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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Tropical Cloud Cover Seen by All-Sky Cameras on Barbados and Adjacent Atlantic Ocean During Two Summers

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Office
of the Director
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TROPICAL CLOUD COVER SEEN BY ALL-SKY CAMERAS ON BARBADOS AND ADJACENT ATLANTIC OCEAN DURING TWO SUMMERS

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ABSTRACT

Analysis of total, low, middle and high cloud cover percentages was made of 1885 all-sky camera photographs. These were taken during parts of July, August and early September of 1963 and 1968 at four locations; two on Barbados and aboard research vessels located 100 and 450 km east of Barbados. A complete discussion of the various methods and equipment is included. The important question of relative weights which an analysis grid should give to overhead and near-horizon clouds is discussed. Relative amounts are meaningful here, but the absolute values are somewhat dependent on the desired application, as should be the case with any type of cloud data.

Results show average cloudiness of 51.8 percent on land and 34.5 percent at sea. Nearly all of this difference is accountable by more low clouds on land. Previous climatologies in this area do not apply well to the adjacent ocean; some satellite and energy budget studies also did not distinguish well between land and sea clouds. When observations are stratified into five disturbance modes based on daily percentage of rainy Barbados stations, total cloud and high plus middle cloud show a strong tendency for more clouds under disturbed conditions. Low cloud is less related to disturbance mode.

Diurnal variations of total and low sky cover on land show a morning minimum increasing to a higher constant value during the rest of the day. At sea the low clouds were most numerous under disturbed conditions in early morning. More high plus middle clouds occurred on both island and ocean during the afternoon than morning.

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1. BACKGROUND AND MOTIVATION

Cloudiness in the tropics is more difficult to measure and define then in middle latitudes because tropical clouds are predominantly convective rather than stratiform. Since cumuli are more isolated and typically have vertical alignment, we need longer data samples and more care in interpreting apparent cloudiness near the horizon. This effect of course varies in importance with the application. Several distinct components of cloud cover evaluation from a surface point must be recognized. These include the packing effect of cumuli near the horizon due purely to geometric considerations of the earth's curvature, since we can see their sides rather than bases. Also, visual observations are biased since observers tend to emphasize clouds at lower elevation angles due to physiological effects. In addition, care must be taken in extrapolating tropical island cloudiness to the open ocean. This report will discuss all of these problems in some detail, and hopefully obtain more objective cloud cover figures from a series of all-sky photographs from both land and ocean by subdividing the cloudiness into portions depending on type, location, time of day, degree of synoptic-scale disturbance, and zenith angle.

Cloud cover in the tropics was compiled by many authors in earlier years; among those maps most often used are Brooks (1927) and Landsberg (1945) based on observer's records. A new seasonal distribution was compiled by London (1957) to study the atmosphere's heat balance. Much of the data for these climatologies necessarily came from island and continental stations, together with some ship reports, despite the large portion of the tropics covered by ocean. Thus, extension of land cloudiness to the sea often was made despite the complicating factor of very localized land effects, such as land and sea breezes, topographic features, and induced diurnal variations due to land heating. In general, extrapolation from land stations has overestimated tropical cloudiness over the oceans (Vonder Haar and Hanson, 1969). Very few estimates of this difference had been found from simultaneous land and sea observations before the meteorological satellite was introduced.

In the last decade, good relative estimates of cloudiness for every part of the world have been extracted from several types of satellites using various methods on different time and space scales. These include figures by Arking (1964) and Clapp (1964), as well as a series of studies dealing with the tropical Pacific by Godshall (1968), Sadler (1968), Quinn and Burt (1968), and Bjerknes, et al. (1969). Several difficulties should be recognized in deducing longer-term cloud cover from satellite data, however, which show that their greatest utility for this type of study probably lies in combination with other types of cloud measurements. Glaser, et al. (1968) found that ground-observed cloud amounts are generally more than satellite amounts, apparently due to the lack of resolution of small cumuli by the scan lines. However, a portion of this difference may be due to a tendency for ground observers to overestimate low cloudiness because of physiological effects, which is discussed in Chapter 4. Other drawbacks to satellite determination of absolute cloud cover include calibration (Woodley and Sancho, 1971), drift and degradation of signal through time, and the necessity of mixing together different times of day, seasons, synoptic conditions and combining adjacent land and sea areas. Comparisons of views from manned spacecraft and meteorological satellite by Soules and Nagler (1969) help bridge the gap between ground-based observations and routine satellite data. However, the analysis of cloud cover from a few specific surface locations should be most useful in determining the errors in each type of observation. Vonder Haar and Hanson (1969) believe that more tropical surface cloudiness data will be very beneficial to radiation investigations. In short, ground-based data from special programs can obtain information for a short time which remote sensing could not accomplish, while satellite data can cover all areas of the ocean, but with less resolution. The analysis of cloud cover from two field programs now will be discussed.

2. LOCATIONS, CAMERAS AND NUMBERS OF OBSERVATIONS

All-sky photographs of the sky are not new to meteorology, but their application for climatological purposes has been infrequent. Among the earliest examples is the discussion by von Arx (1958), where very wide angle lenses are discussed, both in theory and in practice. He shows the development of several systems for reflecting the entire sky plus part of the surrounding ocean or land from a polished surface, which is then photographed from above by a movie camera. It should be mentioned here that the "Weather Aspect Recorder" shown in von Arx (1958) was used to record sky state during the R. V. Crawford cruise operated by Woods Hole Oceanographic Institution in 1957 to the Barbados area. We analyzed all-sky pictures from this cruise; however, due to uncertainties in knowing exact times, the sample was not included in our final results. These 1957 data will be used later when comparing grids, however.

An optical scanning device was developed by Pochop and Shanklin (1966) in order to obtain sky cover in Missouri. Yamazaki and Magono (1970) have shown that an all-sky picture can be reinverted optically; that is, a "normal" looking sky picture can be obtained by re-photography of whole sky pictures. Lyons (1971) used two fisheye cameras on Barbados in 1969 to calculate cloud heights and motion, but not cloud cover.

All-sky camera photographs to be discussed in this paper were taken during the 1963 and 1968 experiments conducted on and around the island of Barbados. The 1963 program was a joint project, including Florida State University and Woods Hole Oceanographic Institution, and is described by LaSeur and Garstang (1964). The photos were taken at most of the same times on the ship as were the panoramic photos analyzed by Holle (1968). The 1968 project included Florida State University, NCAR, ESSA, and several other agencies (see Garstang and LaSeur, 1968). All-sky cameras again were set up on Barbados by Florida State University in 1969 specifically for radiation studies, but these pictures have not yet been analyzed.

2.1 Locations

Barbados has been chosen for experiments primarily because air which arrives there has been unaffected by land for 2500 n mi, except in rare cases of west wind. Thus, the location of observing stations is important to understand many features of the cloud cover. Four sets of cloud pictures will be discussed - there are land and sea photos from both 1963 and 1968. Figure 1 shows the two locations where photos were taken on ships. In 1963, pictures were taken from the R. V. Crawford located at 13°N, 55°W, or some 450 km east of Barbados. In 1968, the pictures were taken on the CGSS Discoverer located 100 km east of East Point, Barbados. There would not appear to be any reason for significant differences between cloudiness at these two stations, and none was found.

Land photographs on Barbados were taken in two rather different locations, and this variation probably contributed to greater cloudiness in one year than the other. The 1963 pictures were taken very near the southeast coast at Seawell Airport (Christ Church Parish) at an elevation of about 125 ft. A ridge rises to 315 ft about four km to the northwest; then the land gently slopes upward to the middle of the island. The 300-ft contour is usually one to three km inland around most of the island. The photos in 1968 were taken at the Florida State University central station, or Radar Site(Garstang and LaSeur, 1968). Figure 1 shows that this was located at Cottage (St. George Parish), where the elevation is 785 ft. An elevation of over 900 ft is found less than three km north of Cottage; while the highest point on the island is Mt. Hillaby (1115 ft), some seven km north-northwest.

2.2 Cameras

Several types of cameras, lenses, film and mountings were used during the field experiments. At sea, the same model of Nikon F "Fish-eye Nikkor" 176° lens was used on the ships in both years. Examples of pictures taken with these cameras are shown in the top half of figure 2. The same cameras and lens are shown by Pochop and Shanklin (1966), except

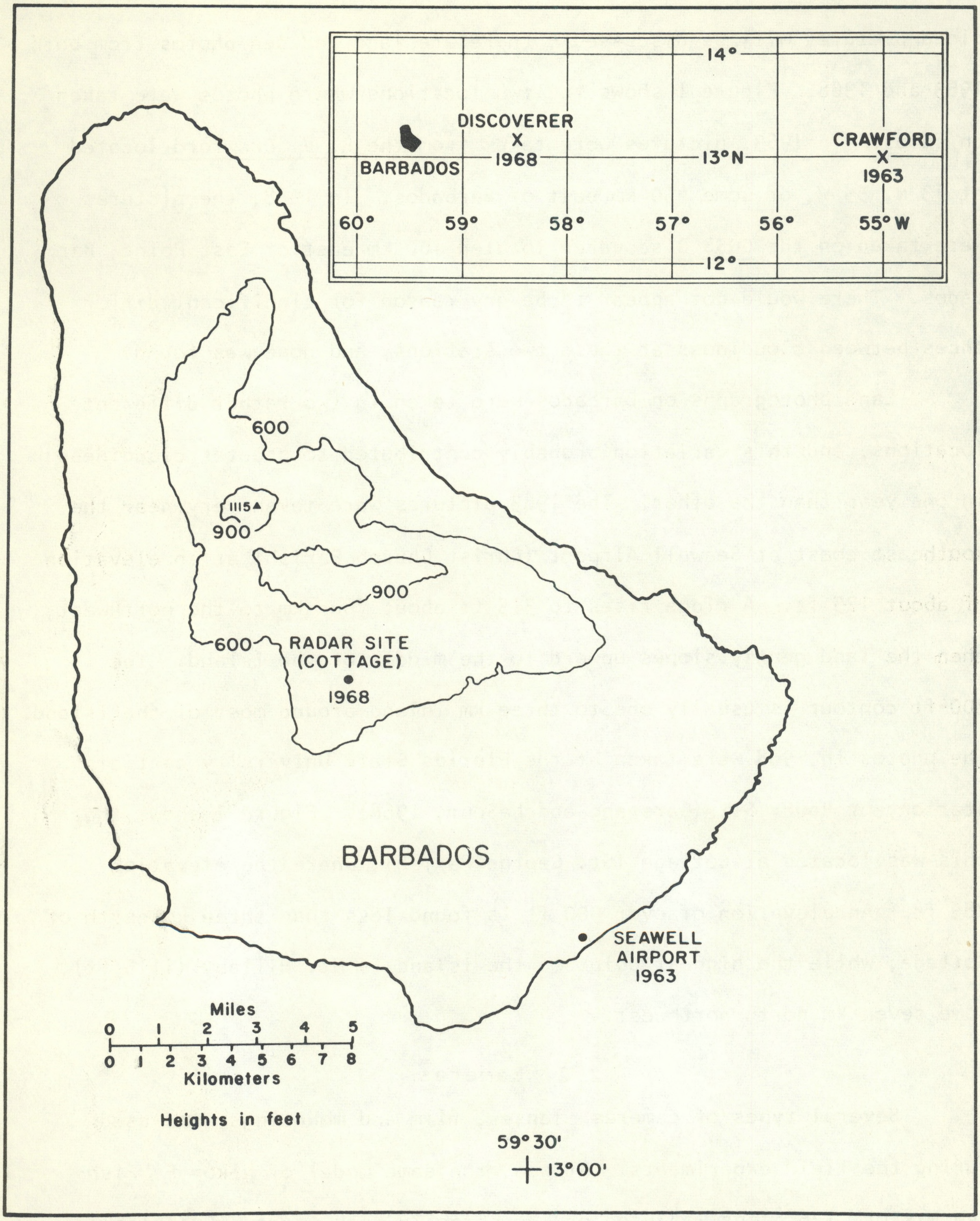


Figure 1. Map showing the four locations where all-sky photos were taken for analysis in this study. The two stations on Barbados are marked with dots, while the two ship stations are marked in inset with crosses.

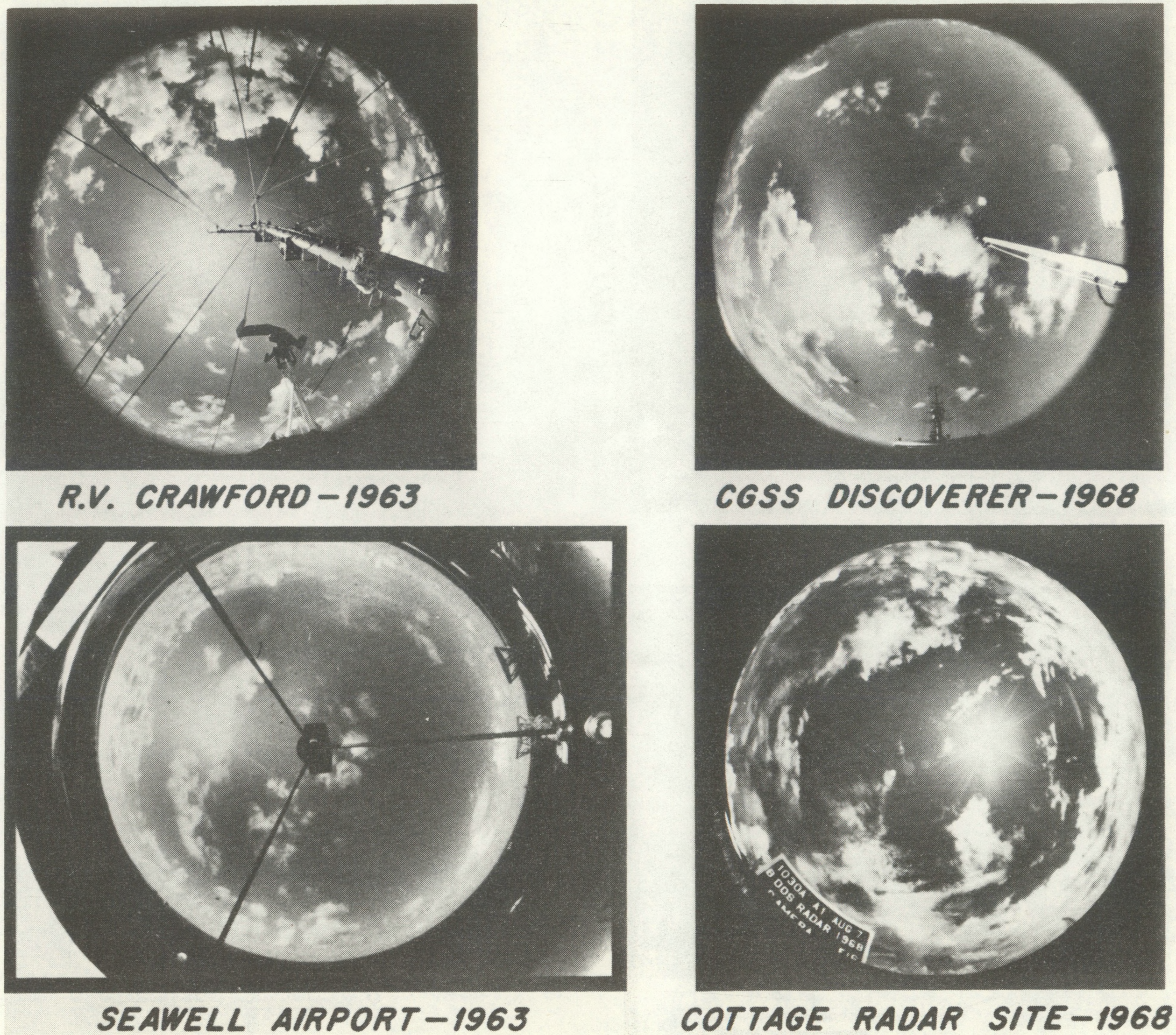
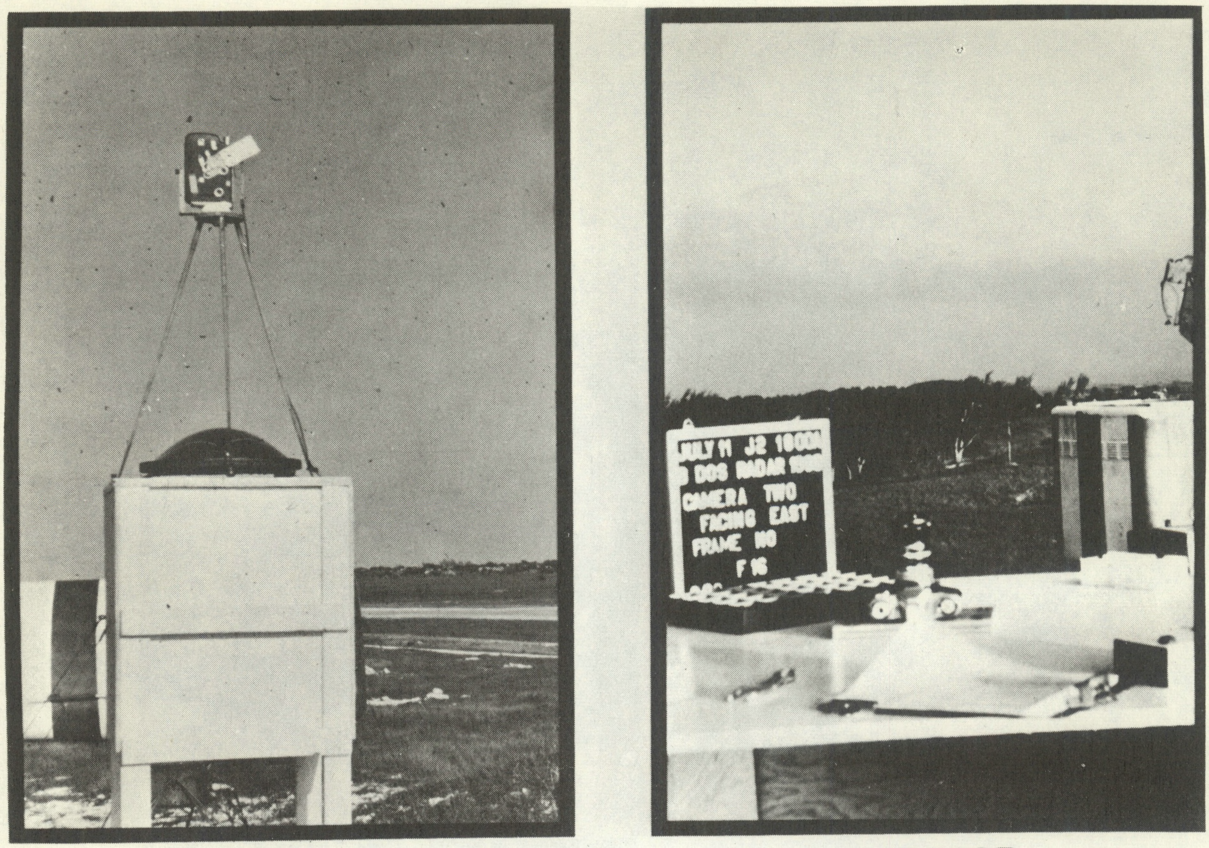


Figure 2. Sample all-sky photos from each of the four camera systems.



SEAWELL COTTAGE

Figure 3. Camera systems used for all-sky photographs at Seawell in 1963 and Cottage in 1968.

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we did not use the motor drive.

At Seawell Airport in 1963 the all-sky photos were taken atop an M-33 radar van, as shown in left, figure 3. This is the same radar system used by Saunders (1965), who supplemented his study of radar data with the all-sky pictures. A Kodak K-100 16mm movie camera using a 15mm wide-angle lens was pointed at a parabolic mirror. The lens was located six mirror focal lengths from the vertex of the mirror. A sample frame is shown in the lower left of figure 2, where we see the camera as a small object in the middle with three supporting struts leading to the edge.

The Cottage Radar Site photos in 1968 were taken with a Zeiss Ikon Contaflex camera holding its standard Tessar f2.8, 50mm lens. On to this lens was mounted a Spiratone "fish-eye 180° lens," although the range of coverage is actually slightly less than the Nikon 176° lens. This system was set each half hour on to a bracket located atop an M-33 radar van, as shown in the right half of figure 3. A sample photo is shown in the lower right of figure 2.

All photos were taken in color. Both cameras in 1963 used Kodachrome II film. Both cameras in 1968 used Ansco 100 film.

2.3 Number of Observations

Photos were taken on part or all of 42 days at sea and 47 days on land in both years. The Seawell photos in 1963 consisted of a time lapse view of the sky taken every several minutes, so that the hourly cloud cover which we extracted is not all that is available. On the Crawford in 1963, the pictures were taken once each hour all day. Both sets of photos in 1968 were taken on almost every day the ship was on station. The land photos were taken on days specified in advance for intensive island data collection, usually in stretches of three or five days. Extensive logs of the photography program were kept, and in 1968 the date and time were placed in the photos themselves (see figure 2). One other feature to note is that for both years together, 71 percent of all observations on land were coupled with a simultaneous all-sky picture at sea.

It is important to have a clear idea of how many pictures were available for analysis in this study. Since there are so many permutations which can be made on the sample, we should appreciate the number of observations in each category. Including all weather types, we find a total of 1885 available observations, distributed among locations as shown in Table 1.

Table 1. Number of All-Sky Photo Observations Analyzed on the Hour (Additional Data on the Half-Hour Indicated in Parentheses).

	BARBADOS	SHIPS	ALL LOCATIONS
1963	296	211	507
1968	359 (331)	358 (330)	717 (661)
Both years	655 (331)	569 (330)	1224 (661)

In 1968 about 60 percent of these photos were taken in August nnd 40 percent in July. In 1963 almost all were in August, except a few days for each station in September. Hence, over 70 percent of the photos for both years together are from August. It should be realized that we will often disregard the 1968 half-hourly observations in order to make comparisons between years somewhat easier. Otherwise, the smaller 1963 sample carries too little weight, since there often are important differences between years. So Table I shows that of the 1885 times analyzed for all locations, somewhat more than half were taken on land. There were 661 times analyzed with half-hourly data in 1968 at both places. The distribution of observations through the day is shown in Table 2.

Table 2. Distribution of All-Sky Observations Analyzed as a Function of the Hour of the Day; 1963 and 1968 Combined (no 1963 Data on the Half-Hour).

Time	Number of Observations Land	Number of Observations Sea
0600	23	29
0630	23	27
0700	42	43
0730	23	28
0800	48	48
0830	30	28
0900	58	48
0930	29	26
1000	57	45
1030	28	27
1100	59	43
1130	30	27
1200	61	48
1230	28	28
1300	60	48
1330	31	27
1400	60	48
1430	28	28
1500	57	48
1530	28	27
1600	57	44
1630	29	27
1700	52	48
1730	28	28
1800	25	23

Most importantly, early morning data in 1963 was sparse, since there were only two observations at 0600 AST at sea and four on land. This should be realized later when examining results in the early morning. Also, no 1963 pictures were available for 1800 AST.

3. DISTURBANCE CLASSIFICATION

There is more to be learned from these all-sky photos than diurnal variations over land and sea, since tropical clouds react differently to weather disturbances than they do in undisturbed conditions, depending on location and time of day. This supports the results of Garstang (1967) who showed that significant differences exist between energy exchanges during different degrees of disturbance. Fortunately, Barbados has a long history of raingage data which has been utilized to quantify the extent or lack of synoptic-scale disturbances. From these reports a classification of the state of the atmosphere has been developed. A similar method using rainfall from several islands is discussed by Simpson, Garstang, Zipser and Dean (1967). For our purposes, we have used rainfall data only from Barbados as shown in Table 3.

Table 3. Classification of Disturbance of Tropical Atmosphere Based on Surface Rainfall of Barbados.

Mode	Description		Percentage of stations reporting rain in 24 hours
1	suppressed	undisturbed	≤ 15%
2	neutral	undisturbed	16 - 55%
3	weakly disturbed	disturbed	56 - 75%
4	moderately disturbed	disturbed	76 - 85%
5	strongly disturbed	disturbed	> 85%

The exact application of this classification system varies somewhat from year to year. On the island in 1963 we used the 24-hour rainfall (0600 of date to 0600 AST of following day) from 75 raingage stations in operation during that summer. The percentage of these stations reporting 0.001 inch or more of rainfall was used to classify the days into modes 1 to 5 according to Table 3. Note that these modes then applied to an entire day at a time.

For the *R. V. Crawford* in 1963 there was no way to obtain meaningful disturbance modes from the meager rainfall observed at the ship. Instead, we used the classification system given by Garstang (1967) based on wind speed, steadiness of wind and synoptic features. The same modes were used in Holle (1968) to analyze panoramic photos on the *Crawford*. Since the determination of modes with this system is less clearly defined than with raingage stations, we divided these hours on the ship only into mode 2 (undisturbed) and mode 4 (disturbed). These periods begin and end at various hours, rather than a fixed time of day.

In 1968 the same modes were applied to both Radar Site and *Discoverer* photos. These were based on Barbados rainfall and Table 3. This time the rainfall for 12-hour periods from 0600 to 1800 AST was the input, using 31 stations in July and 63 stations in August. Table 4 shows the distribution of all analyzed all-sky pictures taken during 1963 and 1968 after these modes were determined. We see that most pictures were taken during undisturbed modes 1 and 2.

Table 4. Distribution of all Usable All-Sky Observations Based on Disturbance Classification; for Land and Sea, 1963 and 1968 (Half-Hours Included).

Mode	Number of Usable Times
1	766
2	622
3	208
4	152
5	137

4. METHOD OF DETERMINING CLOUD COVER

4.1 Routine of Photography

The 1963 island all-sky photos consisted of continuous time lapse film whose exposure was set at one value for the entire time. This worked quite well, since the Kodachrome II color film has a wide latitude of response to outdoor light. In addition, the reflecting mirror (figure 3) had a field of view greater than 180°, hence the overall light reading changes little except near sunrise and sunset, or in very heavy overcast and rainy conditions. An advantage to time lapse motion pictures is the differential motion of various cloud types and layers; this feature facilitates separation under some circumstances when single hourly photos are less adequate.

All other photos were still photos taken three at a time, either hourly, or half-hourly. The first exposure was taken at the proper exposure according to the light meter; the second was taken one f-stop darker and the third was taken one stop lighter. This bracketing procedure is encouraged for several reasons. The light meter reading changes rather slowly through the middle of the day due to the large area of sky being included. However, the sun is present in most pictures (see figure 2), and its brightness in one area will sometimes make clouds difficult to observe. In particular, the differentiation between cloud types was most difficult near the sun, and in most cases the darker photo was the best for this purpose. However, the lightest photo also had the utility of making thin clouds and the time identification easier to see. During early and late hours of the day, when light is changing more rapidly, it is nearly impossible to make a correct exposure every time, and the importance of bracketing to obtain the best resolution of cloud types should not be underestimated.

A level camera is another rather important requirement. Since most all-sky lenses do not have a full 180° view, one hopes to have tree tops or other features available for orientation. On a rolling ship it is also helpful to take three photos and avoid having too much sea on the picture edge. This problem was minimized by the gyro system of von Arx (1958).

4.2 Lens Characteristics

All of the lens or lens-mirror systems used in this study were azimuthally equidistant. That is, the relation is linear between zenith angle and distance of the image point from the picture center. Then half way out from the center of the picture corresponds to a zenith angle of 45°; two-thirds out from the center relates to 60°, etc. Examples of such relations are shown in diagrams by Pochop and Shanklin (1966) and Lyons (1971). The lenses used in this study have been checked either during or after the projects and found to agree with an azimuthally equidistant curve within 3° at any location, which is equivalent to other errors. These comments apply to the still cameras at all times. However, the linear relation held for the Seawell time lapse system only because the lens was located at six mirror focal lengths from the vertex of the reflector (see Chapter 2). So we see that lens systems with linear characteristics will not actually "distort" the sky at all, but only reproduce the sky as it appears from one surface location.

4.3 Determination of a Grid for Analyzing Cloud Cover

In order to design a grid, we must answer the question "what is cloud cover?" One can visualize that if the sun were overhead at noon in some tropical location, and there were perfectly flat or vertical cumuli over the land, the area of shadows from these clouds would be an exact measure of cloud cover. Since clouds move, slant, vary in thickness, are observed from a point on the ground, are at different heights, and do not usually occur with the sun overhead at noon, there may well be no way to obtain the true cloud cover in absolute numbers. For a radiaton balance study, the clouds overhead are much more important than those some distance away. For a study of synoptic conditions, clouds toward the horizon may be of greater importance. Hence, we must tailor our analysis to the intended use.

One general comparison we can make with all-sky photos is to analyze them in such a way that the numbers are similar to an observer's cloud cover. The usual meteorological surface observation considers cloud cover to be the amount of sky covered by clouds. That is, divide the sky into eight or ten or 100 equal parts. By dividing the sky this way, it seems that two opposing effects are being included: (1) the overhead sky is emphasized in that a small cloud overhead contributes more to sky cover than it would if near the horizon; while conversely (2) many small cumuli near the horizon give rise to a packing effect which makes cloud cover greater near the horizon than would be the case if the same clouds were overhead. This is the true nature of observing cumulus clouds from a point on the surface -- again, the lens is not responsible for this apparent effect. Another complicating factor in observing the sky is the physiological effect. Miller and Neuberger (1945) discussed how an observer tends to overestimate elevation angles near the horizon compared to the zenith by up to 20°. This results was confirmed from whole-sky pictures by Merritt (1966). Design of a photographic system to include this effect was discussed by von Arx (1958). While this bias is real enough in observers' records, we do not wish to include this physiological effect in our photo analysis, but instead to avoid this problem by designing an objective method to find cloud cover.

The first consideration in making the grid was to exclude a portion around the outer edge. In our analysis we have ignored the outer 17 percent of the distance from the center to the picture's edge, which corresponds to 31 percent of the total area (see figure 4). This corresponds to not counting the cloud cover at less than about 15° above the horizon. Specifically, we are not including a cloud at 500 ft above the camera which is beyond 1/3 mile. Also, a cloud at 5000 ft above the camera is being ignored beyond three miles, while a cloud at 50,000 ft is excluded beyond 27 n mi. Hence, this ungridded region is very height-dependent. There are several factors which led to this exclusion. Sometimes the ocean or other obstructions protrude above the horizon. At various times the sky is very hazy in the Barbados area and we cannot easily distinguish between cloud and haze around the sun near the horizon. When the air is clearer, at nearly all times we see distant cirrus and the sides of distant cumuli. Figure 2 shows that separating clouds near the horizon into different cloud types is a rather arbitrary decision in many cases. Perhaps the only question is how much area near the horizon cannot be analyzed objectively, rather than whether any should be excluded. Nevertheless, this decision may cause an underestimate of the cloud cover by perhaps several percent compared to the results from analyzing the total circle.

We now must discuss what particular type of grid should be used for the analyzed portion of the sky. There are cogent reasons for using each of several types; no one particular grid will fit all purposes and viewpoints. Hence, the 1963 data were analyzed with a nonlinear grid and the 1968 data with a linear grid. These are shown in figure 4. Results

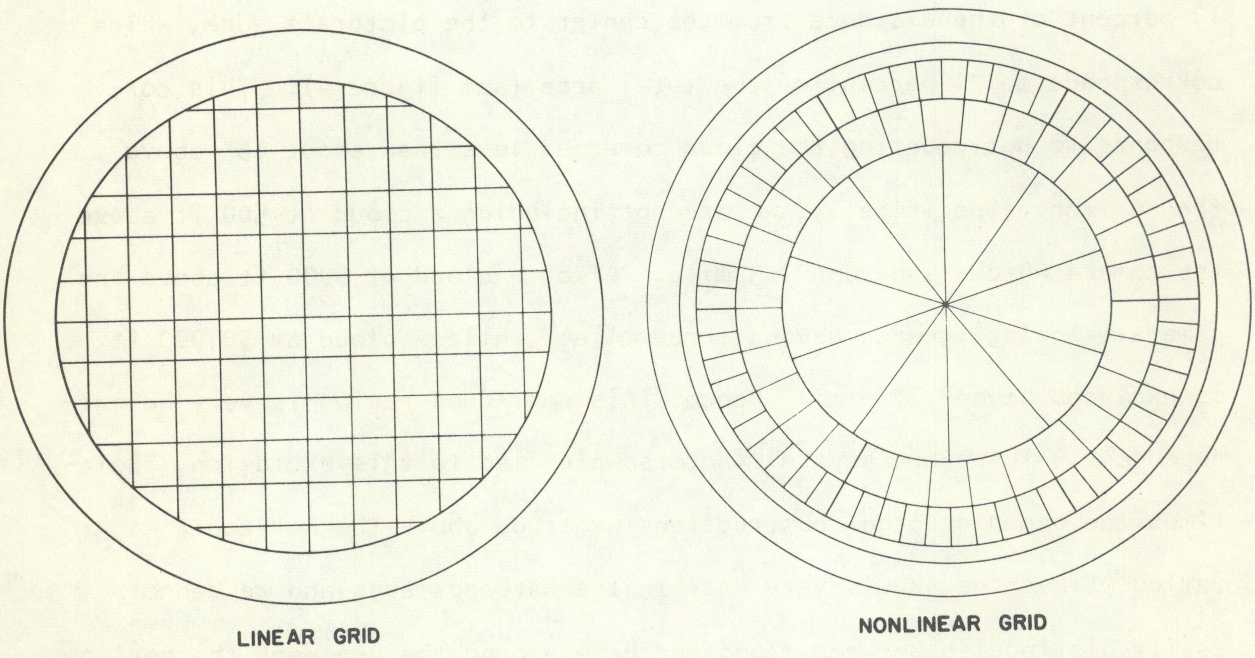

Figure 4. The two grids used to obtain cloud cover percentages from all-sky photographs.

will be seen to be remarkably similar in many respects, and differences between years will be due principally to location rather than grid. The linear grid uses an equal solid angle approach by dividing what the camera has seen in two dimensions into 100 equal parts. This would seem closest to the method which a surface observer is instructed to use (except for completely ignoring the outer circle). We can describe the concentric nonlinear grid as one using a tangent plane approach by noting that in the real sky, a given cloud overhead would later subtend a smaller apparent area if it moved into the distance. Three concentric rings were designed with ten divisions in the center ring, 30 in the middle and 60 in the outer annulus. For this grid one percent of cloud cover overhead corresponds to a given-sized cloud, depending on its height. If this cloud moved outward and was enclosed completely in the outer ring, it would count one percent there also, on this nonlinear gird. Thus, it emphasizes overhead clouds less than the linear grid, although for cloud cover below 50 percent or so, the difference between grids is less due to a greater proportion of clear sky overhead.

A short comparison of grids was made with an independent data sample and showed only small differences between analysis methods. For 119 hours of data (from 1957 cruise) the concentric grid gave an average of 3.5 percent more total cloud cover than the linear, four percent more low cloud and 0.5 percent less middle plus high cloud. Hence, the concentric grid will give somewhat more total and low cloud cover because it is emphasizing those packed near the horizon. As mentioned before, however, our ideal "cloud cover" consisting of vertical shadows cast on the earth would seem to indicate that including cloud cover near the horizon is not entirely desirable for many purposes. It is rather difficult to emphasize one feature on these grids over another. Perhaps the best data to supply in future all-sky analyses is some measure of the radial dependence of cloud cover, so that each user can weight the cloudiness to fit his particular purpose. In a small way, these data were found here by recording separately the percentage of cloudiness rates for the three rings in the concentric grid (see Chapter 4).

4.4 Cloud Level Stratification

The 35mm photographs were mounted on a Recordak MPE film reader and projected on to one of these grids. The 16mm film was projected directly on to the grids, which were mounted on the wall. In both cases the outer edge of the cloud picture just filled the entire circle; hence some clouds were in the ungridded region. The amount of time necessary to find percent cloudiness by visual inspection at one time is quite small. In addition, the three categories of low, middle and high cloud cover can be obtained easily at the same time.

Low clouds are the easiest type to identify because of their typical cumuliform appearance. A completely overcast rainy sky (not frequent at any location) was usually called low cloud. The only difficult low cloud situation occurs when a layer cloud may exist near the two km (6500 ft) boundary between stratocumulus and altocumulus. This is the dividing level between low and middle clouds in the topics, according to the World Meteorological Organization (1956). This boundary could not, of course, be decided for certain, although the analysis was helped in many cases by the more conventional view from panoramic Hasselblad photos similar to those in Holle (1968). These were taken at all locations except Seawell in 1963. There were few cases with this difficulty; however, they tended to occur with large values of cloud cover.

The difference between middle and high clouds was more frequently a problem than the difference between low and middle. Hasselblad wide-angle panoramic pictures were especially useful here. The World Meteorolgical Organization (1956) lists middle clouds in the tropics as extending from two to eight km (25,000 ft), with high clouds from six to 18 km (20,000 to 60,000 ft). It simply is not possible at times to tell the difference bewween middle and high clouds, nor to know their heights. We will stress this in the results by calculating a combined percentage for middle plus high clouds together. In fact, there is probably not a great need, nor sufficient data, to permit separate figures for the two, much less the individual rate for altocumulus, altostratus, etc. There are several cases in 1968 when several experienced observers of tropical convection could not agree on whether an overcast was middle or high clouds. This discussion is particularly important in several cases when a disturbance started with low cloud cover, then only middle-layer altocumulus remained, which later merged into cirrus. The transitions in these situations were made abruptly from one height to another in half-hourly jumps. For the relatively small data sample, this is another reason for combining middle plus high for diurnal variation curves.

5. GENERAL RESULTS

All of the usable photo data were placed on punch cards for each half hour, together with the disturbance mode for that time. The computer was instructed to sort the observations and provide nearly all possible permutations of the data by year, location, mode, time of day, and level of cloud. The number of cases for each subset also was obtained. There are so many possible permutations that single categories sometimes have very few cases, especially for the more disturbed modes (Table 4).

Disregarding time of day, we can obtain many of the significant results. Later (Chapter 5) we will show diurnal components of the cloud cover. In Table 5 we have the total cloudiness for all modes together. We see that the total cloud cover found in this study is 43.5 percent for all observations. Total cloud cover was 40.9 percent at Seawell in 1963 and 56.5 percent at the Radar Site in 1968. At sea, the average total cloudiness was 29.0 percent at the Crawford in 1963 and 36.2 percent at the Discoverer in 1968. Note that when comparing total land cover in both

Table 5. Average Total Cloud Cover in Percent, on Land and Sea for Both Years (Half Hours Included for 1968). Numbers in Parentheses Refer to Observations When Photos Were Taken Simultaneously at Two Stations.

	BARBADOS	SHIPS	ALL LOCATIONS
1963	40.9	29.0	35.9
1968	56.5	36.2	46.3
BOTH YEARS	51.8 (50.4)	34.5 (34.1)	43.5 (42.2)

years to that at sea for both years, the extra 1968 half-hourly data biases these overall results toward the 1968 figures, giving an average land total cloudiness of 51.8 percent and oceanic cloudiness of 34.5 percent. The 1963 average for both locations is 35.9 percent and the 1968 average is 46.3 percent (half-hourly data do not affect this comparison) although a combination figure for land and sea together does not represent any meaningful physical process. The numbers in parentheses indicate that total cloud cover is very similar for (1) all hours and (2) only those 71 percent of the hours with simultaneous land and sea photos. Hence, we will not discuss the simultaneous data again. So we see that the 1968 oceanic total cloudiness is 7.2 percent more than in 1963, while the land difference is 15.6 percent. Part of the Barbados increase in 1968 is attributable to the higher elevation at the Radar Site, but it would appear that the 7.2 percent oceanic increment would represent more real cloudiness over the ocean in 1968 compared to 1963. This is especially true in view of the result we found previously that the concentric grid (used for 1963) tends to give several percent more clouds than the linear grid (used for 1968). It is possible that since Seawell is very near the ocean, cloud amounts are somewhat less due to part of the picture, including oceanic effects.

Breaking down the total cloudiness results of Table 5 into height levels, we find the results shown by Table 6. The first number shows the amount of low cloud, and the second number is the sum of high plus middle cloud cover percentages. At sea there is a remarkable agreement between low cloud cover, both years giving about 13 percent. This is rather

Table 6. Average Low Cloudiness (First Number) and Sum of High Plus Middle Cloud Cover (Second Number) for Land and Sea (Half-Hours Included for 1968).

	BARBADOS	SHIPS	ALL LOCATIONS
1963	24.8/16.1	13.2/15.8	19.9/16.0
1968	39.8/16.6	13.1/23.0	26.5/19.8
BOTH YEARS	35.3/16.5	13.2/21.3	24.7/18.8

reassuring in that different years, grids, locations, ships, cameras and observers were employed. The increase of total cloud cover in 1968 over 1963, which we saw in Table 5, is thus due to an increase in middle plus high cloudiness. Almost all of this increase, in fact, is due to high clouds alone (13.3 versus 6.3 percent). On Barbados the sum of middle plus high cloud is similar in both years. There is about 2 percent less high cloud and about 2 percent more middle cloud in 1968 than in 1963 on land. Thus, the principle difference between years consists of 15 percent more low clouds in 1968. Some of this difference could also be due to the more oceanic character of the sky at Seawell in 1963. We should recall that the increased low cloud on land in 1968 probably obscured some middle and high clouds. Again, the half-hourly data for 1968 bias the combined years' averages in Table 6 toward that year's values. Hence, we conclude from Table 6 that a greater total cloud cover at both stations in 1968 was due to more low clouds on land, and more high clouds at sea.

Stratification of the data by disturbance mode is shown in figure 5. Here we combined data from both land stations and both ships to obtain the largest possible data sample. Total cloudiness is 36 percent for modes 1 and 2, but increases rapidly for higher classifications until 84 percent is seen for mode 5. Low cloud remains in the range 21 to 32 percent at all times. Hence, the increase in total cloud with degree of disturbance is accountable mainly in terms of an increase in middle plus high cloud. Middle cloud separately shows a regular increase with mode; but for reasons discussed previously we cannot easily distinguish middle from high so that the sum is more significant. This sum of middle plus high ranges from 15 percent in mode 1 to 52 percent in mode 5. One should also note that more middle cloud means less chance of observing high cloud; hence high cloud probably also increases at least as much as middle in figure 5. More detail on how these percentages change with location will be shown in Chapter 6 on diurnal variation.

Frequency distributions of cloudiness percentages can help show details in the general results of Table 6, which would not be available otherwise. Table 7 shows that total cloudiness on land for both years together was zero during 2.7 percent of all hours, while each 10 percent category up to 40 percent cloudiness occurred during 10 to 11 percent of the hours. The largest single category was between 91 and 100 percent land cloudiness, which occurred 22.1 percent of the time. At sea, total cloudiness was most frequent between 1 and 10 percent, with a secondary

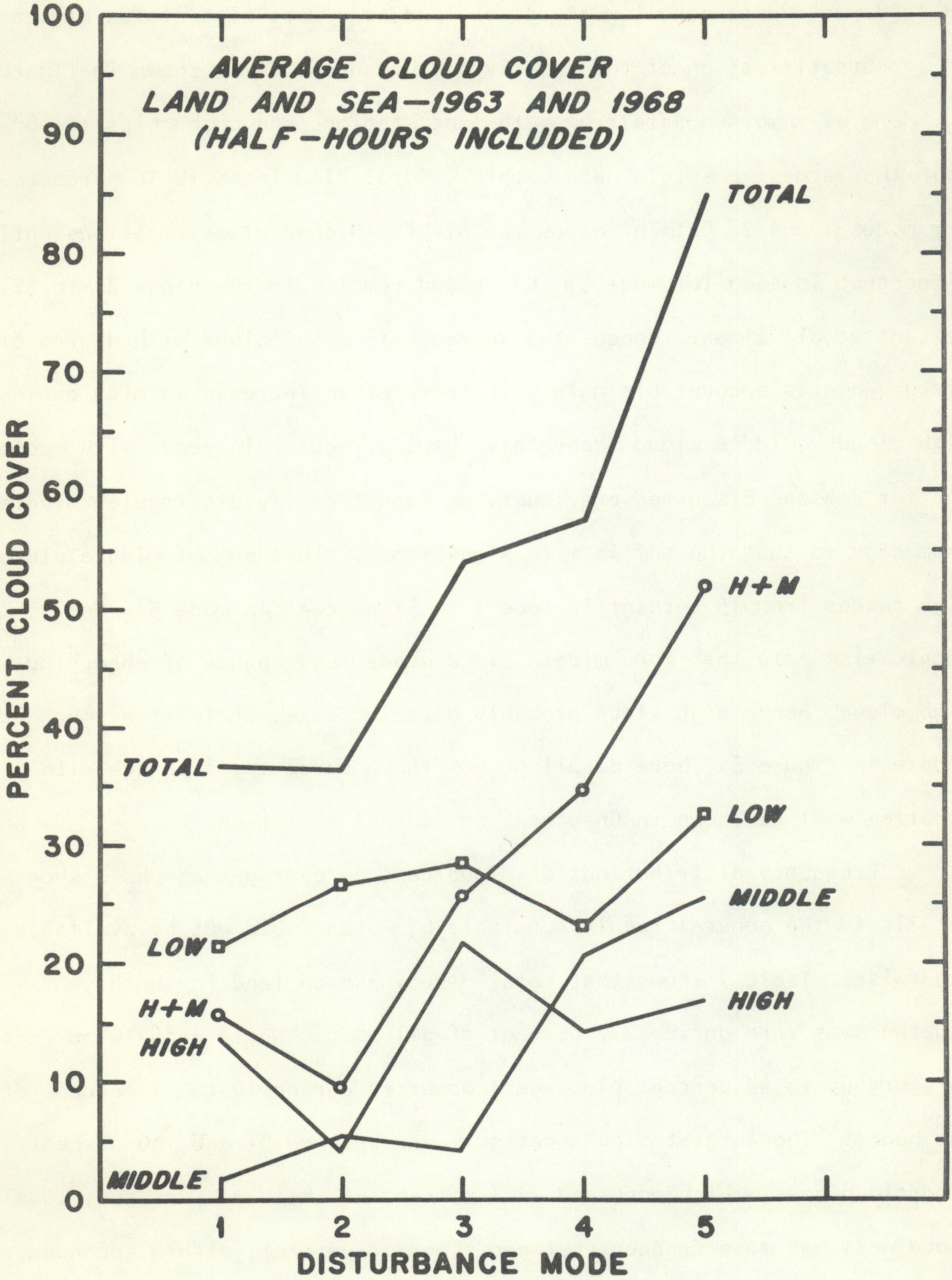

Figure 5. Distribution of total, low, high, middle, and middle plus high cloud cover percentages with disturbance mode. All years, hours and locations are combined.

Table 7. Frequency Distribution of Cloudiness by 10-Percent Categories for Total, Low, and Middle Plus High Clouds on Land and Sea for Both Years Together (Half-Hourly Data Included)

	TOTAL		LOW		MIDDLE PLUS HIGH	
	LAND	SEA	LAND	SEA	LAND	SEA
0% Cloud Cover	2.7%	9.8	8.0	23.7	57.8	43.6
1-10	10.2	27.0	17.5	42.0	12.9	21.7
11-20	10.9	14.5	14.3	13.9	5.4	6.2
21-30	11.0	9.0	13.1	7.3	2.8	2.9
31-40	10.5	6.5	11.8	4.4	2.5	3.7
41-50	7.4	6.2	7.4	2.4	3.7	2.9
51-60	7.4	2.9	6.4	1.3	2.1	2.4
61-70	4.8	2.8	3.4	1.1	3.2	1.0
71-80	5.5	2.3	3.8	1.0	2.9	2.8
81-90	7.5	2.8	5.4	1.0	1.8	3.4
91-100	22.1	16.2	8.4	1.9	4.9	9.4

maximum for nearly overcast conditions.

Looking at low clouds in Table 7, nearly 80 percent of the hours at sea had cloudiness of 20 percent or less, while on land the low cloud occurrences are more evenly distributed up to 50 percent. Middle plus high cloudiness was zero during 57.8 percent of the hours on land and 43.6 percent at sea. Upper clouds were rather infrequent in any other category, except near overcast at sea. Hence, we find that the fairly large maximum at 91 to 100 percent in total cloud cover is not marked for low cloud alone or middle plus high cloud alone. Also, the large frequency of no upper clouds does not extend to a peak in zero percent total cloud cover.

The same figures shown in Table 7 are plotted in figure 6. Here we see a cumulative plot of cloudiness frequencies. The curve for total land cloud cover is nearly linear from 0 to 100 percent of the hours, which indicates an equal distribution of cloud cover percentages. In

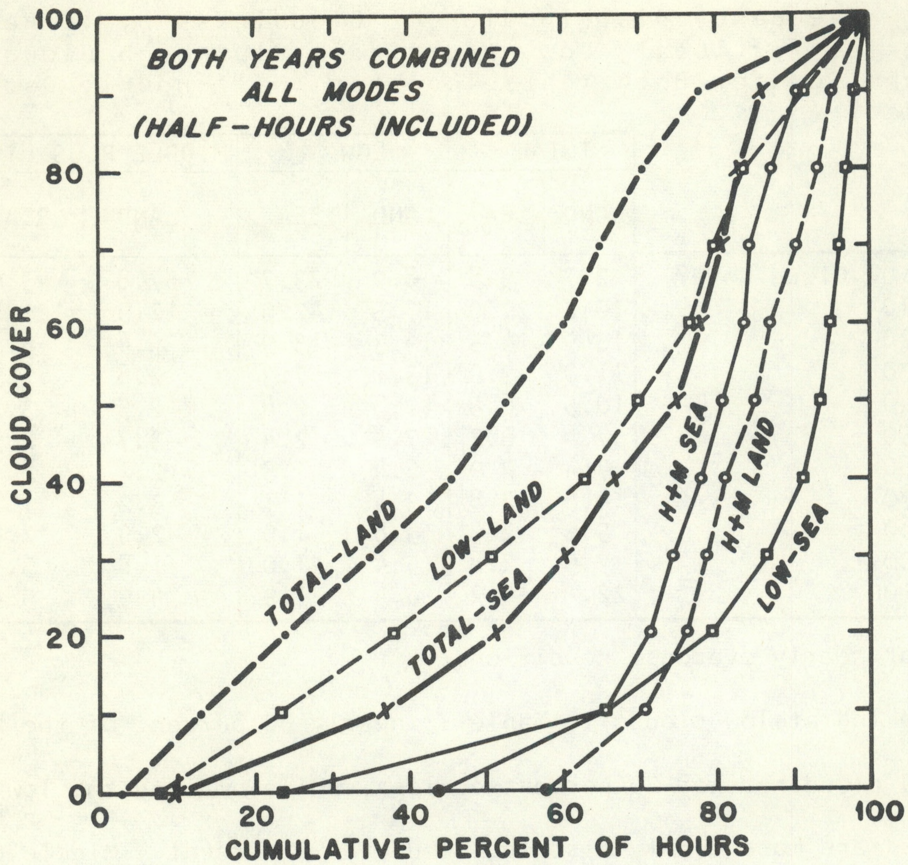

Figure 6. Cumulative percentages of cloud cover frequencies by ten percent categories for all modes, hours and years together. Curves are shown for total, low, and high plus middle cloudiness on land and sea separately.

contrast, the oceanic low cloudiness occurs principally with small cloudiness values, and nearly 90 percent of the hours are seen to have less than 30 percent cloud cover.

One other general result of interest is the radial dependence of cloud cover. We can extract this result only from the 1957 and 1963 data. In Table 8 we see two measures of this dependence using the concentric grid of figure 4. Data are used from the 1957 Crawford cruise (average total cloudiness of 44.6 percent), the 1963 Crawford cruise (30.7 percent)

Table 8. Radial Dependence of Cloud Cover on Distance From Center of Nonlinear Concentric Grid for 1957 and 1963 Stations.

	1957 Crawford		1963 Crawford		1963 Seawell	
	Normalized % of clouds	% of possible hours	Normalized % of clouds	% of possible hours	Normalized % of clouds	% of possible hours
Inner Ring	3.7	65	2.6	60	3.7	64
Middle Ring	4.3	87	3.0	78	4.3	86
Outer Ring	4.7	90	3.0	84	4.6	97

and Seawell Airport in 1963 (44.2 percent). The inner ring on this grid consists of ten sections, and the average cloud cover in these divisions in the 1957 data was 3.7 percent. The middle ring of 30 sections in 1957 averaged 12.8 percent per 30 divisions, which can be normalized to 4.3 percent per ten sections. The outer ring of 60 portions normalizes to 4.7 percent per ten sections. An almost identical dependency is found at Seawell in 1963. However, the middle and outer rings at the Crawford in 1963 have the same rate of cloudiness per ten sections. Despite the differences in location and amount of cloudiness, the percentage of hours with at least one percent of cloud cover in each annulus is rather consistent among stations. There was at least one percent cloud cover in the inner circle during 60 to 65 percent of the hours; at least one percent in the middle annulus during 78 to 87 percent of the hours, and some cloud in the outer ring during 84 to 97 percent of the possible hours. Hence, there is a definite radial dependence in the photos; how to use this knowledge should be determined by the purpose of the photos, as discussed in detail earlier in this paper.

6. DIURNAL VARIATIONS

Results presented in the previous section will now be permuted to look for several specific features on the diurnal scale. Unfortunately, there is no way to photograph and analyze clouds as well at night as during the day. Hence, we will confine attention to the period 0600 to 1800 AST (GMT minus four hours). However, we should note that radar echoes can be used at night, as in Holle (1968). Many different effects due to different mechanisms have been proposed to bring about various peaks and minima in cloudiness in the tropics at different times. Here we can test some hypotheses with a rather homogeneous set of data which has been analyzed objectively.

6.1 All Modes Together

The most general diurnal variation we can show is all land data compared to all sea data, as in figure 7. The number of observations which comprise this set is shown in Table 2, except that half-hourly data in 1968 have been omitted in the figure for clarity. As expected, the land curve (dashed) nearly always shows more total cloud cover than the sea (solid line). These figures would comprise the average total cloudiness of 51.8 and 34.5 percent in Table 5, except for omitting the half-hourly 1968 data. Barbados shows total cloudiness increasing continually from the morning until 1100 AST, then nearly constant until a decrease at 1800 AST. Oceanic total cloudiness decreases after 0800, then increases markedly after 1100 and is the same until sunset. Note that the difference between land and sea total cloudiness is nearly zero at sun-

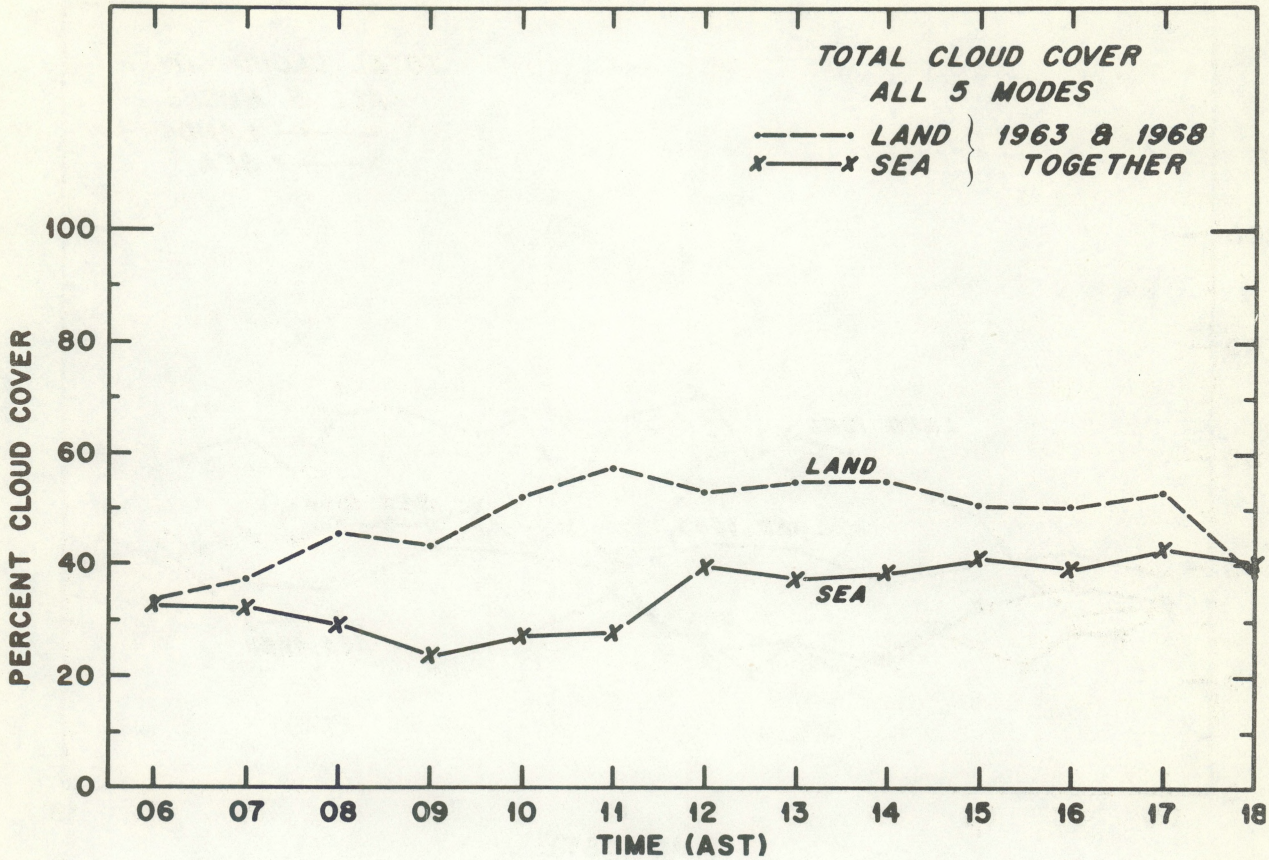

Figure 7. Diurnal variations of total cloud cover on land (dashed) and sea (solid line) for both years and all modes together.

rise and sunset, with a maximum difference at midday.

The diurnal curves of figure 7 now will be unfolded into many other comparisons. Figure 8 shows the difference between years in total cloud cover. This shows diurnal variations of the fact first revealed in Table 5 that total cloudiness was more on both land (dashed) and sea (solid line) in 1968 than at the 1963 locations. At ocean stations total cloud cover decreased after an early morning maximum. In 1963 there were peaks at noon and late afternoon, while in 1968 cloudiness was more and steadier all afternoon. On land the 1963 Seawell data shows little

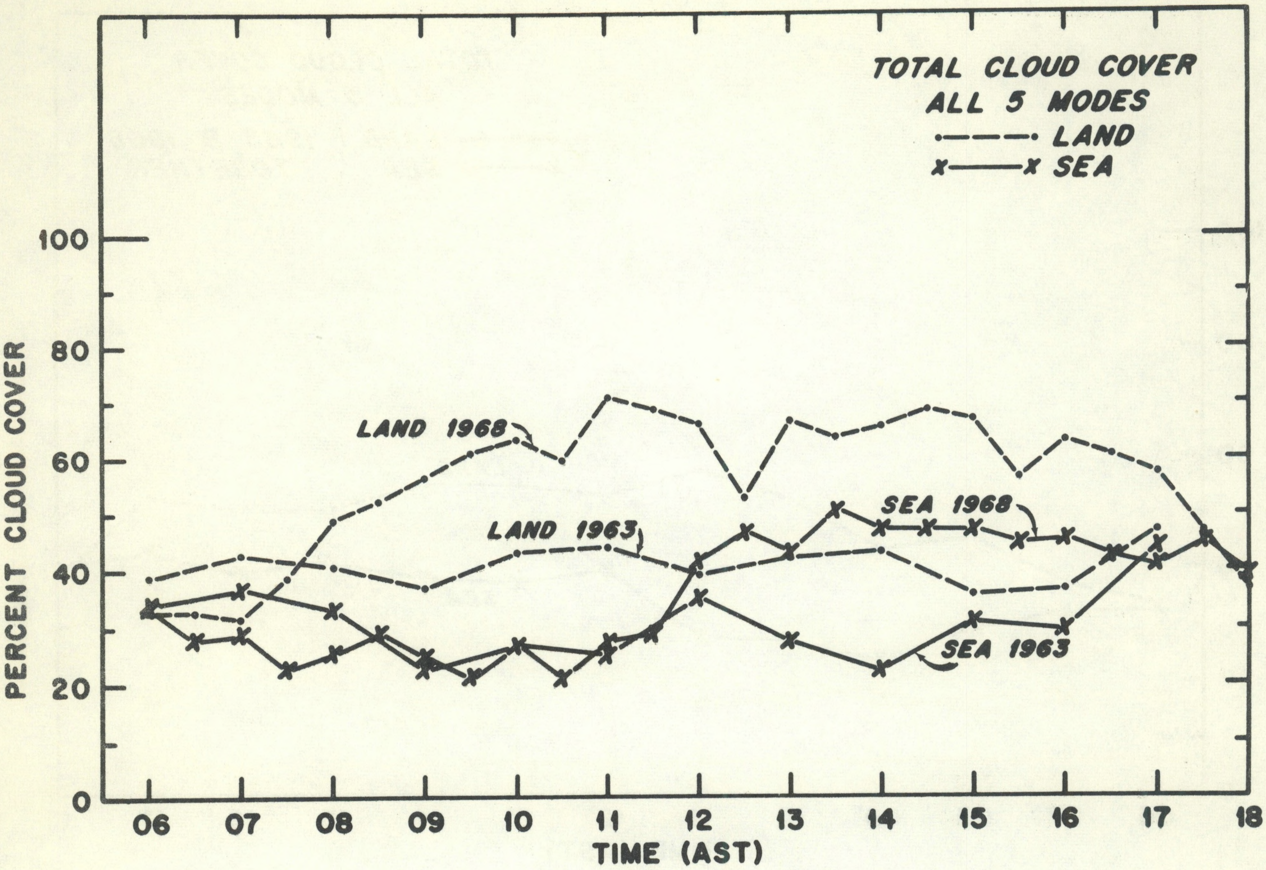

Figure 8. Diurnal variations of total cloud cover on land (dashed) and sea (solid line) by year, for all modes together.

diurnal variation, while the 1968 Radar Site cloudiness had a general midday maximum. (Note here that 1968 half-hourly data can be plotted next to the 1968 hourly figures, unlike figure 6 where 1968 half-hourly values usually will cause greater cloudiness on half-hours than on the hour for both years together).

Now consider the diurnal variations in low cloud cover (square data points) and in middle plus high clouds (open circles) in figure 9, for both years together. These figures comprise the averages shown by Table 6. Low cloud cover on land is greater than any other category and is

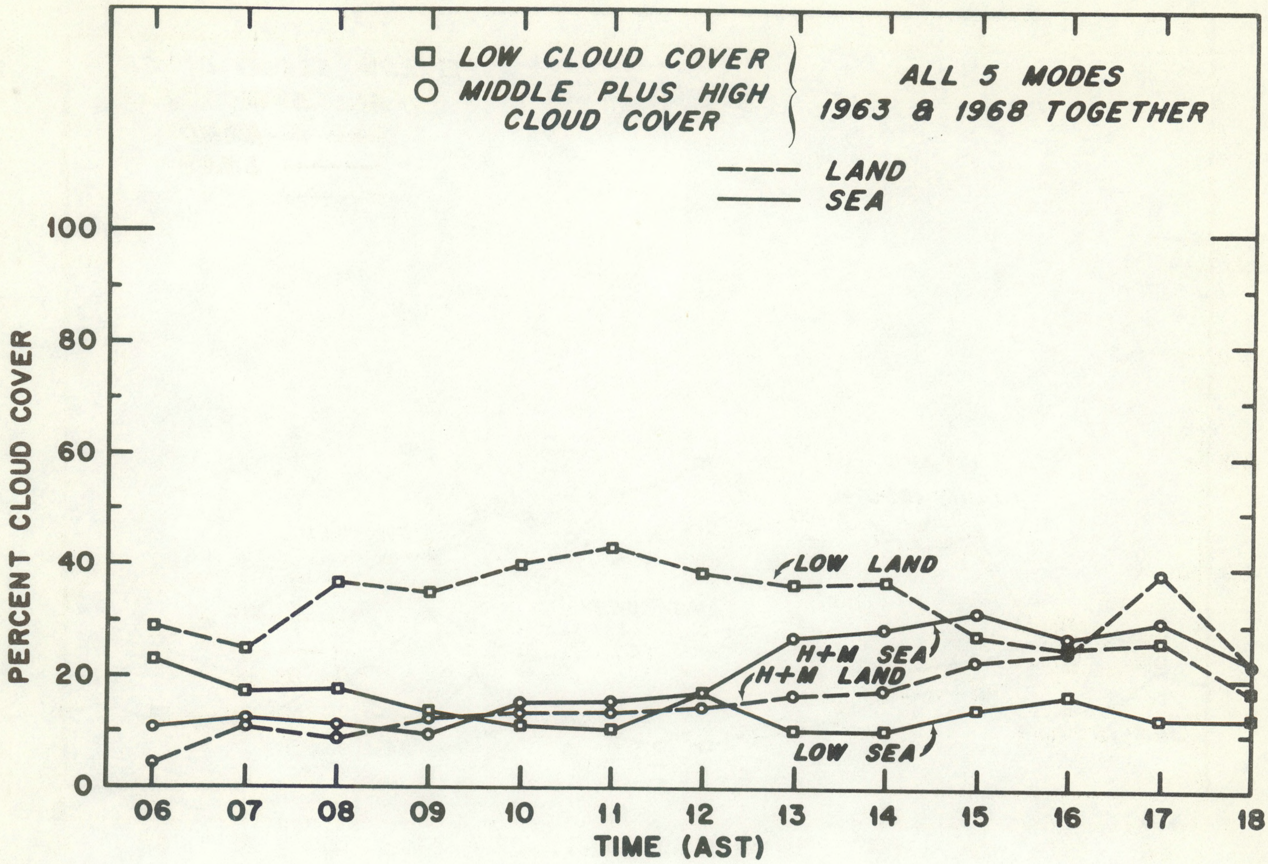

Figure 9. Diurnal variations of low cloud cover (square data points) and middle plus high cloudiness (open circles) on land (dashed) and sea (solid lines) for both years and all modes together.

above 30 percent during most hours, with a general maximum in midday. Low cloud at sea begins with 23 percent at 0600 AST and decreases to less than 20 percent for the rest of the day. Thus, by definition the total cloudiness in figure 7 remaining after low cloud is subtracted must be middle plus high clouds. On both land and sea this cloud cover starts rather low in the morning and increases after noon, especially at sea. It is particularly striking that the difference between land and sea low cloud cover is least at sunrise and sunset, while the difference for upper

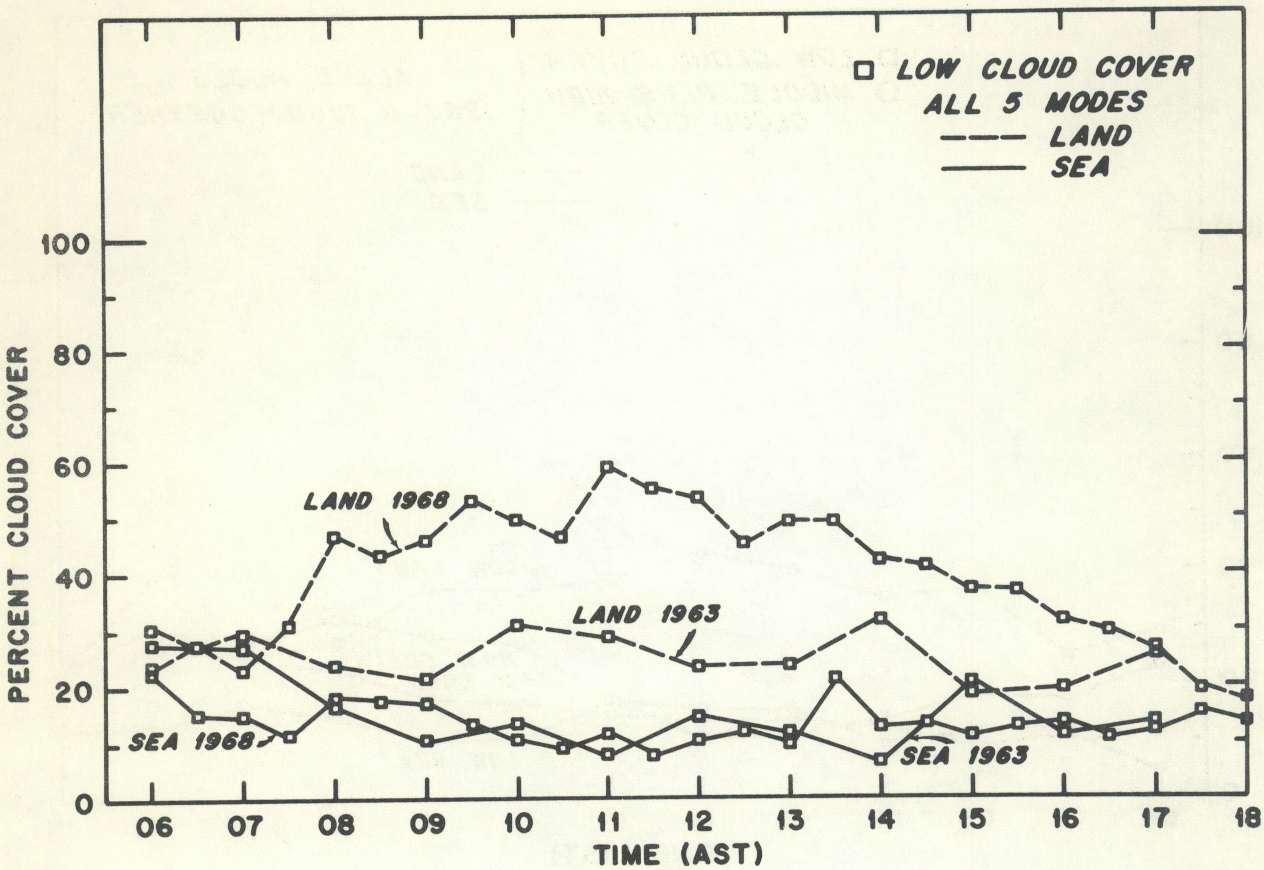

Figure 10. Diurnal variations of low cloud cover on land (dashed) and sea (solid line) by year, for all modes together.

clouds is quite small all day and has little diurnal component.

Now we subdivide the low cloud cover in figure 9 into individual years. It becomes apparent from figure 10 that the low cloud cover at the Radar Site in 1968 is substantially more than at any other station, and exhibits a large diurnal variation with a midday maximum. Low clouds at Seawell in 1963 rank second to the Radar Site almost all day. Neither shows any maxima at sunrise or sunset. In contrast, the low cloud cover at sea was similar in both years. Not only are the percentages similar

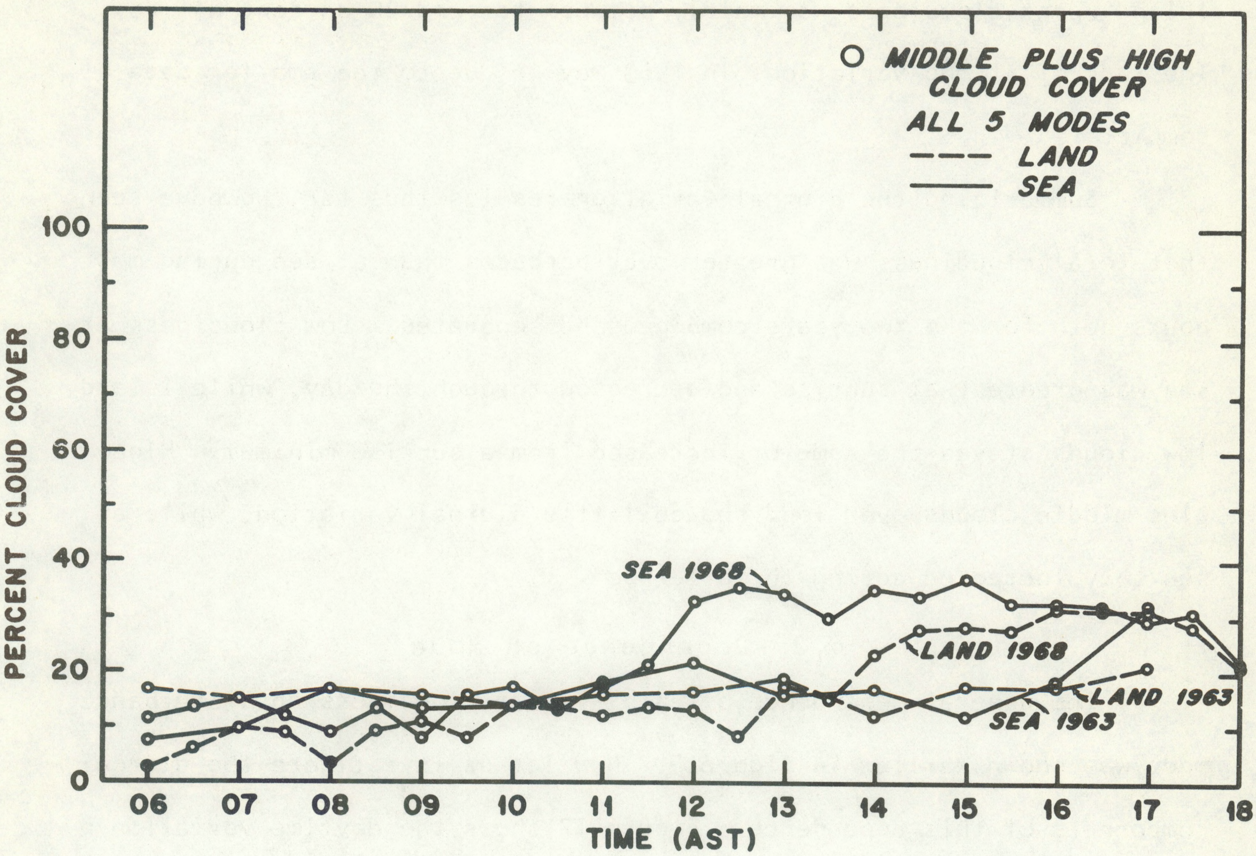

Figure 11. Diurnal variations of middle plus high cloud cover on land (dashed) and sea (solid line) by year, for all modes together.

over the whole day (Table 6), but hourly low cloudiness was almost the same every hour. There were maxima at sunrise, especially in 1963, but none at sunset.

Subdividing high plus middle cloudiness into each year in figure 11, we see no diurnal change from sunrise to noon. However, in 1968 there was a substantial increase beginning at noon over the ship and this upper cloud cover persisted for the afternoon. This is the same upper cloud increase evident in figure 9, as well as in the 1968 sea curve of figure 8.

Island upper cloudiness was mainly between ten and 20 percent all day. The lack of strong variations in 1963 may be due to the smaller data sample.

Summarizing the diurnal variation results thus far, we have seen that total cloudiness was greater over Barbados than at sea during most hours both for the two years combined and separated. Low cloudiness at sea was greatest at sunrise and decreased through the day, while island low clouds stayed the same or increased from a sunrise minimum. High plus middle clouds over land showed little diurnal variation, while at sea they increased during the afternoon.

6.2 Dependence on Mode

The general dependence of each type of cloudiness on disturbance mode was shown earlier in figure 5. Now let us investigate the diurnal components of this dependence. Figure 12 shows the daytime variation by mode of total cloud cover on land for both years together. There appears to be a fairly marked distinction between total cloudiness of almost 50 percent during most hours for modes 1, 2 and 3 compared to about 70 percent much of the time for modes 4 and 5. Note that mode 4 in the morning does not fit well; there are three or fewer cases each hour here; hence, we need not lend much significance to this dip. Total cloudiness for modes 1 through 3 shows clearer skies at sunrise and sunset than at midday.

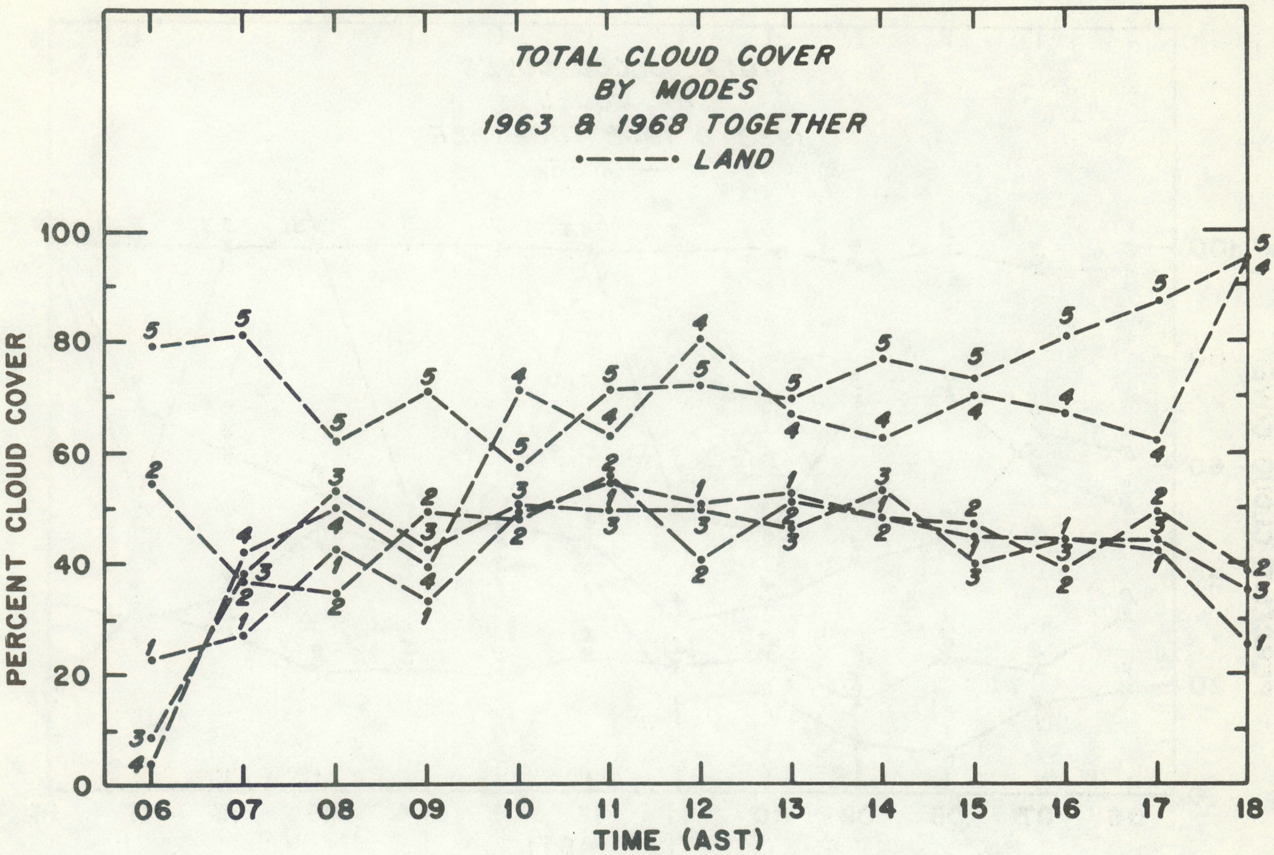

Figure 12. Diurnal variations of total cloud cover by disturbance mode for both land stations together. Numbers near dots indicate disturbance modes 1 through 5.

At sea the total cloudiness distribution in figure 13 shows a much wider variation with disturbance mode than it did on land. Mode 1 total cloudiness is low in the morning, then increases to over 40 percent during the afternoon, but no other category shows this behavior. Mode 2 total cloud cover was rather constant all day. Mode 3 shows a highly variable amount at several times due to few observations (four or less per hour); the composition of this behavior will be examined in later figures. Mode 4 cloudiness is largest in the morning and evening, while mode 5 stays near 100 percent all day for a small sample (two or less per hour).

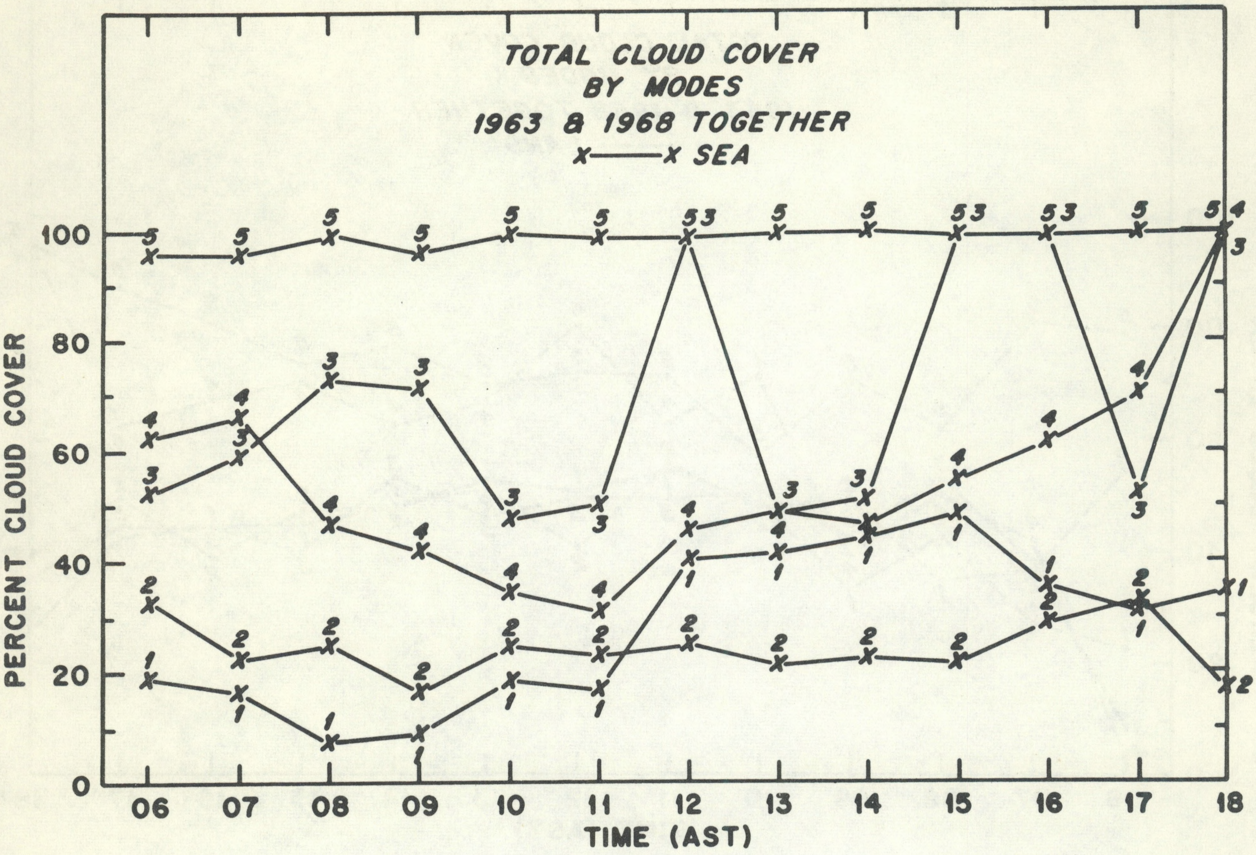

Figure 13. Diurnal variations of total cloud cover by disturbance mode for both ship stations together. Numbers near crosses indicate disturbance modes 1 through 5.

The general conclusion certainly can be drawn from figures 12 and 13 that total cloudiness at sea reacts more markedly as modes change than it does over the island.

Low cloudiness by mode over land (not shown) generally follows an envelope of ± 15 percent around the "Low-Land" curve in figure 9. Modes 2 and 5 are larger than the mean at sunrise and the rest are small, while all five decrease somewhat toward sunset. All five have a general midday maximum.

Oceanic low cloudiness by mode shows little variation after 1000 AST, with nearly all values below 20 percent, as the "Low-Sea" curve in figure 9 shows. The only features of note are large figures of 35 percent or more for modes 3 to 5 during the first few hours of the day; mode 2 also starts with 24 percent at 0600 AST and decreases thereafter. In summary, the photos show that disturbed conditions over the ocean during the first few hours of morning are associated with considerably more low cloudiness than the rest of the day; this is in contrast to Barbados.

Middle plus high cloud cover varies with mode in a rather organized fashion. On land modes 1, 2 and 3 clutter together below 20 percent most of the day with little diurnal change. Modes 4 and 5 increase to over 40 percent from 1100 to 1700 AST and are nearly always more than 1 through 3. The sum in the "High Plus Middle-Land" curve of figure 9 shows some afternoon increase, which then is due to modes 4 and 5 alone.

At sea the middle plus high cloud cover diverges greatly with mode. As over land, all modes indicate less high plus middle cloudiness before 1000 AST. Then, modes 1 and 2 remain mostly below 30 percent all day, while 3 to 5 are over 30 percent. Nearly 100 percent cloud cover for mode 5 persists after 1000 AST. So the greater total cloud cover in mode 3 (figure 13) was due to middle plus high clouds alone. Most interestingly, we can now see that the general oceanic total cloud increase after noon of figure 7 traces to mainly 1968 (figures 8 and 11) high plus middle clouds (figure 9) under disturbed modes 3 and 5 only. So many other such comparisons can be made that we cannot list them here. In summary, the high plus middle cloud mode dependence on both land and sea signifies more afternoon upper clouds under disturbed conditions. Whether this is a general result or only an artifact of this sample is not easily resolved.

7. DISCUSSION AND CONCLUSIONS

Since the period of time for this study is limited, and only a small region was observed, we can compare results only with selected other references. Near Barbados, Brooks (1927) found about 60 percent total cloudiness in July, while Landsberg (1945) found about 50 percent in July. For heat balance studies, London (1957) used about 45 percent in the area of the island for summer, while Houghton (1954) based his data on Brooks and used about 48 percent at 13°N. If we accept about 50 percent from Table 5 as the total mean cloud cover on Barbados, we find that most of these earlier studies were reasonably close to our estimate on land.

Oceanic total cloudiness was estimated at 35 percent from our study (Table 5). Brooks found about 50 percent and Landsberg had somewhat over 50 percent, both for July. London used about 40 percent at sea east of Barbados for summer, while Houghton based his calculations on approximately 48 percent. All of these estimates are probably too high, and can be attributed principally to extrapolation from land to sea when the relations were not really known due to a lack of ship data in sufficient quantity. In view of the large area of the tropics composed of ocean, this error of 10 percent or more could seem rather serious. However, these figures probably only apply to the summertime tropical Atlantic trade wind region which is usually not in the equatorial trough. Nevertheless, the substantial difference between total cloudiness at sea compared to only a small island was found to be 12 percent or more (Table 5), and this was not well appreciated. This difference is most strikingly visible when viewing a time lapse loop of a full day's satellite photos in the Eastern Caribbean on an undisturbed day. We see some very small, but bright and stationary dots over which lower clouds pass from the east and upper clouds also move, if any exist. It is the very localized effect of these islands we are measuring with surface observations from an island, and not at all the overall oceanic cloudiness.

Comparison to satellite cloudiness cannot be made in most circumstances because of coarse resolution or lack of data in the Atlantic Ocean. Although data is presented only by 25 percent categories, we can interpolate from Clapp (1964) a figure of about 50 percent on both land and sea around Barbados for June, July, and August 1962. This applies to both locations, whereas the value is probably true only on the island itself. Hence, care must be taken to distinguish between land-calibrated satellite "cloudiness" and oceanic cloud cover when there is some difficulty in establishing absolute magnitudes. Glaser, et al. (1968) were careful not to extend land-based cover to the ocean when calculating probabilities of sighting land features from spacecraft. We should note here that the results of the present study show that the increase in total land cloudiness is mainly comprised of more low cloud on land (Table 6), rather than more upper clouds. This should not be confused with a possible overestimate in past ground observers' cloud cover which is attributed to spurious cirrus cloudiness by Vonder Haar and Hanson (1968) and Quinn and Burt (1968).

Diurnal variations of low cloud cover during daytime at sea compare well with the sunrise maximum followed by a slow decrease all day found for several cumulus height characteristics in Holle (1968). The same results were found by Lavoie (1963) for low clouds at Eniwetok, a small flat island at 11°N, 162°W. This is quite significant, since there are few apparent island effects on low clouds there. Of course, there are generally more clouds, precipitation and radar echoes at night over the ocean, as shown by Lavoie (1963), Holle (1968) and Kraus (1963), but our all-sky photos could not consider this question.

All-sky photographs have been shown to be a useful method of obtaining cloud cover in the tropics. Care must be taken, however, to understand the lens characteristics, shape of the sky and its interpretation in devising a grid, and the relevance of such pictures to a proposed study. While the statistics obtained here are not absolute values of cloud cover, their intercomparisons should be applicable to many purposes.

Several improvements can be made over some of the camera systems used in 1963 and 1968. If time lapse photos are taken, a time interval of one minute or less is adequate to identify individual cumuli going past; higher clouds are quite coherent even at slower rates. A linear lens should definitely be employed, as was done here. Some tests of a proposed grid should be made in advance of a field program in order to understand the final form of the data. Film must be in color to distinguish sky and haze from thin clouds as well as other difficult situations. A range of stops on the camera should be used when possible, preferably on the dark side by one to two stops, rather than toward the light side. Identification of time and date should be in every picture without fail; no other data are particularly needed, except the location if there is a possibility of confusion. Finally, optical scanning methods are not easily developed and visual analysis is not only less expensive, but takes little, if any, additional time. It also assures that the sun is not mistaken for cloud and makes identification of cloud layers possible. An interesting series of photos will be forthcoming from time lapse all-sky cameras aboard various NOAA ships as they travel in the tropics. These are being collected by the Sea-Air Interaction Laboratory, AOML, NOAA, Miami.

We have found several interesting results from a study of 1885 all-sky photos. (1) Total cloudiness during two summers had an average of 51.8 percent on Barbados and 34.5 percent at two ships in the Atlantic east of Barbados. (2) Total cloud cover was at least 12 percent more on the island than at sea during each summer. (3) All of this increase was due to more low clouds on land. (4) Much more total and low cloudiness occurred on Barbados in 1968 than in 1963, due to the higher elevation of the camera site in 1968. (5) As the atmosphere became more disturbed, much more total cloudiness and high plus middle cloudiness occurred in the mean for all stations together than during undisturbed conditions; low clouds showed little dependence. (6) Diurnal variations of total and low cloudiness on land showed a morning minimum, increasing to a broad, late morning maximum, which persisted until a late afternoon decrease. High plus middle clouds on land increased slowly, but continuously, from a small amount at sunrise to a maximum just before sunset. (7) At sea the low clouds were most numerous in early morning, then decreased to a constant amount after 0900 AST. Middle plus high clouds at sea increase at noon during a relatively small number of disturbed hours and stayed more numerous all afternoon; this specific increase alone comprised the afternoon maximum in oceanic total clouds. (8) Total cloudiness on land was distinctly greater during most hours for modes 4 and 5 than modes 1 to 3. Most of this was due to middle plus high cloud dependence on mode, rather than low cloud. (9) At sea the low clouds were much more numerous under disturbed conditions in the early morning.

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