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1. Introduction

Long track and devastating tornadoes are rare east of the Appalachian Mountains. On 28 April 2002, a cyclical supercell tracked from West Virginia east across northern Virginia and lower southern Maryland as part of a large-scale severe weather episode. Numerous reports of large hail were received as this supercell tracked across West Virginia. The supercell spawned its first tornado (F2 intensity) in Shenandoah County Virginia at 2045 UTC. As the storm continued east, reports of large hail and funnel clouds were commonplace, although tornadoes were not confirmed.

The supercell produced its second tornado shortly after it crossed the Potomac River into Charles County Maryland at approximately 2255 UTC, strengthening to F4 intensity as it crossed the town of La Plata, Maryland. The tornado weakened to a F2 as it crossed Calvert County Maryland, continuing east across the Chesapeake Bay into Dorchester County (U.S. Dept. Commerce 2002).

2. Brief Review of the Synoptic System

Figure 1 shows a dual west to east upper-level jet structure spanned the CONUS on 28 April 2002. ACARS 400-250hPa wind speed observations also reveal a trough within the northern upper-level jet amplified as it moved southeast from the Midwest into the northern Mid-Atlantic Region between 1200 UTC 28 April 2002 and 0000 UTC 29 April 2002. A fast-moving 994hPa surface low located near Milwaukee, Wisconsin at 1200 UTC (Fig. 2) translated to central Pennsylvania by late afternoon (Figs. 3-4), filling to 997hPa as the system slowed.

A boundary which stretched across Pennsylvania from northwest to southeast remained nearly stationary throughout the day, while a cold front

advanced to the Appalachians from central Indiana between 1200 and 2300 UTC on April 28.

Three hourly pressure falls of 5 to 6hPa were observed from the Chesapeake Bay Region north into the lower Susquehanna Valley Region of southeast Pennsylvania on both the 1800 UTC and 2100 UTC analysis as the upper-level trough approached (Strong and Zubrick 2004).

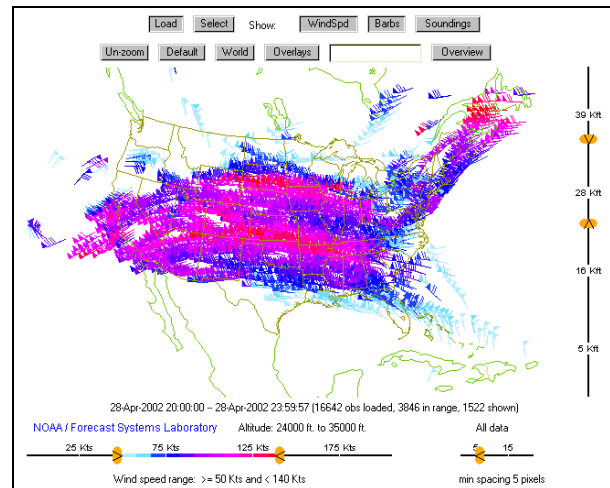


Figure 1. ACARS 24-35kft wind speed observations between 2000 UTC 28 April and 0000 UTC 29 April 2002.

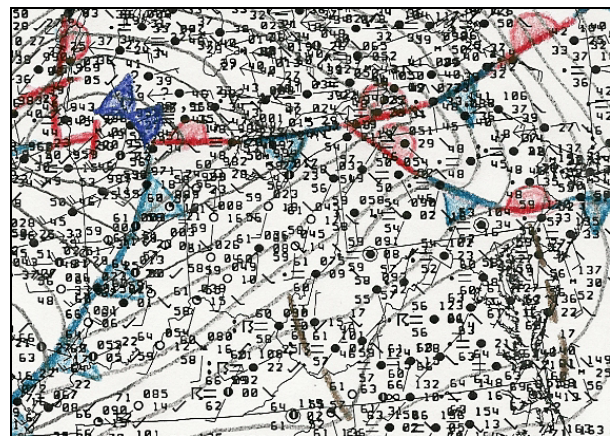


Figure 2. 1200 UTC 28 Apr 2002 Surface Analysis-East U.S. (2hPa isobar increments).

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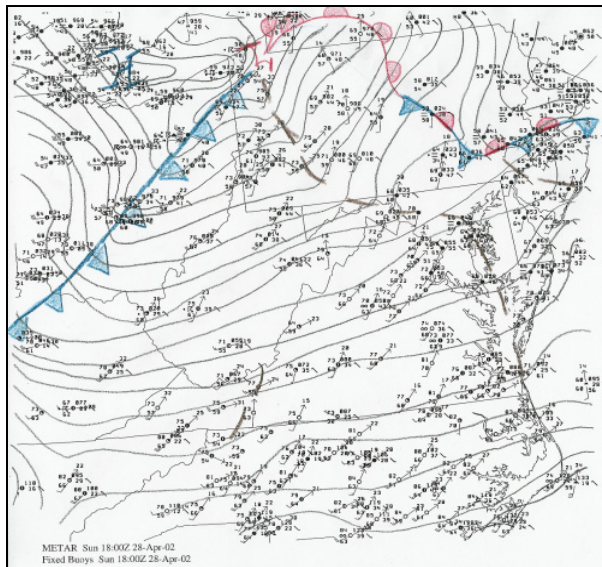


Figure 3. 1800 UTC 28 April 2002 surface analysis Mid-Atlantic (1hPa isobar increments).

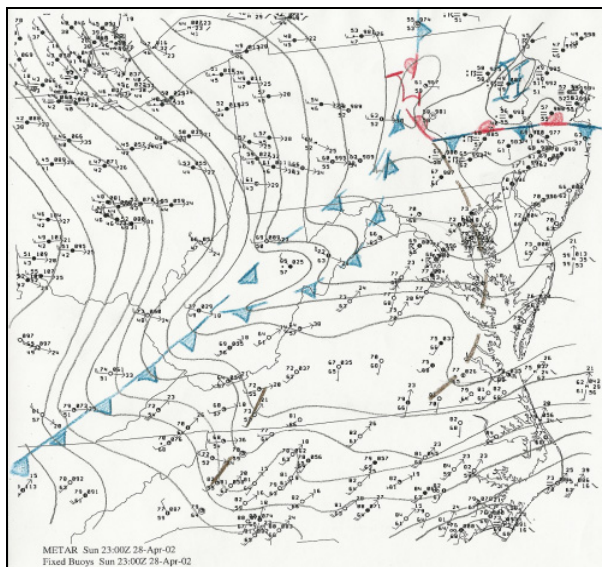


Figure 4. as in Fig. 3 except 2300 UTC.

3. Thermodynamic Environment

Warm advection precipitation served to stabilize the environment during the morning hours of 28 April 2002. Between 1800 UTC and 2100 UTC, surface temperatures climbed into the 21 to 25C range from southwest to northeast across the Mid-Atlantic Region. Surface dewpoints remained in the 15 to 18C range across the same area during the afternoon and evening hours. The supercell that would later produce the La Plata tornado

encountered nearly identical surface temperatures and dewpoints as it tracked east from West Virginia across northern Virginia and lower southern Maryland between 1900 UTC 28 April and 0000 UTC 29 April 2002.

In Fig. 5, the 1800 UTC KIAD RAOB displays weak lapse rates above a stable near-surface layer. With midlevel cooling associated with the approach of the midlevel wave, the 0000 UTC KIAD RAOB reveals much steeper lapse rates from 900 to 500hPa, while lifted indices fell from +3 to -5C between 1800 UTC and 0000 UTC (not shown). When the surface is adjusted for a temperature of 25C and dewpoint of 17C common along the path of the supercell, the surface-based CAPE was 1400 Jkg^{-1} with surface-based CIN of 40 Jkg^{-1} at 0000 UTC.

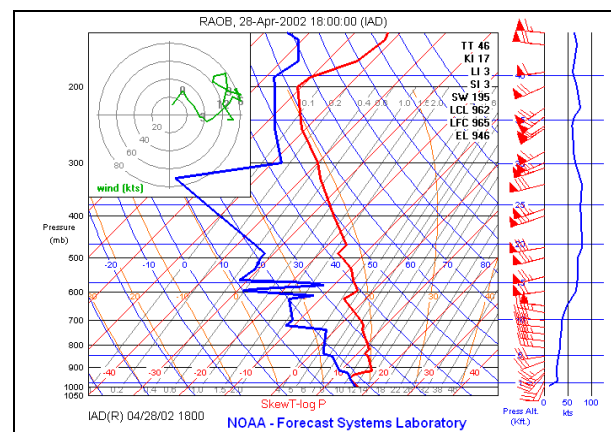


Figure 5. 1800 UTC KIAD (Sterling, Virginia) RAOB - 28 April 2002.

ACARS experimental aircraft soundings (Moninger, et al. 2003) during the late afternoon of 28 April 2002 display a similar trend. The 2120 UTC ascent ACARS sounding from IAD shows lapse rates in the 900-500hPa layer consistent with the cooling trend seen on the KIAD RAOB 1800 UTC and 0000 UTC soundings (not shown). When adjusted for a surface temperature of 25C and a 17C surface dewpoint, the modified 2120 UTC ACARS sounding indicates nearly 850 Jkg^{-1} of surface based CAPE. The 2324 UTC descent ACARS sounding into BWI reveals much cooler temperatures in the 600-400hPa layer when compared to either KIAD RAOB or the 2120 UTC IAD ACARS sounding (Fig. 6). As a result, when adjusted for a surface temperature of 25C and surface dewpoint of 17C, the modified 2324 UTC

BWI ACARS sounding shows surface-based CAPE values rising above 1600 Jkg^{-1} (Fig. 7).

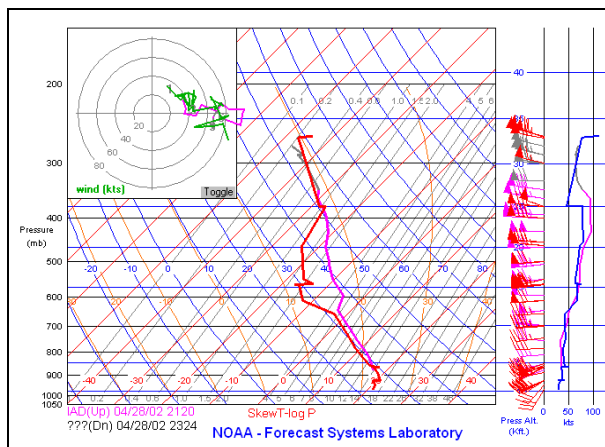


Figure 6. 2120 UTC 28 April IAD ACARS sounding overlaid with the 2324 UTC BWI ACARS sounding from 28 April 2002.

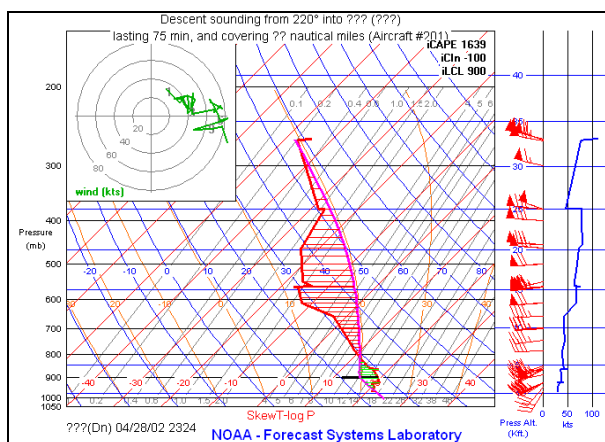


Figure 7. ACARS 2324 UTC 28 April 2002 descent sounding into BWI modified for a surface temperature/dewpoint of 25C/17C.

The 0000 UTC 29 April 2002 KWAL RAOB shows midlevel lapse rates similar to those seen on the 1800 UTC KIAD RAOB (not shown). This indicates midlevel cooling has not yet arrived over the Atlantic Coast. Meanwhile, cooler midlevel temperatures allowed for a moderately unstable environment across lower southern Maryland as suggested by the 2324 UTC BWI ACARS modified sounding. This narrow midlevel cold pool corridor appears to be associated with ascent just ahead of the 500hPa trough axis (Fig. 8).

4. Dynamic Environment

Wind shear was favorable for supercells and tornadogenesis across the northern Mid-Atlantic Region during the afternoon and evening hours. RAOB and ACARS soundings throughout the day indicated substantial veering and speed shear in the lowest km of the sounding.

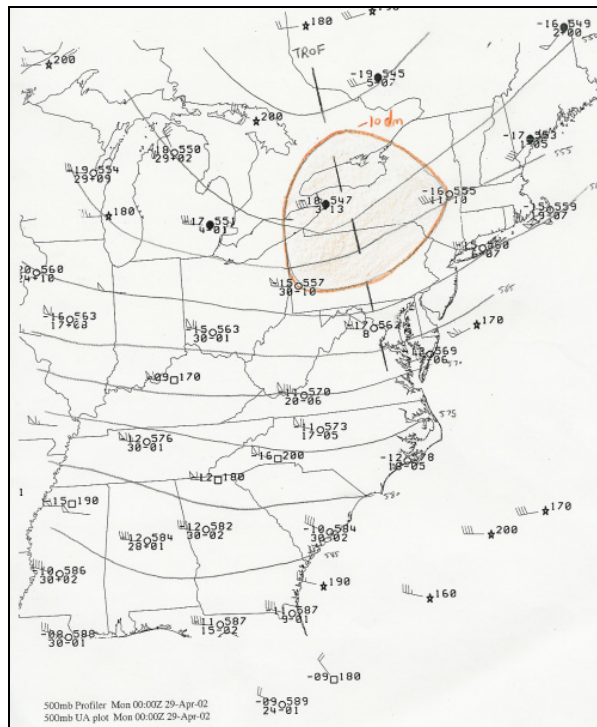


Figure 8. 0000 UTC 29 April 2002 500hPa analysis – Eastern U.S (standard upper air plotting model used).

Beginning about 2100 UTC, the dynamic environment was becoming more favorable for tornadogenesis across lower southern Maryland. The profiler located in Ft. Meade, Maryland observed a low-level jet developing, with winds increasing from 25 to 30kts to between 40 and 50kts in the 2 to 5kft layer (Fig. 9). This low-level jet was likely dynamically-forced by the approaching midlevel trough, with 10 to 13dm 12hr 500hPa height falls observed at 0000 UTC 29 April 2002 across the eastern Great Lakes Region (see Fig. 8).

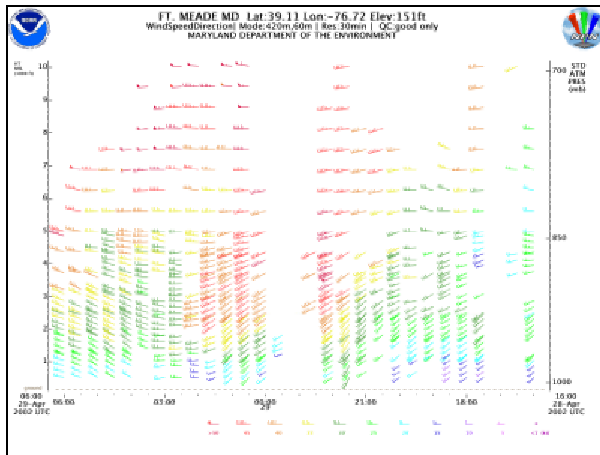


Figure 9. 1600 UTC 28 April–0600 UTC 29 April 2002 Ft. Meade, Maryland wind profiler.

A similar trend was observed by the Richmond, Virginia profiler while the New Brunswick, New Jersey profiler reveals little change in low-level wind speeds during the evening hours on April 28.

Other observational data sets also show the developing low-level jet. ACARS observations show wind speeds in the 1.5 to 5.0kft layer of 25 to 35kts in the Richmond, Virginia to Philadelphia, Pennsylvania corridor between 1700 UTC and 2100 UTC (Fig. 10). ACARS data indicate wind speeds in the same layer increased to 45 to 55kts between 2100 UTC and 0100 UTC (Fig. 11). 925hPa analysis from 0000 UTC 29 April 2002 using RAOB data also displays an identical low-level jet feature, with a 45kt wind observed at 925hPa at KWAL (Fig. 12).

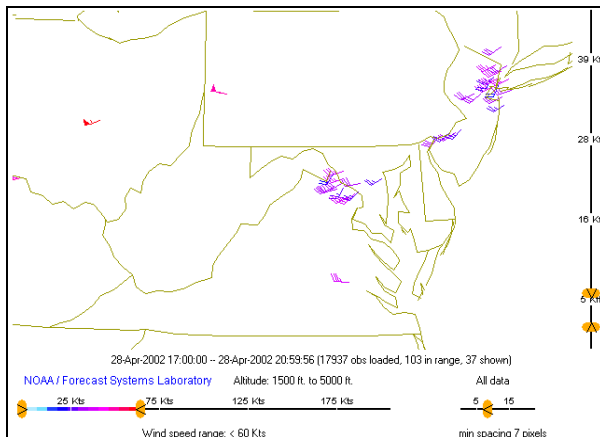


Figure 10. ACARS wind speed observations between 1.5 and 5.0kft from 1700 to 2100 UTC 28 April 2002.

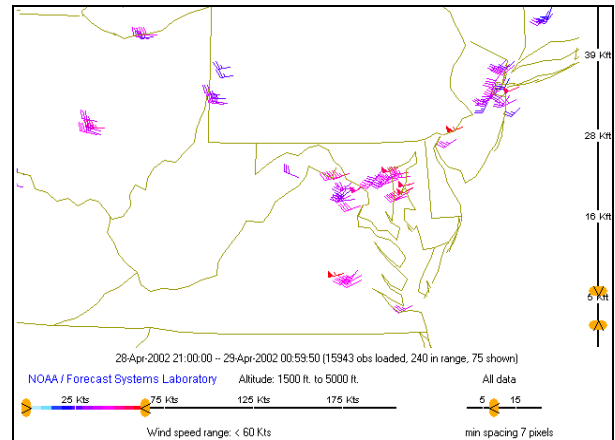


Figure 11. as in Fig. 10 except 2100 UTC 28 April 2002 to 0100 UTC 29 April 2002.

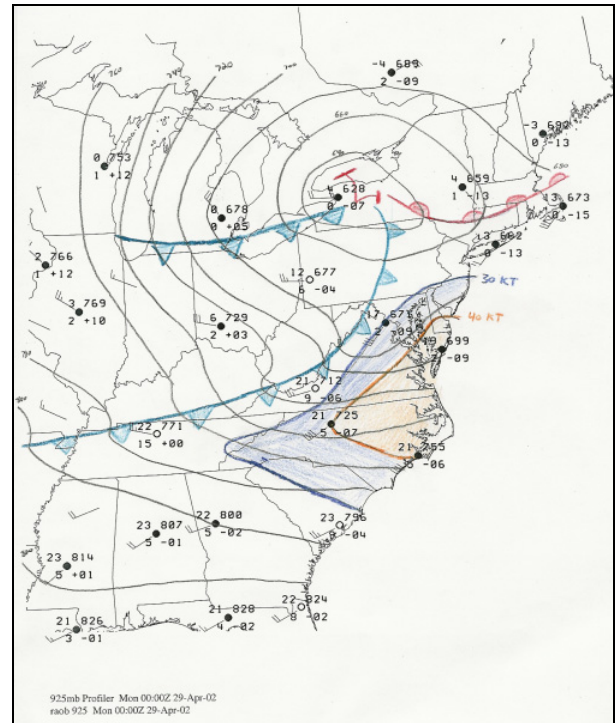


Figure 12. 0000 UTC 29 April 2002 925hPa analysis – Eastern U.S (standard upper air plotting model used).

Model data also indicated the formation of a low-level jet during the evening hours of 28 April 2002. ETA BUFKIT data from the 0000 UTC 28 April 2002 model run indicates a peak of 0-3 km helicity values at KHHK of nearly $300 \text{ m}^2 \text{ s}^{-2}$ at 0000 UTC 29 April, while low-level winds increase to 40 to 50kts in the 850-950hPa layer (Fig. 13). The same model run shows a forecast of 22 ms^{-1} of shear in the 0-2 km layer, with a long but curved hodograph in the aforementioned layer (Fig. 14).

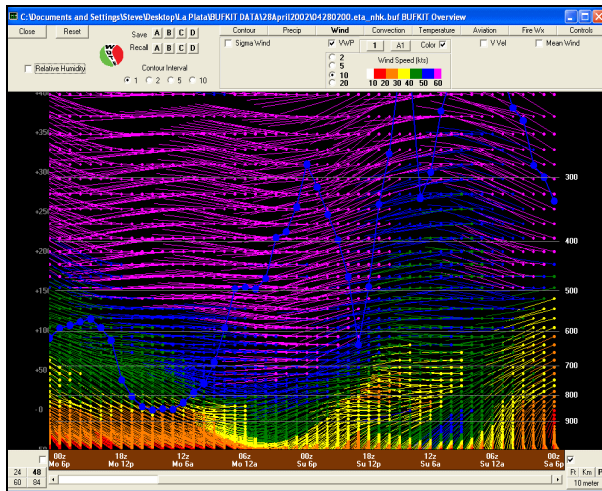


Figure 13. Time-Height between 0000 UTC 28 April and 0000 UTC 30 April 2002 forecast winds (kts) and helicity (m^2s^{-2}) from 0000 UTC 28 April 2002 ETA model run; valid Patuxent, MD (KNHK).

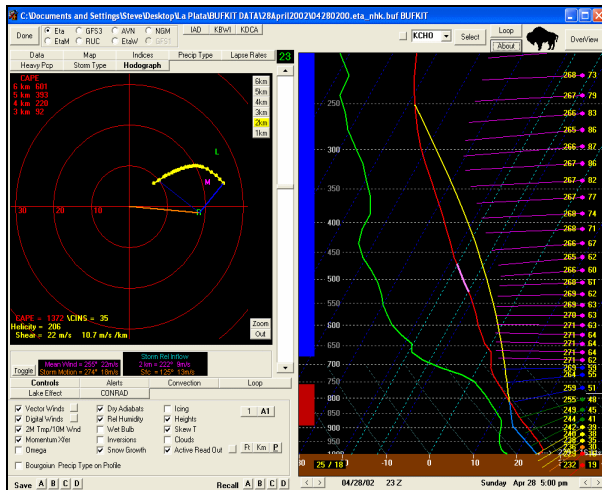


Figure 14. Forecast hodograph and sounding from the 0000 UTC 28 April 2002 ETA valid for KNHK at 2300 UTC 28 April 2002.

The 1800 UTC 28 April 2002 RUC model run also displays the development of the low-level jet feature. The RUC forecast of the 925-850hPa wind speed average shows the development of the low-level jet in the corridor from Richmond, Virginia to Philadelphia, Pennsylvania beginning at 2200 UTC 28 April 2002, and maturing at 0000 UTC 29 April 2002 (Figs. 15-16). When compared to wind speed observations from area profilers, RAOB and ACARS data, the RUC's low-level jet forecast appeared consistent in magnitude and location, but was an hour slow in forecasting development of the jet.

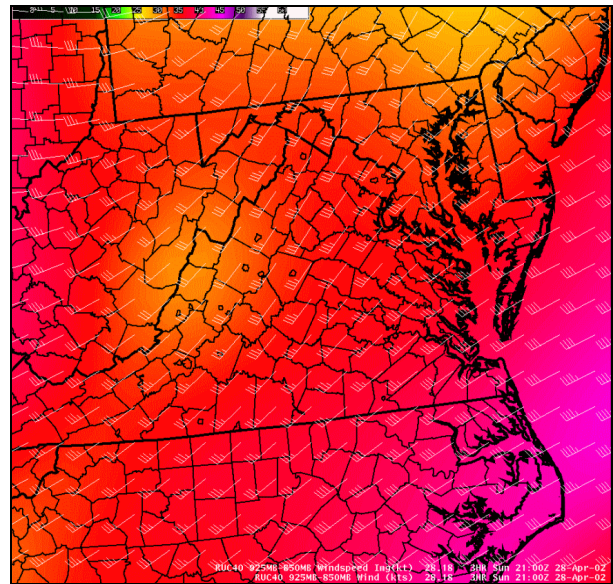


Figure 15. 3 hr RUC 925-850hPa wind speed average forecast valid 2100 UTC 28 April 2002.

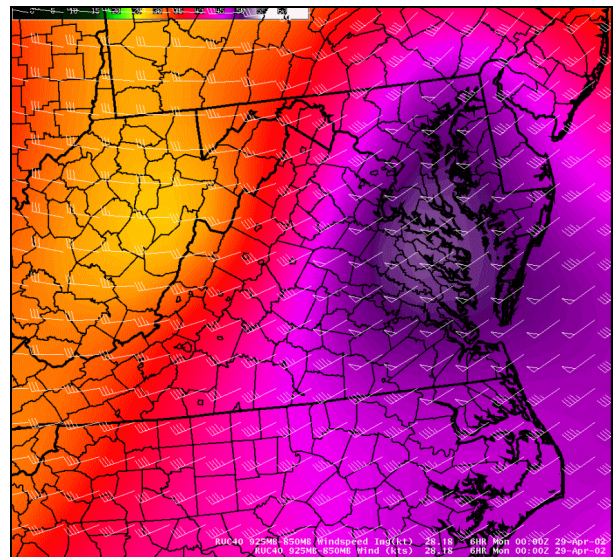


Figure 16. as in Fig. 15 except 6 hr RUC forecast valid at 0000 UTC 29 April 2002.

5. Supercell Interaction with the Mesoscale Environment

As the supercell tracked from the eastern West Virginia panhandle into northwest Virginia between 2000 and 2130 UTC, the storm encountered an environment with a low to moderate amount of instability and moderate shear. A short-lived F2 tornado developed in southern Shenandoah County at 2045 UTC (Manning and Zubrick 2004).

The storm continued on through northern Virginia between 2130 UTC and 2230 UTC, crossing the Potomac River into lower southern Maryland shortly before 2300 UTC. As the storm crossed Fauquier County at 2210 UTC, it redeveloped a hook echo (Figs. 17 and 18).

One possible explanation of this storm behavior is that the storm's updraft was passing across the shear axis of the developing low-level jet. The updraft may have been able to ingest, tilt and stretch enough horizontal vorticity to a vertical axis to reinitiate the low-level storm circulation. Funnel clouds were reported in Fauquier County, however the storm's downdraft cut off the low-level circulation by 2235 UTC.

As the storm progressed further east across the Potomac River, it entered the core of the developed low-level jet between 2300 UTC and 0000 UTC. With substantially increased shear and cooling midlevel temperatures now providing moderate instability, the storm once again developed a hook echo at 2251 UTC over the Potomac River as rotation increased (Figs. 19 and 20). Shortly after, a F2 tornado developed, which later strengthened to F4 in La Plata, MD (Watson 2004). The hook echo and BWER became better defined on KLWX WSR-88D radar imagery just west of La Plata, Maryland around 2300 UTC.

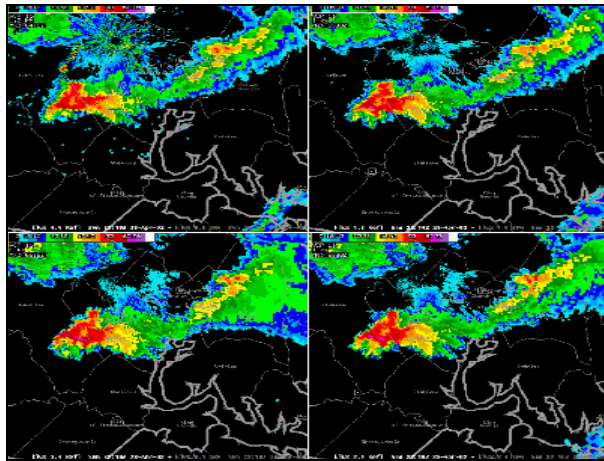


Figure 17. 0.5-3.4 degree reflectivity at 2210 UTC 28 April 2002 from the Sterling, Virginia (KLWX) WSR-88D.

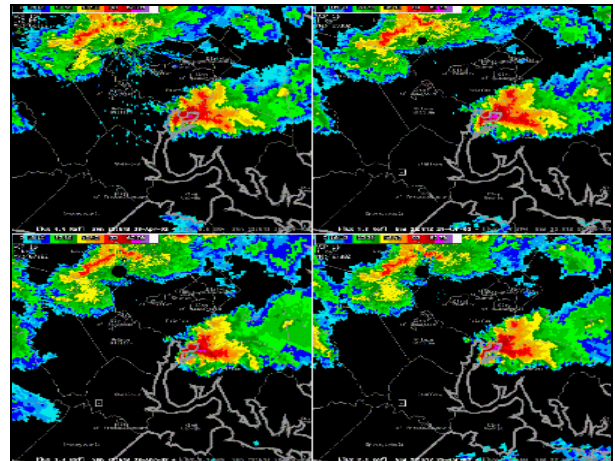


Figure 19. 0.5-3.4 degree reflectivity at 2251 UTC 28 April 2002 from the Sterling, Virginia (KLWX) WSR-88D.

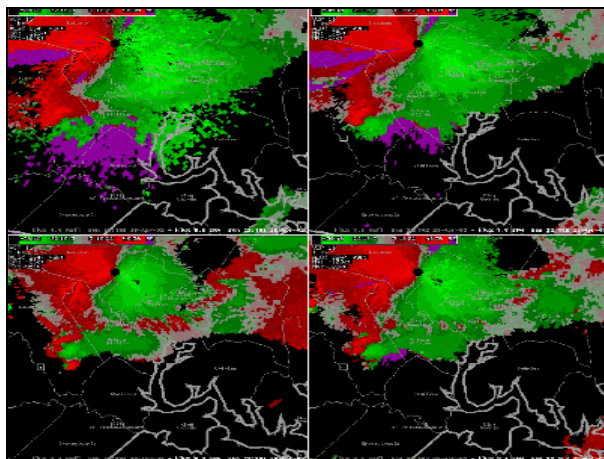


Figure 18. as in Fig. 17 except KLWX storm relative velocity (SRM).

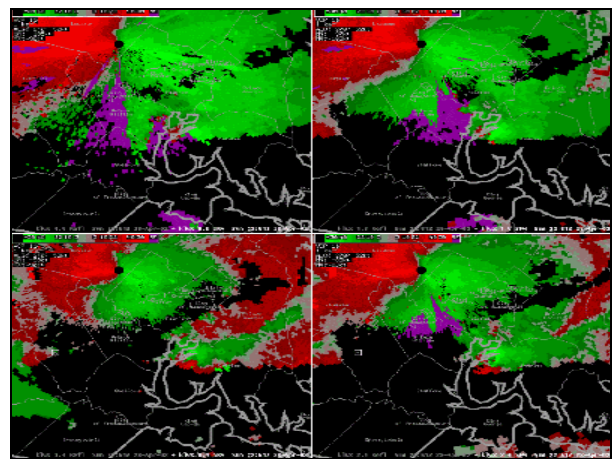


Figure 20. as in Fig. 19 except KLWX storm relative velocity (SRM).

6. Possible Role of the Potomac River Valley in Tornadogenesis

With the second tornado developing just east of the Potomac River, further analysis of the microscale Potomac River Valley environment is justified. Surface observations are available for the coastline of the Potomac River and Chesapeake Bay. However, with exception of the Thomas Point Lighthouse, located about a half mile offshore on the western portion of the Chesapeake Bay, no surface observational data is available over the water channels.

The formation of solenoidal circulation boundaries over the main water channels was unlikely on 28 April 2002. The water temperature observed at Thomas Point Lighthouse (TPLM2-14C at 2300 UTC 28 April 2002) was cool enough for the development of solenoidal boundaries when surface temperatures of 22C-25C over land are considered. However, temperatures along the coast were identical to temperatures further inland. Winds along the western shores also remained southwesterly (an easterly component would signify an ongoing solenoidal circulation associated with a river or bay breeze). Gusty winds observed across the region during the afternoon of the 28th suggested an unfavorable environment for developing solenoidal circulations.

The orientation of the Potomac River may have played a limited role in tornadogenesis, however. Experienced mariners often report that wind flow within the Potomac and Chesapeake main water channel is funneled by the orientation of the waterway. The orientation of the Potomac River west of Charles County, Maryland is nearly south to north. Considering inland winds reported at 2300 UTC 28 April 2002 were nearly uniform out of 230 degrees, surface winds as the supercell crossed the Potomac River several minutes before tornadogenesis were likely backed 50 degrees (with a likely wind out of 180 degrees over the main channel of the Potomac River Valley where the supercell crossed the river). As a result, the supercell may have ingested increased low-level helicities local to that section of the main water channel of the Potomac River several minutes prior to tornadogenesis.

7. Remarks and Conclusions

Directional and speed shear, along with available instability, supported supercells and

tornadogenesis across the Mid-Atlantic Region during the afternoon and evening hours of 28 April 2002. A supercell which crossed into northwest Virginia from eastern West Virginia produced a F2 tornado in Shenandoah County at 2045 UTC in an environment with shear and instability that were common across the region.

During the next several hours, several processes took place which significantly altered the thermodynamic and dynamic environment further east. Cooling midlevel temperatures were observed by RAOB and ACARS soundings during the late afternoon hours. The coolest midlevel temperatures were observed via the 2324 UTC BWI ACARS sounding, demonstrating the narrow corridor of cool air aloft most likely associated with ascent on the leading edge of the midlevel trough. With surface temperatures and dewpoints common across the track of the supercell, this provided a tongue of instability that was not observed further west earlier during the afternoon.

A low-level jet was observed to have simultaneously developed from a corridor between Richmond, Virginia and Philadelphia, Pennsylvania between 2100 UTC and 0000 UTC by regional profilers, ACARS, and RAOB soundings. This provided for increased low-level shear, as winds were observed to increase from about 25 to 35kts to 45 to 55kts between 925 and 850hPa on both regional profilers and ACARS. The BUFKIT interface displayed ETA model data from the 0000 UTC 28 April 2002 run which showed a similar trend in low-level winds and helicity values at Patuxent MD-KNHK. The 1800 UTC 28 April 2002 RUC 850-925hPa wind speed layer average forecast also displayed a similar low-level jet feature which appears consistent in magnitude and location, but may be an hour slow in forecasting the development of the low-level jet when compared to area profilers and ACARS data.

As the supercell tracked east after the first F2 tornado, it encountered the shear axis of the developing low-level jet across Fauquier County at about 2200 UTC. The storm developed a hook echo and increased low-level circulation seen on KLWX WSR-88D reflectivity and storm relative velocity data, as the updraft may have been able to ingest, tilt and stretch horizontal vorticity into a vertical axis. Funnel clouds were reported at this time, however the storm's downdraft cut off the low-level circulation shortly thereafter.

Possible interaction of the La Plata supercell and the Potomac River was addressed. Available temperature and wind data inland and along the coast of the Potomac River and Chesapeake Bay suggest that a Potomac River breeze did not form on the afternoon of 28 April 2002. Surface winds over the main channel of the Potomac River were likely backed 50 degrees where the supercell crossed the Potomac River into Charles County, however. This suggests that the storm was able to ingest a local increase in helicity as it moved into an environment with the greatest instability and deep layer shear, allowing this supercell to produce a rare long-track and devastating F4 tornado east of the Appalachians.

Acknowledgements

The authors wish to thank Bill Moninger of NOAA/Forecast Systems Laboratory for supplying archived ACARS data. FSL websites <http://acweb.fsl.noaa.gov/java/> and <http://www-frd.fsl.noaa.gov/mab/soundings/java/> (restricted) were used to capture ACARS and sounding data.

NOAA's Profiler Webpage was used to capture Wind Profiler data.
<http://www.profiler.noaa.gov/jsp/profiler.jsp?option=s=full>.

The BUFKIT interface was used to analyze and capture model data.
<http://www.erh.noaa.gov/buf/bufkit/bufkit.html>

Further and enlarged images from this paper and other information on the La Plata Tornado can be found on the NOAA/NWS/WFO/LWX web site:
http://www.erh.noaa.gov/lwx/Historic_Events/apr28-2002/laplata.htm

This paper benefited from conversations with Christopher Strong and David Manning of NOAA/NWS Sterling, Virginia.

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