P3.24

ATMOSPHERIC CONDITIONS ASSOCIATED WITH THE EMBRY-RIDDLE TORNADO OF CHRISTMAS DAY 2006

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1. INTRODUCTION

During the early afternoon of 25 December 2006, a tornado with estimated F2 intensity struck the Daytona Beach campus of Embry-Riddle Aeronautical University (ERAU), causing approximately $50 million of damage to the university's training aircraft and buildings before moving eastward and significantly damaging an apartment complex about two miles away. Fortunately, due to the holiday, the campus was empty and there were no casualties there or at the apartments.

Analysis of this case begins with a discussion of Florida tornado climatology. Next, the synoptic-scale conditions observed during the 12 hours preceding the time of the ERAU tornado touchdown are examined. Thermodynamic and wind profiles taken from pre-storm warm sector soundings are compared to Hagemeyer and Schmocker's (1991) dry-season climatological composite soundings. The mesoscale environment in the hours immediately preceding the tornado is examined through a combination of hourly analyses from the Rapid Update Cycle-2 (RUC-2) model (Benjamin et al., 2002), and storm-relative velocity and composite reflectivity radar data from the WSR-88D at Melbourne, Florida. Analysis of the local conditions in the immediate vicinity of the tornado is accomplished using a combination of the data from the Melbourne WSR 88D and the Low-Level Wind Shear Alert System (LLWAS) from Daytona Beach International Airport. Additional analysis of the conditions associated with the tornado's initial touchdown is accomplished through examining the parking diagram for the 65 training aircraft operated by the university and comparing the aircraft tail number positions with damage photographs taken in the days immediately following the event to determine the damage trajectories from touchdown. Finally, an intriguing piece of cockpit data recovered from one of the damaged aircraft suggests that the tornadic winds were approximately 120 kt and associated with a 70-80hPa pressure drop, roughly consistent with the F2 damage recorded by the National Weather Service survey team.

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2. FLORIDA TORNADO CLIMATOLOGY

How unusual are December tornadoes in Florida? This was a common question asked by many students, faculty, and staff in the days and weeks following the event. According to a 1950-1995 climatology presented by Lott et al. (1999), Florida ranks fourth in the nation in average annual number of tornadoes with 46, just behind Kansas. When the numbers are averaged over 100-mile squares by state, Florida has the highest frequency in the nation with 8.4 tornadoes per 10,000 square miles (see their Figs. 4 and 5). According to Hagemeyer (1997), the lowest monthly tornado frequency (less than 50 total during a 45-year period of record) occurs in the months of November and December (his Fig. 6), so if one only considers the tornado climatological frequencies, this was in fact a rare event. However, there are additional climatological considerations, and these are discussed below.

2.1 *Atmospheric Flow Regime and Tornado Occurrence in Florida*

While significant tornadoes are not a common occurrence in Florida in December, there are certain types of atmospheric flow patterns that make severe storms more likely, and these vary by season in Florida. Hagemeyer and Schmocker (1991) developed tornadic environment climatologies for east-central Florida for the dry season (defined as November to April) and the wet season (defined as May to October). Hagemeyer (1997) expanded on that study and defined a *Florida peninsular tornado outbreak as having at least four tornadoes reported in a four-hour period or less*. Using this definition, he documented 35 outbreak cases, classified them under three types, and produced climatological composites for each: 1) those associated with extratropical cyclones; 2) those associated with a tropical cyclone of tropical storm or hurricane strength; and 3) those associated with hybrid cyclones having both tropical and extratropical characteristics. The extratropical cyclone type of outbreak predominates in the dry season, and the Christmas Day case falls into this category. An examination of the Storm Data reports from this day, shown in Table 1 and plotted in Fig. 1 below, confirms that the Christmas Day case had enough tornado reports within the specified timeframe to meet the criteria for a peninsular tornado outbreak as defined by Hagemeyer.

Location or County	Date	Time	Type	Mag	Dth	Inj	PrD	CrD
1 Live Oak	12/25/2006	07:43 AM	Thunderstorm Wind	50 kts.	0	0	10K	0K
2 Lulu	12/25/2006	08:06 AM	Tornado	F2	0	1	0K	0K
3 Pasco	12/25/2006	11:20 AM	Tornado	F2	0	2	3.5M	0K
4 San Antonio	12/25/2006	11:20 AM	Thunderstorm Wind	60 kts.	0	0	30K	0K
5 Webster	12/25/2006	11:47 AM	Thunderstorm Wind	70 kts.	0	0	80K	0K
6 Leesburg	12/25/2006	12:20 PM	Tornado	F0	0	0	250K	0K
7 De Land	12/25/2006	13:22 PM	Tornado	F2	0	5	2.5M	0K
8 (dab)daytona Bch Arp	12/25/2006	13:40 PM	Tornado	F0	0	6	50.0M	0K
9 Center Park	12/25/2006	13:48 PM	Thunderstorm Wind	50 kts.	0	0	10K	0K
				TOTALS:	0	14	56.380M	0

Table 1. Florida Storm Data Reports for 25 Dec 2006 (courtesy of National Climatic Data Center)

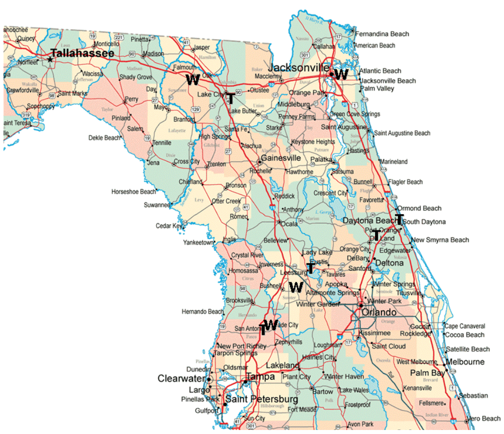


Fig. 1. Severe storm report locations from 25 December. "T" stands for tornado and "W" stands for severe-thunderstorm winds.

2.2 *Florida Tornado Likelihood during El Niño/La Niña Episodes*

An additional consideration in determining the likelihood of December tornadoes in Florida is the presence of El Niño/La Niña. During the start of the 2006-2007 winter season, a strengthening El Niño was being observed over the tropical Pacific (see http://www.cdc.noaa.gov/people/klaus.wolter/MEI/ for a Multivariate El Niño Southern Oscillation (ENSO) Index time series that includes this episode). Several studies have attempted unsuccessfully to determine a clear-cut statistical relationship between tornado occurrences in Florida and ENSO phase. Schaefer and Tatom (1999) found a weak relationship between ENSO phase and annual tornado coverage fraction and number of F2 or greater tornadoes at the 10 percent significance level. Hagemeyer (1999) found a strong relationship between significant (F2 or greater) tornadoes associated with extratropical cyclones and ENSO phase when comparing the strong El Niño and La Niña episodes of 1982-83 and 1988-89, respectively. In his study, the 1982-83 El Niño produced a more favorable synoptic-scale environment with a strong upper-level jet stream over the Gulf of Mexico and Florida peninsula, compared to the 1988-89 La Niña episode, during which the jet stream was displaced north of its climatological position and there was lower tornadic activity.

While the relationship between tornadic activity and ENSO phase is not as well defined for the weaker episodes, it is worth considering the possibility of more or violent severe storms during an El Niño episode because the atmosphere is more likely to display favorable upper-level dynamics for severe storms. Since this El Niño episode was just beginning to emerge in the fall of 2006, it is fairly safe to say that most people in east-central Florida were not expecting a severe-storm outbreak in December until the Storm Prediction Center began discussing it in their Day 2 Outlooks (not shown).

3. SYNOPTIC AND MESOSCALE ANALYSES

3.1 *Primary Synoptic Features at 1200 UTC on 25 December*

Figure 2 shows the surface analysis from the Hydrometeorological Prediction Center (HPC). There is a deepening 1001-hPa surface low moving through the Gulf Coast states with a strong cold front located in the eastern Gulf of Mexico. A coastal warm front is beginning to form over the Carolinas, and a persistent cold wedge can be observed in the pressure and temperature fields over the interior sections of the Carolinas and Georgia. A subjective analysis of surface dew points shows an abundance of moisture from just ahead of the cold front into the Florida panhandle and southern Georgia. Dew points over the peninsula were generally between 68 and 72˚F, indicative of above-normal moisture and temperature conditions (e.g., average high/low temperature for Daytona Beach on 25 December is 69.8/49.9˚F).

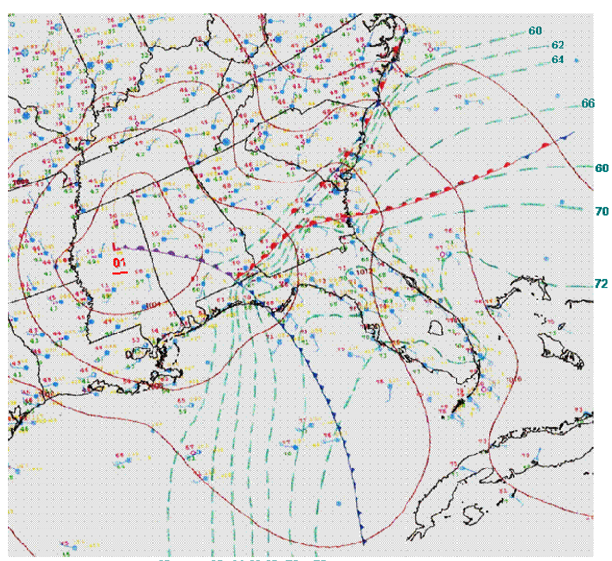


Fig. 2. 1200 UTC HPC surface analysis with dew points ≥ 60˚F shown by dashed green lines.

Figure 3 shows the 850-hPa analysis with the highest dew points subjectively analyzed at 2°C intervals. The above-normal temperature and moisture over the peninsula is due to a strong southerly low-level jet extending from the Florida Keys into the South Carolina coast. The highest dew points were around 14°C along the east coast of Florida. The presence of the low-level jet into South Carolina with its resulting moist advection is an indicator of the potential for severe weather into Georgia and South Carolina later in the day, a fact mentioned by Storm Prediction Center forecasters in their Convective Outlooks. The 925-hPa analysis (not shown) reveals that dew points over the Florida peninsula were around 18°C, indicating the presence of a deep moist layer over nearly the entire state on the morning of the 25th.

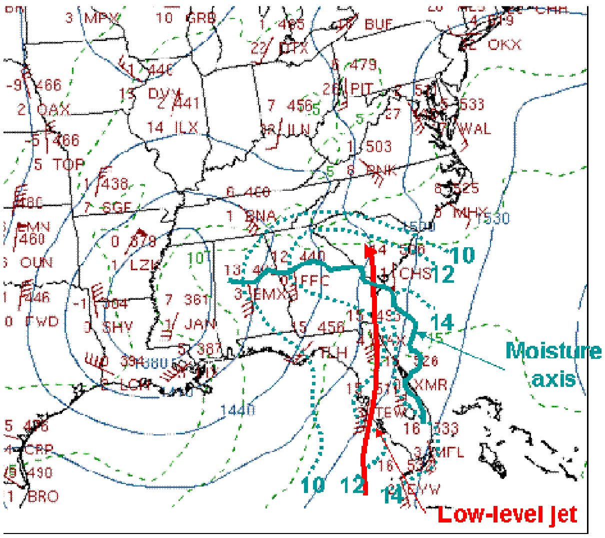


Fig. 3. 850-hPa analysis with dew points ≥ 10°C shown by dotted green lines. The positions of the low-level jet and axis of maximum moisture are labeled (chart courtesy of Univ. of Wyoming).

At 500 hPa (Fig. 4), there is a deep cold core over the Rio Grande Valley of Texas, with temperatures of -26 to -28°C. With the cold core still west of the height trough, the main 500-hPa low over the Ark-La-Tex region will deepen further over the next 6 hours. A curious feature on this analysis is the presence of a -10°C observation from the Tampa Bay (TBW) rawinsonde sounding. This relatively cold temperature was not really picked up by the objectively analyzed isotherms, shown in Fig. 4 by the green dashed lines. When the isotherms are subjectively reanalyzed, accounting for the TBW observation, we see the presence of a weak thermal trough from the Gulf of Mexico into the west coast of Florida. It is possible that as this thermal trough rotated northward during the morning hours, it may have allowed some additional destabilization to take place over the northern half of the peninsula, which could have contributed to the potential for severe storms.

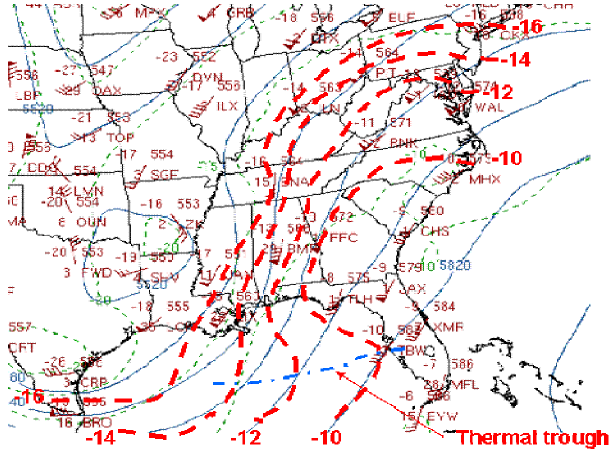


Fig. 4. 500-hPa analysis with reanalyzed isotherms shown by red dashed lines. The thermal trough in the eastern Gulf is shown by the blue dot-dashed line (chart courtesy of Univ. of Wyoming).

The upper-level jet pattern is depicted in the 250-hPa analysis of Fig. 5. Note the strong meridional jet extending from the Gulf of Mexico into the northeast U.S. Jet speeds in the Gulf region were between 100 and 120 kt, but the jet is even stronger over the northeast U.S. and southern Quebec, with speeds as high as 150 kt. Also notice the upper-level diffluence area between the main polar jet over the northeastern Gulf and a weaker, secondary speed maximum present over central Florida. A similar diffluent pattern is also observed at 300 and 200 hPa (charts not shown).

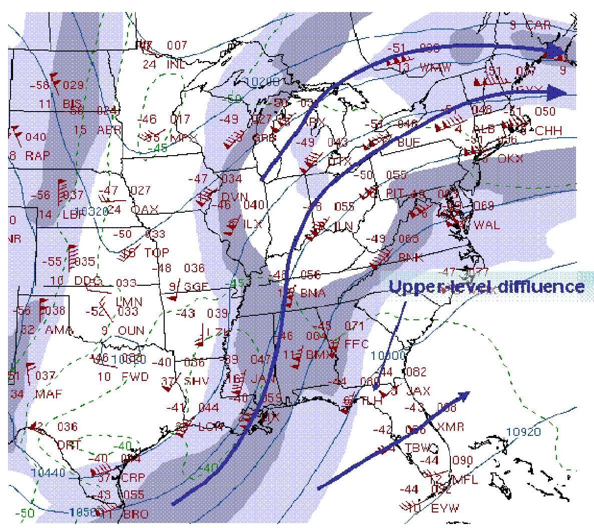


Fig. 5. 250-hPa analysis. Jet positions are subjectively analyzed with thick blue arrows (chart courtesy of Univ. of Wyoming).

The 1200 UTC soundings at TBW and XMR (Cape Kennedy) are shown in Fig. 6. A deep moist layer is evident in both soundings, extending through 770 hPa and 835 hPa at XMR and TBW, respectively. Both soundings have highly unstable Lifted Index values between -6 and -7ºC, and relatively large values of Convective Available Potential Energy (CAPE), with mixed-layer CAPE values of nearly 2000 J/kg at TBW and 2400 J/kg at XMR. These thermodynamic parameters are quite favorable for severe storms. The wind profiles are also favorable for severe storms, with good directional and speed shear as evidenced by the hodographs in the upper right panel of both the TBW and XMR soundings in Fig. 6.

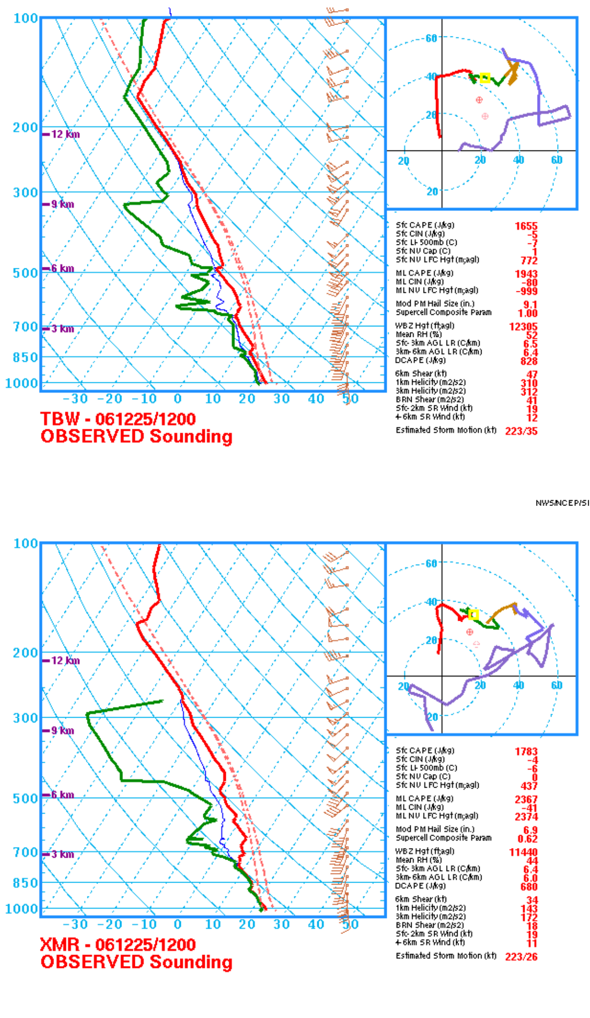


Fig. 6. Skew-T Log-P and wind hodographs for Tampa, FL (TBW, top panel), and Cape Kennedy, FL (XMR, bottom panel) (courtesy of NOAA's Storm Prediction Center archive web site).

The soundings shown in Fig. 6 resemble Hagemeyer and Schmocker's (1991) dry-season climatological composite proximity sounding (see their Fig. 5 and Table 1), and also compare favorably with the mean extratropical outbreak pre-storm soundings discussed by Hagemeyer (1997). This is especially true for the LI and CAPE values at TBW and XMR, which are well in excess of the mean dry-season values of -1.8ºC and 160 J/kg computed by Hagemeyer and Schmocker. Qualitatively, the wind shear profile at TBW also compares favorably with Hagemeyer and Schmocker's (1991) dry-season severe-storm composite sounding and that of Hagemeyer (1997) for the extratropical outbreak type. For example, the storm-relative helicity values in the 0-1km and 0-3km layers at TBW are comparable to Hagemeyer's composite storm-relative helicity of 373 m^2 s^{-2} in the 0-3km layer of his pre-outbreak soundings (his Table 2). In this case, it is more appropriate to compare the TBW and XMR soundings to the pre-storm composites vice the storm-proximity composites, since the tornadoes observed with this outbreak occurred some 4-6 hours after 1200 UTC. It makes sense that the TBW sounding would have the more favorable wind profile, given its proximity to the approaching frontal system and upper-level jet compared to XMR, which is approximately 175 km east of TBW.

3.2 *Mesoscale Analyses*

During the morning hours on the 25th, a well-defined squall line had formed east of the surface cold front, extending from southern Georgia, across northern Florida, and into the Gulf of Mexico. The extent of this feature is shown in the frontal/radar composite analysis for 1500 UTC in Fig. 7 below. By this time, the Storm Prediction Center had already issued tornado watches for parts of coastal South Carolina, Georgia, and most of Florida.

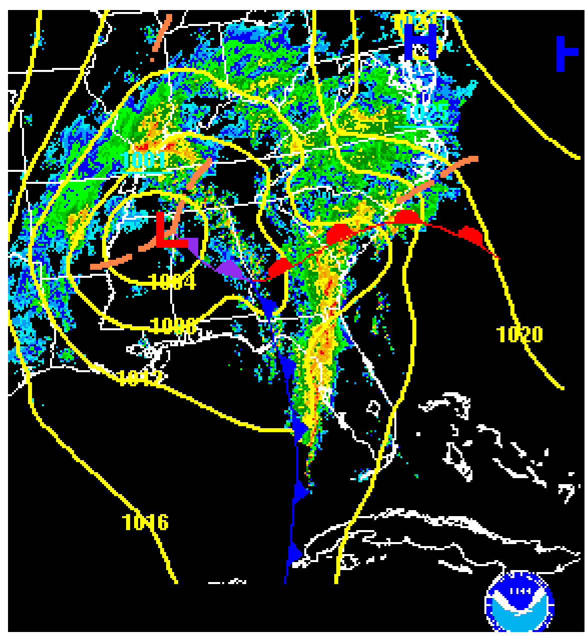
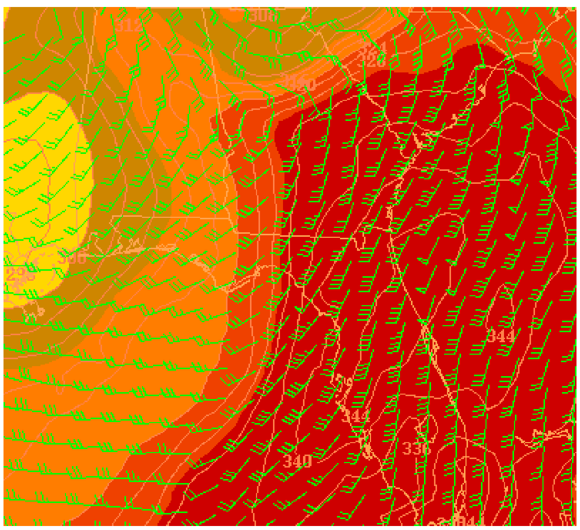


Fig. 7. Composite radar and surface analysis for 1500 UTC (retrieved from HPC archive site at http://www.hpc.ncep.noaa.gov/html/sfc_archive.shtml).

The evolution of the mesoscale environment in the hours immediately preceding tornado touchdown on the ERAU campus is illustrated in a series of 925-hPa equivalent potential temperature θ_e and wind analyses from 1700-1900 UTC (1200-1400 EST), generated from the Rapid Update Cycle (RUC-II) model (Benjamin et al., 2002), and shown in Fig. 8 below. By 1800 UTC (1300 EST), there was a noticeable southwesterly surge in the wind field over the Gulf coast of Florida, just north of Tampa, which became even more pronounced over central Florida by 1900 UTC (panel 'c'). This surge is consistent with surface analyses for the same period (not shown), incorporating data from the Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu/), which includes a number of stations in the sparsely populated interior of the state. Those analyses showed a strong low-level convergence area and dry pool that began north of Tampa at 1700 UTC and spread rapidly north and east, reaching the Atlantic coast just south of Daytona Beach by 1900 UTC.



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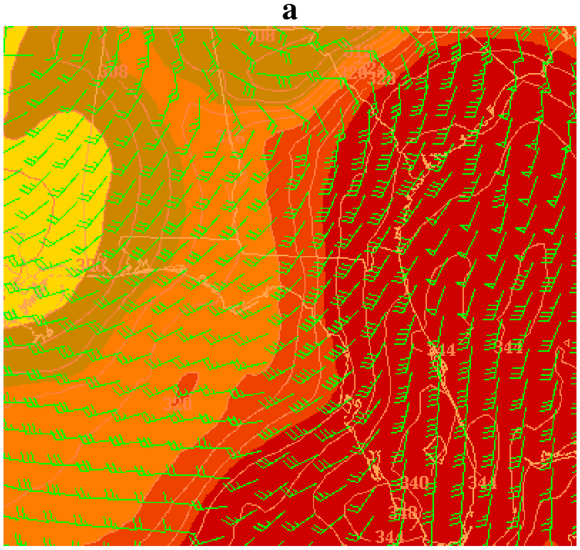

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This low-level convergence area was associated with the pre-frontal squall line, and the dry surge seen in Fig. 8c is consistent with the more rapid movement of the northern part of the squall line, which will be discussed in the next section.

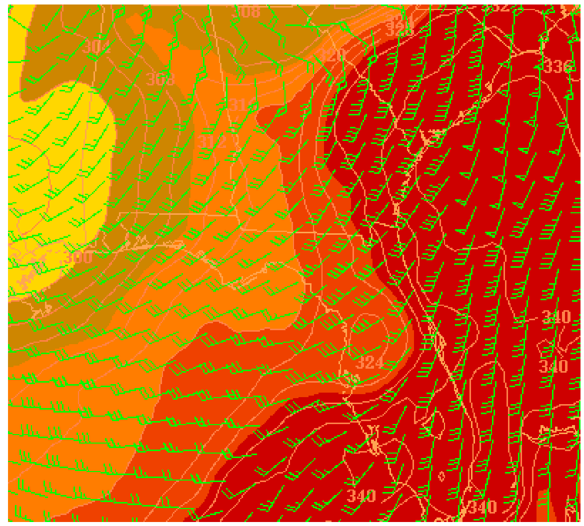

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Fig. 8. RUC-II analyses of 925-hPa θ_e and winds from: a) 1700UTC, b) 1800 UTC, and c) 1900 UTC. θ_e contours are every 4K, with highest values shaded in darkest red.

While the evolution of the low-level thermal, moisture and wind fields showed continued potential for supporting severe thunderstorms throughout the day on the 25th, the upper-level winds continued to support strong diffluence over the eastern Gulf and Florida peninsula, on the eastern edge of a strong jet in excess of 120 kt (see Fig. 9 below).

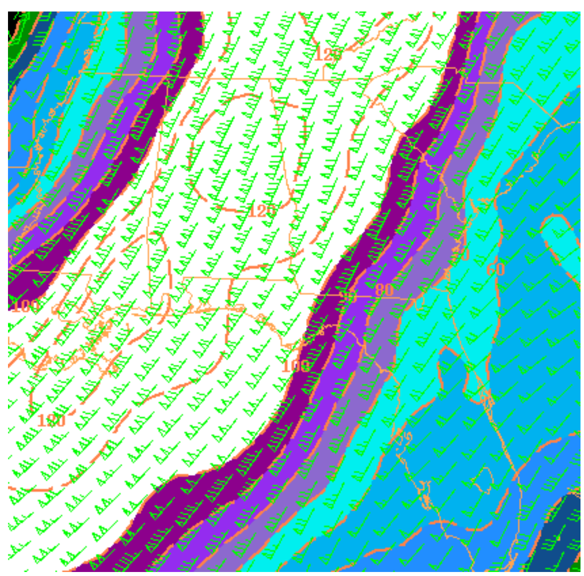

Fig. 9. RUC-II generated 300-hPa wind analysis for 1800 UTC. Isotachs (kt) contoured every 10, with speeds > 100 kt highlighted in white shading.

4. EVOLUTION OF THE SQUALL LINE AND TORNADO

4.1 *Doppler Radar Sequence*

The National Weather Service in Florida issued a number of tornado warnings during the morning and afternoon of the 25th as the squall line continued its eastward trek across the northern half of the state. The warning for Daytona Beach, which included the ERAU campus, was issued at 1325 EST, and the storm was projected to reach the International Speedway and the airport at approximately 1335 EST. The parent cell that prompted this warning had a history of producing storm damage in the area of Deland, Florida, which is about 30 km southwest of Daytona. The WSR-88D storm-relative velocity indicated an area of rotation, which was most noticeable on the 1824 UTC scan, shown in Fig. 10.

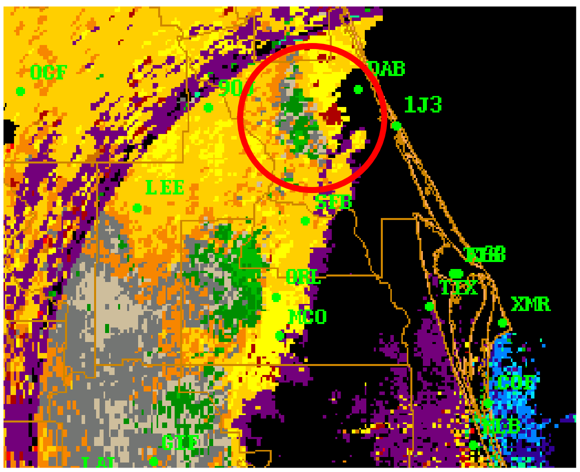

Fig. 10. WSR-88D storm-relative velocity scan for 1824 UTC. Light green shading within red circle indicates inward storm-relative velocities around 15kt, while the maroon shading nearly adjacent to it indicates outbound storm-relative velocities around 30kt, indicating a broad area of rotation as the storm approached the airport (indicated by 'DAB' with green dot denoting location).

In the time immediately preceding the tornado touchdown, the composite reflectivity scans showed that the northern portion of the squall line was starting to move faster than the southern portion, and beginning to take on a bowed appearance. This can be seen in the scan taken at 1837 UTC (see Fig. 11). Subsequent scans show the same trend as the cell moved through Daytona and out to sea by approximately 1900 UTC.

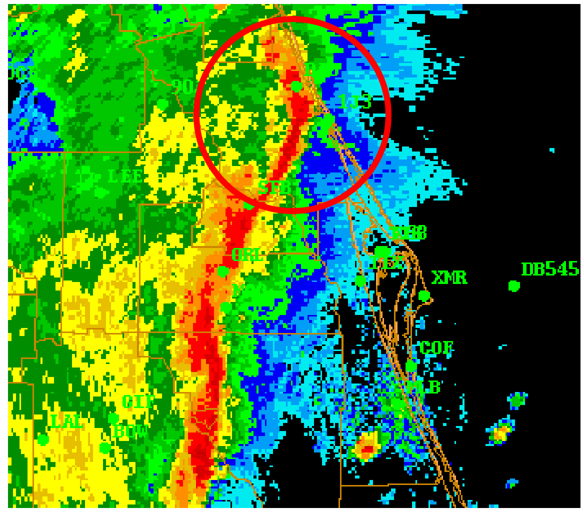

Fig. 11. WSR-88D composite reflectivity scan for 1837 UTC. Highest reflectivity values are 55dBZ, shown by maroon shading. Location of bowing echo segment is shown by red circle. Location of Daytona Beach International Airport (DAB) denoted by green dot. The squall line is passing through DAB at the time of this scan. The National Weather Service Forecast Office in Melbourne, Florida, determined tornado touchdown at DAB to be 1345 EST (1845 UTC).

4.2 *Low-Level Wind Shear Alert System Sequence*

The exact time of tornado touchdown was hard to determine simply from the radar and satellite data alone. This was especially problematic since there were no eyewitnesses either at the airport or on the ERAU campus. One additional data source that has been helpful in determining the time of squall line passage is the Low-Level Wind Shear Alert System data from the Daytona Beach International Airport (DAB) tower network. This dataset contains 10-sec resolution wind information from all nine LLWAS towers surrounding DAB. An animation of the wind field from the towers shows that the strongest wind speed of 45kt from 225º was observed just south of the 250/070 runway complex at approximately 1838 UTC (1338 EST). There were no indications of rotation in the wind field, which covers an area of approximately 30 square km. Interestingly, the LLWAS never sounded an alarm during the cell's passage over the network, suggesting that the portion of the cell's wind field that passed over the network did not display downburst/microburst characteristics, or least not enough to be detected. A LLWAS vector wind analysis from 1837:47 UTC is shown in Fig. 12; this time corresponds to the maximum wind speed observed in the network. Although there is no clear tornadic or mesocyclone signature in the wind field, there is clear evidence of low-level convergence along the east end of the runway complex, just west of the edge of campus. Also, there is some weak cyclonic curvature in the wind field east of the squall line, at towers 2, 3, 7, and 8. These are the towers that still have a predominantly southerly wind direction.

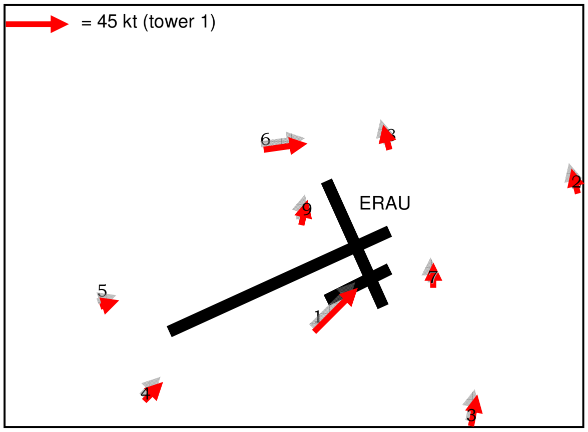

Fig. 12. LLWAS-derived wind analysis for 18:37:47 UTC. Vectors shown in red, with length proportional to speed. The DAB runway complex is shown schematically, and the location of the western edge of the ERAU campus, which is where the tornado touched down, is indicated by the letters "ERAU".

4.3 *Tornado Damage Path Estimation*

The National Weather Service Forecast Office in Melbourne did a damage survey of the ERAU tornado as well as the others which hit east-central Florida on 25 December. The portion of the damage path map pertaining to the ERAU tornado is shown in Fig. 13.

Fig. 13. Daytona Beach tornado damage path estimated by National Weather Service's Melbourne forecast office. Map provided courtesy of http://www.google.com.

The tornado initially did a tremendous amount of damage to the ERAU training aircraft parked on the apron, at the location of touchdown. In order to estimate the damage path during this initial portion of the track, the aircraft parking diagram for 24 December was utilized in conjunction with damage photographs taken immediately after the event to determine whether the trajectories of the damaged and destroyed aircraft could be analyzed, thus giving us additional information about the tornado as it touched down. This analysis is in its preliminary stages, thus results were not available in time for this paper. A cursory look at the damage swath from initial touchdown is evident in the overhead photo taken about a day after the event (Fig. 14 below). Note that the damage swath appears to be wider at the touchdown point on the parking ramp, then it narrows slightly as the tornado moves through campus (from bottom to top of picture, which is in an east-northeasterly direction, consistent with the NWS damage swath estimate from Fig. 13.

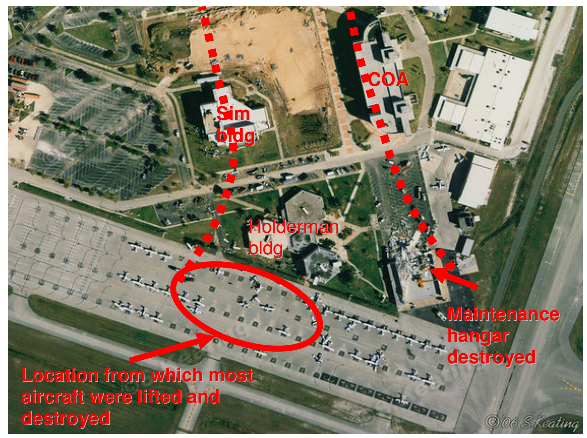

Fig. 14. Overhead photo of ERAU parking ramp and west side of campus, taken about a day after the event. Annotations of damage and estimated path were added by the author (photo courtesy of S. Keating).

The National Weather Service Forecast Office in Melbourne determined that the tornado touched down at the ERAU campus around 1345 EST (1845 UTC), and the path lasted several miles before lifting just west of the Intercoastal Waterway. However, evidence from the radar and LLWAS data suggest that the tornado may have touched down closer to 1338. The first indication of damage from the tornado was a fire that broke out in one of the hangar buildings adjacent to the one that was destroyed (see Fig. 14), due to an airplane being thrown into it by the tornado. The DAB fire and rescue unit was the first to respond to the hangar fire. The 911 call logs from the Port Orange, Florida fire department show an eyewitness calling in damage near campus at approximately 1341, and the P.O.F.D. arriving on campus to relieve DAB fire and rescue at approximately 1345, according to the ERAU Campus Safety Report from this event.

Finally, an intriguing piece of evidence of the tornado's strength was discovered during salvage operations of one of the 50 damaged/destroyed aircraft. The cockpit instrumentation, still fully intact, showed a ground speed reading of 120kt and an altimeter of 2200 feet. If one assumes a standard atmosphere, the altimeter reading corresponded to a pressure change of approximately 75-80 hPa, and based on the estimated width of the tornado (roughly 70-80m), a cyclostrophic wind calculation produces a rough estimate of the wind speed to be around $80ms^{-1}$, which is a little higher than the F-2 damage that was estimated on the ERAU campus and at the Sutton Place Apartments in Daytona Beach.

5. CONCLUSIONS

This study examined the synoptic and mesoscale conditions associated with a tornado that struck the ERAU campus on 25 December 2006 and heavily damaged or destroyed 50 of the university's training aircraft, destroyed the administration building and heavily damaged the ICI athletic center before taking aim on an apartment complex in Daytona Beach and heavily damaging the units there. The NWS Forecast Office in Melbourne estimated the tornado to be an F2, which is unusual for Florida in December, but perhaps not so unusual considering that it was the beginning of an El Niño episode, in which unusually strong upper-level winds are observed over the Florida peninsula. The atmospheric conditions were quite favorable on the morning of the 25^{th}, as a vigorous cold front was moving across the Gulf of Mexico and a strong low-level jet allowed for the advection of unseasonably warm, moist air across the peninsula and into Georgia and coastal South Carolina. A strong upper-level jet in excess of 110kt was observed to the west of Florida, and upper-level diffluence associated with the jet was superimposed nearly coincident with the low-level convergence taking place in advance of the cold front. Favorable vertical wind shear profiles were observed in the morning rawinsonde soundings over the peninsula. The favorable stability and vertical wind shear profiles were consistent with climatological composite soundings taken in advance of dry season, extratropical tornadic outbreaks documented by Hagemeyer and Schmocker (1991) and Hagemeyer (1997).

The pre-frontal squall line moved through the Florida peninsula during the morning and early afternoon hours of the 25^{th}, and the low-level convergence ahead of it continued to provide ample lift and moisture to maintain the severity of the storms as they produced tornadic and straight-line wind damage over portions of east-central Florida. Radar data from the NWS-Melbourne WSR-88D in the hours immediately preceding the touchdown of the ERAU tornado showed evidence of a bowing line segment, which appeared to move faster than the portion of the squall line immediately to its south. Hourly low-level wind and θ_e fields from the RUC-II model showed evidence of an intrusion of dry air along with southwesterly winds behind the squall line, right around the time of the tornado touchdown, which is estimated to be about 1338 EST. The structure and evolution of the cell that produced the ERAU tornado resembles a bow echo, in which convergence around the apex of the bowing segment may concentrate enough low-level vorticity to create an environment favorable for rotating thunderstorms that can produce tornadoes. Such systems have been documented in studies by Przybylinski (1995) and others over the Midwest U.S. More study of cases such as this one over Florida needs to be accomplished in order to discern similarities and differences between the types of systems observed in the dry season here and those in other parts of the country.

Acknowledgements. The author wishes to thank a number of individuals for their assistance during the research and preparation of this paper. Fruitful discussions of the Christmas Day tornado case were held with a number of faculty members in the ERAU Applied Meteorology program, most notably Dr. Frederick Mosher and Dr. Christopher Herbster. Dr. Herbster and Mr. Mike Masscotte were instrumental in obtaining the observational and model data used in this case study, and in facilitating the author's analysis by setting up data access scripts for the NMAP and GARP analysis programs, which were used to generate most of the analyses used in the paper's figures. The ERAU Weather Center provided the computers and data storage facilities for this case study. Mr. Chris Turner from the Federal Aviation Administration kindly provided the LLWAS data that was used in this case study. Ms. Nance Burgin analyzed photos and aircraft parking diagrams used to produce preliminary damage trajectory maps documenting the initial tornado touchdown on the ERAU campus. She also contacted P.O.F.D personnel to gather pertinent information about 911 responses on that afternoon. Ms. Tina Clark from ERAU Campus Safety provided the author with a copy of the Event Report, which was also used in determining the event chronology for the tornado touchdown on campus.

6. REFERENCES

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