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The Benefits of Using Short Interval Satellite Images to Derive Winds for Tropical Cyclones

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ABSTRACT

During the 1975, 1976, and 1977 North Atlantic hurricane seasons, NOAA's National Environmental Satellite Service (NESS) and NASA's Goddard Space Flight Center (GSFC) conducted a cooperative program to determine the optimum resolution and frequency of satellite images for deriving winds to study and forecast tropical cyclones. Rapid scan images were obtained in 1975 at 7.5 minute interval from SMS-2 for hurricane Eloise on 22 September and of tropical cyclone Caroline on 28, 29, and 30 August; in 1976 at 3 minute intervals from GOES-1 for tropical storms Belle on 5 August and Holly on 25 October; and in 1977 at 3 minute interval from GOES-1 for tropical cyclone Anita on 30 and 31 August and 1 September. Cloud motions were derived from these images using the Atmospheric and Oceanographic Information Processing System (AOIPS) at GSFC. Winds that were derived from the movement of upper (approximately 200 mb) and lower tropospheric (approximately 900 mb) level clouds using rapid scan data were compared with the 15 and 30 minute interval data. This was done using visible images having 1, 2, 4 and 8 km resolution for the areas within 650 km of the storm center for the 1975 and 1976 tropical cyclones. Greater than 10 (5) times as many clouds

could be tracked to obtain winds at both levels using 3 and 7.5 minute rapid scan images as when using 30 (15 minute) minute interval images. In addition, by using the frequent images, it was possible to track a few bright areas within the central dense overcast which appeared to be moving with the winds at low levels. For hurricanes Eloise and Caroline the winds that were derived by tracking these bright areas within the central dense overcast had speeds differing in the mean of only 2.5 m/sec from the wind speed measured by aircraft flying at approximately .5 km above the surface in the same quadrant 4 hours later. Full resolution visible images (1 km) were needed to track slow moving low level cloud elements, since on a degraded resolution image, subpixel movement would introduce additive inaccuracies to the wind measurements.

Rapid scan full resolution GOES-1 data for tropical cyclone Anita (1977) provided representative wind fields only outside the central dense overcast at the lower tropospheric level. For this area, aircraft measured wind speeds differed in the mean again by only 2.5 m/sec.

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1. INTRODUCTION

The destruction caused by tropical cyclones affecting the United States has increased at an alarming rate. In the decade from 1965-74, the average annual cost from tropical cyclone damage was 9 times greater, even after adjustments for inflation than during the decade from 1915-24 (Gentry 1966). By contrast the loss of life caused by tropical cyclones decreased considerably after 1935 with the improvement of the warning service.

It is a common belief that improving the warning services requires improved numerical-dynamical models for forecasting hurricane motion and intensity and a better knowledge of the initial meteorological parameters. In particular, the initial wind data at several levels from the surface to the lower stratosphere extending outwards from the center to include the environment of the tropical cyclone are needed. Elsberry (1977) stated that the poor results in forecasting the translation speed from the coarse-grid version of his tropical cyclone prediction model was attributable to the deficiency of wind data for the initial field. Elsberry also noted that additional wind data are not only needed around the tropical cyclone center but within the surrounding cloud system out to approximately 600 km from the center.* In addition Hovermale and Livezey (1977) showed that the introduction of a more realistic outer circulation (300 to 1100 km from the center) to their modeled spin up storm would reduce their vector position errors. For the 1976 Atlantic tropical cyclone season, the vector position errors for the 36 and 48 hour forecasts increased by approximately a factor of 3 for storms over data void ocean areas as compared to storms nearer to coastal stations.

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*Personal Communication 1977

Data outside 600 km from the center are usually obtained from radiosonde networks, transoceanic aircraft flights and from cloud motion wind analysis at approximately the 900 mb and 200 mb level obtained from operational scanning geosynchronous satellites. Within the tropical cyclone cloud systems the only real source of wind data is the hurricane reconnaissance aircraft flights. However, the quantity of wind data obtained from these flights is not sufficient for these numerical-dynamical models and in fact, the tendency in recent years is to reduce the quantity by decreasing the number of flights. Therefore, there is a great need to obtain additional wind data from another source.

An excellent source for the upper troposphere has been the motion of clouds tracked with successive infrared and visible images obtained operationally from the family of geosynchronous satellites at approximately 30 minute intervals. However, less success has been found using cloud tracking to obtain winds at lower levels near tropical storms. One reason for the lack of success is that many of the clouds of the type and size best suited for tracers at low levels do not persist or maintain their identifiability for 30 minutes. This has been observed by many previous investigators. For example, Fujita *et al.* (1975) observed that the increase in spatial resolution is not as important as greater temporal resolution. The authors pointed out that cumulus plumes less than .5 km in diameter have unsteady updrafts and are poor tracers because they do not move with the ambient flow. On the other hand, "cumulus turrets" with horizontal dimensions of .5 to 3.2 km are found to be better targets because their steadier and weaker updrafts allow them to move with ambient flow. However, these clouds were short lived and therefore need to be observed more often if to be used as tracers. Another problem in tracking low level clouds within the area of the tropical cyclone cloud system is that the cirrus associated with the storm often obscures the low level clouds. Therefore, in order to supply the numerical-dynamical models with additional cloud derived low level winds within the tropical cyclone cloud system, more frequent observations from the geosynchronous satellite should be obtained.

To verify this hypothesis, the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) initiated a cooperative project to use rapid scan satellite imagery to obtain more wind data in tropical cyclones during the 1975-1977 hurricane seasons. The goals of the project were to obtain more winds needed by the hurricane researchers (including models) and forecasters and to determine the optimum space and temporal resolution of the geosynchronous satellite data used to derived winds. Limited scan visible and infrared images were obtained at 7.5 minute intervals from the Synchronous Meteorological Satellite (SMS-2) in 1975 and at 3 minute intervals from the Geostationary Operational Environmental Satellite (GOES-1) during the 1976 and 1977 tropical cyclone season for a few hours on selected tropical cyclone days. These were for tropical cyclones Eloise (22 September 1975), Caroline (28, 29, 30 August 1975), Belle (5 August 1976), Holly (26 October 1976) and Anita (30 and 31 August and 1 September 1977). Winds were obtained at the lower and upper tropospheric levels.

2. ANALYSIS

The hypothesis that cumulus and cirrus cloud translation approximates the speed and direction of the ambient flow at the cloud base level has been tested using aircraft observations in the trade wind regime over ocean areas (Hasler, *et al.* 1977). Movement of cumulus clouds 3 to 15 km in diameter with bases at 960 mb and tops at 600 to 700 mb had a vector difference from the ambient flow at cloud base by 1.3 m sec^{-1}. The average difference found between a limited number of cirrus clouds and the ambient flow within the cloud layer was 1.6 m sec^{-1}.

The clouds for the five tropical cyclones were tracked on NASA's Atmospheric and Oceanographic Information Processing System (AOIPS) using a series of infrared or visible SMS-2/GOES-1 satellite digitized images (Billingsley, 1976). This system allows a user to interactively modify digital images and to display the results on a television monitor through utilization of a computer software package called the Meteorological Data Processing Package (METPAK). To track clouds using the METPAK software, a sequence of images at a given time interval must first be registered by aligning recognizable land features in each image. A correction is made for image distortion caused by the satellites oscillating orbit motion and the axes not being parallel to the earth's orbit. The recognizable land feature is earth located by utilizing a navigation algorithm adapted from the University of Wisconsin's McIDAS navigation routine (Smith 1975). The algorithm translates image coordinates (pixel, lines) to earth coordinates (latitude, longitude) with respect to the land feature. The images are then displayed in time lapse sequence on the television monitor. Either the centroid or an identifiable point on the cloud that can be seen on all images (at least 3 images are used) are tracked subjectively by a moving cursor or objectively using an image correlation mode. The displacement of the cloud in earth coordinates divided by the time interval between images gives the wind velocity.

Other options in the METPAK software package varies the spatial resolution of the image and determines cloud height. The cloud height is calculated by estimating the cloud optical thickness for the observed cloud brightness and the infrared emissivity using Kirchoff's law. The cloud optical thickness is calculated by a multiple scattering program designed for the McIDAS at the University of Wisconsin (Smith 1975). The emissivity and the percent of cloud coverage as obtained from the visible image are used to determine the cloud top temperature. The cloud top is then estimated using the standard atmosphere corrected for latitude and date. The cloud height was used to assign the level for which the clouds were tracked. Clouds above the 350 mb level were assigned to the upper-troposphere while those below 700 mb were accepted as low tropospheric clouds except near the center of tropical cyclones. The few clouds found between these levels were not traced.

The spatial and temporal resolutions that were used for clouds tracked for both the lower and upper troposphere for each of the five tropical cyclones are listed in Table 1. Time of observation during the daylight hours was approximately between 1300 to 1900 GMT. Visible images (designated by V in table) were primarily used to track clouds at both levels; however, the infrared (designated by IR in the table) was used to track upper tropospheric clouds for tropical cyclone Eloise in a simulation of nightime coverage.

Table 1

Spatial and Temporal Resolution of the SMS-2/GOES-1 Imagery Used to Track Clouds for Each of the Five Tropical Cyclones

Low Level

Temporal Resolution / Space Resolution	3/7.5 Minutes	15 Minutes	30 Minutes
4 km	Eloise (22/9/75) V		
2 km	Eloise (22/9/75) V Caroline (30/8/75) V Caroline (28/8/75) V	Eloise (22/9/75) V	Eloise (22/9/75) V Caroline (30/8/75) V
1 km	Eloise (22/9/75) V Caroline (30/8/75) V Caroline (28/8/75) V Belle (5/8/76) V Holly (26/10/76) V Anita (30, 31/8/77, 1/9/77) V	Eloise (22/9/75) V Caroline (30/8/75) V	Eloise (22/9/75) V Caroline (30/8/75) V Caroline (28/8/75) V Belle (5/8/75) V Holly (26/10/75) V
High Level			
8 km	Eloise (22/9/75) IR		Eloise (22/9/75) IR
2 km	Eloise (22/9/75) V Caroline (30/8/75) V Caroline (28/8/75) V Belle (5/8/76) V		Eloise (22/9/75) V Caroline (30/8/75) V Caroline (28/8/75) V Belle (5/8/76) V

3. RESULTS

The results from the SMS-2 images of tropical cyclones Eloise and Caroline are presented in Tables 2 through 5. Low tropospheric clouds were tracked for both tropical cyclones using at least 3 successive visible images with spatial resolutions of 1, 2, and 4 km. The time intervals between images were 7.5, 15 and 30 minutes. No cloud element was tracked that could not be delineated in all images of each sequence.

Table 2 shows the number of low tropospheric clouds tracked for hurricane Eloise at radial distances of 222, 444, and 666 km from the center for a given spatial and temporal resolution.

Table 2

Hurricane Eloise 22 September 1975
Number of Low Level Wind Vectors

Distance from Center (km)	0-222	0-444	0-666
30 min 2 km Vis	0	1	
1 km Vis	0	1	9
15 min 2 km Vis	0	5	
1 km Vis	0	6	19
7.5 min 4 km Vis	4	34	
2 km Vis	4	38	
1 km Vis	4	58	119

Improved temporal resolution substantially increased the number of traceable low tropospheric cloud elements. The shorter interval data not only improved the cloud temporal continuity, but also eliminated the ambiguity caused by tracking cloud growth rather than displacement. From the center out to 666 km, the 7.5 minute interval images increased the number of traceable cloud elements by more than a factor of 10 (5) over that of the 30 minute (15 minute) interval images. Within 222 km from the center, cloud elements could only be tracked using shorter interval images.

Figures 1, 3, and 4 illustrate the distribution and the number of wind vectors using 1 km spatial resolution images at time intervals of 7.5, 15, and 30 minutes, respectively. Improved temporal resolutions not only increased the number of traceable cloud elements but also corrected an erroneous wind (west northwest wind 444 km southeast of the center, see Figure 4) caused by tracing cloud growth rather than cloud motion and added wind information within the eye wall.

Improved spatial resolution, in the case of Eloise, did benefit the tracking of small stratocumulus elements in the stable air west of the center and small cumulus elements south and east of the center. At spatial resolution greater than 1 km, no attempt was made to track clouds outside the radius of 444 km from the center of hurricane Eloise. Full resolution (1 km) visible images were also found to be important for tracking low tropospheric clouds within the central dense overcast, where the clouds are difficult to delineate because of the cirrus; and over the land where the cometimes slower moving clouds moved less than one television display pixel using the 2 km and 4 km resolution. In using the infrared images, little information was obtained for tracing lower clouds even at full spatial resolution. Figures 1 and 2 illustrate the distribution and the number of wind vectors that are derived from the motion of low level cloud elements at 1 km and 4 km spatial resolution using visible images at 7.5 minute intervals.

Cirrus clouds were examined for hurricane Eloise using visible and infrared images at 7.5 and 30 minute intervals. The purpose of using the infrared images was to determine if rapid scan images could be of any greater value at night than the 30-minute interval images. The spatial resolution used for the visible and infrared images were 2 km and 8 km, respectively. No additional information was obtained when tracking upper tropospheric clouds by using visible images at 1 km as compared to 2 km resolution.

Table 3 summarizes the results for the high clouds. Within 666 km from the center, approximately 2 times as many clouds could be tracked using the 2 km resolution visible as compared

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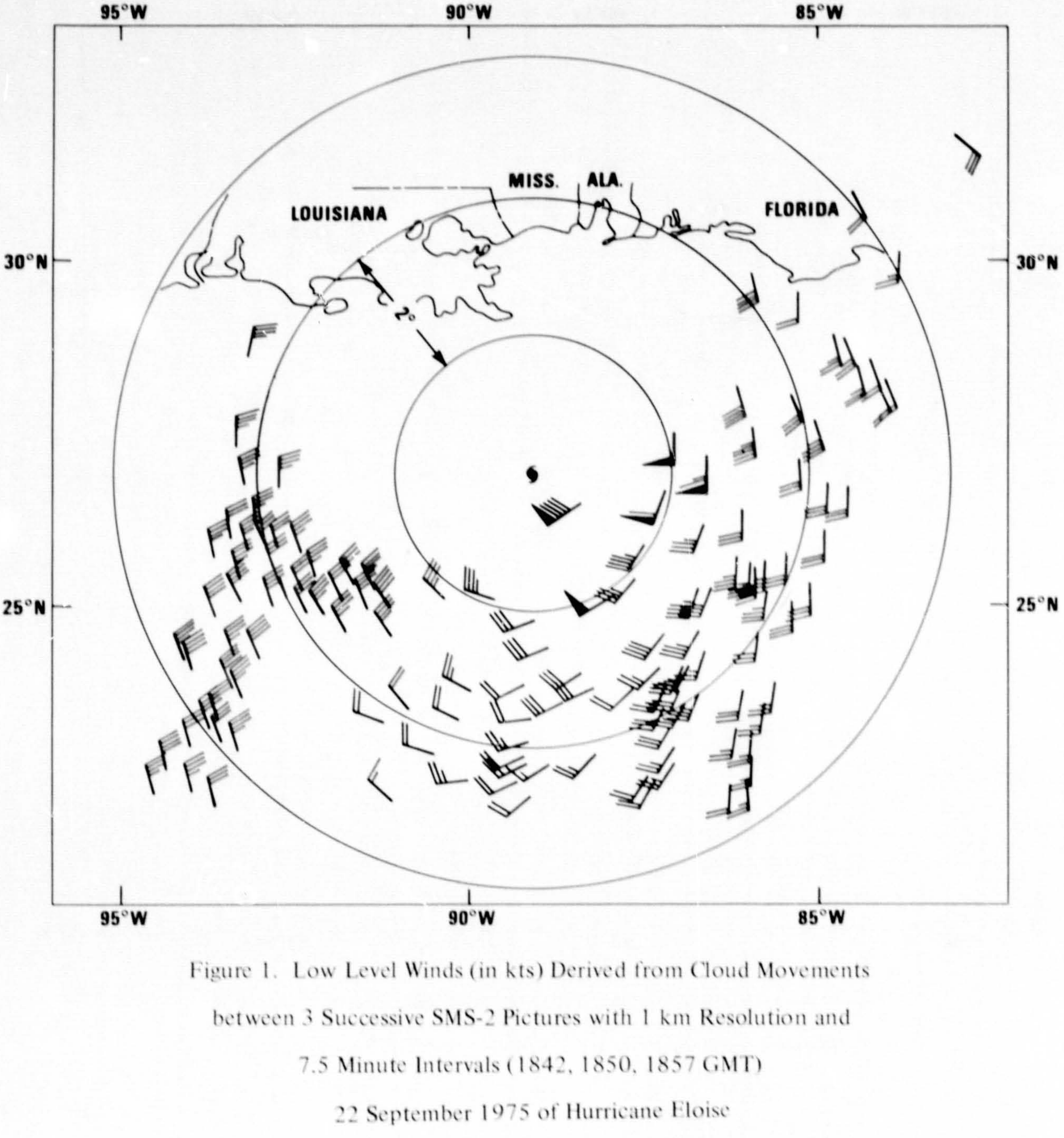

Figure 1. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 1 km Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise

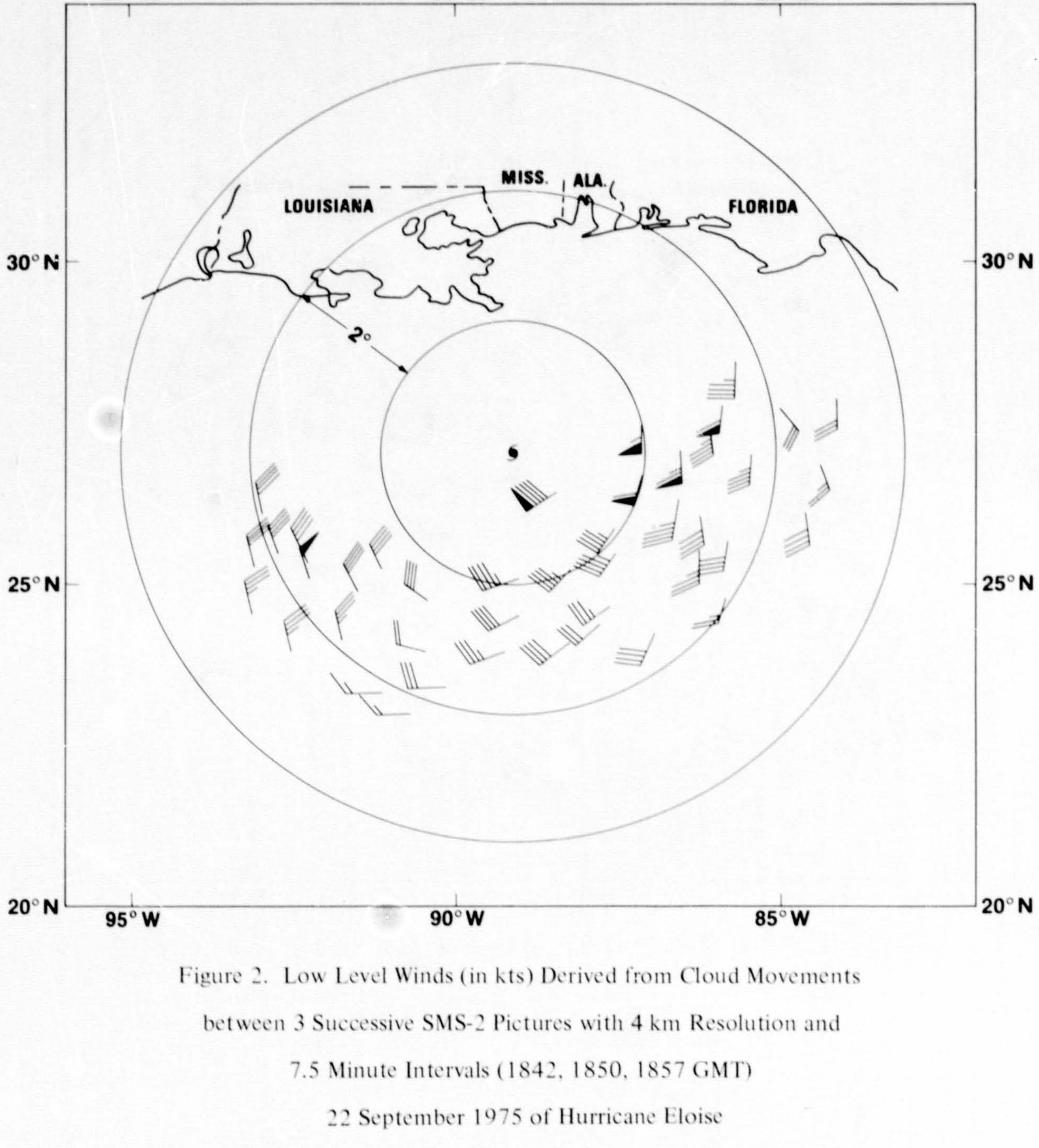

Figure 2. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 4 km Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise

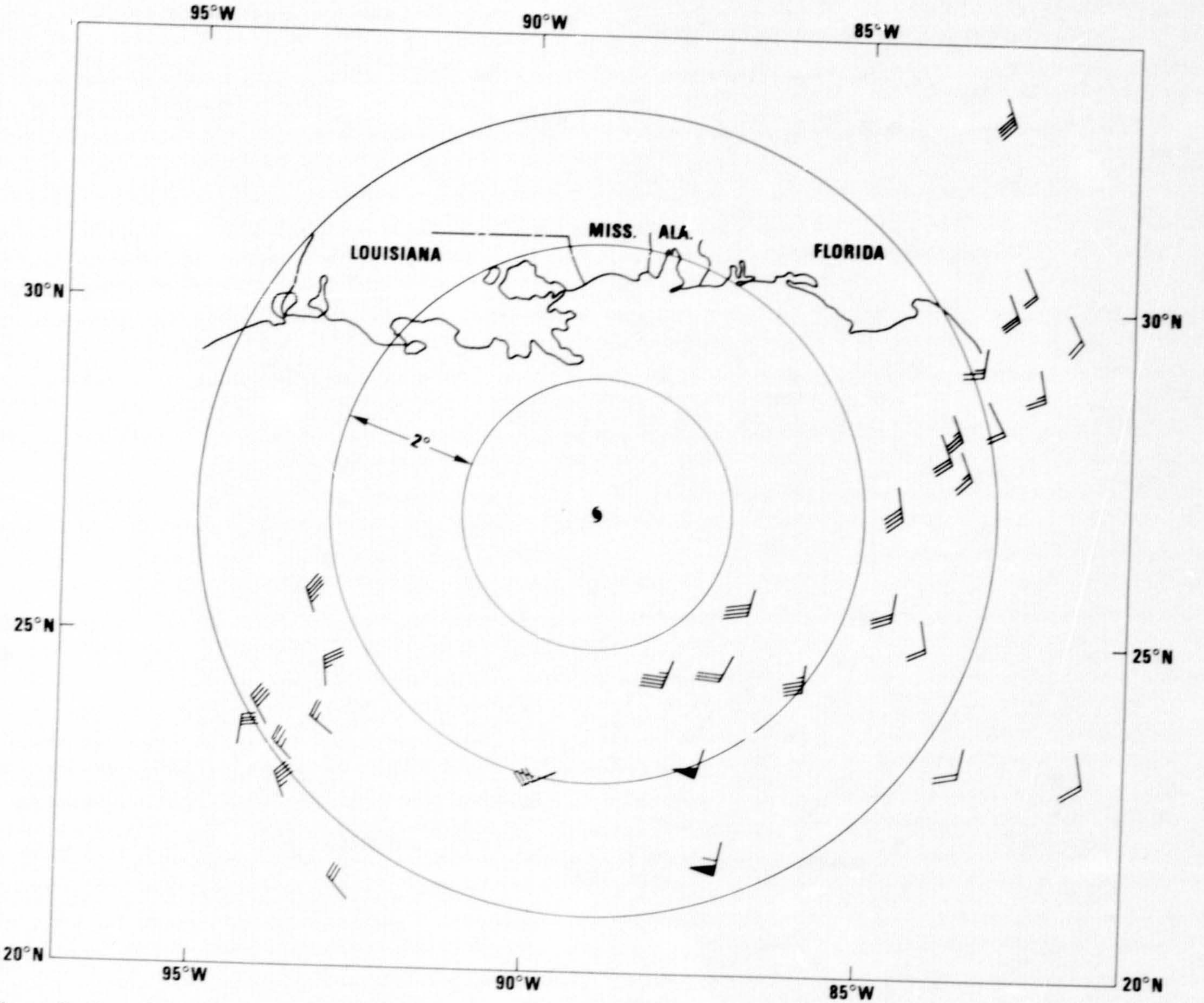

Figure 3. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 1 km Resolution and 15 Minute Intervals (1842, 1857, 1912 GMT) 22 September 1975 of Hurricane Eloise

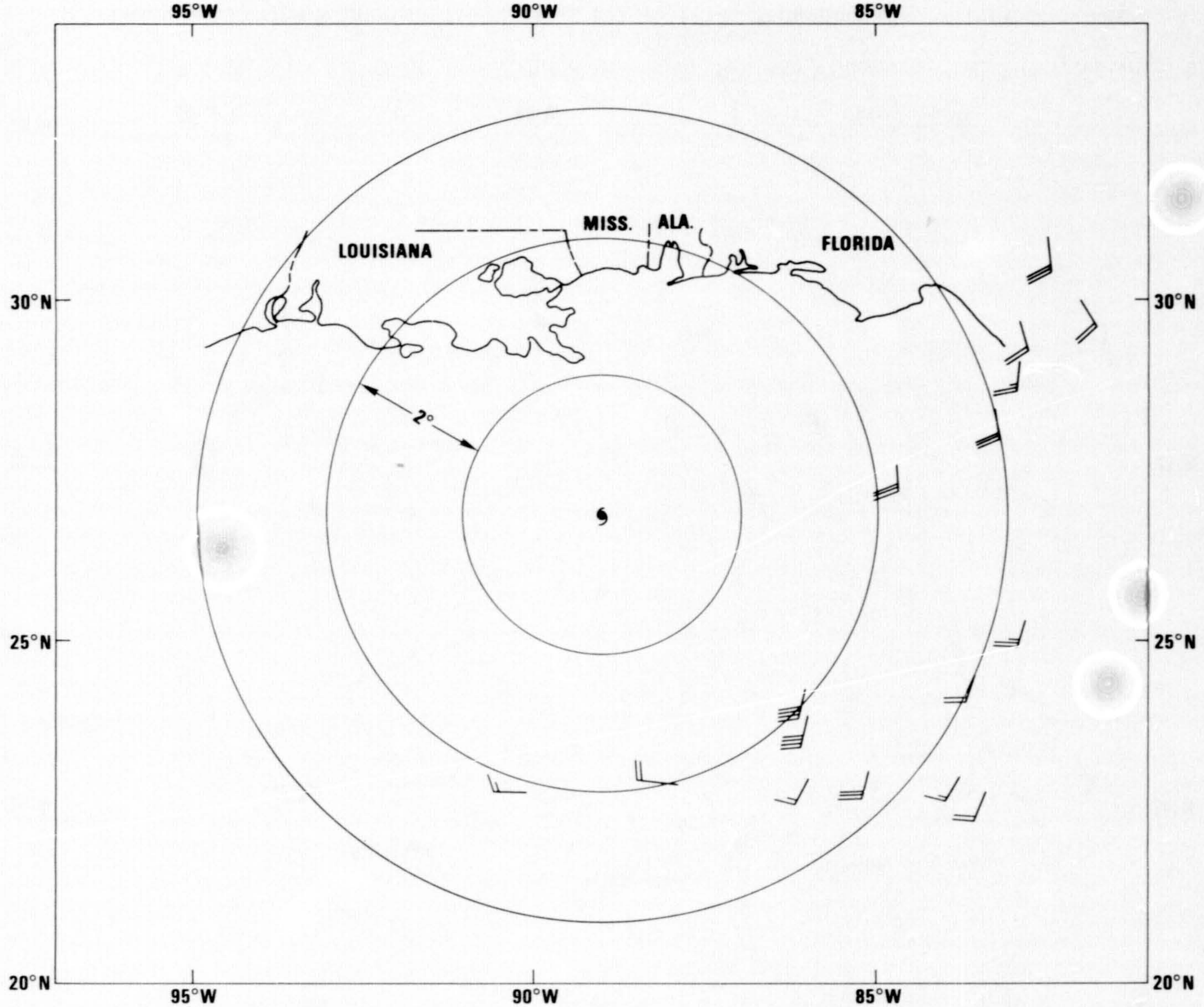

Figure 4. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 1 km Resolution and 30 Minute Intervals (1820, 1850, 1920 GMT) 22 September 1975 of Hurricane Eloise

Table 3

Hurricane Eloise 22 September 1975 1900 GMT
Number of High Level Wind Vectors

Distance from Center (km)	0-222	0-444	0-666
30 min 8 km IR	0	3	6
2 km Vis	0	5	9
7.5 min 8 km IR	1	13	30
2 km Vis	10	44	71

to the 8 km resolution infrared imagery. Thus, the structure of cirrus clouds is best delineated with higher spatial resolution visible images. As was found with the low tropospheric clouds, the improved temporal resolution again increased the number of traceable cloud elements considerably (by a factor of 6 in this case). Figures 5, 6, 7 and 8 illustrate the distribution and number of winds that were derived from tracking high clouds using visible and infrared images at 7.5 and 30 minute intervals. The table and figures show that using low resolution infrared images at short intervals greatly enhances the number of traceable cloud elements, thus infrared images would be more valuable for night time use if they were obtained more frequently.

One of the problems that was encountered in using longer interval visible and infrared images to track cirrus clouds, was the ambiguity introduced by tracking cloud patterns that were repetitive. For example, in Figure 9, an infrared image of hurricane Eloise at 2029 GMT 22 September 1975, there is a repetitive saw-tooth pattern in the western portion of the cloud mass (seen adjacent to A in the figure). This entire pattern was observed moving northward when short-interval imagery was shown in a time-lapse mode. When the imagery was spaced at longer periods (15 and 30 minutes), the direction of the displacement and the motion was uncertain.

Tropical cyclone Caroline was examined on all three days using visible images. Tables 4 and 5 describe the results for tracking lower and upper tropospheric clouds for hurricane Caroline

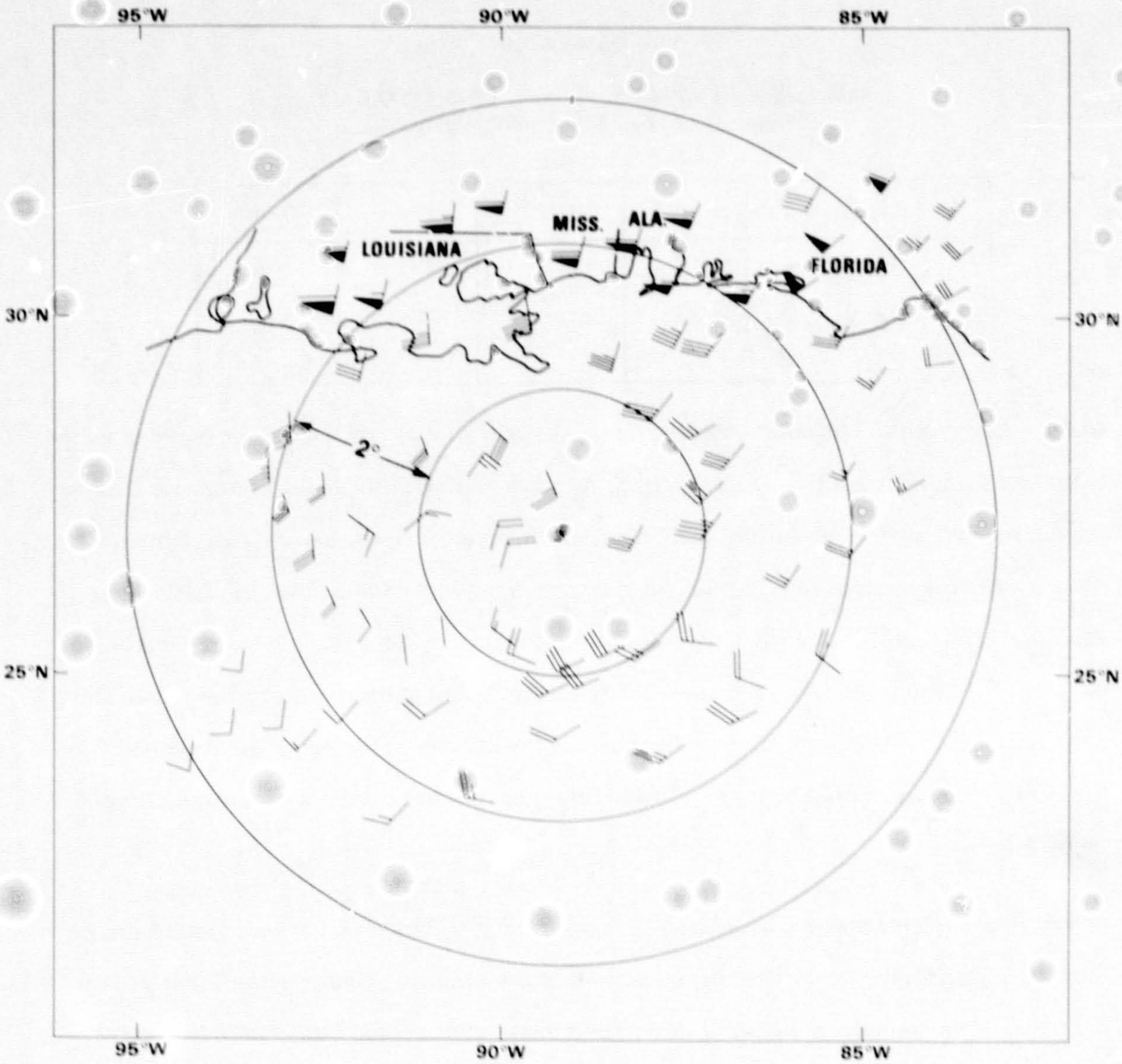

Figure 5. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 2 km Visible Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise

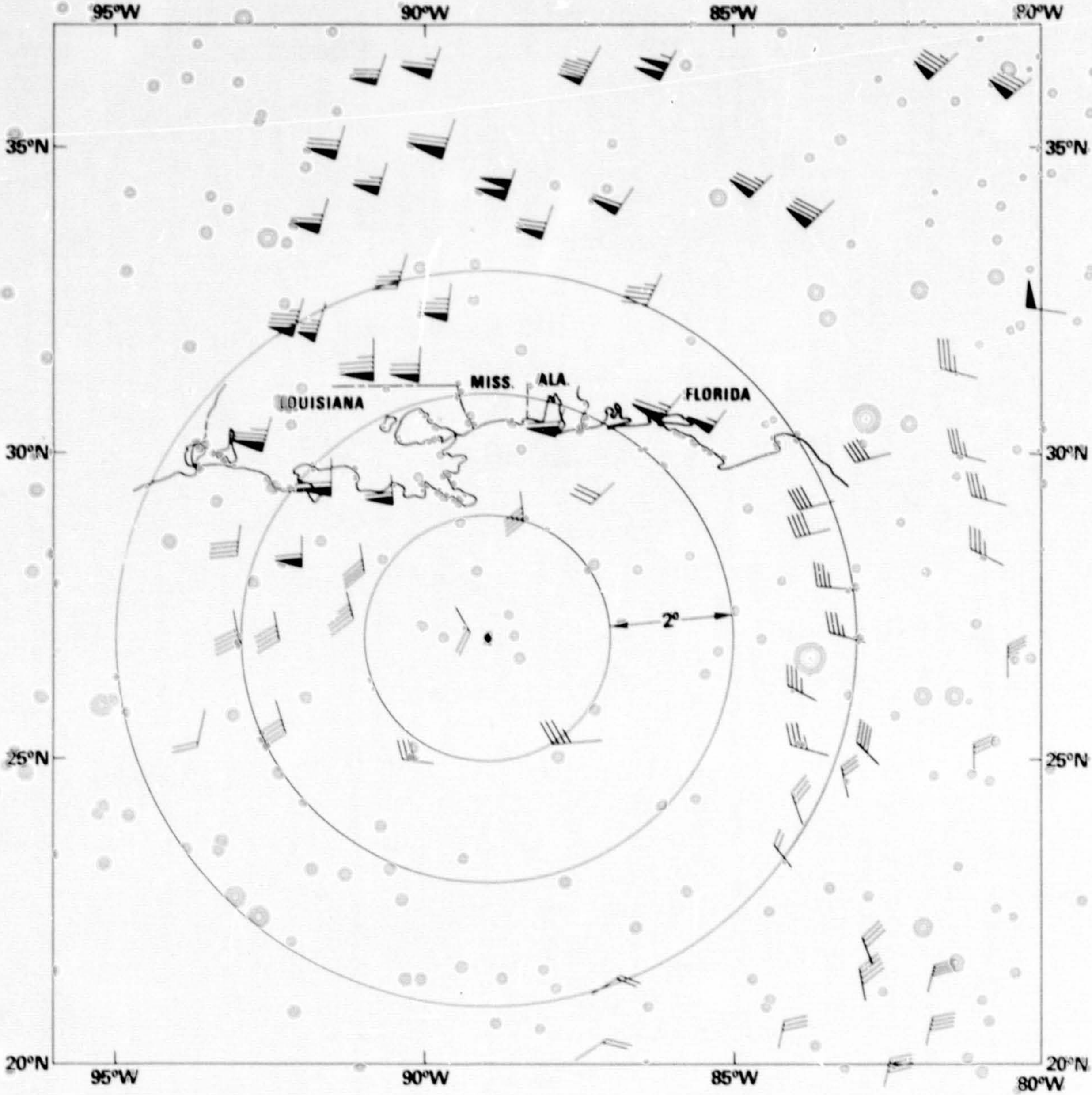

Figure 6. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 8 km Infrared Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise

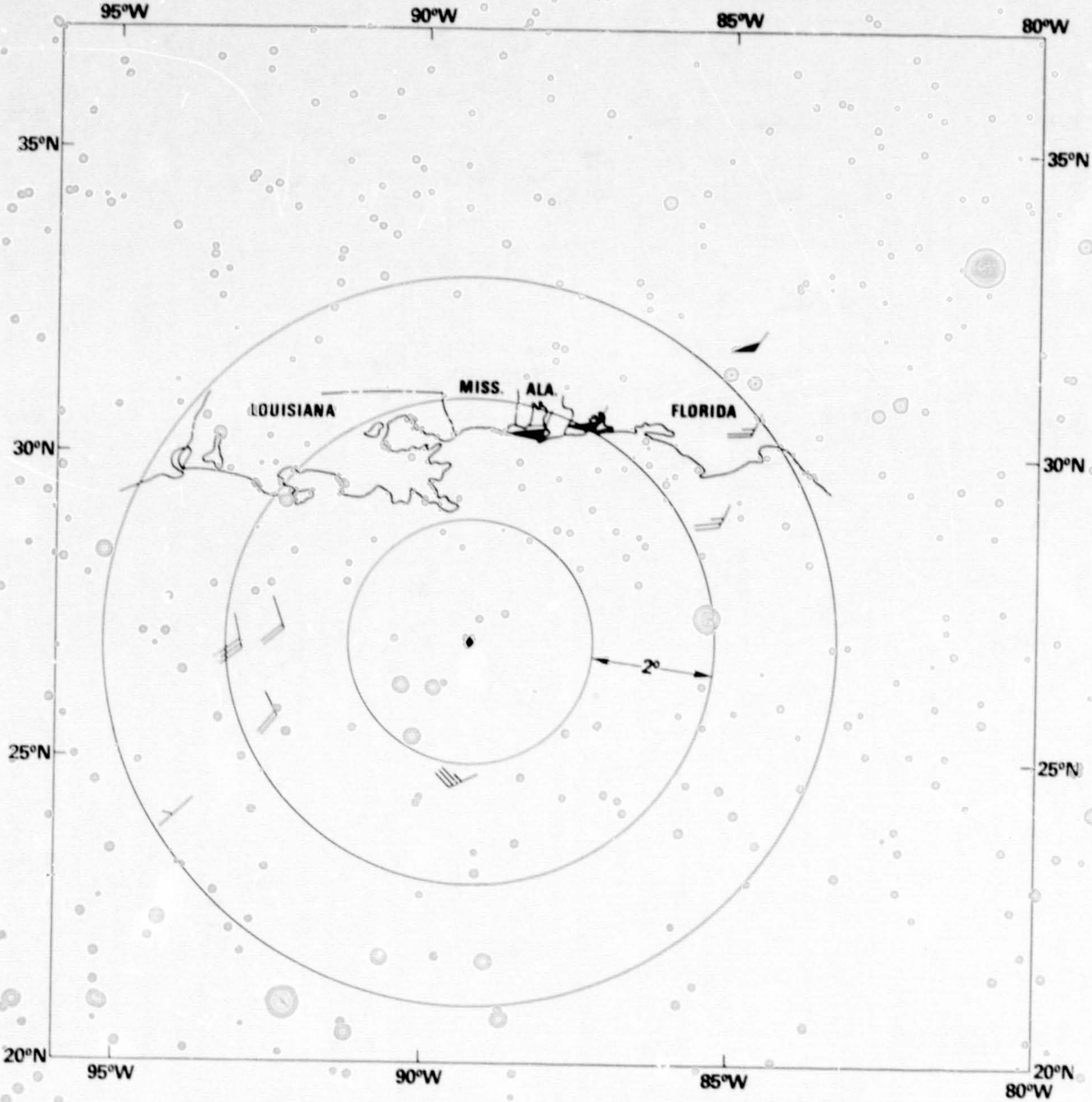

Figure 7. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 2 km Visible Resolution and 30 Minute Intervals (1820, 1850, 1920 GMT) 22 September 1975 of Hurricane Eloise

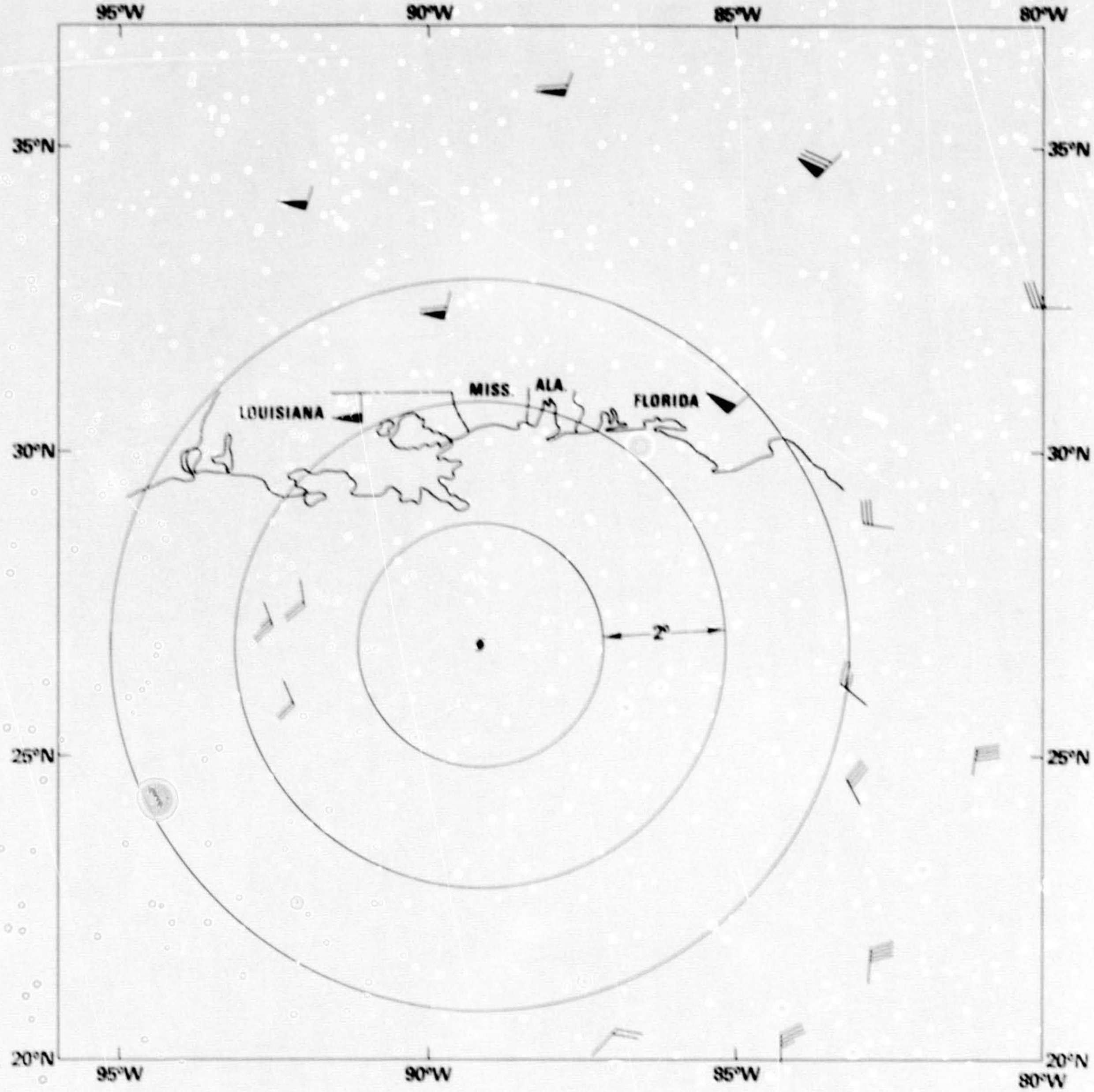

Figure 8. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 8 km Infrared Resolution and 30 Minute Intervals (1820, 1850, 1920 GMT) 22 September 1975 of Hurricane Eloise

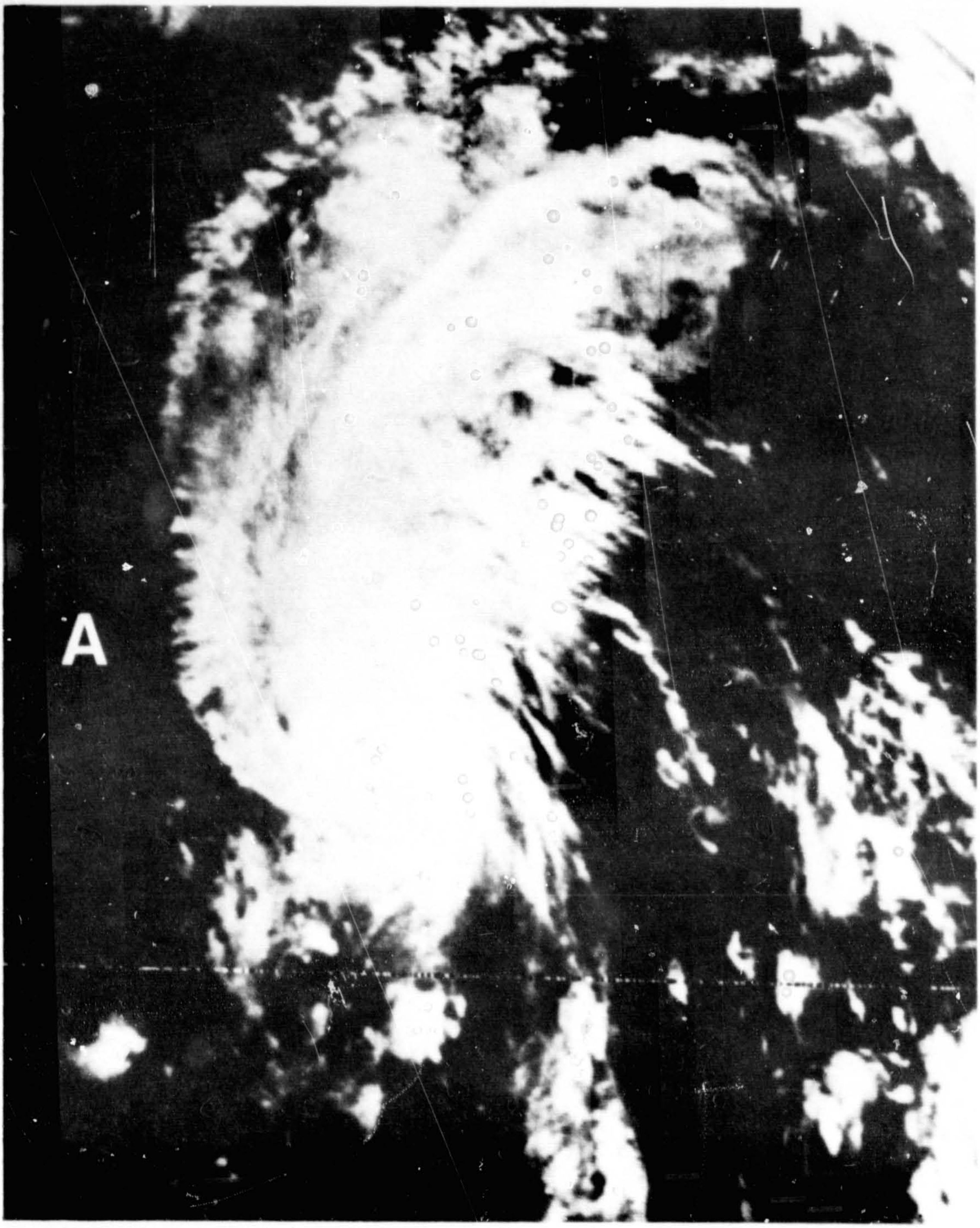

Figure 9. Infrared Imagery of Hurricane Eloise, 1912 GMT, 22 September 1975 (Note Serrated Pattern at "A")

Table 4

Hurricane Caroline 30 August 1975 1800 GMT
Number of Low Level Wind Vectors

Distance from Center (km)	0-222	0-444	0-666
30 min 2 km	0	5	13
1 km	0	3	14
15 min 1 km	17	46	75
7.5 min 2 km	23	65	88
1 km	23	61	121

Table 5

Hurricane Caroline 30 August 1975 1800 GMT
Number of High Level Wind Vectors

Distance from Center (km)	0-222	0-444	0-666
30 min 2 km Vis	0	14	22
7.5 min 2 km Vis	0	55	70

on 30 August 1975. Results for 28 and 29 August were quite similar. For the lower tropospheric clouds obtained from the 7.5 minute interval visible images within 444 km radius from the center, the degradation in the spatial resolution from 1 to 2 km did not decrease the number of wind vectors because only the larger cloud elements were traceable. However, at radii greater than 444 km, improved resolution did increase the number of traceable cloud elements. This was because the clouds to the west were over land and moved less than a television display pixel per time period in the 2 km resolution images. Using visible images whose intervals were 30 minutes, low level clouds over land could not be tracked because of the lack of temporal continuity. Improved temporal resolution again substantially increased the number of traceable cloud elements by a factor of 6 (less than 2) for 7.5 minute interval images as compared with 30 minute (15 minute) interval images for an area whose radius was 666 km from the center. A factor of 3 improvement was found using 7.5 minute interval visible images over that of 30 minute for tracking upper tropospheric clouds. Because of the smoother

texture of the cirrus canopy and therefore a lack of traceable elements, this improvement was not as dramatic as in the Eloise case.

The results from tropical cyclones Belle and Holly obtained from the GEOS-1 images during the 1976 hurricane season are presented in Table 6. The same format was followed for tracking clouds for these storms as was used for the tropical cyclones in 1975. The only difference was that the temporal resolution was compared only between 30 and 3 minute intervals using visible images. No differences in spatial resolution were considered. It can be seen from Table 6 that the rapid scan images again dramatically increased (factor of 6) the number of wind vectors obtained from cloud motion in the upper and lower troposphere for Belle and lower troposphere for Holly when the image interval was reduced from 30 to 3 minutes. Tropical storm Holly at this time had no high tropospheric clouds except in the southeast gradient.

Figures 12 and 13 dramatize the results for tropical storm Holly. The figures show the distribution and number of low tropospheric winds that can be derived from cloud motion using 30-minute as compared to 3 minute interval images. Because of the latitude belt for which the satellite was programmed to take scans, the images and therefore wind vectors in the

Table 6

Tropical Cyclone Belle 5 August 1976 1800 GMT
Tropical Cyclone Holly 26 October 1976 1300 GMT
Number of Low Level Wind Vectors

Distance from Center (km)	0-222	0-444	0-666
Low Level			
Belle 30 min 1 km Vis	0	23	–
3 min 1 km Vis	8	110	–
Holly 30 min 1 km Vis	4	29	48
3 min 1 km Vis	80	225	285
High Level			
Belle 30 min 1 km Vis	0	18	–
3 min 1 km Vis	16	75	–

northern half of Holly were not available. Figure 13 delineates an area of maximum winds (50 kts) to the east of the center obtained from rapid scan images which verify the tropical storm status reported by reconnaissance aircraft. This wind maximum was not observed from the 30 minute interval data.

Rapid scan images are seen from this observation of tropical storm Holly to be particularly valuable for estimating the lower tropospheric wind field nearer to the center in weaker or developing tropical cyclones whose upper tropospheric clouds are not dense enough to obscure the lower level circulation. Even for stronger tropical cyclones that have a more developed high level cloud shield the lower tropospheric wind field sometimes can be estimated near the center. This was true for tropical cyclones Eloise and Caroline. It is hypothesized that some deep convection near the storm center with small lateral area translates with the wind speed at the cloud base level. A few of these tracers appearing as bright spots in the upper cirrus overcast can be tracked using high resolution (both space and temporal) imagery. Maritime trade cumulus clouds (tops as high as 200 mb) have been found from aircraft observation to move very nearly with the ambient flow at the cloud base (Hasler *et al.* 1977). Although there is no aircraft verification that deep convective clouds move with the wind flow at cloud base within a tropical cyclone type circulation, the small vertical shear and the large upward flux of angular momentum near the center suggest that it may happen (Frank 1977). To examine this hypothesis, winds observed from the NOAA research aircraft at an approximate altitude of 1 km outside and .5 km inside the principal cloud shield for hurricane Eloise (2245-0440 GMT 22 and 23 September 1975), and for hurricane Caroline (1634-2332 GMT 30 August 1975) were compared with cloud derived winds. Some small bright convective cells that persisted during the time period were used to infer low level winds near the center. However, the translation of many larger bright convective cells near the center that moved slower than the winds was suspected to be due to cloud growth rather than advection by the wind and were not used. The results that are seen in Figures 10 and 11 show that the cloud derived winds inside and outside the tropical cyclone cloud system compared reasonably well with

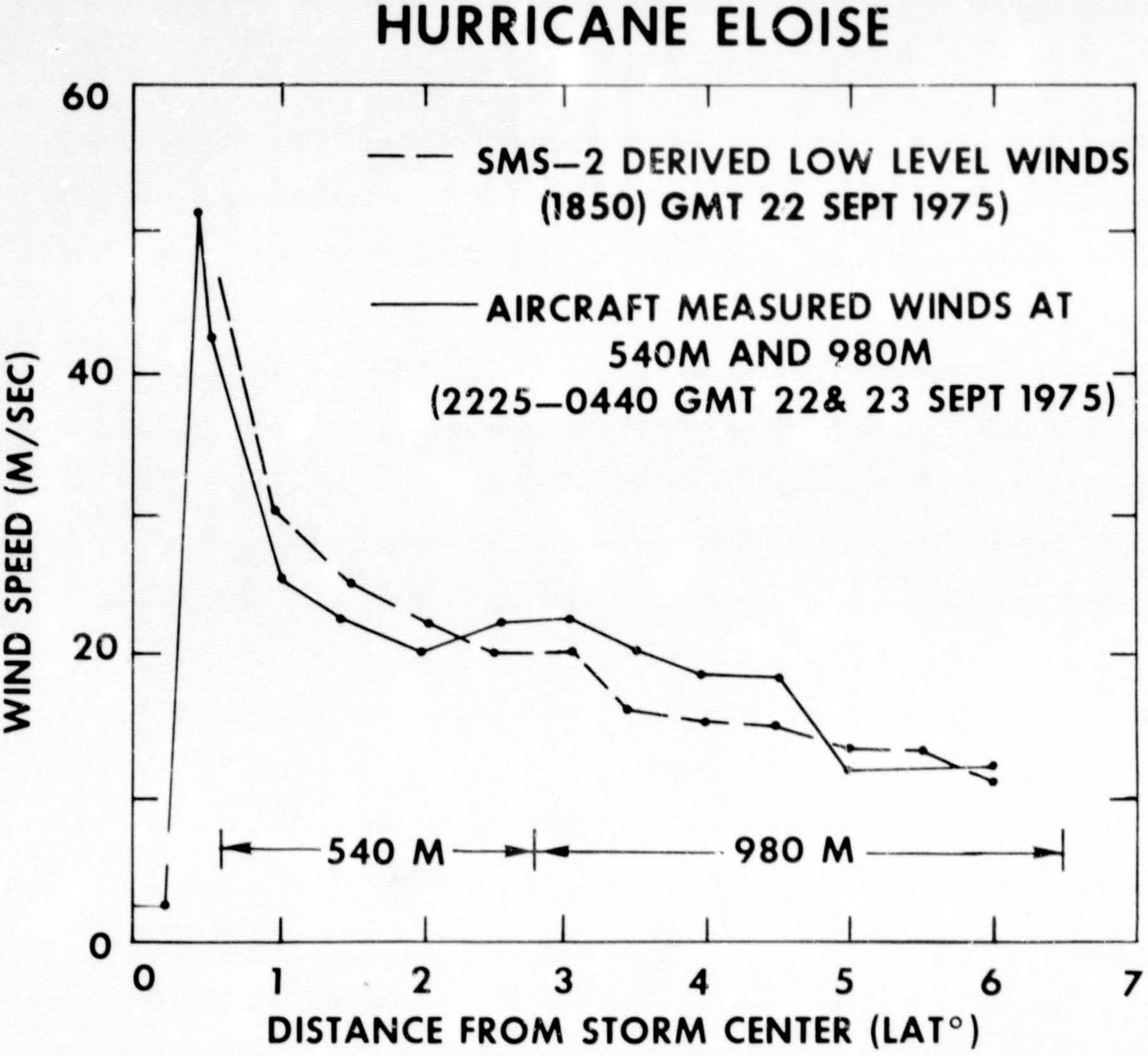

Figure 10. Comparison of Wind Speeds Derived from Cloud Motions between 3 Consecutive SMS-2 Satellite Visible Imagery at 7.5 Minute Intervals with Winds Measured 4 to 6 Hours Later by Reconnaissance Aircraft Flying at 540 and 980 Meters in Hurricane Eloise 22 September 1975

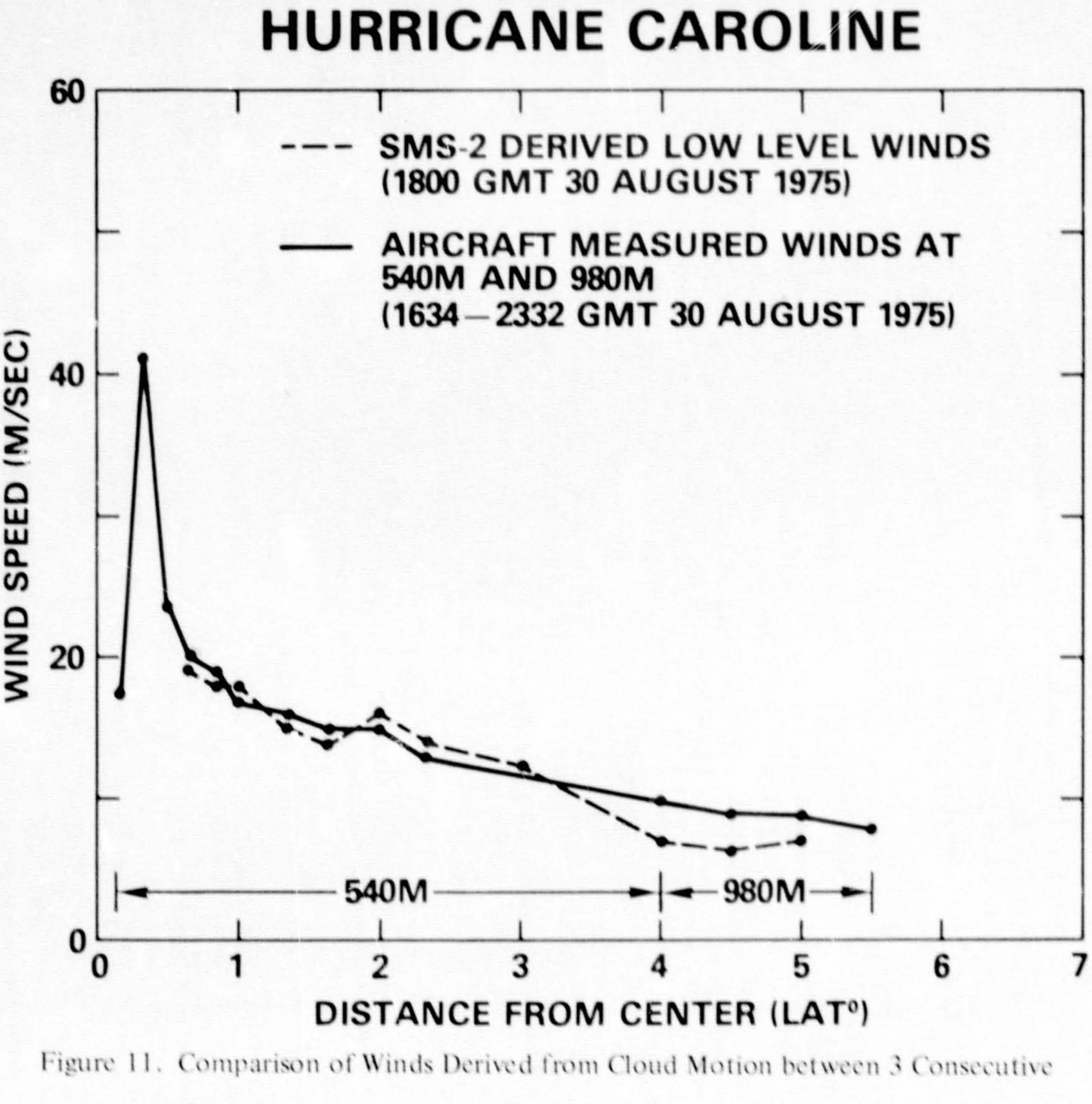

Figure 11. Comparison of Winds Derived from Cloud Motion between 3 Consecutive SMS-2 Satellite 1 km Visible Imagery at 7.5 Minute Intervals with Winds Measured 2 to 4 Hours Later by Reconnaissance Aircraft Flying at 540 and 980 Meters in Hurricane Caroline 30 August 1975

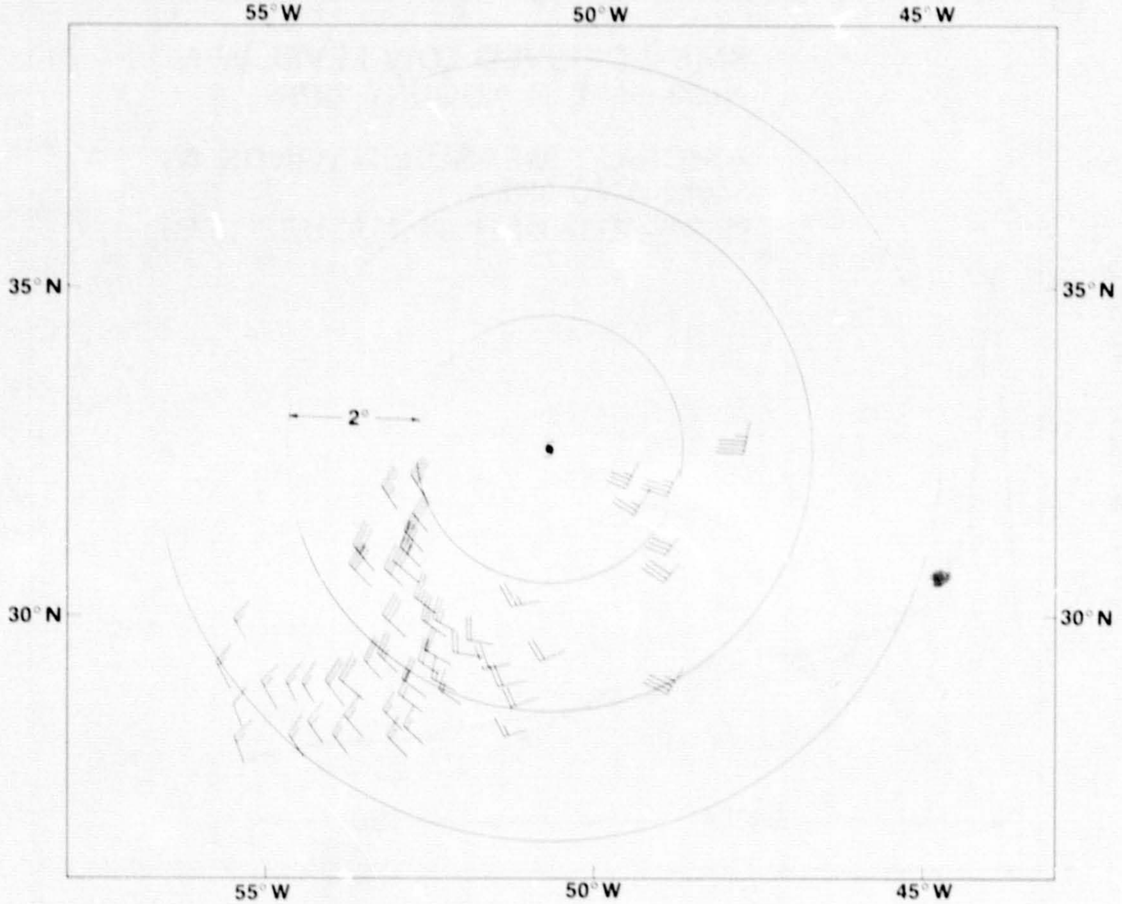

Figure 12. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive GOES-1 Pictures with 1 km Resolution, and 30 Minute Intervals (1530, 1600, 1630 GMT) 26 October 1976 of Tropical Storm Holly

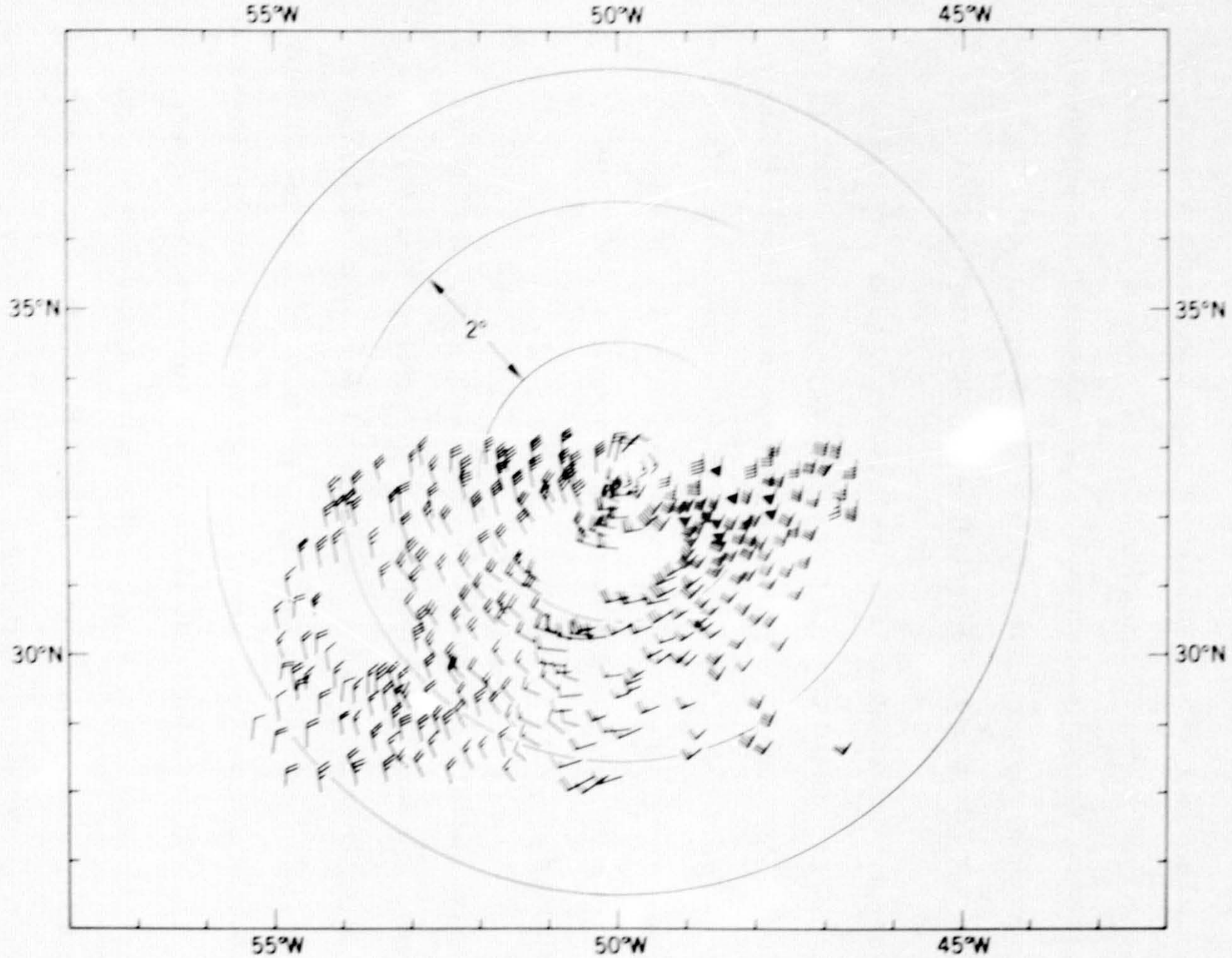

Figure 13. Low Level Winds (in kts) Derived from Cloud Movements between 4 Successive GOES-1 Pictures with 1 km Resolution and 3 Minute Intervals (1342, 1345, 1348, 1351 GMT)

26 October 1976 of Tropical Storm Holly

aircraft measured winds over the same area relative to the storm center even though the times differed by as much as 6 hours. The cell tracked near the center of Eloise approximated Eloise's maximum winds (90 kt wind vector east-southeast of the center, Figure 1 and 2). No cells suitable for tracking could be found within 80 km of hurricane Caroline's center. The average difference in absolute speed of winds obtained by the two methods is approximately 2.5 m/sec for each storm. Considering the time difference in the measurements, this result is no greater than would have occurred if the winds were obtained by aircraft for each case because of the great natural variability of winds in tropical cyclones (Gentry 1964).

This good agreement between satellite and aircraft winds differ from the findings of Gentry *et al.* (1970) in which they tracked large bright convective cells near the center of hurricane Gladys on 17 October 1968 using the 14 minute interval visible images from the Multicolor Spin Scan Cloud Camera on ATS-3. It was found that these clouds moved from 1/3 to 1/2 of the speed of the low level winds. The difference may be attributed to the ambiguity caused by cloud growth when tracking large cells using 4 km visible resolution images at a 14 minute time interval.

Rapid scan (3-minute interval) full resolution GOES-1 data for tropical cyclone Anita on 30 and 31 August and 1 September 1977 at approximately 1600 GMT were used to derive wind fields for both the cloud base and the upper troposphere. At the lower tropospheric level a representative wind field was obtained outside the central dense overcast. Within the central dense overcast, there were no low cloud elements that could be traced. Figure 14 shows an image of tropical storm Anita for 1600 GMT 31 August 1977 together with the derived lower tropospheric wind field. The vector length represents cloud speed while the vector depicts the direction of cloud motion (the vector at the center of Anita locates the center of the storm). From this figure one can detect the directional convergence southwest of the eye. A speed maximum of 40 knots is west and south of the eye. Winds measured by the NOAA research aircraft were compared with the satellite derived lower tropospheric winds where

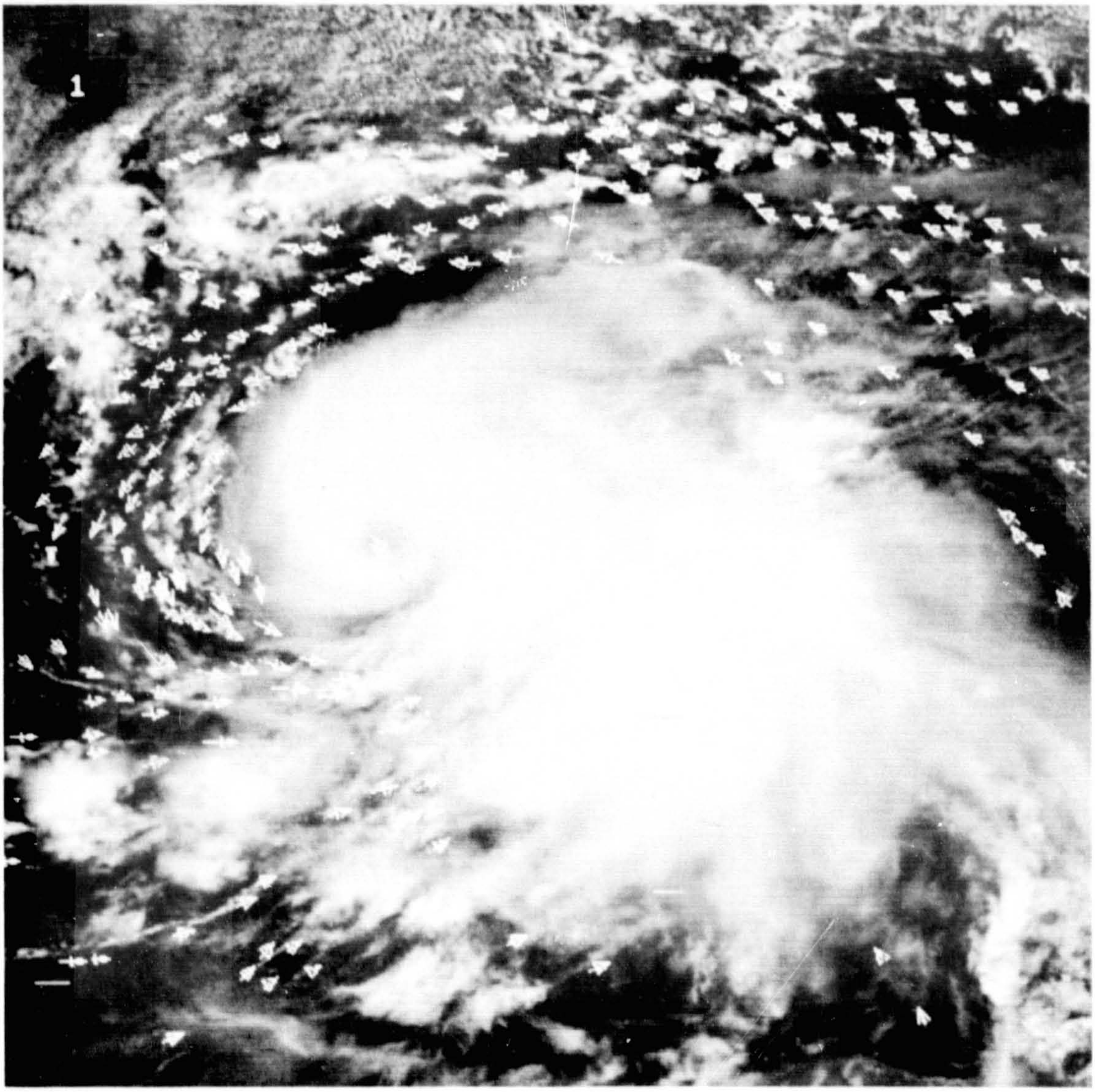

Figure 14. Visible Image of Tropical Storm Anita 1600 GMT 31 August 1977 Together with the Rapid Scan (3 Minute Interval) Satellite Derived Lower Tropospheric Wind Field. Vector Length Represents Cloud Speed While Vector Direction Represents the Direction the Cloud is Moving. Vector at Center Locates the Center of the Storm.

they could be matched in time and space. This was on 31 August 1977 at approximately 1400 GMT when the aircraft flew southwest from New Orleans into the storm at an altitude of .5 km. Comparison was made between 220 and 440 km from the center in the northeast quadrant. Results are in Figure 15 where again the average difference in absolute speed represented by the two methods is approximately 2.5 m/sec. Although the agreement between cloud motion and wind is good in these cases, more events that have both rapid scan satellite and aircraft wind data are needed.

At the upper tropospheric level, (Figure 16) limited scan data again aided in obtaining a representative wind field. Cirrus clouds could be used as tracers both outside and within the central dense overcast.

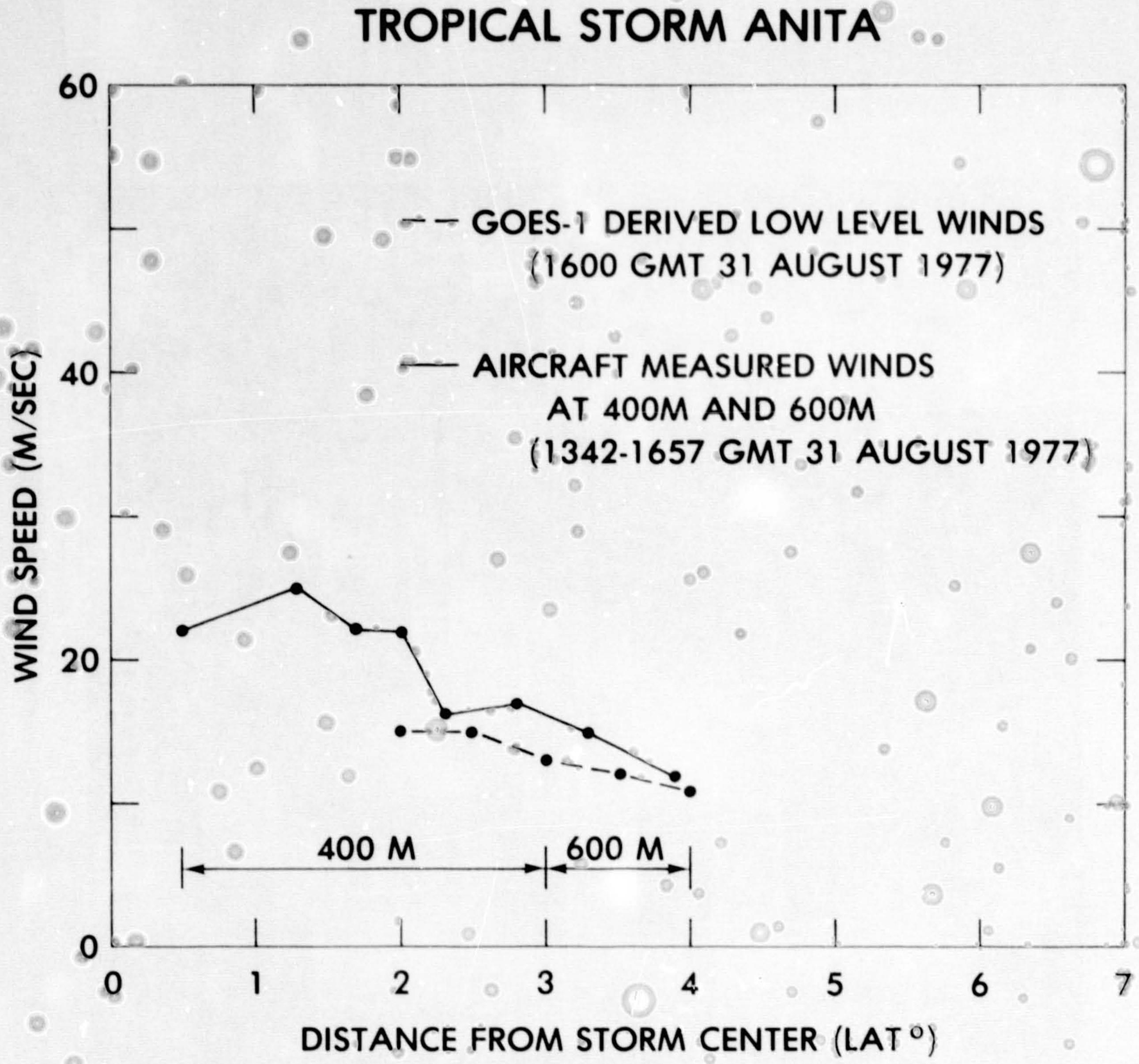

Figure 15. Comparison of Winds Derived from Cloud Motion between 3 Consecutive GOES-1 Satellite Visible Imagery at 3 Minute Intervals with Winds Measured 4 to 6 Hours Later by Reconnaissance Aircraft Flying at 540 and 980 Meters in Tropical Cyclone Anita

31 August 1977

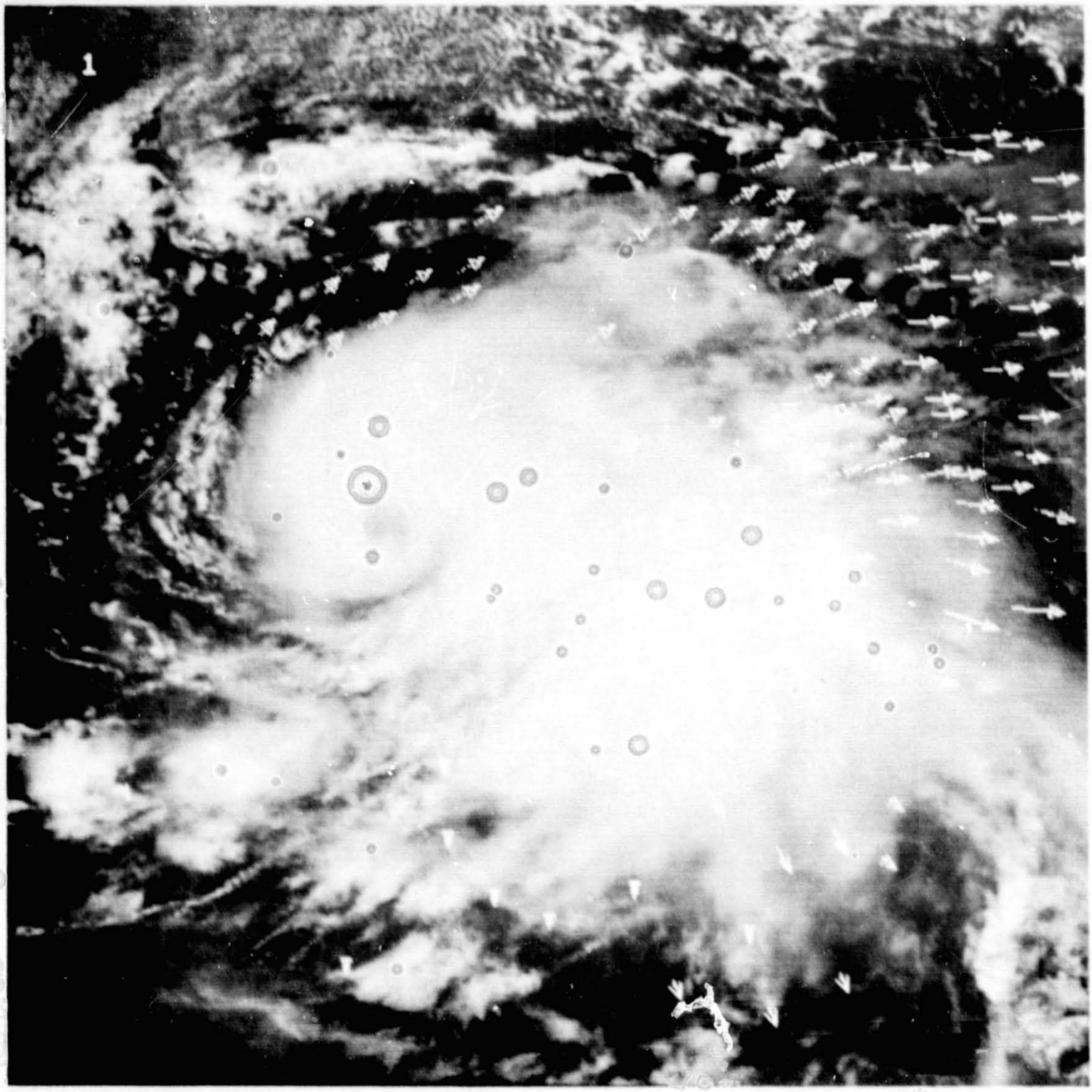

Figure 16. Same as Figure 14 Except Vectors Represent Cloud Motion and Direction at the Upper Tropospheric Level.

4. CONCLUSIONS:

High spatial and temporal resolution satellite imagery makes it feasible to provide a large number of lower and upper tropospheric winds which can be obtained by tracking clouds within 650 km of tropical cyclone centers. Up to 10 (5) times as many low level winds were derived from images spaced at 3 or 7.5 minute intervals as from those at 30 minute (15 minute) intervals. Greater space resolution is especially important when the low level clouds are over land or imbedded in the dense high overcast near the storm center. As long as the clouds are over water and removed from the high level clouds, 2 km space resolution is adequate. Rapid scan full resolution infrared and visible images minimized the "erroneous winds" derived by tracking cloud elements that propagate by growing on one side and dissipating on the other and by tracking repetitive patterns that provided ambiguous indications of direction of movement.

The higher temporal resolution also made it possible to greatly increase the number of traceable upper tropospheric cloud elements both during the day and night. With the rapid scan full resolution visible images it was sometimes possible to derive low level winds within the central dense overcast near the center of tropical cyclones.

Short interval (7.5 minute or less) full resolution images (≤ 2 km) make it feasible to provide many of the wind data not available from other sources between 200 and 1100 km from tropical cyclone centers. These winds are urgently needed to initialize dynamical-numerical model predictions. This additional source of data could provide the input such that the numerical models will give improved forecasts.

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FIGURE CAPTIONS

Figure 1. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 1 km Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise.

Figure 2. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 4 km Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise.

Figure 3. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 1 km Resolution and 15 Minute Intervals (1842, 1857, 1912 GMT) 22 September 1975 of Hurricane Eloise.

Figure 4. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 1 km Resolution and 30 Minute Intervals (1820, 1850, 1920 GMT) 22 September 1975 of Hurricane Eloise.

Figure 5. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 2 km Visible Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise.

Figure 6. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 8 km Infrared Resolution and 7.5 Minute Intervals (1842, 1850, 1857 GMT) 22 September 1975 of Hurricane Eloise.

Figure 7. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 2 km Visible Resolution and 30 Minute Intervals (1820, 1850, 1920 GMT) 22 September 1975 of Hurricane Eloise

FIGURE CAPTIONS (Continued)

Figure 8. High Level Winds (in kts) Derived from Cloud Movements between 3 Successive SMS-2 Pictures with 8 km Infrared Resolution and 30 Minute Intervals (1820, 1850, 1920 GMT) 22 September 1975 of Hurricane Eloise.

Figure 9. Infrared Imagery of Hurricane Eloise, 1912 GMT, 22 September 1975 (Note Serrated Pattern at "A").

Figure 10. Comparison of Wind Speeds Derived from Cloud Motions between 3 Consecutive SMS-2 Satellite Visible Imagery at 7.5 Minute Intervals with Winds Measured 4 to 6 Hours Later by Reconnaissance Aircraft Flying at 540 and 980 Meters in Hurricane Eloise 22 September 1975.

Figure 11. Comparison of Winds Derived from Cloud Motion between 3 Consecutive SMS-2 Satellite 1 km Visible Imagery at 7.5 Minute Intervals with Winds Measured 2 to 4 Hours Later by Reconnaissance Aircraft Flying at 540 and 980 Meters in Hurricane Caroline 30 August 1975.

Figure 12. Low Level Winds (in kts) Derived from Cloud Movements between 3 Successive GOES-1 Pictures with 1 km Resolution, and 30 Minute Intervals (1530, 1600, 1630 GMT). 26 October, 1976 of Tropical Storm Holly.

Figure 13. Low Level Winds (in kts) Derived from Cloud Movements between 4 Successive GOES-1 Pictures with 1 km Resolution and 3 Minute Intervals (1342, 1345, 1348, 1351 GMT). 26 October, 1976 of Tropical Storm Holly.

Figure 14. Visible Image of Tropical Storm Anita 1600 GMT 31 August 1977 Together with the Rapid Scan (3 Minute Interval) Satellite Derived Lower Tropospheric Wind Field. Vector Length Represents Cloud Speed While Vector Direction Represents the Direction the Cloud is Moving. Vector at Center Locates the Center of the Storm.

FIGURE CAPTIONS (Continued)

Figure 15. Comparison of Winds Derived from Cloud Motion between 3 Consecutive GOES-1 Satellite Visible Imagery at 3 Minute Intervals with Winds Measured 4 to 6 Hours Later by Reconnaissance Aircraft Flying at 540 and 980 Meters in Tropical Cyclone Anita 31 August 1977.

Figure 16. Same as Figure 14 Except Vectors Represent Cloud Motion and Direction at the Upper Tropospheric Level.