12.4 USING C-BAND DUAL-POLARIZATION RADAR SIGNATURES TO IMPROVE CONVECTIVE WIND FORECASTING AT CAPE CANAVERAL AIR FORCE STATION AND NASA KENNEDY SPACE CENTER

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1. INTRODUCTION AND BACKGROUND

The United States Air Force's 45th Weather Squadron (45WS) is the organization responsible for monitoring atmospheric conditions at Cape Canaveral Air Force Station and NASA Kennedy Space Center (CCAFS/KSC) and issuing warnings for hazardous weather conditions when the need arises. One such warning is issued for convective wind events (e.g., downbursts), for which lead times of 30 and 60 minutes are desired for events with peak wind gusts of 35 knots or greater (i.e., Threshold-1) and 50 knots or greater (i.e., Threshold-2), respectively (Roeder et al. 2014).

45WS forecasters use a variety of instrumentation to increase protection for personnel, facilities, space launches, and space mission payloads at CCAFS/KSC, including a C-band dual-polarization radar (45WS-WSR) (Roeder et al. 2009) and the Cape Weather Information Network Display System (Cape WINDS) – a network of 29 weather observation towers located throughout and around the CCAFS/KSC complex (Fig. 1). Even with the technology available, forecasting convective winds is a difficult process. It can be challenging to identify which storms will produce threshold-level downbursts (i.e., peak wind gust of 35 knots or greater) from those that will not, and the lead times offered for these events are often shorter than desired by the 45WS.

The purpose of this study is to identify C-band dual-polarization radar signatures that can be used by 45WS forecasters in real-time to:

1) Provide increased lead times for downburst events at CCAFS/KSC;
2) Decrease false alarm ratios (FARs) for 45WS convective wind warnings;
3) Differentiate storm cells that will produce below-threshold wind gusts, Threshold-1 gusts, and Threshold-2 gusts.

Past studies have noted various radar signatures that, when placed in an environmental context, can provide insight into the physical processes occurring within downburst-producing thunderstorms. Examples include the peak value of radar reflectivity factor (Z_h) within a storm cell (Loconto 2006), a column-like region of positive differential reflectivity (Z_{dr}) values above the environmental 0 °C level (Illingworth et al. 1987, Tuttle et al. 1989), and a region of near-0 dB Z_{dr} values extending below the 0 °C level within the descending precipitation core of the storm (Wakimoto and Bringi 1988, Scharfenberg 2003). Additional studies have examined the effects that environmental conditions have on precipitation processes within downburst-producing thunderstorms. Srivastava (1987) showed that precipitation ice can be very important to the formation and intensification of wet downbursts, especially in environments with high relative humidity. Meischner et al. (1991) showed that the melting of falling precipitation ice (e.g., graupel, small hail) over a shallow layer beneath the 0 °C level can significantly enhance downburst intensity. White (2015) indicated how Z_{dr} can be used to examine the melting of precipitation ice.

These and additional radar signatures were explored in this study. Given that the typical lifecycle of ordinary convective cells in the southeastern United States is around 20 – 40 minutes (Smith et al. 2004), attention was given to longer-lived thunderstorm systems (e.g., multicellular convection) in an effort to increase lead times for 45WS convective wind warnings. It was hypothesized that the aforementioned radar signatures can be observed within the multiple updraft-downdraft cycles that occur in multicellular (multicell) convection, which can be used by 45WS forecasters to identify storm systems that may eventually produce a threshold-level downburst at CCAFS/KSC.

Preliminary results of this study indicate that certain dual-polarization radar signatures may offer increased lead times for threshold-level downbursts. Specifically, it was found that the peak height of the 1 dB contour within a Z_{dr} column, the peak height of the 30 dBZ Z_h contour co-located with Z_{dr} values around 0 dB, the peak Z_h value in the storm cell, and the peak value of Z_{dr} below the 0 °C level within a descending reflectivity core (DRC) may offer average lead times of 40 – 46 minutes, especially for multicellular systems.

2. DATA AND METHODOLOGY

2.1 Data

All radar data used in this study were from the C-band 45WS-WSR, and were provided by the 45WS. Environmental conditions were analyzed using atmospheric soundings from the KXMR site at the KSC skid strip. The peak wind gusts from the selected

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downburst events were observed on the Cape WINDS. The KXMR and Cape WINDS data were provided by the 45WS and the United States Air Force's 14th Weather Squadron. For this study, 10 days with threshold-level downbursts were analyzed, which included 14 individual threshold-level downbursts and 4 null events (i.e., downbursts with a peak wind gust less than 35 knots). All threshold and null events occurred from May – September 2015 (i.e., CCAFS/KSC 2015 warm season).

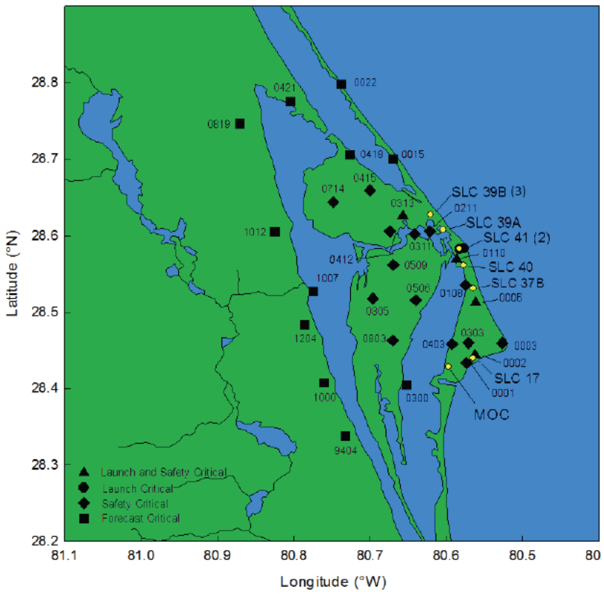

Figure 1. Current set up for the Cape WINDS.

2.2 Methodology

The first step in this study was to identify all threshold-level wind gusts on the Cape WINDS during May – September 2015. A code was written in the Interactive Data Language (IDL) to parse a text file containing all Cape WINDS data and print the date, time, tower ID number, sensor height, sensor direction, 5-minute peak wind gust, and 5-minute mean wind direction for all Cape WINDS sensors that recorded a wind gust of 35 knots or greater during this time period. Raw 45WS-WSR data were then examined at the time of the recorded threshold-level gusts using GR2Analyst (Gibson 2005) to ensure the presence of a thunderstorm at the time and location of the recorded gust.

The raw 45WS-WSR data were then gridded to a Cartesian coordinate system using the Python ARM Radar Toolkit (Py-ART) (Helmus and Collis 2016). For the gridding process, a horizontal and vertical grid resolution of 500 m was used along with a 1 km constant radius of influence. A Cressman weighting function (Cressman 1959) was used for data interpolation. The data were gridded out 100 km in the north-south and east-west directions and 17 km in the vertical direction, with the 45WS-WSR as the grid origin. Raw Z_h and Z_{dr} values were converted from logarithmic units to linear units before linear data interpolation was applied during the gridding process, and were converted back to logarithmic units for visualization.

Py-ART was then used to export each gridded 45WS-WSR volume scan as a Net-CDF file. A separate IDL code was written to read-in and visualize the gridded radar data. For each recorded threshold-level wind gust, the storm cell that produced the gust was identified using a combination of composite reflectivity, horizontal cross sections, and the 5-minute mean wind direction at the time of the recorded gust on the Cape WINDS. The downburst-producing cell was manually tracked back in time using composite reflectivity and horizontal cross sections. At several times in the cell's lifecycle, north-south (N-S) and east-west (E-W) vertical cross sections were taken through multiple locations within the cell to help understand the physical processes occurring within the storm. In cases where storm mergers were observed, all cells within the merger were tracked and analyzed. In multicell events, all cells earlier in the multicell system that were responsible for forming the downburst-producing cell (e.g., through convection initiated along gust fronts from collapsing cells) were tracked and analyzed. Storms that produced a peak wind gust of 35 knots or greater (i.e., met Threshold-1) were tracked until approximately 50 minutes before the time of the recorded peak gust (if possible), while storms that produced a peak wind gust of 50 knots or greater (i.e., met Threshold-2) were tracked until approximately 80 minutes before the time of the recorded peak gust (if possible). Since the recorded peak gust was from a 5-minute observation period in each case, a median time of 2.5 minutes before the recorded peak gust was assumed to be the actual time of the downburst (e.g., a peak gust recorded at 1850 UTC occurred between 1845 – 1850 UTC, and was assumed to have occurred at 1847:30 UTC). The peak wind gust recorded on the Cape WINDS was assumed to be the true value of the peak wind gust in each case.

Additional codes written in IDL were used to examine environmental data, which included calculating the 0 °C height, the height of minimum equivalent potential temperature (θ_e), temperature lapse rates, and relative humidity values from the KXMR soundings. For this study, the KXMR sounding nearest the time of the downburst-producing system was used in each case.

The radar data were analyzed in combination with the environmental data to better understand physical processes occurring within the downburst-producing storm systems. Common trends observed in Z_h, Z_{dr}, and correlation coefficient (ρ_{hv}) were identified using vertical and horizontal radar cross sections on the 10 days analyzed. For the threshold-level events, 4 multicell downburst events were selected before 10 other downburst events were randomly-selected. All 4 null events were selected on days during which threshold-level events also occurred.

3. RESULTS AND DISCUSSION

3.1 Overview

Four radar signatures common among threshold-level downburst-producing storm systems at CCAFS/KSC have been identified in this study:

1) Peak height of the 1 dB Z_{dr} contour within a Z_{dr} column above the 0 °C level;
2) Peak height of co-located values of 30 dBZ Z_h and near-0 dB Z_{dr} above the 0 °C level;
3) Peak Z_h value within the storm system;
4) Gradient in Z_{dr} below the 0 °C level within a DRC, including an increase in Z_{dr} to a value of at least 3 dB.

These signatures imply the importance of precipitation ice in threshold-level downbursts at CCAFS/KSC. The lead times offered by these signatures were relatively long in multicell events, due to the multiple updraft-downdraft cycles observed.

3.2 Signature #1 – Peak Z_{dr} Column Height

The first radar signature identified was the peak height of Z_{dr} columns within threshold-level downburst-producing thunderstorms. An example of this signature is presented in Fig. 2, where the 1 dB Z_{dr} column can be seen approximately 16 to 20 km west of the radar extending to roughly 7.5 km above ground level (AGL), or about 3 km above the 0 °C level. The signature seen in Fig. 2 was present before a 35-knot downburst wind gust was recorded on Cape WINDS Tower 1007 about 48.5 minutes later at 2322:30 UTC. Since positive Z_{dr} values are typical of oblate-shaped liquid hydrometeors and Z_{dr} values around 0 dB are typical of spherical or ice hydrometeors (Herzegh and Jameson 1992), Z_{dr} columns indicate regions where liquid hydrometeors are lofted above the environmental 0 °C level by the storm's updraft (Tuttle et al. 1989). These lofted liquid hydrometeors will either freeze and subsequently melt as they descend back below the 0 °C level and/or evaporate which, along with mass loading, will contribute to negative buoyancy within the storm and lead to formation and intensification of the downburst (Srivastava 1987).

In this study, it was observed that the 1 dB contour within a Z_{dr} column extended at least 1 km above the environmental 0 °C level in 12 of the 14 (85.71%) threshold-level events analyzed. This suggests that the lofting of liquid hydrometeors above the 0 °C level and the subsequent freeze-melting, evaporation, and mass loading processes are important to the formation of threshold-level downbursts at CCAFS/KSC.

The lead times offered by this signature ranged from 11.50 minutes to 78.50 minutes, with a mean lead time of 40.67 minutes and a median lead time of 42.50 minutes. Thus, the mean lead time offered by the 1 dB Z_{dr} contour extending at least 1 km above the 0 °C level was more than 10 minutes longer than desired by the 45WS for wind gusts that meet their warning Threshold-1. Furthermore, the maximum observed lead time for this signature (which occurred in a system that produced a downburst that met warning Thereshold-2) was nearly 20 minutes longer than desired by the 45WS for events that meet their warning Thrsehold-2. Therefore, this signature may offer the lead times desired by the 45WS for threshold-level downbursts. However, a peak 1 dB Z_{dr} column height of at least 1 km above the 0 °C level was also observed in 4 of the 4

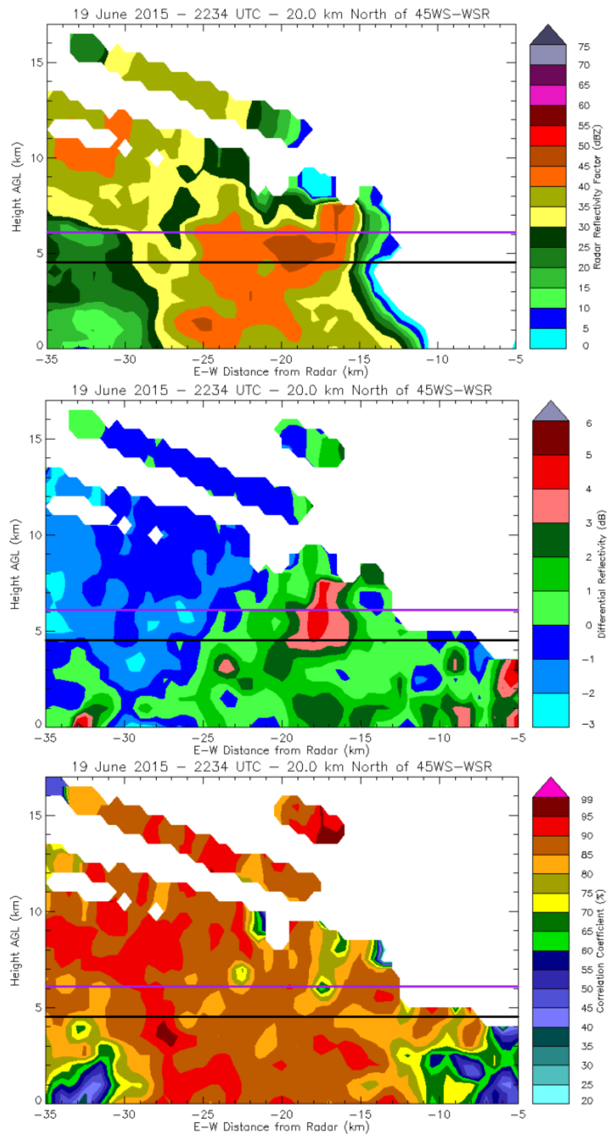

Figure 2. Vertical cross sections taken in the east-west direction (i.e., x-z plane shown) 20.0 km north of the 45WS-WSR during the volume scan that ended around 2234 UTC on 19 June 2015. The top image shows radar reflectivity factor in dBZ, the center image shows differential reflectivity in dB, and the bottom image shows correlation coefficient in percentage form. In each image, the black horizontal line marks the 0 °C level and the purple horizontal line marks the height of minimum equivalent potential temperature calculated from the 0000 UTC KXMR sounding on 20 June 2015.

(100%) null events analyzed in this study. Therefore, while the 1 dB Z_{dr} column height may offer increased lead times for threshold-level downbursts, it may not serve as well for distinguishing storm cells that will produce threshold-level events from those that will not. This signature could possibly lead to a high FAR for 45WS convective wind warnings if used as the sole downburst prediction parameter, but may be very useful if used in combination with other signatures.

3.3 Signature #2 – Height of 30 dBZ Z_h and 0 dB Z_{dr}

The second radar signature identified in this study was the peak height of approximately co-located values of 30 dBZ Z_h and near-0 dB Z_{dr}. An example of this signature can be seen in Fig. 3. In Fig. 3, the region of

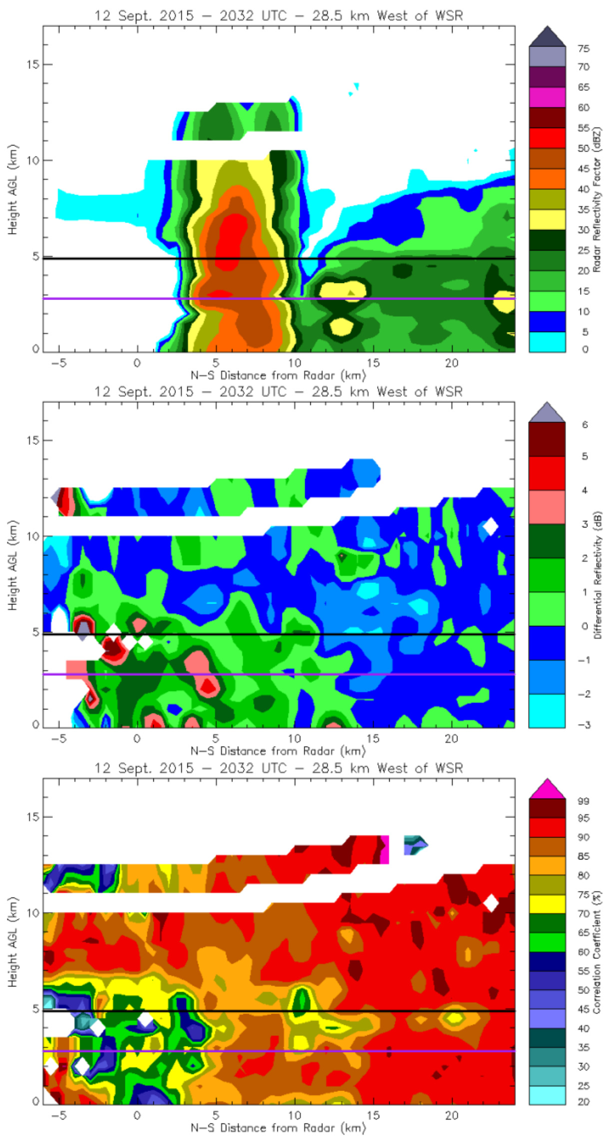

Figure 3. Vertical cross sections taken in the north-south direction (i.e., y-z plane shown) 28.5 km west of the 45WS-WSR during the volume scan that ended around 2032 UTC on 12 September 2015. The variables and horizontal lines shown are the same as in Fig. 1, with the environmental conditions calculated using the 0000 UTC KXMR sounding on 13 September 2015.

co-located values of 30 dBZ Z_h and near-0 dB Z_{dr} can be seen from 3 to 10 km north of the 45WS-WSR extending to 10 km AGL, or about 5 km above the 0 °C level. The signature seen in Fig. 3 was present before a 42-knot downburst wind gust was recorded on Cape WINDS Tower 0421 about 50.5 minutes later at 2122:30 UTC. This signature implies the presence of a significant amount of precipitation ice aloft in the storm cell. Past studies have shown that graupel and small hailstones typically have values of $Z_h \geq 29 – 33$ dBZ (Deierling et al. 2008), so a Z_h value of 30 dBZ was used in this study as the lower boundary for precipitation ice. Z_{dr} values within regions of precipitation ice are generally around 0 dB due to the spherical shape, tumbling, and/or lower dielectric of the ice hydrometeors (Herzegh and Jameson 1992).

Past studies have shown that the melting of ice hydrometeors may contribute more greatly to negative buoyancy within a downburst than evaporation of liquid hydrometeors, despite the latent heat of vaporization being roughly 8.5 times larger than latent heat of fusion, especially in regions where high relative humidity values enhance melting and suppress evaporation (Srivastava 1987). Therefore, the presence of a large quantity of precipitation ice within a storm cell may indicate the potential for negative buoyancy to be enhanced within the downburst via latent heat of melting and downward forcing from mass loading (Srivastava 1987).

In this study, co-located values of 30 dBZ Z_h and near-0 dB Z_{dr} extended at least 3 km above the 0 °C level in 13 of the 14 (92.86%) threshold-level events analyzed. This suggests that ice precipitation is important to the formation of threshold-level downbursts at CCAFS/KSC, as indicated by several past studies.

The lead times offered by this signature ranged from 3.50 to 78.50 minutes, with a mean lead time of 40.88 minutes and a median lead time of 35.50 minutes. As with Signature #1, the mean lead time offered by co-located values of 30 dBZ Z_h and near-0 dB Z_{dr} was more than 10 minutes longer than desired by the 45WS for Threshold-1 events and the maximum lead time offered was nearly 20 minutes longer than desired for Threshold-2 events. However, co-located values of 30 dBZ Z_h and near-0 dB Z_{dr} extended at least 3 km above the 0 °C level in 4 of the 4 (100%) null events analyzed. Therefore, as with Signature #1, Signature #2 may be very useful for offering the increased lead times desired by the 45WS for threshold-level events, but may cause FAR to be relatively high if used alone.

3.4 Signature #3 – Peak Z_h Value

The third radar signature identified in this study was the peak value of Z_h within the threshold-level downburst-producing storm system. An example of this signature can be seen in Fig. 4, where the peak Z_h is around 50 – 55 dBZ. The signature seen in Fig. 4 was present before a 35-knot downburst wind gust was recorded on Cape WINDS Tower 0001 about 24.5 minutes later at 1912:30 UTC. This signature implies the presence of large-sized hydrometeors and/or a large concentration of hydrometeors within the storm cell (Rinehart 2010). A region of large Z_h that develops above the 0 °C level implies the presence of a large quantity of precipitation ice, while a region of large Z_h that develops below the 0 °C level implies the presence of a large quantity of liquid hydrometeors (Loconto 2006). The presence of a large quantity of hydrometeors

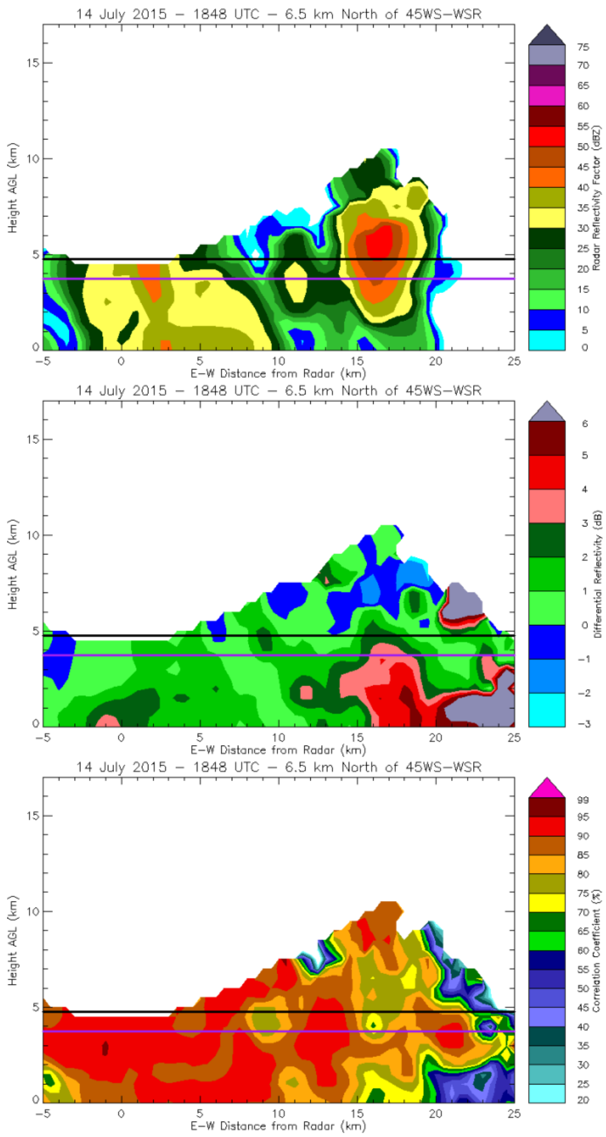

Figure 4. Vertical cross sections taken in the east-west direction (i.e., x-z plane shown) 6.5 km north of the 45WS-WSR during the volume scan that ended around 1848 UTC on 14 July 2015. The variables and horizontal lines shown are the same as in Figs. 1 – 2, with the environmental conditions calculated using the 1500 UTC KXMR sounding on 14 July 2015.

(liquid and/or ice) can enhance negative buoyancy within a downdraft through mass loading (Srivastava 1987). Additionally, melting from the large amount of ice hydrometeors and evaporation from the large amount of liquid hydrometeors can enhance negative buoyancy through latent heat absorption (Srivastava 1987).

For this study, only the peak Z_h value was identified; the location of peak Z_h relative to the 0 °C level will be examined in future work. A peak Z_h of at least 50 dBZ was present in 13 of the 14 (92.86%) threshold-level events analyzed, which suggests the importance of a large quantity of hydrometeors in producing threshold-level downbursts at CCAFS/KSC.

The lead times offered by this signature ranged from 11.50 to 78.50 minutes, with a mean lead time of 45.88 minutes and a median lead time of 48.50 minutes. The mean lead time offered by the peak Z_h value within a storm system, as with the previous two signatures, was more than 10 minutes longer than desired by the 45WS for Threshold-1 events and the maximum lead time was nearly 20 minutes longer than desired for Threshold-2 events. However, a peak Z_h value of at least 50 dBZ was observed in 3 of the 4 (75%) null events analyzed. This indicates that a peak Z_h of at least 50 dBZ in storm systems may offer longer lead times for threshold-level downbursts, but may lead to a high FAR if used as the sole predictor of threshold-level events.

3.5 Signature #4 – Z_{dr} Gradient within the DRC

The final radar signature identified in this study was the gradient in Z_{dr} within the DRC of a downburst-producing storm cell. An example of this signature is provided in Fig. 5, where Z_{dr} values can be seen increasing with decreasing height from about -1 dB to more than 3 dB within the DRC located about 41 – 44 km north of the 45WS-WSR around 2 – 3 km AGL. The signature seen in Fig. 5 was present before a 51-knot downburst wind gust was recorded on Cape WINDS Tower 0019 16.5 minutes later at 2132:30 UTC. Note that Tower 0019 is not shown in Fig. 1, but is located approximately halfway between Towers 0022 and 0015.

This signature indicates the melting of small to moderate sized precipitation ice hydrometeors (e.g., graupel and small hail) over a relatively shallow layer beneath the 0 °C level. Since Z_{dr} is a measure of the reflectivity-weighted mean diameter of a given drop size distribution (DSD) (Jameson 1983), and smaller ice hydrometeors typically melt completely before larger ice hydrometeors do, an increase in Z_{dr} from near-0 dB around the 0 °C level to positive values with decreasing height below the 0 °C level implies the melting of small hail / graupel (Meischner et al. 1991). Given that the latent heat absorbed by melting ice hydrometeors may generate more negative buoyancy within a downburst than the latent heat absorbed by evaporating liquid hydrometeors in regions where relative humidity values are high (Srivastava 1987), regions where Z_{dr} increases sharply over a shallow layer below the 0 °C level may suggest the melting of a large quantity of graupel and/or small hail, which can significantly intensify downbursts (Meischner et al. 1991). Past studies have also noted that Z_{dr} values observed on C-band radar increase from near-0 dB around the 0 °C level to at least 3 dB below the 0 °C level within downburst-producing storms in humid climate regions (White 2015).

In this study, Z_{dr} values increased from around 0 dB near the 0 °C level to at least 3 dB within 2.5 km below the 0 °C level in a DRC in 13 of the 14 (92.86%) threshold-level events analyzed. This indicates the importance of melting ice hydrometeors to intensification of threshold-level downbursts at CCAFS/KSC.

Lead times offered by this signature ranged from 1.50 minutes to 78.50 minutes, with a mean lead time of 40.42 minutes and a median lead time of 41.50 minutes.

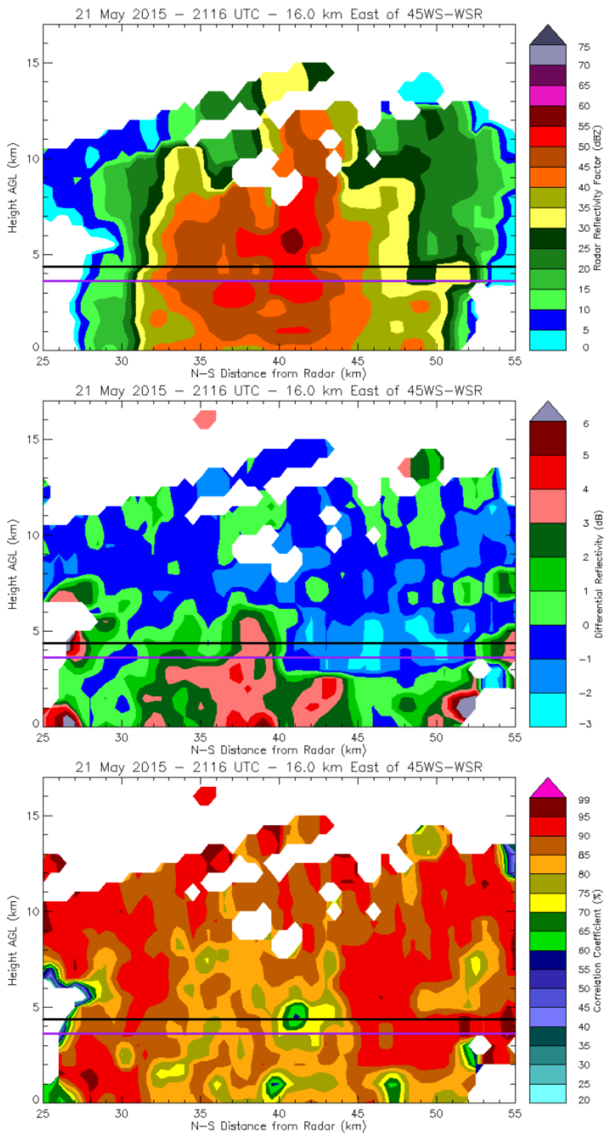

Figure 5. Vertical cross sections taken in the north-south direction (i.e., y-z plane shown) 16.0 km east of the 45WS-WSR during the volume scan that ended around 2116 UTC on 21 May 2015. The variables and horizontal lines shown are the same as in Figs. 1 – 3, with the environmental conditions calculated using the 0000 UTC KXMR sounding on 22 May 2015.

As with the previous signatures, the mean lead time offered by this signature was more than 10 minutes longer than desired by the 45WS for Thrsehold-1 events and the maximum lead time was nearly 20 minutes longer than desired by the 45WS for Threshold-2 events. However, an increase in Z_{dr} to at least 3 dB within 2.5 km below the 0 °C level was observed in the DRC of 4 of the 4 (100%) null events analyzed. Thus, the gradient in Z_{dr} below the 0 °C level, including an increase in Z_{dr} to at least 3 dB, may provide the lead times desired by the 45WS for threshold-level downburst events, but may also lead to a high FAR if used as the sole downburst prediction parameter.

4. SUMMARY AND FUTURE WORK

The purpose of this study was to identify C-band dual-polarization radar signatures that can be used in real-time by 45WS forecasters to increase lead times and decrease FAR for their convective wind warnings, as well as help distinguish storms that will produce a peak wind gust less than 35 knots from those with a peak gust of 35 knots or greater and those with a peak gust of 50 knots or greater. So far, four common radar signatures have been identified amongst threshold-level downburst-producing storm systems at CCAFS/KSC:

1) The 1 dB Z_{dr} contour within a Z_{dr} column extending at least 1 km above the 0 °C level;
2) Co-located values of 30 dBZ Z_h and near-0 dB Z_{dr} extending at least 3 km above the 0 °C level;
3) Peak Z_h value of at least 50 dBZ within the storm system;
4) Z_{dr} increasing to at least 3 dB within 2.5 km below the 0 °C level in the DRC.

Mean lead times offered by these signatures ranged from 40 – 46 minutes, with median lead times of 35 – 49 minutes. The longer lead times were mainly due to the large number of multicell events in the storm sample, which contained several updraft-downdraft cycles and allowed these signatures to be studied well in advance of the wind gust recorded on the Cape WINDS. The longest lead time offered for each signature (78.5 minutes) was due to all four signatures being present in the earliest volume scan analyzed in a Threshold-2 event (for which, storms were tracked back in time to about 80 minutes before the time of the recorded gust).

These signatures are all related to precipitation ice, which suggests that the melting and mass loading of precipitation ice is very important in the formation of threshold-level downbursts at CCAFS/KSC.

This work is part of an ongoing research project. While the radar signatures identified in this study may offer the lead times desired by the 45WS, the false alarm rate for each signature was also large. Future work will include identifying radar and/or environmental signatures that are more exclusive to threshold-level events and less common in null events to decrease FAR for 45WS convective wind warnings. Signatures will also be identified to help distinguish Threshold-1 events from Threshold-2 events. Given the relatively small sample size of 14 threshold-level events and 4 null events used herein, cases will be added to each of these categories to further examine the occurrence of these four radar signatures and any new signatures that are identified.

Other future work will include examining the location of peak Z_h relative to the 0 °C level in threshold-level events. A sensitivity test will be performed on all four signatures identified in this study to examine how varying height / magnitude thresholds affect the number of hits, false alarms, and lead times. Through not discussed herein, several events in this study occurred within the presence of sea breeze fronts, gust fronts, and/or storm mergers. The presence of these features may be useful in forecasting threshold-level downbursts at CCAFS/KSC. Furthermore, environmental data will be examined in more detail to better understand how certain conditions (e.g., relative humidity profile, temperature lapse rate, θ_e profile) can be used to meet the goals of this study. The results of this research project will eventually be integrated into a new algorithm that can be used by 45WS forecasters to aid in the forecasting of downbursts at CCAFS/KSC.

5. ACKNOWLEDGEMENTS

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