P1.4 AN EARLY MORNING MID-ATLANTIC SEVERE WEATHER EPISODE: SHORT-LIVED TORNADOS IN A HIGH-SHEAR LOW-INSTABILITY ENVIRONMENT

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1. INTRODUCTION

Early on the morning of September 23, 2003, an extensive line of thunderstorms moved eastward across the mid-Atlantic region and then continued northeast into southern New England. These storms produced several weak (F0-F1) tornados over Virginia, eastern Pennsylvania and New Jersey, along with numerous reports of damaging winds and flooding from heavy rains (Fig 1). Fortunately, there were no known serious weather-related injuries from this event.

For the operational meteorologists at the National Weather Service in Mount Holly, New Jersey (PHI), this was a very challenging event. The purpose of this paper is to document this event, especially some aspects that were unusual or that made it particularly challenging. First, the evolution of the meteorological environment during the overnight hours leading up to the event is examined. Second, the tornado signatures as they appeared in the high-resolution velocity data from the Fort Dix, NJ (KDIX) WSR-88D radar is described in some detail. Third, some of the operational challenges presented by this event are considered.

2. THE PRE-STORM ENVIRONMENT

Analysis of the surface and upper air environment in which the storms developed is based on output from the Rapid Update Cycle (RUC; Benjamin, et.al., 1994) model and the Mesoscale Surface Assimilation System (MSAS; Miller and Barth, 2002), which were archived off the operational PHI Advanced Weather Interactive Processing System (AWIPS) and re-displayed on the PHI Weather Event Simulator (WES). In the upper troposphere (250 hPa), a 120-kt jet streak extended from the lower Great Lakes northward into Canada, placing the mid-Atlantic region in the right-rear quadrant and associated broad-scale upward motion (Fig 2a). The 500 hPa map showed a low over southern Ontario with a negatively tilted shortwave trough extending south-southeast through the upper Great Lakes into the Ohio Valley (Fig. 2b). At 850 hPa (Fig. 2c), a southerly jet extended from the mid-Atlantic region northward into Quebec, with an associated ridge axis of equivalent potential temperature (theta-e) along it.

At the surface, a deepening low-pressure center moved overnight from Lake Huron northward to James Bay (Fig 2d). From the low, a cold front stretched south across New York, Pennsylvania, and into the southern Atlantic states. The cold front progressed slowly eastward overnight, while a warm front moved north through New Jersey into southeast New York. With the warm frontal passage, surface temperatures remained steady overnight in the low 70s (˚F), but dew-point temperatures rose from the mid 60s to near 70 ˚F. South of the warm front, surface winds over New Jersey gusted from the south, off the Atlantic Ocean, at 15 to 20 kt. An axis of higher surface theta-e temperatures extended from the Delmarva Peninsula northward into the Delaware River Valley.

Upper-air soundings from Dulles International Airport (KIAD) and the Upton, NY, NWS Office (KOKX) indicated that winds aloft backed to the southwest overnight and increased in speed (not shown). At KOKX, downstream from the study area, the 0-3 km helicity increased from 86 $m^2 s^{-2}$ at 0000 UTC to 479 $m^2 s^{-2}$ at 1200 UTC. At KIAD, upstream of the study area, helicity was 446 $m^2 s^{-2}$ at 0000 UTC, but became negative by 1200 UTC as the surface winds veered to northwest behind the cold front. Most of the hodograph curvature was in the lowest 2 km, as the winds veered from southeast at the surface to south at 900 hPa to southwest at 800 hPa. Observed and Eta-model forecast soundings (not shown) indicated that CAPE increased overnight from near zero to 250-500 J kg^{-1}, and the surface-based Lifted Index decreased slightly to around –2 or –3. Soundings also indicated that the level of free convection (LFC) was quite low, between 950 and 900 mb.

In short, this severe outbreak developed in an environment with strong dynamic forcing and increasing mid- to upper-level wind shear. A stable

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air mass from the previous day became marginally unstable overnight. It seems likely that the relatively warm ocean water off the mid-Atlantic coast contributed significantly to the overnight air mass destabilization. Figure 3 shows satellite-derived sea surface temperatures about 48 hours before the event. Water temperatures in the low to mid 70s contrast with the cooler nocturnal land temperatures at that time. While the "marine layer" is often considered a stabilizing factor in spring and early summer when the ocean water is relatively cool, the opposite was likely true for this case when strong southerly (onshore) winds developed. Forecasters should bear in mind the relative land-sea effects as a function of the season.

3. TORNADOS AND MESO-SCALE CIRCULATIONS – RADAR SIGNATURES

This event produced four confirmed tornados in the PHI County Warning Area (CWA). All four tornados were rated F1 on the tornado damage scale. Table 1 shows tornado path lengths, widths and other information. All the tornados had relatively short paths and were short-lived, lasting only five to ten minutes (one or two radar volume scans). All were within about 40 nautical miles (nm) of the KDIX radar, so that the nominal height of the lowest beam angle (0.5 degrees) was about 3000 ft or less.

The tornados in the PHI area all appeared to be of the "non-descending" type (Trapp, et.al., 1999), i.e., the strongest rotation developed and persisted in the lowest 3000 ft. AGL. However, the WSR-88D operational meso-cyclone and TVS algorithms indicated that many of these circulations extended at times to at least 10,000 ft. The WSR-88D Tornado Vortex Signature (TVS) algorithm was triggered for all but the first tornado at 1120 UTC. The meso-cyclone algorithm was triggered with every volume scan from 1129 UTC through 1247 UTC, although often at multiple locations along the wind-shift line.

For each of the tornado circulations described below, the most striking radar signals were seen in the high-resolution (8-bit, 0.25 km range bin) velocity data. This 8-bit velocity data has proven to be a very significant improvement over the older 4-bit velocity, for detection of strong circulations and also strong "straight-line" winds. In the radar reflectivity data (not shown), there were numerous short-line bow echoes and some subtle notches in the leading edge of higher reflectivity (>= 40 dBZ), but nothing that would normally justify a tornado warning.

The first tornado occurred at about 1120 UTC in Narberth, near the southern tip of Montgomery County, PA. Fig. 4 shows velocity data from the KDIX radar around the time of the tornado. The storm relative velocity (SRM) from KDIX at 1118 UTC showed 38 knots of gate-to-gate rotational velocity at 0.5 degree elevation, nominally about 3100 ft above ground level (AGL) at Narberth (Fig. 4c). The previous and subsequent volume scans showed no significant gate-to-gate rotation, as seen in Fig. 4b and 4d. Also, the next higher elevation (1.5 degree, 7400 ft AGL at Narberth; not shown) at 1118 UTC indicated only 21 knots of gate-to-gate rotation. It would have been very difficult to issue a timely warning for this tornado.

The second tornado occurred around 1150 UTC near Sergeantsville in southern Hunterdon County, NJ. The 1147 UTC velocity data from KDIX showed 26 knots of gate-to-gate rotation at 0.5 degree, or about 2850 ft AGL (not shown). This rotation could be tracked backwards several volume scans into eastern PA, from where it moved northeast at about 45 kt. The rotation appeared to be just as strong at 1135 UTC over Buck County, PA, where only "straight-line" wind damage was reported. Rotation was generally strongest at the lowest (0.5 degree) elevation angle, but was occasionally stronger at 1.5 degrees, or about 7200 ft AGL (not shown).

The third tornado occurred around 1215 UTC at Florence in northern Burlington County, NJ. This tornado developed from the best radar-defined meso-scale circulation of the event. This parent circulation was clearly evident on radar for several volume scans as it traveled northeast at 35 to 40 kt, producing a swath of wind damage through several towns along the east side of the Delaware River, across from the city of Philadelphia. Maximum storm-relative rotational velocity with the parent circulation was around 43 knots (Fig. 5a), and the diameter was estimated at 2.5 to 3.0 km, or about four radar beam widths at a 20 to 25 nm range. The tornado itself was associated with a maximum gate-to-gate rotation of 23 knots on the 1211 UTC scan (Fig. 5b). Maximum rotational velocity was consistently found at the lowest elevation slice, at about 1500 ft AGL.

The fourth tornado occurred around 1220 UTC in Mercer County, NJ, starting on the east side of the city of Trenton. Possibly, some of the rotational energy from the Burlington County circulation was transferred northward along the shear axis into Mercer County. However, the velocity images indicate a second distinct spin-up

TABLE 1. Tornados in the PHI warning area on September 23, 2003. Tornado ID numbers are as shown in Fig 1.

ID Number	Time (UTC)	F-Scale	Path Length (miles)	Path Width (yds)	Distance from KDIX (nm)	Nominal Beam Ht. (ft)	Maximum gate-to-gate Rotation (kts)	TVS Algorithm Triggered?
T1	1120	F1	0.8	100	41	3100	38	No
T2	1150	F1	2.6	50	38	2850	26	Yes
T3	1215	F1	1.8	120	21	1500	23	Yes
T4	1220	F1	5.0	100	24	1715	37	Yes

near Trenton (Fig. 5c). The strongest gate-to-gate rotation, about 37 knots, was observed on the 1221 UTC radar scan (Fig. 5d) at 0.5 degree elevation, or about 1715 ft AGL. The rotation was somewhat weaker at the 1.5 degree elevation, at about 4400 ft AGL (not shown). This circulation subsequently evolved into a well-defined bow echo that moved northeast, producing wind damage in Middlesex County, NJ. Note also from Fig. 5 that the radar was switched from VCP 21 (general precipitation mode) to VCP 11 (severe weather mode) between the 1205 UTC and 1211 UTC volume scans.

4. OPERATIONAL CHALLENGES

Several issues relating to situational awareness can be identified for this event. These issues combined with other meteorological factors to make the event particularly challenging to the PHI staff.

The first challenge was the seasonal timing (late September) of the event. The peak months for severe weather in the PHI area are June, July and August, while the frequency of severe weather normally drops off sharply in September. Tropical systems and their associated heavy rain are a more typical problem in early fall. In fact, during the previous week the PHI area had experienced a significant flash flood on September 15th and the effects of Hurricane Isabel on the 18th and 19th.

The second challenge was the time of day. In the PHI area, the event occurred from about 1000 UTC (600 am EDT) to about 1300 UTC (900 am EDT). Climatologically, this corresponds almost exactly to the local diurnal minimum for severe wind events. The event also overlapped the end of the midnight shift and the beginning of the day shift. Thus the weary midnight forecaster had to deal with the onset of the event and then pass appropriate information along to the newly arrived day forecaster.

Third, the severe weather aspect of the event was not well anticipated. Although tornados had occurred in southern Virginia earlier that morning, there was no immediate upstream history of severe weather with the line of convection as it moved east overnight across Pennsylvania and Maryland. Also, convective outlooks issued by the NOAA/NWS Storm Prediction Center at 0053 UTC (0516 UTC) indicated no significant risk of severe weather before (after) 1200 UTC. Since the local office also did not anticipate severe weather overnight, there was no weather spotter activation and subsequently no real-time reports of wind damage, until after 1200 UTC. The relative lack of cloud-to-ground lightning may have also contributed to a lack of public and spotter awareness prior to the arrival of high winds.

Fourth, flooding was a well anticipated but a competing problem that morning. A flood watch and several countywide flood warnings were issued by PHI before the first wind damage at 1000 UTC, and “major flooding” was reported at 1040 UTC in Monroe County, PA. Rainfall estimates from the KDIX radar indicated up to 3 inches of rain had fallen over the parts of the PHI forecast area, and light to moderate rain continued to fall through mid-morning. However, as the severe weather threat developed after 1000 UTC, the staff was forced to shift a large part of its attention from flooding to tornados and wind damage at a difficult time.

5. DISCUSSION AND CONCLUSIONS

Several tornados unexpectedly struck parts of the mid-Atlantic region on September 23, 2003. The environment in which they developed was characterized by strong winds aloft, strong boundary-layer helicity, and marginal instability. The associated thunderstorms were low-topped and fast moving, with only minimal cloud-to-ground lightning. As the line of storms moved eastward from central Pennsylvania and Maryland, the storm character changed from heavy-rain producers to high-wind and tornado producers as well. It is theorized that as the line of storms moved east, the storm environment changed just enough, probably due to the slightly more unstable air nearer the ocean, that stronger low-level updrafts were able to tilt the existing strong helicity into the vertical and produce the very rapid spin-up of tornados. In this kind of environment with strong dynamics and marginal instability there is often a "fine line" between getting no severe events or having significant wind damage, even tornados.

No tornado warning was issued for tornado T1 or T2; tornado warnings were in effect for T3 and T4, but with a lead times of less than five and ten minutes, respectively. The absence of warnings and/or longer lead times is likely the result of several meteorological factors, including the rapid low-level formation, movement, and dissipation of the tornado cyclones, as well as a number of situational awareness issues, including climatology, anticipation, and flooding problems which competed for the forecaster's attention. In the "heat of battle", the radar was not switched to severe weather mode with more rapid volume scan updates (five minutes vs. six minutes) until relatively late in the event. If the recently implemented VCP 12, with a 4-minute update cycle had been available, the chance for timely warnings would perhaps have been improved.

6. REFERENCES

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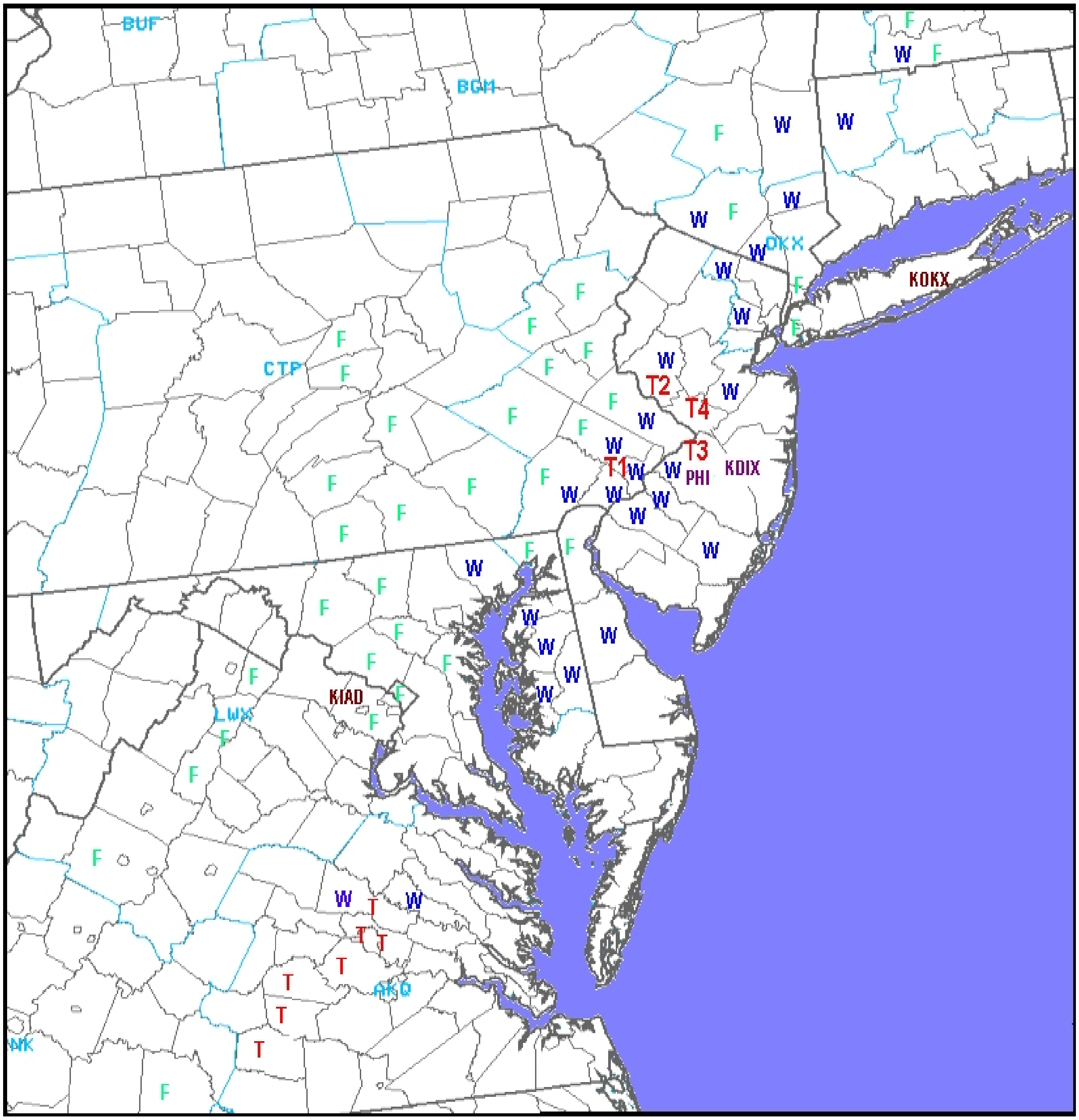

Figure 1. Locations of severe weather and flood events on September 23, 2003. Tornados are indicated by a red "T", wind damage events by a blue "W", and flooding by a green "F". Tornados discussed in the text are labeled T1 through T4. The NWS Mount Holly, NJ Forecast Office (PHI), the WSR-88D radar at Fort Dix, NJ (KDIX), and the upper-air sounding sites at NWS Upton, NY (KOKX) and Sterling, VA (KIAD) are indicated in maroon. Surrounding County Warning Areas (CWA) are outlined in light blue and labeled by three-letter office ID. All locations are approximate.

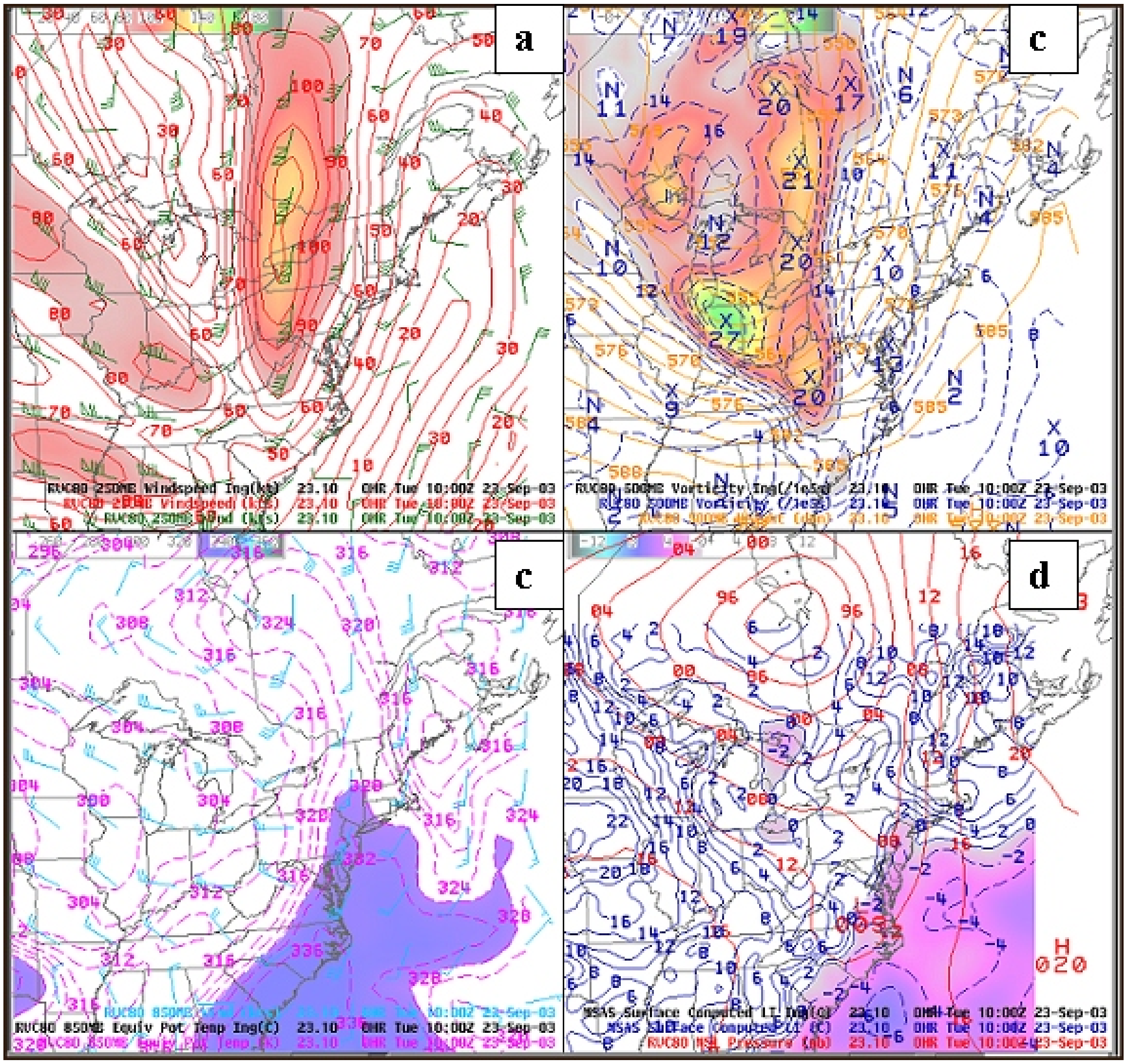

Figure 2. RUC-II and MSAS analyses valid at 1000 UTC on September 23, 2003. (a) 250 hPa wind barbs, and isotachs shaded for greater than 80 kt. (b) 500 hPa height (dam), and absolute vorticity shaded for greater than 12 units. (c) 850 hPa wind barbs, and theta-e shaded for greater than 320 ˚ K. (d) Mean sea-level pressure (hPa; red), and surface-based lifted index shaded for negative values.

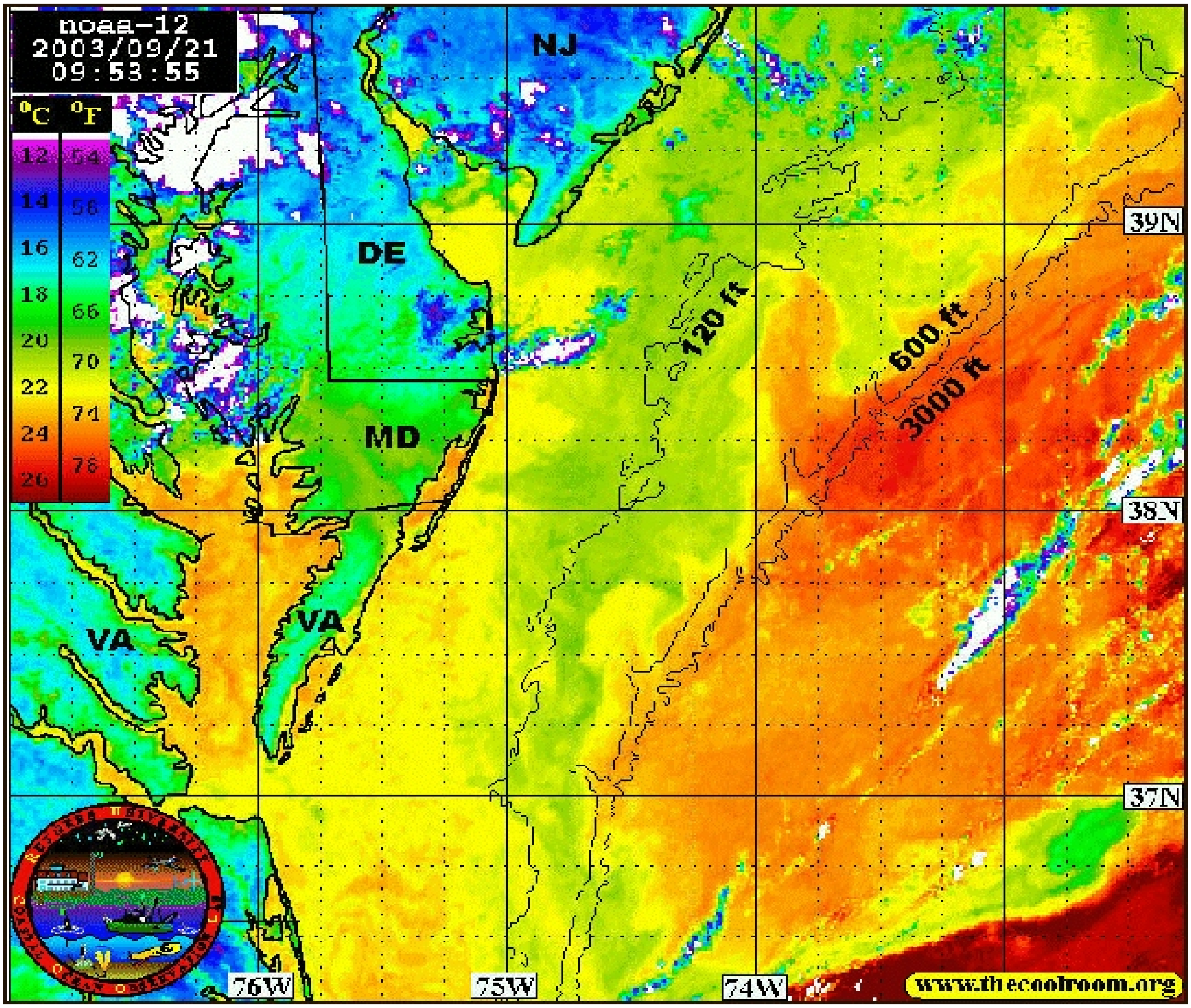

Figure 3. Sea-surface temperature at around 1000 UTC on 21 September 2003. The image is from the NOAA-12 satellite Advanced Very High Resolution Radiometer. This imagery is available on the web site of the Rutgers University Institute of Marine and Coastal Sciences, at **http://marine.rutgers.edu**.

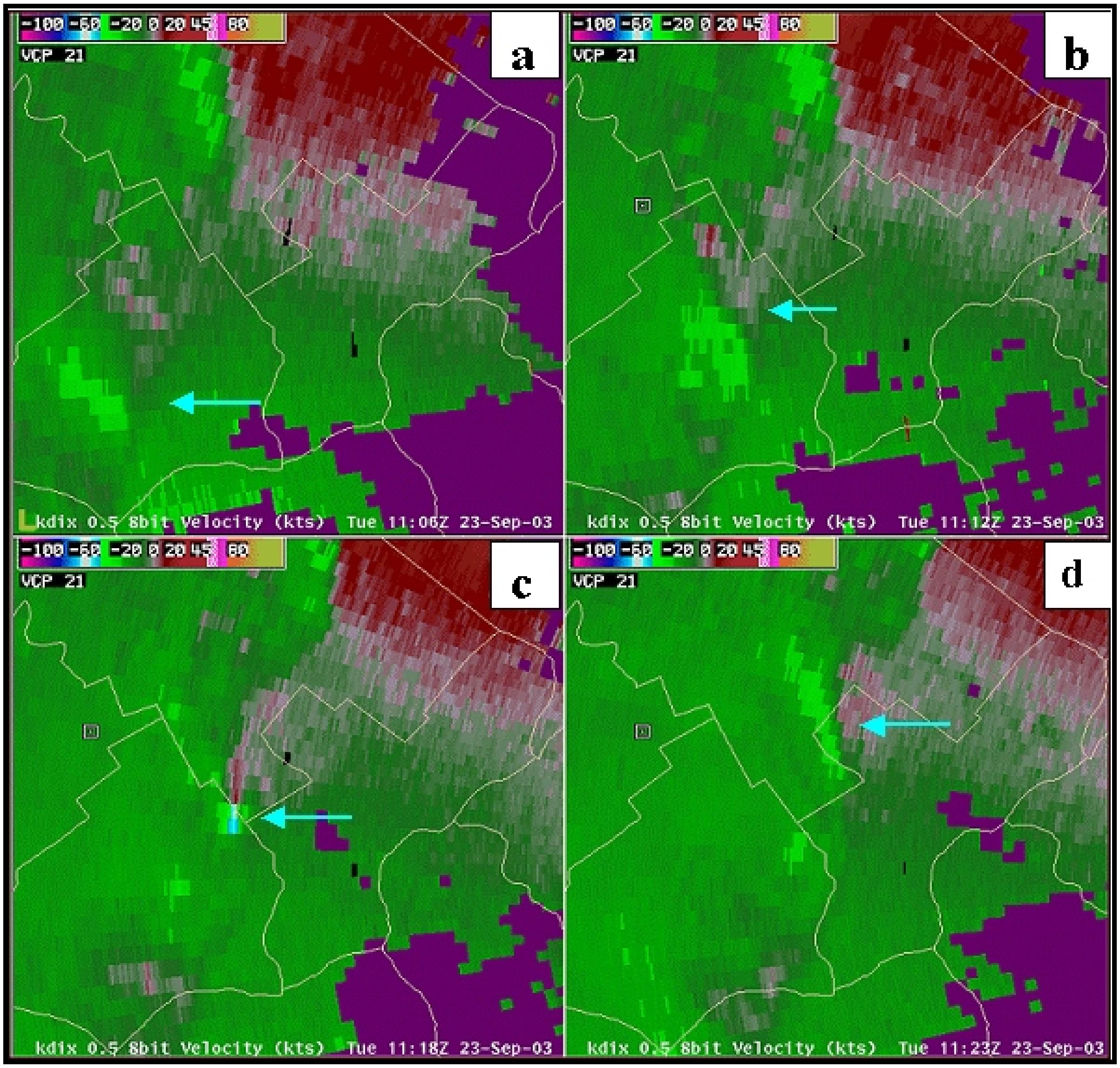

Figure 4. 8-bit, 0.5-degree elevation velocity from the KDIX radar showing the Narberth, PA tornado. (a) 1106 UTC, (b) 1112 UTC, (c) 1118 UTC, and (d) 1123 UTC. Blue arrow shows the location of the tornado-producing circulation, with the tornado occurring in panel (c).

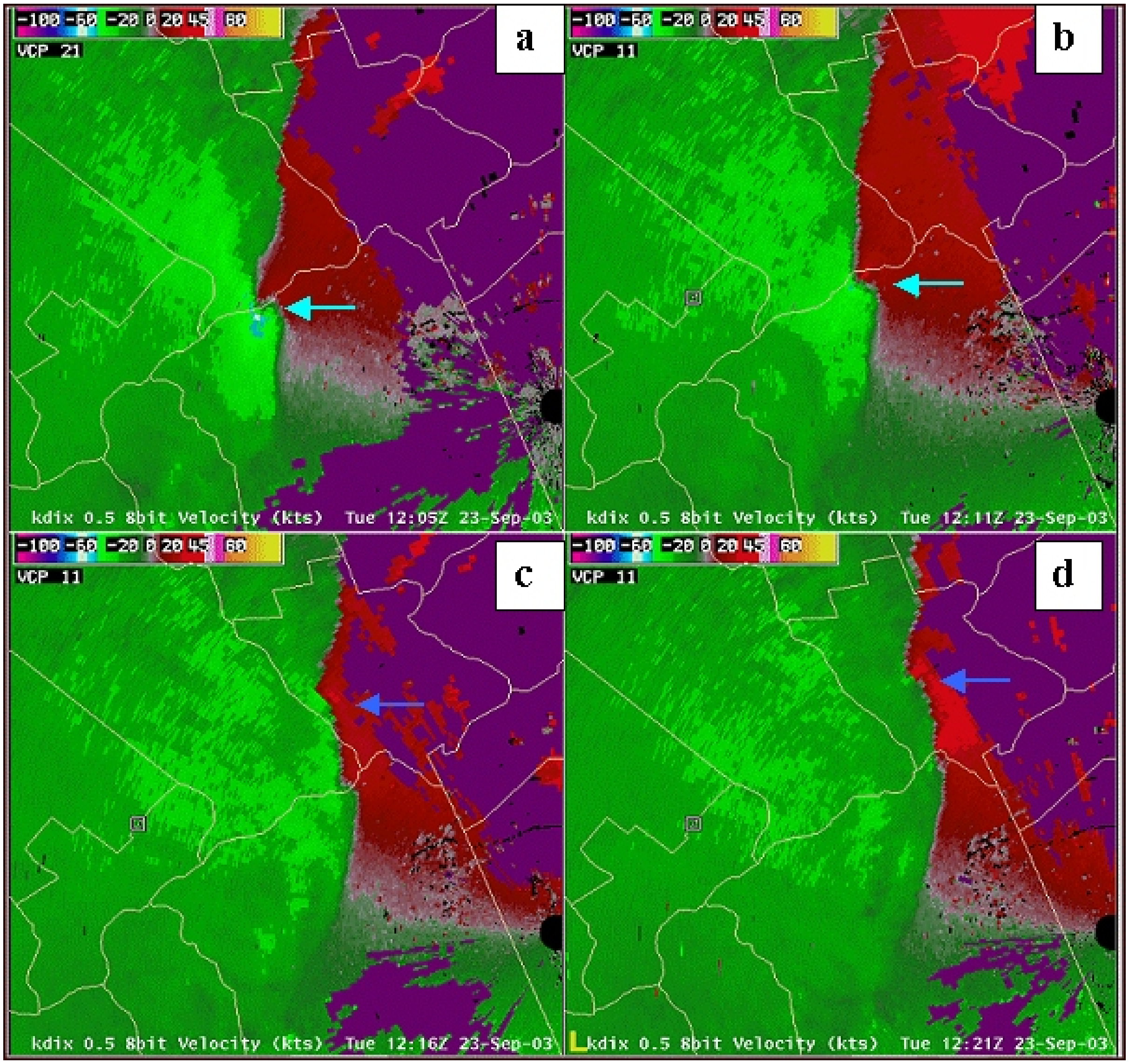

Figure 5. 8-bit, 0.5-degree elevation velocity from the KDIX radar showing the Florence, NJ and Trenton, NJ tornados. (a) 1205 UTC, (b) 1211 UTC, (c) 1216 UTC, and (d) 1221 UTC. Light blue arrows in (a) and (b) point to the Florence tornado circulation. Darker blue arrows in (c) and (d) point to the Trenton tornado circulation.