South Florida Seabreeze/Outflow Boundary Tornadoes

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ABSTRACT
In the late afternoon and evening of 7 August 2003 two tornadoes produced significant damage across parts of metropolitan Palm Beach County, Florida. These tornadoes were produced as a strengthening updraft encountered cyclonic shear along an enhanced east/west sea breeze convergence line meeting a southward moving outflow boundary from the north. The second tornado in particular produced substantial damage to a trailer park and industrial areas in both Palm Beach Gardens and Riviera Beach and crossed a major interstate highway (Interstate 95). Detection and warning of the tornadoes was a challenge for National Weather Service (NWS) forecasters at the Weather Forecast Office (WFO) in Miami due to the distance from both the Miami (KAMX) Weather Service Doppler radar (WSR-88D) and the Melbourne (KMLB) WSR-88D resulting in beam elevation and sampling issues.

1. Introduction
Florida ranks as the top state in number of tornadoes per 10,000 square miles from 1953 to 2003 (DOC, 2003). South Florida's peak months for tornadoes are June and August (Gregoria, 2005), reflecting both the convective "rainy" season from late May through mid October as well as a tropical cyclone influence which peaks around mid August through the end of September each year. Because convection in South Florida during rainy season is almost always related in some way to sea and/or lake breeze convergence, the development of tornadoes is also greatly affected by the boundaries created as the sea and lake breezes begin their diurnal migration.

While the scope of this study is not to address tornadogenesis theory, the paper by Collins et al., 2000 is an excellent source relating to South Florida tornado events. The
data shows non-supercell tornadoes can develop when pre-existing near-surface vertical vorticity is stretched, or when local near-surface horizontal streamwise vorticity is tilted and stretched, provided certain conditions are met. Sources of vorticity can be the sea breeze convergence boundary or a thunderstorm outflow boundary, both common events in South Florida during the convective season (Collins et al., 2000).

On 7 August 2003 beginning about 2110 UTC two tornadoes produced significant damage across parts of metropolitan Palm Beach County, Florida. The first tornado caused scattered F0 (Fujita, 1981) damage in southeast Jupiter along U.S. Highway 1 and in The Falls subdivision. The path length of this tornado was only about 1.5 miles and only about 70 yards wide (Fig. 1). Most of the damage was limited to trees and shrubbery (Fig. 2) although some screens and metal roofing of a shopping center along U.S. 1 (Fig. 3) were damaged.

The second tornado produced damage of F1 (nearly F2) magnitude in Palm Beach Gardens and Riviera Beach (PBG-RB) beginning around 2125 UTC and lasting for about 15 minutes over a path of 4 miles (Fig. 4). An exceptional picture of the second tornado (Fig. 5) was taken by Jeff Hooper of the South Florida Sun-Sentinel. Fortunately, no one was killed, and only 28 minor injuries were reported along with 58 (mostly mobile) homes destroyed, 21 homes sustained major damage, and 150 homes had minor damage (Table 1). In addition, several cars and a few tractor-trailers were moved or tipped over, light poles were snapped, and many roofs in the tornado's path were damaged or torn off. A tornado causing F1 damage produces winds of approximately 73 to 112 mph (Fujita, 1981). Pictures and first-hand surveys by National Weather Service (NWS) meteorologists suggest the worst damage was likely caused by winds in the higher part of that range, i.e., more than 100 mph.

<table>
<thead>
<tr>
<th>Table 1 - PBG-RB Tornado Damages</th>
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<tbody>
<tr>
<td>Deaths</td>
</tr>
<tr>
<td>Injuries</td>
</tr>
<tr>
<td>Homes destroyed</td>
</tr>
<tr>
<td>Homes with major damage</td>
</tr>
<tr>
<td>Homes with minor damage</td>
</tr>
</tbody>
</table>

The PBG-RB tornado first began causing damage near Northlake Boulevard and Military Trail and moved southeast to 'A Garden Walk' mobile home park where the worst damage occurred (Fig. 6). The tornado crossed I-95 just north of Blue Heron Boulevard. As it did so, it turned over a truck on I-95 and then moved in a more easterly direction into Riviera Beach just north of Blue Heron Boulevard. Along the way it severely damaged the roof of a Pepsi-Cola plant (Fig. 7). It continued through neighborhoods in Riviera Beach just north of Blue Heron Boulevard but the damage
swath was narrower and less severe until it lifted or dissipated near the intersections of Blue Heron Boulevard and Old Dixie Highway.

The tornadoes that struck Palm Beach County were unusual in that they occurred in August with low environmental shear but large instability. They were also associated with an atypical weather pattern in South Florida in which thunderstorms move into the metro Atlantic coast area in the afternoons (a more normal pattern with prevailing easterly flow is for showers and thunderstorms to occur along the metro Atlantic coast in the mornings and very early afternoon before moving across the Everglades areas toward the Gulf of Mexico coast in the afternoon and evening). The tornadoes occurred with thunderstorms building toward the south along a sea-breeze convergence line (locally known as the "zipper effect" because the development of thunderstorms toward the south along the sea breeze convergence line has the appearance of a zipper on satellite imagery time lapse loops) reinforced by thunderstorm outflow boundaries from earlier thunderstorms to the southwest and west of the metropolitan area. The tornadoes also occurred in a very low shear environment typical of South Florida in summer.

The tornadoes occurred at significant distances from both the Miami (KAMX) WSR-88D and the Melbourne (KMLB) WSR-88D. Even at such significant distances from data acquisition (RDA) sites at KAMX and KMLB, analysis in real time of rotational velocities, reflectivities, and vertically integrated liquid (VIL) from both sites provided key information to the fact that tornadoes were forming. In addition, realtime mesoscale analysis of surface data provided key information that local convergence was further enhanced by the interaction of the seabreeze with outflow boundaries of earlier thunderstorms north and west. The boundaries provided sufficient cyclonic shear which could then be stretched by strong updrafts associated with the southward propagating "zipper" convection.

2. Overview

a. Synoptic conditions

On 7 August 2003 a positively tilted long wave trough extended over the eastern half of North America, roughly from Quebec, Canada south southwest to Alabama, with a series of short waves rotating through the base of the trough (Fig. 8A). The subtropical ridge, a semi-permanent synoptic feature for South Florida in summer and early fall, extended across the central Bahamas and South Florida into the southeast Gulf of Mexico (Fig. 8B). The prevailing flow across South Florida was south to southwesterly as the axis of the surface ridge was across the extreme south tip of the peninsula including the Florida Keys. Upper flow across South Florida was light, generally less than 10 knots.

Moisture was plentiful with precipitable water around 2.3 inches on the Cape Canaveral 10 UTC sounding (Fig. 9) and 1.9 inches on the Miami 12 UTC sounding (Fig. 10). Average precipitable water for August in Miami is near 1.9 inches (Gregoria, 2005). Deep layer instability was present on both soundings, with afternoon temperatures forecast to rise well into the 90s, maximum surface based convective available potential
energy (SBCAPE) (Fig. 10) was as high as 5000 J/kg. With such light winds, calculated helicity values were very small for both upper air locations, and local circulations including thunderstorm outflow boundaries and sea breezes were expected. Convective inhibition was non-existent and lapse rates were close to adiabatic through the boundary layer.

b. Mesoscale conditions

Palm Beach County is uniquely situated in southeast Florida between Lake Okeechobee to the west and the Atlantic Ocean to the east (Fig. 11). This area is favorable for thunderstorm development on days with weak environmental flow as the lake breeze from Lake Okeechobee and the sea breeze from the Atlantic generate significant low level/surface convergence. In August, the temperature of Lake Okeechobee is normally around the mid 80s to 90 F while the temperature of the Atlantic Ocean is usually in the lower 80s. On 7 August 2003 air temperatures over land reached 96 F at Belle Glade, a town near the southeast coast of Lake Okeechobee, with mid 90s common over interior South Florida away from the coasts.

By 15 UTC on 7 August thunderstorms had developed along the Gulf coast of southwest Florida and had produced an outflow boundary extending north-northwest to south-southeast roughly from Arcadia to Immokalee to Everglades City (Fig. 12). By 17 UTC, the outflow boundary was halfway across the peninsula, bisecting Lake Okeechobee and extending south to Flamingo on the north coast of Florida Bay (Fig. 13). By 18 UTC, the primary area of severe activity was from Lake Okeechobee north to Cape Canaveral, and the outflow boundary had propagated as far east as Fort Pierce to Belle Glade to western Broward county to Flamingo.

At 1930 UTC the temperature reached 94 F at the University of Florida's Florida Agriculture Weather Network (FAWN) site at Belle Glade with a dewpoint reported at 80 F (Fig. 14). On satellite and radar, thunderstorms were developing in the vicinity of Belle Glade while a sea breeze convergence line was evident on visible satellite imagery extending from Jupiter to West Palm Beach to just west of Boca Raton in Palm Beach County (Fig. 15). By 20 UTC the old outflow boundary had moved well off the east central Florida Atlantic coast, but the south end of the old outflow boundary interacted with the sea breeze convergence line to start new thunderstorms over the Atlantic east of Stuart (time lapse Fig. 16). These thunderstorms propagated southward along the sea breeze convergence line, and by 21 UTC visible satellite imagery clearly showed the 'zipper' thunderstorm development effect (Fig. 17). At the same time, the thunderstorms over western Palm Beach County southeast of Belle Glade had produced another outflow boundary which was propagating east-northeast while the sea breeze convergence line was continuing to advance westward (Fig. 18). This helped enhance the updraft along the seabreeze convergence line.

Maximum observed temperature and dewpoints of the three identifiable air masses in Palm Beach County at 21 UTC were as follows:
<table>
<thead>
<tr>
<th>Air Mass</th>
<th>Temperature (F)</th>
<th>Dewpoint (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine layer air behind sea breeze convergence line</td>
<td>85</td>
<td>75</td>
</tr>
<tr>
<td>(Lake Worth C-MAN LKWF1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land area air before sea breeze and outflow boundaries</td>
<td>94</td>
<td>80</td>
</tr>
<tr>
<td>(Belle Glade FAWN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thunderstorm cooled air behind outflow boundary (Belle Glade FAWN)</td>
<td>83</td>
<td>79</td>
</tr>
</tbody>
</table>

c. Vorticity Calculations

At 21 UTC, the Lake Worth (LKWF1) Coastal Marine Automated Network (CMAN) station was reporting sustained south to southeast winds of 15 to 20 knots (8 to 10 m/s), which can be considered representative of the sea breeze. At 22 UTC, the Palm Beach International Airport (PBI) Automated Surface Observing System (ASOS) station reported northeast winds of 10 knots (5 m/s), which was after the converging boundaries had moved through the site. Assuming a 40 to 45 degree angle between the sea breeze wind and the convergence boundaries and assuming an approximate boundary width of 1 to 2 km (from the WSR-88D lowest level 8bit reflectivity data), the pre-existing local vertical vorticity across the boundary can be estimated as follows (using winds in m/s):

\[
\zeta = \frac{7 \text{ m/s} - (-5 \text{ m/s})}{1000 \text{ m}} = 0.012 \text{s}^{-1} \text{ or } \zeta = \frac{7 \text{ m/s} - (-5 \text{ m/s})}{2000 \text{ m}} = 0.006 \text{s}^{-1}
\]

(1)

In the presence of (1) a strong updraft, (2) a long residence time of the convection along the boundary that represents the source of the vorticity, (3) no convective inhibition (CIN), and (4) steep lapse rates from the surface to the level of free convection (LFC) (Fig. 9), this estimation of vertical vorticity should be sufficient for tornadogenesis (Weisman and Klemp, 1982, 1984).

Given the weak environmental shear, an additional source of vorticity (horizontal in this case) could have been the buoyancy gradient across the boundaries (Weisman and Klemp, 1982, 1984). However, the convergent boundaries generated by thunderstorm outflows and the sea breeze both have a cooling effect along their path. In fact, available observations do not support significant thermodynamic differences across these boundaries.
To summarize, very low shear and weak environmental flow combined with abundant low level moisture and thermodynamic instability to produce severe convection in South Florida with numerous storm scale effects (including sea breezes, lake breezes, and thunderstorm outflow boundaries). An outflow boundary from earlier midday storms across central Florida interacted with a sea breeze convergence line to produce a ‘zipper effect’ of thunderstorm development offshore Martin County and northeast Palm Beach County. Thunderstorms that developed along the lake breeze convergence line near Belle Glade produced another outflow boundary that propagated eastward, ultimately enhancing the convergence along the sea breeze convergence line in northeast Palm Beach County and promoting the 'zipper effect'. The combination of these factors ultimately led to tornadogenesis by stretching pre-existing vertical vorticity from colliding boundaries.

3. Analysis of Radar Data

a. Radar Characteristics and Beam Geometry

Palm Beach County is within the coverage areas of both the KAMX and KMLB WSR-88Ds. However, because of the distance (Palm Beach Gardens is about 75 statute miles from KAMX and about 83 statute miles from KMLB), storms occurring over the northern half of Palm Beach County are sampled with a KAMX radar beam width greater than 7000 feet and more than 6400 feet above the surface. From KMLB, the radar beam width is more than 8700 feet and more than 8900 feet above the surface over northern Palm Beach County. Thus, warning forecasters at Miami can only observe broad rotational features of thunderstorm associated mid-level mesocyclones over northern Palm Beach County and must use spotter reports and surface observations in real time to provide accurate and timely warnings. Because of the beam elevation and width at such distances, radar observation of the actual tornado itself or any other low level thunderstorm feature is impossible. Thus, this case is a prime example of the problems faced by operational WFO warning forecasters at long ranges from WSR-88D RDA sites.

b. Radar Product Analysis

However, radar velocity products (created using high resolution Level II archive data and WSR-88D Algorithm Testing and Display Software (WATADS)) clearly showed a mid-level mesocyclone and reflectivity products (including Vertically Integrated Liquid or VIL) clearly showed a high probability of large hail. Figures 19 and 20 show the 0.5 and 1.5 degree elevation angle rotational velocities from KAMX and KMLB and times associated with the tornadic thunderstorm as well as approximate times of tornado touchdowns indicated by the tornado symbols. Note especially the two relative peaks in midlevel rotational velocity immediately before the first report of each tornado, and the subsequent drop in rotational velocity thereafter. The implied tornadogenesis threshold value for this single case could be estimated around 25 knots.
The velocity data is impressive not only for the relatively high rotational velocity values (Fig. 21A) but also the depth of the rotation. A velocity cross section from KMLB at the time of the tornado (Fig. 21B, 2129 UTC) shows a circulation extending at least through 20,000 feet and probably more (radar beam height prevents determination at low levels). Thus the thunderstorm responsible for the tornado displayed classic severe weather signatures of rotational velocity in excess of 25 knots, a deep circulation indicating a mesocyclone extending through at least 20,000 feet of the atmosphere, high VILs indicative of severe size hail, and maximum reflectivities at heights far exceeding the -20C level, indicative of severe size hail (0.75 inches/19 mm) and possibly severe level wind gusts (58 MPH or greater).

The first tornado possibly began as a waterspout, coming onshore in extreme northeast Palm Beach County but causing damage over land for only a short time (Fig. 1). The second, more damaging tornado path was initially south-southwest, following the best convergence and resulting convection between the sea breeze and the surging outflow boundaries from earlier convection north and west of Palm Beach County (Fig. 4). Ultimately, the outflow boundary surge from the west pushed the convergence line back to the east, and the second tornado path in the last stages paralleled that push, turning eastward across I-95 and into Riviera Beach.

The vertically integrated liquid (VIL) provided excellent indication of severe size hail (greater than 3/4 inch in diameter). Fig. 22 is a VIL product from the KMLB radar at 2119 UTC, clearly showing a maximum grid based VIL of 79 g/kg. With the freezing level near 15,000 feet and the height of the -20C near 27,000 feet, Fig. 23 is a reflectivity cross sections from 2109 UTC clearly showing the maximum reflectivity well above levels necessary for severe size hail (greater than 3/4 inch in diameter). Although not classifiable as a weak echo region, the suspension of such high reflectivity values above a gradient of reflectivity is an indication of the strength of the updraft associated with this severe thunderstorm.

4. Summary

It is unusual to have a significant non-tropical-cyclone-associated tornado in South Florida in August. However, in special circumstances like those on 7 August 2003, the combination of outflow boundaries, sea breeze convergence and high surface based instability can overcome the lack of sufficient shear, producing significant tornadoes. The PBG-RB tornado was unusually strong (on the high end of F1) with a long damage path. It occurred at the edge of radar coverage by the KAMX and KMLB radars where the center of the radar beam was 6400 and 8900 feet above the surface of the earth respectively. Thus, it was impossible to observe any low level features in making warning decisions for this tornado event.

WFO Miami meteorologists issued a Special Marine Warning at 2122 UTC until 2315 UTC for the thunderstorms that spawned the first tornado that tore through parts of
Jupiter and Juno Beach. NWS Skywarn spotters called in reports of a tornado as early as 2213 UTC 10 miles north of PGA Boulevard in Palm Beach County. The warning meteorologist was unsure of the report because the location provided was not near any current thunderstorm activity (the spotter provided a location near Interstate 95 rather than accurately estimating the position of the tornado several miles east of Interstate 95). WFO Miami issued a Tornado Warning at 2230 UTC. At 2235 UTC another Skywarn spotter reported tornado debris visible in Palm Beach Gardens at Interstate 95. At 2237 UTC the tornado was reported at Gardens Road and Blue Heron Boulevard, with damage to the Pepsi-cola plant roof. WFO Miami issued a Severe Weather Statement at 2244 UTC updating the Tornado Warning and providing the latest damage information. The tornado dissipated by 2255 UTC and WFO Miami issued a final Severe Weather Statement at 2305 UTC.

In spite of the distances involved from the NWS network of WSR-88D radars, there were signatures of severe weather in products from both KAMX and KMLB. Large VILs, elevated maximum reflectivities, and rotational velocities near 30 knots all were key indications of impending severe weather. Skywarn spotters played a critical role in providing information that tornadoes were forming, helping to fill the data void created by the distances involved.

5. References


6. Figures

Figure 1 - Location map of the Jupiter/Juno Beach tornado.

Figure 2 - Damage to screen on back of home from Jupiter tornado.
Figure 3 - Damage to roofing at Jupiter shopping center on U.S. Highway A1A.

Figure 4 - Location map of Palm Beach Gardens - Riviera Beach tornado.
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