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(NASA-TM-85114) FORECASTING TROPICAL CYCLONE RECURVATURE WITH UPPER TROPOSPHERIC WINDS (NASA) 26 p HC A03/MF A01 CSCL 04B

N84-11659

Unclas
G3/47 42442

NASA

Technical Memorandum 85114

FORECASTING TROPICAL CYCLONE RECURVATURE WITH UPPER TROPOSPHERIC WINDS.

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NOVEMBER 1983

National Aeronautics and
Space Administration

Goddard Space Flight Center
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FORECASTING TROPICAL CYCLONE RECURVATURE WITH UPPER TROPOSPHERIC WINDS

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November 1983

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ABSTRACT

Data from 17 tropical cyclones during the 1974 through 1979 hurricane seasons are used to investigate whether the high level winds far to the northwest, north and northeast of the hurricane center can be used to predict whether the hurricane track will recurve. It was found that when the mean 200-mb winds at about 1500 to 2000 km northwest and north of the storm center equal or exceed 20 m/s that 80 per cent of the storms recurved before traveling as much as 12 degrees of longitude farther west. The high level winds were also used to predict change in direction of forward motion during the next 72 hours. The regressing equations developed explains up to 41 per cent of the variance in future direction.

In addition to the geostrophic winds used in these results, winds were also obtained by tracking clouds with successive satellite imagery. The u-components of the satellite winds are highly correlated with the

geostrophic winds at 200-mb and could probably be used instead of them when available. The v-components are less highly correlated. In fact, in many of the cases when the hurricane was recurving, the v-component of the satellite winds greatly exceeded the v-component of the geostrophic winds. Absence of clouds that would make suitable targets for obtaining high level winds in the area 700 to 1800 km north of the hurricane occurred only with non-recurving storms and suggests that absence of clouds implies presence of circulations that would inhibit recurvature of storm track.

1. Introduction

This research was designed to test the hypothesis that the strength of the west winds in the upper troposphere 500 to 2200 km northwest, north and northeast of the hurricane center could be used to predict whether and when the hurricane would recurve and to determine if the winds derived from tracking of high level clouds by successive satellite imagery could be used to define the wind fields needed for this research.

George and Gray (1977) using 10 years of composited Western Pacific rawinsonde data had found a strong relationship between tropical cyclone recurvature and the upper tropospheric (200 mb) wind field at large distances north and northwest of the storm center 12 to 60 hours prior to recurvature. Their results indicated that the stronger the west component of the winds, the more likely the storm was to recurve. See Figure 1. Their work, however, did not investigate the response time between a given upper tropospheric wind field and the time of recurvature, distance the tropical cyclone travels before recurving after a given upper tropospheric wind field is observed, the percent of individual cases in which recurvature is observed for a wind field of a given intensity or whether the relationship held for Atlantic/Gulf of Mexico recurving and nonrecurving tropical cyclones. In addition to seeking answers to these questions, this research used the SMS/GOES digitized data to track clouds to derive winds at the level of the high clouds around a hurricane to see if these winds could be substituted for rawinds. If so, this would facilitate improving hurricane forecasts in areas of sparse conventional upper air data.

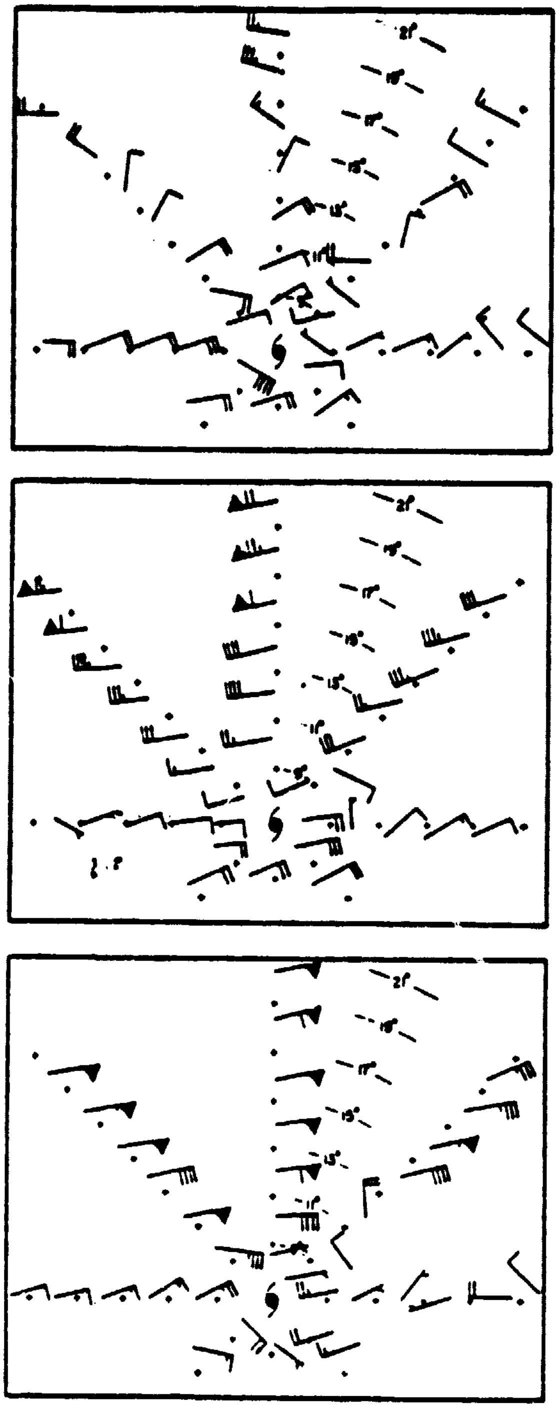

Fig. 1. Composited 200 mb wind direction and speeds: For nonrecurving storms (top), recurving storms (middle) and nonrecurving minus recurving difference (bottom) for 60 hours prior to recurvature. Distance is degrees of latitude (After George and Gray, 1977).

In addition to the work of George and Gray, Guard (1977) tested the hypothesis with Western Pacific storms. His work and that of Chan et al. (1980) suggested that results would be improved if one either typed the storms before applying the hypothesis or included data in addition to the u-components of the 200 mb winds.

2. The Data

The satellite winds were derived by tracking clouds after looping successive imagery on the Atmospheric and Oceanographic Information Processing System (AOIPS) located at NASA/Goddard Space Flight Center. Using imagery at 30-minute intervals (in a few cases the imagery were at 15-minute intervals) winds were obtained for the tropical cyclones and the periods listed in Table 1. The high level clouds were tracked over large areas ranging out to 2500 km northwest, north and northeast of the hurricane centers. In most cases the clouds were believed to be representative of the winds in the layer between 300 mb and 200 mb. For many of the cases clouds were tracked using both the infrared and visible imagery.

Winds derived by tracking clouds are of necessity limited to the times and places where there are suitable clouds to serve as targets. The decision was made in the beginning, therefore, to supplement the satellite winds with other data. Rawins and winds measured by high flying aircraft were used when available. These however, were frequently not found in the desired areas. It was decided, therefore, to calculate the geostrophic winds to insure there would always be some winds over the entire area to be analyzed. Tabulations of the rawind and aircraft reconnaissance winds were obtained from the National Hurricane Center at

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Table 1

Wind Data Assembled - Number of Periods

Year	Tropical Cyclone	Recurved	High Level Clouds Tracked	200 mb Geostrophic Winds Calculated	Track in Figure
1974	Carmen	Yes	17	19	2
1975	Caroline	No	4	3	3
	Eloise	Yes	14	16	2
	Faye	Yes	5	14	4
	Gladys	Yes	9	21	4
1976	Belle	Yes	7	8	2
	Emmy	Yes	13	22	2
	Gloria	Yes	10	11	2
1977	Anita	No	6	8	3
	Babe	Yes	6	6	3
1978	Ella	Yes	4	8	3
	Flossie	Yes		10	3
	Greta	No	1	10	3
	Juliet	Yes		8	3
1979	David	Yes	7	16	4
	Frederick	Yes	2	28	4
	Gloria	Yes		21	4

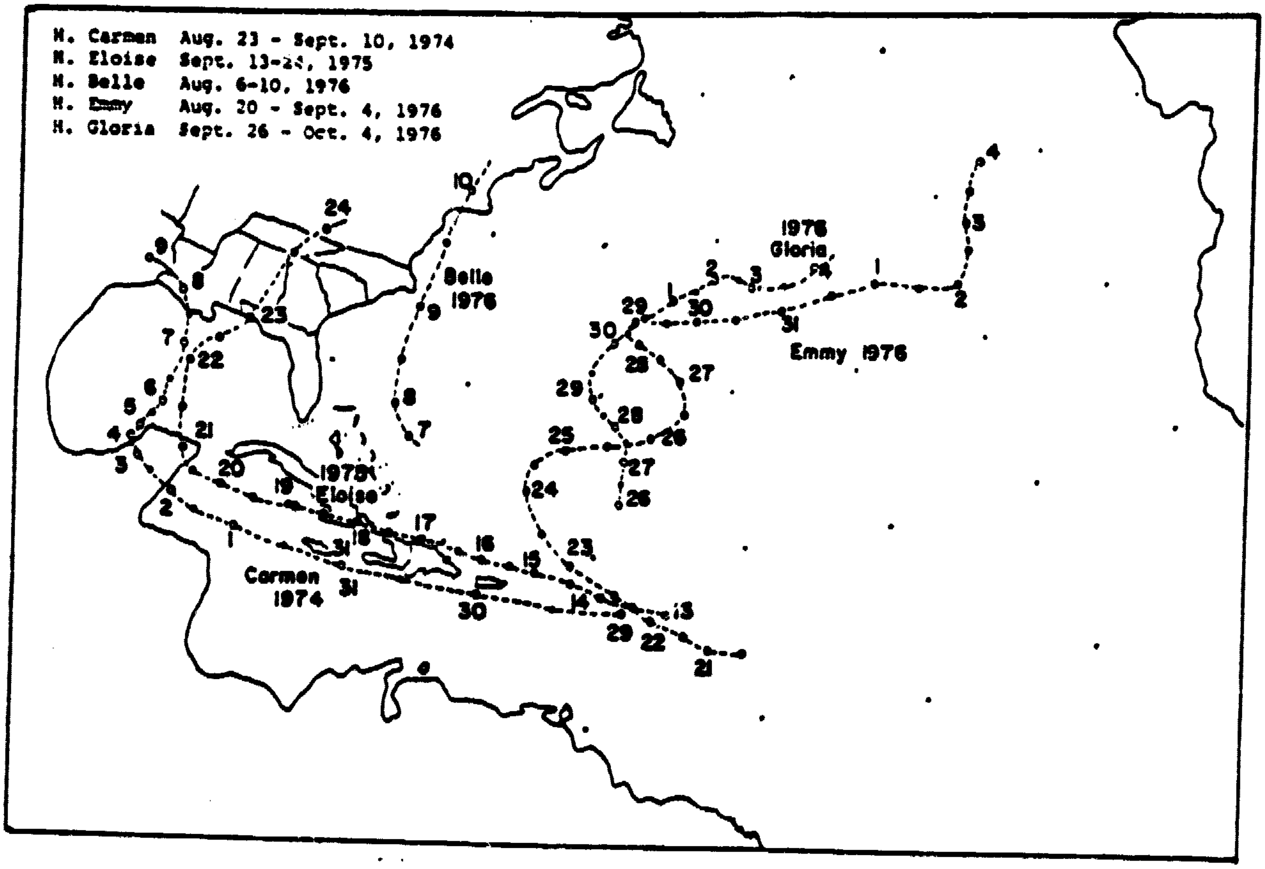

Fig. 2. Tracks of some of the storms used in this study (1974-1976): Adapted from Hope, 1975; Hebert, 1976; and Lawrence, 1977.

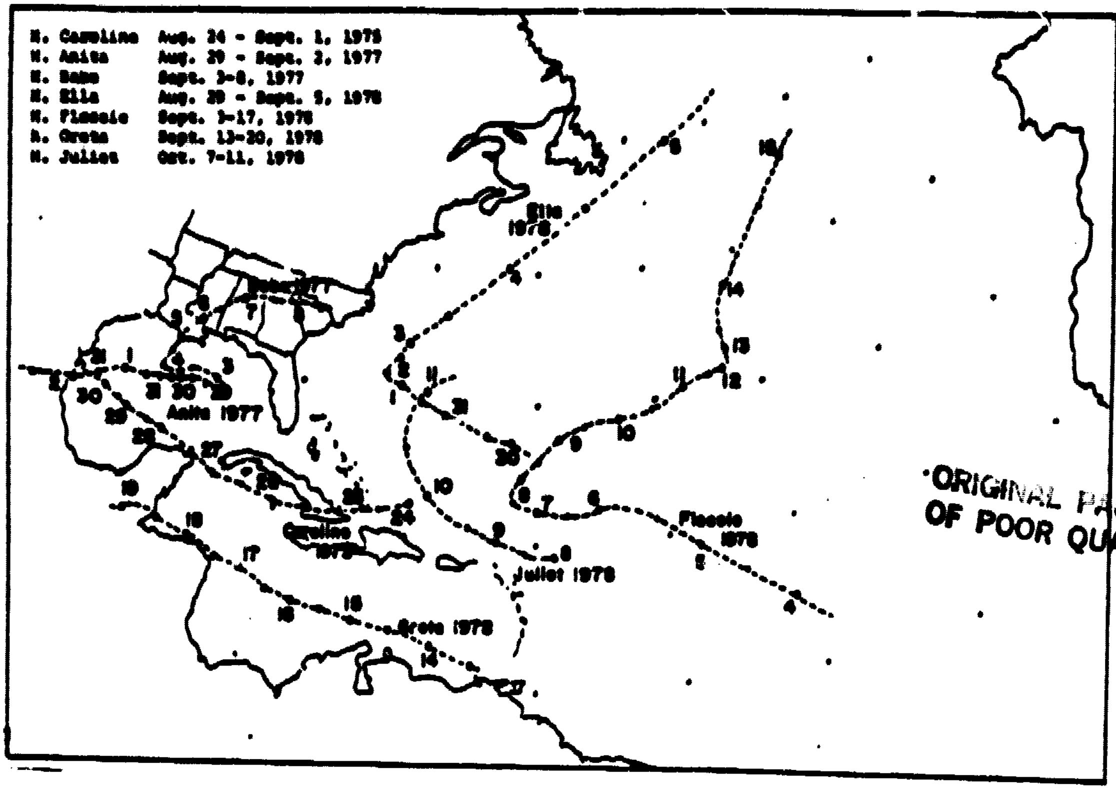

Fig. 3. Tracks of some of the storms used in this study (1975-1978): Adapted from Hebert, 1976; Lawrence, 1978; and Lawrence, 1979.

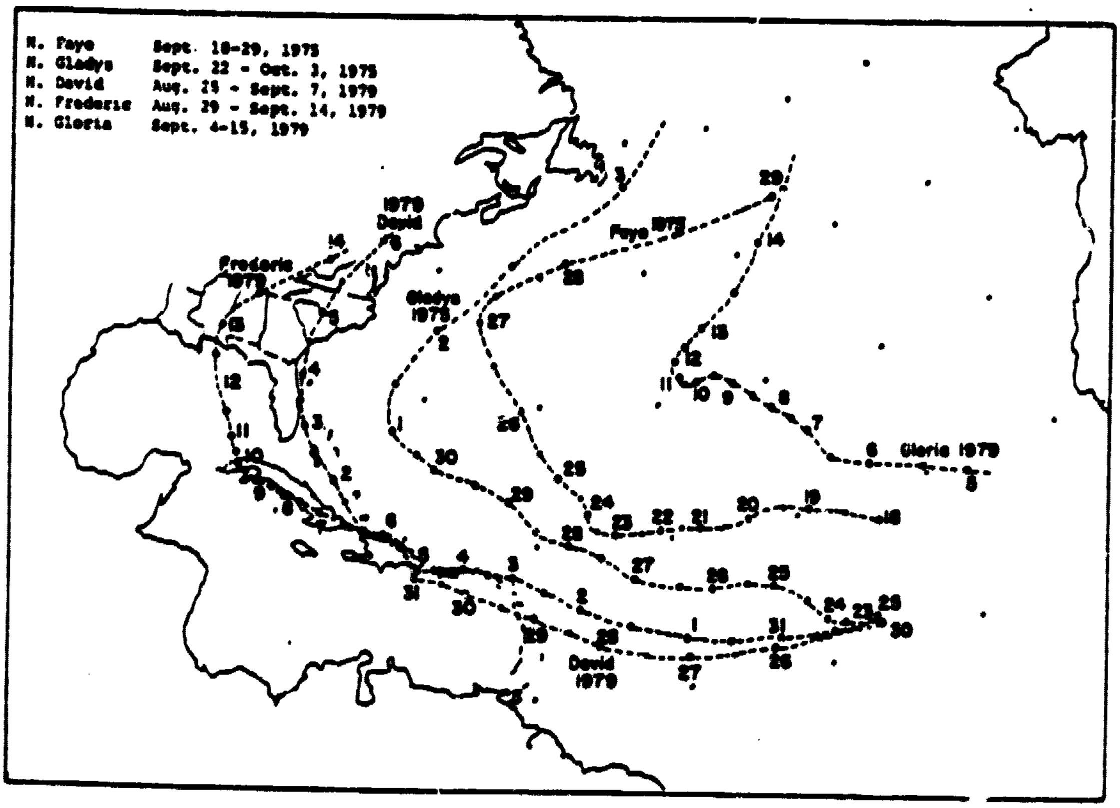

Fig. 4. Tracks of some of the storms used in this study (1975-1979): Adapted from Hebert, 1976; and Hebert, 1980.

Miami along with microfilm copies of all their maps for the storms to be studied. Microfilm copies of the maps prepared by the National Meteorological Center were also secured. Using the latter the geostrophic winds and their u- and v-components were computed from the 200 mb maps and the data were plotted on work charts.

The storms chosen for the study, and the periods for which the satellite winds and the geostrophic winds were obtained, are all listed in Table 1, and their tracks are illustrated in Figures 2-4 as indicated in the right column of the Table. In addition, Table 1 indicates which of the storms recurved. Data have been collected from 17 storms during the years 1974 through 1979. Only three of these storms failed to recurve, but several of the others had periods where the threat of recurvature seemed real at the time forecasts were made and the storm did not recurve until much later. These can be considered non-recurvature cases. Thus, the number of situations of recurvature and non-recurvature are fairly evenly balanced. In this study recurvature was defined as having occurred when the storm motion changed from one with a component toward the west to one where the motion was toward the north or (as was true in most cases) to one with a component toward the east.

After the geostrophic and satellite winds were calculated, the u- and v-components were plotted on regular maps. Examination of these maps and comparisons of the components with the tracks of hurricanes for corresponding periods showed a good correlation between strong u-components northwest through northeast of the storm and recurvature of the stormtrack during the next 60 hours. To put numbers on our relations, a portion of a polar grid was superimposed on the maps with the center on the surface position of the hurricane and with arcs drawn through the northern quadrants at 10, 15 and 20 degrees of latitude radial distance from the hurricane center. Azimuth lines were then drawn at 315°, 337.5°, 360°, 22.5° and 45°.

These arcs and azimuthal lines outlined several sectors that could be examined individually. Note that in Figure 1 the data of George and Gray showed large differences in the 200 mb winds between recurvature and non-curvature cases in the sectors between 10 and 20 degrees north of the storm. For recurvature situations the westerlies at 200 mb extended southward to within about 10 degrees of latitude of the hurricane center. We computed for each of our time periods u- and v-components for various of the sectors. In this paper, however, when there is a reference to an average (unless specified otherwise) the average will be for data between 15 and 20 degrees radius and between azimuths of 315°-360°, 337.5°-22.5°, and 360°-45°. These sectors will be referred to respectively as northwest, north and northeast sectors. Averages were used partially for convenience, but mostly to smooth the data and to determine the relationship between the satellite and geostrophic winds. As will be discussed later there was a rather high correlation between the two sets of winds as long as comparisons were made between spatial averages.

3. The Results

All the recurving storms had mean u-components in northwest and north sectors equal or greater than 20 m/s for two consecutive 12-hour periods either at the time of recurvature or up to 96 hours prior to recurvature. None of the storms which did not recurve had such strong winds with the exception of Anita (1977). Anita, however, had an anticyclonic buffer zone between the hurricane center and the strong westerlies far to the north. There was a large area north of the strong cyclonic circulation around the hurricane center where there were no westerlies evident either in the cloud winds or the 200-mb geostrophic winds. Note in Figure 1 for the recurving storms that the westerlies are continuous to within about 10 degrees of the hurricane center at 200 mb. The cloud patterns north of Hurricane Anita at high levels clearly showed this anticyclonic circulation between the center and the belt of strong westerlies farther to the north. Evidently it shielded the storm from influence by the strong westerlies.

In some cases where the hurricanes recurved more than once, the wind situation was very complex, and there are indications that in some of these cases the recurvature rule did not hold. These will be discussed later. But in general, for the major recurving periods, each one was forecasted correctly by the following rule: When the mean u-component of the geostrophic winds at 15-20 degrees radius (1650 and 2200 km) between azimuths 315° and 22.50° are ≥ 20 m/s and when there were also westerlies at 200 mb between 10 and 15 degrees radial distance between the same azimuths, expect recurvature. In most cases studied it came within 12 to 48 hours, and in all cases recurvature occurred within 96 hours.

A more objective manner of expressing the results is to measure how many degrees of longitude a hurricane will move westward after the defined strong westerlies have been observed. For the 14 cases in this study, the additional westward movements of the individual storm centers after the strong winds were observed were only 2.5 ,2.5, 3.2, 5.0, 5.3, 6.0, 6.0, 6.5, 6.9, 11.0, 11.5, 14.8, 14.5 and 15.0 degrees of longitude. That is 64 per cent of the storms traveled less than 7 degrees of longitude farther west and 79 per cent of them traveled less than 12 degrees farther west. None of the storms traveled more than 15° of longitude farther westward after the winds met the stated criteria.

Some of the hurricanes that had multiple turns in their tracks seemed to support the hypothesis and some seemed to be exceptions. Hurricane Carmen (1974) recurved from moving west-northwestward to moving northerly on September 3 and 4 (Fig. 2). This recurvature was preceded by the strong westerlies. Although the westerlies continued strong, on September 7 and 8 instead of the tract turning more northeasterly it turned northwestward. The storm simultaneously moved inland and dissipated. This change in direction of movement cannot be accounted for by the hypothesis. A probable explanation is that as the storm weakened it was influenced much more strongly by circulations at lower levels than by the circulation represented by the winds at 200 mb.

Hurricane Faye (1975) offers an interesting semi-verification of the hypothesis. On September 23 and 24 the storm movement changed from westerly to northerly and continued moving northerly for about 24 hours (Fig. 4). Then the movement reverted back to the northwest. The storm was rather weak at the initial turn and the westerlies to the north were quite weak. Later the direction of motion changed from north-northwest to north and northeast on September 27. This later recurvature was preceded by the strong westerlies. Apparently something caused the track to change for a short period on September 23 and 24, but without the strong westerlies to the north of the storm the mechanism that originally started the storm moving northward was short-lived and the track reverted to one that had westerly components until such time as there were strong westerlies developing to the northwest and north. Hurricane Emmy (1976) (Fig. 2), while still of tropical storm intensity, recurved on August 24 and 25 with the westerlies rather strong but not quite up to the criteria listed earlier. Later its course reverted to one with westerly components and it did not finally recurve until August 29. This later recurvature was preceded by the strong westerlies.

4. Use of Cloud Motion Winds and Additional Results

The results discussed thus far were based primarily on geostrophic winds supplemented by a few observed winds. One of our objectives, however, was to determine if the satellite winds were adequate for the purpose. High level clouds were tracked for 14 of the 17 storms and for a total of 105 periods. In about 90 per cent of the cases there were high clouds that were suitable targets for obtaining winds in the needed areas. Figures 5 and 6 compare the u- and v-components respectively for the two types of winds. The correlation coefficient between the two types of u's is fairly good, .83. In all cases the comparisons are between mean winds. That is, each point on the illustrations represents the mean wind for an area. In no case was a satellite wind used in this comparison unless it represented the average motion of at least 3 individual clouds. The geostrophic winds were from the same areas as the satellite winds.

The v-components are less highly correlated, .52. Note in particular that in many cases strong positive v-components for cloud motions

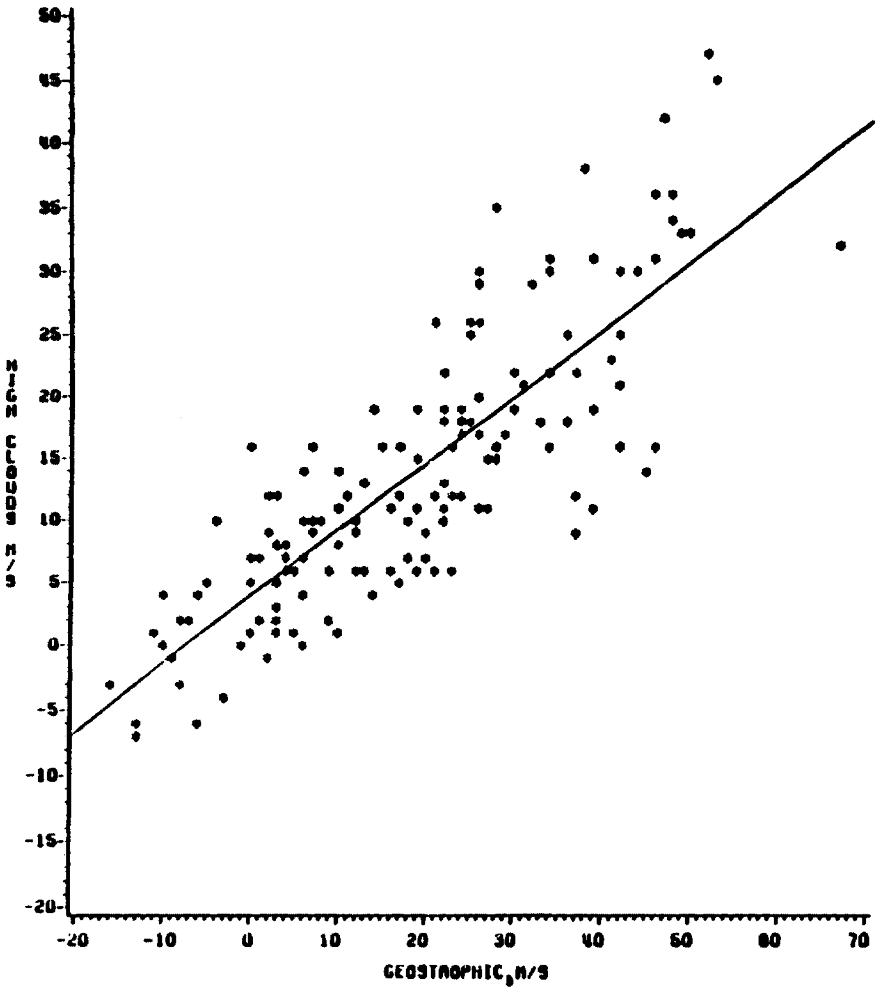

Fig. 5. Comparison of u-components of satellite and geostrophic winds.

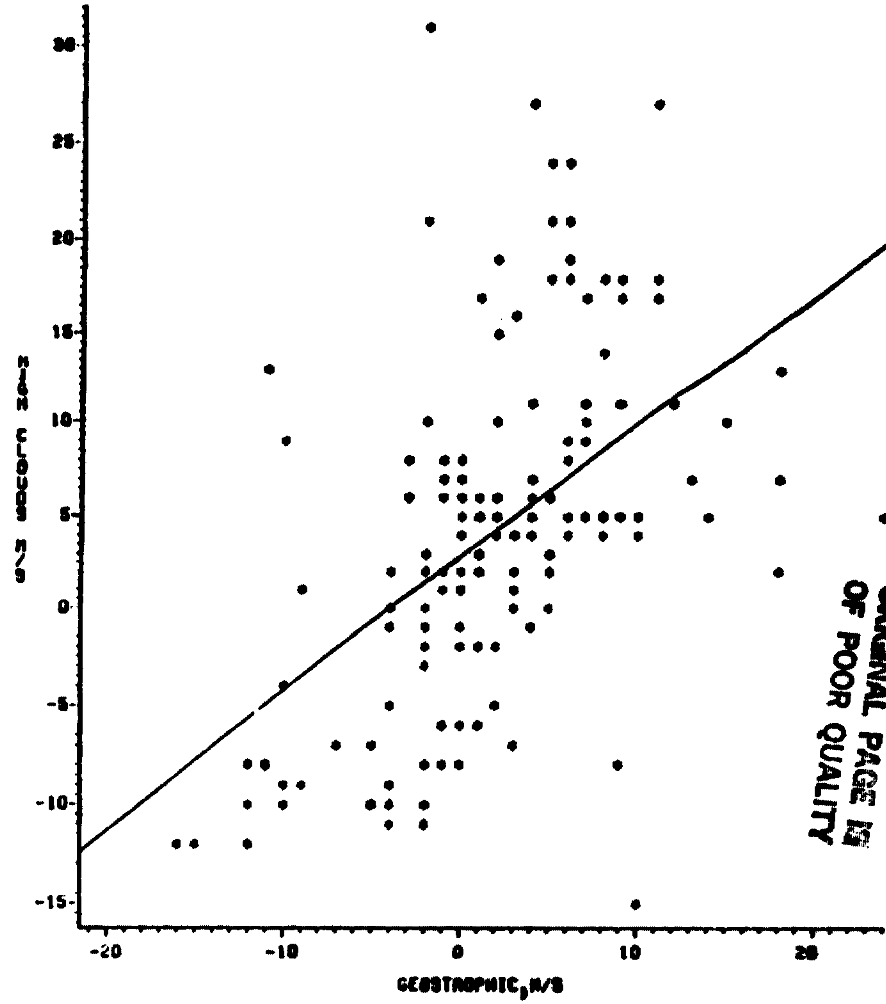

Fig. 6. Comparison of v-components of satellite and geostrophic winds.

are not matched by nearly as high southerly winds in the geostrophic components. It is these cases that often represent the hurricanes about to recurve. That is, when the hurricane has winds with strong southerly components flowing away from the storm center at high levels that are not matched by strong geostrophic winds from the south at 200 mb, there is a high probability that the tropical cyclone will recurve, especially if there are strong westerlies at 200 mb farther north. At least that was true for the cases studied in this research.

There was another indirect result from the effort to obtain satellite winds. In a few cases there were few or no clouds to the north and northwest of the hurricane center to track to derive the high level winds. Notable examples are Hurricane Caroline of 1975 and to some extent Hurricane Anita (1977). Neither storm recurved. In Anita's case there were some clouds, but there were large areas to the north of the hurricane that were relatively cloud free. These two cases suggest that the absence of clouds implies the presence of atmospheric circulations that act to keep the storm from recurving.

5. Use of the High Level Winds in Forecasting Direction of Movement

The principal hypothesis evaluated in the research discussed thus far related to recurvature of hurricane tracks. Efforts were also made to see if the winds could be used to predict changes in direction of movement of the storm center. All cases were used in which at forecast time the hurricane track had a westerly component. The directions at forecast time, t_o, and at 24, 48- and 72-hr are defined as the direction the storm moved during the 24-hr period centered on the respective times. See Fig. 7 for further illustration. The change in direction for the 72 hours following forecast time, for example, is the difference in direction at t_o and at t_{72}, again as illustrated in Fig. 7, angle number 3.

The cases were stratified according to the mean u-components in the northwest sector (Section 2) and the data are plotted in Fig. 8. The error bars represent standard deviations of the direction changes. Note that even though the standard deviations are large there is definitely a correlation between the u-components and the direction changes, especially for the longer periods.

To further check the utility for forecasting of the winds, regression equations were developed to forecast the change in direction of forward motion of the hurricanes for 24-, 48- and 72-hour periods. The u-components in the northwest and north sectors were used as predictors. In addition, a no-yes (N/Y) predictor was used to indicate when there were westerly winds in the sectors 10 to 15° north of the hurricane center. The quantities to be predicted were the change in direction of motion for the three time periods. The changes (in degrees) are considered positive if the track was curving in a clockwise sense.

The northwest and north sector u-components were very highly correlated with each other and were about equally useful as predictors. The presence of positive u-components in the 10 to 15° radial sector (N/Y predictor) was arbitrarily assigned a +8 value and cases without west winds were assigned a -1 value.

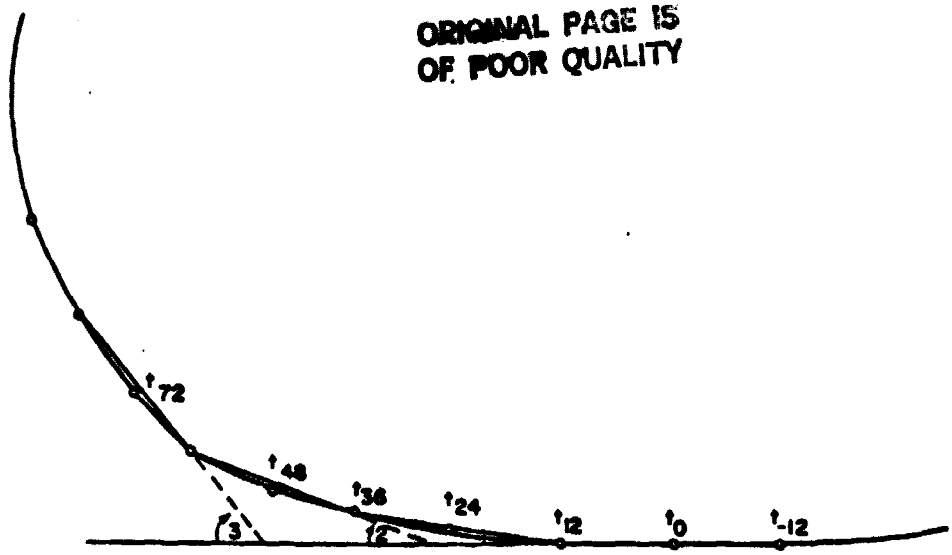

Fig. 7. Direction of motion at forecast time: Illustration of method of measuring direction of motion at forecast time (t_0), 24-hours (t_{24}), 48-hours (t_{48}), 72-hours (t_{72}) and change of direction of motion for various time periods.

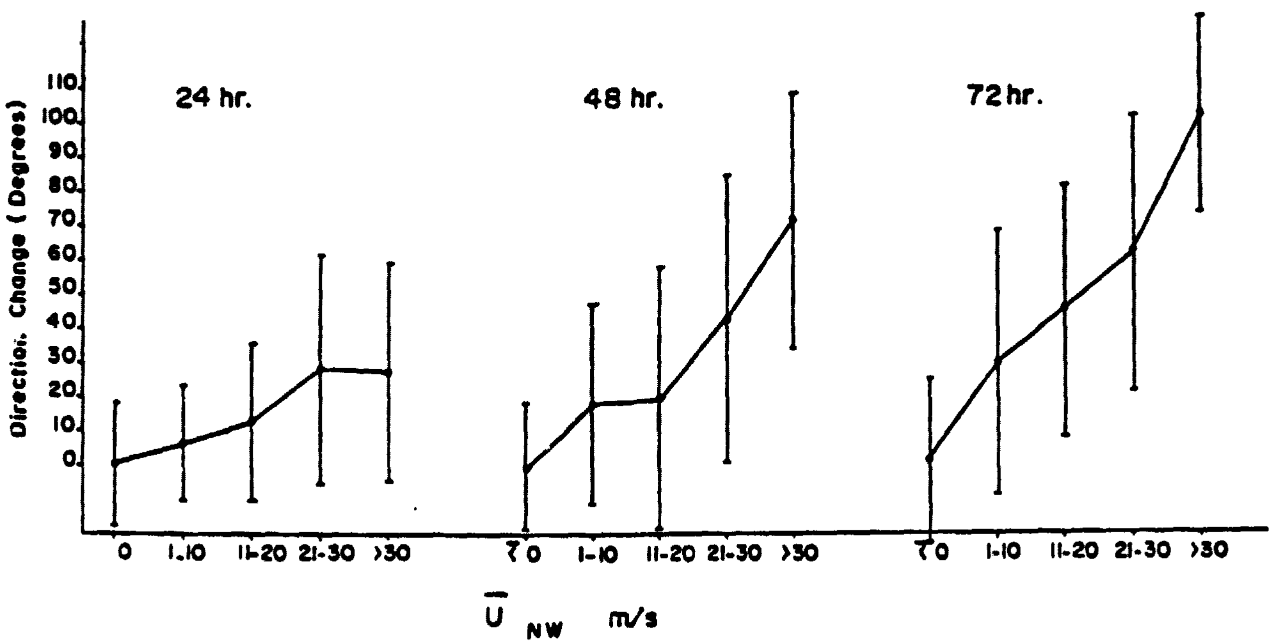

Fig. 8. Storm change of direction of motion versus 200 mb u-component geostrophic winds: Relation of change of direction of motion to strength of the u-components (m/s) of 200 mb, geostrophic winds in the north-west sector (about 1500-2000 km north-northwest of the storm center). Vertical bars represent standard deviation of the changes in direction.

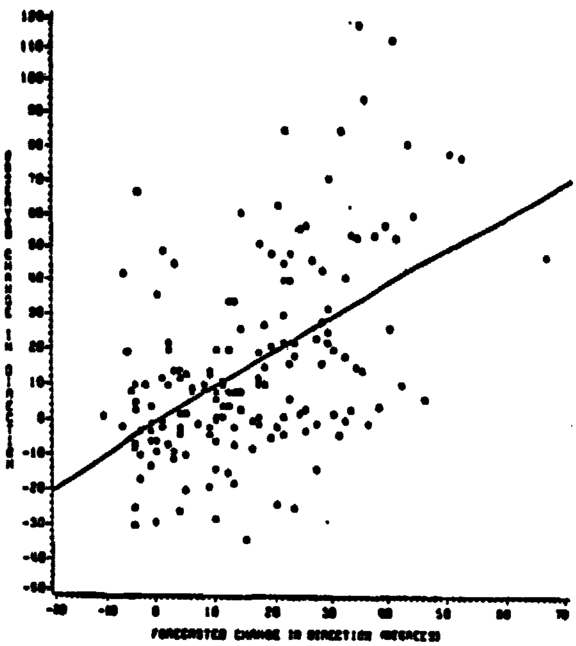

Fig. 9. Verification of 24 hr direction forecast: Comparison of changes in direction of forward movement of storm center for 24-hours with changes forecasted by regression equation.

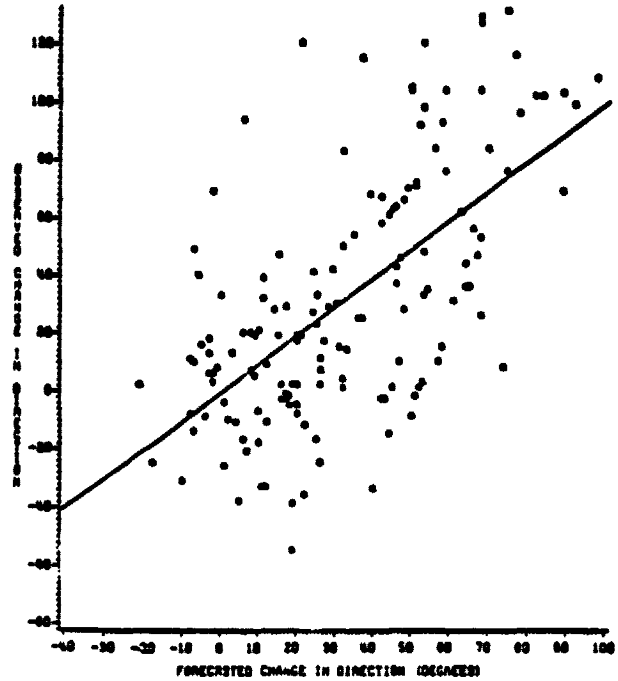

Fig. 10. Verification of 48 hr direction forecast: Comparison of changes in direction of forward movement of storm center for 48-hours with changes forecasted by regression equation.

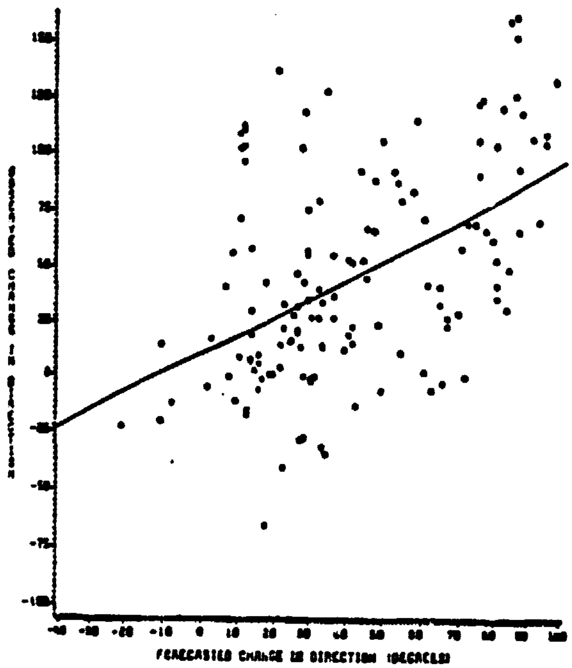

Fig. 11. Verification of 72 hr direction forecast: Comparison of changes in direction of forward movement of storm center for 72-hour with changes forecasted by regression equation.

The regression equations developed were:

$$D_{24} = -2.73 - 0.76 \times NW + 1.40 \times N + 0.90 \times (N/Y)$$

$$D_{48} = -1.79 - 0.41 \times NW + 1.94 \times N + 1.11 \times (N/Y)$$

$$D_{72} = 13.81 + 1.26 \times NW + 0.77 \times N + 0.40 \times (N/Y)$$

Where D_{24}, D_{48} and D_{72} are the changes in direction of motion over the respective time periods, NW and N represent the mean u-components defined in Section 2, and N/Y represents the No-Yes values already mentioned. The errors resulting from applying the equations to the dependent data used in this study are summarized in Table 2 and illustrated in Fig. 9-11.

Table 2

Results of Forecasting Change in Direction of Forward Movement:

	No. of Cases	Mean of Absolute Values of Errors (degrees)	Standard Error (degrees)	Correlation of Forecast and Observed Directions
D_{24}	167	17.9	23.8	.51
D_{48}	153	25.5	32.6	.63
D_{72}	134	28.0	36.5	.64

The per cent of variance explained is greater for the 48-hour and 72-hour forecasts than for the 24-hour forecasts. This seems reasonable (as will be discussed further in Section 6), because the short term motion of the storm center should be strongly influenced by forces closer to the storm center than 15° of latitude. While the results are not sensational, they suggest that the predictors definitely show skill. Furthermore, the skill is great enough that in the many sections of the world where other data are sparse, these results may be as good or better than achieved by other techniques for 48- and 72-hour periods. For example the portion of the variance explained is 41 per cent for the 72-hour periods. There are probably many hurricane forecast techniques used in the last 20 years which do not explain 41 per cent of the variance for 72-hour forecasts.

6. Discussion of Results and Errors

The use of the strong westerlies at approximately the 200 mb level to identify situations favorable for recurvature and in particular the results that nearly 80 per cent of the storms recurve before traveling as much as 12 degrees of longitude farther west after the strong westerlies are observed should be useful in most tropical cyclone areas. Some of the other results, while favorable, may not be impressive enough to suggest replacing other forecast techniques in areas of plentiful data. However, the results should certainly be useful to forecasters in areas of very sparse conventional data. It is interesting that super-gradient southerly winds as revealed by tracking of clouds seem to be associated with storms about to recurve and that large areas of few or no clouds 5 to 12 degrees of latitude north and northwest of the hurricane center are associated with storms not likely to recurve in the near future. Both of these indications deserve further checking with additional cases. While most of the results have been stated in terms of the geostrophic winds, this research suggests that in most cases the satellite winds could be used. The true correlation between the u-components of geostrophic and satellite winds is probably higher than the .83 mentioned earlier. Errors in each set of winds probably caused a reduced correlation. In particular, the geostrophic winds for this project were calculated from gradients read from small scale maps and the satellite winds were obtained from imagery at 30-minute intervals. Accuracy of satellite winds, however, should be as good or better than the geostrophic winds (Hasler, et al., 1977; Rodgers, et al., 1979).

Research done by earlier investigators (see Chan and Gray, 1982a and 1982b for discussion, summaries and references) implies that the movement of a hurricane for the next 12-24 hours is highly related to the ambient circulations and dynamic forces within about 6° latitude distance of the storm center. There is little indication in reports of earlier investigators that existence of strong winds far to the north of the storm would immediately affect the motion of the hurricane center. Yet the results of this research and that of George and Gray (1977) definitely suggest that there is at least a delayed effect. It seems logical that the strong westerlies are highly correlated with or are representative of features of the general circulation which will affect direction of hurricane motion in the next 24-96 hours. If this is true it could explain why for the short term the hurricane sometimes moves in a direction contrary to the hypothesis of this research, but in nearly all cases over longer periods the hurricane tracks do conform to the hypothesis.

The results described in Section 5 using regression equations show that the u-components of the winds contain predictive information about the future direction of motion of the storm for periods out to at least 72 hours when at forecast time the storm is moving in a direction that has a westerly compound.

7. Acknowledgments

The author has benefited greatly by frequent discussions with his colleague Mr. Edward Rodgers. The data for tracking of the clouds were organized and prepared by Mr. Joseph Steranka and other members of the staff supporting the work of the Severe Storms Group of the Goddard Laboratory for Atmospheric Sciences. John Hartley, Wayne Hayes, John Trostel, Pat Atkins, Tony Kinard and Susan Willard all helped with the data processing while they were graduate students at Clemson University. Support for this research came through the Goddard Laboratory of Atmospheric Science under NASA grant number NSG 5349.

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