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Article

The College Park, Maryland Tornado of 24 September 2001

[1,2]**Kenneth L. Pryor,** [2]**Tyler Wawrzyniak, and** [2]**Da-Lin Zhang***

[1] NOAA/NESDIS/Center for Satellite Applications and Research, College Park, Maryland 20740

[2] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland 20742

* Department of Atmospheric and Oceanic Science, University of Maryland, 4254 Stadium Drive College Park, Maryland 20742-2425

* Correspondence: dalin@umd.edu; Tel.: (301) 405-2018

Abstract: The 24 September 2001 College Park, Maryland, tornado was a long-tracked and violent tornado that passed within a close range of two Doppler radars. It was the third in a series of three tornadoes associated with a supercell storm that developed in Stafford County, Virginia, and initiated 3 - 4 km southwest of College Park and dissipated near Columbia, Howard County. The supercell tracked approximately 120 km and lasted for about 126 minutes. This study presents a synoptic and mesoscale overview of favorable conditions and forcing mechanisms that resulted in the severe convective outbreak associated with the College Park tornado. Results show many critical elements of the tornadic event, including a negative-tilted upper-level trough over the Ohio Valley, a jet stream with moderate vertical shear, a warm, moist tongue of the air associated with strong southerly flow over south-central Maryland and Virginia, and significantly increased convective available potential energy during the late afternoon hours. Satellite imagery reveals banded convective morphology with high cloud tops associated with the supercell that produced the College Park tornado. Operational WSR-88D data exhibits a high reflectivity "debris ball" or tornadic debris signature (TDS) within the hook echo, the evolution of the parent storm from a supercell structure to a bow echo, and a tornado cyclone signature (TCS). Many of the mesoscale environmental features could be captured by contemporary numerical model analyses. This study concludes with a discussion of the effectiveness of the coordinated use of satellite and radar observations in the operational environment of nowcasting severe convection.

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1. Introduction

An F3 tornado struck College Park, Maryland, hereafter referred to as the College Park tornado, on 24 September 2001 (see Fig. 1b) with its track passing within a close range of two Doppler radars. It was the third in a series of three tornadoes produced by a supercell storm that developed from the splitting of a pre-existing supercell at its right flank around 1944 UTC over Stafford County, Virginia. This tornado, the most intense one (F3 intensity), developed 3-4 km southwest of College Park from this supercell at approximately 2116 UTC and dissipated over eastern Howard County, Maryland, by 2150 UTC (see its path in Fig. 1a). With a track of 28 km, the College Park tornado remains the only long-track event with an intensity of F3 or greater to directly impact the greater Washington, DC and adjacent suburban Maryland region since 2000. The long-lived supercell that spawned the College Park tornado could be tracked approximately 120 km from Stafford County, Virginia across Washington, D. C. to Howard County, Maryland in 126 minutes.

The College Park tornado produced heavy damage from just west of the campus of University of Maryland to downtown Laurel (Figs. 1a,b). On and near the campus, the tornado caused approximately $15 million in damage, including 10 destroyed trailers (used as temporary facility for the Maryland Fire and Rescue Institute), several heavily damaged buildings, many tossed and destroyed vehicles and two fatalities. It then struck the U.S. Department of Agriculture Research Center, causing an estimated $41 million in damage to buildings and research documents. It continued north through Beltsville (5 km northeast of College Park), damaging homes, businesses, and schools. In downtown Laurel, the tornado tore the roof off a wing of the Laurel High School and then destroyed a single-level house in the neighborhood behind the school. Moving from Prince Georges County into Howard County, the tornado caused damage to 43 homes before finally dissipating in Columbia. Overall, $16 million in damage resulted in Prince Georges County that included 861 residential homes, 560 vehicles, and at least 23 commercial businesses. Approximately an additional $1 million in damage was caused in Howard County. Total damage in Maryland was estimated to be over $73 million.

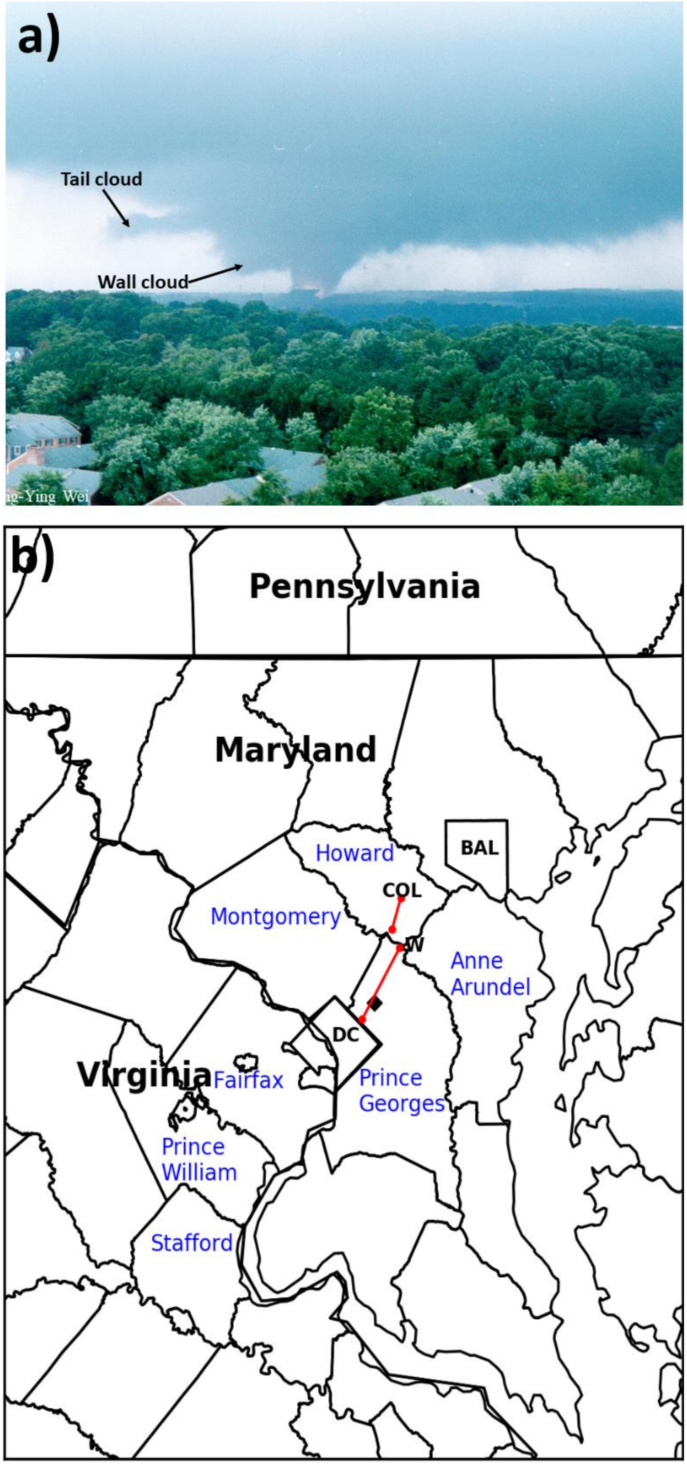

Figure 1. (a) The College Park tornado at 2121 UTC viewed about 2 miles from the northeast (courtesy of Dr. Ming-Ying Wei of NASA). Note an electric discharge with the University of Maryland football stadium in the foreground; and (b) Track of the College Park tornado (two red line segments) from Washington, DC to Columbia, Maryland during the period of 2119 - 2154 UTC 24 September 2001. Black diamond marks the location of College Park, "W" marks the location of severe thunderstorm straight-line wind damage that was observed near Laurel at 2140 UTC, and "COL" marks the location of tornado dissipation near Columbia.

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Tornado climatology as compiled by the National Climatic Data Center (NCDC) indicates that, on average, there is one significant tornado with an intensity damage rating of an F2 to F5 that occurs over the state of Maryland approximately every two years. This climatology is based on data obtained by the Storm Prediction Center's National Severe Weather Database between the years 1950 and 2017 from the National Weather Service/Storm Prediction Center's Online SeverePlot 3.0 (available online at https://www.spc.noaa.gov/climo/online/sp3/plot.php). This dataset reveals that after a 13-year lull in significant tornado activity over Maryland since 2004, a strong EF2 tornado, generated by a high-precipitation (HP) supercell storm, impacted Stevensville, Kent Island, during the early morning of 24 July 2017. Although it was a short-lived tornado that tracked from the Chesapeake Bay onto the Eastern Shore, its nighttime occurrence was especially formidable, and caused major structural damage and injury. The 2017 Kent Island tornado event, as well as other recent strong tornadoes that have occurred in similar humid coastal climates over east Asia, has provided the motivation to revisit the College Park tornado, employing new techniques of numerical weather prediction model, Doppler radar, and geostationary satellite data visualization and analysis in Python modules such as Matplotlib, Basemap, Sounding/Hodograph Analysis and Research Program in Python (SHARPpy, https://github.com/sharppy/SHARPpy) and Python ARM Radar Toolkit (Py-ART, https://arm-doe.github.io/pyart/) .

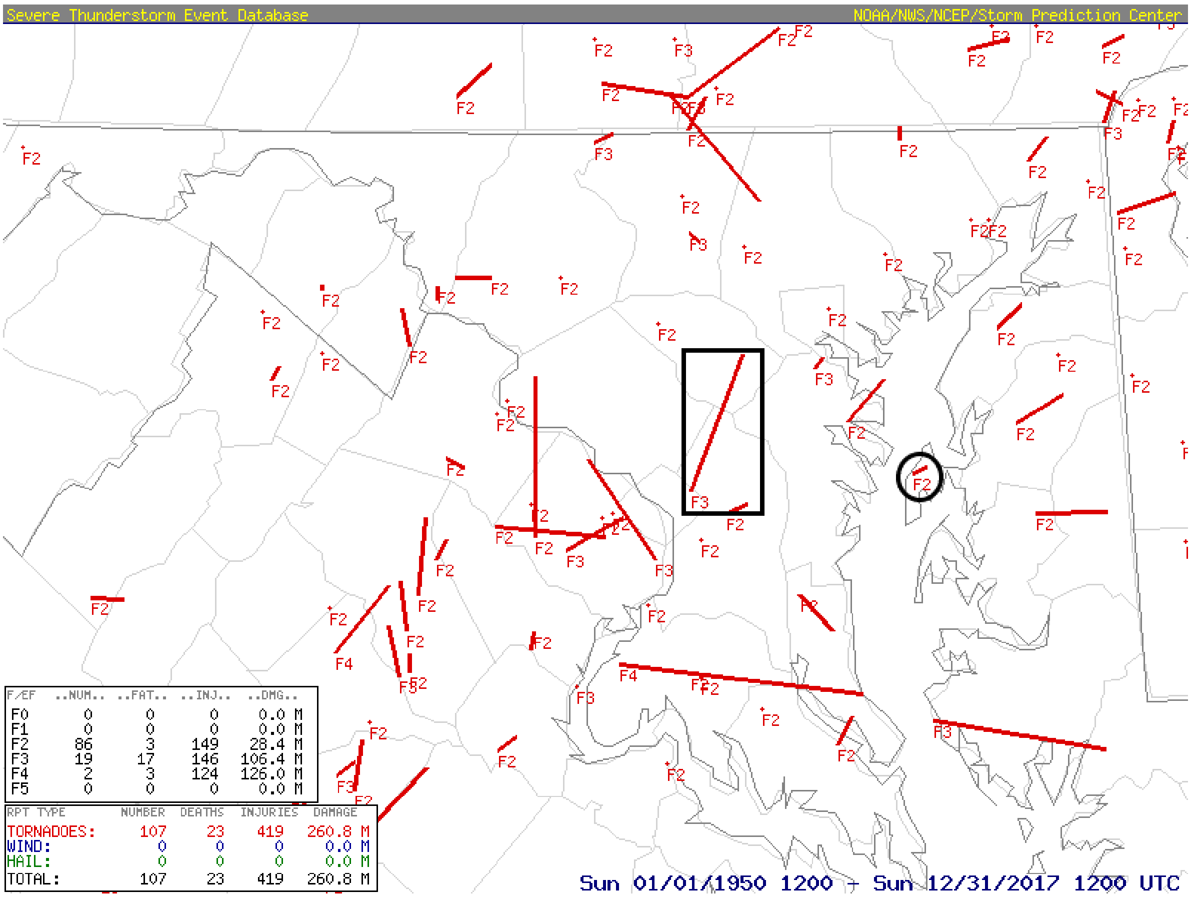

Figure 2. Plot of significant tornado tracks over Maryland and the greater Washington, DC metropolitan area between 1950 and 2017. The track of the College Park tornado is outlined by a black rectangle, while track of the 2017 Kent Island tornado is outlined by a black circle. Courtesy of the National Weather Service/Storm Prediction Center.

There has been considerable progress in the observation and understanding of various facets of tornado outbreaks occurring in midlatitude countries, especially in the United States. An impressive example was the development of a large tornado that occurred around Oklahoma City on 3 May 1999 that has generated a number of publications; it may serve as a model for a strong tornado that had a major impact on a metropolitan area, like in the present case. For example, Bikos et al. (2002) identified important convective morphology from GOES imagery, including a deepening upper-level trough over the western United States and a rapidly propagating jet streak. Several key findings were related to the outbreak of severe convection: (a) developing and dissipating cumulus convection in the dry air west of a dryline over western Texas as the leading edge of jet stream cirrus moved into the area; (b) towering cumulus convection developing in southwestern Oklahoma that would eventually evolve into tornadic supercell activity in the Oklahoma City area; (c) a pre-existing mesoscale boundary separating a region of cumulus cloud lines in an unstable air mass from a stable region characterized by wave cloudiness and its interaction with the evolving supercell storm; and (d) the development of the first storm over southwestern Oklahoma, its rapid intensification into a tornadic supercell, and its movement along the mesoscale boundary toward Oklahoma City. In another study, Foster et al. (2000) noted that the mesoscale boundary, as found by Bikos et al. (2002), served to enhance convergence and the intensity and longevity of the tornadic supercell storm. Most importantly, the surface moisture flux divergence field revealed a large area of moisture convergence over southwest Oklahoma where convective initiation occurred. The convergence along the dryline segments and the mesoscale boundary over central Oklahoma in an unstable air mass characterized by strong vertical wind shear associated with an upper-level jet stream enhanced the favorability for intense, rotating updrafts and the development of tornadic supercellular convection. A synoptic and mesoscale overview of the event given by Thompson et al. (2000) used GOES-8 satellite imagery to show the formation of towering cumulus convection in a gap in the cirrus cloud coverage. Initially, the cirrus cloud canopy suppressed convection by reducing surface heating and boundary layer mixing (Thompson et al. 2000). This cirrus gap eventually led to the formation of multiple supercells, including one that spawned an F5 tornado that moved across the southern Oklahoma City metropolitan area (Thompson et al. 2000).

Previous studies of other tornado outbreaks have also shown specific tornadic supercell storm structures that were similar to the College Park tornado. A two-part study of Mashiko et al. (2016) investigated the vorticity sources leading to the development of a midlevel and low-level mesocyclone, as well as tornado genesis in the 2016 Tsukuba City, Japan tornado event, which is similar to that discussed by Markowski et al. (2008). The circulation of the low-level mesocyclone was strengthened mainly by the baroclinicity associated with the forward flank gust front (FFGF), and the rear-flank downdraft (RFD) was associated with the descending reflectivity core that modulated the low-level rotation and buoyancy field. Mashiko's study highlights the importance of the RFD and resulting tornado genesis. The author states that "a locally intensified RFD outflow surge moved eastward behind the rear-flank gust front (RFGF) near the surface. As the RFD outflow surge approached a strong updraft along the RFGF, a weak vortex on the RFGF near its intersection with the FFGF intensified rapidly and evolved into a tornado". Accordingly, the role of the RFD in the generation of the College Park tornado will be addressed in detail in Section 3.

We have recently seen several reports of tornado events occurring in China where tornadoes used to be rare, some of which were also similar to the College Park tornado. For instance, the EF4 Yancheng tornado had its long life cycle and long track, and it was spawned at the southern end of a line of storms that had developed supercell characteristics (Xue et al. 2016). The Beijing tornado during the heavy rainfall event on 21 July 2012 (Zhang et al. 2013) also formed on the southern end of a line of storms that had oriented northwest-to-southeast (Meng et al. 2014). Based on damage surveys conducted, the maximum damage occurred when the magnitudes of the TVS and a parent mesocyclone were strongest. The favorable environmental conditions for development included low-level moistening and warming, and an increase in the 0-6 km vertical shear.

The College Park tornado appeared to feature several similarities to the above-mentioned significant tornado events causing widespread damage in urban areas, as more will be shown later. In addition, two encouraging aspects of this event were (i) the successful tornado warning and prediction of its track and timing by the NWS' Sterling Office (see Appendix 1), and (ii) the real-time, experimental forecast of a long-lived mesocyclone associated with the tornado. Specifically, the NWS' Sterling Office issued a tornado warning at 2110 UTC, based on Doppler radar observations at 2106 UTC, which included the timing of its passage at College Park (see Appendix 1).

The objectives of the present study are to (i) document favorable conditions and forcing mechanisms at both the synoptic- and mesoscale that resulted in the severe convection outbreak and tornadogenesis using GOES imagery, National Centers for Environmental Prediction (NCEP) Final (FNL) analysis pressure fields, and derived thermodynamic profiles and parameters; and (ii) examine the morphology of the supercell/mesocyclone associated with the College Park tornado and their sequences using Doppler radar data obtained from the Sterling, Virginia NEXRAD, and re-calibrated Geostationary Operational Environmental Satellite (GOES)-8 imager datasets.. This study emphasizes environmental factors and storm structural attributes that favored the generation of intense convective downdrafts and resulting strong outflow winds in a region of large vertical wind shear. The outflow-

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shear interaction has been identified as an important forcing mechanism for tornado genesis.

The next section provides a larger-scale overview of the upper-level and surface features as well as upper-air observations that are favorable for severe convection and tornadic activity utilizing satellite imagery and NCEP FNL analysis output data. Section 3 documents the evolution of the supercell that spawned the College Park tornado, and shows the structures and evolution of the tornado and its parent supercell, as well as convective morphology using high-resolution Doppler radar and satellite imagery. A summary and concluding remarks are given in the final section.

2. Larger-Scale Overview

The 1800 UTC 24 September 2001 NCEP Final (FNL) analysis was selected as the numerical model dataset to most effectively visualize the pre-storm environment over the mid-Atlantic coastal region. The NCEP FNL Operational Global Analysis data are on 1-degree by 1-degree grids prepared operationally every six hours. This product is from the Global Data Assimilation System (GDAS), which continuously collects observational data from the Global Telecommunications System (GTS), and other sources, for many analyses. The FNL analyses are generated by the same model used in the Global Forecast System (GFS), with the analyses prepared about an hour after the GFS is initialized, to ingest more observational data. The GFS uses the FNL from the previous 6-h cycle as part of its initialization. The FNL analysis-generated fields, especially superimposed over satellite imagery, were used to provide a large-scale thermodynamic environmental overview three hours prior to the genesis of the College Park tornado event, which was critical in demonstrating the diagnosis and short-term prediction capability of the contemporary GFS Aviation (AVN) model.

Equivalent potential temperature (θ_e) fields as shown in Figs. 3 and 4, generated at isobaric levels as well as in vertical cross sections, provided a strong signal for severe thunderstorm development. Fig. 3b shows the presence of a cold front about 200 km to the west of College Park at 1745 UTC, corresponding roughly to the leading edge of a large-θ_e gradient, shown in Fig. 3a, that extended westward into the Ohio Valley. Clearly, this cold front would play an important role in lifting the low-level northward-flowing warm and moist air, as represented by a 1000-hPa θ_e ridge. In addition, College Park was located ahead (eastward) of a deep shortwave trough axis within a favorable region of quasi-geostrophic upward motion, as implied by positive differential vorticity advection (PDVA). The shortwave trough extended from the Great Lakes to the lower Mississsippi Valley and, in combination with the cold front, served as a mechanism for enhanced lifting over the Atlantic coastal region.

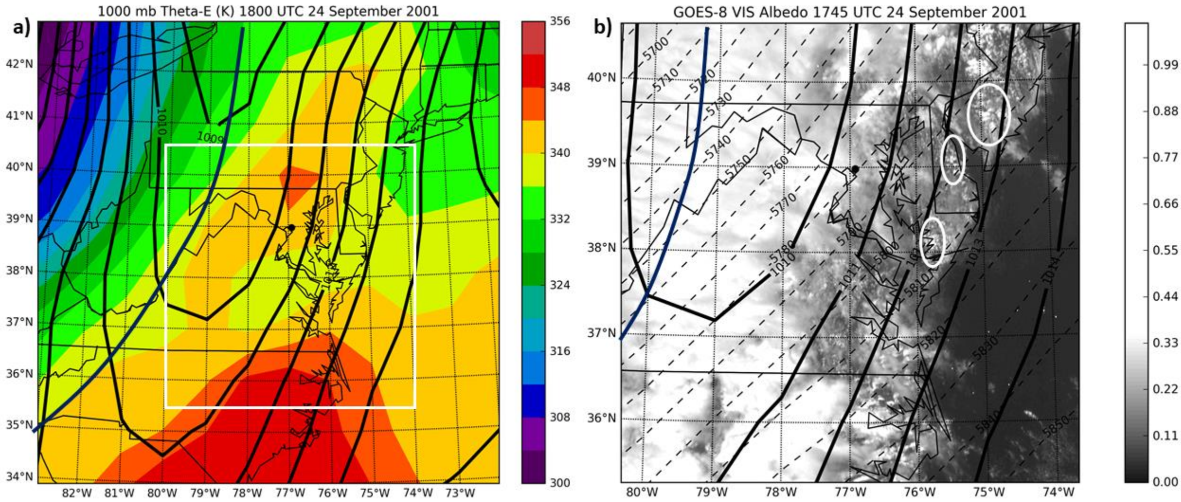

Figure 3. (a) NCEP FNL analysis-generated 1000-hPa the equivalent potential temperature (θ_e, contoured at 4K intervals) with overlying sea-level pressure (hPa, solid) at 1800 UTC; and (b) Sea-level pressure (hPa, solid) and 500 hPa geopotential height (m, dashed) overlying GOES-8 visible albedo imagery over the mid-Atlantic coastal region at 1745 UTC 24 September 2001. White rectangle marks the boundaries of the visible image in (b). White closed curves in (b) mark the location of enhanced cumulus. A black dot indicates the location of College Park.

Regional, high-resolution (1 km) visible imagery was available, in general, every five to ten minutes from 1745 to 2145 UTC while the GOES-8 imager was in rapid scan mode, which allowed for tracking the evolution of tornado-producing supercell storms following the methodology of Line et al (2016). Figure 3b, visible imagery at 1745 UTC, displays a band of bright, thick convective clouds with overlying cirrus extending from western Pennsylvania to western Virginia , that corresponded with the location of the lower tropospheric θ_e ridge. The imagery also shows breaks in the cirrus deck revealing widespread cumulus congestus and enhanced cumulus clusters ahead of the cold front over east-central Maryland and the Eastern Shore (Fig 3b). This revealed the presence of potential instability ahead of the shortwave trough prior to the tornadic event. GOES imagery during the time of development and impact of the College Park Tornado is explored further in Section 3.

The surface analysis shown in Fig. 3 at 1800 UTC indicates that low-level positive θ_e advection was occurring over southern Maryland and the Eastern Shore ahead of the surface front. According to Chaston (1995), such a θ_e tongue, acting upon by a lifting mechanism (i.e., PDVA and/or frontal lifting), can serve as an axis of available potential energy that is convertible into kinetic energy of the subsequent convection. In this case, the θ_e tongue provided a source of warm, moist and positively buoyant air to feed the supercell as it tracked northeastward into central Maryland, producing strong convective updrafts. Moreover, the mid-tropospheric PVA resulted in large-scale ascent over central Maryland during the development of the College Park tornado. The favorable conditions resembled closely the synoptic regulation of the 3 May 1999 tornado outbreak (Roebber et al. 2002).

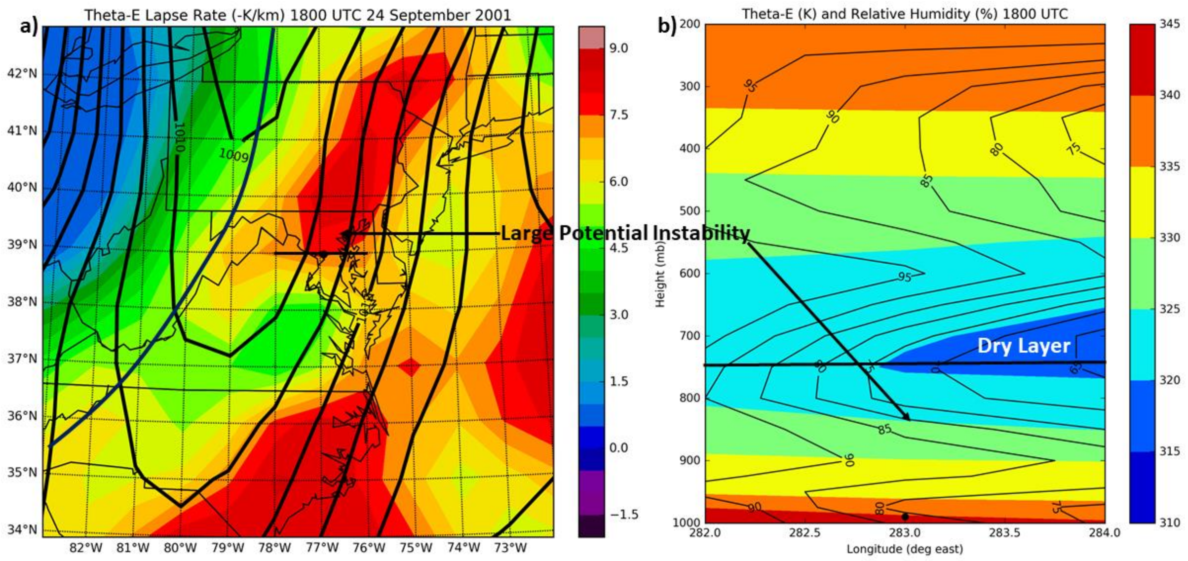

Figure 4. (a) NCEP FNL analysis-generated 1000 – 700 hPa θe lapse rate (-K km^{-1}) with overlying sea level pressure (hPa, solid); and b) Vertical cross section of θe and relative humidity (percent) along the horizontal line at latitude 39°N given in (a) at 1800 UTC 24 September 2001. A black dot indicates the location of College Park.

Fig. 4b, a vertical cross-sectional image over the greater Washington, DC metropolitan area, indicates the presence of high-θe air (i.e., θe > 335K) in the lowest 100 hPa layer in the warm sector, anticipating the generation of intense convection when this high-θe air is lifted at the frontal boundary. Foster et al. (2000) also analyzed a large area of surface convergence over southwestern and central Oklahoma prior to the 3 May 1999 tornado outbreak. All the analyses suggested that the low-level air of tropical origin approaching from the southeast would rise through the cumulus congestus. Thus, the supercell storm that would eventually produce the College Park tornado was predominantly "fed" by the positively buoyant high-θe air (Rotunno 1986). Note that the low-level southerly flow overlain by strong southwesterly flow aloft indicated the presence of strong directional wind shear that was to be a major contributor to the development of storm rotation and the favorability for splitting supercell storms, as mentioned in section 1.

Of interest was the presence of a large vertical θe gradient from the surface to 750 hPa and a well-defined dry layer aloft that was favorable for severe convection and tornadic supercell development. McGinley (1986) and Weisman and Klemp (1986) argued that a dry air layer in the midlevels (650-500 hPa) would enhance storm severity by maximizing the vertical θe lapse rate, thereby increasing convective instability and parcel energy. The 1000 – 700 hPa θe lapse rate (-K km^{-1}) image in Fig. 4a highlights the presence of a surface-based deep layer of potential instability extending from the Washington, DC area northeastward to southeastern New York. This condition would have strongly suggested rapid storm intensification with passage from Virginia into Maryland. Another means by which a midlevel dry layer can enhance storm severity is through the process of entrainment of dry air into moist downdrafts. This process could result in evaporational cooling that increases the strength of downdraft and storm outflows, thereby enhancing convergence along gust fronts and subsequent updraft redevelopment (Weisman and Klemp 1986), and will be further explored in section 3 with the discussion of the role of the rear-flank downdraft in tornado genesis

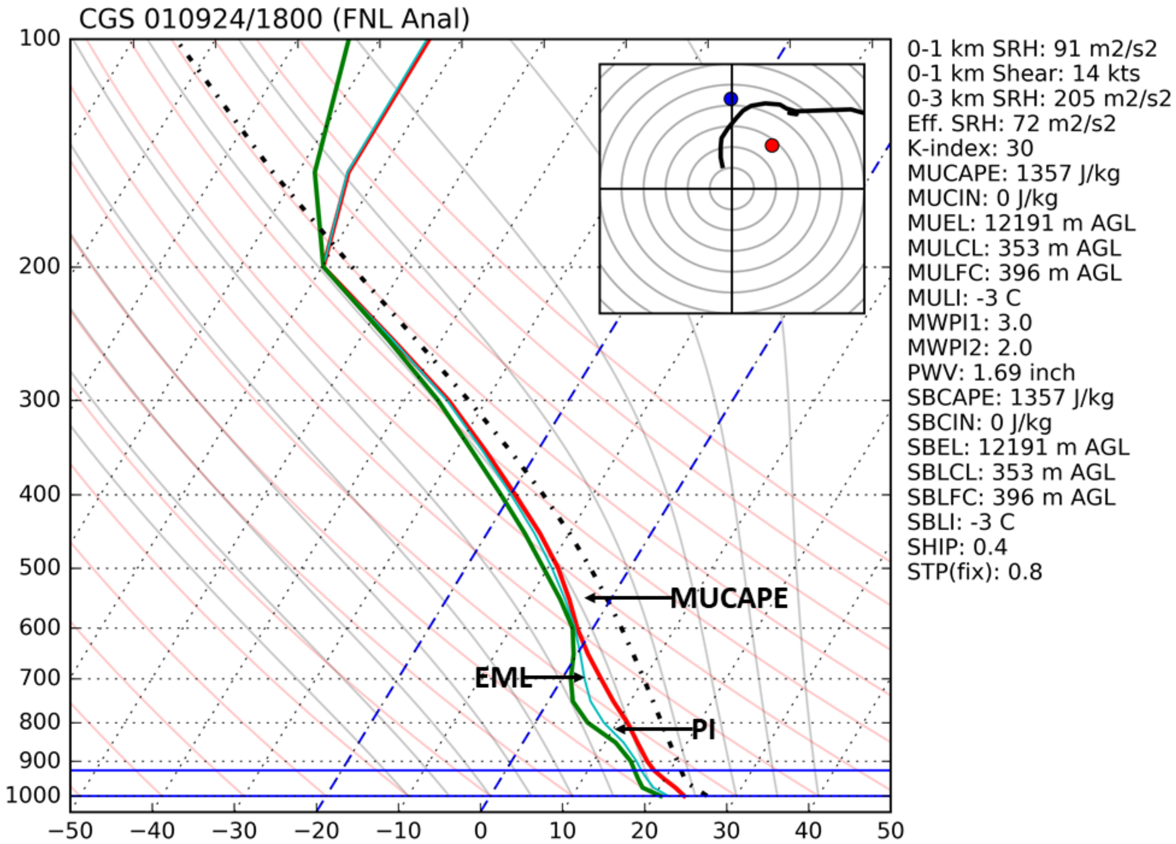

Figure 5. NCEP FNL analysis-generated thermodynamic profile and computed parameters at 1800 UTC 24 September 2001 over College Park, with a hodograph in the upper right corner. "EML" and "PI" denote the presence of an elevated mixed layer and potential instability, respectively. In the hodograph, Bunker's Storm motion right mover is plotted as a red dot and left mover as a blue dot.

Figure 5 shows the FNL analysis-generated sounding at 1800 UTC over College Park, three hours prior to the arrival of the supercell storm. The FNL generates a marginal elevated mixed layer ("EML"; Banacos and Ekster 2010) between 600 and 750 hPa, in which the temperature lapse rate was greater than moist adiabatic, while the dew point curve was nearly parallel to a saturation mixing-ratio line. The EML above 750 hPa served as a cap to the southerly flow of high-θ_e air and potential instability ("PI") and a source of higher-momentum, unsaturated air that could be ingested into the midlevels of deep convective storms as can be seen in Fig. 5. This confirms the significance of a continued southerly supply of high-θ_e air for a potentially unstable environment, given the presence of a deep shortwave trough to the west.

The more recently developed Microburst Windspeed Potential Index (MWPI) (Pryor 2015, Pryor 2017), that was designed to quantify the most relevant factors in convective downburst generation in intermediate thermodynamic environments was applied to diagnose the potential intensity of supercell RFD outflow. The MWPI incorporates: (1) surface-based CAPE, (2) temperature lapse rate between the 650 and 850 hPa levels, and (3) differences in dewpoint-temperature depression (DDD) between the 650 and 850 hPa levels. The MWPI formula consists of a set of predictor variables (i.e. dewpoint depression, temperature lapse rate) that generates output of expected microburst risk on a scale of 1 (marginal intensity) to 5 (severe). In this study, the parameter MWPI1 represents the MWPI calculated for the 650 to 850 hPa layer, while MWPI2 is calculated for the 750 to 950 hPa layer. As illustrated in Fig. 3 of Pryor (2015), an MWPI1 value of 3.0, in which the calculation layer was co-located with the EML and PI layer, corresponded to surface convective wind gust potential of 20 to 23 m s^{-1} (40 to 45 kt). As will be shown in the radar imagery in section 3, Doppler radar-detected outbound velocities of 20 to 25 m s^{-1} (40 to 49 kt) were most likely associated with the RFD surge that initiated tornado genesis near College Park.

In summary, the dynamic lifting mechanism resulting from the combination of PDVA and the eastward-advancing cold front, was amplified by potential instability associated with the lower-tropospheric θ_e ridge over the Atlantic coastal region, and served to stretch vertical air columns to generate low-level vorticity. An elevated, unsaturated layer of conditional instability between the 650 and 850 hPa levels, as detected by the MWPI, fostered RFD generation as this higher momentum air was ingested into the southern and western peripheries of the supercell.

3. Radar and satellite morphology

Before showing the radar and satellite morphology, for completeness, it is desirable to describe the evolution of the supercell storm that produced the College Park tornado. The supercell was first seen at 1915 UTC (not shown). By 2045 UTC (Fig. 6a), there were widespread intensifying deep convective storms over northern Virginia and central Maryland, apparent as a region of relatively high albedo in GOES-8 visible imagery (Setvak et al. 2003). The supercell storm had split over northern Virginia, and was well within the right entrance region of an upper-level jet core. Its left-moving storm was weaker than the right-moving supercell and eventually dissipated by 2029 UTC. However, the right-moving supercell was maintained as a quasi-steady storm, in which three tornadoes were spawned. The first tornado (F0 intensity) had an 18-km path through Stafford and Prince William Counties between 2010 and 2032 UTC and touched down on Quantico Marine Base. The second tornado (F1 intensity) had a 25-km path from Fort Belvior, Virginia to the U.S. Capitol in the District of Columbia, between 2044 and 2112 UTC. The right-flank supercell continued to track northeastward, steered by strong southwesterly flow aloft, as evident by the large 500-hPa geopotential height gradient with southwest-to- northeast oriented height contours, and eventually produced the F3 College Park tornado. By 2115 UTC, as shown in the visible satellite imagery in Fig. 6, the distinctive supercell storm emerged as the elongated shape in the southwest to northeast direction (Fig. 6b) was indicative of the strong shearing aloft associated with the jet stream. Overshooting thunderstorm tops were much more apparent as there was shadowing over the surrounding cloud mass to the east and northeast of the supercell near College Park, as well as to the east of a cluster of convective storms over northern Maryland. The development of the overshooting top near College Park was signifying the further intensification of convection associated with the supercell and the possibility that the storm was becoming severe, producing damaging winds and heavy rainfall.

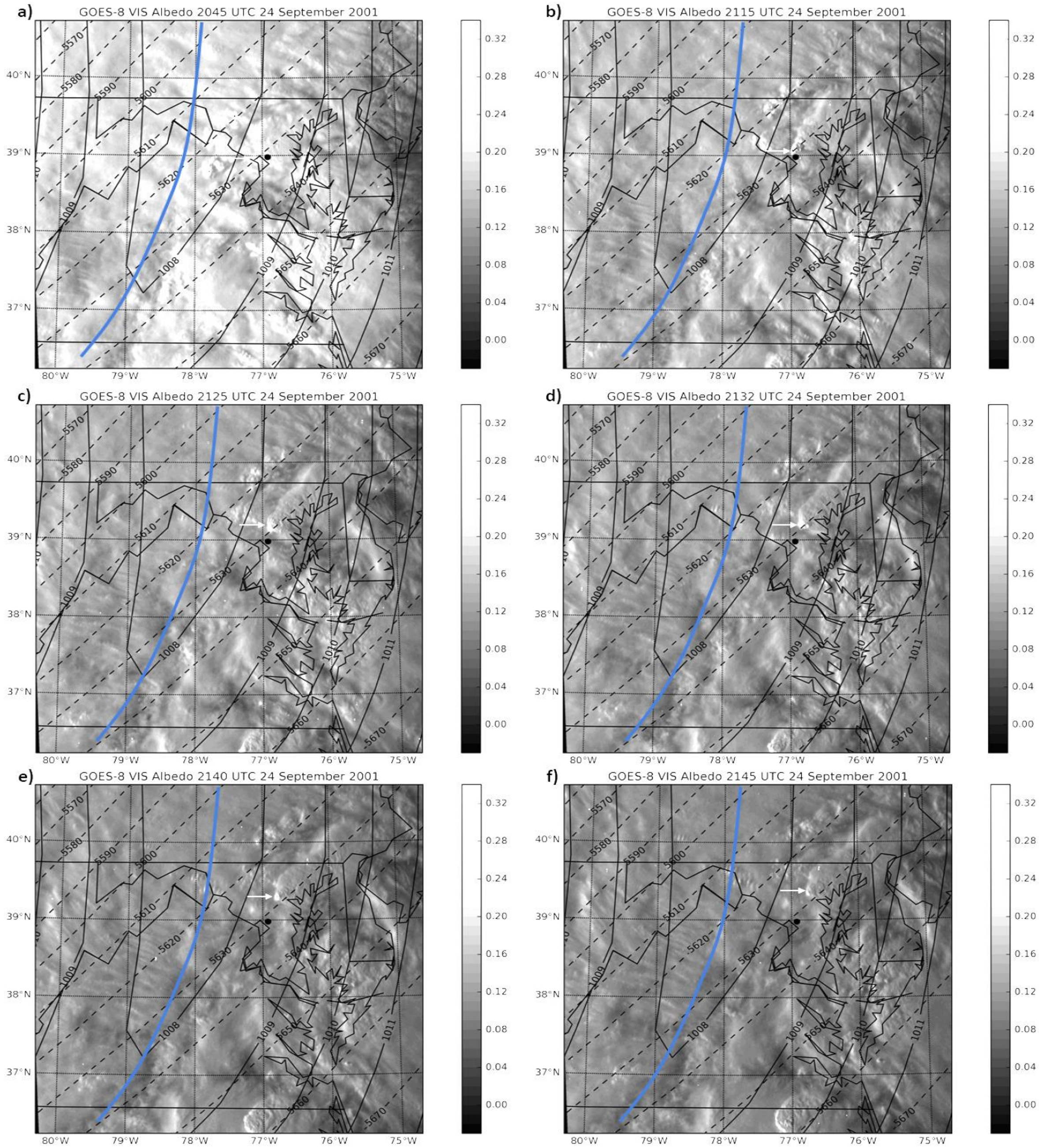

Figure 6. GOES-8 visible albedo imagery over the mid-Atlantic coastal region with overlying sea-level pressure (hPa, solid) and 500 hPa geopotential height (m, dashed) at (a) 2045 UTC; (b) 2115 UTC; (c) 2125 UTC; (d) 2132 UTC; (e) 2140 UTC; and (f) 2145 UTC 24 September 2001. Blue curve marks the location of the cold front. White arrow marks the location of the College Park supercell.

A prominent overshooting top was still apparent in GOES-8 visible imagery in Figs. 6c-f as the supercell storm tracked rapidly northeastward ahead of the cold front, toward the Baltimore metropolitan area. During the time period 2125 to 2145 UTC, deep convection still continued to develop over the Atlantic coastal plain from northeastern North Carolina to southeastern Pennsylvania and track northeastward into a region of large vertical directional (veering) wind shear.

GOES-8 infrared window channel imagery shown in Fig. 7 also tracked important features of the College Park supercell during the time of development and evolution of the tornado. Specifically, GOES-8 split window (channel 4 – 5) brightness temperature difference (BTD) imagery (Inoue 1987) at 4-km resolution displayed a high level of detail in storm structure and was effective in identifying storm-scale features, including cold cloud tops and dry-air intrusions. The BTD imagery was compared to NEXRAD reflectivity imagery, shown in Figs. 8 and 9, to demonstrate that near zero or slightly negative BTD values are associated with high radar reflectivity (> 50 dBZ), and a notch on the western and southwestern (rear) periphery of the supercell storm is associated with the mid-tropospheric intrusion of unsaturated air into the precipitation core of the thunderstorm. This correspondence was especially apparent during the early part of the tornado's track from College Park to Laurel. The interaction of unsaturated environmental air with the heavy precipitation core provided large downdraft energy for intense storm outflow winds that initiated and sustained the tornado. Markowski (2002) reviewed the physical processes of RFD generation, and the role of the RFD in the acceleration of the RF gust front, and generation and enhancement of vertical vorticity at the interface between the RFD and rotating updraft. The combined effect of these processes results in the intensification of a low-level mesocyclone and subsequent tornado genesis. In addition, between 2140 and 2145 UTC, tree damage from severe downburst winds was observed in the Laurel, Maryland area and was most likely associated with a secondary RFD surge (Mashiko et al. 2016).

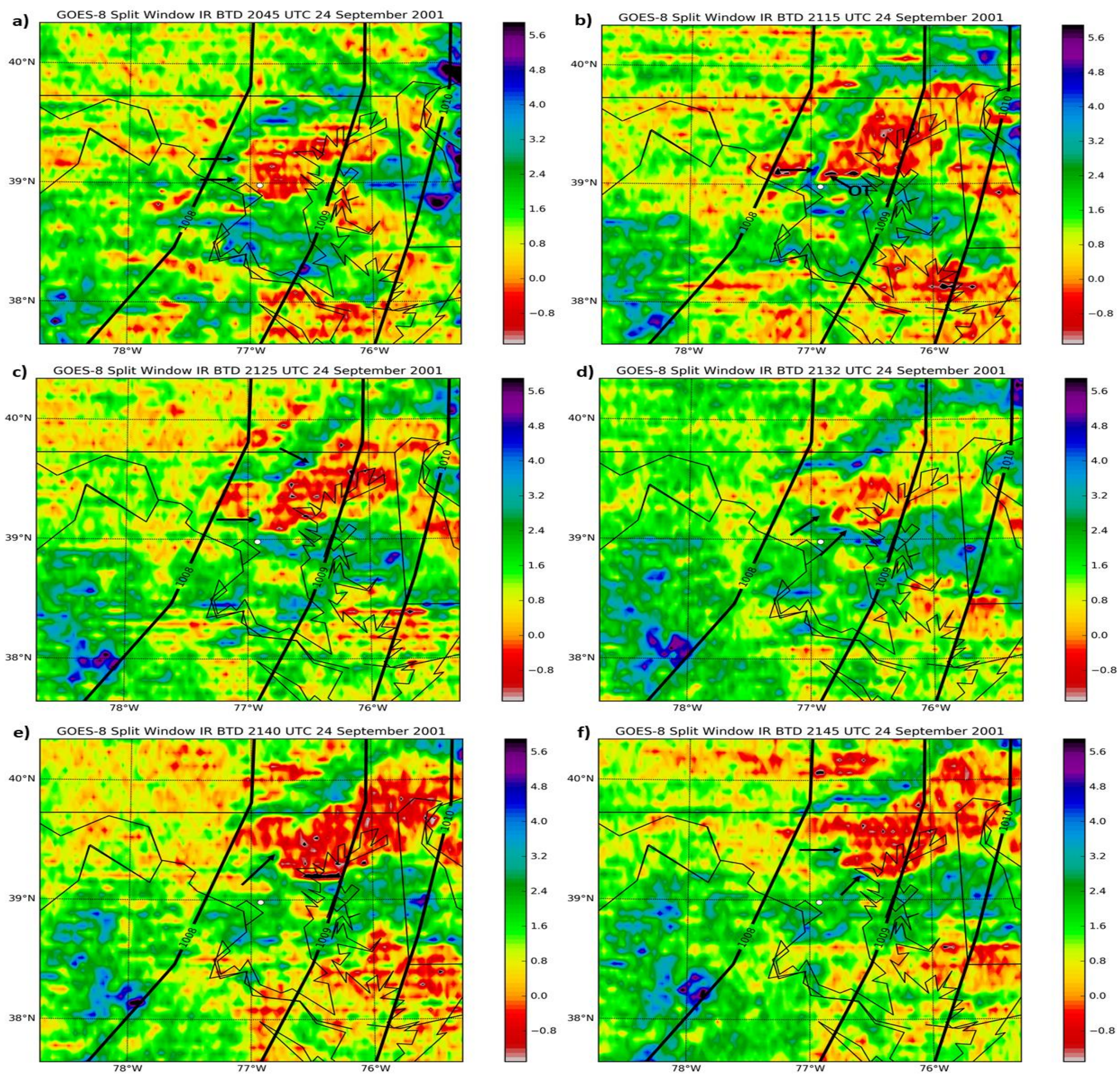

Figure 7. GOES-8 split window infrared imagery over the mid-Atlantic coastal region with overlying sea-level pressure (hPa, solid) at (a) 2045 UTC; (b) 2115 UTC; (c) 2125 UTC; (d) 2132 UTC; (e) 2140 UTC; and (f) 2145 UTC 24 September 2001. Blue curve marks the location of the cold front.

Scans of the College Park tornado were available from the Sterling, Virginia WSR-88D (KLWX) radar. During its lifetime, the tornado was 39-59 km from KLWX. The centerline heights of the lowest elevation angle beam were approximately 400-700 m AGL for the KLWX radar which, operated in volume coverage pattern (VCP) 11 (scans at elevation angles up to 19.5° with updates every 5 min), collected reflectivity and velocity data continuously during the tornado.

Figs. 8 and 9 display a well-defined hook echo near the southern end of the supercell as it tracked across Washington, DC. The hook echo has been frequently identified as an indicator of the existence of an RFD that, through the processes of gust front acceleration and convergence, results in an increase in low-level vorticity concentration and subsequent tornado genesis (Markowski 2002). As the supercell tracked northeastward, the hook echo developed a prominent "debris ball" at its

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eastern tip defining the location of the tornado (see Figs. 8e-f). Higher radar reflectivities (i.e., >45 dBZ) in the debris ball, which constitutes a tornadic debris signature (TDS) (Ryzhkov et al. 2005), began at approximately 2121 UTC near College Park and continued beyond 2146 UTC, when the tornado was located near Columbia, Maryland. During the period of reflectivity maximum, the tornado traveled almost exclusively through populated areas in Maryland, including College Park, Beltsville, and Laurel, with significant amount of debris being generated. Maximum reflectivities in the TDS were approaching 60 dBZ at 2126 UTC, rivaling reflectivities observed in the parent supercell. Additionally, current use of dual-polarization radars has shown through tornadic debris signatures that, in many cases, the large reflectivity in the "ball" of the hook is consistent with damage from debris (Ryzhkov et al. 2005).

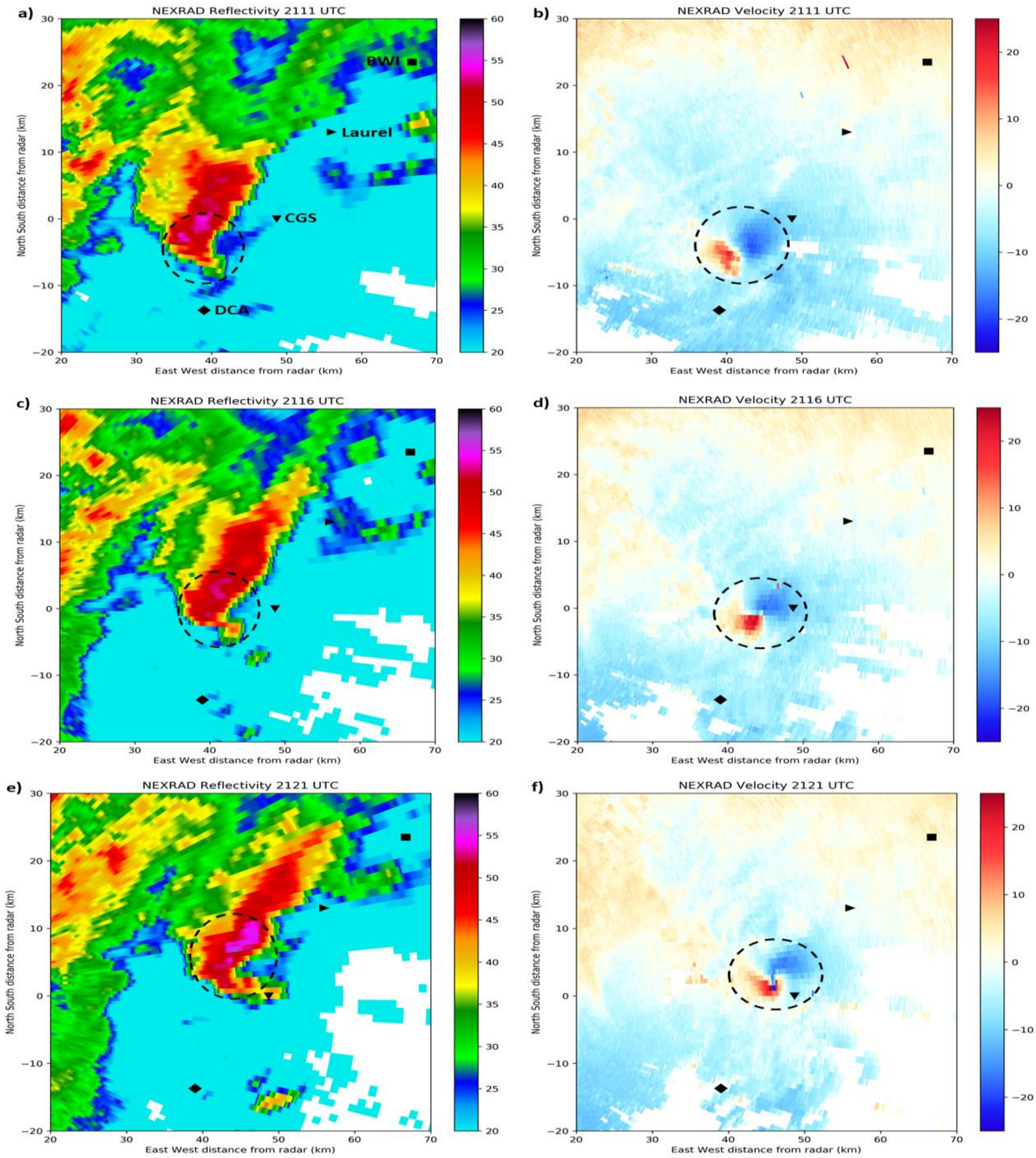

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Figure 8. Sterling, Virginia 0.5° WSR-88D (NEXRAD) radar reflectivity factor (dBZ) and radial velocity (m s-1), respectively, on 24 September 2001 at (a-b) 2111 UTC; (c-d) 2116 UTC; and (e-f) 2121 UTC. Black diamond, inverted triangle, right-pointing triangle, and square mark the locations of Reagan (Washington) National Airport ("DCA"), College Park Airport ("CGS"), Laurel severe wind report, and Baltimore-Washington International Airport ("BWI"), respectively. Black dashed closed curves mark the location of the parent supercell in the reflectivity factor imagery and the tornado signature (velocity couplet) in the radial velocity imagery.

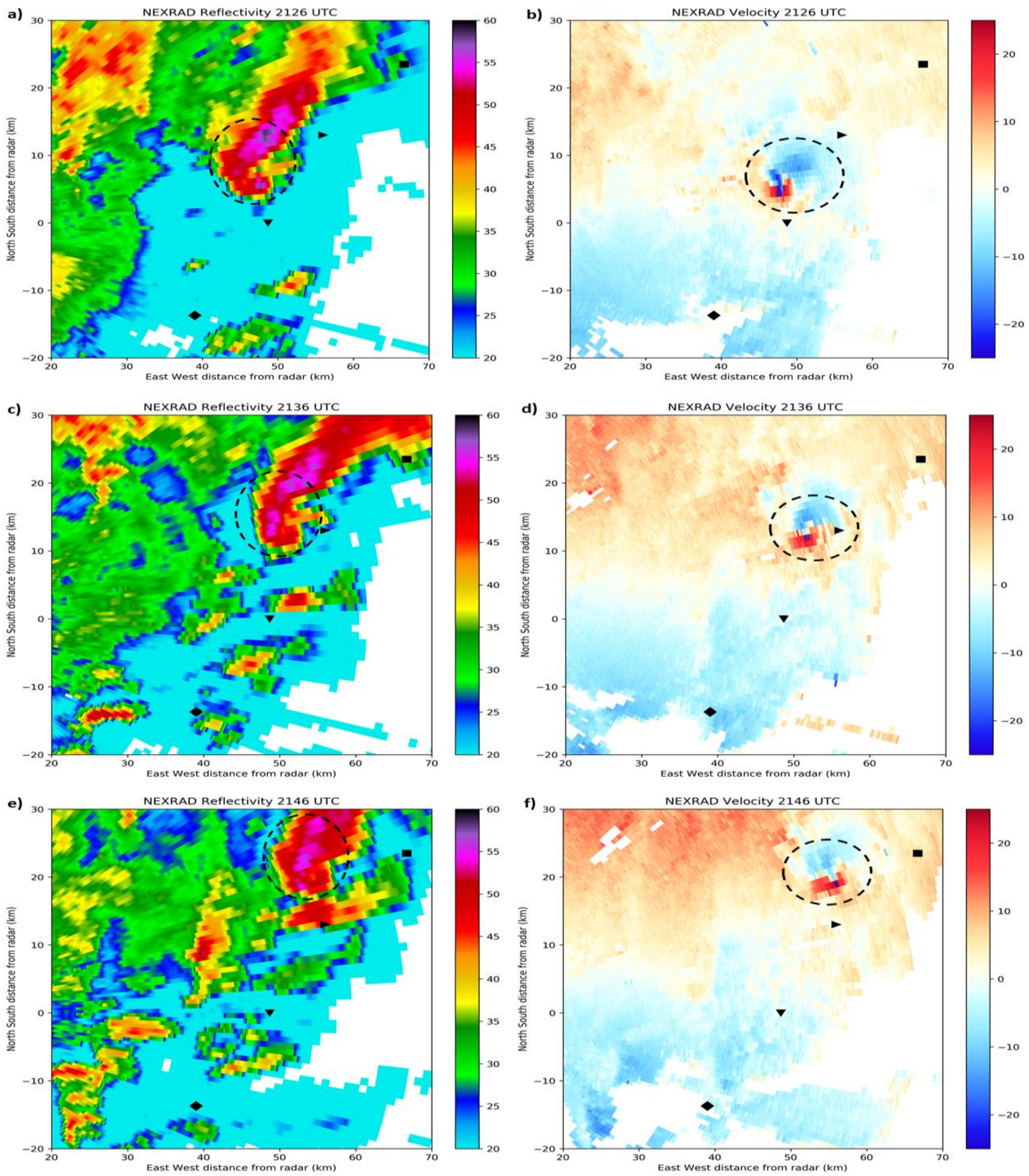

Figure 9. Sterling, Virginia 0.5° WSR-88D (NEXRAD) radar reflectivity (dBz) and velocity (m s-1), respectively, on 24 September 2001 at (a-b) 2126 UTC; (c-d) 2136 UTC; and (e-f) 2147 UTC. Black diamond, inverted triangle, right-pointing triangle, and square mark the locations of Reagan (Washington) National Airport ("DCA"), College Park Airport ("CGS"), Laurel severe wind report, and Baltimore-Washington

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International Airport ("BWI"), respectively. Black dashed closed curves mark the location of the parent supercell in the reflectivity factor imagery and the tornado signature (velocity couplet) in the radial velocity imagery.

Burgess et al. (2002) defined a tornado cyclone signature (TCS) as a "maximum velocity difference across a horizontal distance of less than 1.85 km" in which a "small-scale couplet was identified". The authors also found that "the TCS at low elevation angles, for which the radar beam height was less than 1 km ARL, corresponded relatively well to tornado location, and the trend in its magnitude was similar to that of the tornado F scale". In a similar manner, the associated tornado cyclone signature (TCS) in the present case was readily apparent in radial velocity imagery between 2121 and 2146 UTC, in Figs. 8f and 9, as a couplet of azimuthally adjacent maximum outbound (red shading) and inbound (blue shading) velocities located near College Park. The TCS, just prior to tornado touchdown in College Park near 2020 UTC, was preceded by a strong convergence signature in which outbound velocity was somewhat larger than the inbound velocity. The strong outbound velocity, observed to be near 24 m s^{-1} (48 kt) and 6 m s^{-1} larger than the inbound velocity at 2016 UTC, indicated possible rear-flank downburst occurrence in the form of an RFD surge that served as an initiating mechanism for tornado development. A secondary RFD surge most likely occurred between 2136 and 2146 UTC when outbound velocities again increased to become significantly greater than inbound velocities. During this time period, non-tornadic (i.e. downburst) wind damage was observed in the Laurel area, where there was a break and subsequent westward shift in the tornado track. The TCS signature in radar could be associated with the presence of overshooting tops, thunderstorm cloud elongation, and rear-flank dry-air notches as apparent in GOES split window BTD imagery in Fig. 7. At the end of the lifetime of the tornado, after tracking through the Columbia area, NEXRAD reflectivity imagery observed the evolution of the parent supercell to a bow echo (not shown). Note that the bow echo described herein was shorter lived with a smaller scale than that studied by Davis et al. (2004), and did not result in any observations of severe winds or wind damage. In this case, the bow echo transition was most likely just a signification of weakening of the supercell storm.

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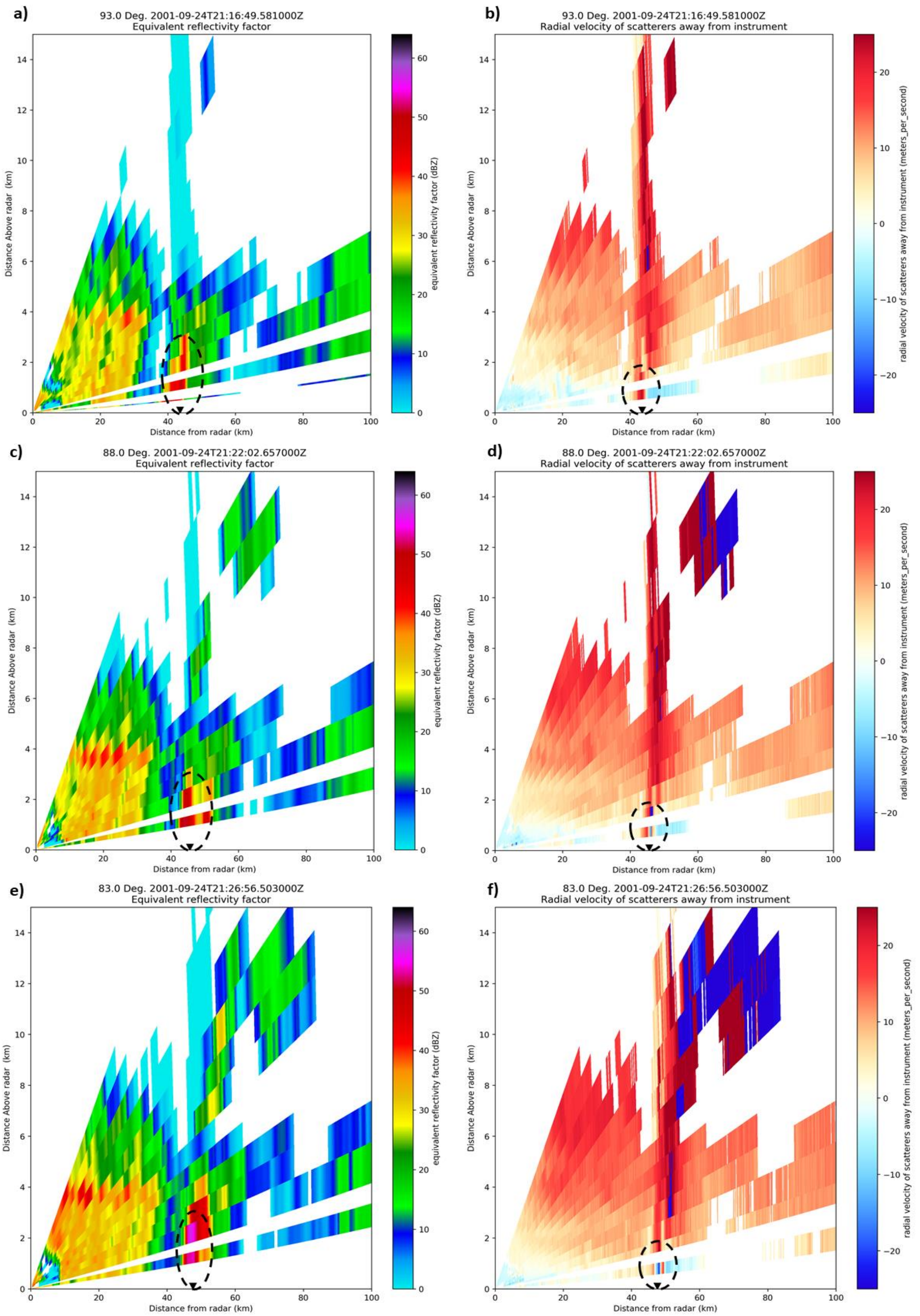

Figure 10. Sterling, Virginia WSR-88D (NEXRAD) cross sections of reflectivity and radial velocity, respectively, on 24 September 2001 at (a-b) 2116 UTC; (c-d) 2122 UTC; and (e-f) 2126 UTC. Black dashed closed curve marks the location of the parent supercell and inverted triangle marks the location of the tornado signature.

In the analysis of the 3 May 1999 Oklahoma City tornado, Burgess et al. (2002) defined the maximum velocity difference in the tornado vicinity, across a horizontal distance of less than 1.85 km, and identified a small-scale couplet referred to as a tornado cyclone signature (TCS). They found that the TCS, at low elevation angles, for which the radar beam was less than 1 km AGL, corresponded well to the tornado location, and that the trend in its magnitude was similar to that of the tornado F-scale. The term "tornado cyclone" has been applied to circulations larger than the tornado (Burgess et al. 2002). They also noted that in most observations of tornadoes, such as those collected by the WSR-88D radar, the vortex core is narrower than the effective radar beamwidth. The signature of the tornado in the radar data thus depends greatly on the characteristics of the flow surrounding the core and on the position of the radar beam relative to the vortex center.

Burgess et al. (2002) defined the quantity of Delta-V as the TCS velocity difference (or storm-relative velocity). This strong correspondence could be well demonstrated in the present case. As displayed in Fig. 8d, by 2116 UTC, the Delta-V had rapidly exceeded 40 m s^{-1} (80 kt) as the tornado was developing southwest of College Park and then continued to increase to near 50 m s^{-1} (100 kt) by 2121 UTC as the tornado reached F3 intensity (Fig. 8f). Peak Delta-V of greater than 50 m s^{-1} was observed at 2126 UTC (Figure 9b) as the tornado was tracking rapidly northeastward toward Beltsville. After 2130 UTC, Delta-V decreased to 40 m s^{-1} as the intensity of the tornado weakened to F2 (Fig. 9d). By 2146 UTC (Fig. 9f), the tornado, moving northeast toward Columbia, was near the end of its lifetime and its intensity had decreased to F1. Consequently, Delta-V had decreased significantly to 40 m s^{-1}. It was also observed that as the tornado intensified from F1 to F3, the TCS moved from a location on the left front quadrant of the hook to the center of the TDS.

The reflectivity cross section also displays signatures that are highly indicative of tornadic activity (Fig. 10). A distinctive bounded weak echo region (BWER) was present during the lifetime of the supercell. A complete description of the three stages in the evolution of a tornadic supercell are featured in Rotunno (1986). At 2116 UTC (Fig. 10a), the mature supercell displayed the following characteristics: the echo top was at its maximum height (~10 km) with a well-defined BWER, suggesting the existence of a strong updraft and intensification of the mesocyclone as it was building down to the lower levels. Weisman and Klemp (1986) noted that the storm rotation originates through the tilting of horizontal vorticity inherent in the vertically sheared flow. At this time, a hook echo was developing on the right rear flank as indicated in the 2111 UTC reflectivity image (see Fig. 8a). By 2121 UTC (Fig. 10c), the BWER ceiling had lowered as it began to fill, indicating that the supercell was in a collapsing phase (Rotunno 1986). The 2121 UTC reflectivity (Fig. 8e) reveals that the hook echo was "wrapping up" south and east of the parent cell, signifying high probability of tornadic development. The development of the hook echo and BWER collapse demonstrated the intensification of the supercell downdraft and a surge of the gust front as it became highly contorted in the vicinity of the main updraft. This is consistent with the subsequent development of a bow echo structure (not shown). It was also apparent that the location of the tornado cyclone had moved toward the center of the mesocyclone.

4. Summary and Conclusions

The 24 September 2001 College Park, Maryland, tornado is noteworthy because of its nearly 30 km length track, and remains the only long-track event with an intensity of F3 or greater to directly impact the greater Washington, DC and adjacent suburban Maryland region since 2000. Employment of recently developed visualization techniques in Python revealed associated features that were identifiable on a number of spatial and temporal scales in satellite, radar and NWP model analysis datasets. The tornado featured many similarities to previous and more recent significant tornado events that resulted in widespread damage in urban areas, e.g., the 3 May 1999 Oklahoma City and 2016 Tsukuba City, Japan tornadoes.

GOES imagery on 24 September revealed many critical elements of the College Park tornadic event; (a) an upper-level westward-tiled trough over the Ohio Valley region; (b) the development of deep convection ahead of a surface front over the mid-Atlantic states with widespread cirrus clouds associated with a jet stream; (c) breaks in the cirrus clouds over south-central and eastern Maryland revealing the presence of widespread cumulus congestus; (d) storm elongation and overshooting cloud tops associated with the supercell, indicative of intense, deep convection in a strongly shared environment; and (e) dry-air notches (intrusions) on the southern and western flanks of the supercell that indicated possible interaction of mid-tropospheric unsaturated air with the precipitation (esp. ice phase) core. The entrainment of unsaturated air into the precipitation core is a typical forcing mechanism for an intense RFD and resulting strong surface outflow. Strong mid-tropospheric PVA, low-level WAA, and vertical wind shear could all be inferred from the satellite imagery. FNL analysis-derived upper-air soundings and vertical θ_e profiles exhibited strong potential instability with moderate CAPE over central Maryland to "feed" deep convection. A striking observation in the imagery was the intensification of the supercell as it moved into a progressively unstable environment and then the appearance of dry-air notches on the periphery of the storm at the approximate times that the supercell produced a tornado.

In a similar manner to research pertaining to the 3 May 1999 Oklahoma City tornado, operational WSR-88D signatures in reflectivity and velocity were shown to have utility in detecting and monitoring the College Park tornado. The radar data revealed (a) a well-defined hook echo; (b) a high reflectivity "debris ball" (TDS) within the hook echo; (c) a tornado cyclone signature (TCS) in the velocity data; (e) a large TCS velocity difference (> 40 m s^{-1}) at the approximate time of tornado touch-down; and (f) collapse of the bounded weak echo region (BWER) at the time of tornado development. In this case, the high-reflectivity TDS of the hook echo was used to infer the presence of a damaging tornado (Burgess et al. 2002). Similar to the observations in the Oklahoma City tornado, the 24 September velocity signatures demonstrated a relationship to the strength of the flow surrounding the tornado. Finally, the evolution of the parent supercell to a bow echo signature was inferred

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as an indicator of the possible development of a downburst at the end of the tornado's lifetime.

In conclusion, the coordinated use of satellite imagery, and radar data and operational modeling guidance at multiple spatial scales have helped the operational forecaster to reasonably predict the outbreak of severe convection as well as the development of the supercell/tornado that tracked through College Park during the afternoon of 24 September 2001. Numerical model guidance could provide a long-term outlook of the conditions favorable for the development of severe convection several hours prior to the tornado event while regional satellite imagery proved to be effective in indicating the existence of these conditions one to three hours prior to tornado touch-down in College Park. In the present case, NWP model data, specifically the FNL Operational Global Analysis, and satellite imagery identified a combination of forcing mechanisms that resulted in the development of the supercell that produced the College Park tornado. Finally, radar imagery proved to be an effective tool in monitoring the structural evolution of the supercell as well as the tornado that tracked through College Park. Of course, the above results are mostly a hindsight view, and they do not imply that any future tornado occurring over the Washington-Baltimore corridor or elsewhere could also be successfully predicted like the present case. Clearly, more research should be conducted in the future to improve the monitoring of tornadic storms through satellite and radar observations, and improve the model initial conditions with more real-time high-resolution observations assimilated and the model physics parameterizations. Artificial intelligence (AI) methods, such as artificial neural networks (ANNs), have recently been proven effective in convective storm analysis and prediction. Early studies by McCann (1992) and more contemporary studies by Collins and Tissot (2016) have demonstrated the utility of ANNs in NWP model parameter evaluation to predict thunderstorm development. Considering recent advances in severe convective storm pattern recognition with the higher-resolution imagery of the GOES-R series (i.e. GOES-16), the neural network method could be feasible in the identification of supercell storm and tornado signatures, and in short term prediction of storm development and tornado genesis.

Appendix 1. Tornado warning issued by the NWS/Sterling Office at 0510 PM LST 24 September 2001

THE NATIONAL WEATHER SERVICE IN STERLING VIRGINIA HAS ISSUED A TORNADO WARNING FOR...

NORTHERN SOUTHEAST MONTGOMERY COUNTY IN CENTRAL MARYLAND

NORTHERN PRINCE GEORGES COUNTY IN CENTRAL MARYLAND

UNTIL 545 PM EDT

AT 506 PM EDT...NATIONAL WEATHER SERVICE DOPPLER RADAR INDICATED A TORNADO 6 MILES SOUTHWEST OF HYATTSVILLE...

MOVING NORTHEAST AT 35 MPH.

THE TORNADO IS EXPECTED TO BE... OVER HYATTSVILLE...

2 MILES NORTHWEST OF BLADENSBURG AT 516 PM

2 MILES SOUTHEAST OF ADELPHI...

2 MILES SOUTHEAST OF LANGLEY PARK AT 518 PM OVER COLLEGE PARK...

3 MILES SOUTHEAST OF HILLANDALE AT 520 PM

OVER GREENBELT AT 522 PM

OVER BELTSVILLE AT 524 PM

Author Contributions: Conceptualization, K. Pryor and D.-L. Zhang; methodology, K. Pryor and D.-L. Zhang; software, K. Pryor and T. Wawrzyniak; validation, D.-L. Zhang; formal analysis, K. Pryor; investigation, K. Pryor and D.-L. Zhang; resources, T. Wawrzyniak; data curation, K. Pryor and T. Wawrzyniak; writing—original draft preparation, K. Pryor; writing—review and editing, D.-L. Zhang; visualization, T. Wawrzyniak and K. Pryor; supervision, D.-L. Zhang; project administration, D.-L. Zhang; funding acquisition, D.-L. Zhang.

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