4} H_n \cos \frac{360}{l_t} n(\theta_t - \varepsilon_n) \quad (5)$$

where $H_n = (A_n^2 + B_n^2)^{1/2}$ and represents the amplitude of the harmonic component.

l_t = 36, the number of data points along the circle
t = subscript that identifies points on the circles
ε_n = phase of the harmonic component given by

$$\varepsilon_n = \frac{l_t}{360} \arctan \frac{A_n}{B_n}$$

The first harmonic has a period l_t equal to 36, the number of data points along a circle. The second harmonic has a period l_t equal to 18 and the nth harmonic correspondingly has a period $36/n$. The mean and the 18 possible harmonics in this analysis should describe the cloud cover estimates along a given circle completely. It is, however, not necessary to compute all 18 harmonics. The variation of cloud cover estimates along each circle can be described adequately by the first few harmonics. In this investigation, therefore, computations were made for the first four harmonics. The number of harmonics computed is thought to be within the limits of usefulness of the concept of harmonic analysis for this purpose. If many harmonics are required to account for the cloud cover variation, then it will be concluded that the cloud cover function is not sinusoidal. The harmonic analysis can still provide a mathematical representation of the function, however. For clarity the subscripts θ_t in $N_{(\theta_t)}$ and $\overline{N_{(\theta_t)}}$ are dropped in the subsequent discussions.

5. Cloud cover parameters obtained from harmonic analysis

The mean of the cloud cover along a circle, $\overline{N}$, the amplitude H_n and the phase angle ε_n corresponding to the harmonic component "n" were the basic parameters used in the description of the cloud patterns.

(a) *The mean of the cloud cover estimates,* ($\overline{N}$)

The mean of the cloud cover estimates $\overline{N}$ is the harmonic of zero value. The changes in the graphs of $\overline{N}$ from one picture to another, where a series of photographs are analyzed, could be indicative of the redistribution, development and dissipation of clouds as the cloud patterns changed from one stage of development to another. However, a better assessment of the redistribution, development and dissipation of clouds can be obtained by analyzing the frequency of a particular cloud estimate N at a radial distance r, as explained in a later section.

(b) *The amplitude* (H_n) *of the cloud cover estimates*

In the harmonic analysis, the amplitudes (or half ranges) show the maximum excursion of the cloud cover values from the mean value. The significance of the amplitudes of a particular harmonic component is usually dependent on the magnitude or the mean value. To eliminate the influence of the mean cloud cover on the amplitudes, the amplitudes are expressed in terms of the appropriate mean cloud cover. For a circle with radius (r) where the mean cloud cover is $\overline{N}$, the quantity $\hat{H}_n$ is computed, where $\hat{H} = H_n/\overline{N}$. $\hat{H}_n$ represents the normalized or relative amplitude. In the particular case of the first harmonic H_n is represented by a_r. Particular identification is given to this component because, due to the asymmetric nature of the cyclone systems it is the most important component. As the cyclone becomes mature and becomes more symmetricalized the parameter often tends toward zero. A graph of this parameter with time affords a means of describing the process of symmetricalization of the cyclone system.

Where there is a non zero cloud cover N, at only one of the 36 data points along the circle, the mean cloud cover along the circle is defined as usual as $N/36$. In that case the amplitude value for all the components will be $2N/36$. The situation mentioned here arises where there are highly localized, spotty clouds at certain radial distances from the center of the cyclone. Along any circle where there is uniform or almost uniform cloud cover, or complete absence of cloud cover, the amplitude is expected to be zero or very small.

In the discussions of harmonic analysis of certain oscillations it is customary to regard the square of the amplitude H_n as a measure of power or energy of the oscillations. This is true in the harmonic analysis of the mechanical or electrical oscillations. In the present application of the harmonic analysis principle such an interpretation of H_n^2 cannot be made. However, the computation of H_n^2 is still of value in this study as will be shown in the following paragraph.

One of the objectives of this study is to be able to characterize a cloud pattern by a particular harmonic component. It was necessary to identify the predominating harmonic components with which the analyzed cloud pattern can be characterized. The fraction of the total variance of the cloud cover along each circle (with radius r) accounted for by a single harmonic component (n) is given by the quantity $H_n^2/2$. In the case of the last harmonic which is not computed here the quantity is H_n^2. The total variance of the cloud cover along a circle is given by S^2 where

$$S^2 \quad \frac{(N \quad N)^2}{l_t} \tag{6}$$

The quantity $\frac{1}{2}H_n^2/S_n^2 \times 100$, here represented by η_r is then the percentage of the total variance of the cloud cover along the circle r accounted for by the harmonic component n. For the cloud pattern η_r is computed as a function of the radial distance and the w. mbers.

For a particular circle of radius r, $\hat{\eta}_r$ represents a cumulative value of η_r for each of the four harmonic components considered; so that for a particular circle r

$$\hat{\eta}_r \quad \sum_{n=1}^{4} \eta_r \tag{7}$$

(c) *The phase angle* ε_n

For each circle, the phase angle ε_n indicates the azimuth distance from the north where the first maximum of N corresponding to the component n is located. Additional maxima are located at (+ $2\pi a/n$) for each integral value of a up to n 1. For each cloud pattern studied, a polar diagram showing the pattern of the distribution of phase angles is drawn for at least the first and second harmonic components.

The quantity ε_n can be uniquely determined from the expression

$$\varepsilon_n \quad \frac{l_t}{360_n} \text{ arc sin } \frac{A_n}{B_n}$$

6. Results

(a) *Analysis of the cloud cover over hurricane Debbie 123248Z August 16, 1969*

(i) *The distribution of satellite observed cloud cover.* To have a proper understanding of the cloud patterns of a tropical cyclone as observed from a satellite photograph, it is useful to study the distribution of the cloud cover estimates N at the various radial distance from the center of the cyclone. Fig. 8a shows the distribution of cloud cover estimates and the contours of equal cloud estimates. This recomposition of the cloud features compares well with the photograph. However, in order to obtain other useful information from such distribution it is necessary to study quantitatively how the cloud estimates change at each radial distance. The changes in the mean cloud $\bar{N}$ at each radial distance cannot be used for such estimation because they are less indicative of the distribution of cloud cover amount at a particular radial distance. For that purpose frequency intervals of cloud cover are established and the numbers of cloud cover amount falling in the interval are counted and recorded. The procedure is carried out for nine concentric circles on the tropical cyclone cloud pattern studied. The intervals considered are: 0 0.45; 0.50 1.45; 1.50 2.45; 2.50 3.45; 3.50 4.45; 4.50 5.45; 5.50 6.45; 6.50–7.45; 7.50 8.45; 8.50 9.45; 9.50–10.00. The central values of each interval is correspondingly 0, 1, 2, 3, 4, 5, . . . 10. Zero and 10 are respectively chosen as the central value for the first and last intervals as it is neither possible to have cloud cover values less than zero nor possible to have values greater than 10. The frequency of cloud cover estimate is identified with the central value of the interval. For example, if for

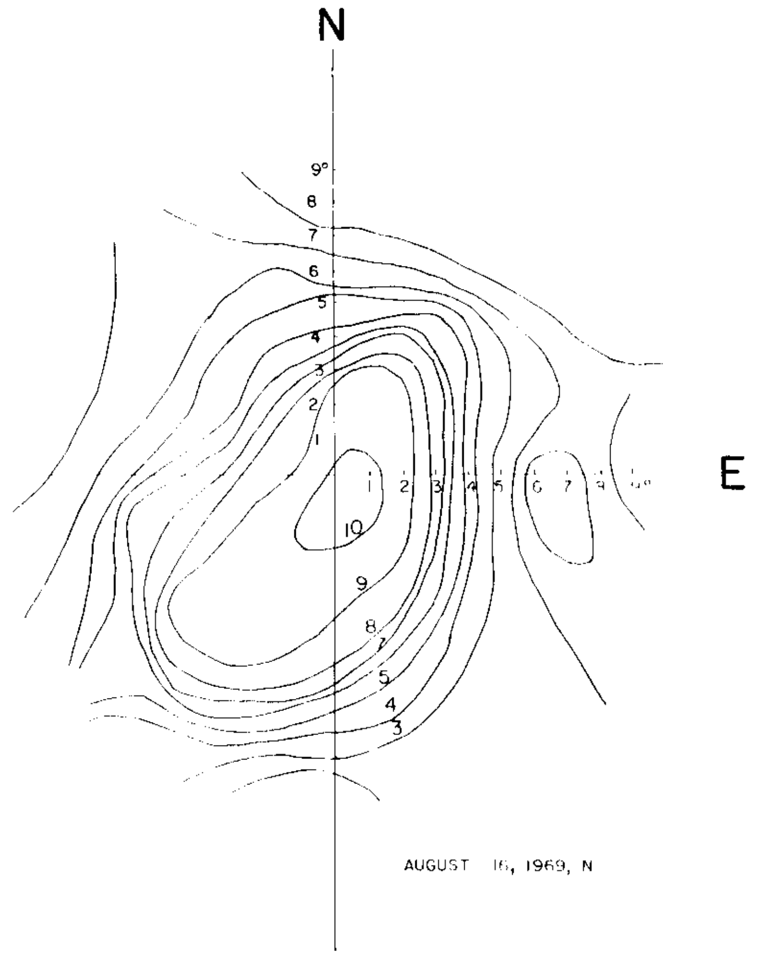


Fig. 8a. The distribution of cloud cover estimates and the contours of equal cloud estimates.

a particular circle, the number of cloud cover estimates between 4.50 and 5.45 is 20, then there are 20 points (out of the possible 36) with five-tenths cloud cover. Twenty therefore represents the absolute frequency of the cloud cover of the interval 4.50–5.45. The use of absolute frequency is preferred to the use of relative frequency or cumulative frequency because it affords an easier method of assessing the increase or decrease of clouds at particular radial distances from the centre of the cyclone as the cyclone developed. Fig. 8b shows the distribution of cloud cover estimates for hurricane Debbie using this approach. One problem that arises in the display of the cloud distribution as

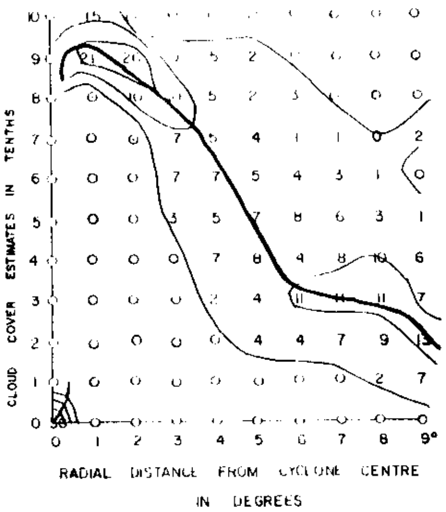


Fig. 8b. Frequency distribution of cloud in hurricane Debbie on August 16, 1969 from Figure 6.

shown, is the characterization of the cloud cover within the eye. If the eye has not formed, then it is sensible to put the number 36 against 10 at $r = 0$ to indicate that the center of the cyclone was still overcast. When the eye has formed, the number 36 is put against zero at $r = 0$. Since the eye has formed at the time of the photograph (according to reports) and also as shown on enlarged photographic product, the number 36 was entered against zero at $r = 0$. One general feature of the frequency distribution requires special mention. Namely, by drawing isolines of frequency on the frequency distribution diagram at intervals of 10, an axis of maximum frequency of cloud cover can always be defined. The axis in this case is continuous. If a series of these photographs are analyzed for a cyclone system, the axis can shift in response to the redistribution of the cloud cover as the cyclone develops. From Fig. 8b it is possible to define a parameter r_x as the radius of maximum frequency of a particular cloud cover estimate *N*. For example the radius of maximum frequency of five-tenths cloud cover estimate of hurricane Debbie at 12:33Z on August 16 is 4.5.

(ii) *The harmonic analysis of cloud cover.* The results of the harmonic analysis of the cloud cover of hurricane Debbie are presented in Figs. 9a, 9b.

Table 1. *Distribution of $\hat{\eta}_r$ from photograph of Debbie August 16, 1969*

n \ $r°$	0	1°	2°	3°	4°	5°	6°	7°	8°	9°
1	0	36	28	46	59	65	72	72	42	
2	0	54	59	42	38	31	18	1	27	
3	0	10	10	5	3	1	4	12	3	
4	0	0	0	5	0	1	1	5	4	
$\hat{\eta}_r$	0	100	97	98	100	98	95	90	76	

The results are presented in the form of polar diagrams. Fig. 9a shows lines joining points indicating the phase angles along each circle for the first and second harmonic components. These lines are here identified as phase curves. The relative amplitudes $\hat{\eta}_n$ expressed as percentage are entered on each curve at the appropriate radial distances from the center of the cyclone. Fig. 9b is the reconstruction of the picture by the addition of the mean cloud amounts *N* and the amplitude of the first harmonic. The reconstruction approximates the original picture.

The usefulness of the phase curves lies in the fact that the shift in the phase curve can be associated with the shift in organized cloud masses (e.g. cloud bands in a hurricane system when a series of photographs showing the evolution of the tropical storms are considered).

Table 1 shows the percentage variance accounted for by the first four harmonic components at various radial distances for the case of Debbie. The table shows clearly that the cloud distribution was accounted for essentially by the first and second harmonic. Within a radial distance of three degrees from the center of the cyclone, the more dominant harmonic was the second harmonic and at greater radial distances, the first harmonic was the more dominant. This points to the asymmetric nature of the tropical cyclone.

(b) *Results from the analysis of the cloud cover over hurricane Abby June 3, 1969*

Fig. 10 shows an ESSA photograph of hurricane Abby. Figs. 11a and 11b are polar diagrams showing the distribution of amplitudes and phase angles for the first and second components respectively. It is observed that the first harmonic component is the more dominant and the distribution of amplitudes reflects the structure of the clouds as observed in the photographs. Fig. 12 compares the

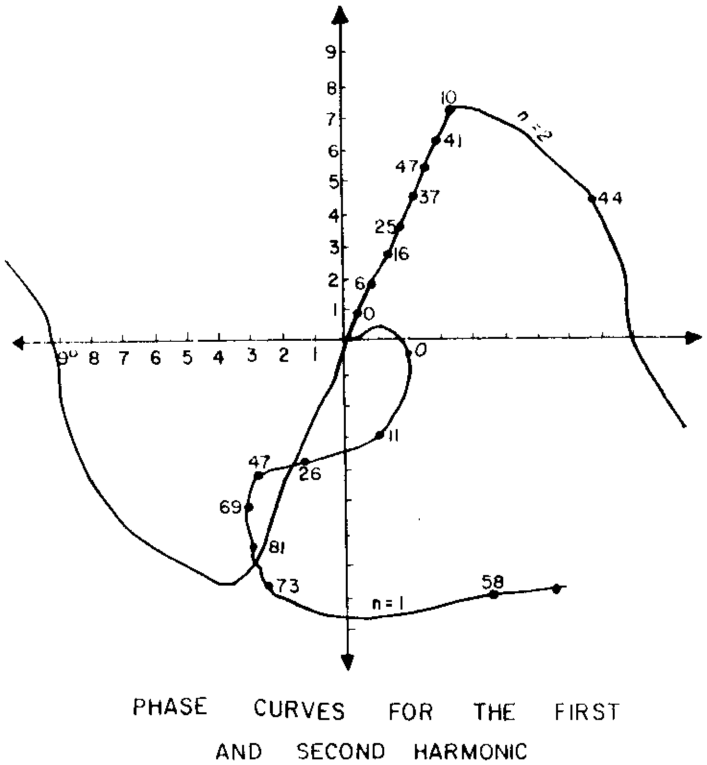


Fig. 9a. Lines joining the points indicating the phase angles along each circle for the first and second harmonic components.

various harmonic components from the analysis of the cloud cover value at the radial distance six degrees from the center of the cyclone. Relative amplitudes have been plotted against azimuthal distances.

The position of hurricane Abby for that date also offered an opportunity to look at the distribution of meteorological parameters under the cyclone cloud cover. On June 3, 1968 about 1800Z, hurricane Abby, then a weak hurricane, was located approximately at lat. 25° N and long. 84° E so that the cloud cover was partly over the ocean and partly over the Florida peninsula and some Caribbean islands. At that location the center of the cyclone was about 5°–7° from seven radio sonde stations; namely Jacksonville (206), Cape Kennedy (794), Grand Bahama (063) and Grand Cayman 384, Swan Island (501) Merida (44) and Boothsville (232).

From the veritical and circumferential distribution of meteorological parameters from those radio sonde stations, the following points are noted. High relative humidities between 90 and 100% are found between the ground and 600 mb level at Grand Bahama, Cape Kennedy and Grand Cayman, (see Fig. 12). At those stations, relative humidities of about 50% could still be found at 250 mb level. At the other stations, relative humidities varied from 30–65% at low levels and fell to about 10% at 600 mb level. Analysis of winds showed considerable low level inflow and cyclonic tangential winds up to about 700 mb level and strong out-

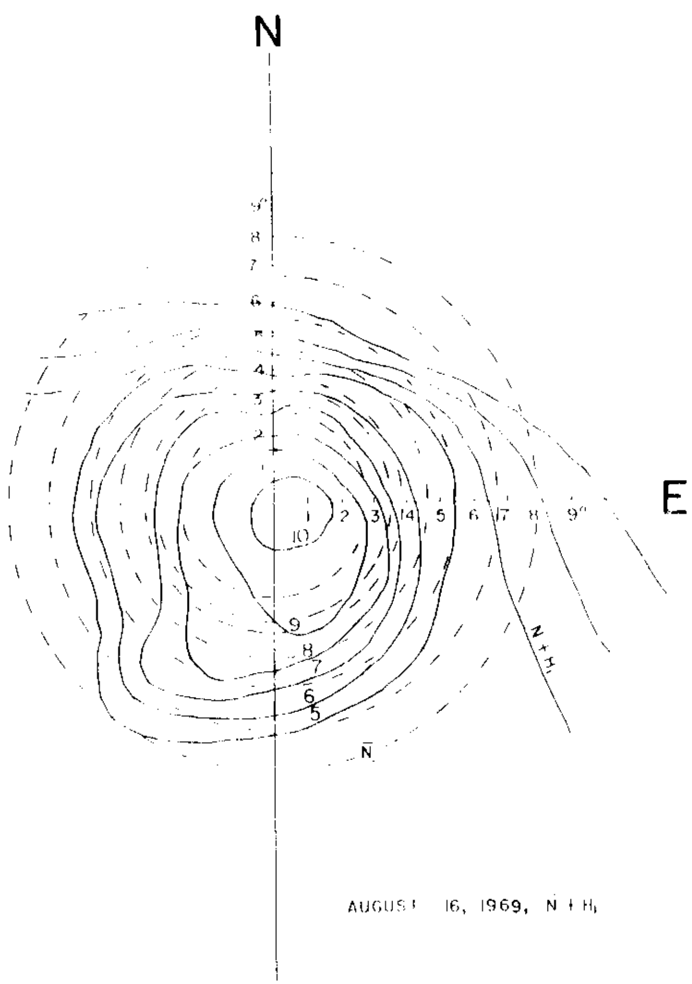


Fig. 9b. Cloud distribution obtained by the addition of the mean cloud amount $\bar{N}$ and the amplitude of the first harmonic.

Fig. 10. ESSA photograph of hurricane Abby.

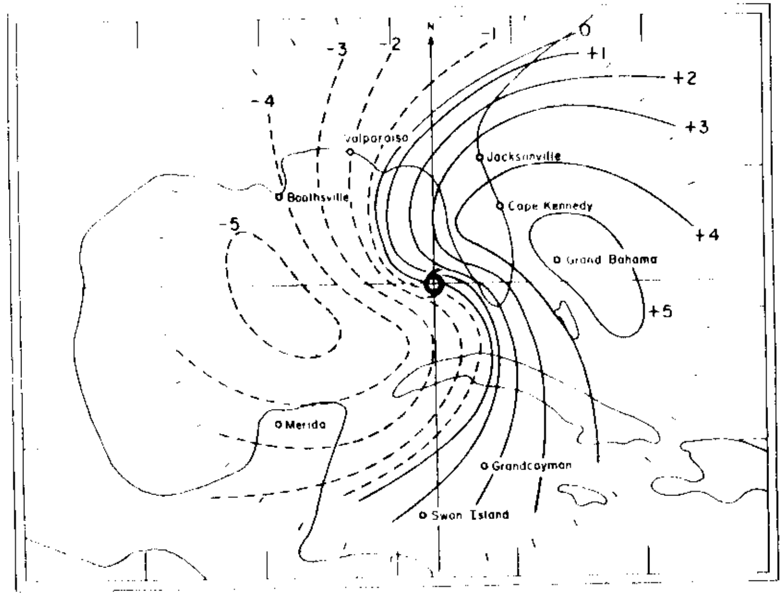
Fig. 11a. Polar diagram showing the distribution of amplitude and phase angles for the first harmonic component for hurricane Abby.

flow and anticyclonic winds at 300 mb and 100 mb levels at those three stations. At Merida and Boothsville there was considerable outflow at low levels (between 1000 mb and 800 mb level) and inflow at the upper levels.

The vertical profile of total static energy showed that there was uniform vertical distribution of equivalent potential temperature θ_e over Grand Bahama. That indicated that the upward transport of mass and energy was more vigorous over the general area of Grand Bahama. At other areas the vertical distribution of total static energy showed the characteristic minimum value at about 600 mbs. It was noted in Fig. 12 that the first harmonic component of cloud distribution, which was the most prominent component, had the highest amplitudes around Cape Kennedy, Grand Bahama and Grand Cayman. The vertical profiles of the meteorological parameters discussed here demonstrated that cloud patterns of tropical cyclones reflected the thermodynamic processes going on beneath the cloud cover.

7. Conclusions

The merit of the photometric method of estimating the cloud cover is that it is less subjective and



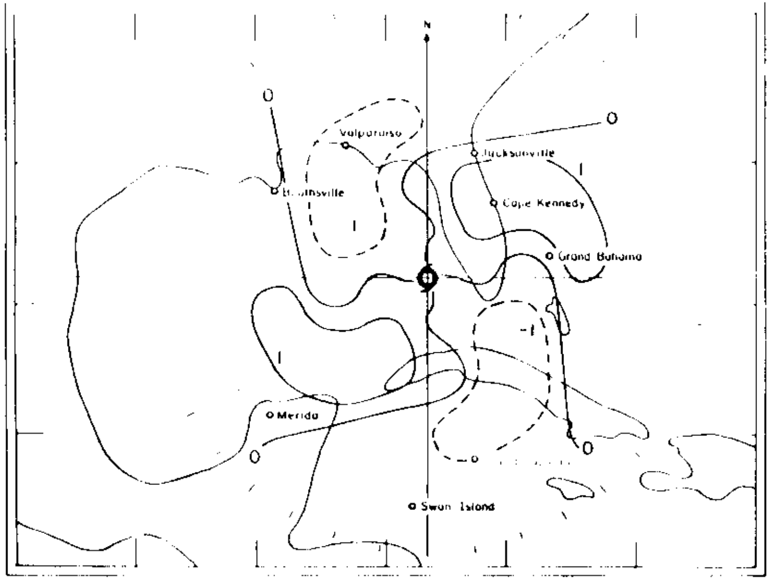


Fig. 11b. Polar diagram showing the distribution of amplitude and phase angles for the second harmonic component for hurricane Abby.

more quantitative than the existing methods of approach. In the data sparce regions of the tropics where satellite photographs may become the primary source of information, the changes in the area covered by cloud as can be indicated by the variation of r_N with time, the changes in the phase curves are capable of providing quantitative information about the tropical cyclone presently provided by mere inspection of photographs.

Two comments about the procedure followed in this paper are necessary. The first concerns the choice of the origin of data points along concentric circles and the second discusses the errors involved in the location of the origin of the polar diagrams drawn on the cloud patterns.

The origin of the data points is immaterial as far as the amplitudes of the harmonic components are concerned. Regardless of the point along a particular circle chosen as the origin of the data points, the amplitudes of the data points still come out the same for that circle. Choosing a consistent direction in this case, the True North will, however, facilitate computations and will avoid the necessity for changing the origin of the data points along the circles each time a cyclone changes its direction of motion, especially in cases where a series of photographs for a particular cyclone is investigated.

The origin of the polar diagrams imposed on the cloud pattern of the tropical cyclones has been located at the reported (given by the U.S. Weather Bureau) center of the circulation accompanying the cyclone cloud pattern. The center of the cyclone is determined from various sources, e.g. (aircraft reconnaissance reports, ship reports, from computation of the flow field accompanying the cyclones, etc.) and it is assumed to be correct to within half a degree. There is no doubt that large errors in the location of the origin for the harmonic analysis computations will lead to errors in the amplitudes of the components. A nearly circular cloud pattern of a tropical cyclone in which the center of the cloud system has been correctly placed should be described only by the harmonic component zero. A small error in the location of the origin for such a case will show ampitudes for the first component especially at some distances away from such an

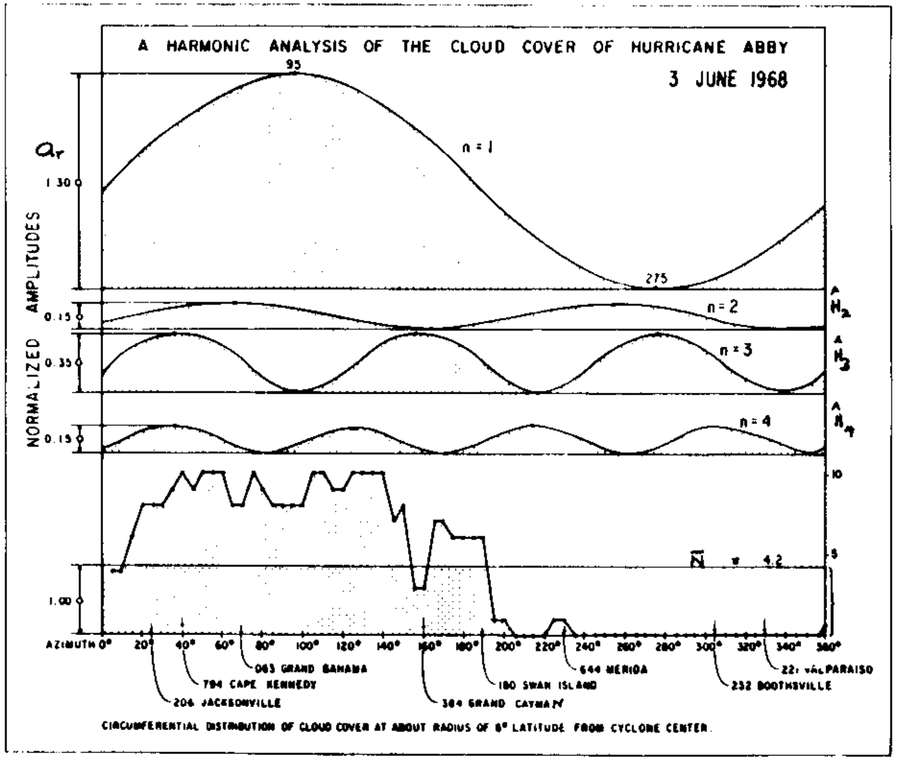


Fig. 12. Circumferential distribution of cloud cover at about radius of 6° latitude from the center of Abby.

origin. Quantitative estimates of such errors have not been carried out in this investigation mainly because considerable efforts have been made to place the origin correctly in each cloud pattern of tropical cyclones investigated. Errors that may arise from incorrect location of the origin are therefore considered small.

The suitability of satellite cloud photographs for tropical cyclone research depends on how well the currently accepted views on the tropical cyclone system are reflected in the satellite photographs of the system and how much of the characteristics or tropical cyclones beyond the familiar ones can further be indentified from such photographs.

8. Acknowledgement

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КОЛИЧЕСТВЕННЫЙ МЕТОД ОЦЕНКИ ОБЛАЧНОГО ПОКРЫТИЯ НАД ТРОПИЧЕСКИМИ ЦИКЛОНАМИ ПО СПУТНИКОВЫМ ДАННЫМ.

Представлен фотометрический метод количественной оценки облачного покрытия над тропическими циклонами по фотографиям со спутников. Этим методом анализируются две фотографии тропических циклонов с нанесенной пространственной сеткой. На каждой фотографии изображены девять концентрических кругов.

В качестве центра каждой группы концентрических кругов используется наблюденный или полученный из метеосводок центр циклона. По этим девяти концентрическим кругам проведены фотометрические оценки облачного покрытия. При этом оценка количества облачности вдоль окружности каждого круга производится с использованием принципов гармонического анализа. Распределение облачного покрова даёт оценку количества облачности И (в долях единицы), а ориентация и развитие облачных образований описывается определенными параметрами и также фазовым углом рассматриваемых гармонических компонент. Эти количественные характеристики рассчитаны как функции радиального расстояния от центра циклона. Используемые параметры позволяют исследовать процесс симметризации тропических циклонов по мере их развития, а также обеспечивают объективные способы изучения изменений в пространственной протяженности облачного покрытия в циклонах. При этом оказалось, что первые две гармоники разложения в большинстве случаев достаточны для оценки облачного покрытия по кругам. Эти кривые, дополненные картиной распределения фазы первых двух гармоник по девяти кругам для каждого анализируемого облачного образования, дают способ изучения изменений в ориентации облачных структур.

С использованием обычных экспериментальных данных для исследования вертикальной структуры тропического циклона и путём сравнения результатов с теми, которые получены из анализа облачности над тем же циклоном, показано, что облачные образования в тропических циклонах часто отражают термодинамические процессы, протекающие под этими образованиями.