SOME INFERENCES FROM SATELLITE PICTURES OF TROPICAL DISTURBANCES

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ABSTRACT

The degree of organization and the size of the cloud patterns in TIROS pictures of tropical disturbances are good indicators of the maximum wind speed as observed by airplanes. The organization varies from unorganized bright cloud patterns, to highly organized spiral arrays of clouds with additional characteristic features, such as the sharp edge of cirrus clouds. Poorly organized clouds are associated with weak disturbances, the most highly organized ones with intense storms.

In addition, within each category a relationship exists between the size of the cloud pattern and the maximum wind speed. Both the organization category and the size of the overcast cloud pattern are related statistically to the maximum wind speed, so that the maximum wind speed can be estimated from the picture of the storm alone. Tests with independent data show that a useful relationship has been obtained. Theoretical justification for the results obtained is necessary but is not yet available.

1. INTRODUCTION

It is well known that disturbances in the Tropics begin as weak systems, that many of them develop to some extent, and that a few develop into hurricanes or typhoons. And it becomes evident, from the numerous satellite pictures of tropical disturbances and cyclones, that the cloud patterns associated with them vary in organization and in size in accordance with the state of development of the disturbance. Many pictures portray clouds which are poorly organized or not organized at all; they represent irregular masses of bright cloud. In other pictures however, the cloud systems appear highly organized indeed, presenting marked spiral arrays of cloud bands, often with well-defined, sharp-edged cirrus shields. From the pictures, it is also evident that the cloud systems associated with these tropical disturbances vary in size from about 150 mi. to 600 mi. or more in diameter.

It is therefore natural to inquire whether these characteristics, which can be recognized readily in the cloud pictures, are related to other meteorological parameters. One such parameter available for study is the maximum wind speed (MWS) near the center of the storm. The MWS has been measured from reconnaissance aircraft on numerous occasions when satellite cloud pictures were also available. Both the organization and size of the clouds will therefore be discussed in relation to the MWS.

2. THE ORGANIZATION OF TROPICAL CLOUD SYSTEMS

A systematic summary of organization in tropical cloud systems [1] is shown in figure 1, an array of pictures which correspond to various stages of storm development. They are pictures of different storms, because all the significant stages of development of a single storm are not often seen by TIROS satellites. TIROS ordinarily photographs a storm once a day, and often some days are missed in a sequence; but significant changes may occur in less than a 24-hr. period. The pictures in figure 1, labeled A to D are early stages of the type studied by Fett [2]. In picture A, an irregular unorganized cloud mass is seen. Picture B is beginning to show some organization; note, for example, the more pronounced convex arc of clouds on the left hand side of the cloud. A faint suggestion of cloud line organization may be noted at the upper left hand edge of the main cloud mass. This disturbance later developed into hurricane Anna, 1961 [3]. In picture C a well formed spiral cloud array is seen, but the center of the spiral is completely outside the brighter overcast area. In picture D, some organization is present, and the center of the organized pattern is covered with cirriform clouds. This suggests that in one type of storm development the overcast cirriform cloud spreads over the cumuliform clouds which had first portrayed the spiral array. However, there is pictorial evidence that different patterns of storm development may occur also.

Experience suggests that the surface wind speed associated with weakly organized cloud patterns, such as those in pictures A to D, is usually well below hurricane force; but the wind may reach up to about 50 kt. or so, in some cases (e.g., [2]).

In picture D, cirrus clouds can be seen shearing off the edges of the brighter overcast areas, in several places, but especially near the right side of the picture; this is evident from the gradual decrease in brightness. Such cirrus outflow in different directions suggests that an upper anticyclone has developed; and since it is well known that
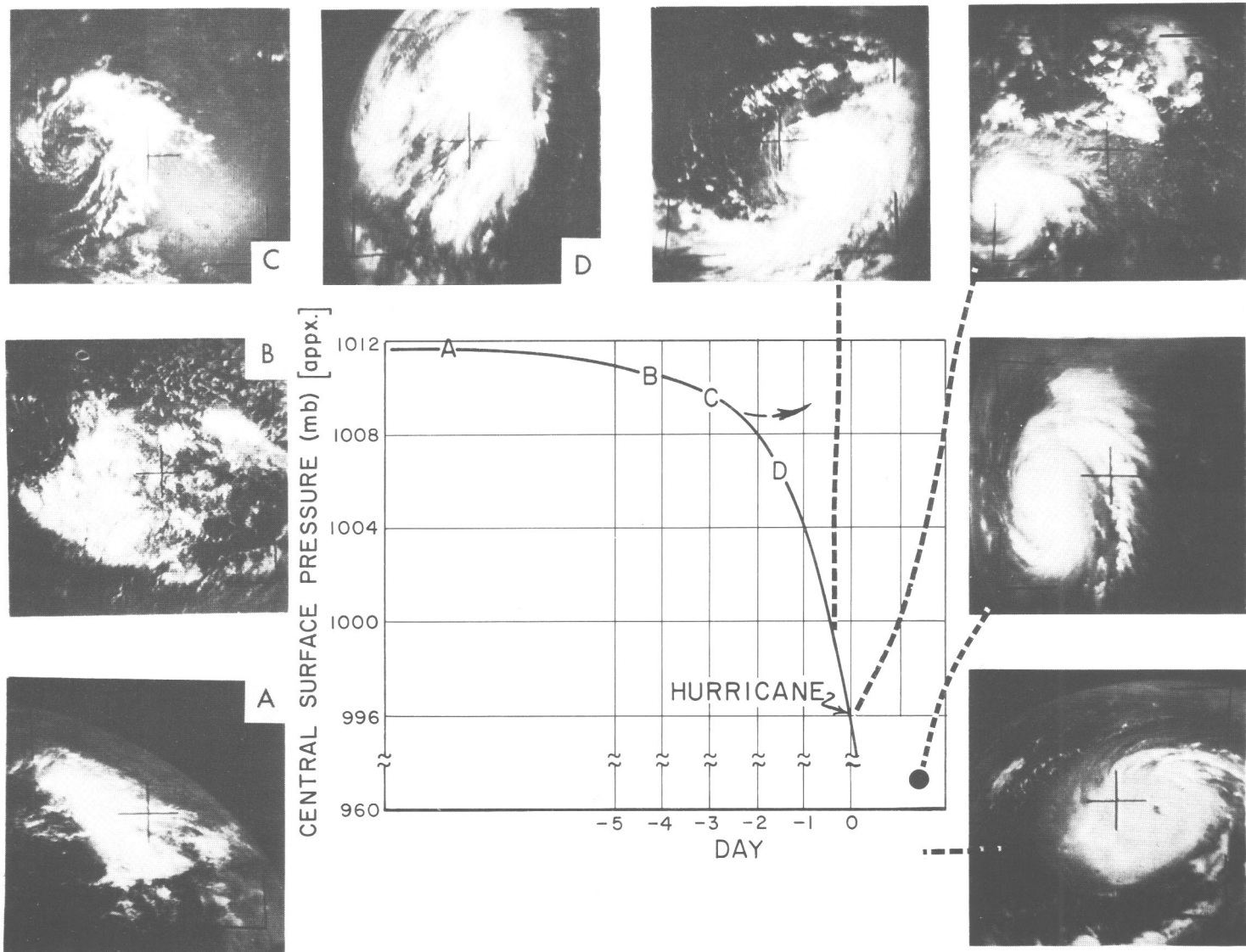
FIGURE 1.—TIROS pictures of different tropical cyclones in various stages of development. The curve of central surface pressure vs. time shows a suggested relationship to the cloud patterns shown in the pictures. Day zero is the time when the storm reached hurricane force.

the development of an anticyclone aloft is an important characteristic of hurricanes, it is likely that the appearance of cirrus outflow is indicative of a developing storm.

Thus the first appearance of such cirrus outflow may be an indicator that outflow aloft has increased, and that the disturbance has developed to a stage in which the surface pressure begins to fall rapidly. In line with this suggestion, a chart of surface pressure vs. time was prepared, and is also shown in figure 1. The pressures were not measured at the times of the pictures A to D in figure 1; but based on estimates in hurricane Anna, 1961, and on studies by Yanai [4] for typhoon Doris, 1958, the surface pressure in developing storms may fall approximately at the rate shown in figure 1. During the development of hurricane Anna, picture B, figure 1, was estimated to lie on the pressure curve as shown. The dashed arrow near C, on the pressure curve, is intended to indicate those

disturbances in which pronounced cirrus outflow does not occur; presumably such disturbances will not develop rapidly. At the time of picture D, with the cirrus outflow beginning, the surface pressure falls more rapidly than before.

Further development is portrayed in the pictures following picture D in figure 1, as additional spiral organization occurs. The picture in the upper right corner represents a cloud pattern associated with a storm of near hurricane force. Often an "eye" is discernible in pictures of storms at this stage. A bright overcast area exists with well defined spiral arms in the uniformly bright cirrus cloud. As the storm develops further to an intense hurricane, the cloud organization increases further, and the cloud size increases. A common characteristic is the sharp edge of the cirrus shield as seen near the bottom of the last picture. The prominent eye is also readily seen
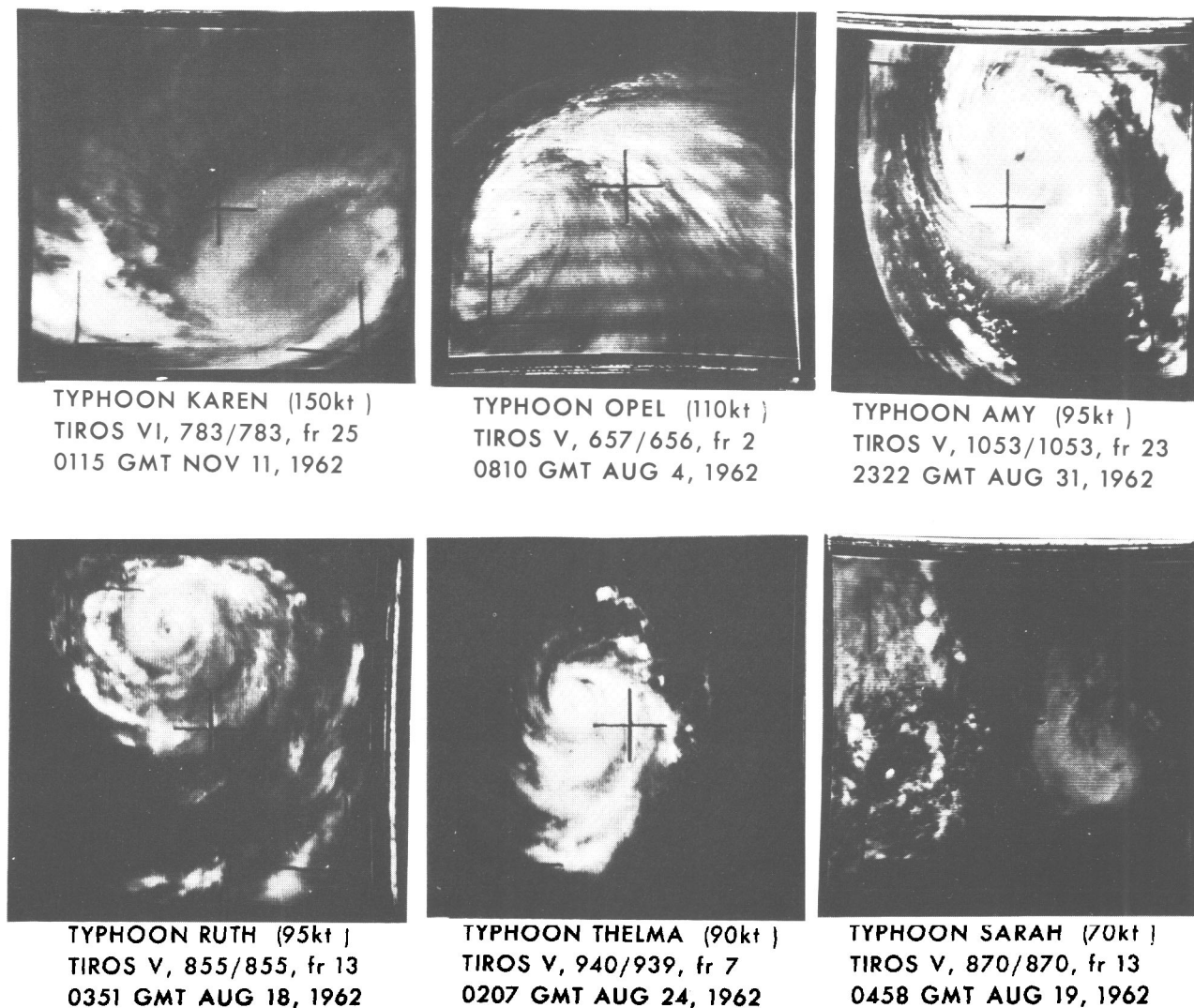
FIGURE 2.—Six TIROS pictures of typhoons, each showing an "eye" in the cloud pattern. The maximum wind speed, observed by airplanes, is given under each picture. The wind speed mainly increases as the cloud size increases.

in the last picture. (For the last two pictures, the surface pressure was reported by reconnaissance aircraft which flew into the storm center.)

Thus we conclude from cloud patterns, such as these in figure 1, that the degree of organization of the cloud pattern is an indicator of the state of development of tropical disturbances, storms, and hurricanes.

3. CLOUD SIZE

But in addition to organization the size of the cloud pattern is also an important indicator of the maximum wind speed (MWS). This may be illustrated with the aid of figure 2. It contains examples of six typhoons in each of which an "eye" was discernible in the TIROS cloud pictures. They have been arrayed according to maximum wind speed based upon observation by reconnaissance airplanes. And although the actual size of the

cloud shield can be measured only after appropriate picture rectification, it is still evident in figure 2 that the stronger typhoons generally have larger cloud shields than do the weaker typhoons. For example, it can be seen, even without picture rectification, that typhoons Opel and Amy have larger cloud shields than Thelma and Sarah.

This same relationship has also been found for storms in which the "eye" is not discernible in the pictures.

To place the evidence about organization and size on a more quantitative basis with regard to the maximum wind speed, the results were treated in more detail in [5].

4. MAXIMUM WIND SPEEDS

All the oceanic cases were assembled in which airplane measurements in tropical cyclones were made and for which pictures from TIROS V and VI (1962) were available. Although somewhat subjective, rules were developed

for grouping the cloud patterns into four "categories" according to the degree of organization [5]. Rules were also devised for obtaining an estimate of the size of the cloud from the TIROS photographs.

Briefly, these rules may be summarized as follows: when an "eye" was discernible the storm was classified in the highest categories; i.e., in categories 3 or 4. If the "eye" was well formed, with a well defined circular, bright cloud, the storm was usually classed as category 4—the most intense storm. If the "eye" was more ragged in appearance, the storm was classed as a category 3 storm. Also the degree to which bands and striations tended to be circular was the characteristic that helped further to decide between categories. The more circular the bands and striations the higher the category to which the storm belonged. This categorization was aided by the presence or absence of relatively large breaks; large breaks in the overcast cloud pattern tended to be associated with the lower categories or weaker storms.

With regard to the size of the cloud pattern, the rules delineated an "overcast circle" diameter. This was an attempt to include the major areas associated with the overcast part of the cloud pattern presumably produced by the central part of the storm. The rules attempted to exclude the cloudiness which lay in the peripheral areas, especially when large breaks separated the peripheral cloudiness from the main clouds.

Also, use of the "overcast circle" diameter was an attempt to include only those clouds which lay over the circulation center; experience showed that the classification scheme of figure 3 should be applied only to well-developed disturbances. For that reason no "overcast diameter" was defined by the rules, if the spiral pattern center lay outside the overcast area or very near its edge.

Because of the difficulty of specifying the "category" and the size by strictly objective means, both of these quantitative estimates must still be considered as preliminary. Moreover, the MWS obtained from airplane observations are subject to considerable uncertainty. The "smoothed" speeds were used in reference [5]. The final "smoothed" speed released by the cognizant agency sometimes differs by more than 50 kt. from the wind reported by the airplane. Although this is not the usual situation, it indicates that the MWS are also in error to an unknown degree. Nevertheless, using the criteria which were developed, 47 cases of nearly simultaneous airplane and satellite observations were obtained and summarized as shown in figure 3.

The data in figure 3 have been divided into two parts. One part contained only those storms in which an "eye" could be discerned in the TIROS pictures; the typhoons in figure 2 are examples of these. It was immediately evident that when an "eye" was discernible in the TIROS picture, the MWS had already reached 60 kt. or more.[1]

Within categories 3 and 4, in which an eye was discernible, there also appeared to be a relationship according to size as indicated in figure 3.

But in many storms, an "eye" is not discernible in the TIROS pictures. Many reasons may be adduced for this. When the picture is near the horizon, the pattern is highly foreshortened and the resolution becomes very poor. At other times, the eye may be filled with low or high clouds; or the sun may be high in the sky and the satellite camera viewing angle may be such that no shadow is cast by the eye wall. Nevertheless, in these "no-eye" cases, a category describing the degree of organization can be assigned to the cloud patterns. Within these categories the MWS also varies with the cloud size as shown in figure 3. The curves for categories 3 and 4 in these cases are the same as the curves for the "eye" cases. But the data have been seprated to bring out more clearly the fact that the presence of the "eye" itself is an important indication of strong winds.

Figure 3 also shows that when the organization is less pronounced, as in categories 1 and 2,[2] the MWS tends to be lower. But in these categories too, there tended to be an increase in MWS with increasing cloud diameter.

The cloud patterns designated as DIA≡ZERO in figure 3 were those in which the spiral cloud organization lay outside an overcast area, or else very close to the edge. Picture C in figure 1 is an example of this. In this case, no MWS was assigned to the storm in reference [5].

5. TEST OF THE RESULTS

A test with independent data was performed with the 1963 storms in the Atlantic Ocean. Two different analysts working independently made estimates of the MWS from the TIROS pictures alone. They considered only those pictures which could be assigned categories 1 to 4, and so could be used with figure 3. Their estimates were then compared with the MWS based on reconnaissance aircraft observations. The contingency tables showing their results are given in figure 4, in which the MWS have been separated into 15-kt. intervals. For the most part the errors, compared to winds based upon airplane observations, were within one 15-kt. category, although one of the analysts on four occasions differed by two 15-kt. categories. Since the "observed" MWS reached to about 100 kt., this agreement suggests the relationship of figure 3 is useful, especially when applied to data-sparse areas, where airplane reconnaissance is not available.

6. DISCUSSION

The application of figure 3 to independent data in 1964 and 1965 has also shown that usable MWS can be obtained from the TIROS pictures alone. However, if one examines

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[1] In subsequent years there have been two cases in which the MWS was as low as 50 kt. when an eye was discernible.

[2] For example, in figure 1, picture D was assigned to category 1; the picture following picture D was designated category 2.
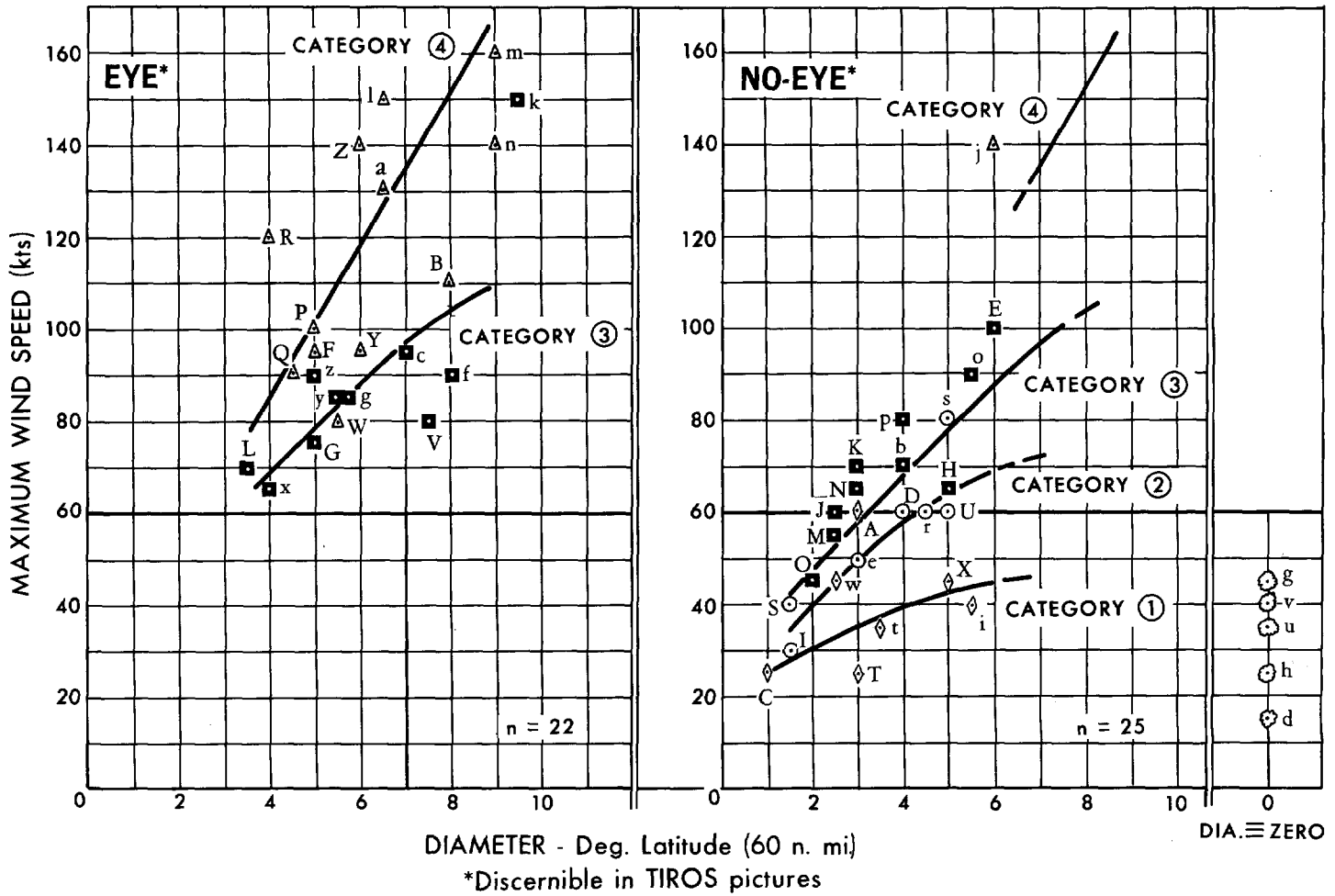
FIGURE 3.—A graph showing the maximum wind speed, as observed by airplanes, in relation to the degree of pattern organization (categories 1 to 4) and to the size of the cloud diameter. In general, the wind speed increases both with the degree of organization and with the size of the cloud pattern.

only those pictures in which the "eye" was discernible then further questions arise.

For example, in a study of 1962, 1963, and 1964 storms in the Atlantic and Pacific Ocean areas, the observations show a tendency for category 3 storms to have smaller diameters than the highly organized, category 4 storms. This tendency is illustrated in table 1. With 75 storm cases in which the eye was discernible in the pictures, about 62 percent of the category 3 storms had relatively small overcast diameters, while only about 30 to 35 percent of the category 4 storms had such small diameters. Actually this effect was not present in the 1962 storms (fig. 3), but was therefore even more pronounced in the 1963–1964 storms than these numbers indicate.

This suggests that the degree of the organization (category) and the cloud pattern size (diameter) may be correlated. Nevertheless, storms with the same overcast diameters tended to have greater intensities when the category was higher.

TEST WITH INDEPENDENT DATA

FIGURE 4.—Contingency tables for Maximum Winds Speeds (MWS), derived from independent data by two analysts, compared with observed MWS.

TABLE 1.—*Distribution of storm diameters in categories 3 and 4— "eye" discernible (1962, 1963, 1964)*

Pacific Ocean (47 storms)

	Diameter 5° or smaller	Total range of diameter sizes (° lat.)
Category 3	15 out of 24 cases; 62%	3 to 9½.
Category 4	8 out of 23 cases; 35%	3½ to 9.

Atlantic Ocean (28 storms)

	Diameter 4° or smaller	Total range of diameter sizes (° lat.)
Category 3	11 out of 18 cases; 61%	3 to 5½.
Category 4	3 out of 10 cases; 30%	3 to 6.

In all the data, moreover, the larger diameter cloud patterns were associated with higher MWS. Why this should be so requires theoretical explanation. There are many intense storms in which the cirrus shield has an abrupt sharp boundary. For example, this was the case in typhoons Amy and Karen in figure 2; it was quite evident in the high resolution Mercury Project picture of hurricane Debbie [6], and many more instances could be cited. This sharp edge appears to be produced by a region of pronounced downward motion which apparently suppresses the clouds right down to the ocean surface. If so, the fact to be explained is why the region where pronounced downward motion occurs at the cirrus level should be farther from the "eye" when the surface wind speed near the center of the storm is greater. Speculative qualitative reasons can doubtless be advanced, but more insight will be obtained through the study of numerical models such as those of Krishnamurti [7], Barrientos [8], and Estoque [9]. These models derive the three-dimensional vertical motion distribution when the horizontal motion distribution is prescribed. In such models one can vary the horizontal wind distribution, including the MWS, to see whether or not a region of downward motion can be produced at the cirrus level near the outer edge of the storm, and if this region moves farther from the center as the MWS is increased.

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