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A STUDY OF A NON-DEEPENING TROPICAL DISTURBANCE

A Report on the Program for Analysis of Data Collected in the Field Observation Program on and near the Island of Barbados, West Indies

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To analyze the data collected in the 1962/63 Field Program. The analysis will proceed in two parts (a) collection, tabulation and organization of all data; (b) analysis of problems which can be delineated according to the dominant scale of motion involved, from convective scale through mesoscale to synoptic scale systems. In particular, emphasis will be placed on the analysis of turbulent scales of motion associated with the transfer of latent and sensible heat between the tropical ocean and atmosphere.

by

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ACKNOWLEDGEMENTS

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ABSTRACT

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Data from an experimental region based upon six islands of the Windward Group in the West Indies, a research vessel in the tropical Atlantic, an instrumented research aircraft, and TIROS VI and VII are used to study the structure of a specific disturbance which moved through the observational network during 15 and 16 August, 1963. Despite the fact that an unusual variety and amount of data is available, difficulties are encountered when an attempt is made to establish the physical and dynamic characteristics of the flow field and the attendant cloud and rainfall patterns associated with this disturbance. Taken individually, each source of data is found to be either inadequate or, in the light of other information, perhaps even misleading. When all sources are treated collectively a number of interesting features of the disturbance are illuminated. By and large, these results bear little resemblance to conventional tropical models such as the easterly wave or equatorial vortex. In fact, it is felt that this study demonstrates that a necessary prerequisite to any modelling is quantitative description from adequate and extensive correlated observations over a wide area and a deep layer. Lacking a continental sounding network in the tropics, the only avenue for

progress would appear to be specifically designed experiments based upon a selected island network and incorporating joint aircraft, oceanographic and satellite programs.

PURPOSE

The purpose of this program following upon the Field Program [La Seur and Garstang, 1964] is to order and analyze the data collected during that program. The original Field Program was set up in such a way that an intensive study could be made of tropical weather processes in a selected region of the tropics. Within this region measurements were obtained of the role and inter-relationship between turbulent scales of motion associated with the transfer of latent and sensible heat between earth-ocean and atmosphere, convective scale motions and synoptic scale motions in the tropical atmosphere. The program of analysis is then logically divided into (a) the ordering, verifying and tabulation of all data; (b) the analysis of problems inherent in the above. This report continues the study [see Garstang, 1965] of the inter-relationship in the tropical atmosphere between the different scales of motion. Here a particular synoptic scale system is analyzed by utilizing various sources of data. Some information is obtained on the structure of the system. In particular, information is obtained on the distribution of cloudiness, rainfall, vertical motion, divergence and horizontal and vertical windfield.

1. INTRODUCTION

From 5 August to 5 September 1963, an intensive observational program was undertaken on and in the vicinity of Barbados, West Indies [13°10'N, 59°30'W], using a research vessel, instrumented aircraft, and an island network of surface observations and soundings. The motivation and main results of this program have been reported on by La Seur and Garstang [1964]. It was hoped to obtain concomitant satellite pictures of the area for comparative case studies, illustrating various types and stages of tropical disturbances. Unfortunately, satellite coverage only coincided with four observing days, two of which were quite undisturbed and uninteresting.

On 15-16 August, however, a disturbance passed through the area which was recorded by ship, island stations, aircraft and satellite photography. Despite these various observational systems, subsequent analysis of the data fails to provide a coherent picture of the structure of this disturbance. Instead, what is most apparent are problems in the interpretation of the various data, difficulties in relating the different scales of motion that are being observed by each system, and lack of any real physical understanding of the weather phenomenon itself. From the outset then, the purpose of this paper is not to resolve problems but to point out the need for and the difficulties inherent in obtaining a quantitative description of low latitude synoptic scale disturbances.

2. THE OBSERVATIONS

The entire area of interest is covered in Fig. 2, frame 29, from TIROS VI orbit 4845 T1 taken at 1107 GCT (0707 local time) 16 August 1963. The white dot labelled "CRAWFORD" gives the location of the research vessel [13°N; 55°W]. This ship made radiosondes, frequent cloud photographs, upper winds, rainfall and numerous boundary layer measurements [Garstang, 1964]. The location of Barbados is given by the black dot. Guadeloupe is shown by the white triangle, and Trinidad, at the intercept of 60°W and 10°N, complete the experimental region. The research aircraft made a photomapping flight as shown in Fig. 13. Figures 3 and 4 show TIROS VII pictures [frames 8 and 9, near 1401 GCT on 16 August 1963] of the northwestern portion of the flight track.

Table 1 summarizes, for the 16th August only, the information supplied by the various observational systems.

2.1 Routine synoptic analysis

It is apparent from Table 1 that, for a disturbance of this nature, very little information is obtained from the standard synoptic observations. Routine techniques of analysis and interpretation in the tropics of meteorological observations depend largely upon the existence of marked

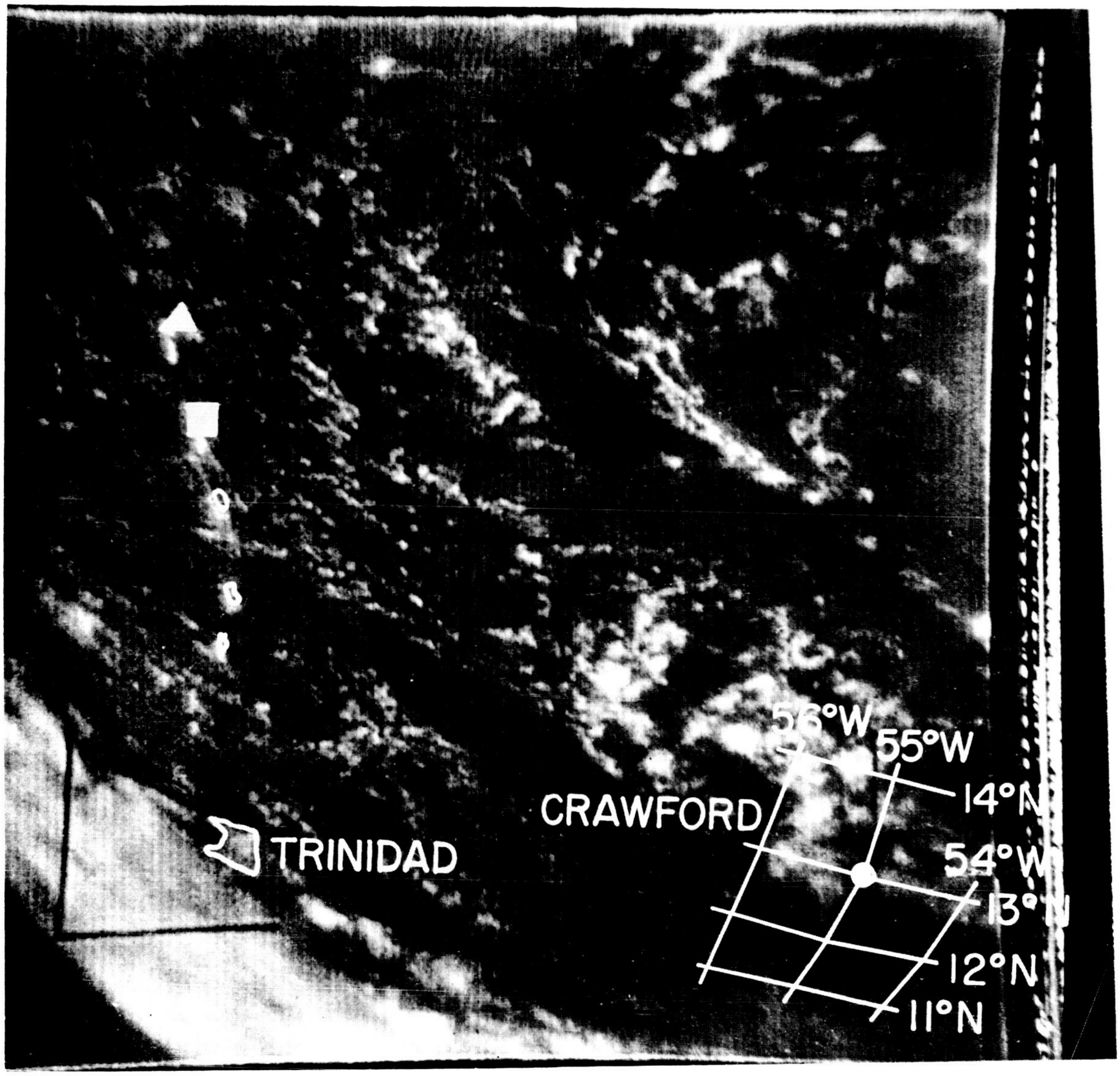

Fig. 1 Satellite picture (frame 12; 846/44) from Tiros 7 taken at 1343:00 GCT (0943:00 local standard time), August 15, 1963. Barbados shown by large black circle, R.V. Crawford by white circle, Trinidad by outline, Martinique by square, and Guadeloupe by triangle.

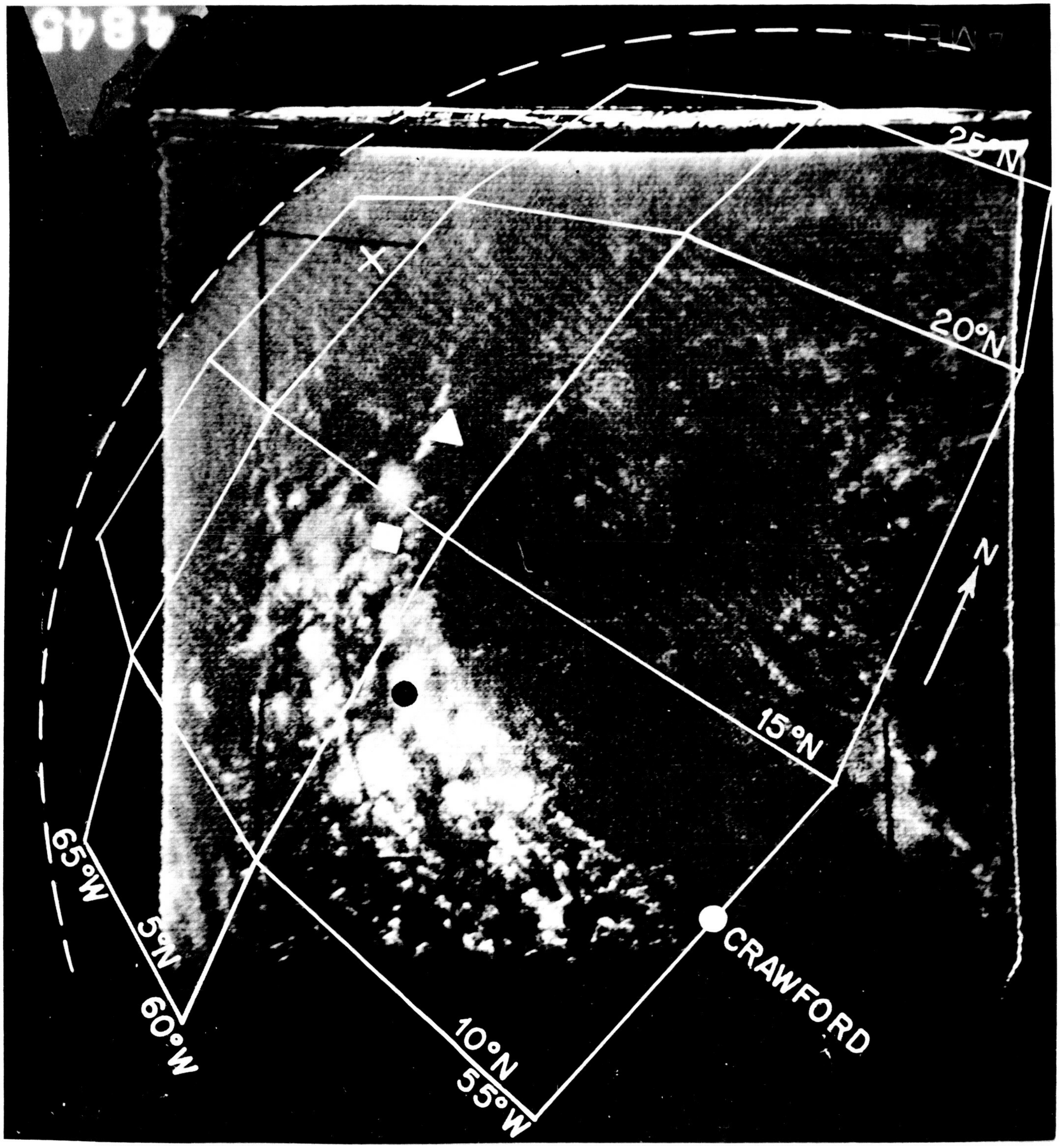

Fig. 2 Satellite picture (frame 29; 4845/4844) from Tiros 6 taken at 1107:30 GCT (0707:30 local standard time), August 16, 1963. Barbados shown by large black circle, R.V. Crawford by white circle, Martinique by square, Guadeloupe by triangle, and Puerto Rico by X.

TABLE 1

INFORMATION SUPPLIED BY EACH OBSERVATIONAL SYSTEM ON 16 AUGUST 1963

Observational System	Type of Weather System	Organization of Wind Field	Organization of Cloud Field	Distribution of Precipitation
Routine synoptic analysis surface, 700 mb, 500 mb, 200 mb	Not identified at any level [Figs. 5 & 6]	Winds ENEly throughout 15-17 August. Surface wind speeds and direction at 1200 GCT on 16 August 080-070, 15 knots	Point observations - difficult or impossible to relate to system as a whole	Observed but not utilized
Special island observations	From distribution and intensity of rainfall system is classified as moderate to strong disturbance. Some evidence for E/W orientation is obtained from the limited N/S extent of the system as it affects the Lesser Antilles	No perturbation of wind field evident. Divergence and vertical motion computations based upon winds show increasing vertical motion in region of disturbance [see Table 2]. Mean hourly surface wind speed and direction on east coast of Barbados on 16 August - 10-11 GCT 090/8.6 m sec^{-1} 11-12 GCT 090/7.2 m sec^{-1} 12-13 GCT 090/9.2 m sec^{-1} 13-14 GCT 080/8.6 m sec^{-1} Winds aloft as shown, Fig. 8	Pronounced increase in cloudiness. Organization cannot be determined adequately	Widespread rainfall over all islands sampled in region Martinique to Trinidad. On 16 August between 65-95 per cent of stations on all islands recorded rain with amounts ranging between 0.2→>> 1 inch [see Table 3]

Research ship observations	Pronounced increase in weather over the ocean station with E/W orientation of the cloud field	As for Island Observations. Surface wind speed and direction at 1200 GCT, 16 August - 070/8.4 m sec^{-1}. Winds aloft as shown on Fig. 7	Marked increase in cloudiness at all levels. E/W organization of cloud mass evident	Widespread showers over ocean
Research aircraft observations	Identified as large region of disturbed weather orientated mainly E/W with NE/SSW organization of convective cloud [see Fig. 14]	None observed	NW/SE orientated cloud shield extending over 400 n mi NNE/SSW orientation of convective elements over most of the disturbed region. Tops generally below 25,000 ft	Widespread shower activity observed over ocean
Satellite observations[1]	System identified primarily as "sizable group of large (AOS) convective clouds in region of Barbados and southern Lesser Antilles". Using Fett's classification scheme the system would fall into the weakest category (A) illustrated by a weak easterly wave	Surface wind field is inferred as "light easterly trade flow in large scale open bands near 57W, 8N to 13N and is also indicated elsewhere". "Southerly trade flow is shown n north of 15N and west of 55W"	Emphasis laid upon both the large organized cloud mass in the vicinity of Barbados and the large open or nearly clear areas on either side. No information available on the "fine structure".	No information

1 Based upon an interpretation of the satellite's pictures kindly carried out by Dr. H. M. Johnson of the U. S. Weather Bureau's Meteorological Satellite Laboratory.

perturbations in the wind (pressure) fields. When such a perturbation does not occur, the form of analysis in current use is inadequate and little or no physical interpretation is possible.

Figure 5 provides some of the information that is available on a routine basis at the surface. The map shown is the standard analysis kindly provided by the U. S. Weather Bureau at San Juan, Puerto Rico. The double hatched line is the so-called "intertropical convergence" as analyzed at San Juan.

Figure 6 shows the 200 mb chart. The main feature of interest is the four southwesterly winds extending from west to northeast of Barbados. They were measured by Doppler radar on KLM westbound Flight 775 and, hence, are likely to be reliable. They suggest the existence of a shearline (at a high angle to cloud field of the disturbance) and possibly an anticyclonic circulation at that level. The former would suggest divergence over a limited region of the disturbance, the latter divergence over a large region of the disturbance.[1]

The available time and data for these routine analyses is obviously insufficient. The only information that is supplied by routine synoptic analysis is that cloudiness and precipitation increase over a significant area. Little light is cast upon the structure of the system responsible

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[1] The word "disturbance" as used in this context refers to the identifiable synoptic scale cloud region as shown by TIROS VI frame 19 in Fig. 2.

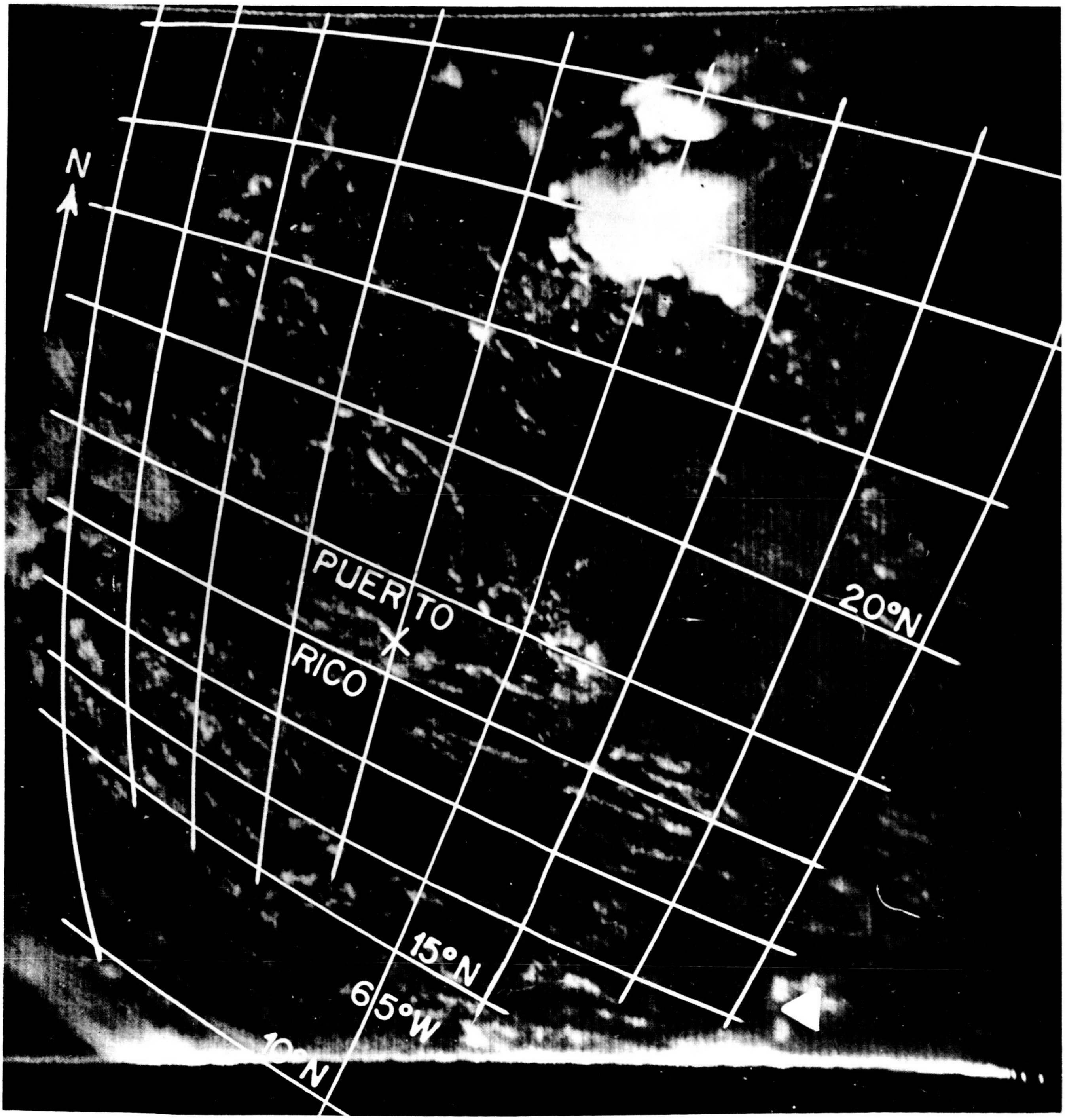


Fig.3 Satellite picture (frame 8,861) from Tiros 7 taken at 1401 GCT (1001 local standard time), August 16, 1963. Puerto Rico is shown by X, Guadeloupe by triangle.

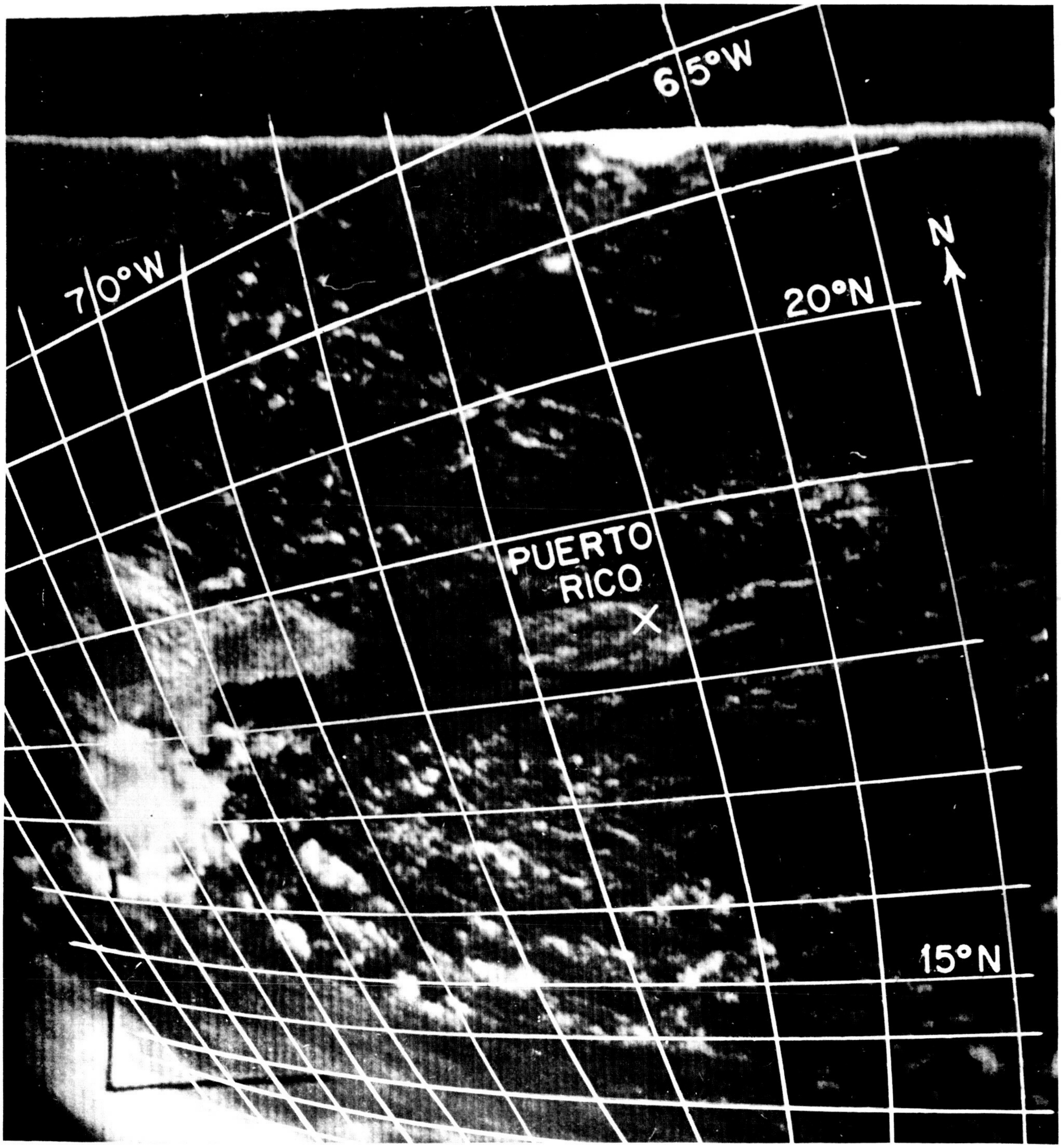


Fig. 4 Satellite picture (frame 9,861) from Tiros 7 taken just after 1401 GCT, August 16, 1963. Puerto Rico is shown by X.

TABLE 2

MEAN VALUES OF DIVERGENCE AND VERTICAL VELOCITY FOR THE LOWER 10,000 FT FOR EACH TRIANGULAR REGION

Date/Time	CRAWFORD/BARBADOS/TRINIDAD 71,524 km^2		CRAWFORD/BARBADOS/GUADELOUPE 83,465 km^2		BARBADOS/GUADELOUPE/TRINIDAD 64,656 km^2		CRAWFORD/GUADELOUPE/TRINIDAD 224,594 km^2	
	Divergence 10^{-5} sec^{-1}	Vertical Velocity cm sec^{-1}	Divergence 10^{-5} sec^{-1}	Vertical Velocity cm sec^{-1}	Divergence 10^{-5} sec^{-1}	Vertical Velocity cm sec^{-1}	Divergence 10^{-5} sec^{-1}	Vertical Velocity cm sec^{-1}
14 August 0000 GCT	-4.10	5.49	-0.26	-0.24	-0.22	2.38	-0.98	1.63
14 August 1200 GCT	-2.16	4.86	0.76	-1.72	-0.64	1.66	-0.90	1.82
15 August 0000 GCT	-3.57	6.96	0.21	-0.69	-0.01	2.17	-0.83	1.50
15 August 1200 GCT	-3.66	8.44	0.23	-0.78	-0.41	2.09	-1.19	3.04
16 August 0000 GCT	-2.80	5.60	0.59	-0.93	-2.37	6.10	-0.93	1.92
16 August 1200 GCT	-3.10	6.62	0.82	-1.56	-1.08	1.28	-1.22	2.95
17 August 0000 GCT	-2.55	4.33	0.28	-0.59	-0.41	0.54	-0.77	1.33
17 August 1200 GCT	-2.64	3.82	-0.24	0.37	-0.24	1.03	-1.08	1.61

for this weather and there is little evidence as to its size or what its future development is likely to be.

2.2 Special island and research ship observations

Figure 5 shows the experimental region enclosed by the major triangle Guadeloupe/R. V. CRAWFORD/Trinidad with Barbados at the common vertex of the interior triangles. Four of the Leeward Islands are included in the network along the western boundary of the region.

The upper air observations made as part of this experimental network at Barbados and the R. V. CRAWFORD allow the construction of time sections for both locations. Cloud heights and the height of the 5 gm/kgm mixing ratio line have been included in these time sections, shown in Figs. 7 and 8. At the R. V. CRAWFORD, the cloud heights were measured from carefully taken photographs, while on Barbados they were determined from an M-33 radar. On these time sections the passage of the disturbace is most clearly marked by the cloud heights and the oscillations in the height of the 5 gm/kgm mixing ratio line. There is little evidence in the wind field to suggest any pronounced circulation. The time change in direction of the light winds near 6 km may be associated with some perturbation but one cannot infer from the cross-sections what this might be.

Some quantitative evidence on the structure of the system is supplied by the network of upper wind finding

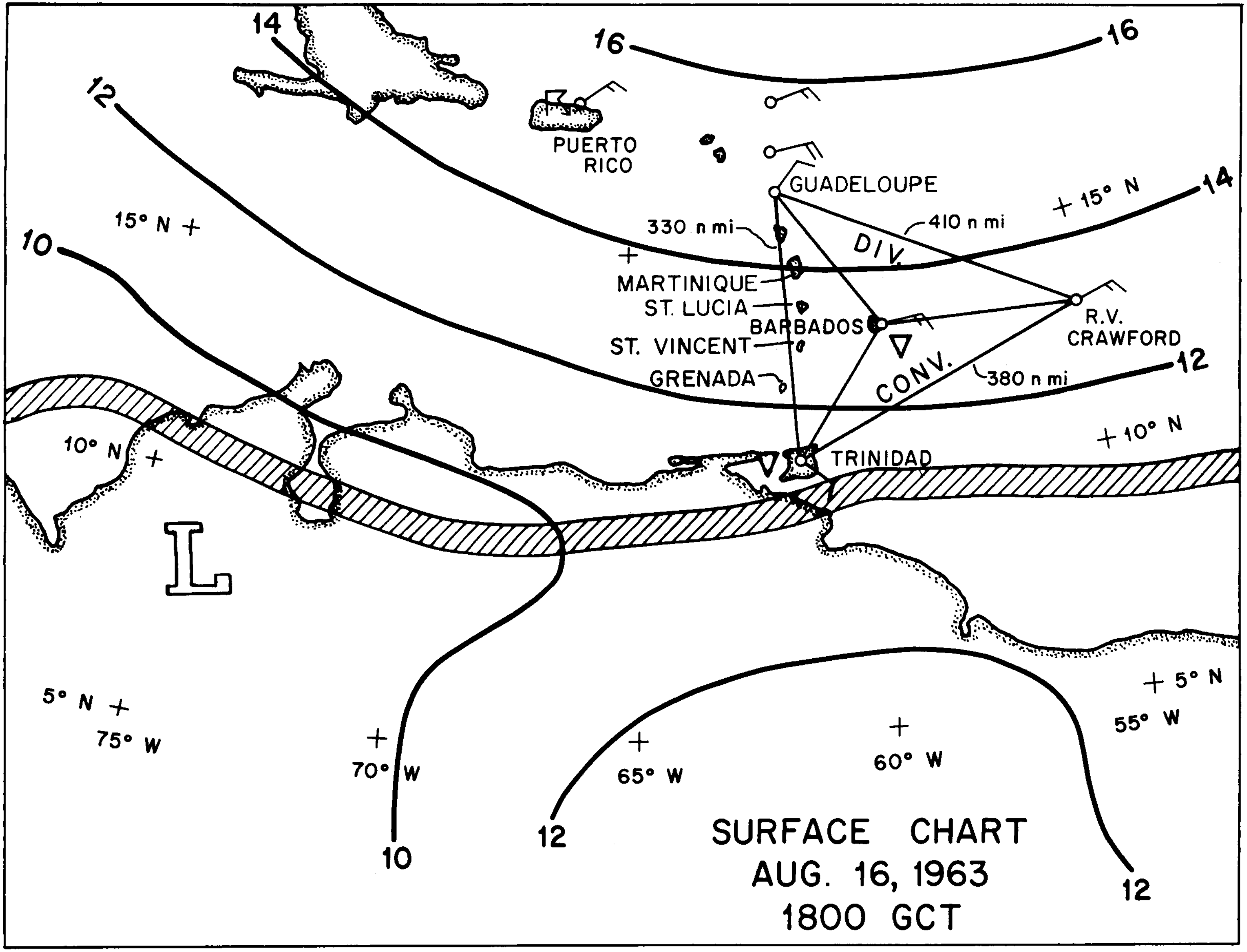


Fig. 5 Surface chart, August 16, 1963, 1800 GCT. Isobars labeled in mb above 1000. Triangles show low-level divergence calculations using kinematic method. ITC as analyzed by U.S. Weather Bureau shown by double hatched line

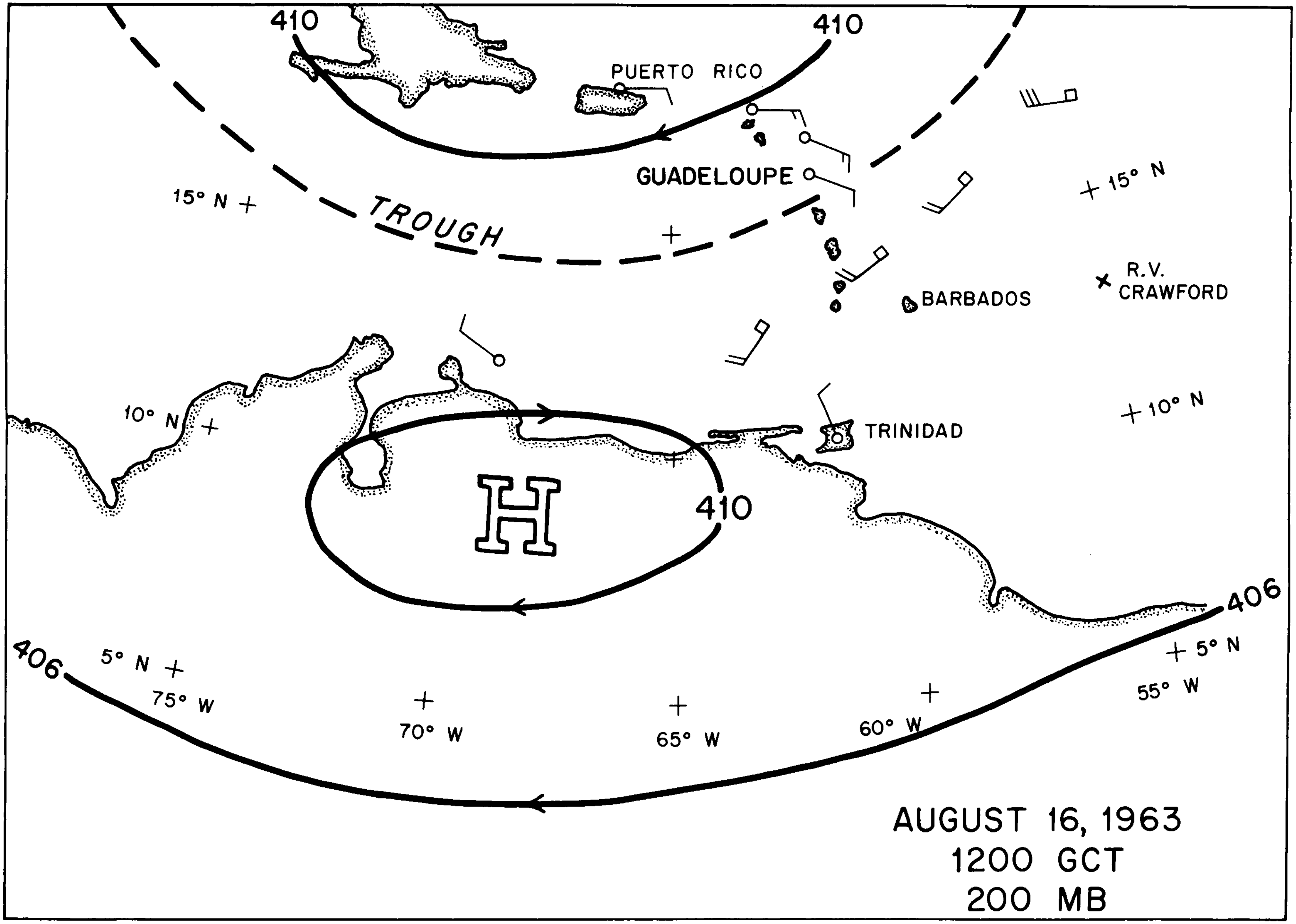


Fig.6 200mb chart for August 16, 1963, 1200 GCT. Contours in hundreds of feet. Shearline (trough) denoted by dashed line. Squares indicate Doppler winds from KLM westbound flight 775.

stations. Table 2 shows divergence and vertical velocities computed by a kinematic method for the four triangles shown in Fig. 5, for the period 14 to 17 August 1963. Within the limitations of this method of computing divergence and vertical motion, the agreement between the aircraft cloud maps [Fig. 14], and the satellite pictures [Figs. 1 and 2], is quite good. At both 0000 and 1200 GCT on 14 August the most equatorward triangle formed by the R. V. CRAWFORD/Barbados/Trinidad shows low level convergence and mean vertical motion in the lower 10,000 ft near 5.0 cm sec^{-1}. The poleward triangle formed by the R. V. CRAWFORD/Guadeloupe/Barbados shows, in the mean, very weak convergence in the lower 10,000 ft at 0000 GCT on 14 August and actually shows weak downward motion (much less than 1 cm sec^{-1}) although the mean divergence averages out slightly negative for the layer. By 1200 GCT on 14 August low level divergence has set in with a downward motion near 2 cm sec^{-1}. The western triangle formed by Barbados/Guadeloupe/Trinidad shows weak convergence and vertical motion of about 2 cm sec^{-1} during 14 August. By 15 August the equatorward triangle shows large vertical motions exceeding 8 cm sec^{-1} near the time of the satellite picture shown in Fig. 1. Cloud photographs taken on the R. V. CRAWFORD at 1200 GCT and 1300 GCT [nearly coincident with the satellite picture on 15 August] shown on Figs. 9a and b support these vertical velocities. The agreement between the large vertical velocities at 1200 GCT and the satellite

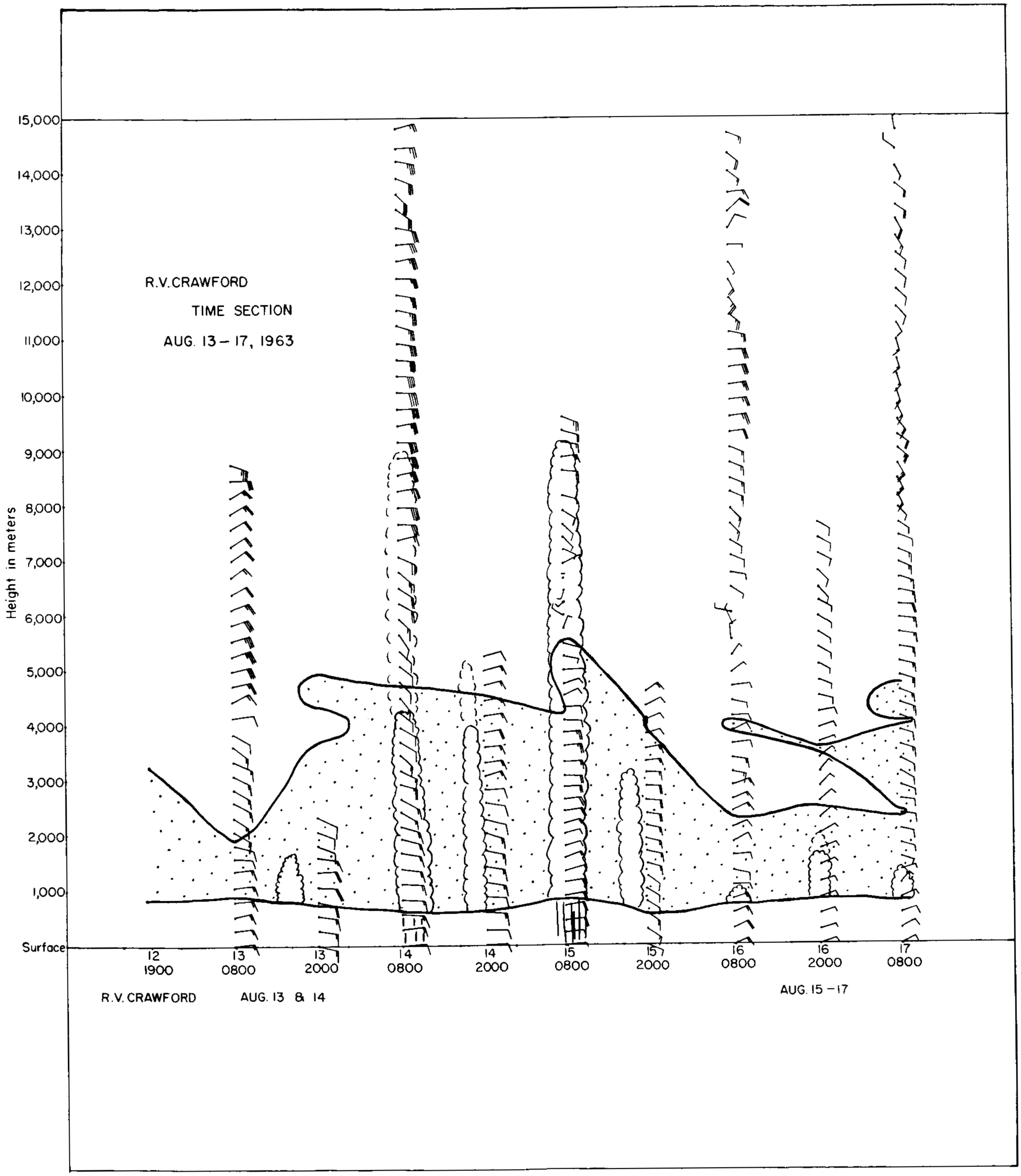


Fig.7 Time cross section for R. V. Crawford (13° N; 55° W) August 12-17, 1963. Times in local standard time (4 hours behind Greenwich). Each full barb is 5m/sec. Dotted region is cloud layer, defined to extend from lifting condensation level (surface air) to 5gm/kgm mixing ratio line. Cloud heights measured from precision photography; dashed clouds are highest seen. Time of maximum disturbed weather is 0800 (local time) August 15, 1963.

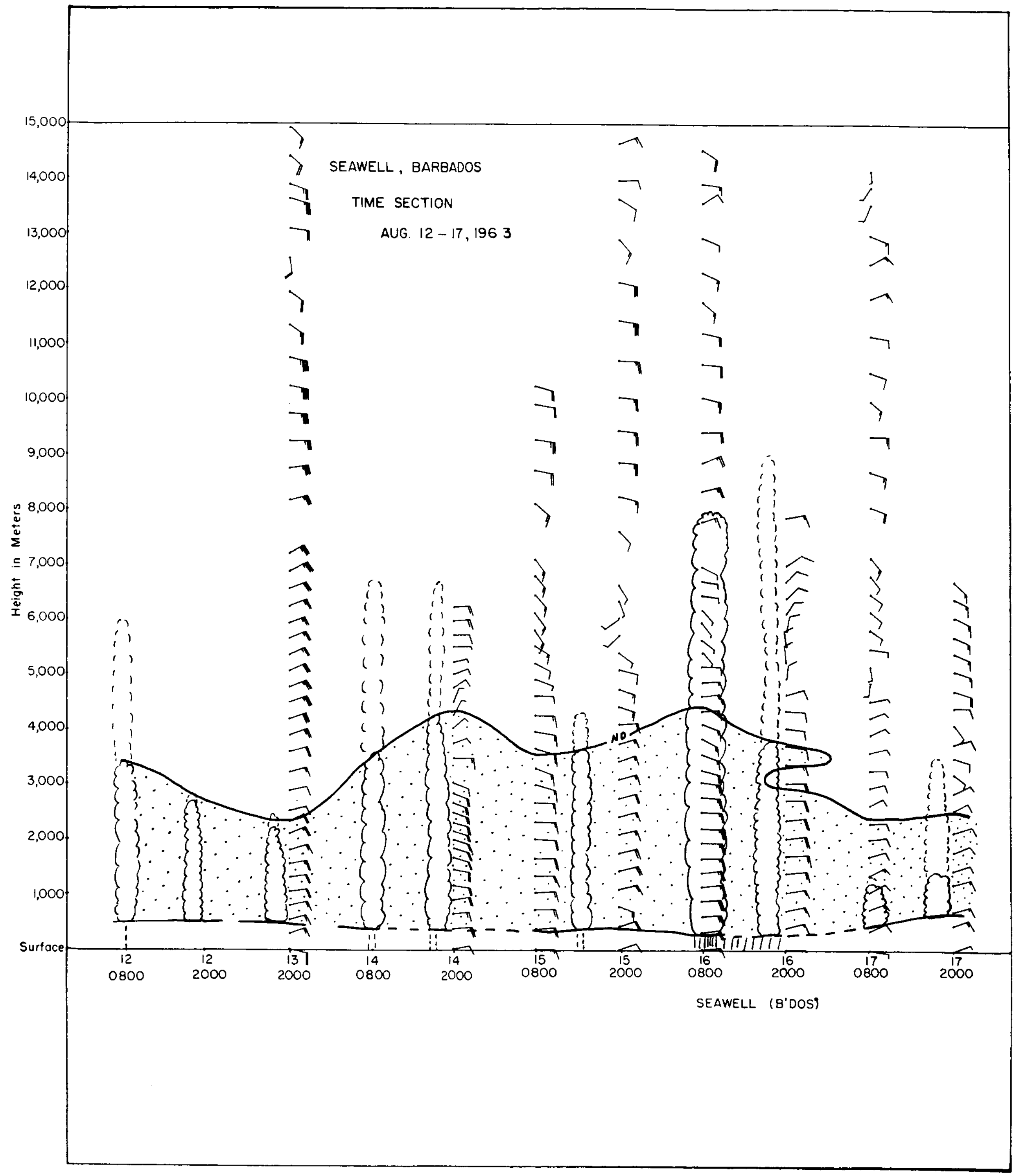


Fig. 8 Time section for Seawell Airport, Barbados, W. I. (13° N; 59°W) August 12-17, 1963. Notation same as fig. 6. Note maximum cloud tops (measured from radar and photography) higher than at R.V. Crawford, often penetrating into dryer upper troposphere.

picture at 1343 GCT is not striking. It is suggested that this may be due to the diurnal decrease of oceanic cloudiness which reaches a minimum between about 1400 and 1500 GCT for these latitudes [Garstang, 1958, 1964]. Figure 9c at 1400 GCT shows a similar decrease in cloudiness that need not necessarily be a change in intensity of the system. The poleward triangle continues to show descent and the western triangle ascent during 15 August. Mean vertical velocities slightly higher than 3 cm sec^{-1} are obtained for the major triangle at 1200 GCT on 15 August. On 16 August vertical velocities in the equatorial triangle have decreased slightly but increase markedly at 0000 GCT in the western triangle, with increased descent in the poleward triangle. These results are in good agreement with the location of the main cloudy and clear regions as shown by both the satellite photograph [Fig. 2] and the aircraft cloud map [Fig. 14]. By 17 August when few traces of the weather system remain, divergence and vertical velocities reach their minimum in all triangles.

The special island observations and the research ship observations give little information on the organization of the cloud fields on the meso- or synoptic scale. However, there is little doubt that an organized atmospheric system of a synoptic scale had been observed. Comparison of Figs. 9a, b and c with Fig. 12b shows the contrast between "foul" and "fair" days on a tropical ocean station. During the

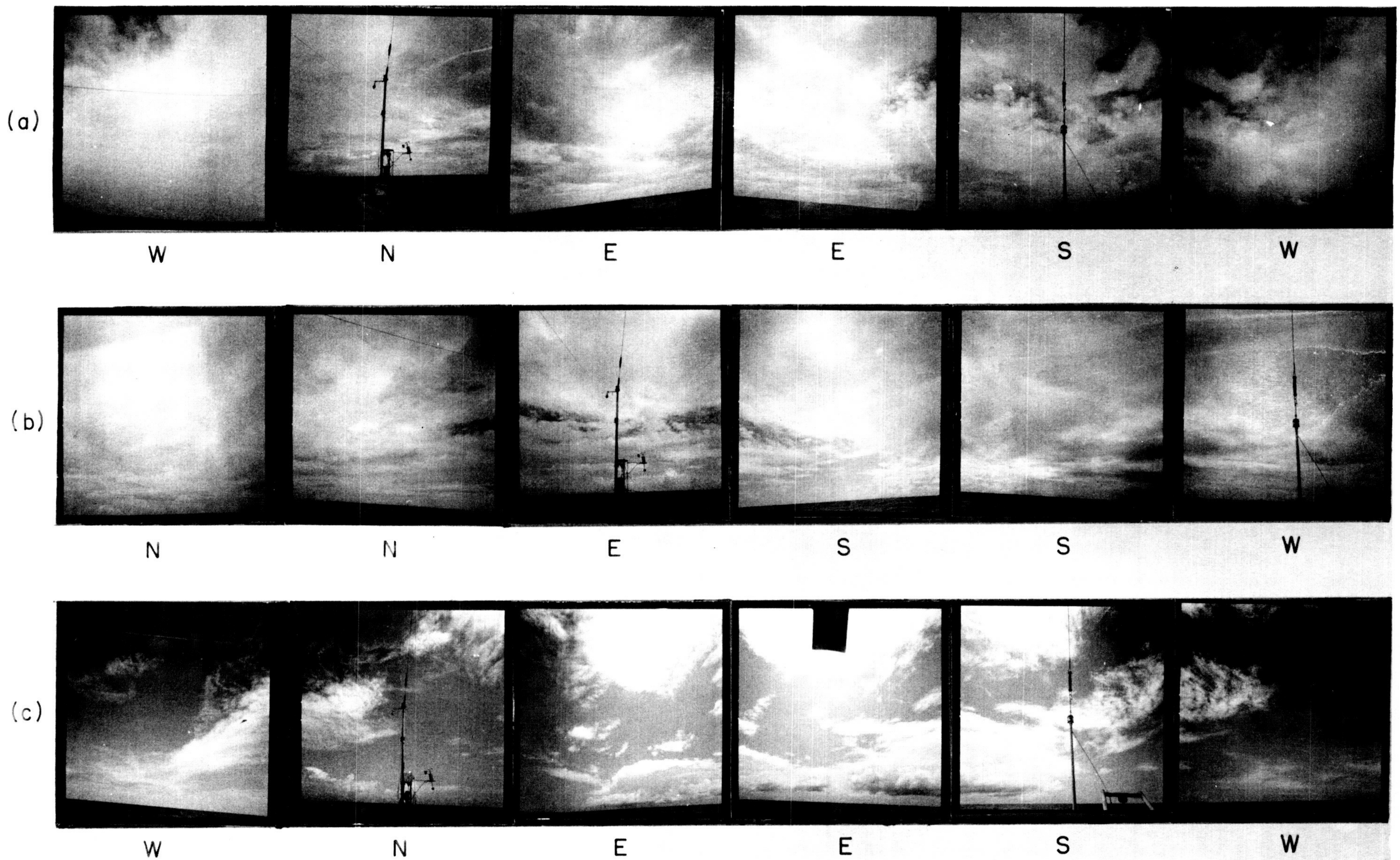


Fig. 9 Panoramic views from the R. V. Crawford of the whole horizion up to an elevation of about 60 degrees. Letters below each picture indicate the orientation of the camera. (a) 1200 GMT 15 August; (b) 1300 GMT 15 August; (c) 1400 GMT 15 August.

(a)

(b)

(c)

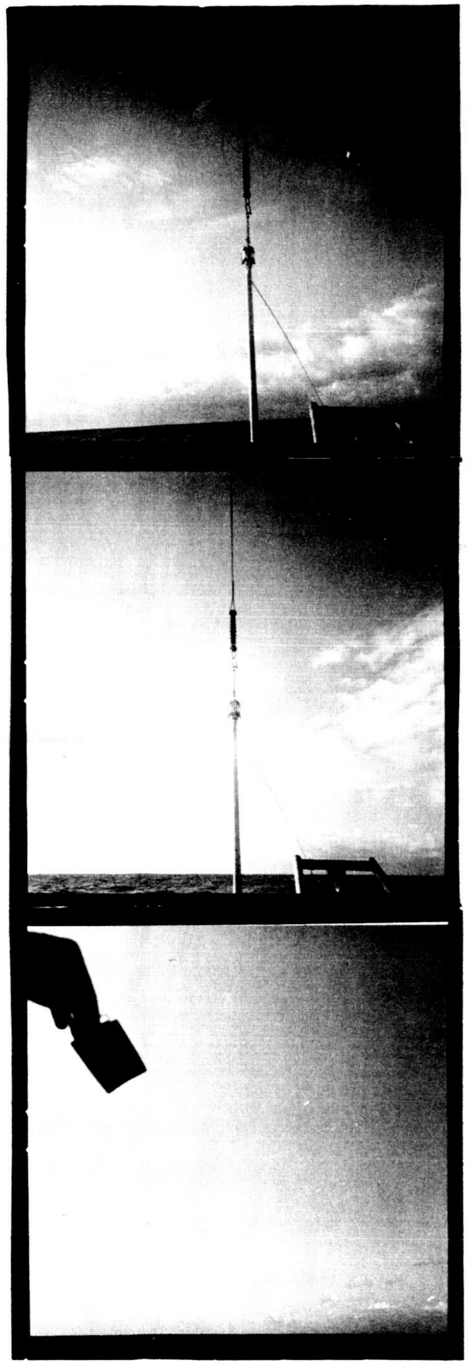
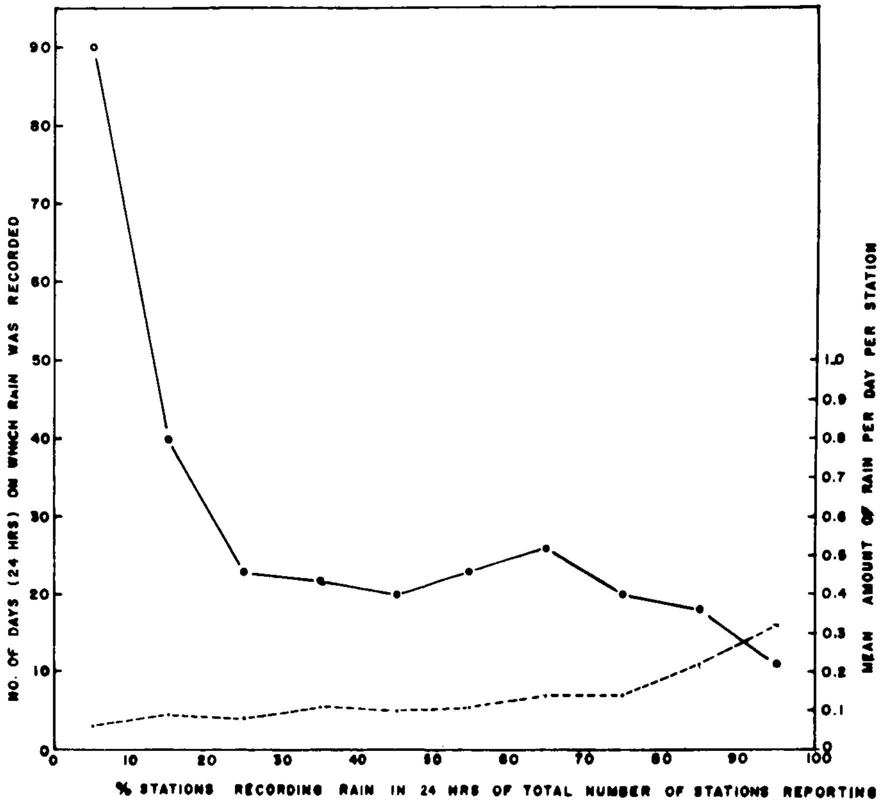


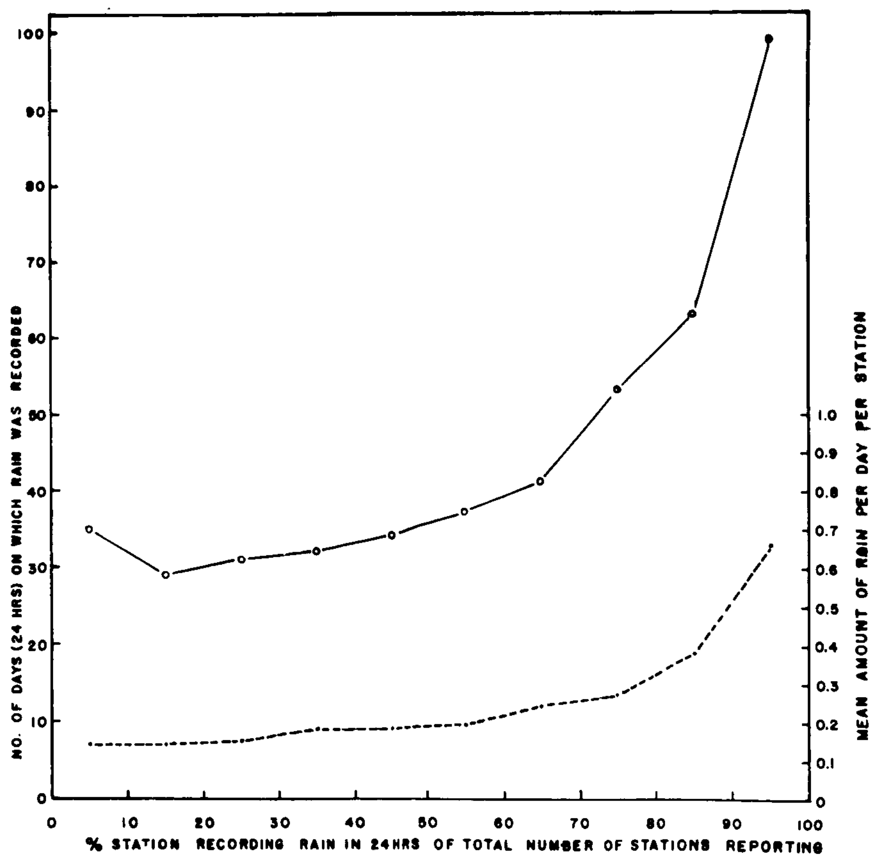
Fig.10 Sky conditions to south of R.V. Crawford position (55° W, 13° N) on August 16, 1963 at (a) 1000 GMT; (b) 1100 GMT; (c) 1200 GMT.

early morning of 16 August Figs. 10a, b and c show that the disturbance now lay to the south and west of the ship's position and that the southeastern and eastern horizon was now clear.

Considerable information is supplied by the island rainfall network. Rainfall records on all of the islands [except Guadeloupe] shown on Fig. 5 were utilized to obtain a classification of "the state of the atmosphere". The number of stations ranged from 90 for Barbados to 12 for Trinidad [La Seur and Garstang, 1964]. A homogeneous set of observations of 24 hour rainfall and occurrence and amount was analyzed for each island for the period 1958 to 1962. Two periods were examined: the months of February and March representative of the dry season; the months of August, September and October representative of the wet season. For each 24 hour period the ratio of the number of stations recording rain to the total number of stations reporting during that 24 hour period was obtained. This ratio was then expressed as a percentage. Percentile intervals were chosen and the number of days and amounts of rain in each interval were tabulated. The amount of rain in each interval was normalized by obtaining the mean amount of rain per station per day over the whole wet or dry season period under consideration. Frequency distributions of occurrence and amount were then plotted for each island. It was found that the southern group of islands - Barbados, Trinidad and Grena-



NO. OF DAYS (24 HRS) ON WHICH RAIN WAS RECORDED
MEAN AMOUNT OF RAIN PER DAY PER STATION
% STATIONS RECORDING RAIN IN 24 HRS OF TOTAL NUMBER OF STATIONS REPORTING



NO. OF DAYS (24 HRS) ON WHICH RAIN WAS RECORDED
MEAN AMOUNT OF RAIN PER DAY PER STATION
% STATION RECORDING RAIN IN 24HRS OF TOTAL NUMBER OF STATIONS REPORTING

Fig. 11. Combined frequency distribution of occurrence and amount of rain for the islands of Barbados, Grenada and Trinidad for a five year period, 1958 to 1962. The solid line represents the number of days (24 hours) on which precipitation fell as a function of the percentage of the stations recording rain out of the total number of stations (126) reporting on that day. The dotted line represents the mean amount of rain per station per day computed from the total amount of precipitation recorded in each ten per cent interval.

(a) Dry season: February and March

(b) Wet season: August, September and October da - had similar distributions, while the northern group - Martinique, St. Lucia and St. Vincent - were also similar. Latitudinal, island and sampling effects can be called upon to explain the similarities. Figures 9a and b show the mean curves for the southern group of islands. On the basis of these distributions the following arbitrary categories were set up:

The occasions on which less than 55 per cent of the stations recorded rain during the 24 hours were divided into two categories:

i) Suppressed mode: on the average equal to or less than 15 per cent of the reporting stations record precipitation during a 24 hour period. The term "suppressed mode" implies that any and all processes contributing to the production of cloudiness and precipitation in the vicinity of the islands are inhibited.

ii) Neutral mode: on the average 16 to 55 per cent of the reporting stations record precipitation during a 24 hour period. Under these conditions cloud and precipitation processes are neither inhibited nor enhanced.

When, on the average, more than 55 per cent of all stations report rain in a 24 hour period, the island group is thought to be under the influence of conditions which actively produce cloudiness and precipitation. This mode is then arbitrarily classified as disturbed and subdivided into three sub-modes:

iii) Weakly disturbed mode: on the average between 56 and 75 per cent of the stations reporting precipitation during a 24 hour period.

iv) Moderately disturbed mode: on the average between 76 and 85 per cent of the stations reporting precipitation during a 24 hour period.

v) Strongly disturbed mode: on the average more than 85 per cent of the stations reporting precipitation during a 24 hour period.

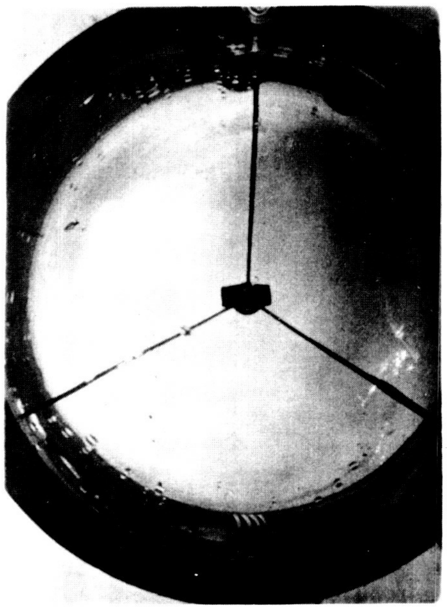
It is important to emphasize that no attempt is made with this system to classify the intensity of the disturbance producing the weather - only the local weather condition itself is categorized. In fact, any connotation as to the mechanism(s) producing the state has deliberately been avoided. Experience would indicate that these influences would range from the large scale, i.e., variations in the characteristics of the subtropical anticyclones and trade wind inversions, through the synoptic scale perturbations such as waves and vortices, to the local effects of the island itself. Furthermore, the interactions between these various scales of influence are undoubtedly important. Table 3 shows the frequency of disturbed, neutral and suppressed conditions for both the southern group of islands, and for Barbados alone. Eleven years of rainfall observations are used from the very dense network of stations on Barbados, as against five years of observations used for the island group. This provides both a check on the method as well as establishing the fact that the dense network on Barbados is probably a remarkably good gauge of the occurrence and non-occurrence of organized weather.

TABLE 3

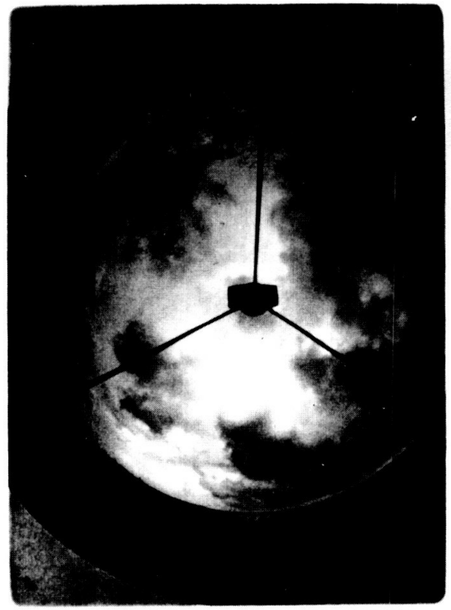
FREQUENCY OF MEAN MONTHLY DISTURBED, NEUTRAL AND SUPPRESSED CONDITIONS PREDICTED BY THE RAINFALL CLASSIFICATION METHOD FOR
(A) THE SOUTHERN ISLAND GROUP OF BARBADOS, GRENADA AND TRINIDAD BASED ON FIVE YEARS OF DATA FOR DRY SEASON (FEBRUARY, MARCH) AND WET SEASON (AUGUST, SEPTEMBER, OCTOBER);
(B) BARBADOS BASED ON ELEVEN YEARS OF DATA FOR DRY SEASON (FEBRUARY, MARCH) AND WET SEASON (AUGUST, SEPTEMBER, OCTOBER)

Islands/Seasons		Disturbed Modes III, IV and V		Neutral Mode II		Suppressed Mode I	
		% of time	No. of days per month	% of time	No. of days per month	% of time	No. of days per month
(A)	Wet Season	56	17	28	9	16	5
	Dry Season	25	7	32	10	43	13
(B)	Wet Season	57	17	28	9	15	5
	Dry Season	37	11	27	8	36	11

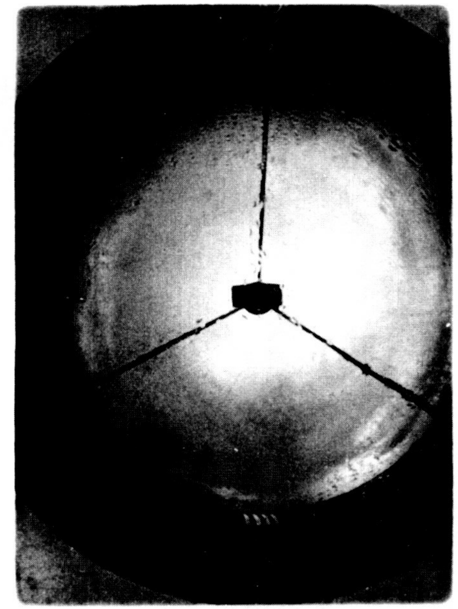
The frequency of occurrence of each major category agrees with other methods of counting the frequency of synoptic scale systems [Garstang, 1964] and with experience in the region. On the basis that the average synoptic



1400 Z (1000 LST)



1600 Z (1200 LST)

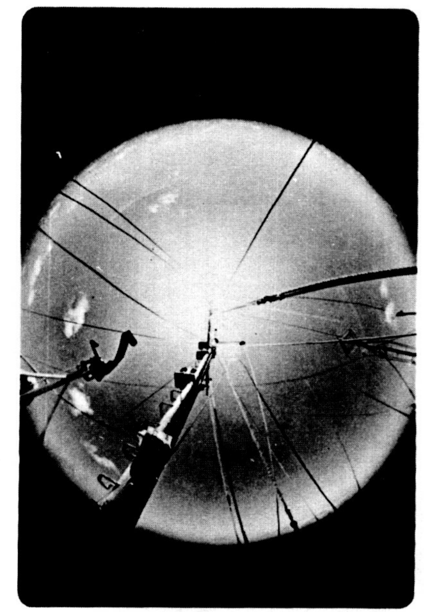


1700 Z (1300 LST)

FIG. 12a. WHOLE SKY CAMERA PHOTOGRAPHS MADE ON BARBADOS (AUG. 16, 1963).

1400 Z (1000 LST)

1600 Z (1200 LST)



1700 Z (1300 LST)

FIG. 12b. FISH-EYE CAMERA PICTURES TAKEN ON THE CRAWFORD

TABLE 4

RAINFALL, WINDWARD ISLANDS, 15-17 AUGUST 1963

Island	Date	Per cent of Stations	Category	Remarks
Barbados 92 Stations	15 August	82	Moderately disturbed	None more than 0.5 inch
	16 August	95	Strongly disturbed	Some up to 0.8 inch
	17 August	35	Undisturbed-neutral mode	Mostly few hundredths
St. Vincent 16 Stations	15 August	94	Strongly disturbed	More than 1 inch at some stations
	16 August	94	Strongly disturbed	More than 1 inch at some stations
	17 August	63	Weakly disturbed	1 inch at 1 station
Martinique 17 Stations	15 August	77	Moderately disturbed	More than 1 inch at some stations
	16 August	65	Weakly disturbed	Much less than previous day
	17 August	53	Undisturbed-neutral mode	Few tenths only
Grenada 41 Stations	15 August	83	Moderately disturbed	1 inch at 1 station
	16 August	86	Strongly disturbed	>> 1 inch at many stations
	17 August	66	Weakly disturbed	> 1 inch at some stations
Trinidad 7 Stations	15 August	43	Undisturbed-neutral mode	Few hundredths only
	16 August	86	Strongly disturbed	Highest 0.2 inch
	17 August	28	Undisturbed-neutral mode	Few hundredths only

disturbance produces about two rainy days, this would imply that for this region during the wet season there are about eight disturbances per month.

This classification is, therefore, applied to this particular disturbance and Table 4 shows the results for all islands used in the Windward group. On Trinidad, St. Vincent and Martinique only a select group of stations were chosen for analysis. Properly chosen, a few stations on a single island will still give an adequate measure of "the state of the atmosphere" once the limits have been chosen from a large sample of data. Examination of Table 4 shows quite clearly that this disturbance produced considerable precipitation over at least a four degree latitude, six degree longitude area. The R. V. CRAWFORD reported 0.195 inches on 15 August (nearly all between 0400-0800 local time), 0.04 inches on 16 August, and no rain on 17 August. From Figs. 9a, b and c showing the cloud distribution in the vicinity of the R. V. CRAWFORD, it is clear that precipitation in the region of the ship was widespread and the amounts recorded on its rain gauges are probably an underestimate of the precipitation that actually fell over the nearby area. No quantitative estimate could be made from the radar used on the ship but the distribution of echoes both in space and time during this period suggests that the above assertion is valid.

As with the cloud information supplied by the island/ship network, the rainfall observations serve only to

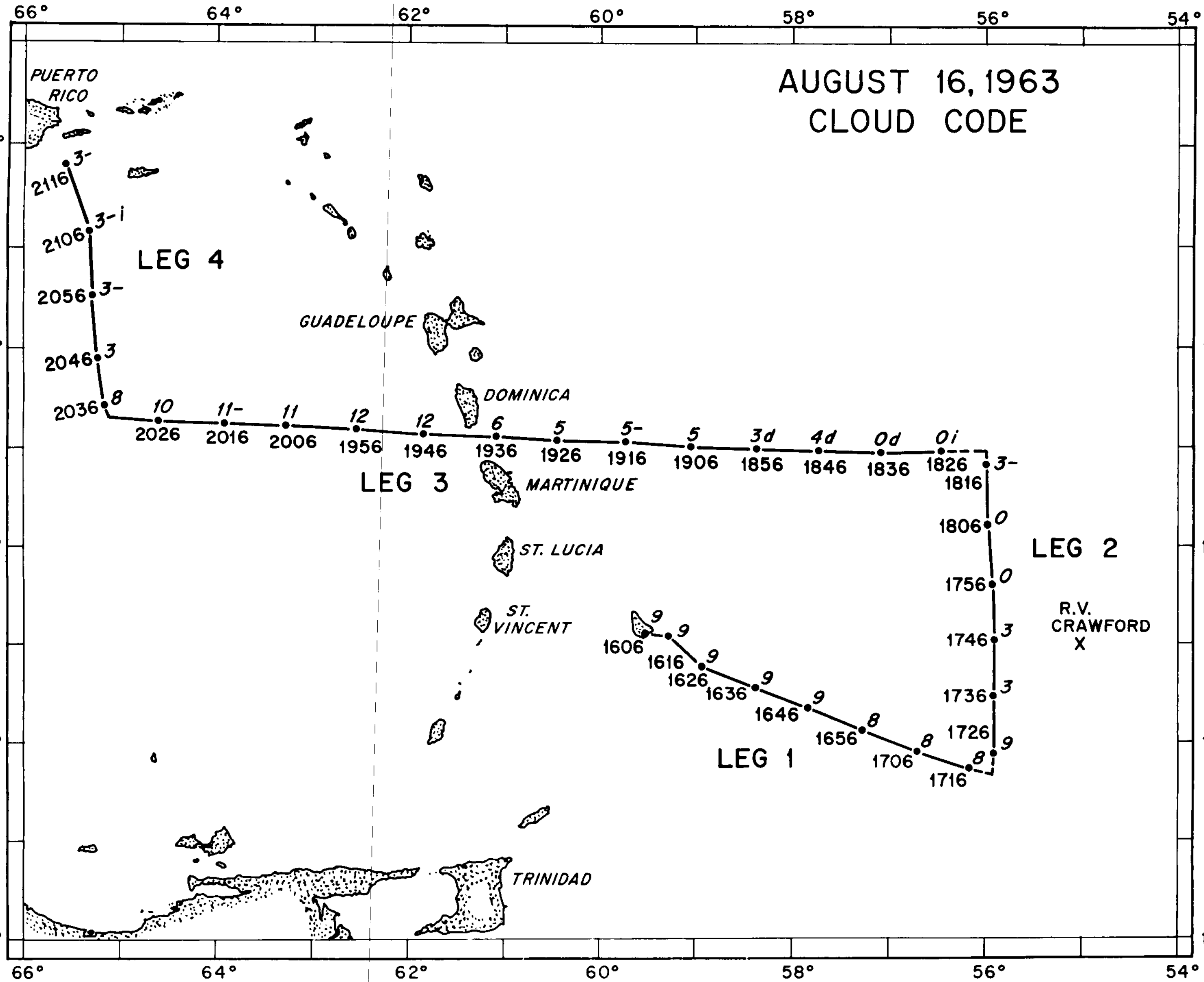


Fig.13 August 16, 1963, track of Weather Bureau research aircraft showing times (in GCT, four digits) and cloud code numbers (one or two digits) code same as that devised for Pacific study by Malkus and Riehl (1964) for use with aerial timelapse photographs. Coding done from prints made at 10 minute intervals. Legs 1 and 2 flown at 1500 ft; Legs 3 and 4 at 10,500 ft.

positively confirm the occurrence of an organized synoptic scale disturbance. Questions concerning the structure of the system, its forward propogation if any, and the concurrent question of development or decay with time, are left largely unanswered. The question is raised whether the intensity or strength of a system is best measured by circulation or by the occurrence, amount and distribution of cloudiness and precipitation. As far as the rainfall observations are concerned, "strongly disturbed" weather prevailed over a large area for at least one day - the 16 August.

2.3 Research aircraft observations

One of the instrumented DC-6 aircraft of the U. S. Weather Bureau's Research Flight Facility executed the photo-reconnaissance track shown in Fig. 13. The times are GCT. Since the flight was five to nine hours later than the satellite picture in Fig. 2, no detailed correlation should be expected. The comparative study carried out by La Seur and Zipser [1964] shows that identification of individual cloud features on both aircraft and satellite pictures is generally only possible if the photographs coincide within 30 minutes or so. It is agreed, however, that useful comparisons of systems can be made at much larger time differences and we shall see that the overall correspondence of what was seen by the aircraft and by TIROS is rather significant.

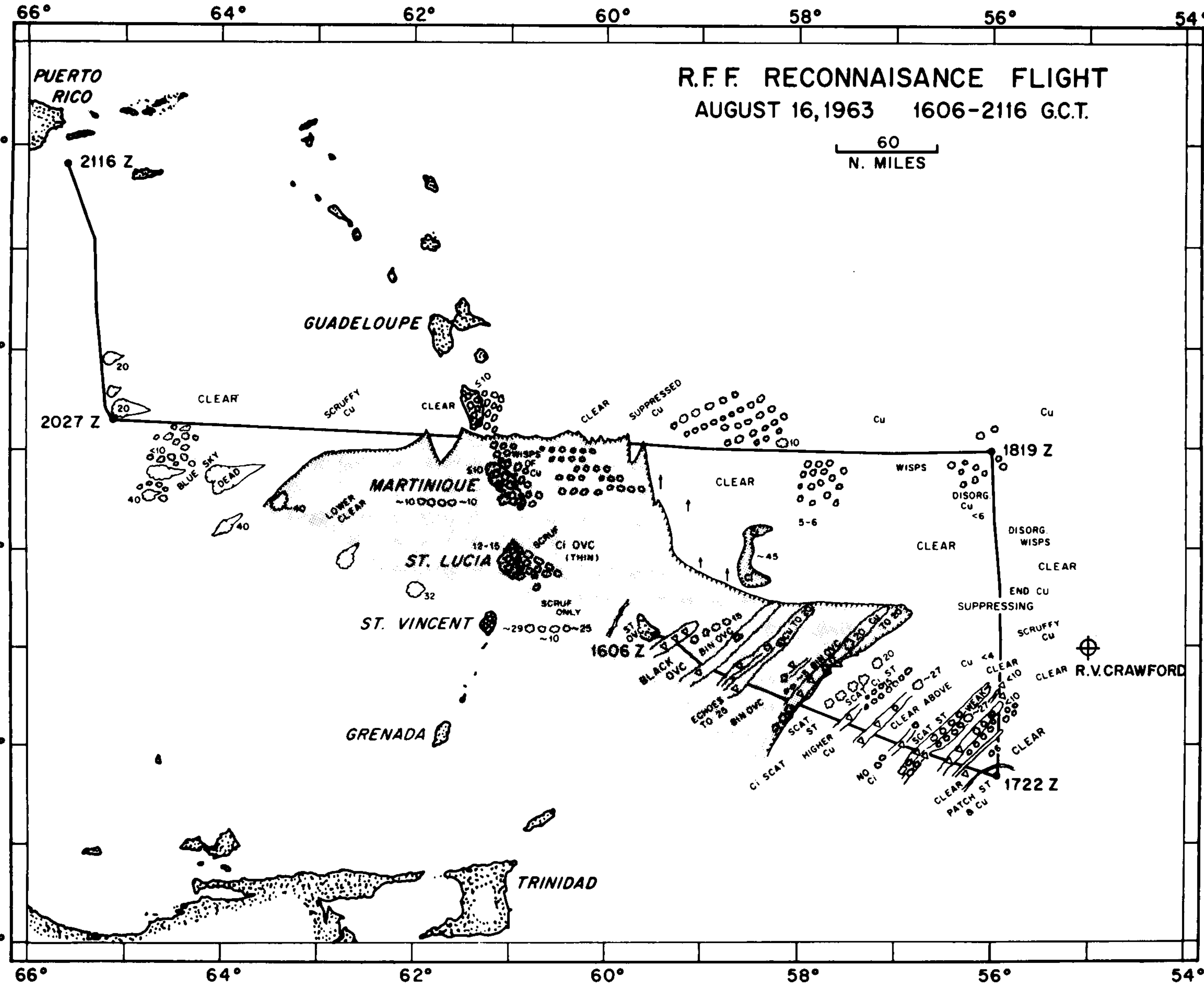


Fig.14 Cloud map constructed from aerial timelapse movies made from Weather Bureau aircraft. Gray stippled region denotes extent of upper overcast or near overcast conditions. Degree of disturbance greatest to south of Barbados and on the south side of the first half of Leg I. Numbers denote cloud top heights to nearest thousand feet.

The aircraft photography was done by time-lapse (one frame per second) 16 mm kodachrome movies. One camera was aimed at 90 degrees to the left of the fusilage and the other nearly straight forward (17 degrees to the right) from the nose. First, prints were made at ten minute intervals and arranged in strips along the flight track. The "Tropical Whole Sky Code" developed by Malkus and Riehl [1964] was then readily applied. The code number is entered above each time along the flight path in Fig. 13.

Codes 9 and 8 (eastsoutheast of Barbados) denote "swelling cumulus" not cumulonimbus, the former with upper sheets from broken to overcast, the latter with upper cloudiness less than broken. In the Caribbean (at latitude 15N) codes 10 and 11 indicate cumulonimbus in mainly clear skies; there were, in fact, only about 4-5 active cumulonimbus towers in view of the aircraft (within about 100 nautical miles of the flight path). The most disturbed-looking region is that coded as 12, where a few cumulonimbi penetrated an apparently independent upper overcast.

None of the "strong disturbance" code numbers 13-16 appear. In contrast, about 20 of these numbers were recorded on a track through a weak Pacific typhoon. Intensity of a disturbance, if it is to assessed from this Whole Sky Code, depends upon both the magnitude and extent of the code numbers. Comparing with numerous Pacific cases, we would be forced from the Sky Code alone to call this disturbance "moderate" since it contained more and a bigger area of high numbers than many "moderate intensity" disturbances analyzed in the Pacific study [Malkus and Riehl, 1964].

The final product of the aerial photographs is the cloud map [Fig. 14]. This was constructed as described by Malkus and Riehl [1964] and in more detail in a manual by Ronne [1959].

The orientation of cloud rows and anvils is particularly informative. The "parallel mode" is clearly exhibited in the small (<10,000 ft) trade cumuli near 15N, from 58W to 60W longitude. The orientation is north of east, becoming east as the island chain is approached; there is no indication of any south of east line-up.

A cross-wind mode is evident along the flight leg extending eastsoutheast of Barbados. If we accept the shear hypothesis of its orientation as developed by Malkus and Riehl [1964], this line-up is consistent with the wind field prevailing at Seawell, Barbados at 1200 GCT (0800 local time, see Fig. 8). This shows moderate (15-25 knots) easterly trades through the lower cloud layer, with much weaker southeasterlies above, giving a shear vector from roughly southwest. It is a bit difficult to see, however, how this wind field would have extended as far east as 57W around 1700 GCT, as the cloud rows apparently did. This point will be checked with the more accurate analysis of the flow field that is now in progress at the Florida State University.

A final orientation clue is provided by that of the anvils between about 63W and 65W latitude. We see pronounced westerly shear in this region, confirming the upper westerlies of Fig. 6. The change in orientation of the 40,000 ft anvils from west to southwest suggests locating the upper trough near 66W, as in Fig. 6. It is possible that over a limited area of about two degrees by four degrees in the region of high code numbers upper level divergence on the equatorial side of the trough provided additional impetus to the system.

However, the disturbance did not long survive its passage into the Caribbean. Research flights in the same region on the day following [Simpson, Simpson, Andrews and Eaton, 1965] showed only slightly above normal activity.

The final interesting feature of the map in Fig. 14 is the unusual cloud configuration associated with the Antilles. The three islands visible from the aircraft (Dominica, Martinique and St. Lucia) have similar patterns with small cumuli extending in a fairly triangular or peaked pattern <u>upwind</u> and cutting off sharply on the lee side. The only downwind cloudiness was a parallel cloud street to the lee of Martinique, but it began rather far offshore to be categorized as an island street. All of these islands are mountainous, and possibly lee-side subsidence was responsible for this downstream cutting off of lower cloudiness [Hosler, Davis and Booker, 1963].

The aircraft obervations succeed in delineating in considerable detail the cloud distributions associated with the disturbance. The cloud map of Fig, 14 provides both perspective and detail which were lacking in the previous observations. Some suspicion is raised by the aircraft observations that perhaps the observed weather is not related to a single atmospheric system. The group of cross-wind cloud rows southeast of Barbados is quite comparable in extent (about 250 miles) to several similar formations mapped by Malkus and Riehl [1964] in the Pacific and associated with a single identifiable disturbance. The group of cumulonimbus towers in the Caribbean is about 300 miles away from the western edge of the Barbados disturbance, or a distance considerably greater than the dimensions of either group of build ups. Therefore, some doubt is cast upon the initial impression that a single synoptic system orientated west-northwest/eastsoutheast propogates westwards.

2.4 Satellite observations

The following interpretation of the satellite observations on 16 August [Fig. 2] were kindly made by Dr. H. M. Johnson of the U. S. Weather Bureau's Meteorological Satellite Laboratory. In this interpretation quoted below TOS means "TIROS observational scale", while AOS means "aircraft observational scale":

1. "A light easterly trade flow is indicated at the more

open conditions (TOS) of large scale open bands near 57W, 8N to 13N; and is also indicated elsewhere.

2. A sizable group of large (AOS) convective clouds, evidently a group of cumulonimbus clouds, is in the region of Barbados and the southern Lesser Antilles.

3. A prominent large (TOS) very open zone which is generally about two degrees of latitude wide extends from east of 50W, south of 15N to about 65W near 20N.

4. Martinique (square in Fig. 2) is under a large (AOS) cloud system. Dominica (see Fig. 13) and Guadeloupe (triangle in Fig. 2) have a relatively small amount (TOS) of island cloudiness, but of relatively large vertical extent. Antigua (17N, 61 45W) is in the large open zone as is Barbuda (17 40N, 61 45W) and has very little evident (TOS) cloudiness, but does have some island cumulus.

5. A very large (TOS) area of relatively open conditions including many cloud lines and cloud bands in what appears to be a generally southeasterly trade flow is shown north of 15N and west of 55W.

6. An extensive area of more intense convective activity, evidently also including cumulonimbus, is shown near 12N, 50W (on TIROS VI frames not reproduced here).

7. This disturbed area, the disturbed area near Barbados, and the more open area between, of small cloud bands (TOS) grouped into a system which is banded on a large

scale (TOS), is significantly, bounded on the north by the large open zone and bounded on the south by another very open zone."

At the Meteorological Satellite Laboratory, efforts are being made to categorize and classify tropical storms from the pictures alone, particularly with respect to intensity and relation to surface winds. A classification scheme for sub-hurricane disturbances has been offered by Fett [1964]. Using his criteria, we find our "storm" in the weakest category (A). This category is described as follows:

"Tropical disturbance - Rotary circulation slight or absent on the surface but possibly better developed aloft. No closed surface isobars, no strong winds (<20 knots) . . . In this phase of development, the outstanding characteristic apparent from the satellite photographs is that of enhanced convection throughout an overcast or nearly overcast area of irregular shape and dimensions . . . Spiral banding . . . is normally not accentuated enough to determine a center of circulation from the satellite photographs."

Figure 2 shows a disturbed region quite similar in appearance to a case used by Fett to illustrate the weakest end of his category (A). From this we, therefore, conclude that this weather system would, on the basis of satellite observations, be classified as weak even though it is not adequately covered by the definition quoted above covering the weakest category.

The information supplied by the satellite observation alone is, therefore, primarily concerned with the large scale features. It is difficult to infer any reliable information from these satellite pictures, as to the structure and dynamics of this weather system. On the contrary, some of the inferences made from the satellite pictures alone appear to be in conflict with other observations. However, had adequate coverage existed such that continuous pictures could have been obtained on 15 and 16 August, and also on the preceeding and succeeding days, a far greater contribution would have been made by the satellite cameras.

3. INTEGRATION OF THE OBSERVATIONS

Individually no one of the above sources provided an adequate quantitative description of the weather system under observation. Of those discussed, the least information was gained from routine synoptic analyses. Clearly, these analyses are not sufficiently detailed to provide the necessary information. Nor, in fact, can they be and still cover the area they are required to cover. It remains to be seen whether a detailed synoptic analysis, using every available observation currently underway at the Florida State University, will indeed provide, from this source, additional insight into the structure and dynamics of this weather system.

The satellite observations provided more information but there seems to be as much disagreement as agreement when conclusions drawn from the satellite pictures alone are compared with the other observations. The inferred surface wind field from the satellite pictures on 16 August does not agree with the observed surface winds. In the tropics where relatively small changes in wind speed and direction are important "light easterly trade and "southeasterly trade" cannot be equated to winds blowing from 080 degrees to 070 degrees with a magnitude of greater than 8 m sec^{-1}. There is, however, a considerable degree of agreement between the cloud observations from the satellite and cloud observations made from the aircraft, island and ship. The large scale cloud features of the system as shown by TIROS on Fig. 2 and by the aircraft on Fig. 14 are in good agreement. However, difficulties appear when the details of the cloud system are compared. The "parallel mode" referred to in Section 2.3 above, is clearly exhibited by the aircraft photographs compiled in Fig. 14. Here the small (<10,000 ft) trade cumuli near 15N, from 58W to 60W longitude are orientated north of east, becoming east as the island chain is approached,there is no indication of any south of east line-up as implied by the satellite interpretation. It may be possible to infer from the satellite pictures [Fig. 2] east-west and then slightly southeasterly orientation of the cumulus clouds west of 66W which is off our map shown in Fig. 14. Furthermore, the westerly shear in the region 63W to 65W of the aircraft track is not apparent from the TIROS pictures.

It is also interesting to compare the island cloud patterns in Fig. 14 with Fig. 2 and Dr. Johnson's comment 4 thereon. Martinique is still under a large (AOS) cloud system in Fig. 14. However, the vertical extent of the island clouds observed by the aircraft, is not large over Dominica. We believe that the difference is real, caused by the semi-diurnal cycle in cloudiness, now well documented from this expedition [La Seur and Garstang, 1964; Garstang, 1964].

The photograph in Fig. 2 was made at 0707 local time, or at the peak of the cloudiness cycle, while the aircraft crossed the island chain at 1530-1540 hours local time, or close to the most suppressed period. The writers' observations on Barbados strongly suggest that the island clouds go through a corresponding vertical development cycle.

The disturbed conditions shown in Figs. 9a, b and c, and Fig. 12a from the ship and from Barbados compare favorably with the satellite pictures closest to these times and positions. Similarly, the fair conditions shown by Fig. 12b coincides with the clear areas in Fig. 2.

The question of westward propogation or of dissipation and intensification remains obscure. From Fig. 1 it would appear that the cloudy region located west of the CRAWFORD had indeed passed over the CRAWFORD during the early hours of the morning of 15 August. Figure 2 and subsequent aircraft observations suggest that this system moved westwards and intensified. Coupled with the divergence and vertical velocity computations this movement and intensification seems likely. Yet synoptic analysis so far suggests that there is only a stationary or slow moving anticyclone at 500/200 mb. It is further puzzling to find that the next day the disturbance has all but dissipated. Further work must be done to clarify these apparent paradoxes.

In integrating the observations from these different systems the problem of definition of intensity arises.

Nomenclature is unimportant unless misinterpretation is likely to result. Certainly if a system in the atmosphere is described as "weak" or even "very weak" and this system proceeds to deposit precipitation in excess of one inch in 24 hours over a region measured in hundreds of kilometers, then it would appear that misinterpretation is likely. On the other hand, when according to the rainfall classification the disturbance is classififed as "strong" and the wind speed does not exceed 20 knots, this may be regarded as misleading. Many other comparative tests in situations of varying circulation strength, cloudiness and precipitation are mandatory to resolve this important point.

The integration of the observations from all sources does not provide us with a complete picture of this disturbance, yet we can enumerate certain facts about this disturbance that by themselves do not say very much, but in light of both our ignorance and perhaps preconceived ideas about tropical synoptic scale systems, are important. In summary, we list the following conclusions:

1. The disturbance is best delineated by its cloud field which during this short period of observation was orientated nearly east-west and reached a size of about 500 nautical miles long and at least 250 nautical miles wide. Embedded within this large cloud shield were moderately developed convective clouds in bands orientated mostly in a southwèst-northeast direction.

2. The disturbance was not related to any pronounced circulation or perturbation in the low level wind field. It was probably related to upper level divergence which, in turn, was associated with an anticyclonic circulation between 500 and 200 mb and/or a shearline at this level. The shearline by itself would not appear to be an adequate explanation.
3. Mean vertical velocities in the lower 10,000 ft of the troposphere associated with the active (cloud/precipitation region) part of the disturbance generally exceeded 5 cm sec^{-1} and rose as high as 8.4 cm sec^{-1}.
4. The active part of the disturbance produced a considerable amount of precipitation over an area at least 250 by 150 nautical miles.
5. The disturbance persisted as an observable synoptic scale system for at least three days. Its previous history is obscure but the possibility that it represents the remnants of a decaying system which was previously well organized over the mid-tropical Atlantic cannot be discounted.

4. CONCLUSIONS

The main conclusion to be drawn is the tremendous benefit potential of this type of study. The benefit should accrue equally to tropical meteorology and to the satellite program. One aircraft equipped with time-lapse cameras only is minimally adequate, if long reconnaissance legs can be flown into numerous disturbances in an island-dotted area, such as the Caribbean, Gulf of Mexico and Marshall Islands region in the Pacific. Several instrumented aircraft flying vertically superposed paths would permit divergence computations and better assessment of the vertical structure of the troposphere.

Except for the full hurricane, our knowledge of tropical disturbances is shockingly bad. Many more types of disturbances exist than are modelled in the textbooks or in the literature. The vertical layered structure of the tropical atmosphere appears to permit different disturbances in each of roughly three layers (low, middle, and high troposphere), which may or may not interact with those above or below. The interaction between layers is poorly understood. The situation examined in this paper is not an isolated instance but one example of many observed east-west orientated cloud systems that occur in the tropics. Work is now proceeding [e.g., La Seur and Zipser, 1964] which will provide some statistical evidence as to the frequency and importance of this type of disturbance. At present little is known about the connection between such a system and low latitude cyclones or hurricanes. It is certain, however, that such systems do play a role in the heat balance of the atmosphere [Garstang, 1964] and in the climatology of the tropics.

Attempts are being made to code the intensity of tropical disturbances, particularly from satellite pictures [Fett, 1964; Timchalk, Hubert and Fritz, 1965]. While the correlation between cloud pattern and wind speed may be useful operationally after the development stage of a closed circulation has been reached, a majority of tropical disturbances, in the sense of the weather, have no closed circulation or strong winds. Most disturbances would fall in Fett's (A) category, which clearly includes a heterogeneous collection of vastly different types of disturbances at several levels.

It would seem less useful at this stage to attempt to refine or further develop categories than to establish dynamic and physical models of the flow field and its attendant cloud and rainfall patterns. Theoretical and numerical modelling of the sub-hurricane tropical disturbance is almost non-existent and must be undertaken if numerical prediction methods are ever to become effective in the tropics.

A necessary prerequisite to any modelling is quantitative description from adequate and extensive correlated observations over a wide area and deep layer. Lacking a continental sounding network in the tropics, the only avenues for progress would appear to be specifically designed experiments based upon a selected island network and incorporating joint aircraft, oceanographic and satellite programs.

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13. ABSTRACT

Data from an experimental region based upon six islands of the Windward Group in the West Indies, a research vessel in the tropical Atlantic, an instrumented research aircraft, and TIROS VI and VII are used to study the structure of a specific disturbance which moved through the observational network during 15 and 16 August, 1963. Despite the fact that an unusual variety and amount of data is available, difficulties are encountered when an attemt is made to establish the physical and dynamic characteristics of the flow field and the attendant cloud and rainfall patterns associated with this disturbance. Taken individually, each source of data is found to be either inadequate or, in the light of other information, perhaps

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13. ABSTRACT (CONT.)

even misleading. When all data sources are treated collectively a number of interesting features of the disturbance are illuminated. By and large, these results bear little resemblance to conventional tropical models such as the easterly wave or equatorial vortex. In fact, it is felt that this study demonstrates that a necessary prerequisite to any modelling is quantitative description from adequate and extensive correlated observations over a wide area and a deep layer. Lacking a continental sounding network in the tropics, the only avenue for progress would appear to be specifically designed experiments based upon a selected island network and incorporating joint aircraft, oceanographic and satellite programs.

14.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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