Multi-Scale Analysis of the 13 October 2001 Central Gulf Coast Shallow Supercell Tornado Outbreak

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ABSTRACT

On 13 October 2001, a mini-tornado outbreak occurred along the central Gulf Coast over a small area (9 tornadoes per ~ 3200 mi^2). This event was part of a larger scale severe weather outbreak that occurred over the preceding five days and extended from Nebraska to Georgia. The number of tornadoes (five F0s, two F1s, one F2 and an F3) accounts for 12.6% of all reported Baldwin County (71) tornadoes from 1950-2001. Single Doppler radar revealed the existence of 52 operator-defined shallow mesocyclones (rotation depths generally < 1.5 km). Synoptically, the event was characterized by a notable diffluent upper tropospheric wind flow pattern, a broad and strengthening low-level jet (40-60 kt) and the propagation of an upper level jet streak (100-110 kt) atop a strengthening surface front during a period of peak solar insolation. The presence of increased 0-3 km SBCAPE (~289 J kg^{-1}) at updraft low-levels (0-3 km) along with relatively strong ambient 0-2 km vertical wind shear likely aided the development of additional storm-scale dynamical lifting forces which potentially set this event apart from past similar, but non-tornadic events. In the updraft low-levels, composite mesocyclone radial Vr-shear values were observed to nearly double from 0.020 s^{-1} to 0.038 s^{-1} between 20 min prior to and the time of tornado formation. During this same period, mesocyclone core diameters halved to ~0.4 nm (0.8 km). Consistent with past findings from similar studies, results suggest that when Vr-shear persists around ~.015 s^{-1}, and a sudden doubling is observed (when correlated with the descent of the maximum shear below 1 km), a tornado may already exist or soon form.

1. Introduction

During the morning and afternoon hours of 13 October 2001, a tornado outbreak occurred over a small area of the central Gulf Coast (9 tornadoes per ~ 3200 square miles) region and relatively close to the coast (< 50 km). Eight tornadoes occurred in Baldwin County Alabama alone. This number of tornadoes (five F0s, one F1, one F2 and an F3, after Fujita, 1973) accounts for 12.6% of all reported tornadoes (71) for Baldwin County during the entire period of record from 1950-2001. Radar velocity data revealed 52 shallow mesocyclones (rotation depths generally < 1.5 km) that were detected under the National Weather Service (NWS) Mobile, Alabama (KMOB) WSR-88D radar coverage area (out to 240 km) between 1100-2100 UTC. The latter does not account for mesocyclones that developed outside of the time range examined, nor the mesocyclones that evolved beyond ~120 km whose low-level rotation was confined to heights below the radar horizon.

This paper examines both the synoptic and mesoscale environment that produced the event tornadoes. Finally, trends in several WSR-88D storm-relative velocity parameters relating to the event tornado producing mesocyclones prior to, during and just after tornado formation are also examined in order to establish how long warning lead times could have potentially been.

2. Event Synoptic Evolution

The event was characterized by the evolution of an unseasonably strong and deeply-reflected longwave trough (Fig. 1) that ejected from the southern Rockies on 0000 UTC 13 October 2001. During the ensuing 24 h period, the trough became negatively tilted and moved over western Louisiana by 0000 UTC 14 October 2001 (Fig. 2). According to Pennsylvania State University records (source Penn State Eyewall Homepage, http://eyewall.met.psu.edu/), the trough was anomalously deep and traversed far south given the time of year. As measured by the M_{total}, a method that objectively measures climatological anomalies, this synoptic scale energy passage ranks as the fourth highest on record for all Octobers between 1948-2002 (Hart and Grumm, 2001). Figure 3 shows the departure (measured in standard deviations) of several meteorological parameters (temperature, height, winds and moisture) from their mean background fields on this day. For precise details on the M_{total}, refer to the following link (http://eyewall.met.psu.edu/ranking/ranking.html).

The 1200 UTC 13 October 2001 upper air data revealed a notably diffluent (and divergent) upper tropospheric wind flow (Fig. 4), a strengthening 40-60 kt lower tropospheric jet (Figs. 5a-b) and a destabilizing warm sector ahead of an approaching cold front (Fig. 6). Although not shown, the lower tropospheric winds were convergent and were becomingly increasingly situated below the mid- and upper tropospheric divergence associated with the approaching upper trough. The 1200 UTC KMOB 0.5 ° radar reflectivity data (see Fig. 7a) indicated the presence of two distinct convergence lines that were initiating isolated deep convection. Convergent Line A lies to the west of Convergent Line B. Aligned nearly parallel to the boundary layer wind flow, both convergence lines slowly moved eastward at ~ 9 kt. Although a few weak tornadoes were produced by shallow mesocyclones over portions of northern Mobile Bay in association with Convergent Line B, there was a brief cessation in tornado production throughout the late morning hours as Convergent Line B moved eastward. Figure 7b reveals that Convergent Line A later moved to a location over Baldwin County Alabama by 1800 UTC and became the main focus for the initiation of severe deep convection that later manifested as the tornado outbreak.

It is generally well understood that the primary role of the synoptic scale, as it pertains to severe weather development, is to transport lower tropospheric moisture and destabilize the lapse rate through synoptic upward vertical motions. Owing to the fact that there are numerous ways to destabilize the lapse rate, it is surmised that in this event, the right entrance region of the upper level jet streak became situated atop increasingly warm, moist and unstable air near peak solar insolation time, deep-layer lapse rates destabilized to their greatest values of the day. The latter occurred in two primary ways. First, synoptic vertical motions were forced through the process of differential divergence in the downstream air between 1200-1800 UTC. Secondly, it was observed that diabatic heating, versus low-level warm air advection, was solely responsible for destabilizing the lapse rate below 850 mb. Respectively, Figures 8a and 8b, depict boundary layer mixing ratio and equivalent potential temperature closest to the time of tornado production.

Note that close to the surface, both thermal and moisture gradients are well north of the event tornado region. Figure 8c shows a partial account of the total number of severe weather reports received by the NCEP Storm Prediction Center for 13 October 2001. Interestingly, the majority of reports are clustered where both the highest boundary layer equivalent potential temperature (> 345 K) and absolute moisture (> 16.5 g kg-1) values were present.

Next, a comparison of NCEP ETA Model cross sections will be made for two separate times. The cross sections were taken across the right entrance region of the upstream upper tropospheric jet streak for each time. The cross sections shown in Figures 9a-c are valid 1800 13 October 2001, while Figures 10a-c are valid 0000 UTC 14 October. For both times, southern Oklahoma defines Point A while the eastern Gulf of Mexico defines Point B. A red triangle was annotated on Figs. 9b-c and 10b-c to indicate the upstream location of the air that would eventually flow over southwestern Alabama. It should be mentioned that the 1200 UTC ETA Model was estimated to be ~2-3 h too slow with the eastward progression of the upper trough. However, the model did appear to have a reasonably accurate representation of the event synoptic features and their magnitudes. Upon comparison, the upper- and lower tropospheric jets coupled to form a thermally direct transverse ageostrophic circulation. The evolution of the ageostrophic circulation is clearly visualized in Fig 10c. This mesoscale vertical circulation is surmised to be partially responsible for the initial development of a severe squall line that later moved through the region just hours after the tornado outbreak ceased. Figures 9b and 10b demonstrate also that mid-tropospheric cold air advection clearly lags well to the west of the surface front (also seen in Fig. 2).

The evolution of the low-level jet was touched upon earlier. The model data clearly shows that the eastward development of the low-level jet served not only to maximize moisture transport along its' axis, but additionally, it helped focus the relatively high absolute values of water vapor (see Fig. 8a) in the vicinity of where the event tornadoes occurred. Figures 9c and 10c show the vertical evolution of moisture flux convergence. It is seen that the depth of moisture flux convergence (> -3 g kg^{-1} / 6h) increased from just below 850 mb to as high as 700 mb over the 6 h period, while nearly doubling in magnitude at the surface (-12 g kg^{-1} / 6h to -24 g kg^{-1} / 6h). Figure 11 is a 1200 UTC NCEP ETA Model time section nearest where the tornadoes occurred. Shown are wind divergence, upward vertical motion and moisture flux convergence. The latter serves as further evidence that localized strong upward vertical motions were associated with the vertical coupling of the upper and lower tropospheric jets and that this played a primary role in destabilizing the mid-tropospheric lapse rate.

3. Characteristics of the pre-storm environment

Figure 12 is a modified 1700 UTC sounding for the location of the event tornadoes in Fairhope, Alabama (FAI). The sounding was constructed using the Skew-T Hodograph Analysis and Research Program (SHARP; Hart and Korotky 1991). Using a surface parcel described as [Potential Temperature = 300 K (or 81 F) and a mixing ratio = 19.9 g kg^{-1}(or 76 F)], a surface-based Convective Available Potential Energy (or SBCAPE) value of ~3877 J kg^{-1} was obtained with a meager 9 J kg^{-1} of Convective Inhibition (CINH). Observed storm-relative helicity (SRH) values were 438 m^2 s^{-2} given a forecast storm motion vector of 221° / 28 kt (or 30R75 discussed later). Actual storm motion vectors were used in the SRH calculations shown in **Table 1** (discussed in detail below). Upon closer inspection of the 1700 UTC FAI sounding, an absolutely unstable layer existed between the surface and ~850 mb. Over the event tornado region, GOES infrared satellite imagery revealed that nearly six full hours of solar insolation occurred and surface temperatures resultantly warmed into the lower 80s F. Surface dewpoints rose very little between 1200-1700 UTC and remained in the mid 70s F. The level of free convection (LFC) was computed as 544 m (or ~1702 ft) and is shown in Figure 13. This observation closely matched KMOB ceiling height observations just prior to and after 1700 UTC.

Hodographs were generated for 1200, 1500 and 1800 UTC using a combination of KMOB WSR-88D VAD (100 ft or ~ 308m) winds, surface wind observations and observed storm motion vectors. The 1800 UTC MOB hodograph (see Fig. 14) was chosen for discussion as it was obtained with 40 km and 1 h of tornado occurrence. Upon closer inspection, it is seen that the majority of vertical wind shear, which contributes to the production of horizontal vorticity, exists in the lowest 1.5 km. **Table 1** yields information on the evolution of the vertical wind shear profile for the other times leading up to 1800 UTC. Note also in Table 1 that the 0-2 km SRH accounts for ~90% of the total 0-3 km SRH. It is inferred from the three-hourly hodographs that new cell growth was occurring on the south-southeast flanks of mature updrafts (see direction to which storm-relative inflow vectors are pointing). The observed storm motion vectors veered (176 to 198 degrees) and strengthened (21 to 38 kt) between 1200-1800 UTC. Further, the presence of increased 0-3 km SBCAPE (~289 J kg^{-1}) at updraft low-levels along with relatively strong ambient vertical wind shear within the same vertical layer, likely aided the development of additional dynamical lifting forces which potentially set this event apart from past similar, but non-tornado producing mesocyclone events.

4. Radar Analyses

Of the seven confirmed tornadoes that occurred, six were selected for further study (three F0s an F1, F2 and an F3). Unfortunately, archive level II radar data are not available for this event. Also, the archive level IV radar data set contains base data from only the lowest elevation slice (0.5°). Although the data no longer exist, a notable component of radial divergence began to appear at 1.5° (~4900' AGL), with nearly pure divergence at 2.4° (~7900' AGL). Due to the shallow depth of the event mesocyclones, approximately 95% of the tornado warning decisions were made using both reflectivity and velocity data obtained from the 0.5° elevation slice. Various trends in operator-defined mesocyclone characteristics were examined from four volume scans (T_0-4) prior to T_0 until one volume scan after (T_0+1). The parameters evaluated include: rotational velocity, low altitude mesocyclone diameter, low altitude maximum horizontal shear and the radar range of the mesocyclones. These parameters were temporally averaged into a composite in order to identify any potential methods by which to gain additional tornado warning lead time.

a. Mesocyclone trends prior to tornadogenesis

A time series plot of low-level horizontal shear (Vr-shear) for each of the six mesocyclones is shown in (Fig. 15). Each plot shows an overall increase in Vr-shear between (T_0-4) and T_0 as each mesoscyclone evolved at a nearly constant height. The data show that the Vr-shear dramatically increased in four of the six tornado producing mesocyclones during the aforementioned time. For further analysis, the mean Vr-shear and rotational velocities values were composited to examine the overall trends in this event.

The composite plot of the 0.5° Vr-shear for the six mesocyclones (Fig. 16) shows significant intensity changes between T_0-4 and T_0+1. Most notable, and similar to the findings of Grant and Prentice (1996), is that the Vr-shear nearly doubles from 0.020 s^{-1} at T_0-4 to 0.038 s^{-1} at T_0. As expected, the average 0.5 ° rotational velocity (Fig. 17) also indicates a steady increase from 22 knots at T_0-4 to 33 knots at T_0 . Both peak Vr-shear and rotational velocity values correlate well with the mean time of event tornado formation. A slight decrease in composite rotational velocity and shear were then noted between T_0 and T_0+1. The steady increase in composite Vr-shear and rotational velocity values were observed simultaneous to a mesocyclone core diameter contraction (Fig. 18) by nearly half (0.9 nm at T_0-3 to 0.5 nm at T_0-1). It should be noted that the average low-level mesocyclone diameter was found to be smaller than 1.0 nm diameter.

b. Mesocyclone rotational velocity and shear nomograms

For well over a decade now, radar warning meteorologists have used rotational velocity and Vr-shear to evaluate mesocyclone rotational intensity. The recognition of the importance of these parameters in bridging the gap between the existence of a persistent and rotating updraft and the production of a tornado lead to the development of nomograms for warning purposes. In this event, the magnitude of each tornado producing mesocyclone is plotted on an appropriate nomogram for comparison to past mesocyclones, whose data originally defined the mathematical shape of these curves.

Both rotational velocity and Vr-shear at T_0-2 and T_0 are plotted on the Operational Support Facility (OSF, 1997) 1 nm rotational velocity and Vr-shear nomograms, respectively. A plot of the T_0-2 rotational velocities (see Fig. 19) show that five of six mesocyclones are classified as 'Minimal' strength (as only the F3 tornado producing mesocyclone measured in the 'Moderate' range). The latter observation points to the fact that when using rotational velocity, in some cases, tornado warnings may have to be issued with 'Minimal' mesocyclone strength classifications. As the mesocyclones progressed to T_0, a plot of the rotational velocity values (Fig. 20) show the F3 tornado producing mesocyclone had strengthened into the "Strong" category, while three others strengthened into the "Moderate" range. Only two of the weaker F0 tornado producing mesocyclones remained in the "Minimal" range at T_0.

Next, the Vr-shear trends of the event mesocyclones were plotted two volume scans before T_0. Figure 21 indicates two of the mesocyclones (producing an F2 and F3) fell in the "Tornado Likely" range, three fell in the "Tornado Probable" range (producing an F1 and two F0s), and one of the weakest mesocyclones (producing an F0) fell in the "Tornado Possible" range. In comparison, a plot of the Vr-shear values at T_0 (Figure 22) indicates a significant increase in Vr-shear for all six mesocyclones, with five of the six occurring in the "Tornado Likely" category. The remaining mesocyclone fell into the "Tornado Probable" classification. Given the Vr-shear observations in this event, the above suggests that more weight and operational consideration should have been given to trends in Vr-shear leading up to the time of tornado production. This is consistent with both the findings of Burgess et al., (1995), Grant and Prentice (1996) and

Medlin (2001). However, it must be emphasized that the decision to warn should not solely be based upon radar. As outlined by the Warning Decision Training Branch in the "Tornado Warning Guidance: Spring 2002," radar operators must continually incorporate a variety of meteorological data sources into the warning process, including the use of multiple radars, spotter reports, temporal trends in radar algorithm output, surface, satellite and lightning observations. Of most importance, is to have a sound understanding of the Near Storm Environment (NSE) before the event unfolds.

c. The F3 Foley, Alabama Tornado

The Foley, Alabama tornado formed near 1:20 PM CST and produced damage consistent with F3 intensity. Figure 23 shows a WSR-88D 0.5° storm-relative velocity image of the parent mesocyclone beside a photograph taken of the associated tornado at the approximate time of the aforementioned image. This tornado produced a damage path approximately 1/4 sm wide and 1 sm long. The tornado damaged an entire pecan orchard with more than 30 mature pecan trees either snapped or uprooted, tossed numerous vehicles airborne. The most notable evidence of the latter was a large panel truck that was loaded with heavy tools. The truck was tossed over 60 feet (Fig. 24). The tornado totally destroyed two mobile homes, two well-constructed large cement block buildings (Fig. 25), and caused major damage to three other cement block buildings (Fig. 26). Of the six tornadoes examined, the Foley tornado exhibited the greatest Vr-shear and rotational velocity values, measuring .051 s^{-1} and 45 kt, respectively.

5. Conclusions

During the morning and afternoon hours of 13 October 2001, eight tornadoes occurred over Baldwin County Alabama. This number of tornadoes accounts for 12.6% of all reported tornadoes in this county during the period of record from 1950-2001. The event longwave trough was anomalously deep and traversed far south given the time of year. Objectively, the longwave trough evolution ranks as the fourth highest on record for all Octobers between 1948-2002. The event was marked by a notable diffluent upper tropospheric wind flow pattern, a broad and strengthening low-level jet (40-60 kt) and the propagation of an upper level jet streak (100-110 kt) atop a strengthening lower tropospheric front during a period of peak solar insolation. Synoptic upward vertical motions were enhanced over the downstream tornado event location and these played a primary role in destabilizing the mid-tropospheric lapse rate. The presence of increased 0-3 km SBCAPE (~289 J kg-1) within the updraft low-levels, along with relatively strong ambient vertical wind shear conditions within the lowest 2 km, likely aided the development of additional storm-scale dynamical lifting forces that potentially sets this event apart from past similar, but non-tornadic events.

From a radar perspective, it is important to note that trends in 0.5° composite rotational velocity were of little assistance in providing tornado warning lead time in this event. Composite values were observed to fall into the " minimal" category on the 1.0 nm diameter mesocyclone strength nomogram between T_0- 4 to T_0 which is when valuable lead time could have been gained. Since the Vr-shear computation accounts for distance between the maximum in- and outbound velocity couplets when diagnosing operator-defined mesocyclones, it was found to have some potential in providing warning lead time in this event given observed trends.

Composite Vr-shear values were observed to nearly double from 0.020 s^{-1} approximately 20 min prior to tornado formation to 0.038 s^{-1} at the time of tornado occurrence. Also during this period, mesocyclone core diameters halved to ~0.4 nm (0.8 km). Consistent with similar past findings and during this event, when the horizontal shear is observed to persist around ~.015 s^{-1}, and next a sudden doubling is observed (when correlated with the descent of the maximum shear below 1 km), a tornado may already exist or soon form. Although not the case in this event, past tornado producing mesocyclones have been observed to suddenly spin-up and produce tornadoes in less than two successive radar volume scans (ie.. ~10 min). Even though the increasing trend in Vr-shear shows some promise as a warning tool, the radar warning meteorologist is still tasked with deciding when to warn despite the observed trend of any parameter. Such a finding continues to place much emphasis on assessing the local pre-storm environment, radar reflectivity evolutions and spotter reports into the final warning decision process.

6. References

Burgess, R.L. Lee, S.S. Parker, S.J. Keighton, and D.L. Floyd, 1995: A study of mini supercells observed by WSR-88D radars. Preprints, *27th Conference on Radar Meteorology*, Vail, Colorado, American Meteorological Society (AMS).

Fujita, T.T., 1973: Tornadoes around the world. Weatherwise, 26, 56-83.

Grant, B., and R. Prentice, 1996: Mesocyclone characteristics of mini supercell thunderstorms. Preprints, *15th Conf. On Weather Analysis and Forecasting*, Norfolk, VA, AMS., 362-365.

Hart, J. A. and W. Korotky, 1991: The SHARP workstation. A Skew-T Hodograph Analysis and Research Program. NOAA\NWS, Charleston, WV, 300 pp. [Available from NWS Eastern Region Scientific Services Division.]

Hart, Robert E., Richard H. Grumm, 2001: Using Normalized Climatological Anomalies to Rank Synoptic-Scale Events Objectively. *Mon. Wea. Rev.,* **129**, 2426– 2442.

Medlin, J.M., 2001: <u>A Single-Doppler Analysis of the Outer Rainband Mesocyclones Associated with Hurricane Opal of 4 October 1995</u>. UAH Masters Thesis, 89 pp.

Operational Support Facility, 1997: Tornado Warning Guidance. Operations Training Branch, Norman, OK (now Radar Operations Center, Warning Decision Training Branch)

Radar Operations Center, 2002: Tornado Warning Guidance: Spring 2002. [Available at http://www.wdtb.noaa.gov/resources/PAPERS/twg/index.html]. Warning Decision Training Branch, Norman, OK.