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## **A Multi-Scale Analysis of the Atmospheric Conditions Associated with the Daytona Beach Tornado of Christmas Day 2006**

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### **ABSTRACT**

This case study describes a severe-storm event over Florida, Georgia, and South Carolina on 25 December 2006, with a particular focus on an F2 tornado that struck Daytona Beach, FL and caused over \$50 million in damages. The severe weather occurred over a 12-h period and was associated with a deep upper-level trough and surface front moving through the southeastern U.S. Morning soundings over Florida showed low to moderate CAPE and strong vertical wind shear, consistent with seasonal composite tornadic soundings for the region. A quasi-linear convective system moved onshore near Tampa during the midmorning hours, the northern half of which accelerated and produced bow echoes that resulted in two tornadoes and nontornadic wind damage over Pasco, Sumter, and Lake Counties between 1620 and 1725 UTC. This portion of the line then moved into Volusia County and spawned F2 tornadoes in Deland and Daytona Beach after 1800 UTC. Data from the Melbourne National Weather Service Forecast Office's Weather Surveillance Radar-1988D (WSR-88D), Daytona Beach International Airport (DAB) Automated Surface Observing System (ASOS), and DAB Low Level Wind Shear Alert System (LLWAS) were integrated to analyze conditions at the east end of the DAB runway 7L/25R complex, where the tornado first appeared. The LLWAS is normally used by air traffic control personnel for monitoring airport wind-shear conditions. The 10-s LLWAS wind data filled critical temporal and spatial gaps in the WSR-88D and ASOS data, and captured evidence of strong winds and cyclonic curvature nearly coincident with the locations of the radar-identified velocity couplet and tornado itself.

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### **1. Introduction**

During the early afternoon of 25 December 2006, an F2 tornado struck Daytona Beach, FL, causing over \$50 million in damage to the campus of Embry-Riddle Aeronautical University, nearby homes, and businesses. The tornado was one of six reported across Florida and Georgia, along with 14 reports of severe-thunderstorm wind damage across Florida, Georgia, and South Carolina, all of which were associated with a deep upper-level trough and surface front over the southeastern U.S. The severe-storm reports spanned about 12 h, from the first reports in Ocilla and Fitzgerald, GA, around 0700 UTC (0200 Eastern Standard Time), to the last reports in Daytona Beach, and

Center Park, FL, shortly before 1900 UTC. Figure 1 shows a map of the *Storm Data* reports from 25 December (NCDC 2006).

#### *a. Motivation for the study*

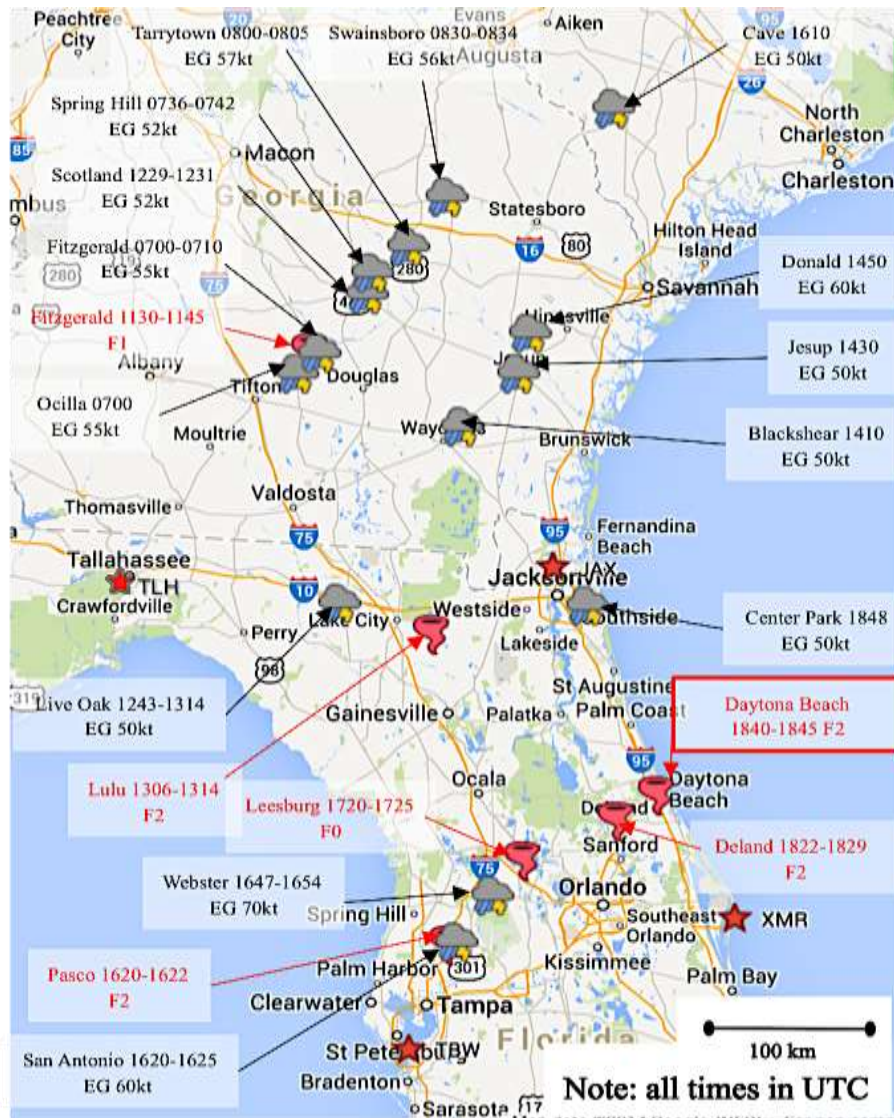
Beyond the personal motivation for this study (a tornado strikes the campus where the author is employed), there are several important reasons for examining this case in detail. First, while the tornado climatology for the Florida peninsula<sup>1</sup> shows that significant ( $\geq$ F/EF2) tornadoes are

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<sup>1</sup> Hagemeyer (1997) and Hagemeyer et al. (2010) define the Florida peninsula as the geographic region south of 30° North Latitude; any references to the Florida peninsula in this paper use that convention.



**Figure 1:** NCEI (formerly known as NCDC) *Storm Data* reports for 25 December 2006. Initial tornado locations, times, and ratings are indicated by red tornado icons with labels, while severe thunderstorm locations, times, and estimated wind gusts (in kt) are shown by thunderstorm icons with labels. Locations of the four rawinsonde sites used in the sounding analysis (Tallahassee, TLH; Jacksonville, JAX; Tampa Bay, TBW; and Cape Canaveral, XMR) are shown by red stars with their three-letter identifiers. Map created using Google Maps™ Engine.

relatively infrequent, they have tremendous potential for damage and loss of life when they do occur. Hagemeyer et al. (2010) examined 2105 documented tornadoes from the National Centers for Environmental Prediction's (NCEP) Storm Prediction Center (SPC) 1950–2008 database, and found that while only 11.5% (242) of peninsular tornadoes were significant, they were responsible for 97% of fatalities. These results are consistent with the SPC

Annual U.S. killer tornado statistics data (<http://www.spc.noaa.gov/climo/torn/fatalmap.php>), which show that from 1991 through 2015, 92.1% of Florida's fatalities were reported with F/EF2 and F/EF3 tornadoes. The Florida fatality figure is in contrast to 36.3% from significant tornadoes for the rest of the country during the same period. Nationally, 57.9% of fatalities were reported due to F/EF4 and F/EF5 tornadoes during this period, while Florida had zero occurrences of such tornadoes.

Of the 242 significant tornadoes documented by Hagemeyer et al. (2010), 145 occurred when Florida was in the dry season, which they defined as the period from November through April. The dry season on the Florida peninsula begins when the sea-land breeze circulation ceases to be the dominant control on the local climate. It is typically characterized by an increased frequency of frontal passages associated with midlatitude cyclones that form and track over the Gulf of Mexico and the southeastern U.S. The dry season accounts for nearly 81% of deaths from significant tornadoes in Florida. Figure 2 shows the tracks of 49 dry-season significant tornadoes in the coverage area of the Melbourne National Weather Service Forecast Office (MLB NWSFO) Weather

Surveillance Radar-1988D (WSR-88D) from 1980 through 2006. These dry-season tornadoes comprised nearly three quarters of all significant tornadoes recorded.

There are several important demographic factors pertinent to the Florida dry season that are likely related to the casualty statistics reported above. First, Florida has a large population of temporary residents during the winter months; Smith and House (2007) estimated their population at over 1.2 million during the winter of 2005. A large fraction of these temporary residents are elderly “snowbirds”, the majority of whom come to Florida from the midwestern or northeastern U.S. for the warm winters (Smith and House 2006).



**Figure 2:** Tracks (red) of 49 dry-season significant tornadoes for the period 1980–2006 within the MLB WSR-88D’s 230-km (124-nm) range circle, obtained from the SPC online severe-weather climatology (Hart 2005).



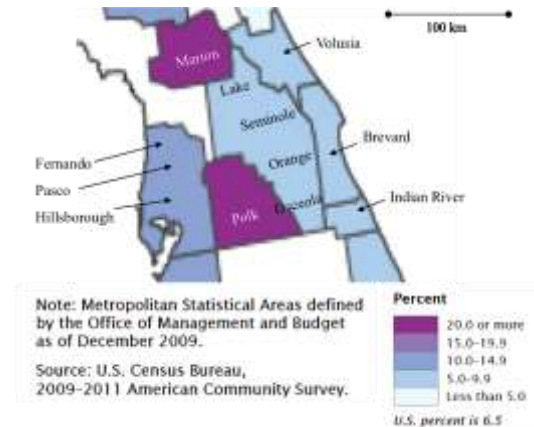
This unique demographic factor can add to the risk of unusually lethal outcomes from winter-season severe-storm events not in the “more typical” times of year such as spring. This fact became clear shortly after the 25 December 2006 event, when two EF3 tornadoes struck Lake, Sumter, and Volusia Counties from 0810 through 0855 UTC on 2 February 2007. Known as the Groundhog Day tornadoes, this event had 21 fatalities and is the second deadliest tornado event in Florida’s recorded history (NWS 2007; Simmons and Sutter 2007).

Second, 9.2% of Florida’s housing units are mobile homes, nearly 3% above the national average, according to the latest available figures (2014) from the U.S. Census Bureau (<http://factfinder.census.gov>). Figure 3 shows a map of mobile homes in central Florida as a percentage of all housing units. Five counties in the region (Fernando, Pasco, Hillsborough, Marion, and Polk) are above the state average, while the remainder is close to the state average. All 21 fatalities in the Groundhog Day event occurred in mobile homes within Lake County (Simmons and Sutter 2007). Hagemeyer et al. (2010) offers more detailed discussion regarding manufactured housing and tornado vulnerability in Florida.

Although the tornadoes in the 25 December 2006 event occurred in the morning and early afternoon, from 1950 through 2006, nearly half of Florida’s tornado deaths occurred between 2200 and 0600 local time, which is the highest rate in the country (Simmons and Sutter 2007). This is important because a considerable number of dry-season tornadoes in Florida occur during the evening and overnight hours (Hagemeyer et al. 2010).

Of the six tornadoes reported in the event under study, five were in Florida, and four of these were rated as F2. The Daytona Beach tornado caused no fatalities and only six injuries. However, the Embry-Riddle campus was empty due to the holiday. Lanicci (2016) estimates that had the tornado hit during regularly scheduled Monday afternoon classes at the 5000-student institution, there would have been between 400 and 500 faculty, students and staff in or near the path of the tornado due to its track right through the center of campus (Fig. 4). Additionally, as the tornado appeared at the east end of Daytona Beach International Airport’s (DAB) runway 7L/25R complex, Comair Flight 580, inbound to

DAB from New York’s LaGuardia Airport, was preparing for final approach onto the same runway. Due to a power outage in the DAB radar approach control facility caused by the thunderstorm, the aircrew lost contact with air traffic controllers and instead deviated to the south of its original track. The flight eventually was turned around and landed safely at 1906 UTC (Lanicci 2016). Indeed, this case had the potential to be much worse in terms of casualties.



**Figure 3:** Percentage of central Florida housing units that are mobile homes. Figure adapted from Mazur (2013).

#### *b. Previous severe-storm studies over central Florida*

There are not a lot of individual dry-season severe-storm case studies for this part of Florida, save for the 22–23 February 1998 tornado event, which was the deadliest in Florida’s recorded history. This event produced 62 individual reports of severe thunderstorm wind, hail, and tornado damage in 36 of Florida’s 67 counties, resulting in 42 fatalities, 263 injuries, and over \$100 million of property damage across the state (NWS 1998; NCDC 1998). Several investigators have studied this case. Wasula et al. (2007) examined the rapid development of tornado-producing supercells in the central portion of the peninsula after sunset, and the role that a diabatically induced surface front and mesolow may have played in their development and intensification. Hodanish et al. (1998) and Williams et al. (1999) documented the use of an experimental lightning detection system known as the Lightning Imaging Sensor Data Applications Display (LISDAD) in use at the MLB NWSFO to diagnose storm intensification. These LISDAD studies compared lightning flash

rates from the supercell that produced an F3 tornado in Kissimmee, FL, on 23 February 1998 with radar-derived quantities such as maximum reflectivity and storm rotational velocity ( $V_r$ ). The LISDAD was used to study other severe storm events in central Florida during the 1990s.

These studies examined flash rates in both dry- and wet-season thunderstorms in an attempt to document sudden increases (jumps) in flash rate preceding a storm's intensification to severe criteria (e.g., Table 1 in Williams et al. 1999).



**Figure 4:** Photograph of Embry-Riddle campus with locations of worst damage shown by markers numbered 1–5. Each location has an associated inset picture showing the damage. The ICI Center is located to the east of Spruance Hall (marked '5') and not included in the picture; however, the roof damage is shown by the picture marked '6' in upper right corner of figure.

A number of climatological studies have been conducted over the central Florida peninsula for the purpose of documenting favorable conditions for tornadic thunderstorms. Most notable among these are Hagemeyer and Schmocker (1991) and Hagemeyer (1997; hereafter H97). The former produced seasonal composite mean soundings, hodographs, cross sections, and diagnostic severe-storm parameters for tornadic environments in the dry and wet seasons. The latter built on this work by analyzing 1448 tornadoes over the Florida peninsula from 1950 through 1994 in order to define "a peninsular Florida tornado outbreak" and develop suitable outbreak climatology.

H97's definition of a peninsular Florida tornado outbreak is "the occurrence of four or more tornadoes in 4 h or less." Using this definition, he identified 35 outbreak cases and

categorized them as being associated with 1) extratropical cyclones (27 cases); 2) tropical storms or hurricanes (five cases); or 3) "hybrid cyclones having both tropical and extratropical characteristics" (three cases). As was done in Hagemeyer and Schmocker (1991), composite mean soundings and hodographs, and diagnostic parameters were computed for the three outbreak types. H97's composite mean soundings, computed using data from TBW, West Palm Beach (after 1977), Miami (prior to 1977), Key West, and XMR, were categorized as pre-outbreak (sounding before the start of the outbreak) or inflow-proximity (sounding within 2 h and 111 km of a tornado appearance). H97's criterion for inflow-proximity is consistent with that used in other proximity studies, as documented by Potvin et al. (2010). Additionally, H97 screened soundings that were not representative of the storm inflow

environment. Both Hagemeyer and Schmocker's (1991) and H97's composite diagnostic parameters characterized dry-season tornadic environments in this region as having high shear with relatively low CAPE. Soundings from the present case will be compared to several of H97's composite mean parameters in section 3.

### c. Study objectives

This study first seeks to investigate the atmospheric conditions over central Florida during the morning of 25 December and compare them with H97's climatology. Next, the evolution of the severe weather-producing squall line over central Florida during the morning and afternoon of 25 December is examined to determine if severe-storm signatures were discernable in sequences from the WSR-88D. Examination of the near-storm environment at the DAB complex at the time of the tornado's appearance is made using a blend of data from WSR-88D, DAB Automated Surface Observing System (ASOS), and DAB's Low Level Windshear Alert System (LLWAS; FAA 1989). The availability of high-resolution wind tower data from LLWAS provides a unique addition to the conventional data sources, as LLWAS are neither normally available to meteorologists nor archived. Last, a comparison is made of the atmospheric conditions associated with this event to those found in other cold-season severe-storm studies over the southeastern U.S. in order to put this event into a climatological perspective.

## 2. Data and methods

Data from the SPC mesoscale analysis archive ([http://www.spc.noaa.gov/exper/ma\\_archive/](http://www.spc.noaa.gov/exper/ma_archive/)) were used to construct composite analyses of low- and upper-level synoptic-scale features for 1200, 1500, and 1800 UTC on 25 December. The SPC analysis blends the most recent NCEP 40-km mesh Rapid Refresh (RAP) model forecast with surface observations and RAP analysis and forecast upper-air data. At the time of this case, the analysis/forecast model data came from the Rapid Update Cycle (Benjamin et al. 2004). Bothwell et al. (2002) provide details of the SPC analysis procedure. Additionally, sounding stability and wind shear parameters from the four Florida rawinsonde locations (TLH, JAX, TBW, and XMR, shown in Fig. 1) were compared to dry-season composite mean tornado sounding data from H97.

The evolution of the squall line that spawned the Daytona Beach tornado is examined through analysis of WSR-88D level-II base reflectivity and level-III storm-relative velocity (SRV) and mesocyclone detection algorithm (MDA; Stumpf et al. 1998) data obtained from the NCEI archive (<http://www.ncdc.noaa.gov/data-access/radar-data/nexrad-products>). The WSR-88D data, available in 4–5-min increments, were displayed and analyzed using Unidata's Integrated Data Viewer (IDV; <http://www.unidata.ucar.edu/software/idv>) and NCEI's Weather and Climate Toolkit (WCT; Ansari et al. 2013). The WSR-88D SRV graphics were analyzed manually to compute maximum outbound ( $V_{out-max}$ ) and minimum inbound ( $V_{in-min}$ ) velocities at the 0.5, 1.3, 2.4, and 3.1° elevation angles. This was done in order to determine the depth and width of any mesocirculations, and was used in combination with the output from the MDA to determine location and intensity of radar-indicated circulations.

To examine details of the squall line's passage over DAB itself, ASOS data in 1-min increments were obtained from NCEI for altimeter setting, wind direction, and wind speed. The ASOS data were examined for discernable wind shifts and pressure drops/jumps from 1800 to 1900 UTC. The ASOS data were compared to DAB LLWAS wind direction and speed data available in 10-s increments to obtain additional details of the squall line's passage through the DAB runway 7L/25R complex.

The DAB LLWAS network consists of nine wind towers strategically placed around the immediate vicinity of the airport runway complex in order to detect microburst and other hazardous wind-shear conditions. The tower elevations vary from 27.4 to 45.1 m, and the network covers an area about 7 km in the east–west direction by 5 km in the north–south direction. After the tornado, the FAA manually collected wind direction and speed data from the towers for 1830–1900 UTC and provided them to the author. The LLWAS winds were integrated with the WSR-88D SRV and MDA data, and with the ASOS altimeter and wind data to provide details of the low-level circulation as the squall line passed through DAB and spawned the tornado.

### 3. Atmospheric conditions over Florida during the morning of 25 December

#### a. Synoptic-scale analyses

Figure 5a shows the 1200 UTC NCEP Weather Prediction Center (WPC) surface analysis over the southeastern U.S. An occluding surface cyclone with a central pressure of 1000 hPa was located over northern Mississippi with a trailing cold front over the eastern Gulf of Mexico. From southern Georgia into the Florida peninsula, surface air temperatures and dewpoints ranged from 18–23°C (mid-to-upper 60s to lower 70s °F). These readings were 8–14°C (15–25°F) above normal for December (PRISM Climate Group, Oregon State University, <http://prism.oregonstate.edu>). The precipitation pattern in the WSR-88D mosaic (Fig. 5b) resembled a typical midlatitude “comma” type cyclone pattern, and the prefrontal squall line extending from the Big Bend of Florida, to the eastern Gulf of Mexico had the appearance of a quasilinear convective system (QLCS) as defined by Trapp et al. (2005).

Figure 6 shows composite analyses of low- and upper-level synoptic-scale features and accompanying Geostationary Operational Environmental Satellite (GOES) infrared (IR) imagery for 1200, 1500, and 1800 UTC. At 1200 UTC (Fig. 6a), the dark green shading over nearly the entire Florida peninsula and surrounding area indicates relatively high dewpoints at both the surface and 850 hPa, accompanied by a broad area of 21–23-m s<sup>-1</sup> (40–45-kt) winds from the south-southwest at 850 hPa. There was a deep upper-level trough centered over southern Texas; 500-hPa temperatures at both Del Rio and Corpus Christi were –26°C. A strong polar jet stream appeared at 500 and 300 hPa, with the core of strongest 500-hPa winds (>41 m s<sup>-1</sup>) extending from Mississippi and Alabama into the northern Gulf of Mexico. The GOES imagery at this time (Fig. 6b) displayed a V-shaped pattern of anvil cirrus over the Gulf of Mexico, suggesting storm-scale divergence.

The composite analyses of low- and upper-level synoptic-scale features for 1500 and 1800 UTC (Figs. 6c,e respectively) show that the low-level moist layer persisted over eastern Florida, while the upper-level jet stream strengthened over the Gulf Coast region during this time. By 1800 UTC, a 500-hPa jet maximum was observed from the Florida panhandle into Georgia (Fig. 6e). The strongest low-level winds

remained over the Florida peninsula and became slightly more southwesterly over the northern half by 1800 UTC, resulting in more unidirectional vertical wind profiles than at 1200 UTC. While unidirectional wind profiles may not be as favorable for rotating thunderstorms, it would support the continuation of the squall line over the peninsula for at least several more hours during the afternoon, along with the potential for damaging thunderstorm winds. The GOES imagery for this timeframe (Figs. 6d,f respectively) shows that while the anvil cirrus from the squall-line thunderstorms warmed between 1515 and 1815 UTC, several small cold-cloud tops remained over east-central Florida at 1815 UTC (arrows in Fig. 6f).

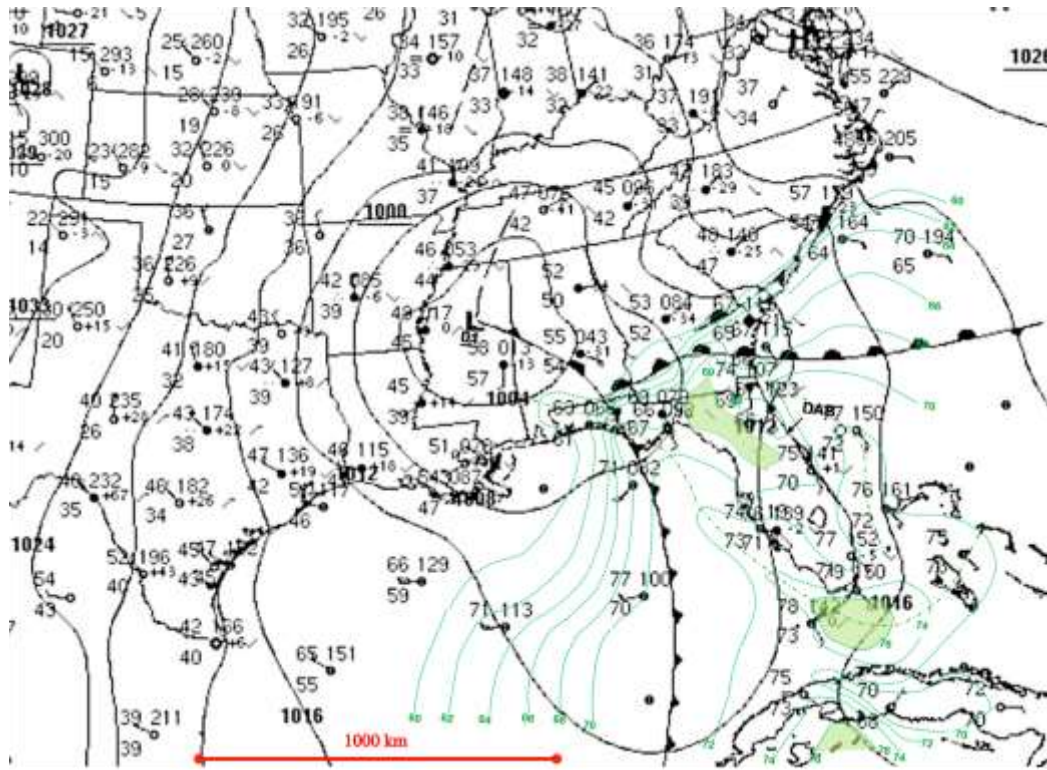
#### b. Analysis of soundings

Four 1200 UTC rawinsonde soundings bounded the Florida severe weather area of interest (locations in Fig. 1). The TLH and JAX soundings (Fig. 7a) were close to saturation through nearly the depth of the troposphere, while TBW and XMR (Fig. 7c) had identifiable mid- and upper-level dry layers, indicating the possibility of greater potential instability over this part of the peninsula, which could support thunderstorms with strong downdrafts (Duke and Rogash 1992).

Since H97’s climatology did not include TLH and JAX, any conclusions drawn from comparisons between these soundings and H97’s composite mean soundings are limited. An additional limitation of sounding comparisons comes from the inherent smoothing of features associated with development of composite mean soundings. Thus, the comparisons were made to determine whether the stability and wind-shear characteristics of this air mass were representative of known dry-season tornadic environments over this part of Florida.

Severe-storm stability parameters were derived from the 1200 UTC soundings in Figs. 7a and 7c, and compared to those from H97’s dry-season composite mean soundings, reproduced here as Figs. 7b and 7d. Using H97’s criteria, the TLH and JAX soundings were treated as inflow-proximity soundings, since they were taken within 2 h of the first severe-storm reports in Live Oak and Lulu (see Fig. 1), and were at the high end of his distance criterion. Since the TBW and XMR soundings preceded the first severe-storm reports in west-central Florida by more than 4 h, they were classified as pre-outbreak.





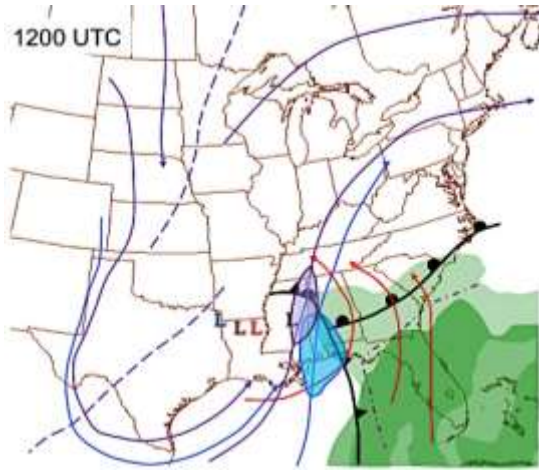
(a)



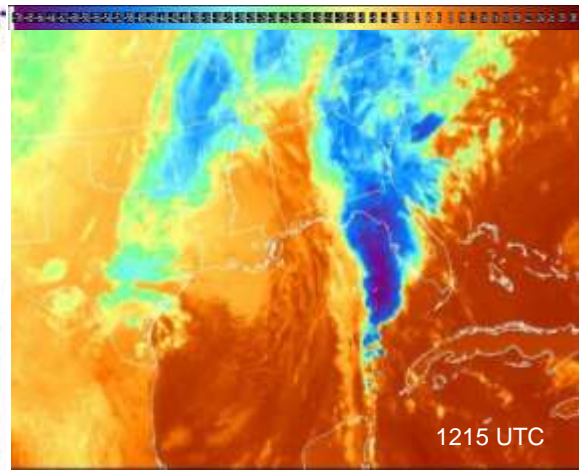
(b)

**Figure 5:** a) 1200 UTC surface analysis and manually analyzed dewpoints [green dashed lines, starting at 60°F (15.6°C), contoured every 2°F (1.1°C)]. Maximum dewpoint areas are shaded green, and green dot-dashed lines denote axes of high dewpoints (adapted from NCEP WPC archive, [http://www.wpc.ncep.noaa.gov/archives/web\\_pages/sfc/sfc\\_archive.php](http://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php)); b) 1200 UTC WSR-88D mosaic obtained from NCEI's Geographic Information System-based archive (<https://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=radar&theme=radar&display=nexrad>). Click image for enlargement.

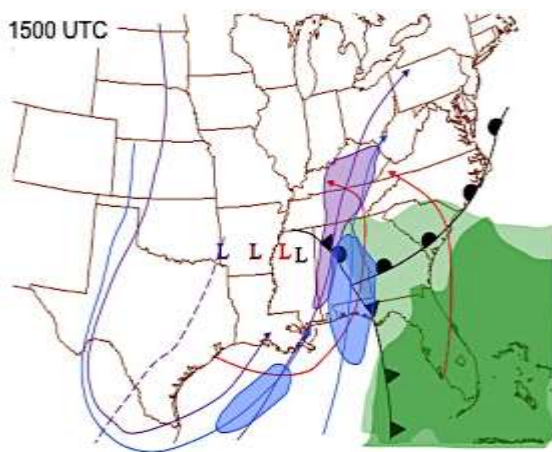




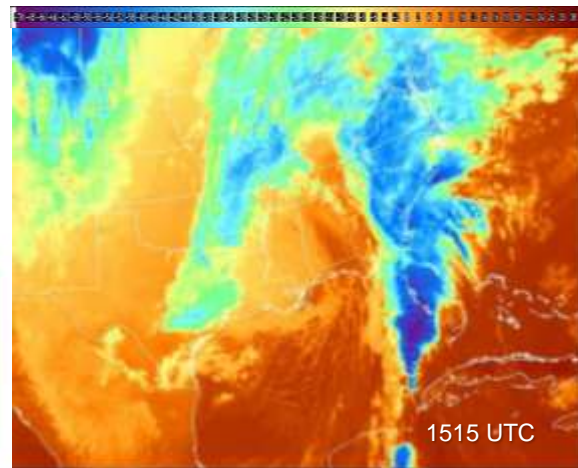
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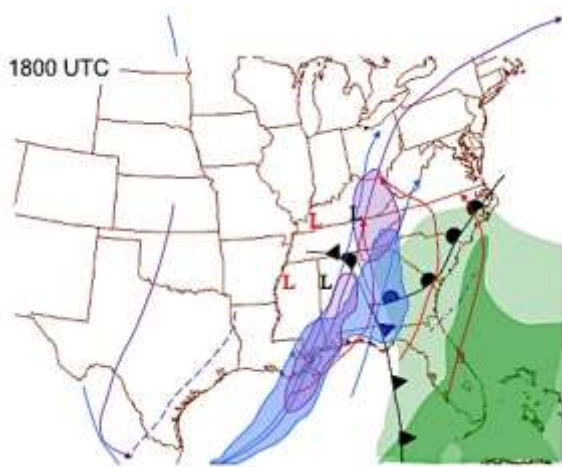
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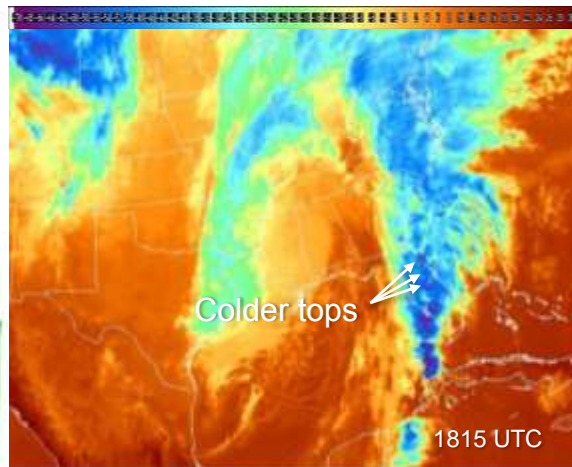
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(d)



(e)

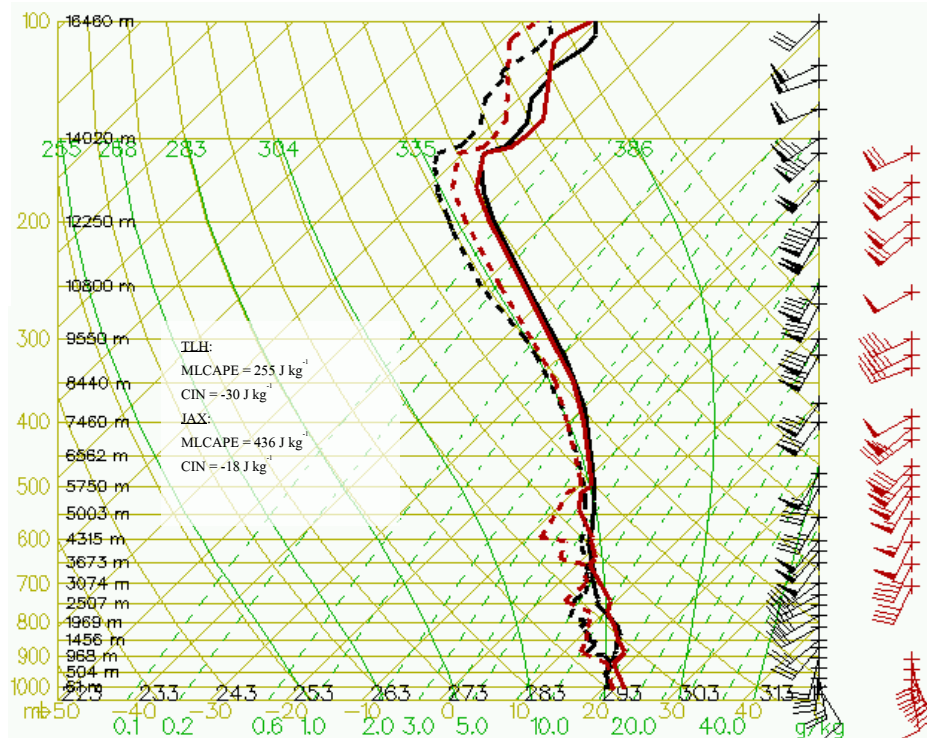


(f)

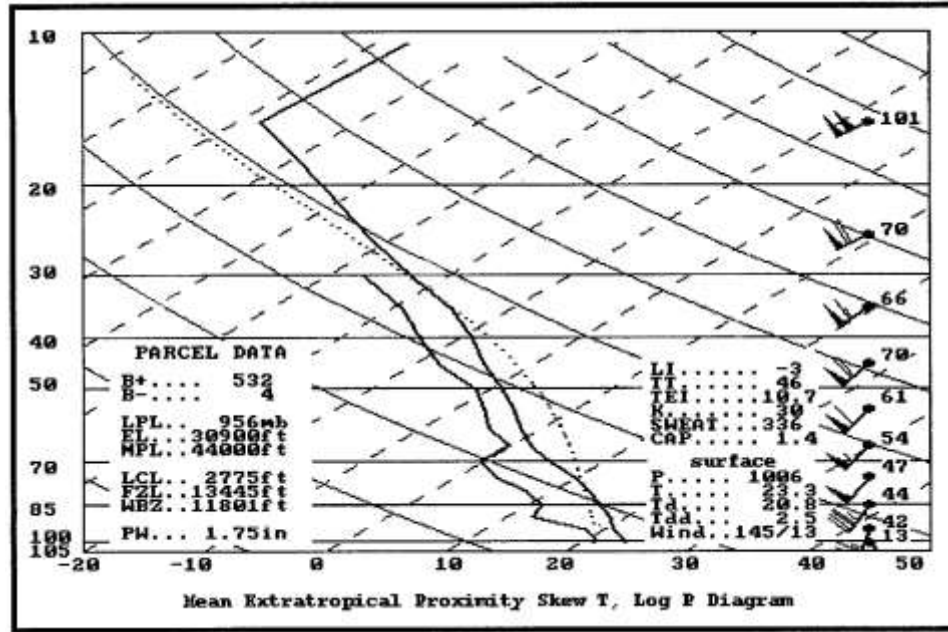
Level	Symbol	Key	Level	Symbol	Key
Surface	L	Low	500 hPa	L	Low
	■	Dewpoint > 20°C (68°F)		↗	Jet (shading > 41 m s <sup>-1</sup> [80 kt])
850 hPa	L	Low	300 hPa	L	Low
	↗	Winds > 20 m s <sup>-1</sup> (40 kt)		↗	Jet (shading > 61 m s <sup>-1</sup> [120 kt])
	■	Dewpoint > 10°C		•-•-•	Axis of Diffuence
700 hPa	L	Low		----	Geopotential height trough

(g)

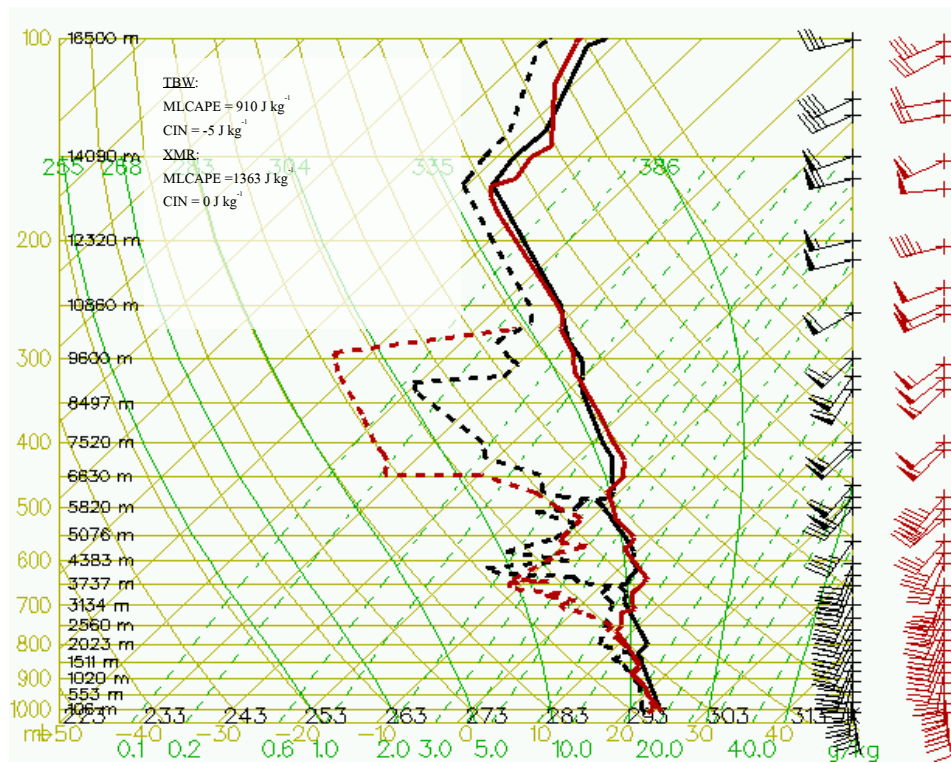
Figure 6: a) 1200 UTC composite analysis; b) 1215 UTC GOES IR image; c) 1500 UTC composite analysis; d) 1515 UTC GOES IR image; e) 1800 UTC composite analysis; f) 1815 GOES IR image; and g) composite analysis chart symbols. GOES images were obtained from University Corporation for Atmospheric Research Image Archive (<http://www2.mmm.ucar.edu/imagearchive/>). Click images for enlargement.



(a)

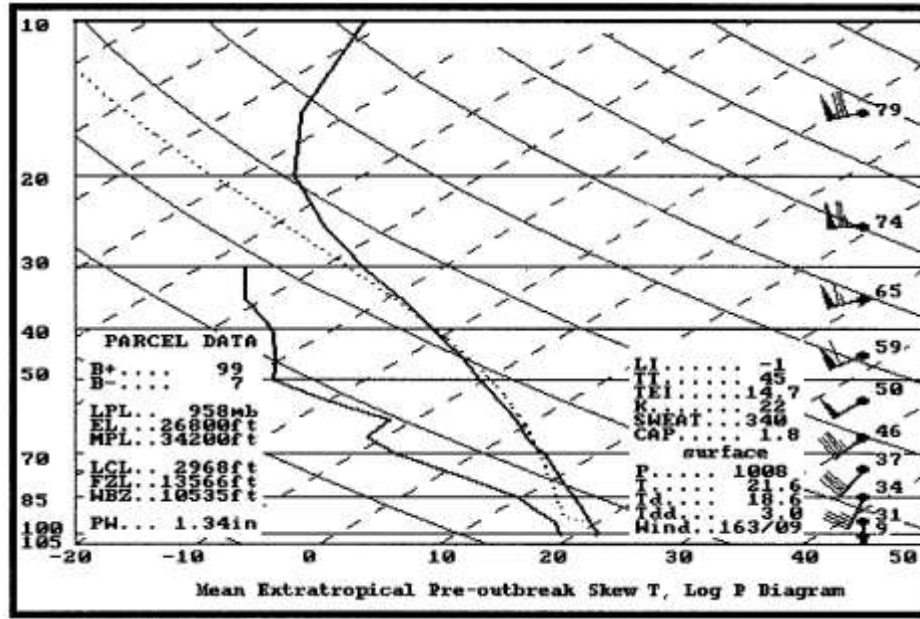


(b)



(c)





(d)

Figure 7: Skew  $T$ -log $p$  diagrams for a) 1200 UTC at TLH (in black) and JAX (in red), b) Composite mean inflow-proximity sounding from H97, c) 1200 UTC at TBW (in black) and XMR (in red), and d) Composite mean pre-outbreak sounding from H97. 1200 UTC soundings were obtained from the Plymouth State University archive (<http://vortex.plymouth.edu>).

The sounding stability comparisons show that TLH and JAX (Fig. 7a) had mixed-layer CAPE (MLCAPE) values that were lower than H97's proximity composite mean of  $532 \text{ J kg}^{-1}$  (Fig. 7b). By contrast, TBW's MLCAPE ( $910 \text{ J kg}^{-1}$ ) and XMR's MLCAPE ( $1363 \text{ J kg}^{-1}$ ) were higher than H97's pre-outbreak composite mean of  $99 \text{ J kg}^{-1}$ . All four soundings had convective inhibition (CIN) values  $> -50 \text{ J kg}^{-1}$ .

Hodographs from the four 1200 UTC soundings were compared to those from H97's composite mean soundings in Fig. 8. The TLH 0–2-km winds (Fig. 8a) were not as strong as H97's inflow-proximity composite mean, but had more directional shear. From 2 to 6 km, the TLH hodograph had a slightly backing profile before veering above that level. The 0–6-km shear, a measure of the potential for long-lived thunderstorms (Rasmussen and Blanchard 1998), was  $25 \text{ m s}^{-1}$ , which is the same as H97's inflow-proximity composite mean, and within the range of shear values favorable for supercell formation, according to Markowski and Richardson's (2010) Fig. 8.5 (reproduced here as Fig. 9). The JAX hodograph (Fig. 8b) had a veering profile through most of the troposphere, with stronger 3–7-km wind speeds

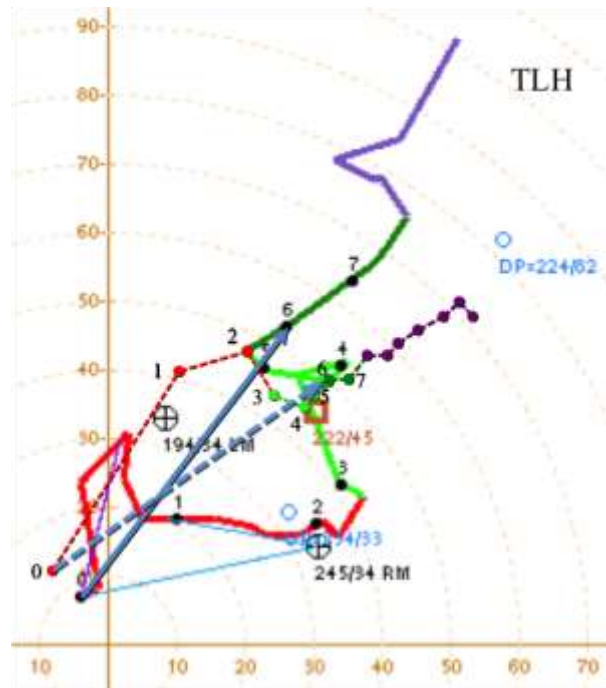
than the H97 inflow-proximity composite mean. The JAX 0–6-km shear was  $31 \text{ m s}^{-1}$ , well into the favorable range for supercells (Fig. 9), and exceeded the H97 inflow-proximity composite mean.

Farther south, the TBW winds were stronger than H97's pre-storm composite mean hodograph through the entire troposphere, but displayed a similar veering profile to H97. The 0–6-km shear of  $24 \text{ m s}^{-1}$  was within the range of values favorable for supercell formation, according to Fig. 9, and exceeded the H97 pre-storm composite mean value of  $19 \text{ m s}^{-1}$ . At XMR, the 0–2-km winds were stronger than H97's pre-storm composite mean, but displayed a similar veering profile to H97. The 0–6-km shear of  $17 \text{ m s}^{-1}$  was in the overlap region between multicells and supercells, according to Fig. 9.

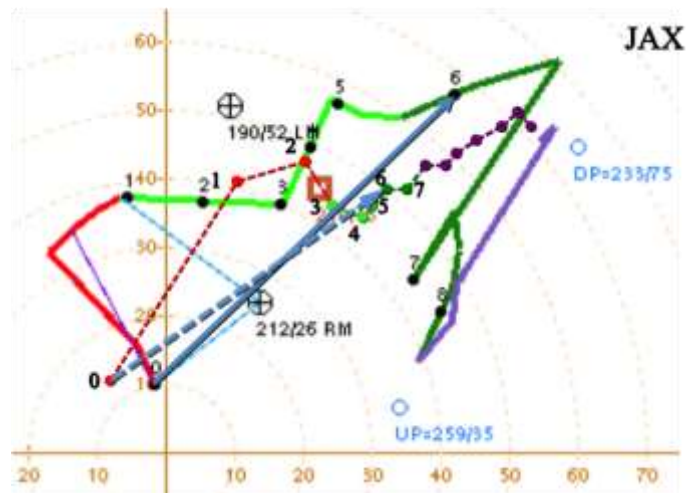
The sounding-parameter comparisons described above show that the static stability over the peninsula was lower than H97's dry-season tornado composite mean soundings in the south, but higher in the north. The relatively low MLCAPE values observed at TLH and JAX in this case were not unusual

considering the time of year. The hodographs showed that with the exception of a portion of the TLH sounding, all four stations had veering profiles. Three of the four stations had 0–6-km shear magnitudes that appeared to favor supercells, and were comparable to or exceeded

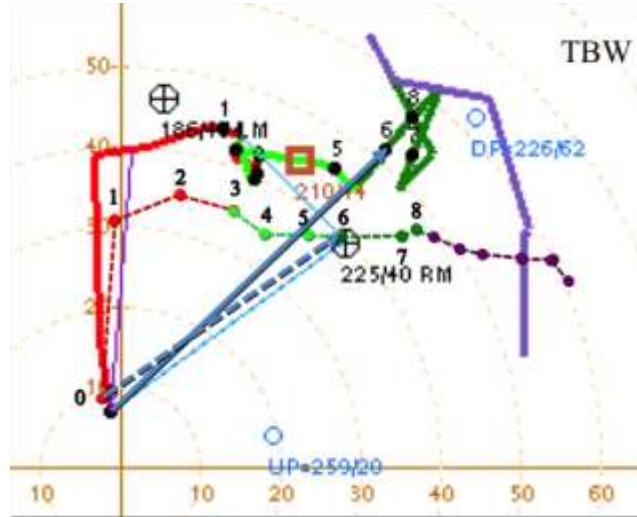
H97's composite mean values. These soundings are considered to be relatively low CAPE and high shear, using the “low CAPE, high shear” sounding criteria of Sherburn and Parker (2014).



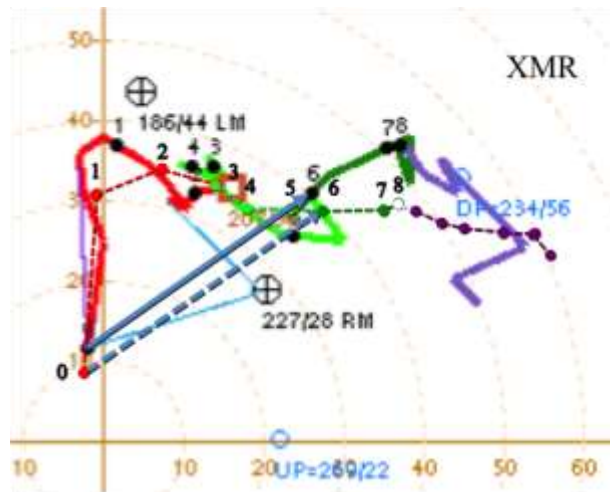
(a)



(b)



(c)



(d)

**Figure 8:** 1200 UTC hodographs for: a) TLH, b) JAX, c) TBW, and d) XMR. Thick solid lines trace the 1200 UTC hodographs; red denotes the lowest 3 km, light green 3–6 km, dark green 6–8 km, and purple above 8 km. Thin dashed lines denote the composite mean hodographs from H97, using the same color scheme as the 1200 UTC hodographs. The solid blue arrow plotted from the sounding origin is the 0–6-km shear vector for each sounding; the dashed blue arrow is the 0–6-km shear vector from the appropriate H97 composite mean hodograph.



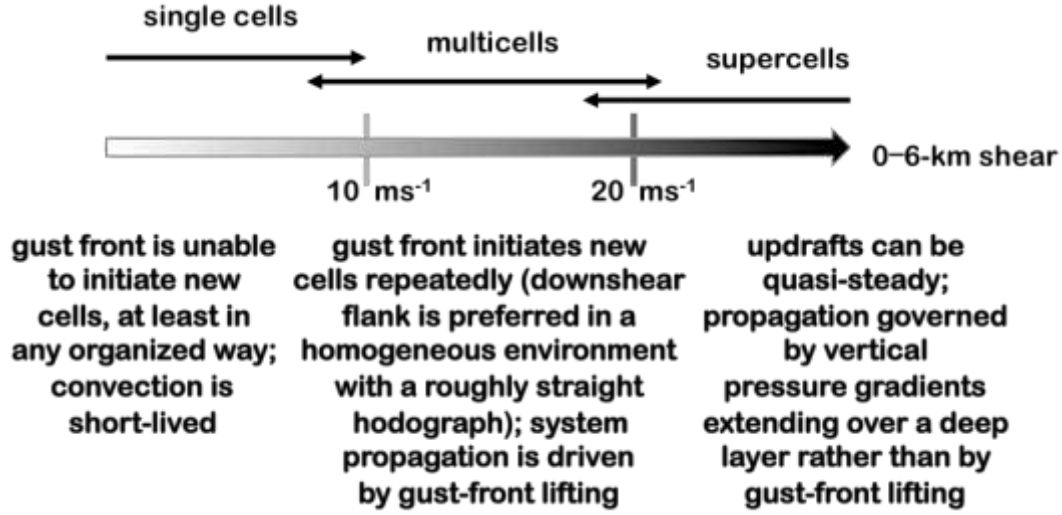


Figure 9: Spectrum of convective storm types based on 0–6-km wind shear [figure adapted from Markowski and Richardson (2010) with permission of the publisher].

#### 4. Meso and storm-scale analyses

##### a. Bow echo evolution over central Florida

The portion of the QLCS over central Florida that produced the Daytona Beach tornado had a history of severe thunderstorm wind damage and tornadoes after it moved onshore from the Gulf of Mexico during the midmorning hours of 25 December. Figure 10, which shows the strongest MLB WSR-88D base reflectivities at 1703 and 1803 UTC, depicts the QLCS path through east-central Florida. A bow echo formed over central Pasco County shortly after 1600 UTC and was responsible for an F2 tornado and severe-thunderstorm wind damage between 1620 and 1625 UTC (**T1**, **W1** in the figure). By 1700 UTC, the bow echo had crossed into southern Sumter County, where it was responsible for severe-thunderstorm wind damage in the Webster area at 1647 UTC (**W2**). During the next 30 min, the bow echo moved into the southern half of Lake County, where it produced an F0 tornado in Leesburg (**T2**). By 1800 UTC, the bow echo had a sharply curved apex as it moved into southwest Volusia County.

For 1803–1828 UTC, which included the period of the Deland tornado, MLB WSR-88D SRV images were analyzed manually for evidence of cyclonic rotation, and the rotational velocity  $V_r$  (Falk and Parker 1998) was computed using the formula in Eq. (1):

$$V_r = \frac{|V_{in-min}| + |V_{out-max}|}{2}, \quad (1)$$

where  $V_{in-min}$  denotes the minimum inbound velocity, and  $V_{out-max}$  denotes the maximum outbound velocity, as depicted by the SRV. The SRV images at the 0.5° elevation angle for three representative times (1803, 1816 and 1828 UTC) were chosen for Fig. 11.

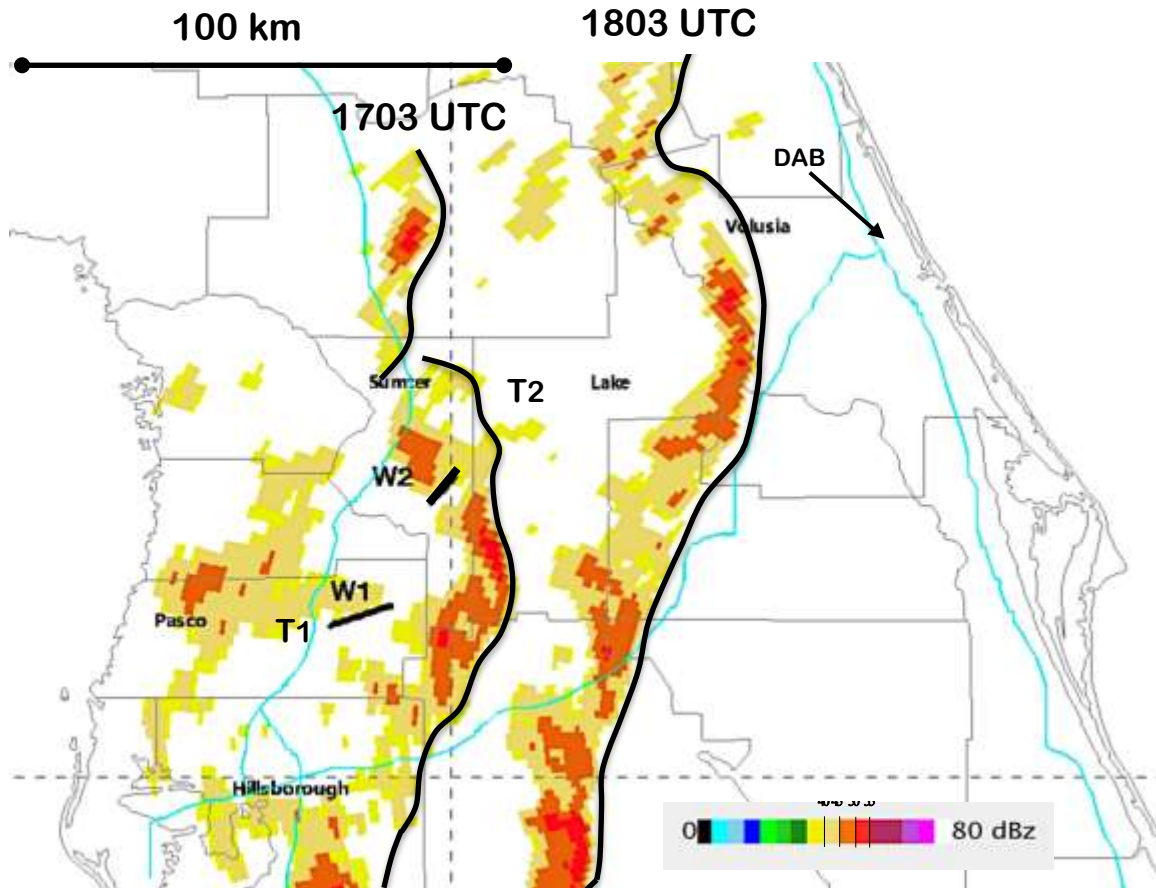
At 1803 UTC, the SRV image (Fig. 11a) showed two areas of cyclonic rotation (labeled with subscripts 1 and 2 in the figure), each of which had a diameter of  $\approx 4$  km. Evidence of the rotation was observed at higher elevation angles, but the diameters were broader than at 0.5°. At this distance from the MLB WSR-88D (100–125 km), the lowest elevation angle is  $\approx 2$  km AGL, so the circulation might be difficult to detect at higher elevation angles. At this time,  $V_r$  was estimated to be  $11.3 \text{ m s}^{-1}$  (22 kt).

By 1816 UTC, the bow echo had moved  $\approx 15$  km, equating to a speed of  $17 \text{ m s}^{-1}$ . The SRV field in Fig. 11b showed the same two rotation areas as at 1803, but circulation #2 had strengthened, with  $V_r$  estimated at  $13.4 \text{ m s}^{-1}$  (26 kt). Additionally, the MDA identified a mesocyclone associated with circulation #2 (shown by an **m** in the figure), extending from 1.7 to 4.3 km in altitude, which is notable considering the range from the radar (115 km). The Deland tornado, which occurred at 1822 UTC, was rated at F2; it tracked northeast for

nearly 5 km, destroying 52 residences, damaging 162 others, and seriously injuring five people (NCDC 2006).

At 1828 UTC, the bow echo was approaching DAB. While the two circulation areas were still discernible on the SRV plot (Fig. 11c),  $V_r$  had

decreased to  $10.3 \text{ m s}^{-1}$  (20 kt) for both. Despite the difficulties associated with manual analysis of the data, the  $V_r$  values were consistent for the 25 min of scans at four elevation angles, ranging from  $8.2$  to  $13.4 \text{ m s}^{-1}$  (16–26 kt).

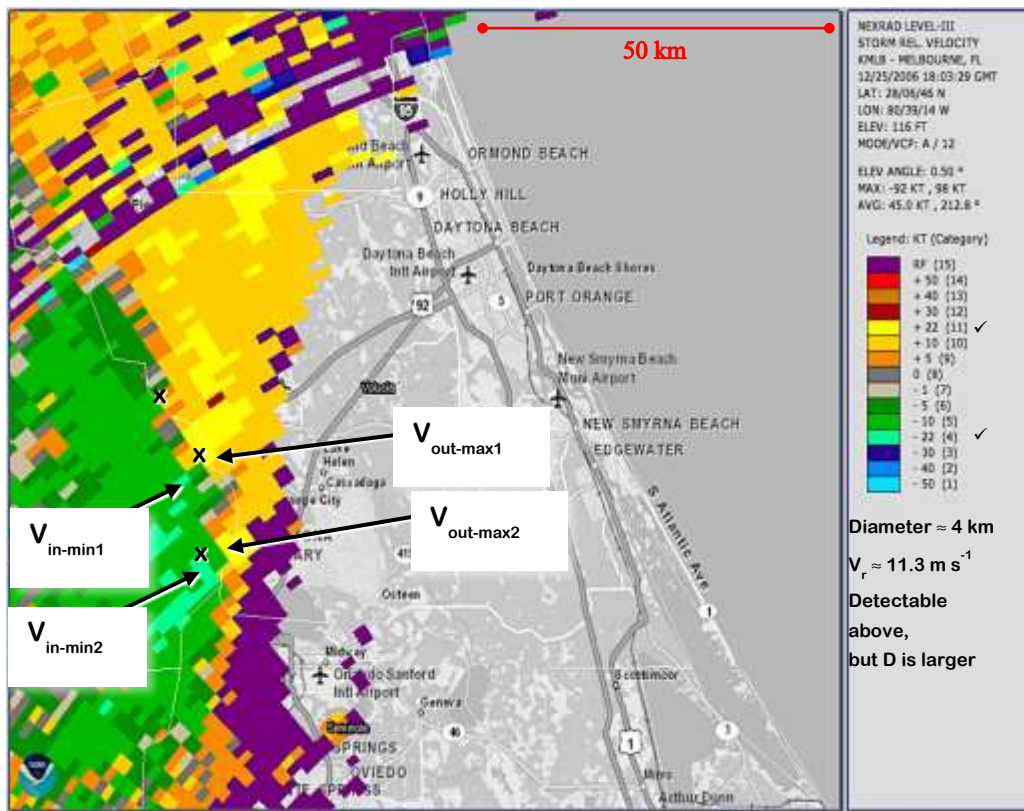


**Figure 10:** QLCS evolution over central Florida for 1703 and 1803 UTC using MLB WSR-88D base reflectivities  $\geq 39$  dBZ (scale shown in lower right). The long curved black line denotes the leading edge of strongest reflectivities; locations of severe-storm reports are shown by **T** for tornado and **W** for severe-thunderstorm wind damage; short solid line shows damage path of severe-thunderstorm winds in Pasco, Sumter, and Lake Counties. Counties are outlined and labeled in grey/black; main interstates are shown in light blue; DAB location shown by arrow.

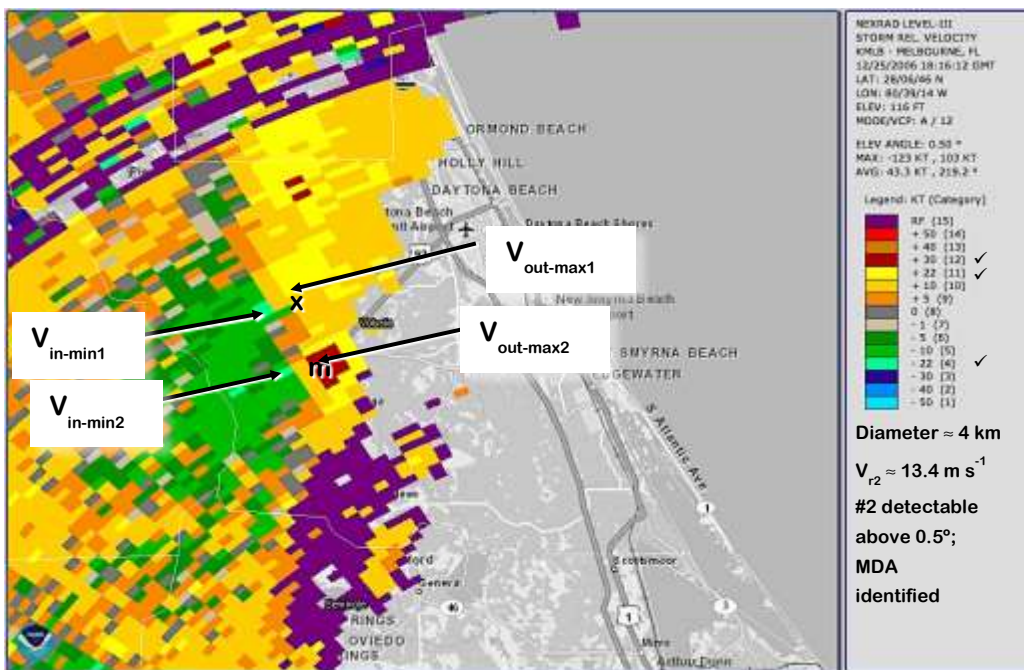
*b. ASOS, WSR-88D and LLWAS analysis of DAB tornadogenesis location*

Figure 12 shows the DAB ASOS altimeter and wind time series for 1800–1900 UTC. The altimeter showed a steady drop from the top of the hour, which began to quicken around 1831 UTC. From 1831 to 1835 UTC, the altimeter dropped  $\approx 1.1$  hPa. After 1836 UTC came a steeper altimeter rise, taking 3 min to increase

$\approx 2.0$  hPa. DAB ASOS winds were fairly uniform from the south-southeast between  $5$  and  $10 \text{ m s}^{-1}$  (10–20 kt) until 1836 UTC, when they veered to between  $240^\circ$  and  $270^\circ$  over the next 3 min. As the direction changed, the speeds increased to  $14$ – $18 \text{ m s}^{-1}$  (28–34 kt). The ASOS data suggest that the gust front associated with the bow echo crossed the airfield between 1836 and 1839 UTC.

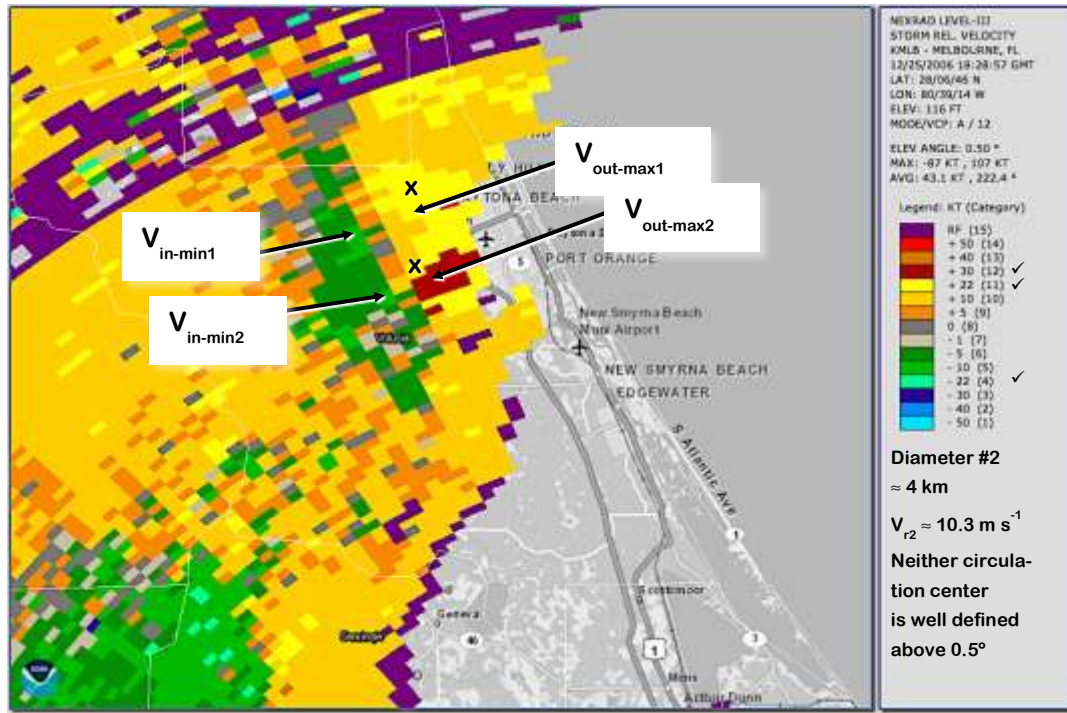


(a)



(b)



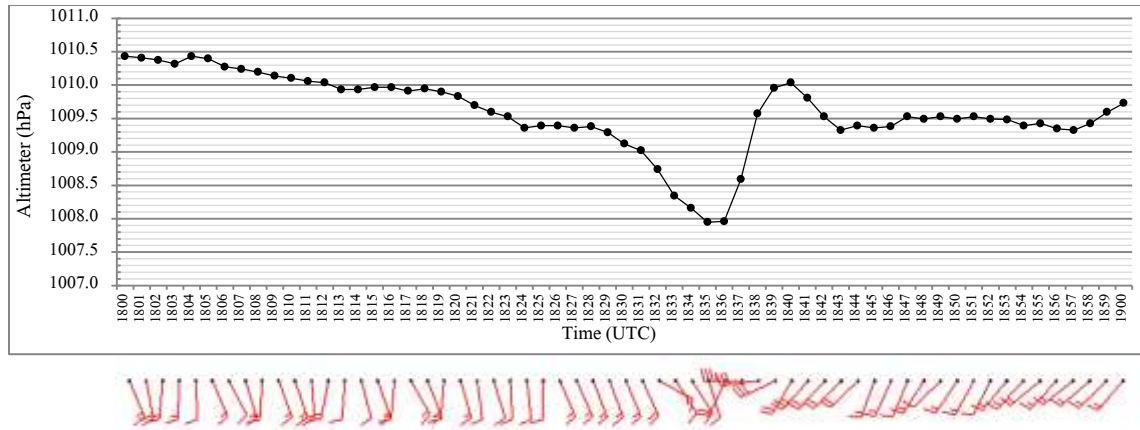


(c)

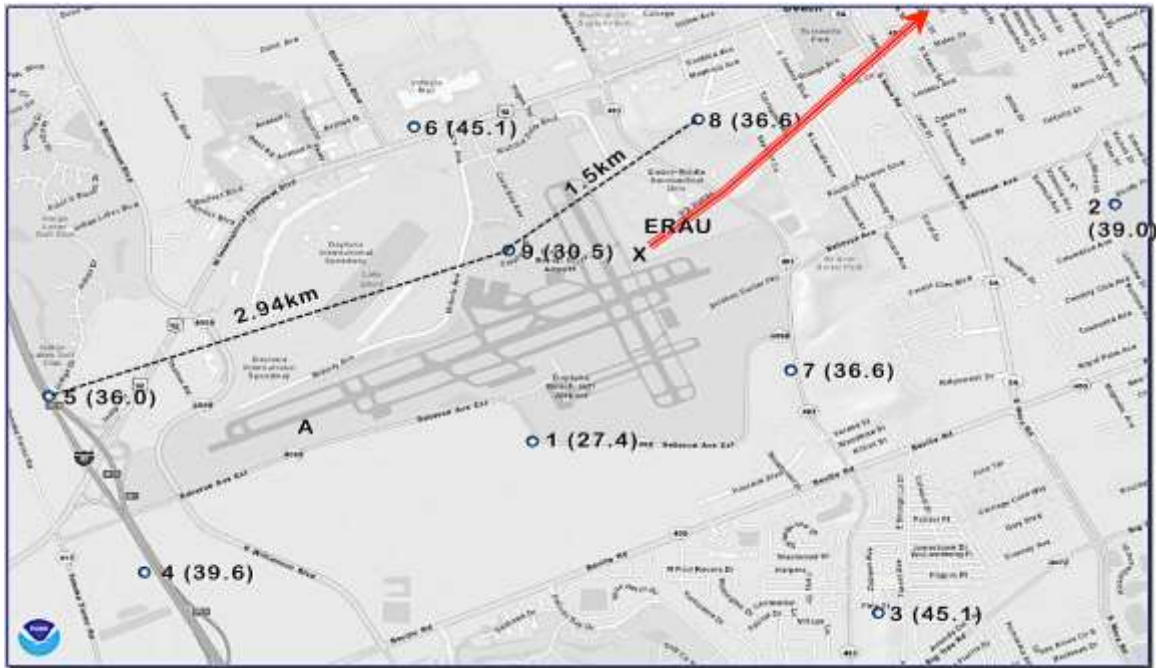
**Figure 11:** MLB WSR-88D 0.5° elevation-angle SRV sequence for a) 1803 UTC, b) 1816 UTC, and c) 1828 UTC. The arrows indicate locations of  $V_{out-max}$  and  $V_{in-min}$  for radar-detected circulations labeled as #1 and #2, and corresponding intensities are shown by checkmarks on the legend. The locations of MDA-indicated rotation areas are shown by an **m** for mesocyclone, and an **x** for other shear types. Geographic points of reference (e.g., DAB Airport) are shown on the map using conventional symbols and labeling.

The next step was to integrate the DAB LLWAS network data with the WSR-88D data (specifically, base reflectivity, SRV, and MDA output). Comparison of these data with the DAB ASOS data provided an additional quality and consistency check. A plot of the DAB LLWAS tower network is shown in Fig. 13 (wind direction and speed time series from each individual LLWAS tower are shown in the Appendix). Given the high temporal resolution of the LLWAS data, integrating the LLWAS and WSR-88D was done by producing LLWAS plots at 1-min intervals for 18:33:14–18:41:41 UTC; the starting and ending times were chosen to coincide as closely as possible with the available WSR-88D volume scans. When WSR-88D SRV and MDA information were available, these data were included on the LLWAS wind plots. An animation of the LLWAS winds from 1834 to 1843 UTC was also produced, and can be found at [ejssm.org/ojs/public/vol11-5/llwas\\_anim.mp4](http://ejssm.org/ojs/public/vol11-5/llwas_anim.mp4).

The results of the LLWAS/WSR-88D analysis are shown in Fig. 14. At 18:33:14 UTC (Fig. 14a), the leading edge of the heaviest rainfall had just crossed Interstate 95 and was entering the western edge of the DAB runway 7L/25R complex. There was an identifiable velocity couplet to the southwest of DAB; the diameter was estimated at 2.5 km, and the  $V_r$  was estimated at  $10.3 \text{ m s}^{-1}$  (20 kt). This circulation was identifiable at levels above the 0.5° elevation. The MDA indicated a *three-dimensional correlated shear* between 2 and 3 km altitude, which NWS (2006) defines as “indicating a 3-dimensional shear region (i.e., vertically correlated) that is not symmetrical.” At this time, the winds over the DAB LLWAS network were still fairly uniform from the south-southeast, while the ASOS altimeter dropped from 1008.34 to 1008.16 hPa between 1833 and 1834 UTC.



**Figure 12:** Time series of DAB ASOS altimeter and wind for 1800–1900 UTC. Top panel is 1-min altimeter setting (hPa) with corresponding wind direction and speed (5-s averages in kt) plotted below. Altimeter is based on a mean of three ASOS barometric sensors. Data obtained from the NCEI ASOS archive (<http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/automated-surface-observing-system-asos>).



**Figure 13:** Map of LLWAS locations around DAB. White circles with black borders show tower locations. The tower number is indicated in black with the elevation (m) in parentheses. ASOS location (**A**) is shown for reference. **ERAU** denotes the location of the Embry-Riddle campus; an **X** marks the tornado's appearance location, and a red line with arrow shows its path. The black dashed line shows the location of a time series for Towers #5, #9, and #8 described in Fig. 14j; distances (in km) between Towers #5 and #9, and between #9 and #8 are shown for spatial reference. *Click image for enlargement.*

The LLWAS-only plots for 18:34:11, 18:35:10, and 18:36:09 UTC (Figs. 14b–d, respectively) showed a wind shift associated with the bow echo's passage across Interstate 95, which is just west of DAB. There was a great

deal of horizontal wind shear between the two towers (#5 and #4) that were reporting westerly winds between 13 and 21 m s<sup>-1</sup> (25–40 kt), and those 3 km to the east that were still southerly at 5–8 m s<sup>-1</sup> (10–15 kt). The ASOS altimeter

reached its lowest point (1007.95–1007.96 hPa) at 1835 and 1836 UTC.

By 18:37:26 UTC (Fig. 14e), a strong SRV velocity couplet appeared at a location north of runway 7L/25R, between Towers #5 and #9. The calculated  $V_r$  was at its highest value ( $15.9 \text{ m s}^{-1}$ ; 31 kt). The MDA identified an *uncorrelated shear*, defined by NWS (2006) as “a region of shear that is large and symmetrical but not vertically correlated.” This feature was identified at  $z = 2 \text{ km}$ , which essentially coincides with the lowest elevation scan. An interesting feature on this plot is the curvature of the LLWAS winds, specifically between Towers #5 and #9 (about 2.9 km apart), which is in remarkable agreement with the SRV velocity couplet despite the altitude differences between the WSR-88D elevation scan (2 km) and the tower heights (36.0 and 30.5 m, respectively). This location also had the strongest base reflectivity value (nearly 54 dBZ); the wind shift associated with the gust front was nearly coincident with the highest reflectivities as they crossed runway 7L/25R. The ASOS altimeter had risen rapidly to 1009.57 hPa by 1838 UTC.

By 18:38:26 UTC (Fig. 14f), the winds had shifted at nearly all towers, but the cyclonic turning appeared to be more pronounced, now located between Towers #9 and #8, about 1.5 km apart. By 18:39:25 UTC (Fig. 14g), the wind shift associated with the bow echo passage had been observed at all towers except for #2 (the easternmost one), and by 18:40:24 UTC (Fig. 14h), the winds had shifted at all nine towers. At 18:41:41 UTC (Fig. 14i), the velocity couplet had weakened and moved northeast of DAB. The MDA identified an uncorrelated shear to the northwest of the velocity couplet, again at an altitude close to the lowest elevation scan (about 2.1 km).

Comparison of the LLWAS and the ASOS winds showed that the two sets of observations were fairly consistent despite the differences in temporal resolution and measurement height. Comparing the wind shifts at each tower with that from the ASOS suggests that the estimated time of the gust-frontal passage through the eastern edge of the runway 7L/25R complex was likely between 1838 and 1839 UTC. This

refined estimate is important given that the tornado appeared on the northeast side of the runway 7L/25R complex, east of the intersection with runway 16/34, and about 0.75 km east-southeast of Tower #9.

Figure 14j shows a time series of winds for Towers #5, #9, and #8 for the period 1837–1839 UTC. The time series shows that the cyclonic curvature in the LLWAS winds between Towers #5 and #9 was no longer discernible after 18:37:37 UTC, and the cyclonic curvature between Towers #9 and #8 began to appear at 18:38:26 UTC. The time series also shows that the cyclonic curvature between these towers appeared to intensify from 18:38:26 through 18:39:06 UTC. The circulation between Towers #9 and #8 appeared to be stronger than that between Towers #5 and #9. This is especially important given the shorter distance between Towers #9 and #8, compared to Towers #5 and #9 (1.5 vs. 2.94 km), and the proximity of Tower #9 to the tornadogenesis location.

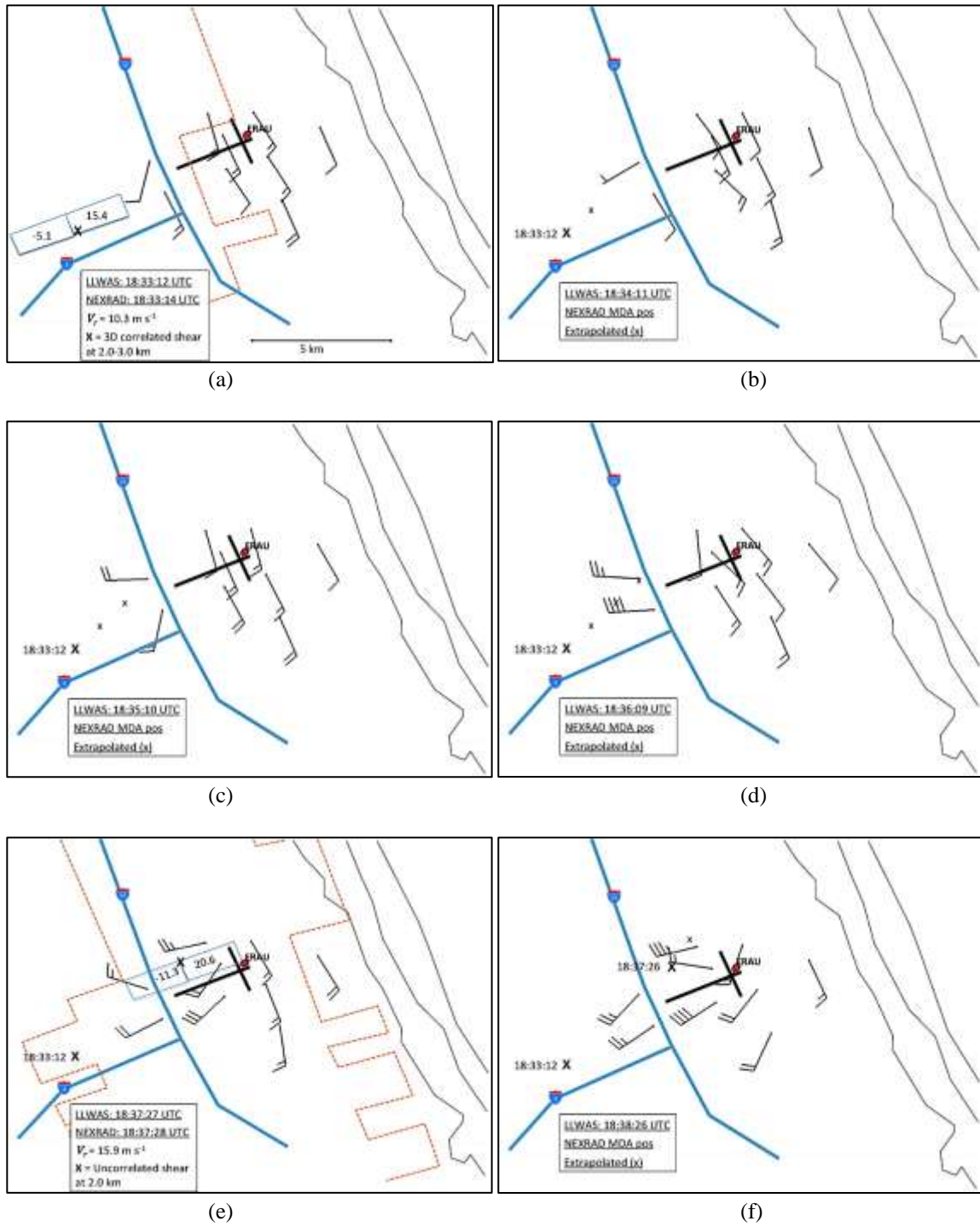
Based on the LLWAS-observed wind shifts, the bow echo crossed DAB’s runway 7L/25R in about 3 min, which is an estimated speed of around  $18 \text{ m s}^{-1}$ , consistent with earlier calculations. The best estimate of tornadogenesis on the eastern end of DAB runway 7L/25R appears to be 1838–1839 UTC.

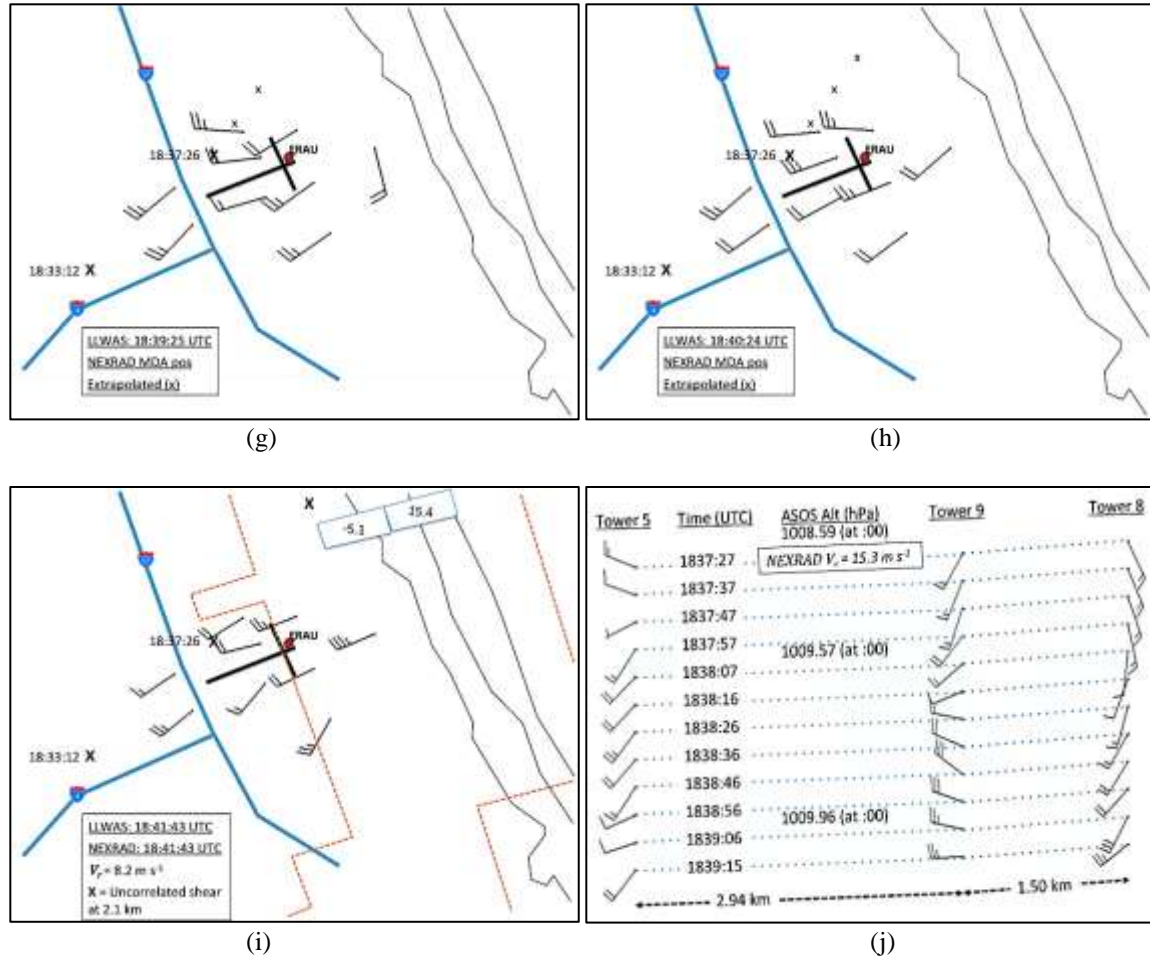
## 5. Discussion

### a. Convective mode and relation to mode-specific storm climatologies

In examining this case within the context of cold-season bow-echo climatology, the synoptic situation resembled the Gulf Coast bow echoes category documented by Burke and Schultz (2004). The 25 December 2006 case had upper-level southwesterly flow, a trough centered over the central states, and an approaching surface frontal trough over the Gulf of Mexico (see their Figs. 9a, b). About half of the 20 Gulf Coast bow echoes identified in their study’s 4-y period of record were classified as squall lines. Out of this number, at least four to five bow echoes appeared to transit the northern portion of the Florida peninsula (see their Fig. 9c).







**Figure 14:** One-min LLWAS and WSR-88D analyses over DAB and surrounding area between a) 1833 UTC and i) 1841 UTC. Black intersecting lines in center of each panel show DAB runways 7L/25R and 16/34. Each panel shows LLWAS winds plotted in kt. When available, locations and intensities of  $V_{in-min}$  and  $V_{out-max}$  (in  $m s^{-1}$ ) derived from the WSR-88D SRV are shown by rectangles depicting the sizes of the pixels in the image. An X shows the location of MDA-derived shear; positions between WSR-88D scans were linearly extrapolated and shown by an x. The inset box shows the time stamp of each data source along with values of  $V_r$  and MDA shear type and altitude(s). Brown dashed lines in Figs. 14a, e, and i show the boundaries of base reflectivities  $\geq 39$  dBZ. Red explosion icon denotes tornado appearance location, and ERAU denotes campus location. j) Time series of winds at LLWAS Towers 5, 9 and 8 for the period 1837–1839 UTC (isochrones at 10-s intervals are shown by blue dotted lines). Distance between towers is shown at bottom; other important information from ASOS and WSR-88D SRV analysis is shown at time of occurrence.

In addition to comparing the 1200 UTC sounding data with H97's climatological means, it is also possible to examine these in relation to other cold-season severe-storm climatologies. The MLCAPE values from TLH, JAX, TBW, and XMR ranged from 255 to 1363  $J kg^{-1}$ ; three of the four sites were within the 25<sup>th</sup>–75<sup>th</sup> percentile range of MLCAPE values for QLCS-producing EF2+ tornado events tabulated by Thompson et al. (2012; see their Fig. 5). The

1200 UTC sounding MLCAPE values were above the median for winter-season QLCS-producing EF1+ tornado events within the same study (see their Fig. 17). By contrast, three of the four 1200 UTC sounding MLCAPE values were below the mean for cold-season Gulf Coast bow echoes (1295  $J kg^{-1}$ ) studied by Burke and Schultz (2004; see their Table 3). Since their study used most unstable CAPE, this result is not surprising.

One additional comparison was made with data from the SPC Tornado Environment Browser (<http://www.spc.noaa.gov/exper/envbrowser/>). Choosing a grid point in southwestern Volusia County for cold-season tornadoes (20 cases), the mean MLCAPE was  $741 \text{ J kg}^{-1}$ , with 25<sup>th</sup> and 75<sup>th</sup> percentile values of 540 and  $1055 \text{ J kg}^{-1}$ , respectively. The TLH and JAX MLCAPE values fell below the 25<sup>th</sup> percentile, which is not surprising considering the distance from the grid point location. The TBW MLCAPE was between the median and 75<sup>th</sup> percentile, while the XMR MLCAPE was above the 75<sup>th</sup> percentile. It was not possible to know the convective modes for the 20 cases that made up the sample. Overall, the observed MLCAPE for the 25 December 2006 case was either within or below that found in other climatological studies and data sources (with the exception of XMR, which was higher).

Regarding the vertical shear, a direct comparison is a little more difficult since not all studies used the same parameters. Fortunately, the SPC computes the same parameters as discussed in Thompson et al. (2012), so one is used here. The effective bulk wind difference (EBWD) is defined as “magnitude of the bulk vector shear from the ‘effective inflow base’ upward to 50% of the equilibrium level height with the most unstable parcel in the lowest 300 mb.” (<http://www.spc.noaa.gov/exper/mesoanalysis/help/begin.html>). The four Florida soundings had 0–6-km EBWD values of  $24.2 \text{ m s}^{-1}$  (TLH),  $32.9 \text{ m s}^{-1}$  (JAX),  $29.8 \text{ m s}^{-1}$  (TBW), and  $22.1 \text{ m s}^{-1}$  (XMR). These values were near or above the median value for QLCS-producing tornadoes in Thompson et al. (2012; their Fig. 2). Notably, the JAX EBWD exceeded their 90<sup>th</sup> percentile value of  $32.4 \text{ m s}^{-1}$ .

#### *b. Use of mesocyclone identification nomograms in this case*

Once thunderstorms develop, the WSR-88D is one of the tools that forecasters depend upon for identifying the potential for tornadoes to develop. While the MDA is useful for helping forecasters detect low-level rotation that may lead to mesocyclone formation, it is not relied upon as the sole source. Manual techniques for determining mesocyclone strength have been used in the field for many years, and have been enhanced with the advent of 8-bit radar data in 2003 (Frugis and Wasula 2013) and dual-polarization radar (Istok et al. 2009) in 2011.

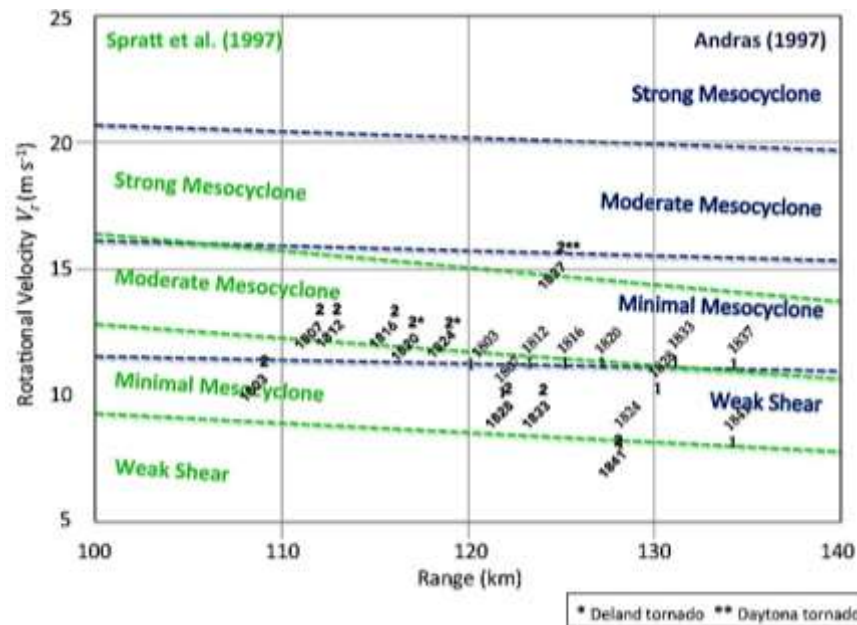
For the purposes of this study, two techniques for diagnosing radar-detected circulation strength were employed and compared. One is the MDA-derived nomogram for diagnosing mesocyclone strength based on Great Plains observations (Andra 1997), assuming a mesocyclone diameter of 6.5 km. In Florida, use of the MDA and its associated nomogram presented challenges (S. Spratt, personal communication). Thus, the MLB NWSFO developed, and uses, a modified nomogram that assumes a smaller diameter (1.85 km) than the MDA version (Spratt et al. 1997). This nomogram accounts for smaller circulations and increasing distances from the radar. While the MLB nomogram originally was developed for tropical cyclone tornadoes, they use it for both tropical and extratropical cases (S. Spratt, personal communication).

For the 25 December 2006 case, manual measurements of  $V_{in-min}$ ,  $V_{out-max}$ , range, and diameter were made and placed into a spreadsheet for calculating  $V_r$  at the elevations where a circulation could be detected in the SRV data. Both types of nomograms were employed for analyzing the SRV data in order to determine the mesocyclone strength in the period before and after the tornado occurrence at DAB. One caveat that should be mentioned is the distinction between mesocyclones associated with supercells and mesovortices associated with squall lines and QLCS (e.g., Agee and Jones 2008). NWS (2006) defines a mesocyclone as a circulation area that is “sufficiently large, vertically correlated, and symmetrical.” Mesocyclones are typically detectable at multiple levels above the planetary boundary layer, and often seen in the right-rear flank of a supercell thunderstorm (NWS 2015), while mesovortices tend to be low-level features seen near the leading edge of a QLCS. Although the convective system on 25 December was a QLCS with bow echoes, the nomograms were still useful for determining the *relative* strengths of the mesoscale circulations detected by the WSR-88D, and thus determining the *potential* for tornadoes.

The results of the comparison are shown in Fig. 15. Although two circulations were identified in Fig. 11 and plotted in Fig. 15, only circulation #2 (associated with the DAB tornado) is discussed here. Using the MDA-derived nomogram criteria (blue dashed boundaries in the figure), the  $V_r$  values for circulation #2 were in the *minimal mesocyclone* category and

remained fairly constant for the period 1803–1824 UTC (recall that the Deland tornado was reported at 1822 UTC). From Fig. 11, recall that the diameter was consistently estimated at 4 km. The MLB-derived nomogram (green dashed boundaries in Fig. 15) placed circulation #2 in the *moderate mesocyclone* category. Interestingly, Fig. 15 shows that  $V_r$  for circulation #2 decreased during the next two scans before reaching its maximum value during the 1837 UTC scan (right before the DAB tornado appearance). Using the Andra (1997) nomogram, circulation #2 was in the lower portion of *moderate mesocyclone* category at

1837 UTC, while in the MLB nomogram, it was in the lower portion of the *strong mesocyclone* category. In both the 1837 and 1841 UTC scans, the diameter was estimated to be 2.5 km, consistent with the strengthening circulation just preceding the DAB tornado. Putting circulation #2 into a climatological perspective, the strongest  $V_r$  fell just below the median value for QLCS EF2 tornadoes at 6000–10 000 ft (1829–3048 m) above radar level within a 70–101-mi (113–163-km) radius of the radar site in the study of Smith et al. (2015; their Fig. 7).



**Figure 15:** Mesocyclone nomogram comparison plot for 1803–1841 UTC. The numbers 1 and 2 refer to circulations identified on the WSR-88D SRV plots in Fig. 11. The times are plotted above the  $V_r$  and range values for circulation #1, and below the circulation #2 values. Circulation classifications from the Andra (1997) MDA-derived nomogram can be made by using the blue dashed boundaries and labeling, while those from the MLB NWSFO nomogram can be made by using the green dashed boundaries and labeling. Asterisks next to circulation #2 values for 1820, 1824 and 1837 UTC denote closest available WSR-88D SRV scans to the Deland and Daytona tornadoes, respectively.

## 6. Conclusions

This research provides a useful addition to a somewhat thin case-study literature on central Florida peninsula severe thunderstorms and tornadoes occurring during the dry season. It complements previous severe-storm climatological studies by documenting pre-outbreak conditions that were mostly consistent with composite mean tornadic soundings for dry-season types of events on the Florida peninsula. It is also consistent with results of previous cold-

season severe-storm climatological studies, which find the vertical shear to be of greater relative importance compared to the static stability. While several indicators suggested the possibility of supercells over the peninsula on 25 December, the convective system was a QLCS with bow echoes.

WSR-88D data were used to determine likelihood of mesocyclone formation through employment of a widely used MDA-derived intensity nomogram, as well as one developed



and used by the MLB NWSFO. The results of  $V_r$  calculations based from the SRV and MDA data gave a fairly reliable indication of the potential for low-level circulation that could be favorable for tornado formation.

A unique addition to the data analysis for this case was the LLWAS network wind data. As stated earlier, LLWAS data are mainly used by air traffic control personnel for monitoring the terminal airspace for dangerous wind-shear conditions. The history of the LLWAS can be traced back to efforts to improve situational awareness of low-level wind conditions around the terminal airspace as a result of several high-profile airliner accidents in the 1970s and 1980s (e.g., Joint Airport Weather Studies Project; McCarthy et al. 1982). The LLWAS system has gone through several generations in development and deployment, and is typically used in conjunction with other airport weather monitoring systems such as the Terminal Doppler Weather Radar (Meyer et al. 1999; Miller et al. 2002). The reader is also referred to an LLWAS primer available from NCAR (2012).

The present study appears to be the first time that LLWAS data have been used in a meteorological case study not involving wind shear, downbursts, or microbursts. An interesting aspect of the LLWAS network performance in this case is that there was not enough of a speed loss or gain between towers to cause either the wind shear or microburst alarms to sound (C. Turner, personal communication, 2007). However, the LLWAS captured the surge in winds associated with the bow echo's transit across the DAB network, along with considerable horizontal wind shear and a suspected cyclonic circulation in the vicinity of the DAB tornado's appearance. Considering that tornadic thunderstorms have struck large international airports, such as Lambert St. Louis International Airport in April 2011 (NWS 2011), LLWAS potentially could provide another source of high-resolution wind data that could be used by meteorologists for real-time monitoring and nowcasting.

While this case study was able to capitalize on some unique observational data sources, there

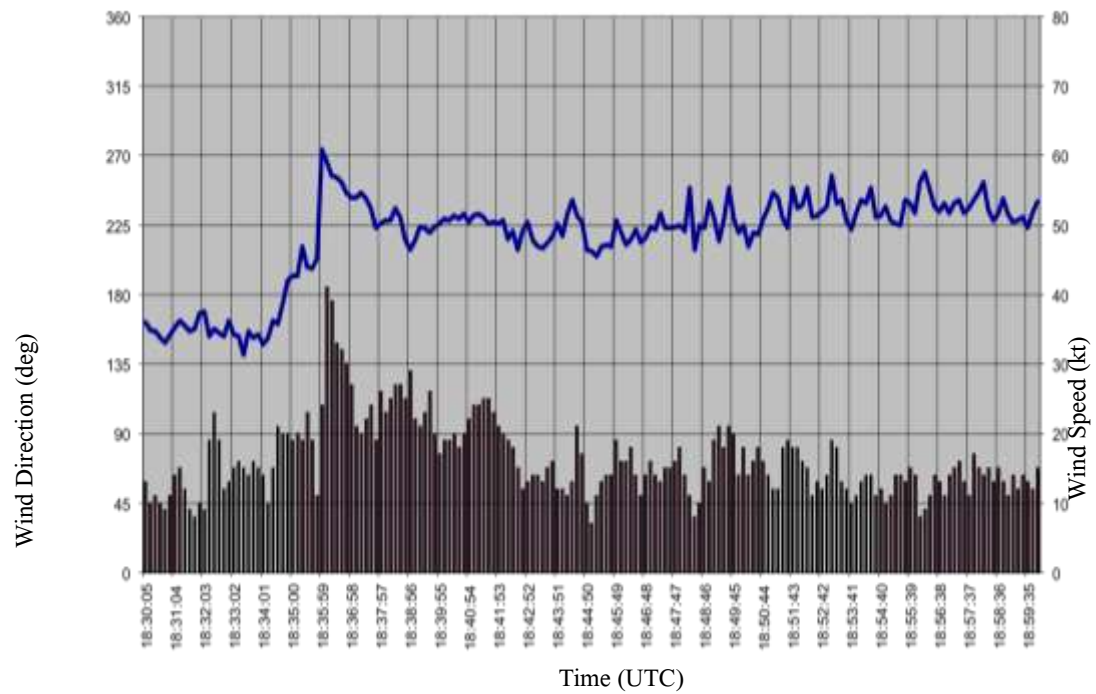
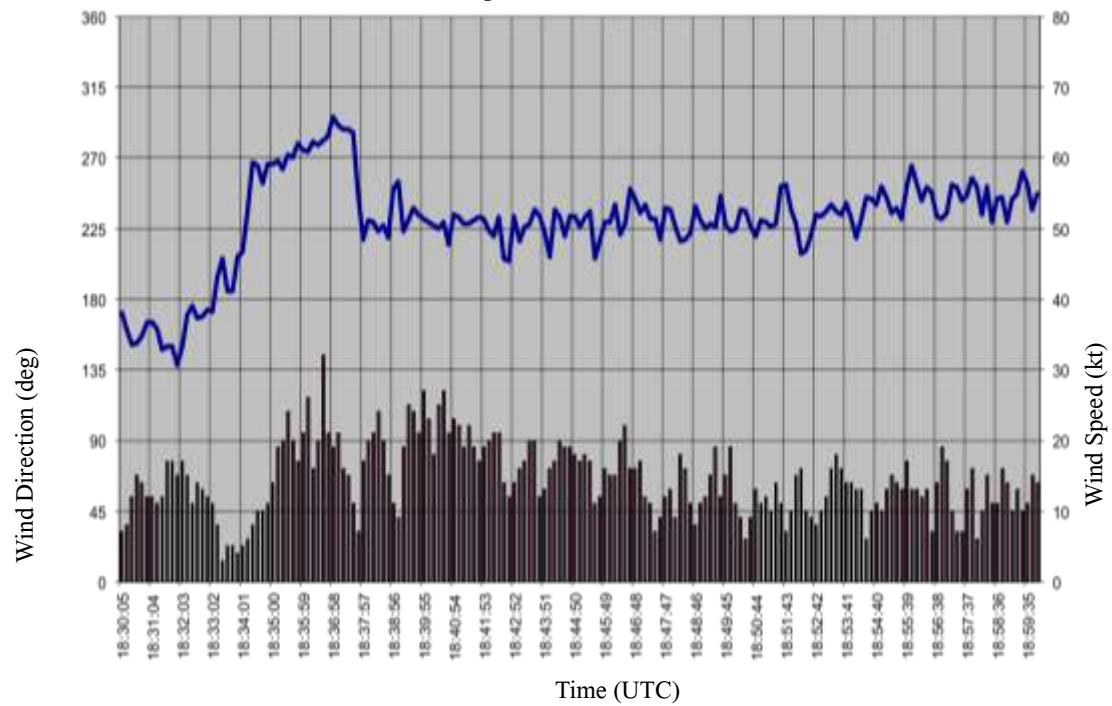
are limits to the information that can be gleaned from these sources alone. Employing mesoscale numerical weather prediction models to perform additional research on cold-season severe-storm cases such as this one could reveal additional insights that observational data alone cannot provide. Such studies are needed to improve our understanding of the structure and dynamics within evolving squall line, QLCS and bow echo environments, and compare cases such as this one with the results of other simulation-based studies (e.g., Trapp and Weisman 2003; Atkins and St. Laurent 2009a,b). Additionally, it would be an interesting challenge to examine the utility of assimilating unique data sources such as LLWAS into a mesoscale model, given the small spatial scale, low-elevation measurements, and high temporal resolution.

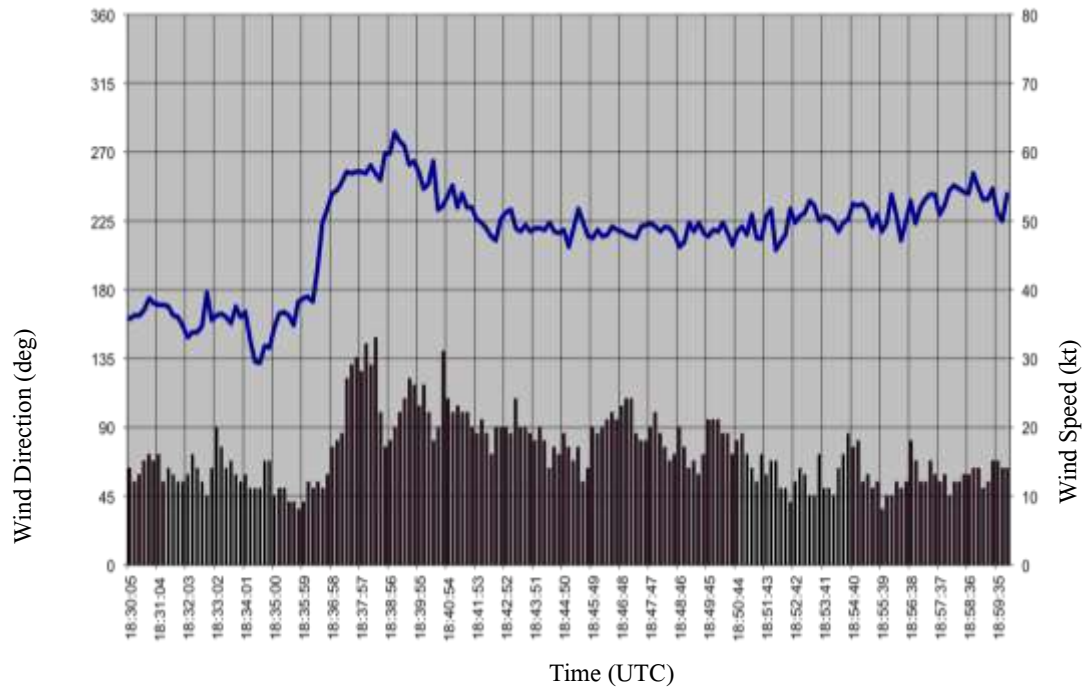
#### ACKNOWLEDGMENTS

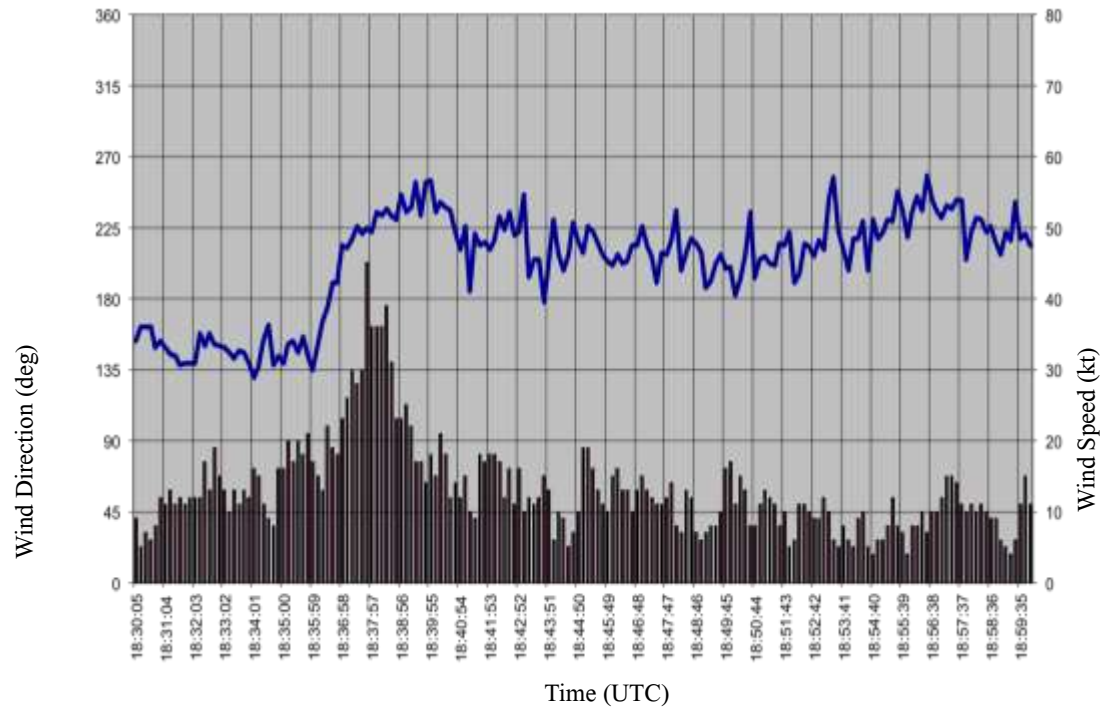
I would personally like to thank Dr. Frederick Mosher and Dr. Christopher Herbster of the Embry-Riddle Meteorology program for the many fruitful discussions of this case, and for providing valuable observational data used in this study. I would like to thank Mr. Chris Turner from the FAA for providing the unique DAB LLWAS data, which he manually tabulated for all nine towers for the time period that was used in this case study. The three reviewers (K. Sherburn, B. Boustead, and R. Thompson) provided me with thoughtful suggestions and guidance that allowed me to expand my knowledge base and gain an appreciation for the rapid advances made in severe-storm climatology and storm environmental analysis over the last 10 y.

#### APPENDIX

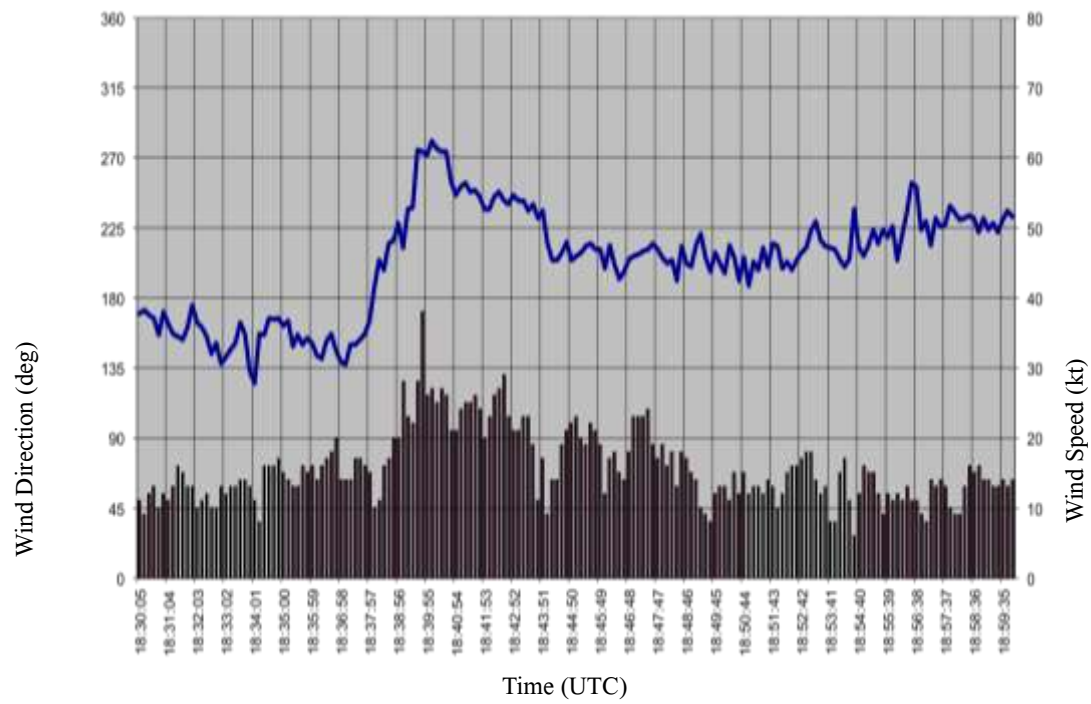
This section contains detailed LLWAS wind direction and speed plots at each individual tower during the 1830–1900 UTC period. In each graph, the blue line denotes wind direction, while the bars along the bottom indicate the speed in kt. Wind plots are shown in four groups from west to east, with towers in each group from north to south (refer to Fig. 13 for tower locations): Group 1: Towers #5 and #4; Group 2: Towers #6, #9, and #1; Group 3: Towers #8, #7, and #3; Group 4: Tower #2.

Group 1: Towers #5 and #4

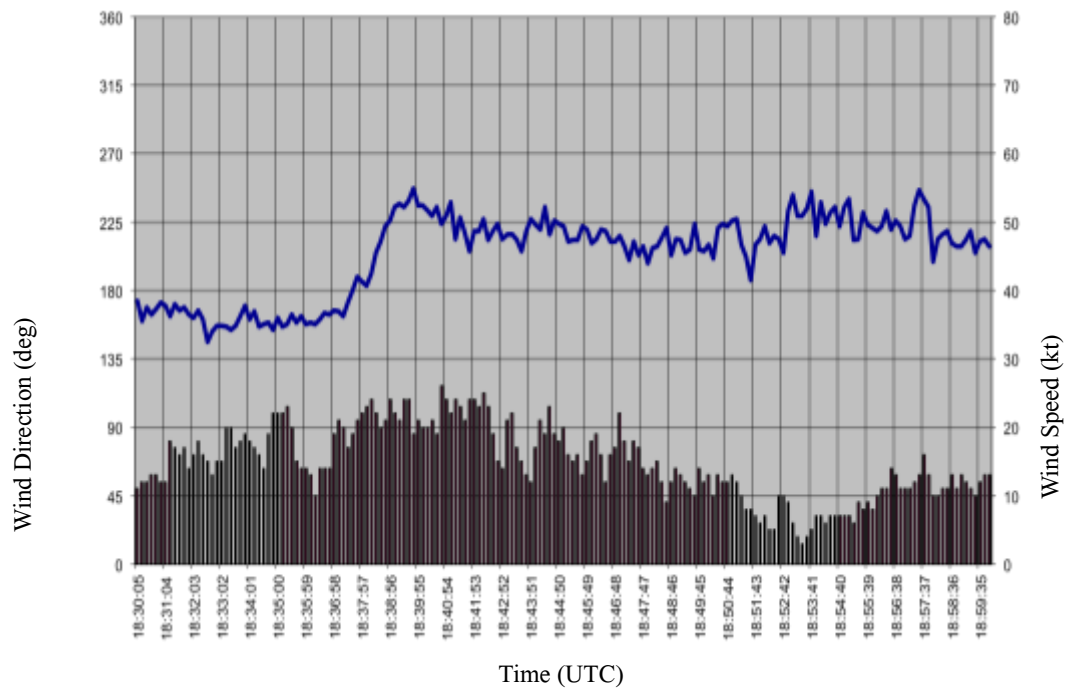
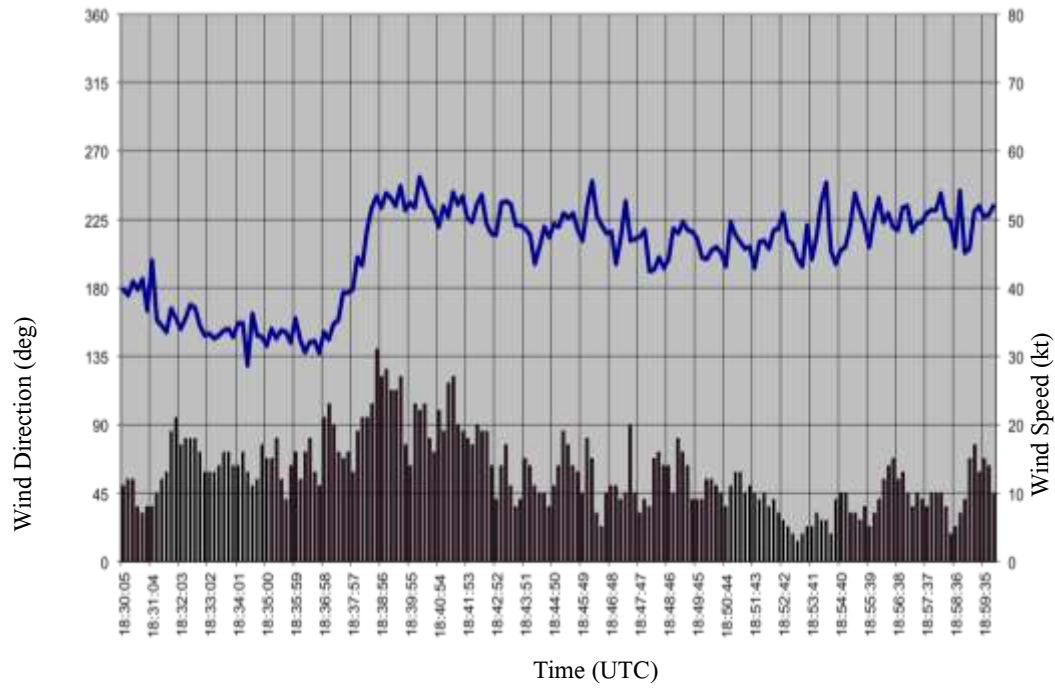
Group 2: Towers #6, #9, and #1



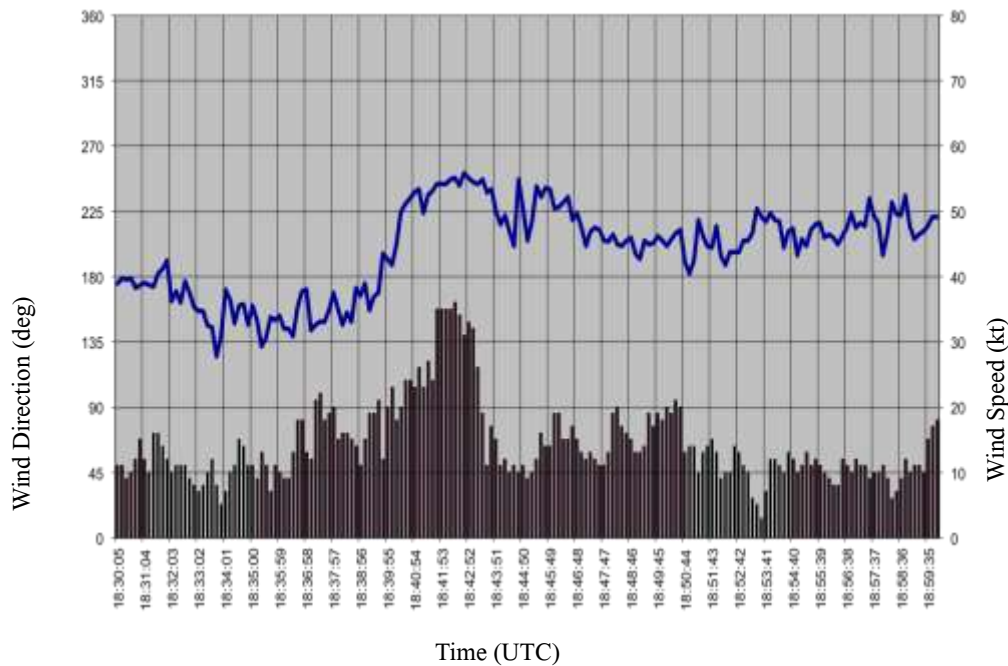
Group #3: Towers #8, #7, and #3







## Group 4: Tower #2



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## REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

### REVIEWER A (Keith D. Sherburn):

#### *Initial Review:*

**Recommendation:** Accept with major revisions.

**General Comments:** This article provides a nice case study of the Christmas Day 2006 high-shear, low-CAPE tornado event in Daytona Beach, Florida. While the data presented are sufficient, the analysis would benefit from inclusion of additional severe weather parameters, such as the significant tornado parameter, and increased clarity and elaboration in some arguments. The majority of comments herein are minor, but taken on the whole, they lead me to wish to see a revised manuscript.

**Major Comments:** At the end of the introduction, it would be appropriate to elaborate on the “unique demographic characteristics” of Florida, including some citations. This is discussed a little bit later on in the manuscript, but it would add some support to your introduction. Likewise, you could expand on the thought that, “long-lived cells were possible, but rotating cells would be less likely.” It is not readily apparent to the reader how this conclusion was reached.

*I reorganized the Introduction to include a section called “Motivation for the study”, which consolidates the demographic information and includes some additional information to strengthen the arguments presented.*

The use of the term “severe-storm parameters” when describing Fig. 4 throws me off. When I hear parameters associated with severe thunderstorms, I think of composite parameters such as the significant tornado parameter or supercell composite parameter (or even CAPE, shear, etc., which are addressed separately). Although approximate values can be inferred from the given soundings, it would support your case study to include some of these composite parameters; this is especially true considering that this is a high-shear, low-CAPE environment, where these parameters often underestimate the severe threat (see Sherburn and Parker 2014). Granted, this is primarily a QLCS event, so these two parameters may not be especially applicable; however, there do appear to be some embedded supercellular features. In final regard to Fig. 4 (and similar panels in Fig. 7), it may be more appropriate to refer to these as composites of relevant mesoscale and synoptic scale ingredients or features rather than severe-storm parameters.

*I changed the wording to “composite analyses of low- and upper-level synoptic scale features” (note this is now Figure 6 and I’ve consolidated the 1200, 1500, and 1800 UTC analyses into a single figure. I didn’t include any composite parameters in the revision, but added EBWD and ESRH in the revamped Discussion section. I also replaced the original figures that compared the shear parameters with Hagemeyer (1997) with hodographs obtained from a site that Rich Thompson so kindly provided to me (<http://www.spc.noaa.gov/exper/soundings/archive>)).*

Is there a reason why evidence was required to know that a cold pool had formed? Given that the bow echo had, “already produced straight-line wind damage and tornadoes”, a cold pool was present for some time. Additionally, the last paragraph in this section seems disjointed. Your discussion on the utility of supplemental observations is warranted, but the structure of the last couple paragraphs in this section could be cleaned up.

*This was removed in the revision.*

**Second Review:**

**Recommendation:** Accept with minor revisions.

**General Comments:** This revised manuscript, detailing the Christmas Day 2006 tornado affecting Embry-Riddle Aeronautical University and Daytona Beach International Airport, is generally in good shape and, overall, provides a clearer motivation and more thorough exploration than the original manuscript. While I still have a handful of suggestions, the author has sufficiently addressed my previous comments and suggestions, and no significant revisions appear to be necessary.

Some passages could use extra attention and clarity in the manuscript's next iteration. For example, the discussion in lines 70-78 regarding tornado-related fatalities in Florida is a bit confusing. I am not sure that I follow the argument that "strong tornadoes ... responsible for 97% of tornado fatalities" is consistent with "92% of fatalities were reported in F3 or weaker tornadoes." [Are] the majority of tornadoes, then, F2 and F3 tornadoes? A more direct statement here could be helpful for clarity.

*Agreed. I used the SPC annual U.S. killer tornado statistics data to develop a more coherent argument in this section that should make more sense to the reader.*

Further, while I appreciate the discussion on evening and overnight tornadoes, especially given the environmental parameter space in which this event occurred, I'm not sure that it is relevant to the case study at hand. After all, the tornadoes here occurred during the daylight hours. As a result, this discussion could be trimmed or omitted.

*I trimmed it and added a caveat-type statement.*

I have some concerns regarding your definition of "inflow-proximity" soundings. While TLH and JAX may be within two hours of the first severe-storm reports, they are well-removed from the tornado event of interest. Given that recent modeling work corroborates anecdotal evidence of rapid environmental evolution (e.g., King and Parker 2015) preceding severe high-shear, low-CAPE events, I am not convinced your "inflow-proximity" soundings are representative of the environment supporting the tornado of interest. While the comparison between observed soundings and Hagemeyer (1997)'s mean soundings is worthwhile, I feel that the time spent on this portion of the study is a bit disproportionate to the supporting evidence provided. If you'd like to include this discussion in its entirety, I would recommend using more hesitant language and a mention of this method's caveats (e.g., mean soundings likely smooth important features; offset in time and space of soundings and tornado event of interest).

*I modified this section to state that I was most interested in determining whether the pre-storm environment was consistent with the climatology for that area in terms of static stability and vertical wind shear. I also realized that the TLH and JAX soundings were not part of Hagemeyer's (1997) climatology, so I added a cautionary statement to that effect.*

Along the same lines, you spend an awful lot of time comparing storm-relative helicity values among the different soundings; however, these values are subject to a number of caveats, including the calculation of the storm motion vector, as mentioned. These discussions could be pared down due to the given uncertainties and the observed convective mode.

*Another reviewer had similar comments, so I decided to delete the SRH/ESRH discussion from the paper (two of the three reviewers commented on the paper's length, which was further justification).*

Finally, the comparison of observed deep-layer shear vector magnitudes and the supercell parameter space seems a bit off. Namely, a 0–6 km shear vector magnitude of 25 m s<sup>-1</sup> is well within the range generally thought favorable for supercell formation; I think the typical cut-off is around 18 m s<sup>-1</sup> (35 kt). This is also generally considered the threshold for "high shear" in high-shear, low-CAPE literature (covered by Sherburn and Parker 2014, as cited in the manuscript). Some adjustment to the wording within this section is thus warranted.



*Agreed. Don't know how I missed that! Changes made.*

*[Minor comments omitted...]*

**REVIEWER B (Barbara M. Boustead):**

**Initial Review:**

**Recommendation:** Accept with major revisions.

**General Comments:** The paper has the feel of a preprint or term paper and needs much work to reach publication readiness. That said, I do understand that this is an event that is close to home to the author. There do appear to be kernels meaningful and interesting results, and I encourage the author to take the time to prepare the manuscript to support those results so that this paper can be published.

The paper as a whole feels unfocused and lacks clear purpose or intent of the study. Case studies have their role, but this one feels like the author had a kitchen sink of stuff about that event that he wanted to pull together without a “so what” conclusion to shape and form the analysis. Is it the LLWAS analysis (as I believe it should be)? If so, then that needs to be highlighted more in the title and introduction. Is it the mesoscale and synoptic environment which somehow uniquely contributed to this event? If so, then this should be the focus of background material. Whatever the focus is, that should be strengthened substantially in the paper, with deeper analysis and more background information as well as clearer conclusions and perhaps a revised title.

*I totally reorganized the Introduction based on your recommendations. There is now a “Motivation for the study” subsection that discusses FL peninsula tornado climatology, with specific focus on strong (F/EF2+) events in the dry season and their disproportionate casualty statistics. This information is combined with additional demographic information about transient population (snowbirds), mobile home percentages of total housing units, and occurrence of nocturnal tornadoes. This information is then presented against the backdrop of a companion study I submitted to another journal that focused on how close Daytona came to a catastrophic event on that day. I should've put more of that information in the earlier revision. I added a subsection “Previous severe-storm studies over central Florida” to illustrate the paucity of individual case studies for this region, save for the 22–23 February 1998 event. I added information about other severe-storm studies for this region, and used that to put Hagemeyer's climatological studies into a little better perspective.*

*Finally, I included a “Study objectives” subsection that outlines my intentions to:*

- 1) Investigate the atmospheric conditions on the morning of 25 Dec. to compare them to Hagemeyer's climatology;*
- 2) Examine the NEXRAD data to look for signatures characteristic of QLCS and bow echoes, and integrate that information with the unique wind tower data obtained from the LLWAS; and*
- 3) Put this case into a climatological perspective with cold-season severe-storm climatological studies. I chose to put ‘3’ into the Discussion section in order to focus on the case itself in sections 3 and 4.*

The structure of the paper needs attention. Section headers, especially sections 3 and 4, do not match the information presented under them. Section 3, for example, includes mesoscale in addition to synoptic-scale environmental information. For section 4, the label “squall line” feels too broad and inaccurate. The analysis of the LLWAS information, which seems to be one of the primary components of the paper and perhaps the most interesting contribution to the body of literature, could use its own section.

*I renamed these sections in the revision. In the revision, section 3 (“Atmospheric conditions over Florida during the morning of 25 December”) has two subsections, “Synoptic scale analyses” and “Analysis of soundings”. In the first subsection, I consolidated the 1200 UTC surface analysis and regional radar*

*mosaic, the 1200–1800 UTC composite analyses and GOES imagery, and the 1800 UTC wind cross section so that the discussion is more focused. The sounding-analysis subsection has all of the discussion of stability and wind shear parameters. I think this presents a better organizational feel to the revised paper. I chose to add some additional information about the LLWAS in the Discussion section.*

All numerical values in the paper need to be revisited to use metric values consistently, including meters per second for wind and motion speeds, hPa for pressure (including pressure levels), °C for temperature, and m or km for distances; also, ensure that numbers are formatted properly, with a space between the number and each unit in the label (i.e. “25 m s<sup>-1</sup>”). If you believe that the English units are important for understanding, then include those in parenthesis. Dates should be stated in a common format (i.e. “25 December 2006”) rather than colloquially (“the 25th” or “Christmas”).

*These changes have been made in the revision. There are a couple of exceptions where it wasn't practical (e.g., Fig. 5a, surface chart, which is in °F, and ASOS winds in Fig. 14, which remain plotted in kt [although I use m s<sup>-1</sup> in the text]. Also, the LLWAS tower time series graphs remained displayed in kt.*

There are a number of grammatical errors that I will not correct in this first review, other than my comments here, as I expect that the entire paper will change substantially and most of the sentences containing grammatical errors will change. My second review will be much more particular with the details. I'd recommend to the author to have an in-house friendly review of the grammar before resubmitting the manuscript. Be certain to define acronyms before first use, and be sure to use NCEI instead of NCDC everywhere. *[Editor's Note: Where the NCDC subsidiary of NCEI preceded NCEI, or was a specific data source, the acronym NCDC is acceptable for use in citations. Also, some acronyms are common enough (e.g., CAPE, NCDC, NOAA, NWS, et al.) to not need expansion. If there are any questions on one, feel free to ask the editor.]*

*Noted. I believe that these inconsistencies have been changed in the revision.*

Finally, if the author wishes to critique NWS operations, I would strongly suggest partnering with an NWS co-author or someone with experience in analyzing NWS warning operations to validate the methodology and impacts of the warning process, or at least indicate some communication with NWS staff who worked during the event and document the statements made. Otherwise, the critique feels undersupported and out of place and should be removed.

*I removed all references to individual NWSFO warnings in the revision.*

Section-by-section comments are a bit on the brief side, but they are requesting broad changes, rather than specific details, at this point.

**Major Comments:** In addition to the summary above, here are a few more specific comments:

1. Introduction: The paper suffers from a lack of thorough literature review and background. It provides a good description of the event and its impacts, but it stops there. The tornado climatology of Florida and its vulnerability to tornado damage and casualties have been studied in the past and should be included here. Additionally, since the title alludes to multiple scales of analysis, these scales should be specific in the introduction, with supporting background literature. From the introduction, I should be able to anticipate the intent of this paper and should have a sense that the author is aware of past research that is related to it.

*Please see my responses to first general comment on page 1. I believe that the organizational changes made have addressed the reviewer's concerns here.*

2. Data and methods: LLWAS is not terribly commonly used, and the readers would benefit from more information about the system, either in the introduction or here.

*I chose to place additional information about the LLWAS in the Conclusions rather than here. My primary reason for doing that is because I believe that the Conclusions are a good place to mention that there is not a lot of literature on employment of the system save for conference papers and tech reports that provide a more project-focused discussion (e.g., use of the LLWAS with TDWR and testing of its accuracy). This is a good place to advocate for its increased usage in severe-storm research, especially given its heritage (e.g. JAWS project from the 1980s). If the reviewer feels that this is better placed in section 2 after reading the revised paper, I can certainly do that.*

Data sources were covered here, but methodology was not described. What was done with the data? What analyses were performed? This section feels quite brief, and it needs to be more specific. In particular, analysis of rotational shear (which I'll describe more in my review of section 4) should be documented here.

*Although I did include some additional methodological descriptions in the revision, I embedded a good portion of the analysis methodology for the NEXRAD and LLWAS data in section 4 (retitled, "Meso and storm-scale analyses"). It seemed better to put the descriptions here where they could be adjacent to the results of the analyses themselves. Here again, I am open to moving this should the reviewer still believe that it needs to be in section 2 after reading the revised paper.*

3. Synoptic-scale conditions over Florida during the morning of 25 December: The organization of this section needs work. Right now, it seems to bounce from a broad synoptic overview to sounding analysis and then back to a synoptic overview. I'd suggest organizing from large to small spatial scale (the "forecast funnel" model), and then from farther in advance to near the time of the events being studied.

*As mentioned earlier, I reorganized this section as, "Atmospheric conditions over Florida during the morning of 25 December", and included the synoptic-scale and sounding-based analyses as subsections. I then titled section 4, "Meso and storm-scale analyses", and had subsections describing the QLCS evolution from 1600 to 1800 UTC, and one on the integrated analysis of NEXRAD, ASOS, and LLWAS in the vicinity of the DAB tornadogenesis. I believe this provides both a temporal and spatial progression that is more coherent.*

I am a fan of the composite images drawn to depict the synoptic environment of this event. ... The analysis does, and should, delve into mesoscale analysis, and for that reason, I suggest retitling the section header. Be certain to specify what type of CAPE and CIN you're using (SB? ML? MU?), as well as the layer of SRH being analyzed (0–3km? Effective?). I like the concept of Fig. 6, but the figure itself is so busy with words that it is cluttered. The 0–3-km SRH discussion (lines 336–346) implies that value of  $215 \text{ m}^2 \text{ s}^{-2}$  is not favorable for tornadoes, but while it does fall outside the envelope in H97, it is still supportive of tornadoes.

*This section has been revised and the figure has been replaced with a series of hodographs (Fig. 9 in the revision). Specific mention of MLCAPE has been added, and caveats regarding usage of 0–3-km SRH have been added based on recommendations from another reviewer. Both SRH and ESRH are used in the revision; the former in section 3b and the latter in the Discussion as a means to place this case into the context of severe-storm climatological studies other than Hagemeyer's (this was also done as part of my responses to other reviewer comments).*

Use caution when examining the 0–3-km SRH (lines 400–408), as those are highly dependent on storm motion. Since the tornadic circulations were embedded within a squall line, rather than following Bunkers supercell motions, these values may not be representative.

*Yes, thank you for pointing this out. Another reviewer also stated this. I was able to find a document online that explains the storm-motion assumptions of the version of SHARP that Hagemeyer likely was using, and I pointed out that the parameters for these soundings are taken from the SPC database, which in 2006 was using the Bunkers method. As mentioned above, I've added a caveat to the SRH discussion that describes*

*these different methods (along with a link to that online SHARP document), and that they should be considered carefully because of the supercell assumption.*

In the discussion of Fig. 7e, the position of the jet as discussed here is not consistent with the earlier discussion. Also, 500-hPa winds have little relationship to surface winds (i.e. strong downdrafts, straight-line wind damage, or bow echoes).

*I believe that with consolidation of the synoptic-scale composites in a single subsection, that any inconsistencies have been resolved. The statement regarding 500-hPa winds has been removed.*

I'd like to see further analysis of the mesoscale environment, including and especially boundaries, as well as pockets of locally higher low-level shear and/or instability.

*While I didn't specifically examine these, I believe that the revised figures using the NEXRAD base reflectivity and SRV/MDA provide a reasonable analysis of the mesoscale environment as the bow echo moved into Volusia County after 1800 UTC.*

4. Squall line over central Florida: The section on the DAB tornado timeline using the LLWAS and one-minute ASOS data are the main reason that the paper was accepted (with major revision), as I think it is the most unique and substantive part of the paper. Ensure that all pressure units are in hPa throughout the section, including in Fig 12. Because the data are unavailable in real-time and usually not shared outside of the aviation community, you have an opportunity to demonstrate benefit of their analysis, via your access to the data, to the community.

*Changes have been made in the revision, and the new Fig. 16 should provide a better integration of these data sources.*

I would suggest using  $V_r$ -shear plots to characterize the rotation, with criteria for rotation width and distance from the radar that are vetted in the literature (i.e. Atkins and St. Laurent 2009 or one of many others), to make the analysis of mesocyclones and associated tornadoes less subjective and more precise.

*I probably spent more time on this part of the revised study than any of the other sections. I obtained both an MDA-derived nomogram from the Falk and Parker paper and adapted it to MKS. I also spoke to Scott Spratt, the WCM at MLB, and he provided me with a link to a 1997 WAF paper where they employed a modified version of the nomogram to TC outer rainband tornadoes. He told me that they use this nomogram for both T as well as ET systems. I chose to put some of my  $V_r$  calculation results in section 4, but the nomogram plots in the Discussion. My rationale is that putting the nomogram results in the Discussion was consistent with my intent of putting this case into a proper context regarding convective mode, which was a point that one of the other reviewers made. I believe that the results presented in Figs. 12, 16, and 17 in the revised paper have improved the precision of the analyses.*

I reiterate that the analysis of warning operations feels out of place and unsupported in its current state here. A co-author with knowledge of the warning operations may be able to provide insight. Otherwise, references to the warning process, especially ones that are unsubstantiated (i.e. "Based on this new report, the Melbourne NWSFO issued a new tornado warning..." Unless you have directly contacted the warning meteorologist—and if so, it should be cited—the statement is an assumption of their reasoning for issuing a new tornado warning), should be removed from the paper, leaving the focus on the storm and its impacts.

*Removed in the revision.*

With the radar images, for this analysis, it would make sense to use the closest radar to the circulations. The radar used in Fig. 10 seems awfully distant from the circulation. Also, keep in mind that at these ranges, the radar is only going to be able to observe the mesocyclone, rather than the actual tornadic circulation.



*Figures 9–11 have been replaced in the revision. The new Fig. 11 shows an overview of the system as it crossed central Florida. I chose to concentrate primarily on the 30 min prior to the DAB tornado and the period 1833–1841 UTC at DAB itself in order to shorten it and keep the reader focused primarily on the DAB event.*

5. Discussion: Many points of the discussion would benefit from further expansion and background. For example, when citing the statistic that 78% of FL peninsula tornado deaths are associated with dry-season events, how many of the total events are dry-season? (In other words, is that 78% proportionate or disproportionate?). The assumption that the population does not expect tornadoes in the dry season should be documented and substantiated, as should the claim that transient residents don't expect severe weather. The point about the benefit of real-time mesonet data warrants further expansion and documentation.

*Please see my response to the first general comment on page 1. That addresses the reviewer's first two comments about the Discussion. In the revised paper, the Discussion is totally different, so the reviewer's last point has been addressed by means of my eliminating this from the revision.*

It is important to understand the bow echo/QLCS structure and the environment ahead of it. It would be useful to overlay 0–3-km shear vectors over the bow to show areas where there is line-normal shear, highlighting areas of interest given the ambient shear.

*This was done indirectly in the revision by means of including the hodographs for the four rawinsonde stations, along with plots of the 0–6 km shear vector, per recommendation from another reviewer. One could look at the shear vectors in Fig. 9 and infer the orientation to the QLCS/bow echo. I didn't specifically mention this in the revision. If the reviewer believes that it should be discussed more directly after reviewing this revision of the paper, I am certainly open to doing so.*

6. Conclusions: You mention that comparison of case studies to conceptual models could be beneficial, but such comparisons in this study are superficial at best. What conceptual model does this fit and how, and what about it was surprising or did not fit the model?

*The only conceptual model was shown by Hagemeyer in a 1998 conference paper and it was likely not based on any rigorous compositing of surface and upper-level features associated with dry-season tornado events on the peninsula. I have eliminated this from the revision.*

*Hagemeyer, B. C., 1998: Significant extratropical tornado occurrences in Florida during strong El Niño and strong La Niña events. Preprints, 19th Conf. on Severe Local Storms, Minneapolis, MN, Amer. Meteor. Soc., 412–415.*

The section on ENSO is out of place in this paper and can be removed.

*Done in the revision.*

Reviewer reference:

Atkins, N.T., and M. St. Laurent, 2009: Bow echo mesovortices. Part II: Their genesis. *Mon. Wea. Rev.*, **137**, 1514–1532.

*[Minor comments omitted...]*

## **Second Review:**

**Recommendation:** Accept with minor revision.

**General Comments:** While significant improvements have been made to the manuscript since the first draft, I believe there are still a few lingering major issues to correct before it is ready for publication. There

is still some meandering of focus, as well as some scientific corrections to make. The paper is too long for the information contained in it, and I think significant trimming can be done. The paper has come along enough that I will include some of the more overarching “minor” grammar/style corrections, as well, noting that they collectively are a major requirement for publication. I do like the extended discussion of the LLWAS wind profiles, in comparison to the ASOS and WSR-88D winds; it remains the most interesting part of the paper, and I would like to see it highlighted even more. The analysis could get a stronger mention in the abstract and perhaps even in the title.

*Approximately 700 words and three full pages were deleted from the earlier draft. Two full figures were eliminated and several others were consolidated. I added a figure (14j) that shows a time series of winds at LLWAS Towers 5, 9, and 8 for the period 1837–1839 UTC, right around the time of the tornado’s appearance on the east end of DAB runway 7L/25R. This time series focuses on the appearance of the second suspected cyclonic circulation (between Towers 9 and 8), and highlights the utility of having such data available at 10-second intervals. I added some information from the NEXRAD SRV and ASOS altimeter onto that chart in order to show how the information could be integrated. The abstract has been modified but I left the title as is, since the LLWAS is not the main focus. I did add a statement in the Conclusions that referenced the STL tornado in April 2011 and how LLWAS could potentially be used as a monitoring and nowcast tool in the airport environment. Hopefully this version of the paper is clearer and more focused.*

**Major Comments:** Below are specific comments requiring major revision:

1. Several scientific errors in analysis need to be corrected.
  - a. In the discussion on 0–3-km storm-relative helicity, it is more correct to say that it differentiates tornadic potential, rather than supercell potential (which is better determined by 0–6-km bulk shear). The paragraph needs to be revisited in that context.

*This discussion has been deleted from the revision.*

- b. The discussion about Bunkers storm motion comes around to state that Bunkers motion is not representative because the storms are not supercells. This is exactly the case, and any storm motion used in the rest of the study should be calculated from actual storm motion, rather than estimated from Bunkers or any other algorithm. The whole discussion could be boiled down to one sentence that Bunkers motion is not appropriate, with a description of how actual storm motion was calculated.

*This discussion has been deleted from the revision.*

- c. The 0–6-km shear vectors in Fig. 9 should originate from the point of the surface wind, rather than from the origin.

*Corrected in the revision.*

2. The paper should be pared down to cull sections that are extraneous or, frankly, not all that interesting or unique. For example, having five panels of regional composite radar as the line/bow crosses the FL peninsula (Fig. 11) is overkill, especially since a regional composite was shown in Fig. 5b already. One composite near the time of tornado evolution would be adequate before zooming in on the QLCS segment of interest. The other tornadoes in the event deserve a brief mention, but the combination of the event overview and single-image regional radar should take up roughly a paragraph for context. Section 4a is likely too long and detailed, detracting from the more research-quality results later in the paper, and I can’t discern the features as you describe them, anyway (for example, the images don’t allow me to see that the reflectivity gradient had tightened).

*In the revision, I have one figure (10) that summarizes the QLCS progression from 1700 to 1800 UTC. The associated discussion of section 4a now encompasses lines 662–683.*

3. Several figures are still hard to read or need other significant revisions.
  - a. Figure 2: With red highways and red boundaries, the red tornado tracks are difficult to spot. The green background may also be a problem for color-blind readers; a simple white or light tan would be better to ensure the tornado tracks stand out. Also, please include the years of the included tornadoes in the caption.

*Modified for readability in the revision.*

- b. Figure 7, if it is retained, needs an inset map to show the cross-section axis from a plan view. That said, I think it is overkill to include it; there is no argument that there was a jet max that aided lift, and that jet is depicted elsewhere, such as in Fig. 6.

*This figure was deleted in the revision.*

- c. On the Figs. 12 and 13 series, whatever is written on there is unreadable and should be either larger (if it is important) or removed (to prevent distraction). I'm assuming that the radar data are from the 0.5° level, but this needs to be specified in both the text of the paper (lines 782–783) and in the figure caption. The labeling in Fig. 12d is too small. The underlying base map is unnecessarily cluttered with some kind of dual coloring that is not included in a legend and not relevant to the radar imagery; it would be better as a solid color. The rectangle highlighting the DAB airport area should be bolder; is a more precise outline available to use?

*In the revision, the text and figure captions were modified to clarify the elevation angle being examined. Fig. 13 was deleted, and in the revision, only the SRV displays were retained (now Fig. 11); these were enlarged and the map background changed to grey scale. The location of DAB should be easier to see in these three panels.*

- d. Figure 16: The gray lines for the runways are hard to discern from the wind barbs.

*Now Fig. 14 in the revision, the changes were made.*

- e. None of your maps include the location of the Embry-Riddle campus. It would be helpful/interesting to see its location in relation to DAB. Perhaps Figure 15 or 16 would be the place?

*In Fig. 14, the tornado appearance location is now shown by a symbol, and the campus location by ERAU.*

4. In the discussion section, I'm not sure of the purpose of discussing EBWD and ESRH at length. BWD and SRH were discussed earlier, and this is essentially something of a repetition, but different enough to be somewhat confusing. I'd rather see you use one or the other throughout the paper.

*The original purpose of including these was to address concerns in earlier drafts about use of appropriate shear diagnostics from the soundings, and to put this case into a proper climatological perspective regarding convective mode. In the revision, I deleted the discussions pertaining to SRH and ESRH, and kept the 0–6-km wind shear discussions. Since this was a QLCS with bow echoes, I also deleted a lot of the references to supercells, except where I thought it appropriate (e.g., latter part of section 3b).*

5. The nomograms in section 5b are old, based on 4-bit radar data, and few offices still use them. They would have been in use at the time of the tornado in this case, but the analysis does not have much extension into current operations. Newer studies that are investigating  $V_r$  for the purposes of impact-based warnings make better use of the high-resolution data that we have now. Be sure all the language in this section is past tense, and consider adding language that recognizes the advance in technology in the 10 y since this case. That said, thank you for including  $V_r$  information for the mesocyclones associated with this tornado. I would have liked to see the  $V_r$  information in a more traditional chart (time on the x-axis,  $V_r$  on the y-axis) to see the evolution, and I still think it would add useful information if you can include it. Finally, keep in mind that the nomograms helped detect the strength of a mesocyclone, not the location (line 1208) or potential for development.

*I added a short passage about the recent advances in radar data resolution, and modified the wording to emphasize that older techniques were being employed in this study. I confirmed with Scott Spratt at the MLB NWSFO this afternoon that the older nomograms are still used at MLB when the new dual-pol data sets and 3-D reflectivity/velocity profiles don't show that much. I consolidated the old Figs. 17a and b into a new Fig. 15 that has the criteria for both nomograms on the same chart, and more clearly displays time stamps on the observations. Modifications have also been made to the discussion on how the nomograms are employed.*

*[Minor comments omitted...]*

**REVIEWER C (Richard L. Thompson):**

**Initial Review:**

**Recommendation:** Accept with major revisions.

**General Comments:** This work examines a cool-season tornado event across the FL peninsula from 25 December 2006, with specific emphasis on an F2 tornado formed at the DAB airport and damaged the Embry-Riddle Aeronautical University campus, in associated with a bow echo. A synoptic overview of the event is provided, and sounding-derived parameters are compared to the climatological work by Hagemeyer for FL tornadoes. On the storm scale, high-resolution observations from the DAB complex were combined with WSR-88D data to describe the near-storm environment and to identify changes in storm structure leading up to tornado formation.

The case itself is reasonably interesting, and the near-surface observations around DAB provide a unique look at a QLCS tornado event. As it stands, this version of the paper is a clear improvement to an earlier version submitted to a different meteorological journal. I would like to see this event put into the larger perspective of cool-season tornado events across the CONUS, and would like to see a bit more discussion regarding convective mode and how the storm environment compared to other climatological studies like Thompson et al. (2012), where supercell and QLCS tornado environments were examined. Mostly minor changes to this work will improve the presentation and make it worthy of publication in EJSSM.

*Rather than addressing this here, I address it in the context of the specific comments mentioned below.*

**Specific (substantive) Comments:** Do you know if the virtual temperature correction was used in the CAPE/CIN calculations, and which lifted parcels were chosen? I assume the virtual temperature correction was not applied to your soundings since the listed CAPE values are  $\sim 200 \text{ J kg}^{-1}$  lower than what I can reproduce for the same soundings using NSHARP software (lifting the lowest 100-mb mean parcel, with the virtual temperature correction applied). Hagemeyer (1997) used what I think was the PC version of SHARP from sometime in the early 1990s, which likely didn't include the virtual temperature correction.

*In the revision, I used the MLCAPE and CIN calculated from the soundings you provided me at <http://www.spc.noaa.gov/exper/soundings/archive>, which I believe does use the virtual temperature correction. I was able to locate what appears to be a SHARP user's guide at [http://www1.ncdc.noaa.gov/pub/data/software/cdrom/rsonde/sharp\\_exe/](http://www1.ncdc.noaa.gov/pub/data/software/cdrom/rsonde/sharp_exe/), which has links to a number of the menu items including the stability calculations. I wasn't able to discern whether the program used a virtual temperature correction. I have used the MLCAPE values from the soundings you provided in the revision. I would agree that Hagemeyer's calculations didn't include this correction because I didn't see it in the documentation I found from NCEI. I didn't mention the virtual temperature correction in the revision. If you think it should be highlighted after reading this revision, I would be more than happy to include it.*

What storm-motion assumption goes into your SRH estimates? Hagemeyer (1997) likely used the 30R70 (30 degrees right of and 70% the speed of the mean wind, though I don't recall the layer used for the mean calculation). The SPC mesoanalysis graphics used the Bunkers et al. (2000) supercell motion estimate in



2006, and now use the updated estimate documented by Bunkers et al. (2014). It's worth noting that you're assuming a supercell motion for your SRH estimates, yet the event is QLCS in nature.

*According to the documentation I found (described above), the version he likely used assumed a 30R75. As I've now included hodographs (Fig. 9), I inserted a caveat to the SRH values calculated in this case, based on your comments.*

Storm longevity appears to be related to much more than just 0–3-km shear, especially when discussing supercells. Bunkers et al. (2006) found that vertical shear through a deeper layer (0–8 km) was the best discriminator between short- and long-lived supercells. Similarly, the early numerical modeling work by Weisman and Klemp suggested that vertical shear needed to extend through at least the lowest 5–6 km AGL to get sustained supercells, and these findings were later confirmed by multiple proximity-sounding investigations. Hodograph shape and length are helpful to anticipate storm type (in combination with buoyancy profiles), but no hodographs are shown. Additionally, convective mode should probably be discussed w.r.t. this case, since the tornadoes were apparently produced by mesovortices with a bow echo, yet the other cited tornado events were supercellular in nature. I have recreated the observed soundings for this case: <http://www.spc.noaa.gov/exper/soundings/archive>.

*I replaced the 0–3-km shear with the 0–6-km shear. I was able to determine that I could compare the values computed from the soundings you provided with those of Hagemeyer. I included these in hodographs (Fig. 9) and compared them to those of Hagemeyer by graphing them on the same chart. I also included the shear vectors for both sounding and composite on each hodograph chart. Thank you for providing me with this site. It made the comparisons easier to do because I had the SPC/NSSL documentation to fall back on, vs. using the values calculated from either the Plymouth State or Univ. of Wyoming archives, which I had done in the earlier draft. Neither site provides documentation on how they calculate their values; Plymouth State apparently used a version of WXP, and I was able to find some documentation on that, but your sources are much better.*

*I also introduced a discussion of convective mode in the Discussion section. Based on recommendations from another reviewer, I employed  $V_r$  nomograms in the revised analysis and included comparisons of mesocyclone strength between the MDA-derived (Andra) version and one provided me by Scott Spratt at the MLB NWSFO. I address the somewhat ambiguous (to me) idea of using a tool that is more associated with supercells in a case that was a QLCS with bow echoes. I saved it for the Discussion because I wanted to concentrate on reporting the results of the analysis in section 4. I was not that familiar with the latest literature on convective mode determination in a climatological setting, and I think I (hopefully) provided adequate justification for using them.*

It would be nice to see this event compared to the cool-season events from Thompson et al. (2012; Figs. 17–22). This biggest difficulty in such a comparison, however, is the difference in vertical shear parameters presented by each.

*I attempted to do this in the Discussion section, and compared the 1200 UTC soundings in this case with a number of the figures in your paper. I also used the Burke and Schultz (2004) paper on cold-season bow echo climatology, although some comparisons were difficult (e.g., 0–5 km shear vs. 0–6 km shear).*

Ultimately, ENSO phase is trumped by near-storm environment. The only meaningful aspect to something like ENSO would be the tendency for “favorable” storm environments to occur across FL in particular ENSO phases. Still, the ENSO phase is irrelevant once you can observe the details of the storm environment, and any expectations of a more- or less-active tornado season make no difference in specific day-to-day weather events.

*I understand your reasoning, but during an ENSO phase we see a strengthening of the polar and subtropical jets at these lower latitudes. Hagemeyer has done extensive study of the relationship between ENSO phase and a higher likelihood of severe weather environments being observed here. Having said this, I changed the Conclusions section entirely and this no longer appears in the revision.*

There has been no discussion of convective mode or QLCS mesovortices versus supercell mesocyclones, though both appear to be relevant in this case. For example, buoyancy was larger than is typically seen with QLCS tornadoes in the cool season (primarily across the Southeast U.S.). The squall line is just assumed to be present in this paper, with little attempted explanation for why a linear mode should continue. This is example where I would like to see the details of this event put into greater perspective than just previous FL tornado events.

*I attempted to do this in the Discussion section by calling on the literature that I alluded to earlier. The inclusion of the Burke and Schultz paper was interesting because the CAPEs for their Gulf Coast bow echoes were higher than in this case; however, that is likely because they were using MUCAPE.*

*[Minor comments omitted...]*

**Second Review:**

**Recommendation:** Accept.

**General Comment:** I have no significant concerns.

*[Minor comment omitted...]*