11A.3A CHARACTERISTICS OF A TORNADO OUTBREAK ASSOCIATED WITH THE REMNANTS OF TROPICAL STORM BILL

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1. INTRODUCTION

On the night of 1 July 2003 the remnants of Tropical Storm Bill crossed portions of the southeast United States and Southern Appalachians. As these remnants tracked across north Georgia and upstate South Carolina, they produced a small tornado outbreak in sections of east Georgia and southeast South Carolina. Post storm surveys verified 4 F1 tornadoes and 2 F2 tornadoes (NCDC 2003) across the National Weather Service Forecast Office Charleston, South Carolina (CHS) county warning area (CWA; see Fig. 1), making it the largest tropical tornado outbreak in that area since Hurricane Earl took a similar track in 1998.

This nighttime outbreak occurred in a low CAPE, highly sheared environment, similar to what has been found in previous studies of tropical tornado outbreaks (McCaul 1991). In addition, radar and mesoanalysis discovered several mini supercells which tracked across the region, along with a warm frontal boundary which likely enhanced severe convection.

This study will review this tornado outbreak, with an assessment of its synoptic and mesoscale environment within the scope of current and historical research of tornadic events associated with tropical cyclones. A radar analysis of the tornadic storms will show the importance of maintaining situational awareness and monitoring persistent mesocyclones. It will be shown how obtaining current storm relative helicity (SREH) measurements from the Velocity Azimuth Display (VAD) profile can lead to improved and warning decision making. Future warning improvements will also be discussed.

2. TROPICAL STORM BILL OVERVIEW

Tropical Storm Bill formed in the southern Gulf of Mexico on 29 June and made landfall at King Lake, LA at 1900 UTC 30 June with maximum winds of 50 kt. (see Fig. 2) (Avila 2003). As Bill tracked northeast across Mississippi, the storm weakened to a Tropical Depression at 0600 UTC 1 July. Tropical Depression Bill then headed northeast across Alabama and into northern Georgia the night of 1 July, before finally losing its tropical characteristics and becoming extratropical at 1800 UTC 2 July near the Tennessee and Virginia border (Avila 2003). 24 tornadoes were reported across the Gulf States and the Carolinas as Bill tracked across the southeast and southern Appalachians (NCDC 2003).

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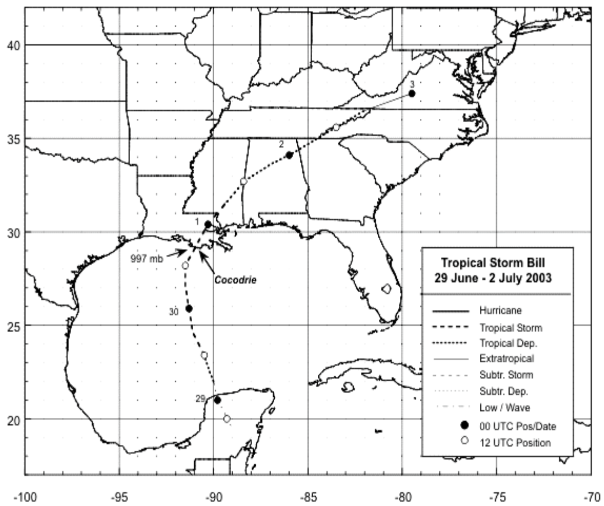

Fig.2. Best track positions for Tropical Storm Bill, 29 June - 2 July, 2003. Track after landfall is based on analyses from the NOAA Hydrometeorological Prediction Center. (Avila 2003)

3. SYNOPTIC ENVIRONMENT

As the remnants of Bill advanced across Alabama and Georgia the night of 1 July, areas of southeast Georgia and South Carolina were located in the northeast quadrant of the advancing remnant low pressure center, an area that has been shown to be a favorable location for the development of tropical cyclone tornadoes (Hill et al. 1966). Similar tracks of landfalling tropical systems have also produced past tornado outbreaks across Georgia and South Carolina, including Beryl in 1994 and Earl in 1998.

At 1200 UTC 1 July, a stationary front was located along the Virginia and North Carolina border as shown in Fig. 3. As the remnants of Bill approached during the afternoon on 1 July, the front pushed south into central South Carolina. Storms formed over southern Georgia during the afternoon and converged on the slow moving front. Fig. 4 shows the surface convergence associated with the front over southern areas of South Carolina, with northeast surface winds and dew points in the 60s across much of northern South Carolina. This boundary would prove to be an important source of convergence and help initiate severe convection during the night.

The track of Bill kept southeast Georgia and South Carolina in the warm sector, maintaining a moist and unstable atmosphere. Atmospheric soundings taken across the Southeast and the Carolinas at 1200 UTC 1

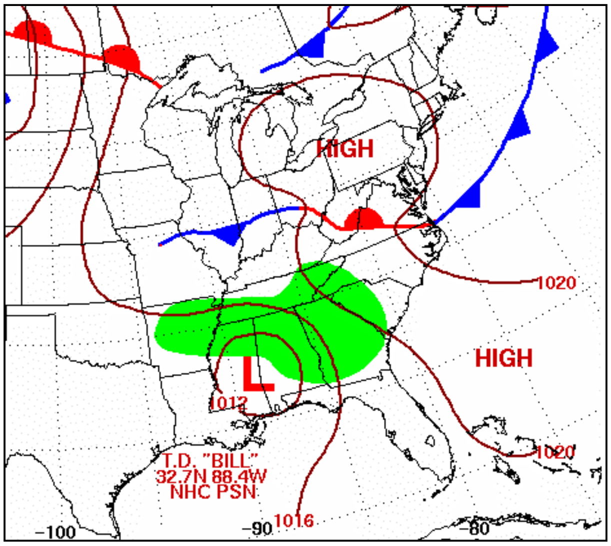

Fig 3. Surface weather map at 1200 UTC 1 July 2003 depicted by the Hydrometeorological Prediction Center.

July however showed only modest CAPE generally less than 700 Jkg^{-1}. Highest CAPE was found along the Florida coast where JAX sounding indicated 1800 Jkg^{-1}.

Shear values were found to be highest over the Gulf States at 1200 UTC 1 July with 0-3 km SREH at Atlanta and Birmingham of 343 m^2s^{-2} and 831 m^2s^{-2} , respectively. Further to the east, SREH was generally below 100 m^2s^{-2}, as backing surface flow and the low-level jet were not forecast to increase until 0000 UTC 2 July. McCaul (1991) found that an atmosphere characterized by strong shear and weak convective instability was highly favorable for tropical cyclone tornado development. Due to abundant cloud cover and ongoing widespread precipitation, instability and CAPE remained low across Georgia and South Carolina through the afternoon of 1 July and was forecast to remain low through 1200 UTC 2 July.

As Tropical Depression Bill approached the southern Appalachians, forecast models indicated a midlevel dry intrusion approaching from the southwest. Fig 5 shows this wedge of dry air in the eastern semicircle of the advancing tropical system, similar to what Curtis (2004) found in his investigation of "large" tropical cyclone tornado outbreaks. This drier air was forecast to move northeast along the Florida and Georgia coasts by 0600 UTC July 2. Novlan and Gray (1974) McCaul (1987) and most recently Curtis (2004) have shown that these dry midlevel intrusions may play a key role in the development of large tornado outbreaks during land falling tropical cyclones.

4. MESOSCALE ENVIRONMENT

The threat for severe weather was increasing through the late afternoon hours on 1 July as dry air in the 700-500hPa layer was forecast to advance northeast across southeast Georgia and coastal South Carolina. Tornado watches were in effect by 4pm on the afternoon of 1 July for much of central Georgia and areas of southeast South Carolina as the midlevel dry air increased convective instability and the threat for isolated supercells. Because area soundings showed only modest CAPE values and relatively high SREH, mini supercells (McCaul 1987; Davies 1990) were an increasing threat. Numerical simulations of supercells by McCaul and Weisman (1996) in hurricane environments produced these pronounced reductions in both horizontal and vertical size of developing supercells.

During simulations (McCaul and Weisman, 1996) these mini supercells showed an absence of cold surface outflow, which led to a reduction in low-level vorticity. They showed that unless additional forcing and mesoscale vorticity was present, mesocyclones and tornadoes were uncommon. Markowski et al (1998) showed during the VORTEX-95 project that 70% of tornadoes were associated with boundaries and hypothesized that these boundaries brought enhancements of horizontal vorticity and allowed for low-level mesocyclogenesis. Tropical rainbands can be one source of these boundaries, but were absent during this outbreak as the unorganized remnants of Tropical Storm Bill moved across the Southeast.

While McCaul and Weisman (1996) have shown a lack of cold pool generation in tropical thunderstorm environments, the midlevel dry air advecting into Georgia and South Carolina (see Fig 5) increased the storms' ability to form cool outflow. Romine (2002) through numerical simulations of Hurricane Opal showed how vertical vorticity in mini supercells increased as a function of a dry profile. The evaporative cooling in the midlevels generates negatively buoyant air that feeds the cold pool.

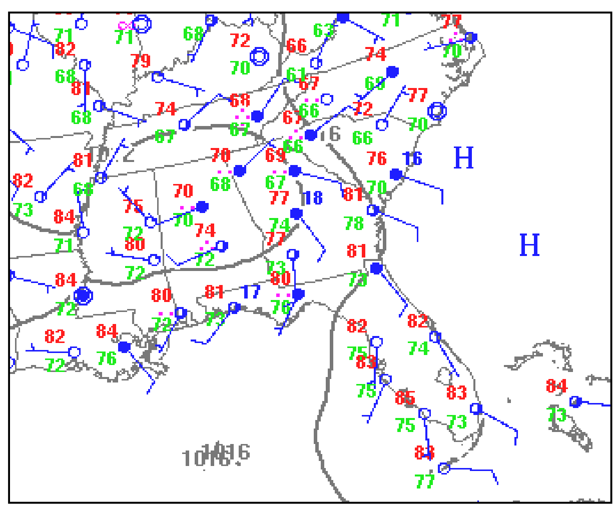

Fig. 4 Surface station plot at 0000 UTC 2 July 2003

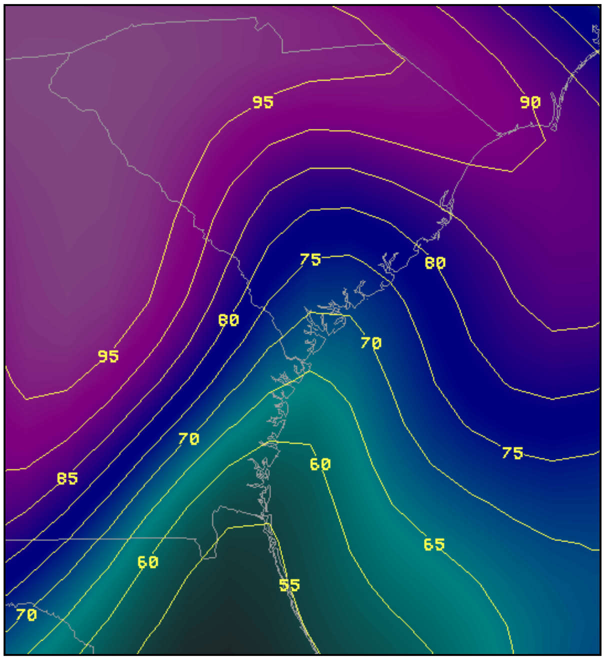

Fig 5. 06 hr forecast of 700 hPa Relative Humidity from the 2100 UTC RUC model run, valid 0300 UTC 2 July.

It is this formation of a baroclinic boundary that increased the likelihood of tornado formation within the mini supercells and subsequent smaller tornadic cells. Curtis (2004) concluded after examining 13 large tropical cyclone tornado outbreaks, that 11 occurred along pronounced relative humidity gradients at 500 and 700 hPa. Fig. 5 shows the midlevel dry air wedge over mainly coastal Georgia and South Carolina with the strongest gradient of humidity along the Georgia-South Carolina border. While the largest shear and helicity values were found over both central Georgia and South Carolina, it can be hypothesized that the lack of tornadic storms over these areas was a result of moist midlevels.

5. RADAR ANALYSIS

Isolated severe convection began to form early in the afternoon of 1July across portions of southeast Georgia while widespread non-severe weather was ongoing across central Georgia closer to the center of TD Bill. By 2200 UTC 1 July, KCLX radar was indicating a severe cell over Toombs County approaching the CHS CWA. This storm had a well-established appendage and was highly suspect for being tornadic. As the storm crossed into Jenkins County Georgia, the supercell structure became more apparent at 2359 UTC with a hook echo, bounded weak echo region (BWER), deep mesocyclone, and large inflow notch. While the diameter of the mesocyclone was fairly broad at over 4 km, an F1 tornado occurred near Scarboro Georgia (see Fig. 6) with a track of 4.5 miles. Echo tops were found to be less than 40 kft, VIL of around 40 kgm^{-3}, and no CG lightning strikes were indicated. Another mini supercell quickly developed across Jenkins County Georgia by 0049 UTC 2 July. Although a strong and persistent mesocyclone was indicated, no evidence of a tornado was found.

By 0128 UTC, a cluster of strong convective cells was organizing into a north-south line across portions of southeast Georgia. Fig. 7 shows the KCLX base reflectivity at 0148 UTC when a supercell was moving into western Screven County. This cell too had a history of producing mesocyclones, but was much larger in scale than the two previous supercells that had already developed across portions of the CWA. Echo tops were over 50 kft with VIL of 50 kgm^{-3}. This convective cell resembled an HP supercell as the low-level base reflectivity took on a kidney bean shape with the mesocyclone on the eastern flank of the storm. Due to the shallow nature of the mesocyclone with this storm, the Mesocyclone Detection Algorithm (MDA) on the KCLX radar was not triggered. Rotational velocity of 40 kt was noted on the storm relative velocity (SRM) 0.5 degree scan over western Screven County by 0203 UTC near Thomasboro. While no evidence of a tornado was found, trees and power lines were reported down near the towns of Thomasboro and Woodcliff.

At 0208 UTC a small shallow mesocyclone developed on the southern flank of this thunderstorm cluster and moved into far eastern Bulloch County approaching the Screven County line. By 0223 UTC, strong rotational velocity of 55 kt was observed near Clito on the 0.5 SRM elevation slice (see Fig 8). Because the mesocyclone was very small and shallow, the MDA on the KCLX radar was not triggered. F2 tornado damage including downed trees and damaged mobile homes was found near Clito Georgia with a damage path of 7 miles as it crossed into Screven County. This storm continued on its path into central Screven County and produced another F2 tornado near the community of Farmdale where a 6 mile damage path was discovered with downed trees, power lines, and an overturned automobile.

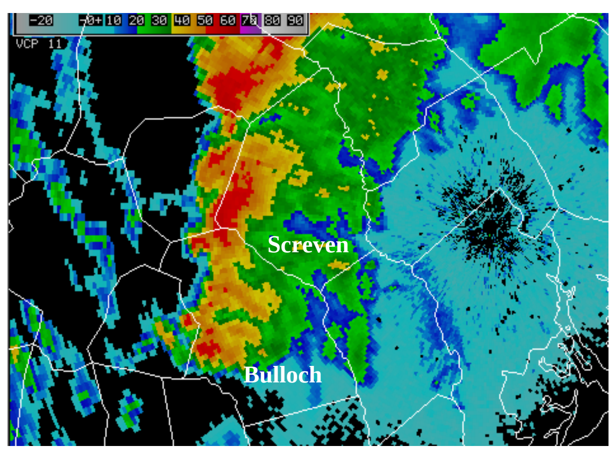

Fig 7. KCLX 0.5 degree base reflectivity at 0148 UTC 2 July 2003.

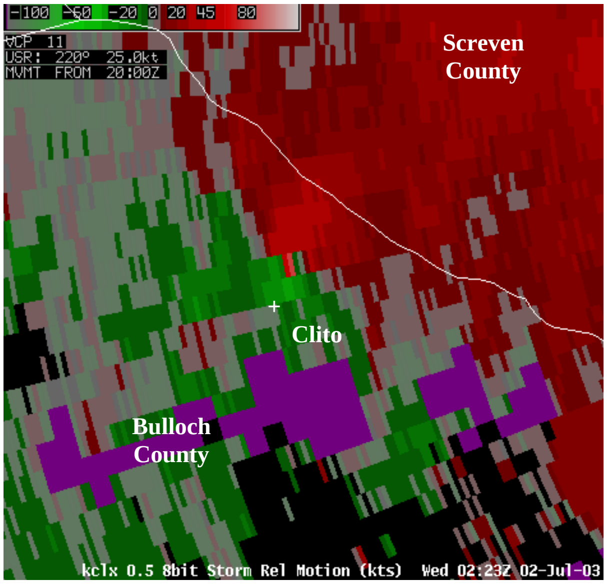

Fig 8. KCLX 0.5 degree storm relative velocity at 0223 UTC 2 July 2003.

Less than 40 minutes later, at 0258 UTC, a shallow storm with echo tops of only 25 kft, developed a hook appearance in the 0.5 degree reflectivity less than 5 miles northwest of Clito. Analysis of 0.5 degree SRM detected inbound velocities of 74 kt. As this storm moved across the Bulloch and Screven County line, a F1 tornado occurred near Blitch with a 3 mile long path of tree damage.

By 0332 UTC this cluster of severe and tornadic storms had crossed the Savannah River into southeast South Carolina. At this time, SRM 0.5 degrees showed 2 distinct and persistent areas of rotation across sections of Hampton County in South Carolina. Although these areas of rotation were located within 50 km of KCLX, the MDA was not triggered. The strongest of these rotations moved across northern Hampton County with the 50 dBZ low-level reflectivity core showing a hook appearance. At 0402 UTC, at a distance of only 25 km from the radar, KCLX detected rotational velocities of 45 kt just west of the town of Hampton South Carolina (see Fig. 9). These winds were detected on the 0.5 degree SRM slice at a height of 870 ft agl. A storm survey conducted by the Charleston National Weather Service Office found a 10 mile path of F1 tornado damage including structural damage to a Dollar General Store in the town of Hampton **(**see Fig. 10).

Over the next hour, this storm moved northeast into northern Colleton County while strengthening and gaining supercell characteristics. By 0502 UTC a well-defined hook echo developed, VIL surged to 45 kgm^{-3}, and echo tops increased to over 40 kft. A F1 tornado was reported near Smoaks South Carolina with tree and mobile home damage. This tornadic supercell continued to move northeast into northern Dorchester County with a very impressive reflectivity gradient and mesocyclone. Despite these persistent severe characteristics, wind and tornado damage were neither reported nor found over Dorchester County.

By 0600 UTC, most of the convection pushed northeast out of the CHS CWA. There were several small storms on the order of less than 10 km across that formed over sections of southeast South Carolina. While many had a hook appearance in the 0.5 base reflectivity, these remaining storms lacked the persistent mesocyclones and gate to gate shears that the earlier tornadic storms possessed.

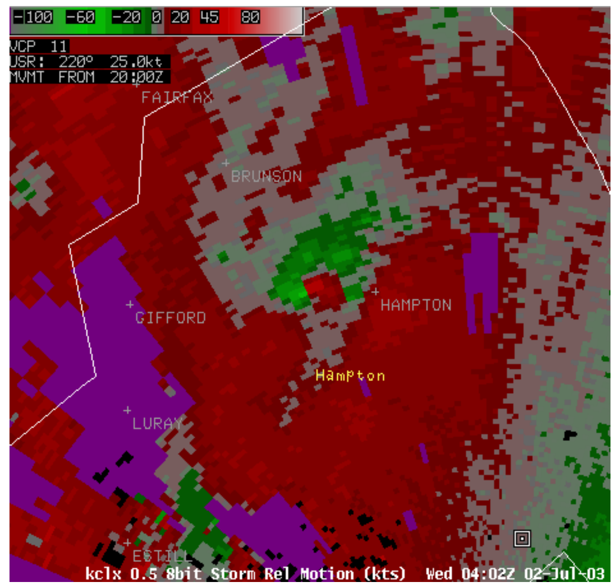

Fig 9. KCLX 0.5 degree storm relative velocity at 0402 UTC 2 July 2003.

6. HODOGRAPH MODIFICATION

On the 1200 UTC 1 July sounding at Charleston (CHS), light east winds at the surface quickly veered to the southwest at 3 km and westerly at 6 km. While these veering winds increased the probabilities of rotating storms, speeds less than 30 kt throughout the 0-6 km layer produced a 0-3 km storm relative helicity (SREH) of only 110 m^{2}s^{-2}, well below the recommended level of 150 m^{2}s^{-2} for mesocyclones (Davies-Jones et al, 1990). Sounding locations upstream of Charleston such as Tallahassee Florida (TLH) showed much stronger winds in the lowest 3 km, which led to larger values of 0-6 km SREH. As the remnants of Bill moved northeast across the area, model forecasts indicated an increase in the wind fields and thus a subsequent increase in low-level SREH.

Because wind fields were forecast to increase substantially the night of 1 July, the 0000 UTC 2 July sounding and hodograph taken at CHS did not fully represent the atmosphere over the Georgia and South Carolina coasts later that night. The KCLX radar was in operation the night of 1 July and was located within 100 km of all the verified tornadoes. For further analysis of this outbreak, wind speed and direction were taken off the KCLX VAD Wind Profile and used to estimate the increasing helicity values across Georgia and South Carolina. The RAOB software (Environmental Research Services, 2004) was used for this analysis.

While the 0000 UTC 2 July CHS sounding did show a dramatic increase in low-level wind speeds from earlier in the morning, speeds were to reach a maximum between 0300 and 0600 UTC. Knowing that the stronger winds were to the southwest of CHS at 0000 UTC 2 July, the authors used the 0000 UTC winds from the KCLX VAD profile to modify the 0000 UTC 2 July hodograph. 0-3 km SREH increased from 269 m^2s^{-2} to 388 m^2s^{-2}. Of particular interest was the large increase in 0-1 km SREH from 100 m^2s^{-2} to 246 m^2s^{-2}. One reason for this large increase in SREH was a larger storm motion vector taken off the actual reflectivity radar loops.

This large increase in SREH was further seen at 0300 UTC 2 July when a low-level jet formed and low-level winds increased to near 50 kt. SREH values at 0300 UTC for 0-1km and 0-3 km were 411 m^2s^{-2} and 588 m^2s^{-2} respectively (see Fig 11). Using winds on the 0500 UTC VAD profile showed a slight decrease in SREH values at 331 m^2s^{-2} and 446 m^2s^{-2} for the 0-1km and 0-3 km layers. This decrease in winds was expected as the remnants of Bill began to move through the southern Appalachians and the strongest wind fields advecting north of the Charleston area.

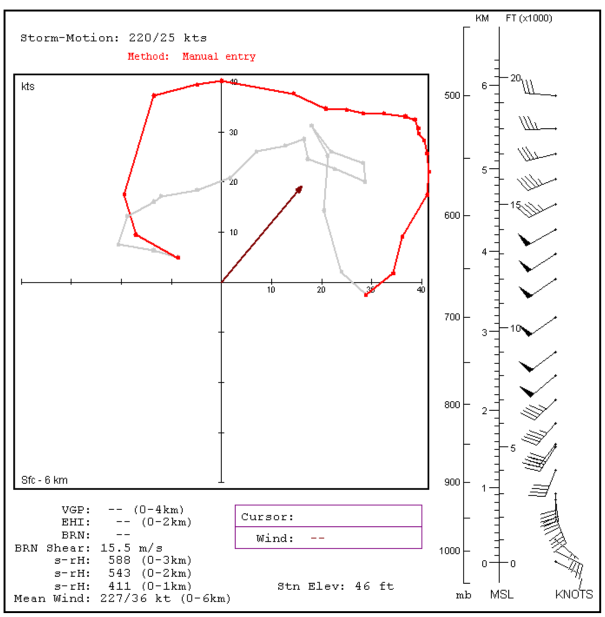

Fig 11. Modified hodograph using 0300 UTC 2 July KCLX VAD profile winds.

7. SUMMARY

This tropical cyclone tornado outbreak displayed many of the same aspects as previously researched outbreaks. The lack of instability, along with high values of shear, led to several occurrences of tornadic mini supercells. Despite low values of CAPE, the presence of a warm frontal boundary helped to maximize convergence and initiate the severe convection. The wedge of midlevel dry air intruding into coastal areas of Georgia and South Carolina helped to further destabilize the atmosphere and helped develop a stronger cold pool associated with the tornadic supercells. The lack of midlevel drying over central South Carolina and Georgia is one explanation as to why these areas saw little in the way of severe and tornadic convection despite having larger shear values.

This was a rare nighttime event. While most of the documented outbreaks occurred during the afternoon hours at the time of peak heating and instability, most of the reported severe weather, including the tornado touchdowns, occurred after 0000 UTC. We conclude that it was due to all the other “ingredients” coming together that the storms were able to form and sustain their strength despite the loss of daytime heating.

While assessing WSR-88D performance of past tropical outbreaks, Spratt et al (1997) found several techniques for warning forecasters to utilize in order to produce more timely warnings. These techniques were a valuable key in producing the timely warnings during this TS Bill tornado outbreak.

The usefulness of the Mesocyclone Detection Algorithm is often questioned in tropical events, and this case is no exception. With most of the tornadic mesocyclones being very small and shallow, the vertical structure of the mesocyclone was not always sufficient to trigger the mesocyclone alerts. In many cases, the mesocyclone alert was triggered well after the tornado had already touched down. While some of the parameters for the algorithm are adaptable, Spratt found little improvement when thresholds were lowered to account for the smaller size of the tropical mesocyclones. The diligent effort of watching the 0.5 and 1.5 degree elevation scans of both base velocity and SRM proved more reliable in recognizing and warning on the small tornadic mesocyclones.

Spratt also found that the trend of the mesocyclone can be just as important as the rotational velocities found within the mesocyclone. The persistence of both high reflectivity and mesocyclones can be a valuable tool in the warning process. As in this case, several hook echoes seen with 0.5 degree base reflectivity gave the warning forecaster confirmation of the tornadic cells.

8. FUTURE WARNING IMPROVEMENTS

Warning lead-time and accuracy during tropical cyclone tornado outbreaks should improve with time as new technology helps the warning forecaster with better decision making. The new Volume Coverage Pattern (VCP) 12 on the WSR-88D will give the warning forecaster several additional low-level elevation slices to interrogate shallow tropical mesocyclones. With visual identification of mesocyclones being so important during these tropical outbreaks, the introduction of high resolution 8-bit velocity and reflectivity products from the WSR-88D helped in the identification of several tornadic mesocyclones (see Fig 12). The use of an alternate color scale to view velocity products, away from the traditional red-green color scheme, proved invaluable when maintaining watch over the small mesocyclones (see Fig 13).

The ease at which warning forecasters can update a real time hodograph has been an operational issue for several years. The new ability of AWIPS to create a real time hodograph using a VAD wind profile will help the warning forecaster maintain a constant watch over changing values of shear and helicity without the tedious and time consuming job of data entry into a PC software program.

With the influx of public and private surface observations, the increase in large surface observation mesonets will improve our ability to analyze and track the movement of surface boundaries, leading to better mesoanalysis and forecasts of storm structure. If the locations of mesoscale and storm scale boundaries are identified, warning forecasters will be able to better anticipate which storms may become tornadic.

9. REFERENCES

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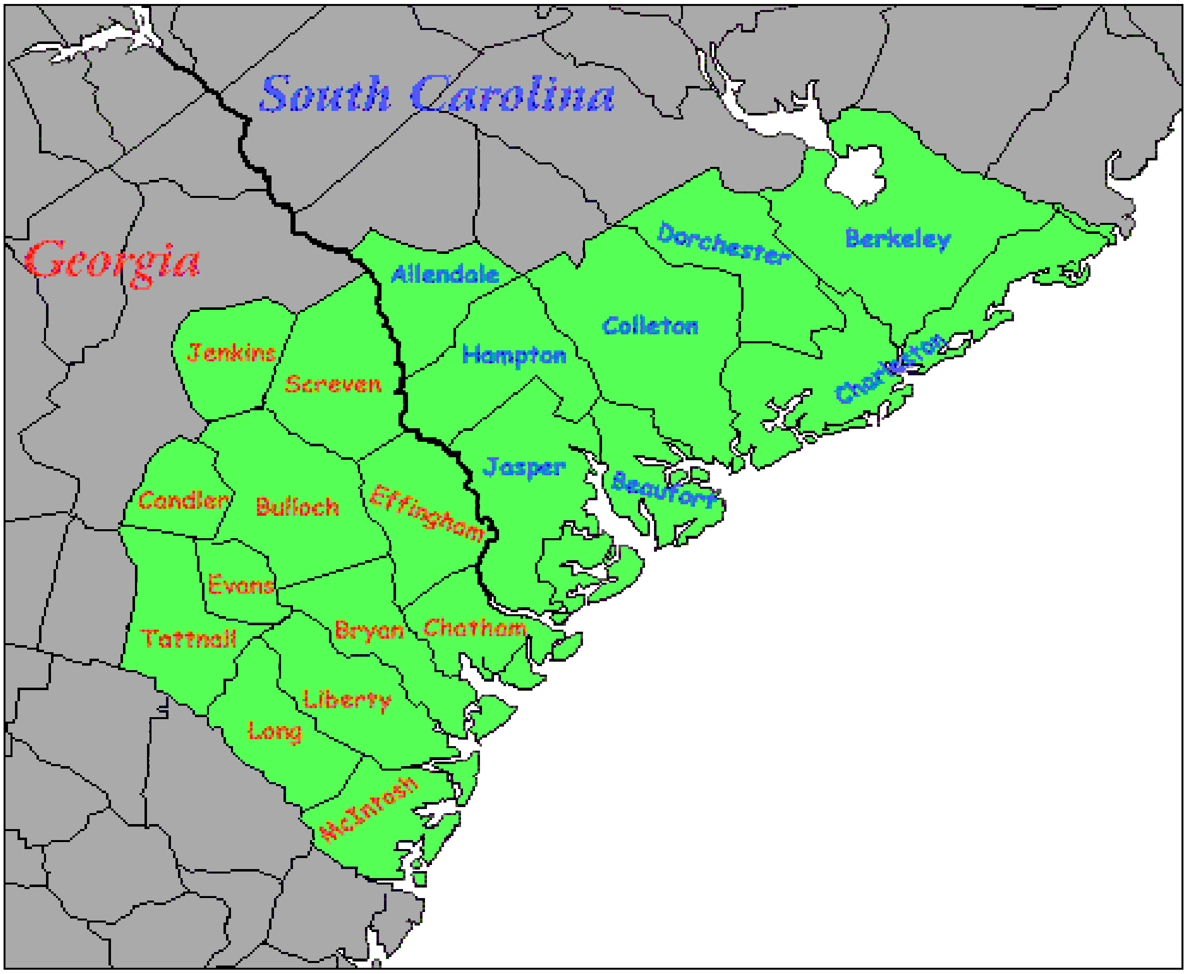

Fig 1. County Warning Area (CWA) for the National Weather Service Charleston South Carolina

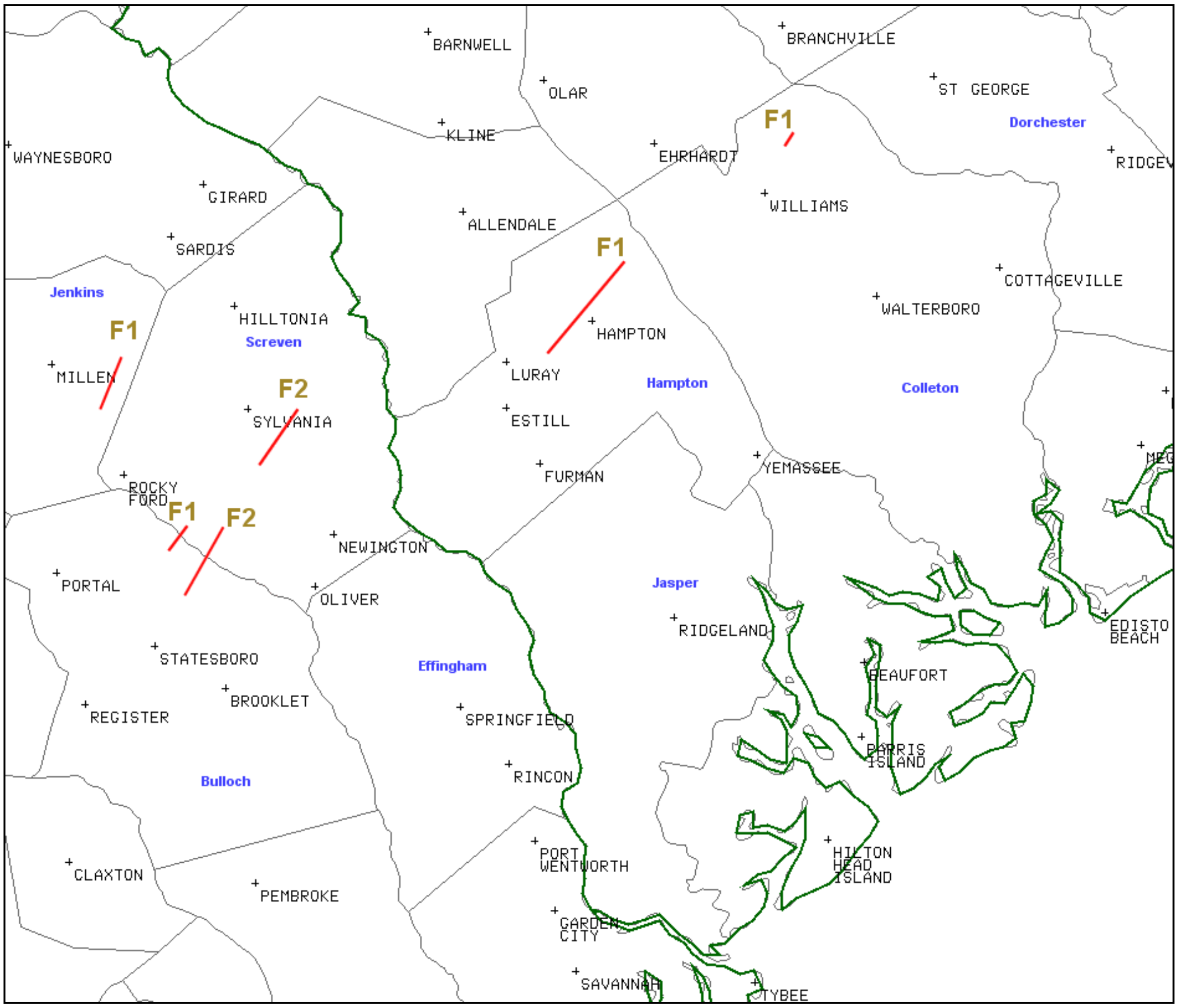

Fig 6. Tornado tracks across the CHS CWA. Tracks obtained through Storm Data (2003)

Fig 10. F1 tornado damage in the town of Hampton South Carolina

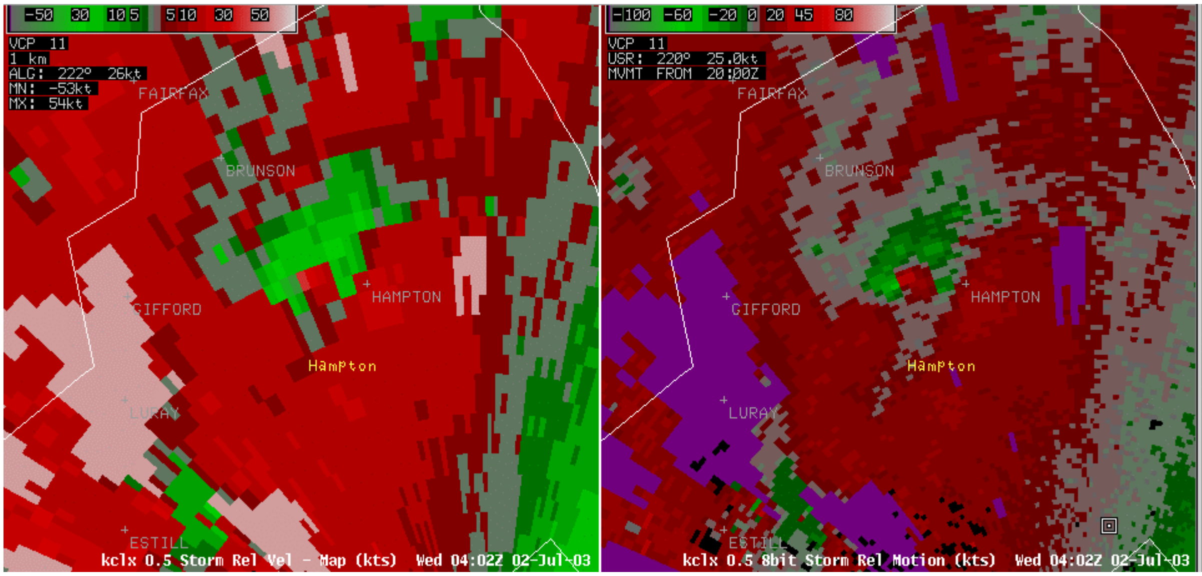

Fig 12. 4 bit (left) and 8 bit (right) KCLX 0.5 degree storm relative velocity at 0402 UTC 2 July 2003

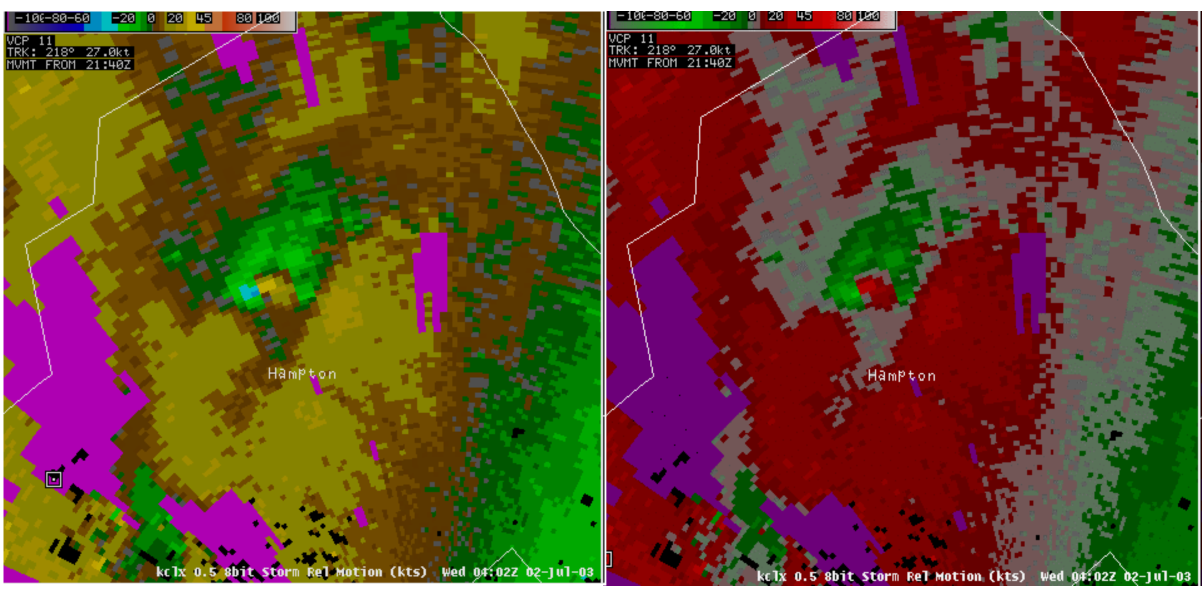

Fig 13. 8 bit KCLX 0.5 degree storm relative velocity at 0402 UTC 2 July 2003. Left image is using an alternate color scale. Right image is using the traditional Red-Green scale.