P2H.14 WSR-88D ANALYSIS OF TORNADIC AND NONTORNADIC DEEP CONVECTION IN LANDFALLING TROPICAL CYCLONE RAINBANDS

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1. INTRODUCTION

Tropical cyclones (TCs) making landfall commonly spawn tornadoes within their rainbands. In the United States, as much as 10% of the lives lost during tropical cyclones are a result of the tornadoes spawned in these storms (Novlan and Gray 1974). Forecasting such tornadoes has proven difficult due to the small nature of shallow supercells. Previous studies have looked at the environmental conditions which help to spawn these tornadoes and the radar characteristics once the cells are onshore. It is already known that tornadoes occur after the TC rainband has reached the coast. It is not apparent, however, if these tornado producing cells show certain storm structures, such as a mesocyclone, while still offshore that may help to successfully forecast tornado development.

Previous research has found a common climatology for TC tornadoes (Novlan and Gray 1974; Gentry 1983; McCaul 1991). McCaul (1991) found that over 70% of the storms with a Gulf Coast landfall produced tornadoes. This is due to the location of the onshore flow of the TC rainband in the favorable right-front quadrant. Most tornadoes occur 200-400 km from the center of the TC in convective cells embedded within the outer-rainbands. A majority form within 200km of the coastline with a distinct spike at a range of 100km from the coast. Another important aspect of the climatology is the TC motion. Gentry (1983) found that 81% of the hurricanes producing at least six tornadoes were moving between 300° and 30° as they crossed the coastline or recurving.

Several observational and numerical studies have recognized environmental conditions that seem favorable for TC tornado formation (Novlan and Gray 1974; Spratt et al. 1997; Curtis 2004; Schneider and Sharp 2007). Atmospheric instability can be enhanced by the intrusion of midlevel dry air adjacent to the rainband. As a result of the dry air above 850 mb, the Convective Available Potential Energy (CAPE) is increased. Eleven out of 13 tornado outbreak cases, producing 20 or more tornadoes, were found to have evidence of a dry intrusion at midlevels over the outbreak area for landfalling TCs. A moderate CAPE (> 500 J/kg) is typical of the TC tornado environment. Strong low-level shear (> 20 m/s over lowest 3 km) and low – level storm-relative helicity (> 100 m^2/s^2) are other important factors for tornadogenesis. Lastly, a low-level convergence axis (e.g. the coastline) seems to be a triggering mechanism for outbreaks due to the increased horizontal vorticity which can be tilted and stretched by an updraft.

Studies have also looked at the storms which spawn the tornadoes (McCaul and Weisman 1996; Spratt et al. 1997; Schneider and Sharp 2007). TC tornadoes are normally spawned by “mini-supercells” which contain a small mesocyclone located at low levels with the most rotation located 1.5 km above the ground and extend no higher than 4.5 km. The mesocyclone is typically only a few kilometers in diameter and shrink in size prior to tornadogenesis. Echo tops for the “mini-supercells” are usually shallower than the classic Great Plains supercells due to lower CAPE values. On radar, these cells can exhibit a slight hook echo.

There are two methods by which TC tornadoes are believed to form. The first method originates when higher velocity air aloft is transported to the surface by a downdraft. Air velocities near the surface are lower due to the effect of friction and the loss of heat fluxes once the system moves onshore. The resulting contrast of high velocity and low velocity air causes vertical vorticity (Novlan and Gray 1974). This rotation can then be converged and stretched by an updraft. This faster rotating pocket of air can then become a tornado if a connection is made from the cloud base to the surface. Another possible method to produce a tornado is for the mini-supercell to come onshore and the surface winds lose velocity due to friction. The reduced surface wind speeds below the faster moving mid level winds creates horizontal vorticity. This can then be tilted and subsequently stretched by an

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updraft to form a tornado (Gentry 1983). While most of the tornadoes form inland, some form within 10 km of the coast leading to the belief that these mini-supercells developed offshore.

Our main focus of study is the landfall of Hurricane Ivan and cells within its outer-rainband prior to and after landfall. Using WSR-88D data from the Tallahassee radar (TLH), we documented common trends in radar-derived parameters for both tornadic cells prior to tornado genesis and nontornadic cells. Our overall goal is provide improve warning decision criteria for forecasts.

2. DATA AND METHODS

Hurricane Ivan made landfall on 16 September 2004 at around 0700 UTC as a category 3 hurricane at Orange Beach, Alabama. Over 115 tornadoes spawned as a result of this hurricane making it the largest TC tornado outbreak on record. Many tornadoes were reported in the vicinity Tallahassee FL, (i.e., in the right front quadrant) as a series of outer rainbands moved onshore. As a result, we employed Level-2 WSR-88D data obtained from National Climatic Data Center (NCDC) for the Tallahassee (TLH) radar. Cells were classified as tornadic or non-tornadic based on the NCDC Storm Reports. Data from 1200 UTC on 15 September to 1200 UTC on 16 September was used to track multiple cells. All radar analyses were performed using the GR2Analyst software.

Numerous parameters for were tabulated from each volume scan within which a cell could be identified, including maximum radar reflectivity, rotational velocity, maximum spectral width, mesocyclone size (if present), vertically integrated liquid (VIL), echo tops (ET), and a basic characterization of cell shape (e.g. hook echo or not). The first three parameters were tabulated at elevation angle. For this article we focus on maximum reflectivity, rotational velocity, and echo tops. We have found these variables to provide the best trends.

Maximum reflectivity can be useful in determining if there are possible updrafts/downdrafts based on increases or decreases in reflectivity at different elevation levels. For example, a persistent elevated reflectivity maximum would be suggestive of an echo free fault or bounded weak echo region and a strong updraft, while a descending reflectivity maximum would suggest a strong downdraft. For each cell the maximum reflectivity was tracked and recorded at each elevation angle. These were often located in close proximity to any hook echoes and/or inflow notches. An example of this can be seen on the left side of Figure 1.

Echo tops were also used to infer strong updrafts/downdrafts, assuming a prominent increase (decrease) in ET tops suggests a strong updraft (downdraft) The will also be measured using GR2Analyst software estimated the ET for each cell using the maximum elevation of the detectable radar reflectivity.

Doppler radial velocities can be used to compute rotational velocity and detect mesocyclones. Rotational velocities were computed by first identifying greatest inbound and outbound velocity within the target cell, then subtracting the two velocities and taking the average of the absolute value of that difference. An example of this can be seen on the right side of Figure 1.

Timelines for each parameter were constructed for each cell to identify and document any significant trends prior to tornadogenesis. Attention was also given to trends prior to and after landfall.

3. RESULTS AND DISCUSSION

Multiple tornadic and nontornadic cells were documented following the discussed methods. Preliminary findings indicate that a distinct sequence of events occurred prior to landfall and tornadogenesis within several of the tornadic cells.

Prior to landfall, there is a general increase in reflectivity values at all levels. While this could be the cell gaining strength, it is more likely that the radar is detecting the upper levels of the cell at first and as the cell approaches the radar, the altitude for each elevation angle decreases and the radar is able to detect the core of the cell. It is important to note that there appears to be a somewhat cyclical appearance where the reflectivity will increase at a given elevation angle and then decrease. This could be a sign that the cell is going through typical supercell processes such as updrafts and downdrafts even before it makes landfall. It is possible to suggest that a bounded weak echo region (BWER) is detectable in each of the tornadic cells prior to or just at landfall. This can be seen in the base reflectivity with higher reflectivity values at higher elevation scans and lower reflectivity values at lower scans for the same time. Possible BWERs can be seen in Figure 2a at two points before landfall and possibly 3a at landfall. After landfall, the BWER is most visible for both cells after approximately 15 minutes. It may be possible that this was occurring while the cells were still over the ocean but the radar was unable to detect enough of the cell due to the increase in altitude as the radar beam travels away from the radar. The BWER is a strong signal that these cells are most likely supercells with strong updrafts. A BWER can also be seen in Figure 5a, however, this cell did not produce a tornado. At least 20 minutes prior to tornadogenesis a BWER can be found. It is important to note that the cells also exhibited a either a prominent hook echo or an inflow notch prior to tornadogenesis (Figures 1a and 1b).

Rotational velocities also increase prior to landfall. The cell in Figure 3b exhibits higher rotational velocities at the 1.5 elevation angle than at the 0.5 elevation angle while the cell is still over the ocean. This suggests that updrafts are stretching the cell and increasing the rotational velocity aloft. Shortly after this occurs the rotational velocities at the 1.5 elevation angle decrease while the 0.5 elevation angle increase. Downdrafts may contribute to this evolution by drawing the higher rotational velocity air downward toward the lower part of the cell. Nontornadic cells also show this quality prior to landfall as can be seen in figures 4B and 5B. After landfall, this effect is seen for both the tornadic and nontornadic cells showing the continuation of updrafts and downdrafts in all of the cells.

The parameter exhibiting the most striking relation to tornadogenesis is echo tops. Before landfall, all cells exhibit both increases and decreases in ET. This suggests that strong episodic updrafts are present while the cells are still offshore. For each cell, there is a slight increase in ET just as the cell makes landfall suggesting that the increased frictional convergence at the coast provides a modest enhancement of updraft strength. After landfall, the cells continue to experience increases and decreases in ET. Just before tornadogenesis, both tornadic cells experience a decrease in ET which is suggestive of strong downdrafts (see Figure 2c and 3c). This downdraft could transport the large rotational velocities at midlevel down toward the surface and air in tornado formation.

Prior research of hurricane spawned tornadoes utilizing radar data (Spratt et al. 1997, McCaul et al. 2004, Schneider and Sharp 2007) noted that "mini-supercells" exhibited a cyclical pattern (similar to the traditional mesocyclones of the Great Plains). Ivan's mini-supercells also exhibited a cyclic evolution. The tornadic cells exhibited a hook echo in the reflectivity data. Spratt et al. (2007) found that vertical motions can be enhanced by "incipient boundaries" which is consistent with the increase in echo tops at landfall. It is interesting to note that the echo tops in Ivan's mini-supercells were much higher (at ~45000 ft) than those studied prior (~30000 feet). However, such higher echo tops are consistent with the local equilibrium level based on the 1800 UTC Tampa Bay sounding (Figure 6). Higher echo tops are most likely due to the CAPE being distributed over a greater depth.

In summary, tornadic cells appear to be distinguishable from nontornadic cells based on the evolution of three radar-derived parameters. In particular, tornadoes tend to form 15-20 minutes after the appearance of a (bounded) weak echo region that coincides with a rapid increase in echo tops (Figures 2a,c and 3a,c), and 5-15 minutes after a pronounced increase in rotational velocities. Thus, for detection of tornadoes, radar operators should watch for a BWER coincident with a rapid increase in echo tops (updraft) followed by an increase in rotational velocities (and possibly a decrease in echo tops). While the nontornadic cases may contain BWERs, they do not coincide with prominent increases in either echo tops or rotational velocities.

We are currently tracking additional cells within Ivan's outer rainbands (as well as other landfalling hurricanes that spawned tornadoes) to determine if these trends are widely consistent and statistically significant.

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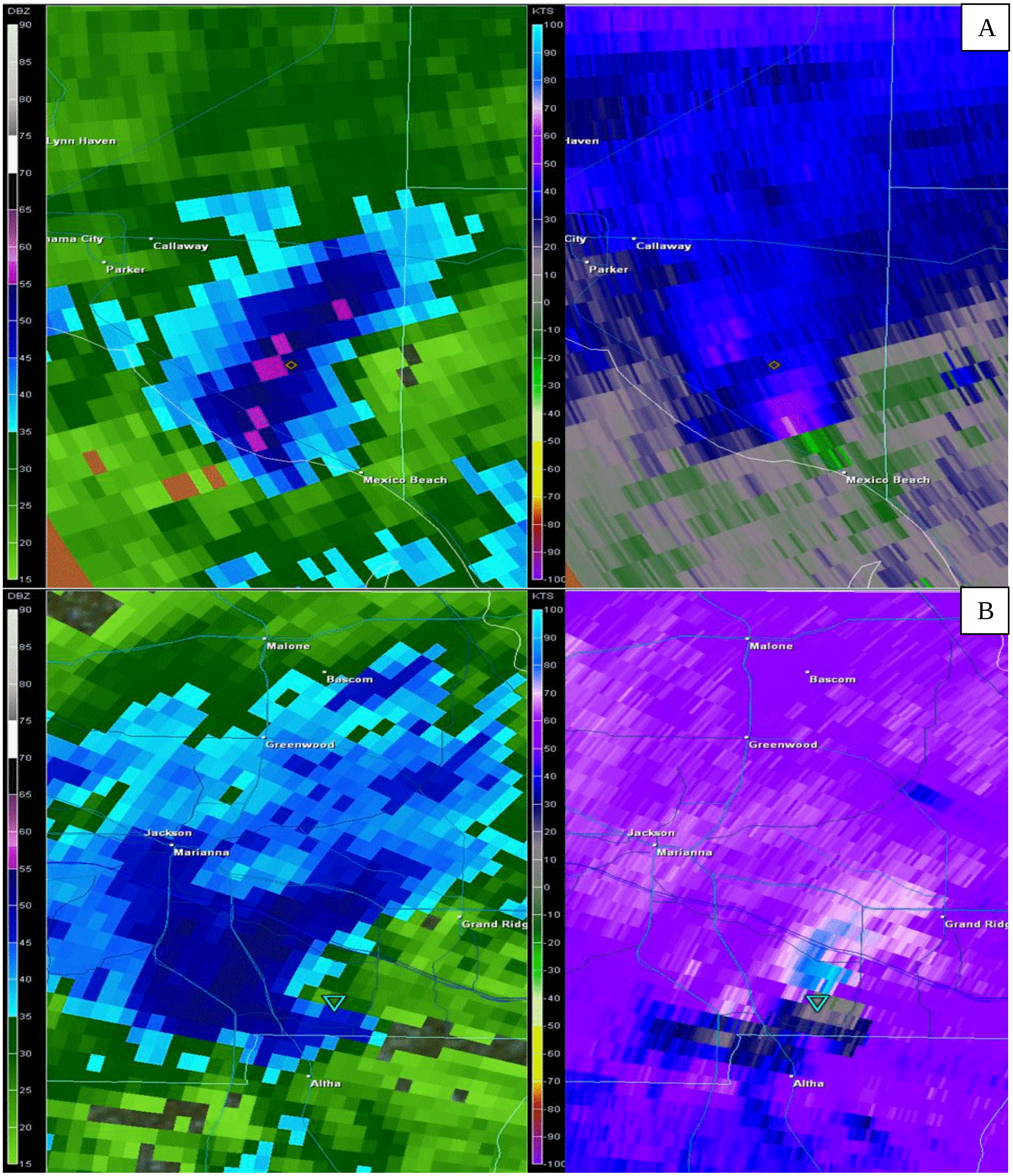

Figure 1. Base Reflectivity and Rotational Velocity for (a) cell that produced tornadoes at 2040 and 2100 UTC and (b) produced tornadoes at 223, 230, 240, 250 UTC.

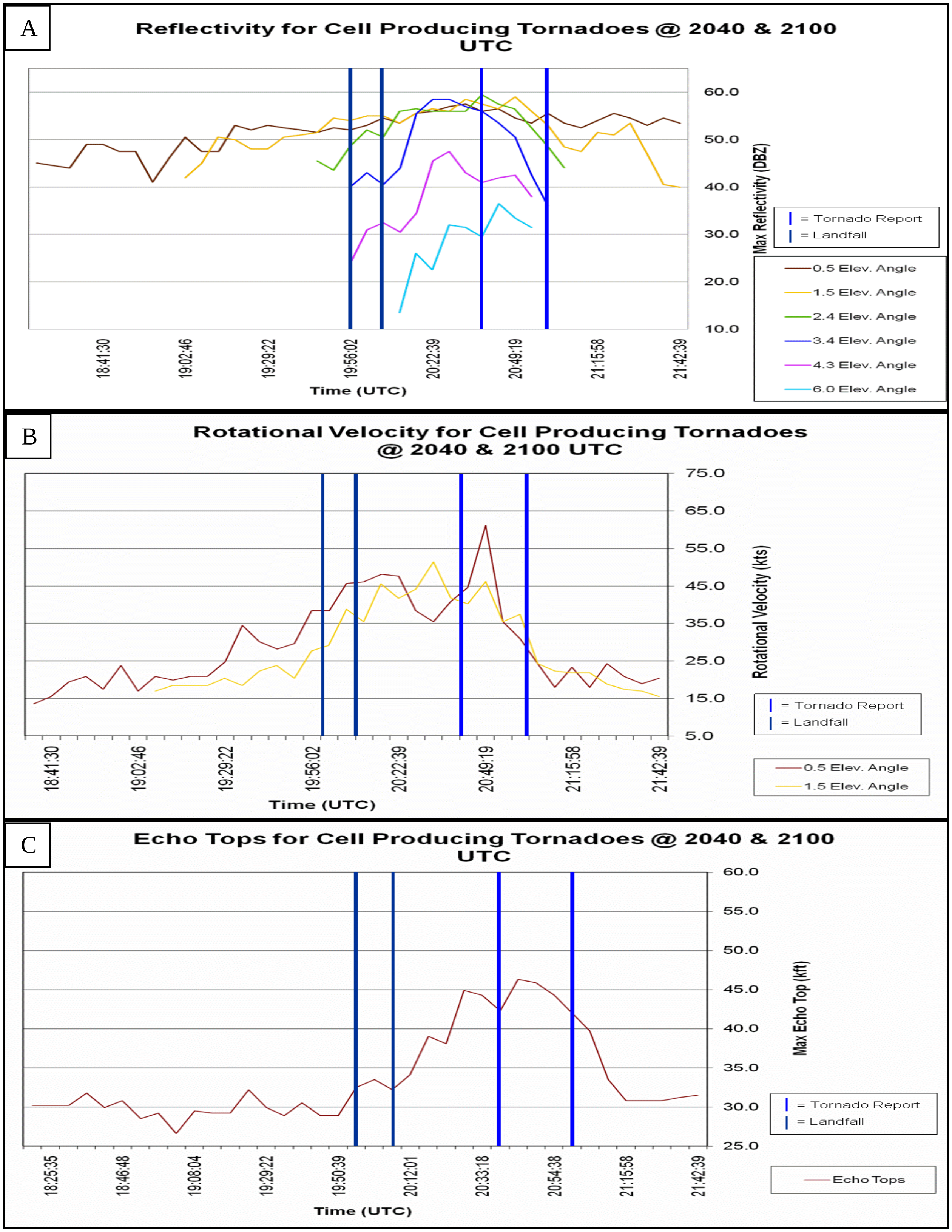

Figure 2 . Radar parameters for a cell that produced tornadoes at 2040 and 2100 UTC.

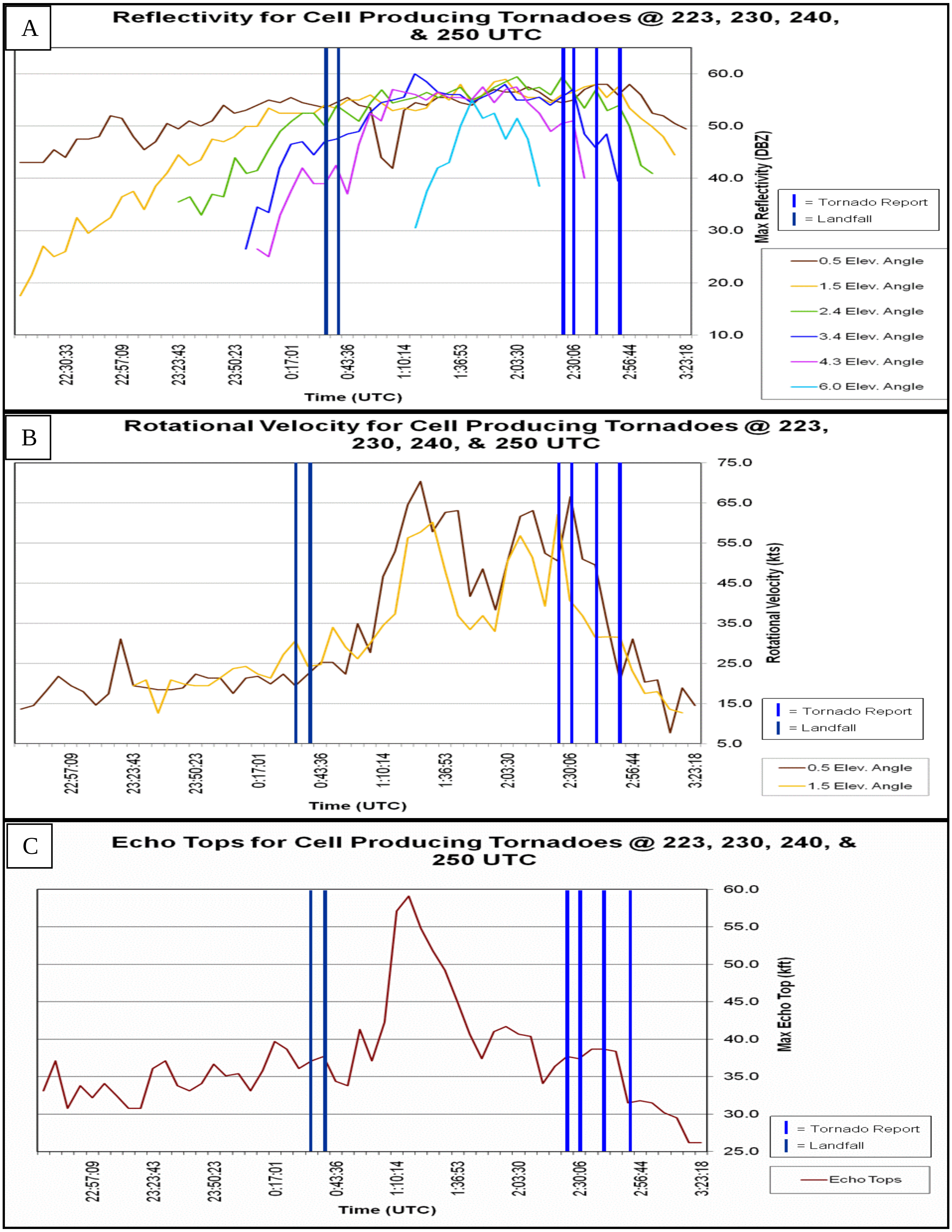

Figure 3. Radar parameters for a cell that produced tornadoes at 223, 230, 240, and 250 UTC.

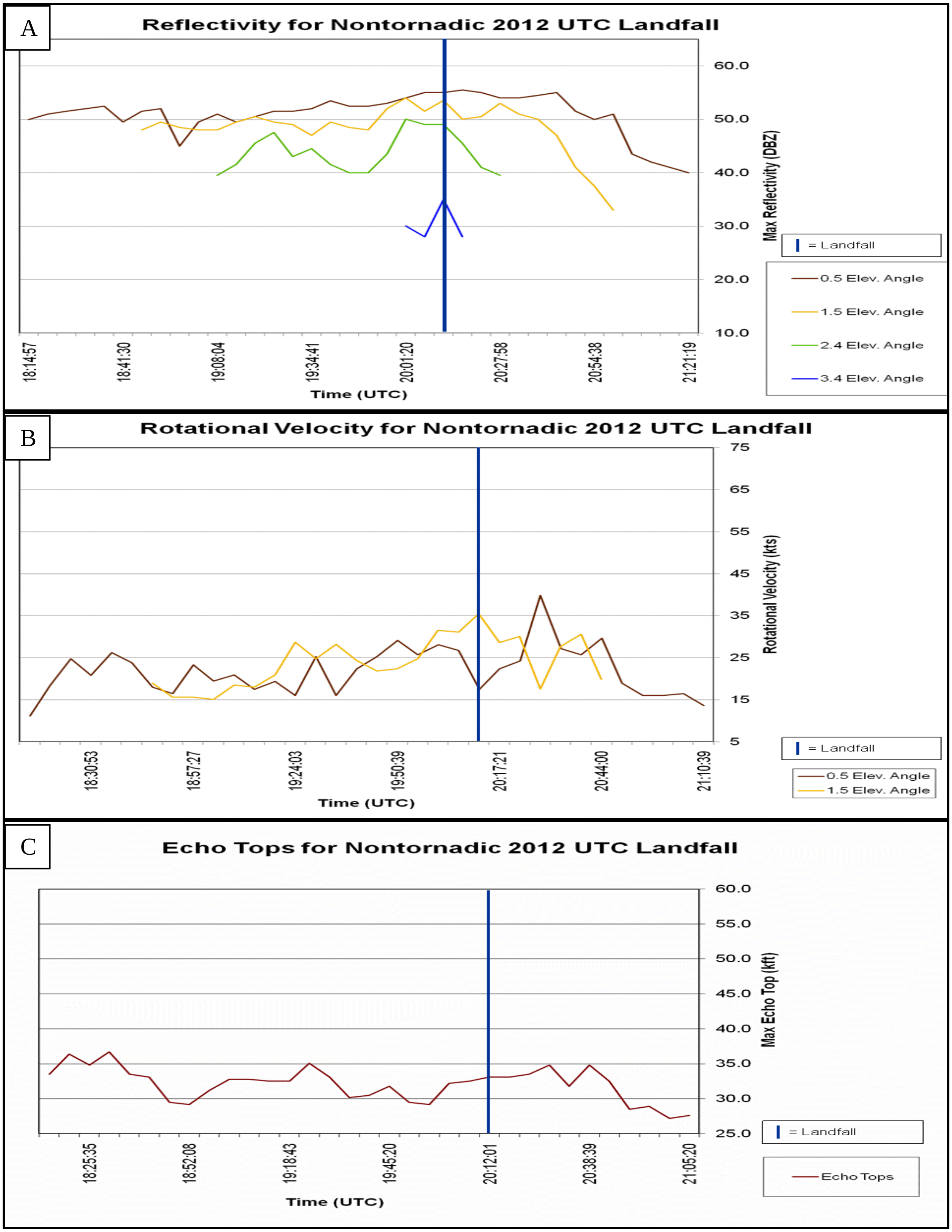

Figure 4. Radar parameters for a nontornadic cell that made landfall at 2012 UTC.

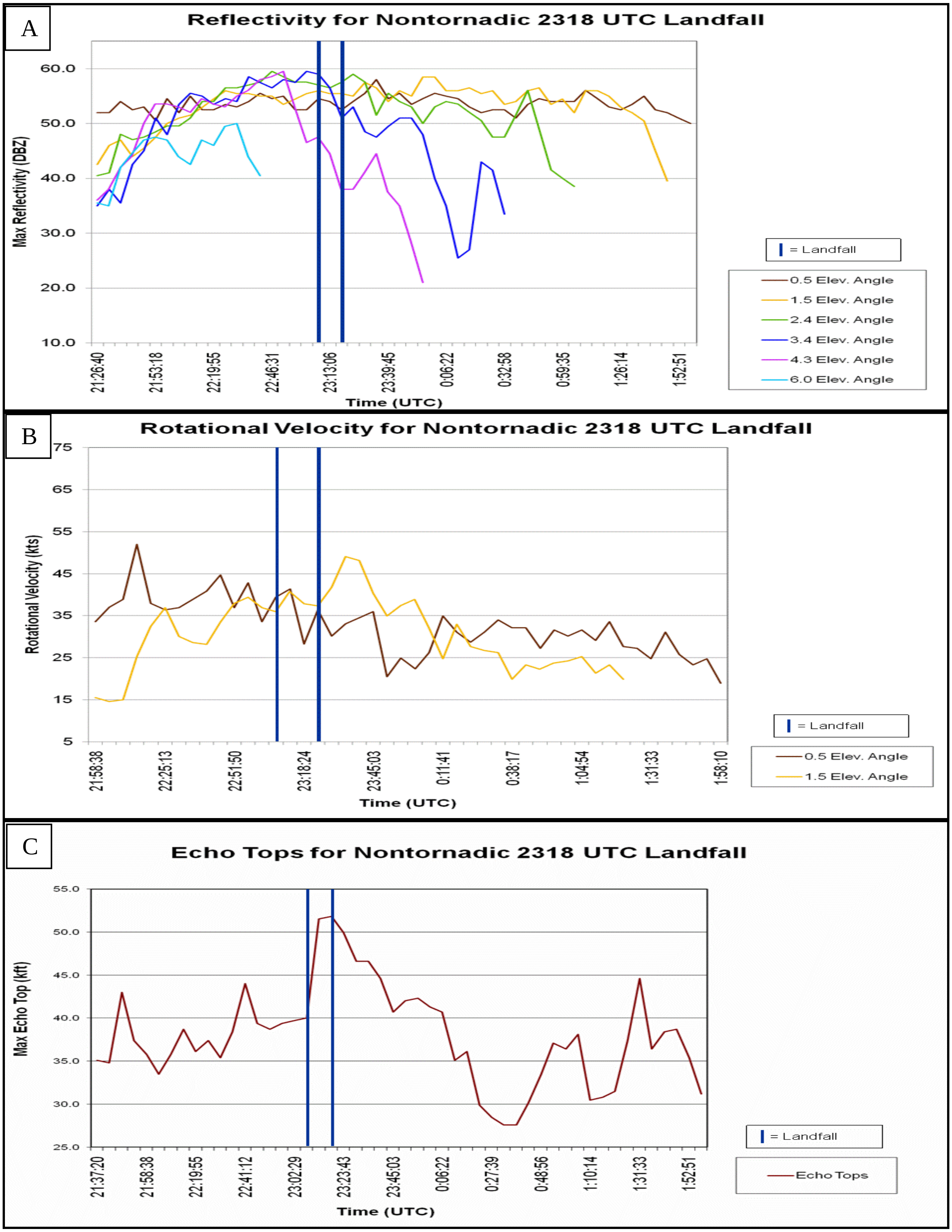

Figure 5. Radar parameters for a nontornadic cell that made landfall at 2318 UTC.

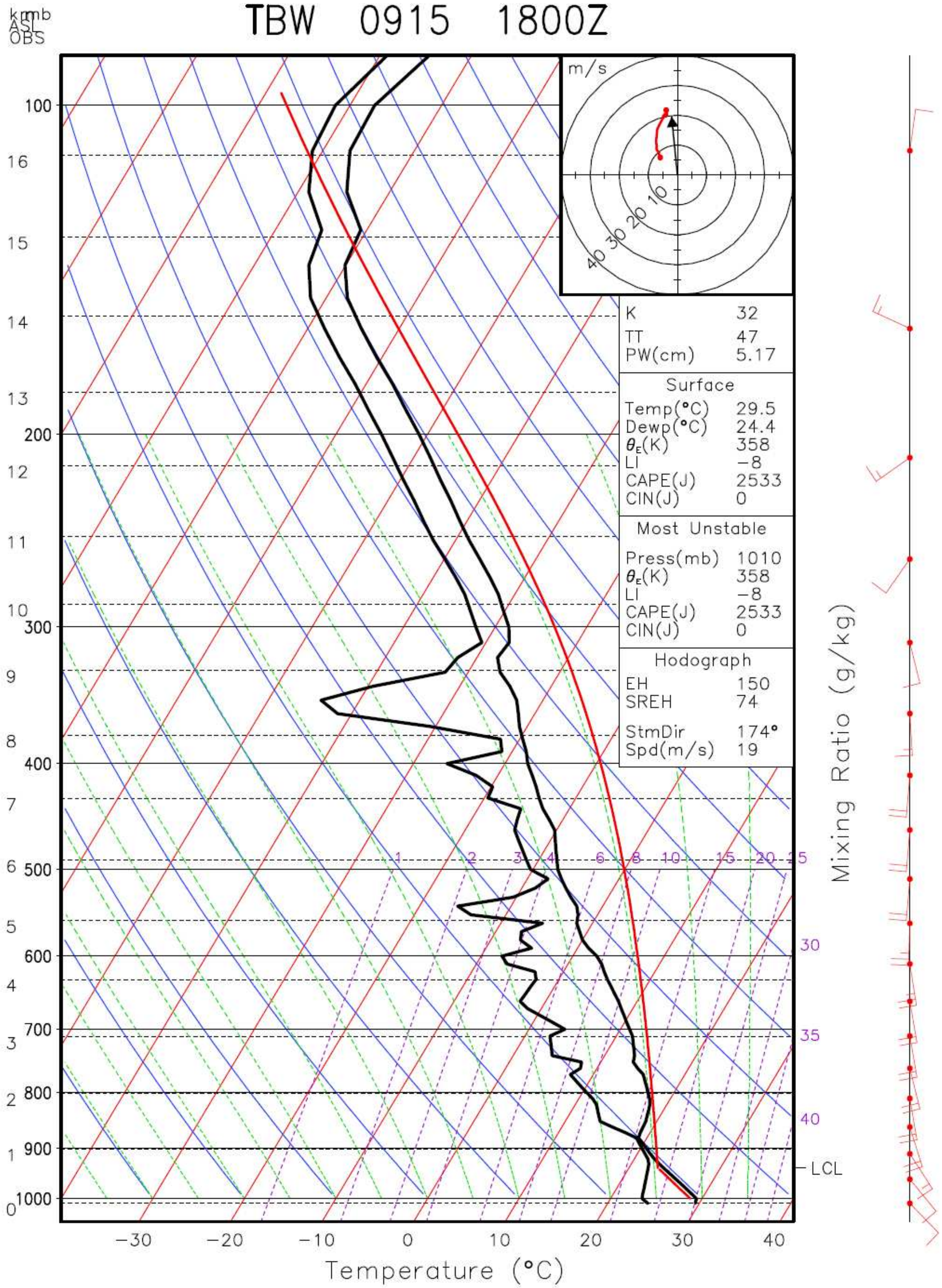

Figure 6. Skew-T sounding for Tampa which is upwind of Ivan's rainband.