11.4 MAJOR LAND-FALLING HURRICANES AS MESOSCALE CONVECTIVE SYSTEMS: A PARADIGM SHIFT FOR WFO OPERATIONS

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1. INTRODUCTION

Along the Atlantic and Gulf Coasts of the United States, recent land-falling hurricanes have forcefully challenged the Nation's Weather Enterprise to evaluate the availability and quality of the decision-making information it provides to societies at risk. To be effective, decision-makers who are responsible for managing the safety and security of people through devastating hurricane events not only require deliberate weather information well before onset, but also information which flows more frequently and with greater detail as the event itself unfolds. These details must be cast in situational context according to the character of the tropical cyclone and its associated hazards, along with appropriate consideration for the societal and environmental complexions of the threatened area of potential impact.

With tropical cyclones, the direct threats to land include high winds, coastal flooding, inland flooding, and tornadoes, each of which can be accentuated by local terrain/bathymetry effects or by mesoscale convective implications. Ideally, recommended safety actions for reducing the personal risk of death or injury from a particular hazard should not consequently keep someone at (increased) risk from another. For example, shoreline residents heeding evacuation orders to escape the impending surge waters should not, in turn, find themselves subject to undue risk from dangerous hurricane winds. Even those who relocate from inadequate shelter (e.g., mobile homes) to more substantial refuge do so in the effort to reduce personal risk from destructive winds, wind gusts, and tornadoes. However, hurricane events rarely play out in ideal fashion due to inherent complexities and the diversity of scenarios when intersecting societies with natural disasters. When dealing with expansive weather systems and large populations, risk can be smartly reduced, but it cannot be eliminated, especially among coincident hazards. Therefore, it is incumbent on operational meteorologists to keep the safety of a local population at the forefront throughout the entire impacting event.

Short-fused warnings for severe convective wind gusts ($\geq$ 50 knots) or tornadoes associated with outer rain-bands may be issued by local National Weather Service (NWS) Forecast Offices (WFOs) during the approach or departure of a tropical cyclone to prudently warn those involved in preparedness or recovery activities. Specifics regarding the timing, location, and magnitude of convective winds are considered a service toward fulfilling the agency mission to protect life. Yet, in the vicinity of the cyclone core (that is, with the passage of its inner rain-bands and eye-wall), there is hesitancy to provide detailed wind information or to issue short-fused warnings for extreme winds or wind gusts. The traditional preference for dealing with the cyclone core is to revert to treating the system as solely synoptic in nature. In other words, accepting what is being said and done regarding the generalized wind threat as sufficient. More so, higher gusts are often mentioned in area forecasts and local statements with little urgency or specifics. Sadly, this occurs at the time when WFO meteorologists actually know the most about the mesoscale structure of its core, with the ability to assess the distribution and magnitude of potential gusts associated with identifiable and track-able features.

Since the inner core of a tropical cyclone is actually a mesoscale convective system (MCS), treating its passage more like a convective event would allow for greater focus on the most life-threatening wind impacts. Consider that Fujita (1978, 1992) surmised that convective scale downdrafts were responsible for the most severe wind damage in hurricanes. Other research is now being done to understand the structure and behavior of the hurricane boundary layer, some noting the implications of small-scale rolls (as sampled by radar) which exhibit vertical and horizontal coherency and are approximately aligned with the mean wind direction (Lorsolo and Schroeder 2006, Wurman and Winslow 1998). These results, and others, collectively support the presence of mesoscale irregularities in the surface wind field which may locally enhance damage. Although significant additional research is needed, considerable observational experience has been gained through opportunities provided by the record 2004 and 2005 seasons. As for coastal WFO operations, warning strategies during hurricanes should be transitioned to employ similar protocol as used during significant extra-tropical convective wind events (e.g., severe squall lines, derechos, discrete supercells, etc.). This operational shift should be concomitant with balanced adjustments to hurricane preparedness and mitigation strategies.

This paper will explore the advocated rationale for issuing special bulletins for extreme winds using two recent hurricanes. Meteorological assessments and specific warning strategies for (major) Hurricanes Charley and Jeanne (2004) will be discussed. Radar imagery of the eye-wall features will be shown, along with a sample of short-fused warning products designed to save lives in the final moments. Detailed, post-

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hurricane ground and air damage survey results will be shared, which confirm tornado-like damage within widespread regions of lesser wind damage. Additionally, the value of these warnings will be shown as extracted from customer feedback obtained by the NWS Service Assessment on Hurricane Charley.

2. RATIONALE FOR SHORT-FUSED WARNINGS

Hurricane Charley serves as an excellent forensic to challenge the advocated paradigm. On 13 August 2004, Charley made landfall along the southwest Florida coast as a Category 4 hurricane, forecast to accelerate rapidly northeast across the central Florida peninsula by late in the evening (Fig. 1). Extreme winds and gusts were thrust onshore near Punta Gorda and continued inland to Arcadia and Orlando. Harrowing experiences of failed roofs, blown-out doors and windows, and fallen trees on buildings jeopardized the lives of sheltered individuals as Charley's winds rapidly increased to 130 knots and surprisingly diverted (east; right of track) through Charlotte County during its landfall. Later, 100 knot and 85 knot winds and gusts would move through DeSoto and Orange Counties respectively. Importantly, this occurred within locations considered as being 'event-prepared' since they were already under long-fused hurricane wind warnings. However, a tale of three cities has emerged in the wake.

2.1 HURICANE CHARLEY - PUNTA GORDA, FL

For Punta Gorda (Charlotte County), hurricane conditions were forecast and expected well in advance. Preparations were made for the coastal city, but anticipation was not for the extreme winds which were realized. Prior to onset, there was an over-emphasis by media and residents on the "skinny black line" of the forecast track, which earlier in the day had indicated Tampa Bay as the proposed location for landfall. Even when accounting for uncertainty, the exactness in actual cyclone track and intensity over short periods can make huge differences in the magnitude of wind experienced at any given location. Too, the distribution and vigor of convection about the center yields valuable insight to the downward transfer of momentum and the ability for further damage. There were four deaths within Charlotte County attributed to inadequate sheltering and flying debris (Pasch *et al.* 2004). Short-fused wind warnings might have cut through the information barrage to elevate urgency, motivating them to action.

2.2 HURRICANE CHARLEY - ARCADIA, FL

At a shelter in Arcadia (DeSoto County), an inland city within a second-tier county from the coast, several people had wisely huddled together to hide from Charley's fierce winds. According to first-person accounts, most were aware that the core would pass nearby, but no one was privy to the extent of the hurricane-force winds which would directly affect them. As the winds grew louder and stronger, anxiety within the building increased. Soon after, the roof began to give way, and would eventually collapse. Panic set in as smaller groups scrambled to find safety, some within a designated safe room. The core of Hurricane Charley was effectively like a large F2 tornado striking the building due to its compact radius of maximum winds and continued intensity over land (e.g. a slower inland wind decay). Last second actions taken to save lives were the same as recommended calls-to-action within tornado warnings. Special bulletins highlighting the threat with specific locations and times (e.g., pathcast) might have provided shelter coordinators with vital information for moving people to designated safe areas within the shelter before the arrival of extreme winds.

2.3 HURRICANE CHARLEY - ORLANDO, FL

The city of Orlando (Orange County) is the most densely populated interior city in the state of Florida and is host to countless summer visitors. Many times, it is also the city of refuge for evacuating coastal populations seeking to escape deadly hurricane surge waters. With Charley, many residents from the Tampa Bay area had relocated inland hoping to minimize their personal risk. This decision was made with the issuance of the coastal hurricane warning and based on the earlier track forecast. With Charley advancing inland along a slightly different path, Orlando was placed squarely within the projected path. However, media attention was primarily centered on covering the landfall story and little information was being relayed about the danger. The city is used to tropical cyclones crossing the central peninsula, but until this time the highest documented wind gust to affect Orlando was 64 knots. This occurred during the passage of Hurricane Donna in 1960 with minimal hurricane-force. Despite the inland hurricane wind warning already in place, people were generally unsuspecting of Charley's continued extreme winds until about one hour before being hit. The unprecedented nature of the imminent threat required an urgent and decisive short-fused alert to focus attention and to prompt immediate live-saving responses.

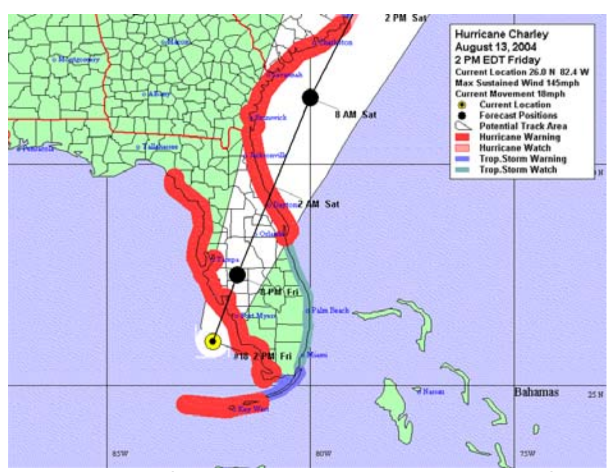

Fig. 1 1800 UTC 13 August 2004 National Hurricane Center forecast for Hurricane Charley. The forecast moves the center of the hurricane across the WFO Melbourne forecast and warning area between 0200 and 0600 UTC 14 August 2004.

3. PARADIGM IN PRACTICE

As the inner core of a hurricane circulation moves within 465 km (250 nmi) of the United States coast, it is imperative that WFO operations shift from a more general assessment of hazard threats toward dedicated radar analyses of mesoscale features. The following sections detail radar-based assessments and associated warning decisions which were made in real-time at WFO Melbourne as Hurricanes Charley and Jeanne impacted East Central Florida. Comprehensive summaries of the impacts of Hurricanes Charley and Jeanne upon East Central Florida, including multiple radar loops, meteorological data, and the complete suite of products issued by WFO Melbourne are available at: http://www.srh.weather.gov/mlb/

3.1 CASE #1

At 2244 UTC, Melbourne WSR-88D indicated the core of Hurricane Charley (Fig. 2) approximately one hour away from the WFO Melbourne forecast and warning area and approaching Orlando from the southwest at 20 knots. Although the back side of the eye-wall was eroding, the leading side (e.g., north and east quadrants) continued to possess very intense convection, with 50-60 dBZ reflectivity cores. Velocity data (not shown) revealed winds in excess of 100 knots at the 1500 m level (lowest sampled elevation) and recent reports from emergency management personal along the (inland) path of the center indicated extensive to catastrophic wind damage. Based upon earlier staff discussions, prior coordination with emergency management, and up-to-the-minute radar analyses of persistent deep convection and co-located significant wind fields, the decision was made to produce and disseminate special tornado warnings (Fig. 3).

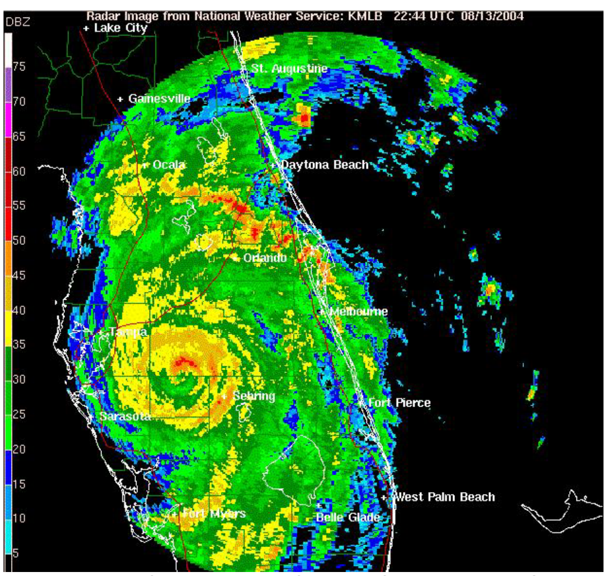

Fig. 2 Base reflectivity image from WFO Melbourne WSR-88D at 2244 UTC 13 August indicating the center of Hurricane Charley advancing toward the Melbourne forecast and warning area.

Although this critical information was also included within frequently issued Hurricane Local Statements, a higher priority message type was needed to assure receipt by the largest audience possible. Of all available short-fused products, the tornado warning receives the highest level of visibility via the Emergency Alert System (EAS) and is easily distinguishable from other short-fused statements, whose issuance often becomes "routine" during hurricane landfalls. In addition to the EAS-activated special tornado warning, numerous weather statements were also issued to provide additional details on the timing, location, and degree of anticipated extreme wind impacts. In short, the operational paradigm was to deal with Charley by employing a mesoscale approach, making optimum use of short-fused bulletins and statements.

BULLETIN - EAS ACTIVATION REQUESTED
TORNADO WARNING
NATIONAL WEATHER SERVICE MELBOURNE FL
645 PM EDT FRI AUG 13 2004

THE NATIONAL WEATHER SERVICE IN MELBOURNE HAS ISSUED A

* TORNADO WARNING FOR...
SOUTHERN LAKE COUNTY
ORANGE COUNTY
NORTHWESTERN OSCEOLA COUNTY
IN EAST CENTRAL FLORIDA

* UNTIL 745 PM EDT

* AT 642 PM EDT...THE NATIONAL WEATHER SERVICE HAS ISSUED A TORNADO WARNING FOR DESTRUCTIVE WINDS OVER 100 MPH AND TORNADOES IN THE EYE WALL AND INNER RAIN BANDS OF HURRICANE CHARLEY.

* THE LEADING EDGE OF HURRICANE CHARLEYS DESTRUCTIVE WINDS IS EXPECTED TO MOVE INTO THE KISSIMMEE AND GREATER ORLANDO AREA BY 715 PM.

THE THREAT FOR DAMAGING WINDS AND TORNADOES WILL LAST THROUGH 9 PM OR LONGER.

PEOPLE IN THE PATH OF THIS ADVANCING STORM ARE URGED TO QUICKLY PREPARE FOR ITS APPROACH. THIS IS A DANGEROUS SITUATION! ACT NOW.

IF YOU ARE IN THE PATH OF THIS STORM...THE SAFEST PLACE IS IN A STRONG BUILDING ON THE LOWEST FLOOR. MOVE TO AN INTERIOR ROOM SUCH AS A BATHROOM OR CLOSET. KEEP AWAY FROM WINDOWS. IF NECESSARY...GET UNDER A WORKBENCH OR OTHER PIECE OF STURDY FURNITURE. USE BLANKETS OR PILLOWS TO COVER YOUR BODY. ABANDON YOUR MOBILE HOME OR RV FOR MORE SUBSTANTIAL SHELTER.

Fig. 3 Special tornado warning issued by WFO Melbourne at 2245 UTC 13 August for Metro Orlando to heighten awareness of the imminent onset of destructive winds associated with the eye-wall of Hurricane Charley. Emergency Alert System (EAS) activation ensured widespread dissemination – to provide a final opportunity to take protective action.

Fig. 4 illustrates the northeast quadrant of the hurricane core spreading into the warning area, south and west of Orlando. The image from the Melbourne WSR-88D at 0006 UTC 14 August has reflectivity values (left) below 40 dBZ filtered out. The higher reflectivity area correlates well with the excessive base velocity values (right) with outbound velocities below 64 knots filtered out. In this image, base velocity values (3-4kft height) greater than 70 knots were evident across much of the warning area, with peak winds of 90-100 knots coincident with the location of the highest reflectivity returns (50-55 dBZ). The wind direction (120-160 degrees) during the time of the highest winds across this region provided excellent sampling of the extreme winds by the Melbourne radar, with only slight underestimation. Over the next 2-hr period, wind gusts between 65 and 91 knots were recorded by airport

Automated Surface Observing Systems (ASOS) within the warning path.

Since the strategy (at the time) called for issuing a 1-hr duration tornado warning for the *onset* of the extreme winds (85 knots or greater; sustained or gusts) for precise areas, the warning was not re-issued even though the conditions persisted beyond the 2345 UTC expiration time. Severe Weather Statements and Hurricane Local Statements were instead used to provide detailed follow-up information to the tornado warning. Likewise, the warning was not extended to upstream counties along the track, as radar-detected maximum winds decreased below the 85 knot (~100 mph) criteria beyond Orange County (e.g., Orlando and vicinity). Data from a preliminary post-analysis of the surface wind produced by the Hurricane Research Division (Burpee et al. 1994; Powell 1998) confirms the lessening of winds below 85 knots along the track north of Orange County (Fig. 5).

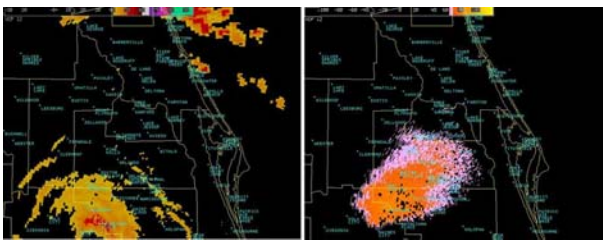

Fig. 4 Base reflectivity image (left) from the Melbourne WSR-88D at 0006 UTC 14 August 2004 indicating the eye-wall of Hurricane Charley approaching the Orlando Metro area. Reflectivity values below 40 dBZ have been removed. The coincident base (radial) velocity image is depicted on the right. Velocity values below 64 knots have been removed.

3.2 CASE #2

Several weeks after Hurricane Charley's passage across Central Florida, Hurricane Frances made landfall along the Southeast Florida coast and crossed Central Florida from the opposite direction. Although Frances' impacts were significant, maximum winds across the WFO Melbourne forecast and warning area remained below the threshold of 85 knots established earlier for the special tornado warning and, therefore, no such warnings were issued. However, a few weeks later, a third hurricane made landfall on the Florida peninsula, nearly at the same location as Frances. Hurricane Jeanne was a Category 3 hurricane at landfall with maximum sustained winds of 105 knots, and tracked inland across Central Florida and into the Gulf of Mexico north of Tampa. Based on experiences gained from using the special tornado warning during Hurricane Charley, the strategy was again implemented and several specialized tornado warnings for the onset of extreme hurricane wind conditions were issued – this time for the Southeast Florida coast.

The first specialized tornado warning was issued at 0058 UTC Sept 26 for Martin and Saint Lucie Counties in vicinity of where the center would make landfall, as the leading edge of the eye-wall was expected to begin impacting the coast around 0200 UTC. Radar imagery indicated deterioration of the eastern portion of the eye-wall as landfall approached; however, the western half remained strong, with a wide rain-band containing reflectivity above 40 dBZ and radial velocity values above 100 knots. One particular smaller-scale feature of interest was a cell containing high reflectivity echoes (50-55 dBZ), embedded within and rotating around the inner edge of the eye-wall. The feature initially became apparent on radar at 0216 UTC (Fig. 6), just offshore the tornado warning area, and persistently rotated rapidly southwest and onshore by 0232 UTC with a forward speed near 50 knots. The enhanced reflectivity area remained intact and track-able for over 30 minutes, before weakening well inland.

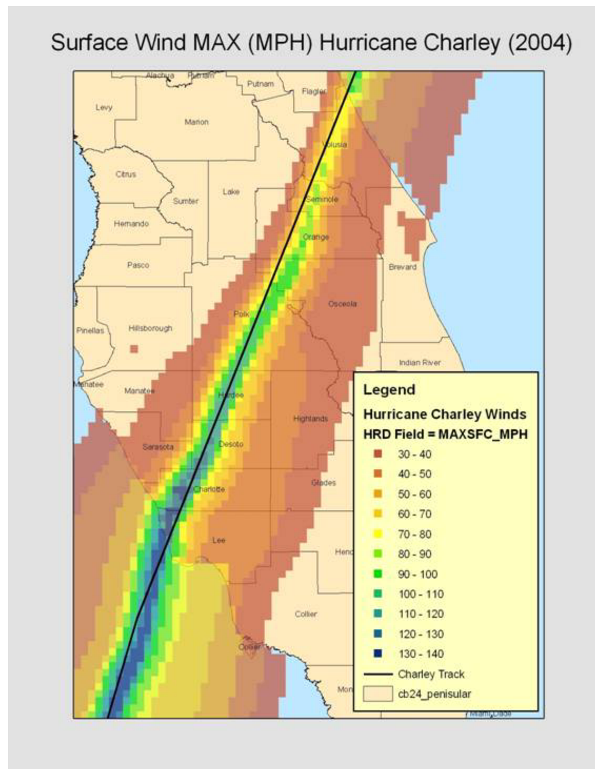

Fig. 5 Preliminary maximum sustained wind swath (mph) from Hurricane Charley obtained from the Hurricane Research Division and re-plotted by WFO Melbourne. Note winds decreasing below the 90-100 mph (below 85 knots) beyond Orange County (Metro Orlando area).

As the eye-wall spread northwest during the evening, two additional tornado warnings for extreme winds were issued for the coastal counties of Indian River and Brevard, located further north from the initial warning area. Additional transient features such as the one previously noted were observed within the eye-wall during the time of landfall. As Hurricane Jeanne continued to move inland, the intensity of the inner rain-bands gradually lessened and Doppler detected wind velocities dropped below 85 knots across areas north and west of those which were placed under the earlier tornado warnings.

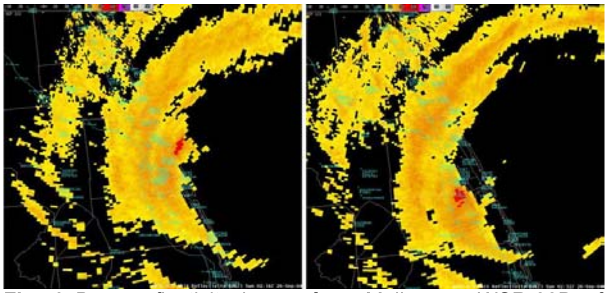

Fig. 6 Base reflectivity image from Melbourne WSR-88D of Hurricane Jeanne's inner core at 0211 UTC 26 Sept 2004 (left) and then 0232 UTC (right). Values below 40 dBZ have been removed. Note the cell with reflectivity above 50 dBZ just offshore, embedded within the eye-wall and later translating onshore and inland.

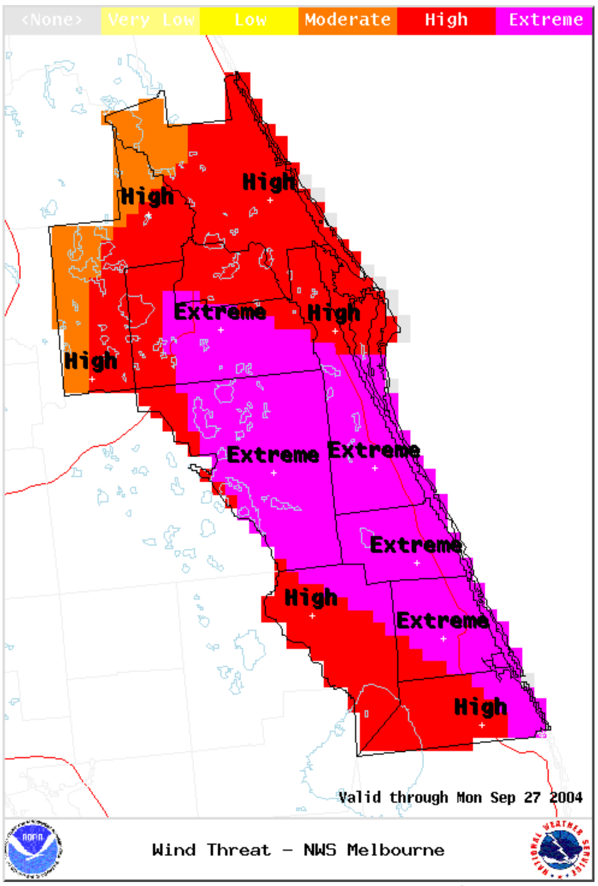

Fig. 7 Local Wind Threat graphic issued by WFO Melbourne at 0120 UTC 26 Sept 2004. The threat of major hurricane-force winds, sustained or gusts (greater than 96 knots or 110 mph), is depicted in purple.

During the event (as with Hurricane Charley), WFO Melbourne also provided an assessment of the local wind threat (Fig. 7). Threat assessments were made available with each issuance of the Hurricane Local Statement for all related hazards, to include high winds and gusts. This was done to further prepare residents for the onset of extreme winds. Note the similarities of the projected wind threat at 0120 UTC 26 Sept 2004 with the preliminary post-event wind analysis produced by the Hurricane Research Division (Fig. 8). The analysis confirms maximum winds greater than 85 knots (100-110 mph) along the coast within the extreme wind threat and tornado warning areas, north of the track of the hurricane's center.

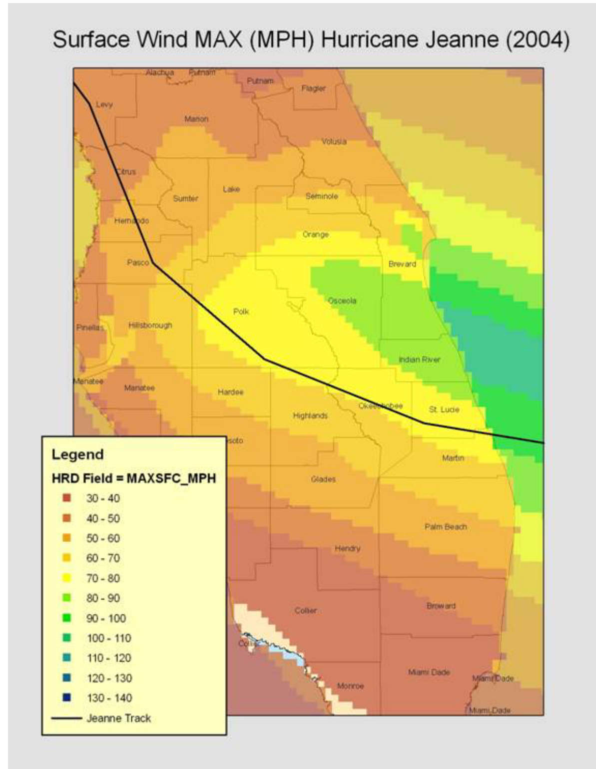

Fig. 8 Same as Fig. 5 except for Hurricane Jeanne. Note the winds greater than 85 knots (100-110 mph) along the coast north of the hurricane track and within the special tornado warning area.

4. POST-HURRICANE VERIFICATION

Extensive post-hurricane air and ground surveys were conducted by WFO Melbourne staff throughout the regions impacted by Hurricanes Charley and Jeanne.

The damage swath across the interior of Central Florida (e.g., Orlando and vicinity) associated with Hurricane Charley was very narrow, owing to the small, concentrated eye-wall (Fig. 1). Along the track of the eye-wall, damage was generally representative of a Category 1 hurricane. However, several isolated swaths of enhanced damage were apparent from air surveys. Two of the most impressive damage swaths were noted over the southeast portion of the area placed under the tornado warning for excessive winds. These swaths occurred within a heavily forested area and were nearly 3 km in length, with widths ranging from 180 and 275 m. The gradient of tree damage was very distinct along the swath edges, with a majority of trees toppled within the path and few trees felled farther outward. These tornado-like damage (F1 on the Fujita scale) paths were indicative of a Category 2 hurricane. Other enhanced damage swaths were apparent elsewhere along the track of the eye-wall, but were less distinct.

During the landfall of Hurricane Jeanne, multiple enhanced swaths of wind damage were also documented along the path of the (much larger) eye-wall. Three very notable damage paths were observed from the ground and air across the northeast portion of the tornado warning areas. Although the character of the damage paths was similar to those observed after Hurricane Charley, the path lengths and widths were about an order of magnitude less (.2-.8 km long and 18-45 m wide). One path was through a wooded area with numerous trees blown down, directly adjacent to areas experiencing minimal tree damage. The other two paths occurred through a very large mobile home community, with a linear swath of extreme structural damage adjacent to regions of much less pronounced damage. The mobile home damage was consistent with high-end Category 2 hurricane intensity. Along the path of the high reflectivity echo shown in Fig. 6, several enhanced areas of damage were noted on the barrier island and again beyond 10 km inland. Fig. 9 provides several examples of the damage paths which were documented after Hurricane Jeanne.

Fig. 9 Photographs of enhanced wind damage associated with Hurricane Jeanne taken from air surveys conducted by the authors. These tornado-like swaths of enhanced damage were observed in extreme Southern Brevard County and occurred as the eye-wall passed over the region. Tree and structural damage within the swaths was much greater than that observed immediately adjacent to the paths.

5. SUMMARY

Despite widespread, extensive property damage along the tracks of Hurricanes Charley and Jeanne, no direct wind-related fatalities occurred across East Central Florida. The intense focus and communication of the threat posed by the extreme eye-wall winds likely played a role in minimizing casualties. The effectiveness of the unique (tornado) warning strategy was further evident through positive feedback provided by several emergency managers and media representatives. The Hurricane Charley Service Assessment (NOAA/NWS 2006) cited the warning strategy as a "best practice."

The authors believe that as with extra-tropical severe weather events, turbulent mixing occurring within embedded convective cells likely led to the isolated regions of enhanced (tornado-like) damage. While the hypothesis of the mechanism is associated with downward accelerated vertical motions within transient convective features within the eye-wall, the resultant phenomena responsible for such observed damage remain illusive. Possible candidates include downbursts (Stewart 2000), mini-swirls (Fujita 1992), tornadoes Wakimoto and Black 1992), and roll vortices (Morrison et al 2005). Researchers are thereby challenged to pursue an improved understanding, with a particular plea to the entire severe local storms community for greater appreciation of tropical cyclone cores as mesoscale convective systems.

Important societal questions arise as to the value of short-fused warnings for extreme hurricane winds associated with the passage of its inner bands and eye-wall. Is the provision of this information helpful to emergency managers? Is it useful for an anxious public? Is it beneficial to warn those inside an already battened-down neighborhood shelter, to inform them that it is time to quickly move to their designated safe room? The authors believe the answer is yes.

Finally, a working team was put together post 2004 to refine the criteria, granting authorization to issue specialized warnings with standardized language for the imminent onset of tropical cyclone related sustained winds greater than or equal to 100 knots (115 mph). Several of these warnings were issued with the more powerful storms of 2005, receiving mixed reviews. Oddly, convective gusts are ignored within the new criteria, opting for a definition qualified by sustained winds only (and of higher value). Using this definition, if Hurricane Charley were to occur today, short-fused wind warnings would not be issued for Orlando.

6. DISCLAIMER AND REFERENCES

Readers are advised that the stated positions of the authors do not necessarily reflect those of the National Weather Service or its parent agency (NOAA). References are available upon request.