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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

ATLANTIC TROPICAL AND SUBTROPICAL CYCLONE CLASSIFICATIONS FOR 1976

Washington, D.C.
April 1977

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D. C. Gaby, J. B. Lushine, B. M. Mayfield,
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ABSTRACT. Estimates of the locations and maximum sustained winds of all tropical and subtropical cyclones in the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico were made using techniques developed by Dvorak (1975) and Hebert and Poteat (1975, 1976). The techniques were applied to pictures from the Geostationary Operational Environmental Satellite No. 1. The estimates were compared with the National Hurricane Center's "best tracks" data to establish the measure of accuracy achieved. These data are not completely independent because the "best tracks" themselves are determined partly from the satellite estimates; however, comparisons were made only during periods when aerial reconnaissance was also available. The average difference between satellite locations and best track locations was approximately 17 nautical miles with a standard deviation of about 14 nautical miles. The accuracy in estimating the maximum sustained wind showed an average absolute difference of about 8 knots, an average algebraic difference of minus 4 knots, and a standard deviation of about 9 knots. These results and other information are presented together with an assessment of the capability of the present operational satellite system.

I. INTRODUCTION

For the past six hurricane seasons, the Miami Satellite Field Services Station (SFSS) of the National Environmental Satellite Service (NESS), co-located with the National Weather Service's National Hurricane Center (NHC), has provided "classifications" of all tropical and subtropical cyclones in the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. Classification includes fixing the location of the storm circulation center, making an estimate of the maximum sustained wind speed, and describing certain characteristics of the storm such as the trend of development and indications of probable future change. These classifications, together with information from other sources, are used by the NHC to formulate their advisories and warnings. This brief memorandum presents the results obtained at the Miami SFSS for the 1976 hurricane season, together with an assessment of the capability of the present operational satellite system to provide such information.

An evaluation of the Miami SFSS performance in making tropical cyclone classifications was first published by Gaby et al. (1975) for the 1974 season. A similar report was issued for the 1975 season. The expected

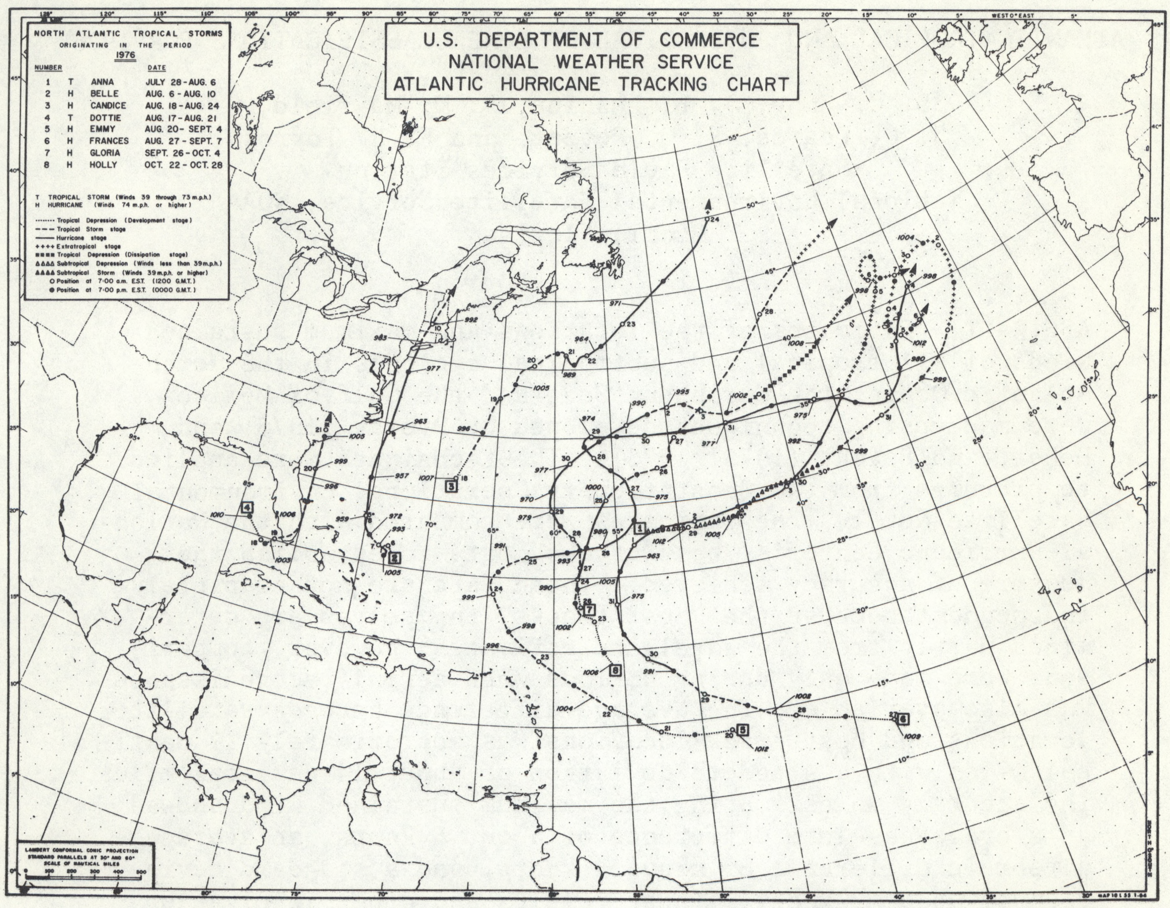

Figure 1.--National Hurricane Center official tropical cyclone tracks 1976.

reduction in military aerial reconnaissance of such storms will require an increasing reliance upon satellite information and makes such evaluations of performance capability more important. Any evaluation of performance would be unrealistic without the use of independent data such as that traditionally provided by aerial reconnaissance. A significant decrease in such reconnaissance may make future evaluations difficult or impossible.

II. BASIS FOR COMPARISONS

No absolute measure of accuracy in estimating location and strength of cyclones is possible because there is no absolute "ground truth", i.e., neither the exact location nor the precise wind strength of the storm is known at any given time. The degree of this uncertainty varies. However, comparisons are made with the NHC's official best tracks (figs. 1 & 2) and with data contained in individual preliminary storm reports[1] on the assumption that these data represent the closest possible approximation to the truth. These best tracks and maximum sustained wind speeds are determined by the NHC hurricane specialists during post analysis using all available

[1]Preliminary storm reports are available from the NHC.

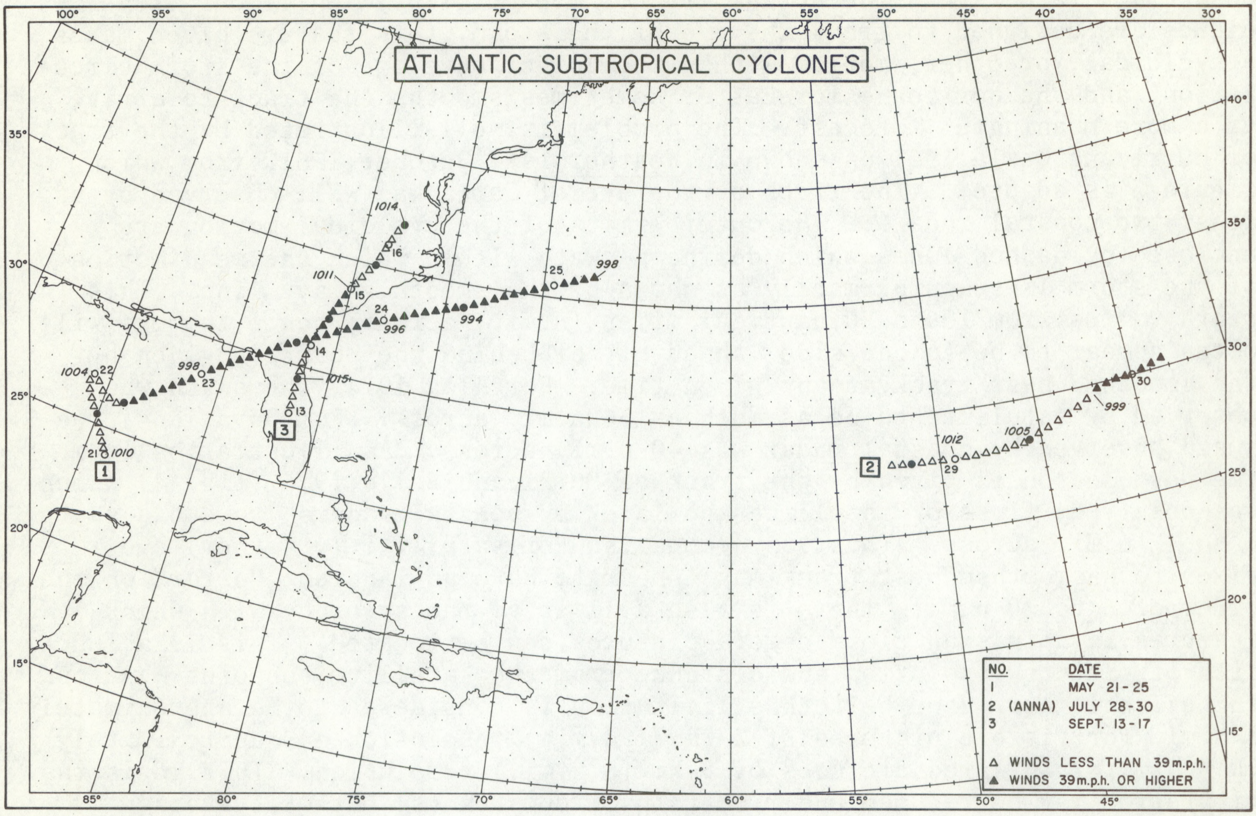

Figure 2.--National Hurricane Center official subtropical cyclone tracks 1976. Subtropical storm No. 2 later became Tropical Storm Anna. (See fig. 1.)

data. Typically, these data include reconnaissance aircraft observations, ship reports, rawinsonde and pibal observations from land stations, radar observations from land stations, and satellite observations. The authors, recognizing that the satellite information was used by the NHC in determining the best tracks data, minimized the effect of this dependency by evaluating satellite locations only during periods when aerial reconnaissance data also were available. Evaluations of wind speed estimates were made only when reconnaissance was available and the minimum central pressure was below 1000 mb or the current intensity (CI) number (Dvorak technique) was 2.0 or greater or the subtropical intensity (ST) number (Hebert-Poteat technique) was 1.5 or greater. During operational classifications, the current central pressure determined by reconnaissance is rarely known to the satellite meteorologist at the time he renders judgment.

III. ESTIMATES OF LOCATION

An evaluation of location accuracy is difficult. Since there is no "ground truth", we compare location estimates with the official best tracks as the best available approximation of ground truth. Even if ground truth were available, i.e., if one knew the actual track of the eye or storm circulation center exactly, it is often more practical to show the smoothed best track rather than the actual track. (See fig. 3.) While our techniques are designed to track the eye of the storm, this feature often makes a cycloidal, or other, motion within the larger envelope of the storm circulation, and the hurricane forecaster sometimes smooths the track to arrive at a more meaningful forecast. The problem is well-illustrated by the track of Hurricane Carla 1961 as shown in Weatherwise, October 1961, from which figure 3 is adapted. The track of the eye of Carla was well-observed by at least two coastal radars. The outer limits of the cycloidal motion are enclosed by dashed lines which define a swath within which the mean motion of the storm lies approximately as shown by the smooth, heavy line. This swath varies from 10 to 20 nautical miles (n.mi.) across; hence the eye will often appear to be to one side, ahead of, or behind the position given by the smoothed best track at any given time. For Alma 1974, the swath was observed by satellite to be as much as 36 n.mi. across. For Dora 1964, the swath observed by coastal radar was 40 n.mi. across. An illustration from the past season is given by the track of Hurricane Belle 1976 (fig. 4) which was observed, first by satellite and later by coastal radars, to cut a swath 6 to 17 n.mi. across. Thus, any comparison of satellite (or other) eye fixes to a smoothed best track may appear to have an inherent "error" on the order of 3 to 20 n.mi. There is also a limit to the accuracy with which features in spin scan cloud camera pictures can be located. This is a function of picture resolution and distance from the satellite subpoint. Across the Atlantic hurricane belt this limitation is considered to be approximately 4 n.mi. for visible pictures of 2-km (1 n.mi.) resolution and approximately 20 n.mi. for infrared pictures of 8-km (5 n.mi.) resolution. This registration error may be reduced under certain circumstances, but will average about 8 to 12 n.mi. for all imagery used at the Miami SFSS. The "fix vs. track error" and registration error may cancel each other or be additive, so the overall "error" in location will average about 12 n.mi. In summary, we can locate the eye very accurately by day but not quite so well by night; however, the short-term movement of the eye does not necessarily represent the movement of the storm system.

Table 1 shows a comparison between satellite-located storm positions and NHC official best tracks in 1976. *We note an average difference of about 17 n.mi., with a standard deviation of about 14 n.mi. and a range from 0 to 89 n.mi., for 115 cases.* Significantly better storm positions were obtained for cyclones of hurricane intensity. *Considering only storms classified as T-4.0 or higher or where the NHC official data indicated maximum winds 65 knots or greater; corresponding values were an average difference of about 14 n.mi., with a standard deviation of about 10 n.mi. and a range from 0 to 49 n.mi., for 64 cases.* From the warnings aspect, this is most fortunate since these storms are the most damaging.

Figure 5 shows the steady improvement in location estimates over the years; the accuracy is nearing what may be a plateau or a best-estimate lower limit of about 12 n.mi. using the current low-resolution infrared imagery at night and the current procedure of comparing satellite eye fixes with a smoothed best track. Further improvement is not likely until we have higher resolution in the infrared imagery or improved understanding of hurricane dynamics, and a technique that does not depend entirely upon tracking the eye or circulation center.

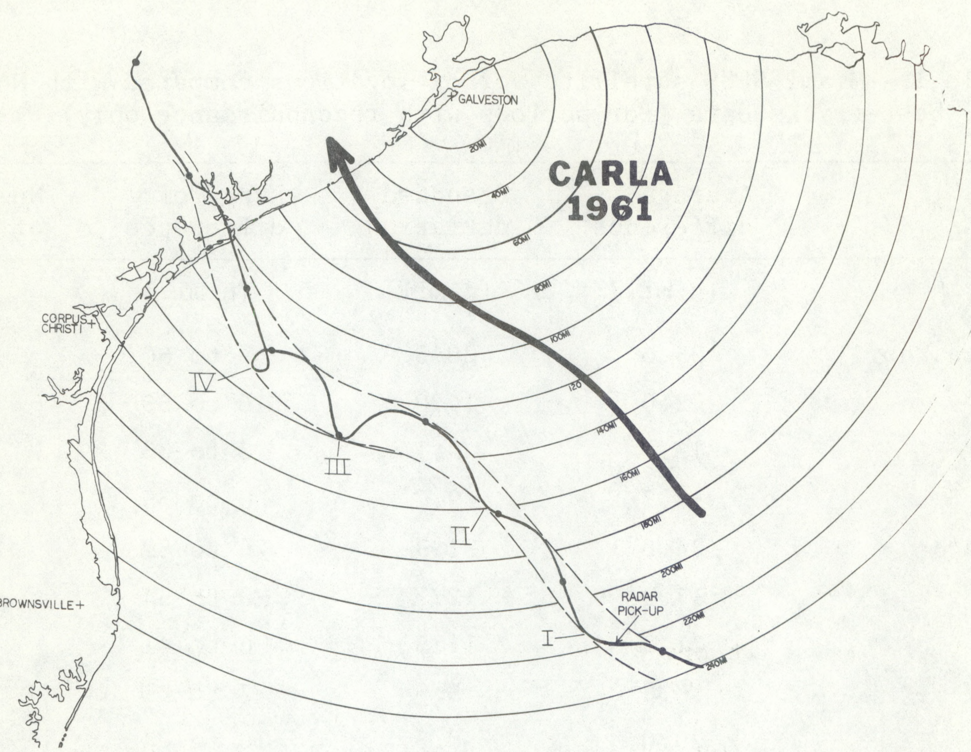

Figure 3.--The track of the eye of Hurricane Carla 1961 as observed by coastal radars. (Adapted from Weatherwise, October 1961.)

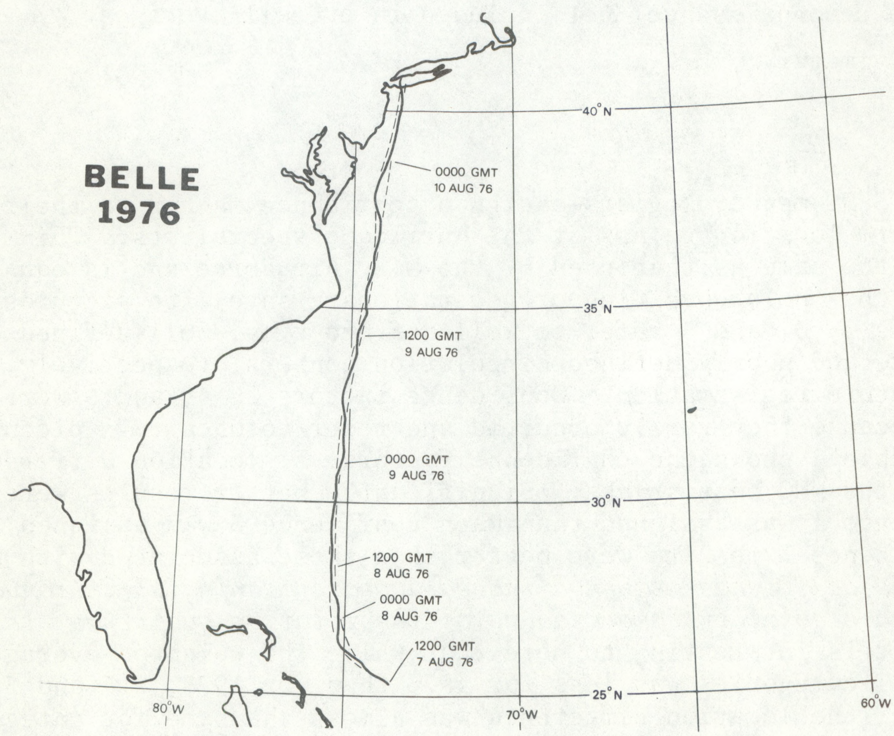

Figure 4.--The track of the eye of Hurricane Belle 1976 as observed by geostationary satellite (GOES-1) and coastal radars (Wilmington, Cape Hatteras, Atlantic City, and New York City).

Table 1.--Miami SFSS satellite vortex locations compared with NHC best-tracks data (for periods with reconnaissance only).

Storm, no.*	Average difference (n.mi.)	Standard deviation (n.mi.)	Range of difference (n.mi.)	Number of cases
Subtropical no. 1	25.6	20.5	7 to 60	5
Anna, 1**	22.0	14.0	10 to 55	9
Belle, 2	13.1	9.1	3 to 33	14
Candice, 3	14.7	9.7	0 to 35	21
Dottie, 4***	24.3	31.9	6 to 89	6
Emmy, 5	17.2	12.7	0 to 54	36
Frances, 6	21.5	11.5	6 to 41	15
Gloria, 7	9.8	5.3	3 to 21	14
Holly, 8	29.0	30.3	10 to 74	4
All combined	17.0	14.3	0 to 89	115

* See corresponding numbers within squares on figure 1.

** No aerial reconnaissance; not included in overall averages.

*** Weak, IR imagery.

The Miami SFSS meteorologists assign a confidence factor to their estimates of storm location to assist the hurricane specialists. The method is essentially the same as that used by the U.S. Air Force and is equally well-suited to either polar-orbiting or geostationary satellite pictures. Confidence factors 1, 3, and 5 refer to well-defined eyes, well-defined circulation centers, and poorly defined circulation centers, respectively, with reliable picture registration. Confidence factors 2, 4, and 6 were not evaluated because they rarely occurred and refer to uncertain picture registration. Table 2 shows the confidence factors vs. location difference as compared to the NHC best tracks. Significantly better results were obtained when confidence 1 was assigned than when confidence 3 was assigned; similarly, confidence 3 results were better than those associated with confidence 5. *The confidence assigned indeed appears meaningful in conveying to the hurricane specialist some measure of the relative quality of the satellite fix.* It is interesting to note that while the weighted-average confidence for all categories was less for 1976 than for 1975, 2.7 and 3.2, respectively, the location difference was almost the same for category 1 (well-defined eyes), 11.6 and 11.0 n.mi., respectively. This appears to support the suggestion that we are nearing what may be a best-estimate lower limit of about 12 n.mi.

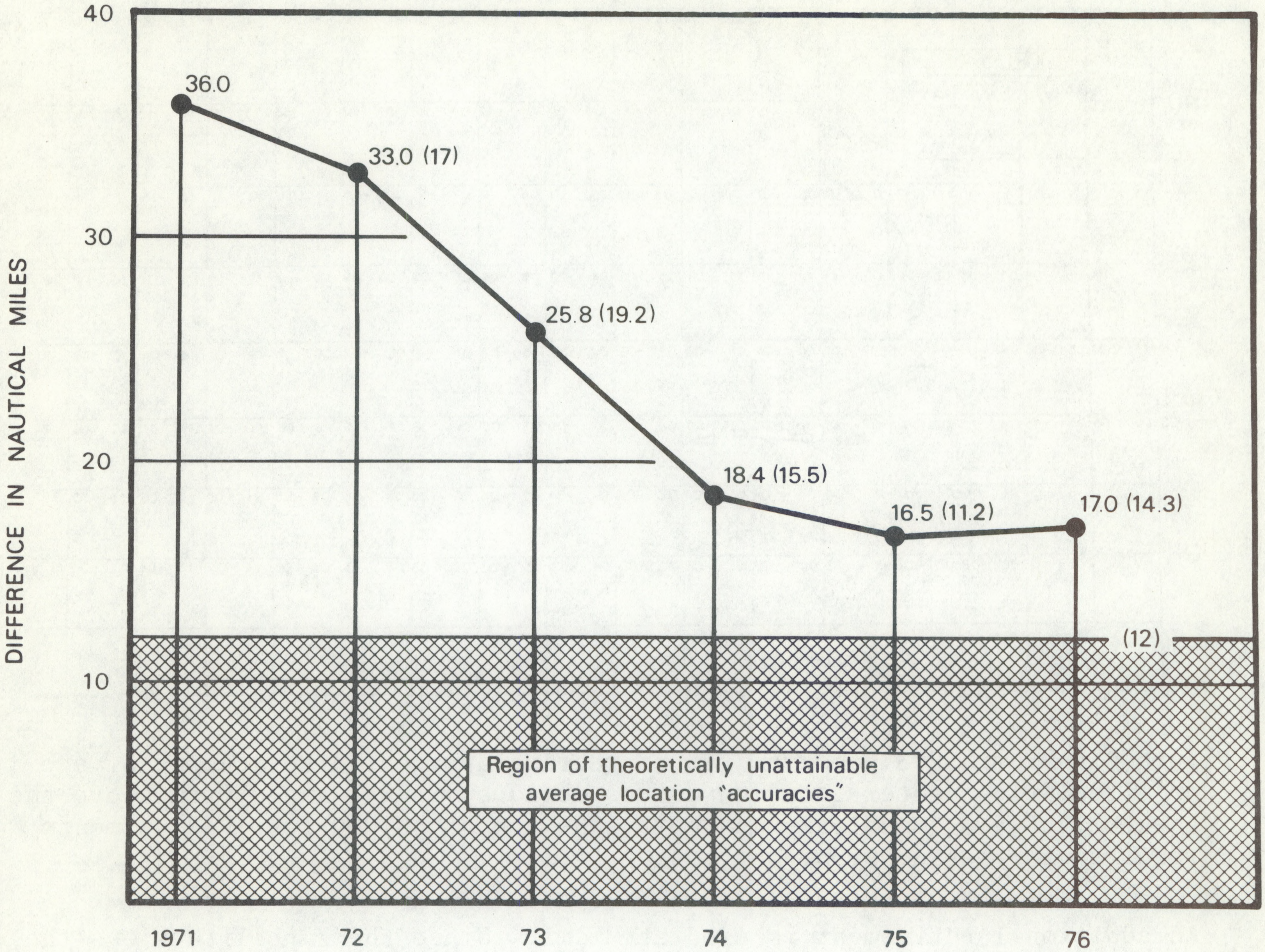

Figure 5.--Improvement in Miami SFSS tropical-subtropical cyclone location "accuracy". Average location differences as estimated by SFSS. Figures in parentheses are standard deviation.

Table 2.--Comparison of confidence factors with satellite vortex location differences.

Satellite vortex location factors	Confidence factor		
	1	3	5
Average difference (n.mi.)	11.6	16.4	26.0
Standard deviation (n.mi.)	6.5	13.6	18.7
Range of difference (n.mi.)	3 to 26	0 to 74	3 to 89
No. of cases	32	54	22

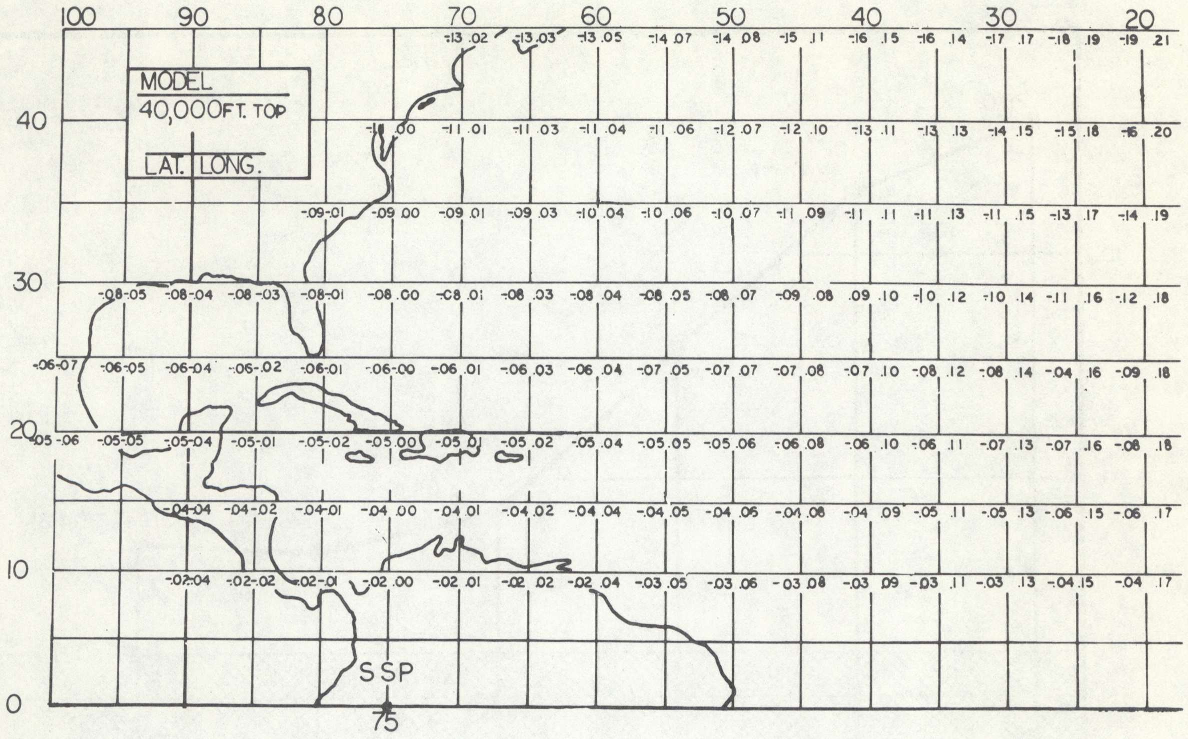

Figure 6.--Miami SFSS nomogram for correcting apparent displacement of eye or circulation center location due to oblique viewing angle from above the Equator at 75W. Model assumes hurricane top at 40,000 feet; adjustments required for lesser or higher tops.

An additional refinement is used at Miami. Since the satellite views the top of a hurricane eye or circulation center from an oblique angle, the eye or circulation center at the surface is always closer to the satellite subpoint than it appears. Figure 6 shows the nomogram used at Miami to correct for the apparent displacement of a storm due to the viewing angle from the Geostationary Operational Environmental Satellite No. 1 (GOES-1) at 75W. Note that for a hurricane, such as Belle, making landfall in New York, the correction needed is nearly 0.1 degree of latitude or about 6 n.mi. The amount of correction depends on the location of the storm, and also becomes significant in the western Gulf of Mexico, near the Azores Islands, and across higher latitudes.

IV. ESTIMATES OF MAXIMUM SUSTAINED WIND SPEED

Estimates of the maximum sustained wind speed were made using the techniques developed by Dvorak (1975) with some slight modifications and by Hebert-Poteat (1976). Values of maximum wind speed were objectively interpolated between CI-numbers (Dvorak technique) when parameters such as the size and shape of the central dense overcast, width and extent of banding features exceeded or did not quite meet the criteria for a specific T-number (Dvorak). A subjective adjustment, never exceeding half a T-number, was sometimes made to allow for the diurnal increase in cirrus cloud amount often seen in early afternoon. Somewhat less constrained rates of

Table 3.--Miami SFSS estimated maximum sustained wind speeds minus NHC best track data (comparisons only for periods with reconnaissance; minimum central pressure below 1000 mb, CI number 2.0 or higher, or ST number 1.5 or higher). Standard deviations based on algebraic average difference.

Storm, no.*	Absolute average difference	Algebraic average difference	Standard deviation	Range of difference	Number of cases
	(kt)	(kt)	(kt)	(kt)	
Subtropical no. 1	12.0	-12.0	0	--	1
Anna, 1**	0.6	-0.6	1.7	-5 to 0	9
Belle, 2	5.6	-5.6	6.1	-16 to 0	14
Candice, 3	9.1	-4.5	10.0	-20 to +10	21
Dottie, 4	6.0	+6.0	4.2	0 to +10	5
Emmy, 5	8.2	-2.3	10.0	-20 to +17	36
Frances, 6	4.3	-3.1	5.8	-15 to 0	15
Gloria, 7	8.6	-7.9	7.8	-20 to +5	14
Holly, 8	12.5	-12.5	8.7	-20 to 0	4
All combined	7.7	-3.9	9.1	-20 to +17	110

* See corresponding numbers within squares on figure 1.

** Not included in overall averages. No aerial reconnaissance. Subtropical part of time.

development, based upon earlier research by Sheets (1970), were permitted when supported by overwhelming evidence. Less constrained rates of weakening, based upon research by Lushine (1977), were routinely permitted. All classifications were made using pictures from the GOES-1 satellite, which is above the Equator at 75W. Visible spectrum pictures with 2-km resolution were used during daylight whenever possible; 8-km resolution infrared pictures were used at night.

Table 3 shows a comparison between satellite maximum wind speed estimates and the NHC official best tracks data. The values achieved do not appear as good as those for last year. We attribute this to the fact that in the 1976 season no storms occurred in the most favorable viewing areas of the Caribbean Sea and the Gulf of Mexico. *We note an average absolute difference of about 8 knots, an average algebraic difference of about minus 4 knots with a standard deviation of about 9 knots, and a range from -20 to +17 knots, for 110 cases.* Maximum wind speed estimates for cyclones of hurricane intensity were not significantly different.

The Dvorak technique is designed to provide reliably consistent results when used by satellite meteorologists with widely different experience

Table 4.--Comparison of estimates of maximum sustained wind speeds by individual meteorologists.

Maximum sustained wind speed factors	Meteorologist P	Q	R	S
Absolute average difference (kt)	6.9	7.9	7.8	8.6
Algebraic average difference (kt)	-3.6	-3.7	-3.0	-5.1
Standard deviation (kt)	8.9	9.4	9.8	9.2
Range of difference (kt)	-20 to +10	-16 to +17	-20 to +9	-20 to +12
No. of cases	33	27	20	30

levels. Table 4 shows an evaluation of the performance of the four SFSS meteorologists who made the bulk of the classifications. *Note that there are no significant differences in results among the individuals.* Two of these meteorologists had many years of experience, and two had much less experience. These results support those shown for last year by Gaby et al. (1976) and indicated by earlier testing before the technique was adopted for operational use. The Miami SFSS will not make such comparisons between individuals in the future.

Only one subtropical cyclone is included in table 3. However, four of the named storms were subtropical for part of their lifetimes. For portions of Anna and Candice, either Dvorak (tropical) or Hebert-Poteat (subtropical) classification technique could be used with nearly identical results, indicating that these techniques do mesh well one with the other. Depending on how one counts them, between 6 and 11 percent of the classifications were made using the Hebert-Poteat subtropical classification.

The Miami SFSS meteorologists assign a confidence number to their estimates of maximum wind speed as an aid to the hurricane specialists. Although the method is subjective, it reflects the meteorologist's thinking in determining the classification T-number. Confidence 1 means he is certain of his T-number determination, confidence 2 means he is tempted to vary up or down by ½ T-number, and confidence 3 means he is uncertain by more than ½ T-number; these confidence numbers apply equally to ST-numbers. Table 5 shows the confidence numbers vs. the classification intensity difference as compared to the NHC official data. One may note a smaller average difference and a smaller standard deviation for confidence 1 than for confidence 2. There was no instance of confidence 3. *It appears that the confidence number assigned to a classification is meaningful in conveying to the hurricane specialist some measure of the relative quality of the individual wind speed estimate.*

Table 5.--Comparison of confidence numbers with maximum sustained wind speed estimate differences.

Maximum sustained wind speed factors	Confidence numbers 1	2	3
Average absolute difference (kt)	6.9	8.9	---
Average algebraic difference (kt)	-2.6	-6.1	---
Standard deviation (kt)	8.7	9.3	---
Range of difference	-20 to +17	-20 to +17	---
No. of cases	67	40	0

V. EFFECT OF TIME OF DAY

Experience and reasoning would lead one to expect that the classifications should be better with visible than with infrared imagery, and that the afternoon classifications (1830 GMT) would be best and the late night classifications (0630 GMT) the worst. The Miami SFSS duty meteorologists are deliberately scheduled so they make two classifications on each shift, with the expectation that the later classification would be better because of a greater familiarity with the storm. To meet the NHC deadlines, classifications ideally are made from imagery at 0030, 0630, 1230, and 1830 GMT. The Dvorak classification technique, developed initially from visible imagery, is used most; our experience with using infrared imagery from geostationary satellites for classification purposes is still limited. Table 6 shows that the time of imagery has a rather significant influence on location estimates. As expected, the best estimates for location occur with afternoon data, and the next best with the morning data using visible imagery. A comparison between the average of nighttime comparisons (0030 and 0630 GMT) and the average of daytime comparisons (1230 and 1830 GMT) shows an overall improvement of nearly 5 n.mi., or almost one third, by using visible rather than infrared imagery. Table 7 shows, interestingly, the estimates of maximum wind speed are similar for all time periods; no significant differences are apparent.

VI. SUMMARY

This report of Miami SFSS performance in classification of tropical and subtropical cyclones presents results in line with those of recent years. We appear to have approached a limit in our ability to accurately estimate the location and maximum wind speed of these cyclones. It is significant that we do considerably better in locating the cyclones when using the higher resolution visible imagery by day, particularly for storms of

Table 6.--Comparison of satellite vortex location difference as a function of time of imagery.

Satellite vortex location factors	Time of picture (GMT) 0030	0630	1230	1830
Average difference (n.mi.)	18.0	20.0	16.6	12.0
Standard deviation (n.mi.)	11.4	18.2	15.7	7.3
Range of difference (n.mi.)	0 to 49	4 to 89	0 to 74	0 to 30
No. of cases	28	26	27	29

Table 7.--Comparison of maximum sustained wind speed estimate difference as a function of time of imagery.

Maximum sustained wind speed factors	Time of picture (GMT) 0030	0630	1230	1830
Average absolute difference (kt)	7.3	8.3	6.9	7.9
Average algebraic difference (kt)	-3.2	-5.0	-3.9	-4.4
Standard deviation (kt)	9.4	9.2	8.1	9.8
Range of difference (kt)	-20 to +17	-20 to +17	-20 to +12	-20 to +12
No. of cases	28	26	27	29

hurricane intensity. Overall better estimates of maximum wind speed would probably result from higher resolution in the infrared imagery used at night if it were available.

ACKNOWLEDGMENTS

We thank John Hope and Paul Hebert, NHC hurricane specialists, for their reviews of the initial draft and their many helpful comments and suggestions. We wish to express our appreciation to the staff of the General Electric Management and Technical Services Company, Miami, Fla., for their excellent and most willing technical support. Our thanks go to Suzanne Melisano for typing the manuscript and tables.

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