

Unusual Tornadoes Associated with Hurricane Michelle

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ABSTRACT

Hurricane Michelle was the 13th named storm in an active 2001 hurricane season, beginning as a tropical depression off the coast of Nicaragua on October 29, developing into a hurricane on November 2, and striking the south coast islands of Cuba as a category 4 hurricane on November 4. Michelle moved through the Bahamas on November 5, before weakening over the southwest Atlantic Ocean on November 6. Two tornadoes struck South Florida on November 5, a waterspout which came ashore on Key Biscayne as an F0 tornado, and an F1 which moved through the business section of Belle Glade. These two Florida tornadoes are therefore somewhat unusual because they formed in the left rear quadrant (relative to storm motion) of a tropical cyclone, traditionally a less favored quadrant for tornadic activity associated with tropical cyclones.

1. Introduction

Hurricane Michelle was the 13th named storm in an active 2001 hurricane season. The storm started as a low pressure area in the southwest Caribbean Sea, finally organizing into a tropical depression off the coast of Nicaragua on October 29, and into a tropical storm on October 31. Michelle became a hurricane on November 2, and struck the south coast islands of Cuba as a category 4 hurricane on November 4. Michelle moved through the Bahamas on November 5, before weakening over the southwest Atlantic Ocean on November 6 (Fig. 1).

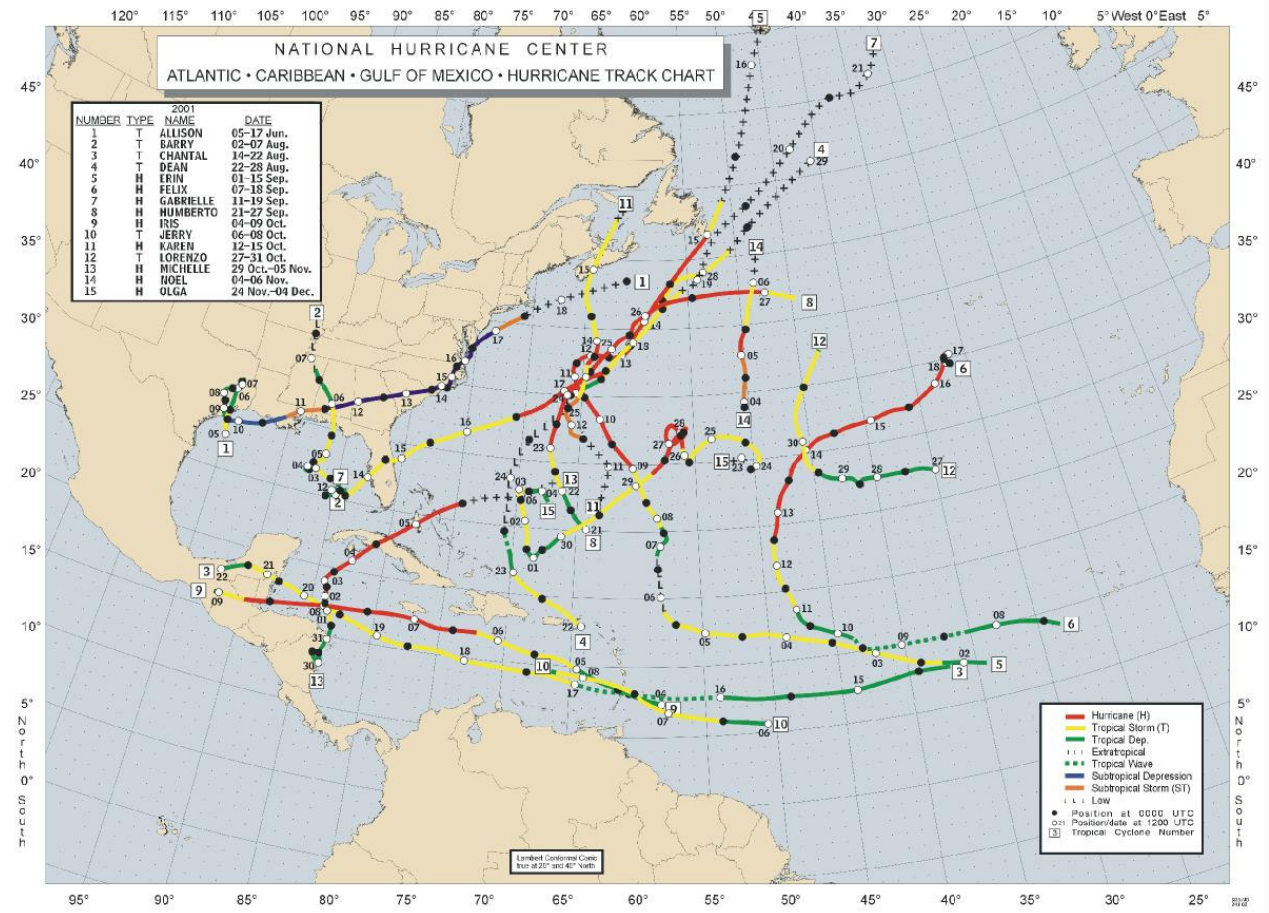


Fig. 1 - 2001 Atlantic Hurricane Season composite chart from the Tropical Prediction Center. The track of Hurricane Michelle is No. 13 that starts east of Nicaragua. [Click the image for a larger and more readable chart.]

Many excellent papers have been written through the years about hurricane environment tornadoes ([McCaul, 1991](#); [Novlan and Gray, 1974](#); [Gentry, 1983](#); [Weiss, 1985](#); [Hagemeyer and Hodanish, 1995](#); [Spratt et al., 1997](#); just to name a few). It is not the purpose of this short internet paper to review hurricane environment tornado theory or all of the WSR-88D radar considerations, and the author urges the reader to consult the papers referenced to get a much more complete treatment of this complex and challenging subject.

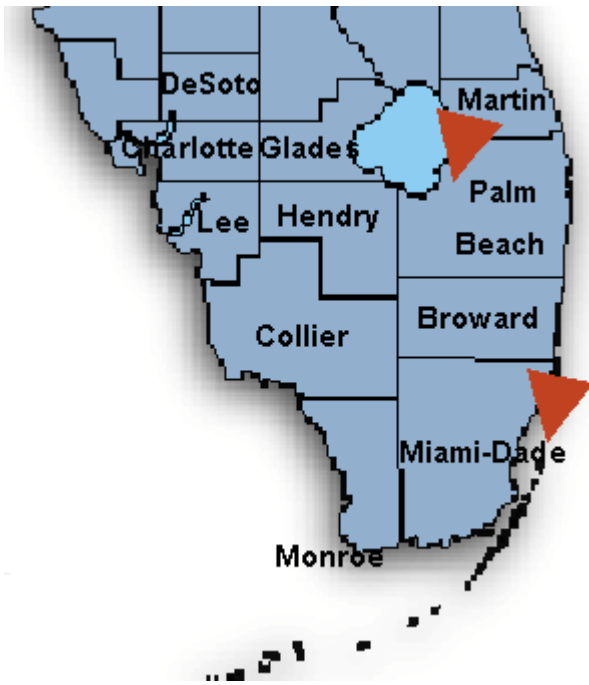


Fig. 2 - Outline Map of South Florida showing location of tornadoes

South Florida experienced only the fringe effects of Michelle's circulation, although two tornadoes occurred on November 5 (Fig. 2). A waterspout moved onshore Key Biscayne, a barrier island of Miami-Dade County, as an F0 tornado at about 1025 EST and destroyed two chickee huts. At about 1403 EST on Monday, November 5, the stronger of the two tornadoes (F1 on the Fujita scale) associated with Hurricane Michelle's circulation struck Belle Glade, a town in western Palm Beach County near Lake Okeechobee. This tornado moved through downtown, blowing out the windows of vehicles and buildings and blowing over signs and trees. Interestingly, these tornadoes occurred in the left rear quadrant (relative to storm motion) of Michelle's circulation (Fig. 3), traditionally not a favored quadrant for tornado formation ([Novlan and Gray, 1974](#); [Gentry, 1983](#); [McCaul, 1991](#)).

This paper will briefly examine the synoptic and mesoscale environment that produced the tornadoes, including reflectivity and velocity radar products from the KAMX WSR-88D radar. The possible influence of Lake Okeechobee and the Atlantic Ocean in the development of these tornadoes is briefly discussed.

2. Data Analysis

a. Surface data

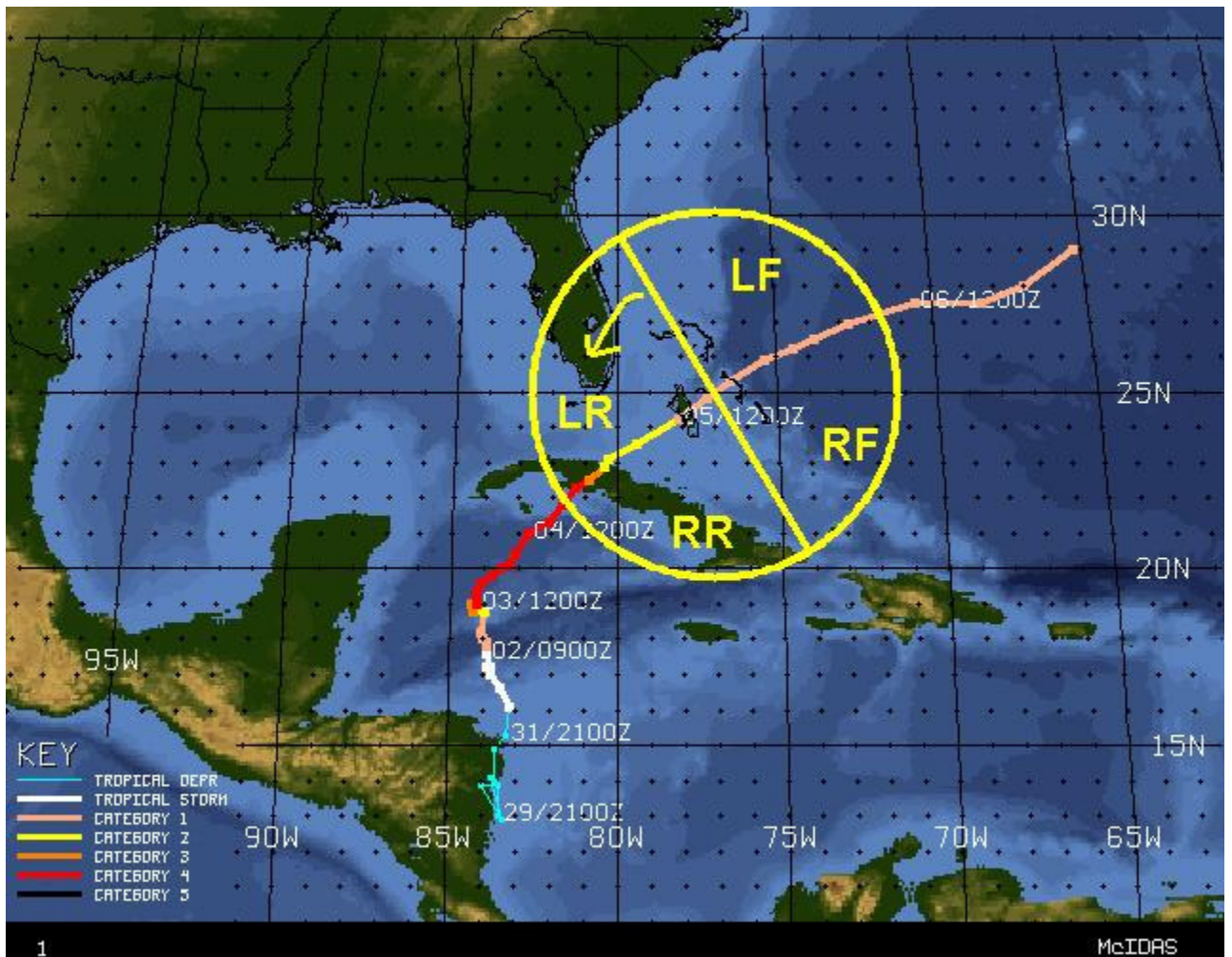


Fig. 3 - Track of Hurricane Michelle Oct. 29 - Nov. 6, 2001. Yellow arrow shows direction of low level flow across South Florida. Quadrants are relative to storm motion.

As Hurricane Michelle moved northeast across Cuba and through the Bahamas, South Florida remained on the left side of the storm in a northeast flow at first that gradually backed to a northerly flow (Fig. 3). The strongest sustained wind on land in South Florida, 34 knots, as well as the highest wind gust on land, 44 knots, occurred at Miami Beach at 1005 EST on November 5 from the northeast. However, winds over land were for the most part less than tropical storm strength except near the Atlantic beaches. Daytime temperatures on November 5 were generally in the mid 70s with dewpoints in the low to mid 60s, not really what one would expect in South Florida with a nearby hurricane. Typically, tropical cyclones affecting South Florida bring temperatures in the

80s with dewpoints well into the 70s, perhaps even near 80. As rain squalls moved into West Palm Beach around 1400 EST, just about the time the tornado struck Belle Glade, the temperature dropped from 75 degrees to 67 degrees with a dewpoint temperature of 65.

Previous papers on the subject of tropical cyclone associated tornadoes ([Hill, et al., \(1966\)](#), [Orton \(1970\)](#), [Novlan and Gray \(1974\)](#), and [Gentry \(1983\)](#)) have shown that plotting tornado locations relative to true north is preferred to plotting tropical cyclone locations relative to tropical cyclone motion. This is mainly because the well known affinity of tropical cyclone associated tornadoes for the northeast quadrant is most easily seen when using locations plotted relative to true north. For this case, if plotted relative to true north, both locations would be in the left *front* quadrant rather than the left *rear*. Because Michelle on this day was moving northeast at nearly 15 knots, this author believes the most appropriate frame of reference is one relative to storm motion. Regardless of which reference frame is chosen, the two Florida tornadoes associated with Hurricane Michelle occurred in a less favored location (i.e., well away from the northeast quadrant) according to all the previous literature on the subject.

The University of Florida (UF) Institute of Food and Agricultural Sciences (IFAS) operates a Florida Automated Weather Network (FAWN) site at the UF Agricultural Research Station southeast of Belle Glade. Wind speeds at the FAWN site were generally less than 10 mph around the time the tornado struck downtown Belle Glade, and the wind direction was generally northwest ([Table 1](#)). Because the wind direction backed from north to northwest around 0900 EST (not shown), this may indicate some lake breeze effect from Lake Okeechobee, only a few kilometers northwest of Belle Glade. Unfortunately, there was no indication that the tornado passed near the Belle Glade FAWN site in the data retrieval.

Table 1

TIME (EST)	T (F)	T _d (F)	WIND DIR (deg)	WIND SPEED(mph)
1200	70	70	332	6
1215	70	69	329	6
1230	71	69	330	7
1245	71	69	321	7
1300	71	69	322	6
1315	72	70	306	7
1330	70	70	295	7
1345	69	68	300	6
1400	68	68	3	5
1415	68	68	300	7
1430	68	68	320	2
1445	69	69	329	2
1500	70	70	314	6

Table 1 - FAWN Observations at the University of Florida Everglades Research and Education Center near Belle Glade, FL

Lake breezes from Lake Okeechobee are common mechanisms for convective initiation over South Florida in the summer months, and from years of observing convective patterns across South Florida they have served as source regions for weak tornadoes (or landspouts) over the lake region. The water temperature at Lake Okeechobee on this date was around 19 degrees C in the center of the lake to about 22 degrees C in the south part of the lake (about 66 to 72 degrees F) based on data provided by the South Florida Water Management District (SFWMD) for data collection station L006 (meteorological data available in [Fig. 13](#)) and data collection station LZ40 on Lake Okeechobee. Additional meteorological information in graphical form is shown for the SFWMD Belle Glade station ([Fig. 14](#)). Those water temperatures, combined with ambient air temperatures in the 70s, means that if a lake breeze was present, it would probably have been fairly weak. However, even a weak baroclinic boundary can serve as a potential source of vorticity and spin-up tilted into the vertical by an updraft ([Rasmussen et al., 1995](#)). From operational tornado warning guidance from the National Severe Storms Laboratory, the air mass immediately on the cool side of a low level boundary can be quite rich in local

streamwise vorticity, which quickly can be tilted and stretched to produce the low level mesocyclone and may have aided in tornadogenesis.

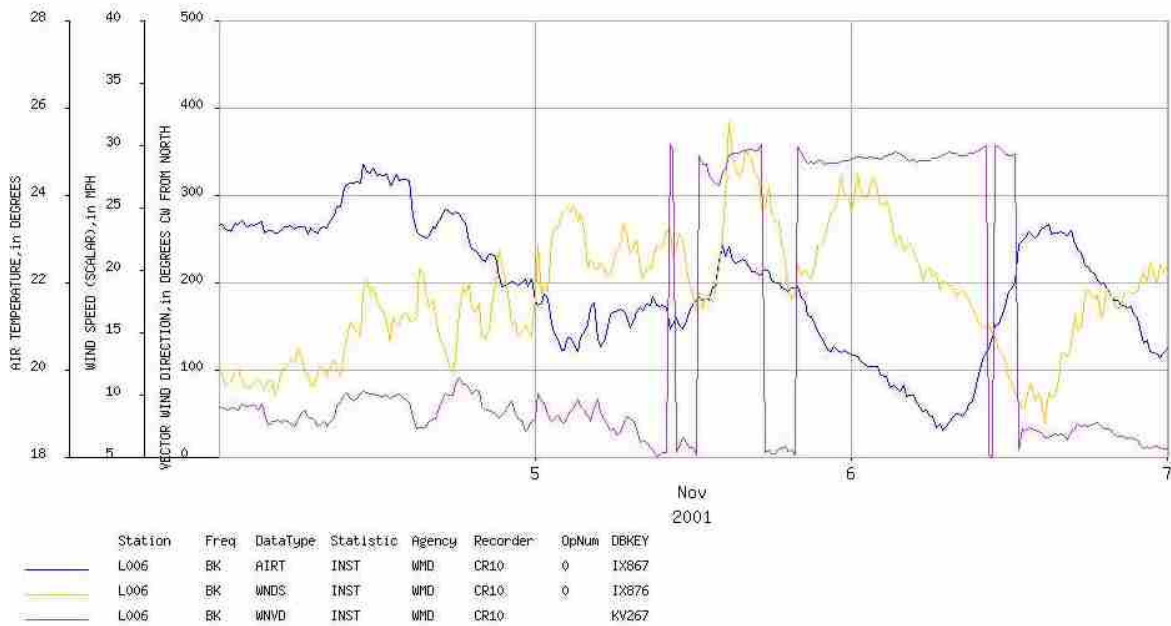


Fig. 13 - Graph of Air temperature (degrees C), wind direction (degrees) and speed (mph) for station L006 on south Lake Okeechobee, about 16 km northwest of Belle Glade. Courtesy of Eric Swartz, South Florida Water Management District, West Palm Beach, FL. Note no sudden change in prevailing wind direction as the wind backed from northeast early on November 5 to north around noon. Note also the peak wind speed out over Lake Okeechobee was around 32 mph from the north in the early afternoon.

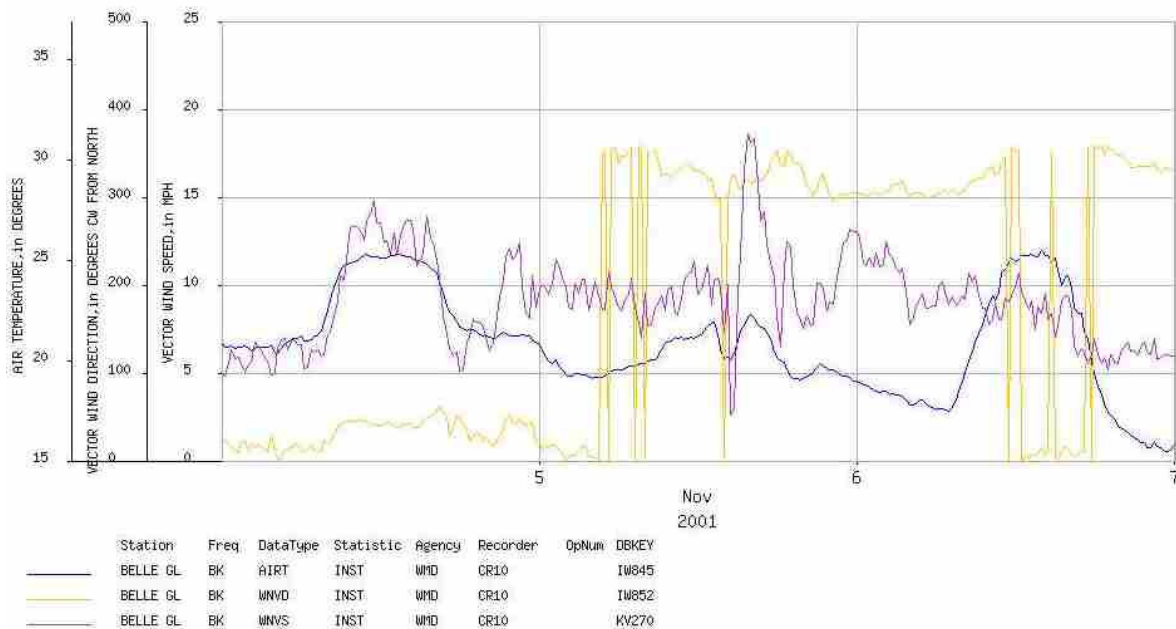


Fig. 14 - Graph of Air temperature (degrees C), wind direction (degrees) and speed (mph) for the Belle Glade station, located approximately at the same place as the University of Florida Everglades Research and Development Center. Courtesy of Eric Swartz, South Florida Water Management District, West Palm Beach, FL. Note the change in wind direction from prevailing northerly to northwesterly around 0900 or 1000 EST on November 5, possibly showing an effect from Lake Okeechobee.



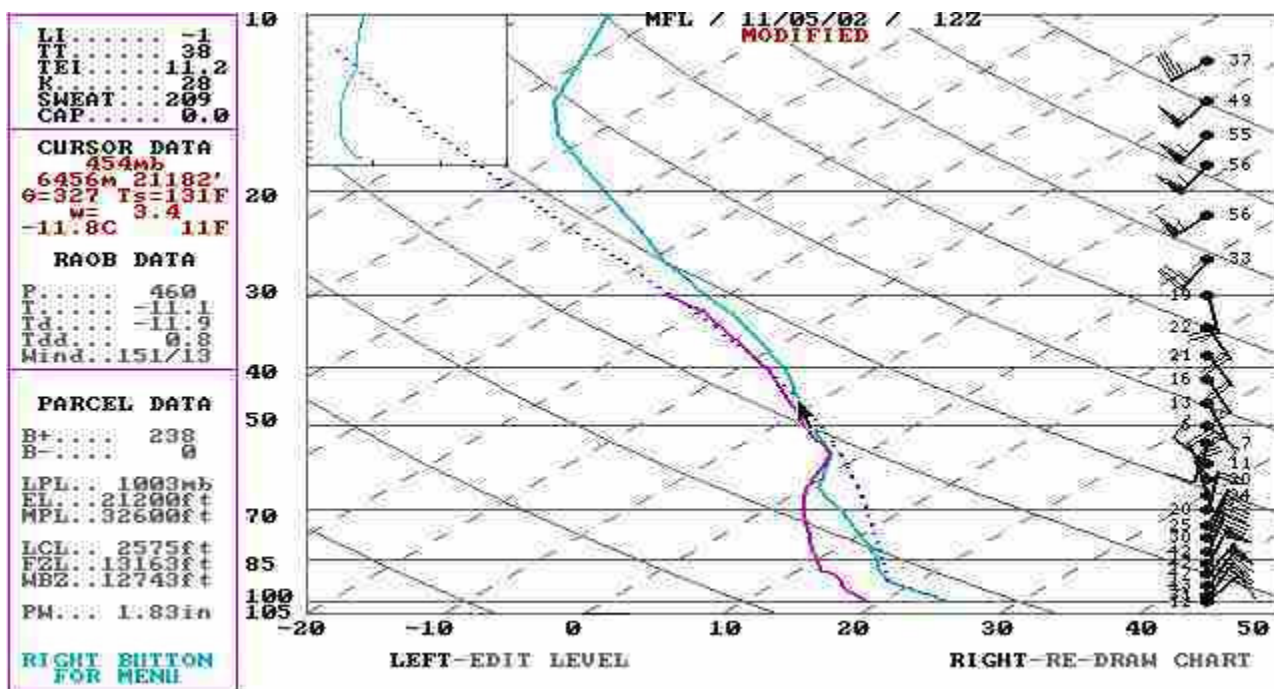
Fig. 15 Click the lightning symbol for a time lapse KAMX WSR-88D Reflectivity loop showing the storms responsible for producing the tornado at Belle Glade hugging the east coast of Lake Okeechobee. Time lapse from 1310 EST to 1424 EST on November 5, 2001.

A time lapse ([Fig. 15](#)) of the reflectivity from the KAMX WSR-88D shows the convection hugging the east coast of Lake Okeechobee. A mesoscale baroclinic boundary associated with a lake breeze could be an additional source of vorticity for the storm, and (speculating even further) could have been the difference as to whether or not the storm

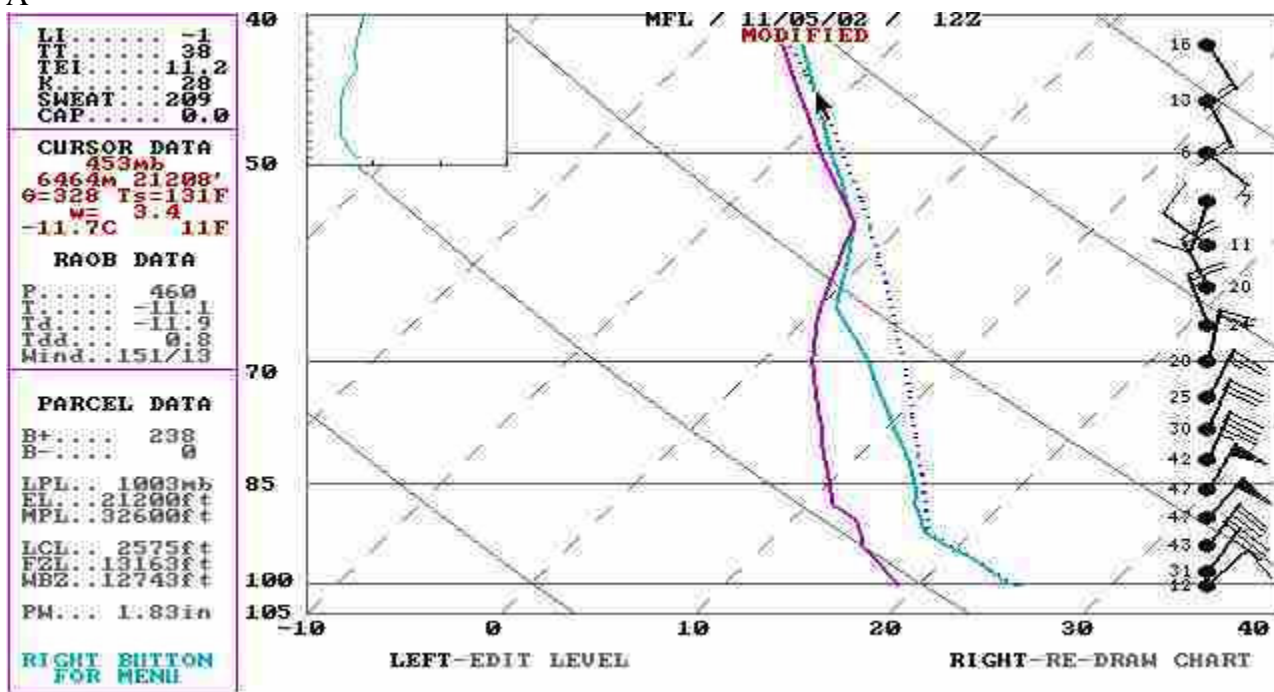
would produce a tornado. This is analogous to mid latitude thunderstorms interacting with an old outflow or warm frontal boundary resulting in the intensification of low-level mesocyclogenesis and subsequent tornado formation ([Markowski et al., 1998](#)). [Collins et al. \(2000\)](#) showed rapid storm development and subsequent mesocyclogenesis near the intersection of a quasi-stationary frontal boundary and an old outflow boundary. A tornado formed near this intersection. In our case, the storm interacting with the lake breeze mesoscale boundary is analogous to observations shown by [Markowski et al. \(1998\)](#) where the storm's updraft taps the local vorticity associated with the low level boundary. Admittedly, there is no available hard evidence of a lake breeze this day.

b. Upper air data

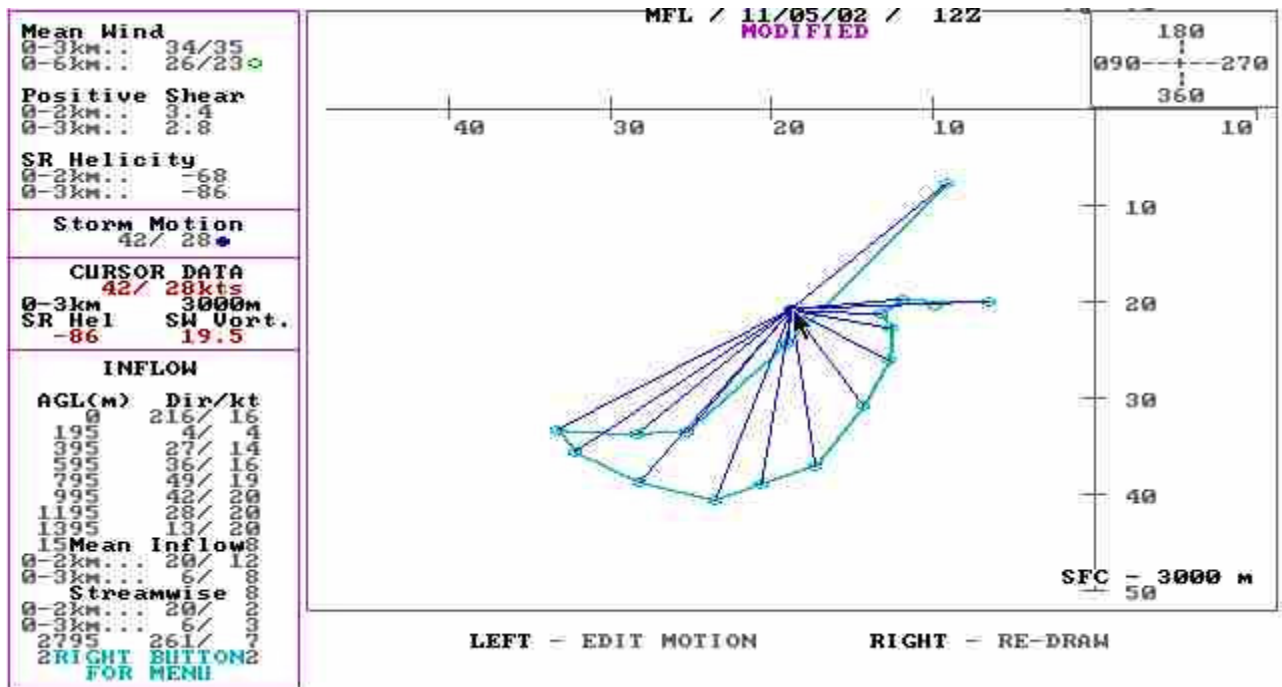
The nearest rawinsonde locations to Belle Glade are the NWS WFO Miami site in west Miami and the Patrick Air Force Base site near Melbourne. The Miami site is about 112 km south of Belle Glade, and Patrick Air Force Base is about 209 km north, so the Miami site is therefore used as possibly more representative of the atmosphere near Belle Glade. The wind profile at Miami is immediately characterized by slightly *backing* winds and very strong speed shear (36 knots in the lowest 1 km) ([Fig.4A, B, C](#)). The instability is small, with estimated most unstable surface based convective available potential energy (CAPE) around 240 J/kg with an estimated maximum temperature of 77 degrees and a dewpoint of 66 degrees F. The equilibrium level would therefore be only around 21,000 feet on this sounding! However, the instability is much larger at Patrick Air Force Base, with estimated CAPE near 1000 J/kg and an equilibrium level near 30,000 feet ([Fig. 4D](#)). This small instability and large shear is somewhat similar to what McCaul found in the right rear quadrant ([McCaul, 1991](#)). For a location in the right rear quadrant (storm relative) about 200 km away at an azimuth of 240 degrees, McCaul found a typical CAPE would be somewhat less than 400 J/kg and the Bulk Richardson Number (BRN) shear (measured over 6 km) would be around $6 \text{ m}^2\text{s}^{-2}$. The BRN shear for the Miami sounding was $8 \text{ m}^2\text{s}^{-2}$ and for Patrick it was $6 \text{ m}^2\text{s}^{-2}$, but since most of the shear was confined to the lowest 1 km, a measurement over 6 km may not be appropriate. Because of the distance between Belle Glade and the Miami upper air site, however, it's possible that while the speed shear is representative, the backing winds may not be, at the time of the tornado.



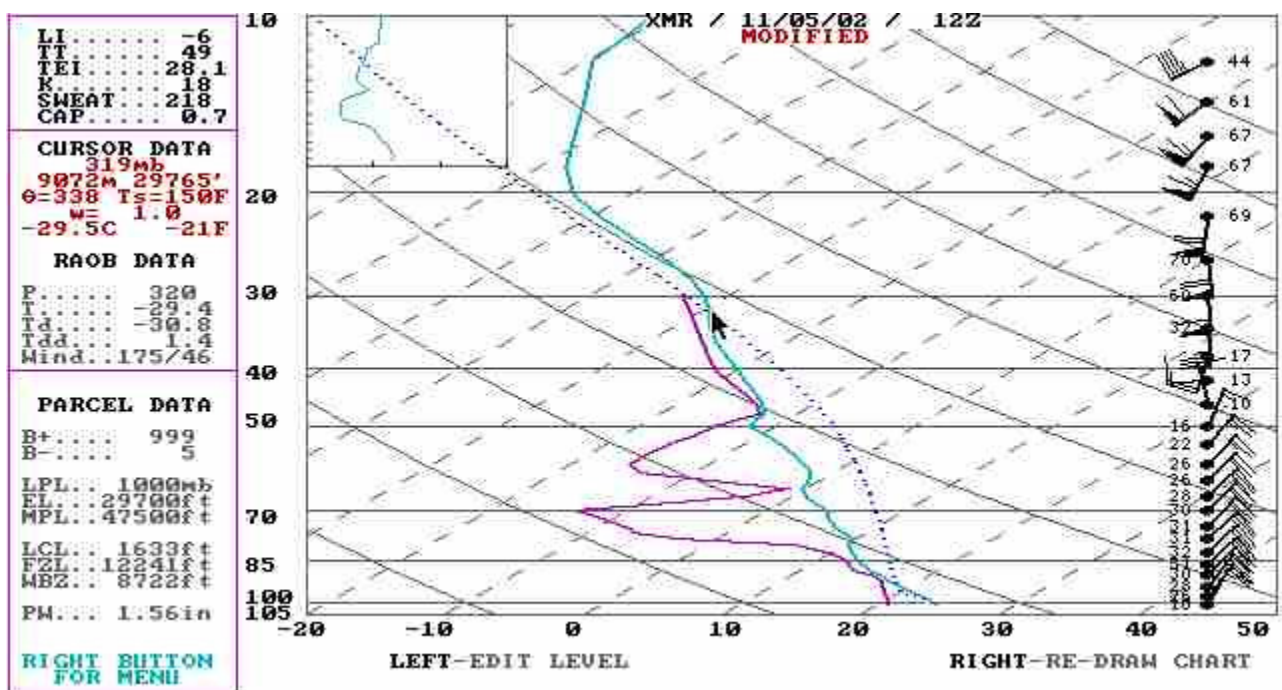
A



B



C



D

Fig. 4 (A, B, C, D) A - 0700 EST sounding at Miami, B - close-up of surface to 400 mb of sounding at Miami, C - Hodograph at Miami for surface to 3 km, D - 0700 EST sounding at Patrick AFB.

A VAD wind profile time series ([Fig. 5](#)) from the KAMX WSR-88D for the time of the tornado may also help to see what the wind profile evolution was like. Immediately one can see that the winds at Miami were still backing at the time of the tornado, but that the shear did not appear to be as strong in the lowest 1 km (surface wind at Miami International Airport at 1 PM EST was north at 10 kt gusting to 15 kt increasing to approximately 20 kt at 1 km). Surface heating contributing to diurnal mixing of the boundary layer probably contributed to a more uniform wind profile by the time of the tornado.

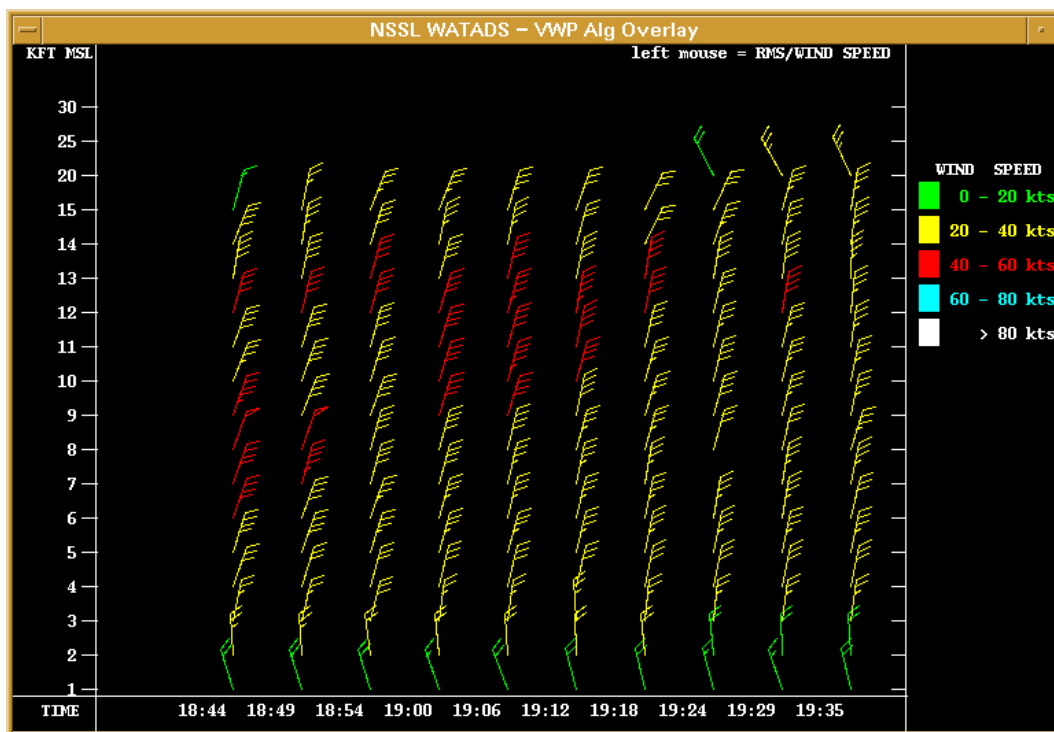


Fig. 5 - VAD wind profile from the KAMX WSR-88D Doppler Radar around the time of the Belle Glade tornado (times are in UTC in the figure...1906 UTC = 1406 EST).

3. Description of the event

The tornado apparently moved into the downtown area of Belle Glade around 1400 EST. Eyewitness accounts from the *Palm Beach Post* newspaper follow:

BELLE GLADE -- A humdrum senior citizens' quilting session turned into a melee Monday afternoon when a tornado ripped through the western Palm Beach County governmental complex, shattering windows and snapping palm trees like matchsticks.

Tom Werner, manager of the western county senior center, was supervising a six member quilting class about 2 p.m. as a nasty storm raged outside. The rain was coming down in sheets, obliterating much of the view out the window, but something caught his eye. "I looked outside and saw everything swirling around, trees flipping over," he said. "I hit the floor and yelled, 'Tornado!,' and everyone else ran into the men's room. One lady said there was a man in there, but she didn't care." The tornado came from the north, cutting a swath through the sugarcane field across State Road 80, knocking over trees and shattering car windows in the government complex parking lot. It knocked down a few ceiling tiles and blew out windows in the courthouse, property appraiser's office and senior center.

In the nearby sugarcane fields, stalks lay flattened by the strong winds. At about 5 p.m., wind damaged a car in the parking lot of Pahokee Elementary School, but most of the damage appeared to be limited to the complex. No one was injured. ... Dena Pittman, a property appraiser, was working at her desk when she looked out the window and saw a stop sign in the parking lot bend in half. "I said, 'Oh my God, that's a tornado,' and crawled under my desk," Pittman said. She and co-worker Cindy Reese huddled there with another employee as the storm whistled and roared like a freight train outside. When they went outside, Reese saw her car covered by a fallen tree. Luckily the tree hit a picnic table first and did little else besides coat the Pontiac Grand Am with dirt and leaves. "It was scary," Pittman said. "You should have seen us -- I was in tears. We were all just shaking."

Deputy Jimmy Pickell was pulling his squad car into the sheriff's office substation there when he saw the tornado and reported it to dispatchers at 2:07 p.m., dispatcher Artisha Williams said. Cpl. Danny O'Neal walked inside about the same time and said winds had burst a window in his squad car, Williams said. The Glades native had never experienced a tornado. "It was blowing up against the building, and we could actually feel the building shake," Williams said. "I've never felt something like that before. It was scary, but nobody's hurt at all. It was over really quick."

The NWS Weather Forecast Office (WFO) in Miami did not issue a warning for the tornado. The fact that South Florida was in a traditionally unfavorable location for hurricane environment tornadoes and the apparent weakness of the convection probably discouraged forecasters from issuing a tornado warning.

4. WSR-88D Radar

The NWS WSR-88D Miami (KAMX) location is in south Miami-Dade County, about 120 km south of Belle Glade. This is the closest NWS Doppler radar to Belle Glade, since Melbourne's radar (KMLB) is about 160 km north and Tampa Bay's radar (KTBW) is about 200 km northwest. Because of this distance, the center of the radar beam is about 6,000 feet above ground level (agl) over northwest Palm Beach County. This, of course, inhibits the ability to detect small tornadoes, because much of the evolution of small,

weak tornadoes occurs below the radar beam. Also, as discussed in Spratt et al. 1997, great distances between the radar and the storm result in sampling problems that limit the usefulness of the radar. Even so, the archived data from the KAMX radar does contain important clues that possibly could be used in a similar situation in the future to issue accurate and timely warnings.

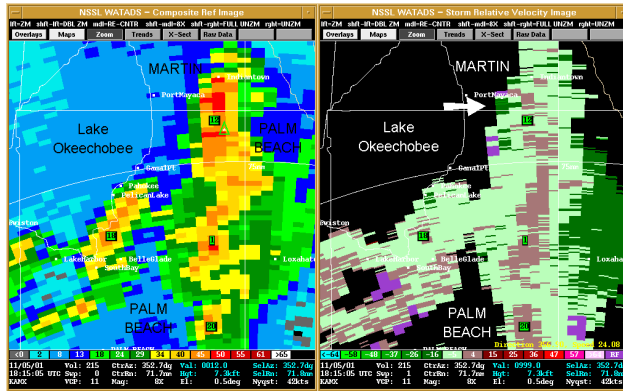


Fig. 6 (A, B) KAMX WSR-88D Composite Reflectivity (A) and Storm Relative Velocity (B), 1315 EST, white arrow points to developing circulation in all storm relative velocity products.

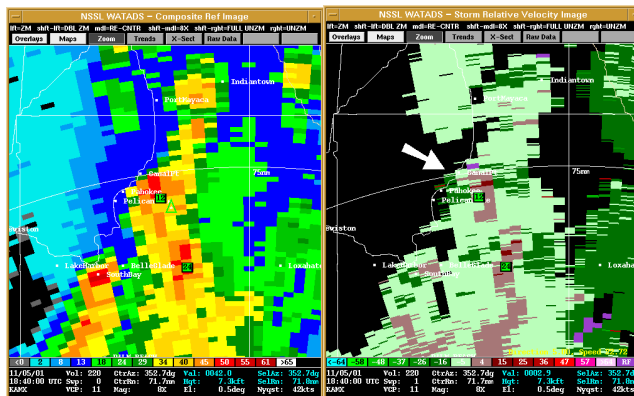


Fig. 7 (A, B) KAMX WSR-88D Composite Reflectivity (A) and Storm Relative Velocity (B), 1340 EST

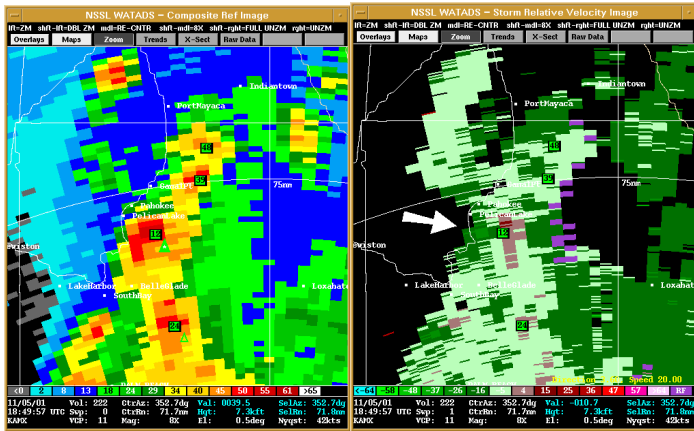


Fig. 8 (A, B) KAMX WSR-88D Composite Reflectivity (A) and Storm Relative Velocity (B), 1349 EST

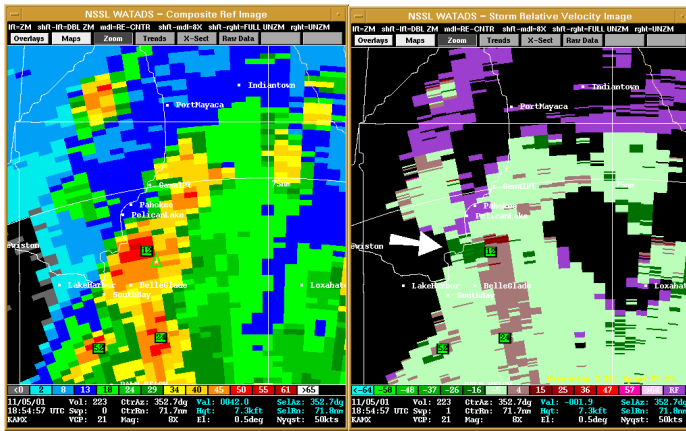


Fig. 9 (A, B) KAMX WSR-88D Composite Reflectivity (A) and Storm Relative Velocity (B), 1354 EST

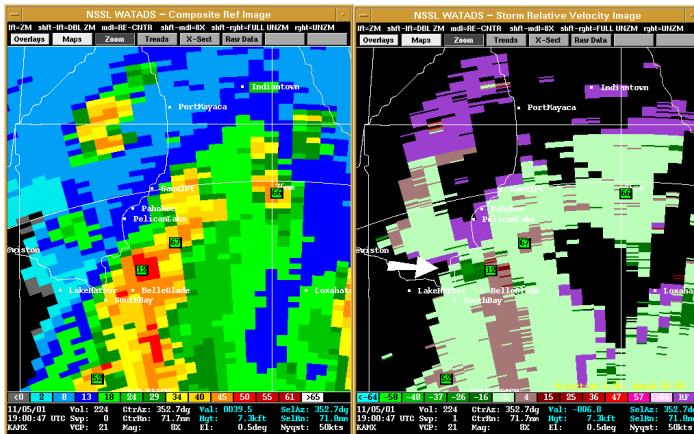


Fig. 10 (A, B) KAMX WSR-88D Composite Reflectivity (A) and Storm Relative Velocity (B), 1400 EST

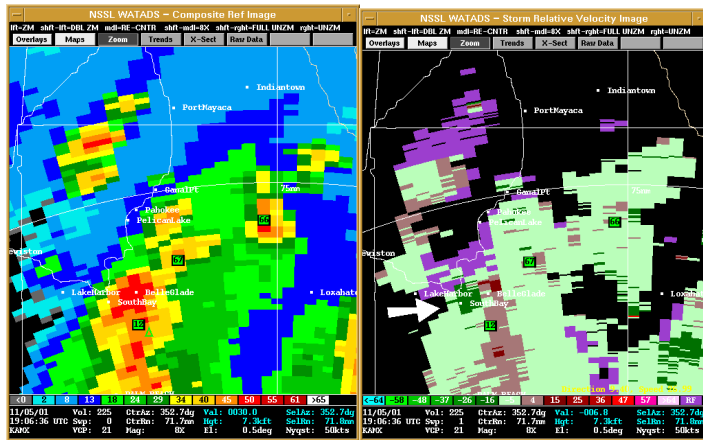


Fig. 11 (A, B) KAMX WSR-88D Composite Reflectivity (A) and Storm Relative Velocity (B), 1406 EST

The first hint of weak rotation with the band of heavy showers occurring from western Martin County east of Port Mayaca south into central Palm Beach County was evident on the storm relative velocity (SRM) WSR-88D product at 1315 EST ([Fig. 6B](#)). Inbound velocity maximum of 23.3 knots was separated by outbound velocity maximum of 4.9 knots resulting in a rotation velocity (V_r) of approximately 14 knots. The overall mesocyclone core diameter was about 3 km while the circulation was sampled at a height of about 8,900 feet agl. The circulation was located within reflectivities of 45 to 50 dBz. By 1349 EST, the storm had moved south-southwest with the general flow around the hurricane (the storm motion used in the SRM product was from 347 degrees at about 25 knots) and was located just southeast of Pahokee, a town in northwest Palm Beach County on Lake Okeechobee ([Fig. 8A](#)). At 1349 EST, the V_r had increased to 18.9 knots near 7,500 feet agl while the overall core diameter remained 3 km ([Fig. 8B](#)). Maximum reflectivities in the vicinity of the core diameter increased to 56 dBz. A low level rotational velocity near 25 knots has occasionally been observed by the author in both Mississippi and South Florida with weak tornadoes.

At 1354 EST, the storm was about halfway between Pahokee and Belle Glade, which are about 16 km apart ([Fig. 9A](#)). The V_r had increased to 22.4 knots at about 7,000 feet agl ([Fig. 9B](#)). The circulation's core diameter remained at 3 km at this elevation. apart at these mid levels, and the horizontal shear reached a maximum at 0.006 sec^{-1} . At 1400 EST, the V_r slightly dropped to 21.9 knots ([Fig. 10B](#)). By 1406 EST, the storm was moving into Belle Glade ([Fig. 11A](#)), and the magnitudes of V_r had further dropped to 20.9 knots ([Fig. 11B](#)). The core diameter did not change much and continued to remain at 3 km while the maximum reflectivities within the region of the circulation slightly dropped to 52 dBz at 6,500 feet agl. The tornado was observed by Palm Beach County Sheriff's Deputy Pickell at 1407 EST. Since we were not viewing the actual tornado from the Miami WSR-88D but rather the rotation in the mid levels of the storm, it is not unusual for the rotation to not show a 'gate-to-gate' couplet even when the tornado was reported on the ground. Even so, a cursory examination of the estimated V_r and the horizontal shear associated with the storm that spawned the tornado showed that both parameters were maximized about 12 minutes before the tornado was observed at Belle

Glade ([Table 2](#)). At the next highest elevation slice (1.5 degrees), V_r was not as large nor as easily identified with the convective cell that produced the tornado between 1330 and 1406 EST. However, it is interesting to note that V_r at 1.5 degrees was maximized at 1406 EST (the time the tornado occurred at Belle Glade) when it reached 10.2 knots.

Table 2

TIME (EST)	ROT VEL (KTS)	SHEAR (SEC ⁻¹)
1310	12.6	.004
1315	14.1	.004
1320	18.0	.005
1325	16.0	.005
1330	19.4	.005
1335	15.5	.004
1340	21.4	.006
1344	15.1	.004
1349	18.9	.005
1354	22.4	.006
1400	21.9	.006
1406	20.9	.006

Table 2 - Estimated rotational velocity (knots) and shear (sec⁻¹) for the mid level mesocyclone associated with the Belle Glade tornado.

Spectrum width products have been recommended by [Klazura and Imy \(1993\)](#), [Spratt et al. \(1997\)](#), and others as a way to locate mesocyclones and tornadoes at larger distances from the radar because it provides a measure of variability of the wind speed measurements due to turbulence and rotation. Tornadoes in the plains states have been associated with spectrum width values from 16 to 20 knots ([Herald and Drozd, 2001](#)). Examination of the spectrum width products in this case proved spectrum width products valuable once again, in that values of spectrum width greater than 16 knots were associated with the reported location of the tornado as it moved into Belle Glade. In fact, based on spectrum width products, the parent tornadic circulation may have formed east of Pahokee at 1345 EST ([Fig. 12A](#)), where spectrum widths from 20 to 22 knots were measured. Spectrum widths in the same 20 to 22 knot range were observed just south of Runyon at 1400 EST ([Fig. 12B](#)), but had dropped back to 16 to 18 knots over Belle Glade at 1406 EST ([Fig. 12C](#)). Based on additional spectrum width products, the tornado may

have been active still as far south as Okeelanta at 1415 EST (not shown). The rotation was evident on WSR-88D products as the storm moved into uninhabited Everglades areas of southwest Palm Beach County and northwest Broward County until 1500 EST (not shown).

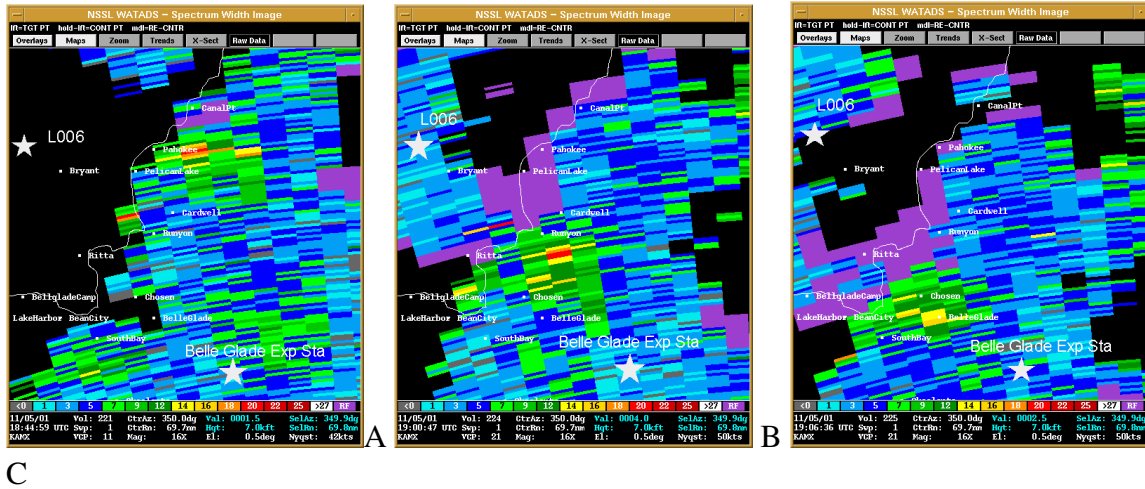


Fig. 12 (A, B, C) Spectrum Width Products from the KAMX WSR-88D radar at Miami for 1345 (A), 1400 (B), and 1406 (C) EST on November 5, 2001

5. Conclusions

This case is quite unusual in that two tornadoes have been observed and documented in the left rear quadrant (relative to storm motion) and more than 200 km away from the center of a tropical cyclone. This fact alone has implications for operational NWS offices because we now know that all areas affected by the circulation of a tropical cyclone must now be aware of the possibility of tornadoes with convection.

The rotational velocities were lower with this storm than would normally concern the warning forecaster for mid latitude rotating thunderstorms. However, the persistent rotation of this one particular storm with rotational velocities above 22 mph (20 knots) should be sufficient in the future to cause concern and at least the issuance of a severe thunderstorm warning. As outlined in papers mentioned previously, this case is further evidence for the following parameters for tornadoes in a tropical cyclone environment:

- presence of large amounts of vertical shear in the environmental hodograph or sounding, regardless of direction
 - persistent rotational velocities around or greater than 22 mph (20 knots)
 - horizontal shear values around 0.005 /sec
 - large (greater than 16 knots) spectrum width values
-

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