P1.8 THE FLASH FLOOD OF 12 JULY 2004 IN BURLINGTON COUNTY, NEW JERSEY: A CASE STUDY

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1. INTRODUCTION

On 12 July 2004, very heavy rainfall occurred over parts of eastern Pennsylvania, New Jersey, and the northern Delmarva Peninsula (Delaware and eastern Maryland). Some thunderstorms also produced severe weather, including two weak tornadoes and other reports of wind damage. However, the most serious weather hazard on this day was flash flooding.

Rainfall estimates from the KDIX (Fort Dix, New Jersey) WSR-88D radar (Fig.1) show several locations that received heavy precipitation. While most the radar coverage area received at least one inch of rain, excessive rainfall occurred from southeastern Berks County to northwestern Chester County in Pennsylvania, and also across southern New Castle County and northern Kent County in Delaware. A third area of excessive rainfall was found from Philadelphia County in Pennsylvania to western Ocean County in New Jersey, including much of Burlington County. The majority of the excessive rainfall, particularly over New Jersey, occurred in just a 4-hour period during the late afternoon and early evening hours, approximately from 2200 UTC (600 pm EDT) to 0200 UTC on 13 July (1000 pm EDT on 12 July.)

Burlington County will be the primary focus for this paper, because it contained the greatest rainfall report (13.2 inches) and the most severe flooding, and also because the storms over that area exhibited several characteristics that distinguished them from other thunderstorm activity that day. The following sections of this paper will describe briefly the societal impact of the floods and the National Weather Service response to the event, and then discuss in more detail the hydro-meteorological setting and the distinctive characteristics of the Burlington County flood event.

2. SOCIETAL IMPACT

Based on precipitation frequency estimates from NOAA's National Weather Service Office of Hydrologic Development (NOAA 2004), this event represented a one-in-one-thousand year flood. Fig. 2 shows a subjective analysis of the storm-total rainfall over southern New Jersey, based primarily on rain gage reports from National Weather Service volunteer spotters. The excessive rainfall caused record-breaking flash flooding along nearly every stream in the Rancocas Creek Basin, leading to the failure or damage of 44 dams in Burlington County and subsequent national media attention. Fig. 3 shows a map of the areas affected by the flooding, including the three main branches of the Rancocas Creek. The governor of New Jersey declared a state of emergency on 12 July for the hardest hit communities in Burlington County. On 16 July President Bush declared Burlington County a federal disaster area.

The combination of the dam failures and stream flooding caused the destruction of seven homes in Lumberton and Southampton Townships, with major flood damage to around 200 homes, flood damage to about 1000 homes in total, countless water rescues from vehicles and homes, the closing of 25 major roads including the New Jersey Turnpike, New Jersey State Routes 70 and 73, the contamination of drinking water and failure of sewage systems, and serious damage or destruction of fourteen bridges. Some roads remained closed for weeks following the flooding, as portions of their infrastructures needed to be completely rebuilt. In addition to the structural damage, crops in Tabernacle Township, especially the cranberries and peaches, suffered damage. Total property damage from the flooding in Burlington County was estimated at 50 million dollars.

3. OPERATIONAL PRODUCTS

The National Weather Service Forecast Office (NWSFO) in Mount Holly, New Jersey issued numerous products during this flood event. A special weather statement (SPS) was issued on 11 July highlighting the upcoming potential for heavy rainfall. A flood watch (FFA) was then issued during the early morning hours on 12 July. For areas that were not included in the flood watch, another SPS was issued highlighting the continued potential for more localized very heavy rainfall. Flash flood warnings (FFW) and flood warnings (FLW) were issued during the morning of 12 July for parts of eastern Pennsylvania as convection quickly developed. Throughout the

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day, numerous FFW's, FLW's, and flood statements (FLS) were issued. In addition to these products, several severe thunderstorm warnings (SVR) were issued along with a couple of tornado warnings (TOR). These particular warnings were confined across Maryland and Delaware as these areas were near or south of a stationary frontal boundary. Numerous follow-up FLS's were issued during and after the event. The final flood statement for the Rancocas Creek was issued around 600 pm EDT on 16 July, when the North Branch of the Rancocas at Pemberton (see Fig. 3) finally fell below flood stage.

4. HYDRO-METEOROLOGICAL ENVIRONMENT

4.1 Antecedent hydrological conditions

Conditions over southern New Jersey, including Burlington County, are not generally favorable for flash flooding. The topography is flat, rising to less than 200 feet above sea level, and the soil is sandy and rather porous. Streams in the area, including Rancocas Creek, respond slowly to heavy rain, usually over a period of days. Nevertheless, flash flooding does occur given sufficiently heavy rain over a short time. For example, overnight on 20-21 August 1997, parts of Cumberland, Atlantic and Ocean Counties in New Jersey received up to 13 inches of rain in a few hours, resulting in extensive flash flooding.

June 2004 was somewhat drier than normal, with a rainfall deficit estimated around one inch. Rainfall for the first 11 days of July was near the normal of about 1.5 inches. Flash flood guidance for Burlington County, issued by the mid-Atlantic River Forecast Center (MARFC) on the morning of 12 July, was 3.25 (5.5) inches for a one-hour (three-hour) period. However, rain fell over the area during much of the day prior to the flood-producing storms, and the Automatic Surface Observing Stations (ASOS) at the South Jersey Regional Airport (VAY) measured 1.72 inches of rain between 1200 UTC and 2100 UTC.

4.2 Synoptic-scale setting

The large-scale weather pattern on the morning of 12 July 2004 featured a broad upper-level high-pressure ridge over the western and central U.S., resulting in west-northwesterly flow aloft east of the ridge over the mid-Atlantic region. A mid-level shortwave trough over the eastern Great Lakes that morning moved southeast towards the mid-Atlantic region in the afternoon. At the surface, a quasi-stationary front extended from the Great Lakes southeastward across Pennsylvania to the Delmarva. A portion of this front is shown in Fig. 4. North of the front, high pressure over New England maintained a relatively cool east to southeast flow off the Atlantic Ocean, while south of the front, a south to southwest flow re-enforced a warm and humid air mass which became quite unstable with afternoon heating.

4.3 Mesoscale setting

The focusing mechanism for the most intense and persistent convection during the day was the frontal boundary across Pennsylvania, northeast Maryland, and northern Delmarva (Fig. 4.) As noted above, the air mass south of the front became very moist and unstable, with surface dew points in the mid 70s, and surface-based CAPE's of 2000 to 2500 Jkg^{-1}. Conditions north of the front over eastern Pennsylvania and northern New Jersey were quite different, as cloud cover and steady rain kept both temperatures and dew points in the mid 60s (see Fig. 4). Hourly analyses of surface equivalent potential temperature showed the strength of this "cool pool" actually increasing during the day. The contrast from north to south across the front was therefore much stronger by late afternoon than it had been that morning. The theta-e analysis in Fig. 5 depicts both the surface frontal zone and the "cool pool" to the north.

4.4 Factors supporting heavy rainfall

Both observed and model forecast soundings on 12 July indicated a deeply saturated tropical air mass over the mid-Atlantic region. At 0000 UTC on 13 July, the observed upper air sounding from Wallops Island, VA showed precipitable water (PW) of 56.4 mm (2.22 inches) or 175 percent of the July normal, while the sounding from Sterling, VA (IAD) showed PW of 62.5 mm (2.46 inches) or 195 percent of normal. Soundings from the 40-km RUC model analysis around that time over southern New Jersey (see Fig. 6) also indicated PW over 50 mm (2 inches).

Examination of moisture transport vectors (wind vectors multiplied by mixing ratio) between 12/1800 and 13/0000 UTC in each of the four lowest 50-mb layers of the atmosphere showed steadily increasing maxima focused over or near southern New Jersey at all levels. Transport winds were from the southeast just above the surface, veering to southwest at 800-850 mb. Fig. 5 shows winds and moisture for the lowest 100-mb layer over the mid-Atlantic area at 2200 UTC. Low-level frontogenesis (not shown) was also maximized over this area. Winds were relatively light, less than 15 m/s (30 kt) though the lower half of the troposphere, and the 0 to 6 km bulk shear was only about 15 m/s (30 kt). On the other hand, instability, as measured by surface-based CAPE from LAPS and RUC-40 soundings, was a rather modest 500 Jkg^{-2} or less.

5. CHARACTERISTICS OF THE BURLINGTON COUNTY STORMS

Compared with the severe-weather and flash-flood-producing thunderstorms earlier that day over northern Delmarva, the storms over Burlington County occurred in a relatively stable environment. Even so, they produced the heaviest total rainfall in the region that day, as indicated by radar estimates (10+ inches) and surface measurements (13 inches). The storms that produced the heaviest rainfall produced no severe weather.

Why did the Burlington County storms produce the heaviest rain of the day? First, the surface data shown in Fig. 4 supports the roughly east-west surface boundary extending across Burlington County and adjacent parts of southern New Jersey. This boundary (not to be confused with the main quasi-stationary front in Delmarva) separated relatively cool east to east-northeast winds over central New Jersey from somewhat milder, moister and stronger southeast winds to the south. This boundary is believed to be the southern edge of the "cool pool" which developed and strengthened during the day over eastern Pennsylvania and northern New Jersey. It likely acted as a focusing mechanism for the storms that evening and "guided" them along similar tracks. Southeast of this boundary, southeast winds were gusting at 20 to 30 kts along the New Jersey coast, as shown in Fig. 4. Moreover, VAD profile winds from the KDIX radar (not shown) indicated strengthening southeast flow in the lowest few thousand feet above the surface, from around 25 kt at 1800 UTC to around 35 kt at 2200 UTC. This increase is consistent with the above-mentioned increase in low-level moisture transport as analyzed by the RUC model.

Second, the Burlington County storms were likely very efficient rain producers. It is believed that rain production in these storms was dominated by warm-cloud collision-coalescence process. Several factors support this conclusion. One factor is the presence of a deep warm cloud layer. The LAPS and RUC soundings (e.g., Fig 6) over southern New Jersey show a lifting condensation level around 200 m, and surface reports indicate cloud bases around 500 ft. More importantly, the RUC sounding in Fig. 6 shows the freezing level around 4400 m (14,000 ft); thus the warm cloud depth was likely greater than 4 km. Of course, the high freezing level would be characteristic of the larger-scale environment of the mid-Atlantic region that day.

A more distinctive factor for the Burlington County storms was the relative lack of lightning over the area. Over 15,000 cloud-to-ground lightning flashes occurred in the northern mid-Atlantic region during a six-hour period from 2000 UTC (400 pm EDT) to 0200 UTC (1000 pm EDT), but the vast majority of them are along the main frontal zone south of New Jersey, and only a handful in Burlington County. The lightning pattern is shown is Figure 7, which should be compared with the rainfall pattern in Figure 1. This scarcity of lightning is typical of storms with radar echoes predominantly below the freezing level, which contain mostly liquid water. Radar data from KDIX and Dover, DE (KDOX) showed echo tops generally below 30,000 ft, while earlier that afternoon the prolific lightning producers further south had echo tops above 50,000 ft. Echoes greater that 50 dBZ extended up to around 20,000 ft over Burlington county, compared to around 40,000 ft earlier in the day over Delmarva.

Yet another factor is the history of the low level air feeding the storms. Recall that the main quasi-stationary front was separating southerly and southwesterly winds over Delmarva from southeasterly wind to the north over southern New Jersey (Figs 4 and 5). The upstream trajectories north of the front thus extended well out over the Atlantic Ocean, while trajectories to the south extended south or southwest over the mid-Atlantic States. (This was a nearly steady-state condition during the day on 12 July, so the streamlines are believed to approximate trajectories.) It has been found (Wallace and Hobbs; 1977) that oceanic air masses are characterized by a wider distribution of condensation nuclei sizes, which produced a broader spectrum of drop sizes that are more conducive to warm-rain collision processes. Thus warm rain processes would be favored for the Burlington County storms more than for the Delmarva storms.

A final consideration is that the strongest storms over Burlington County, like the earlier Delmarva storms, appeared to be slow-moving supercells, with organized rotating updrafts. Velocity data from both KDIX and KDOX radars (not shown) depicts a persistent mid-level rotation in the storms, and they were clearly moving to the right of the mean flow. The radar-observed "right-mover" storm motion was from 270 to 290 degrees at 8 to 10 kts, which is consistent with but slightly slower than the right-moving supercell motion determined from the RUC and LAPS analyses, using the Bunkers technique (Bunkers, et.al., 2000). Supercell formation was supported by 0-3 km helicity values in excess of 200 m^2s^{-2} (300 m^2s^{-2}) as determined from the LAPS (RUC) analyses at 2200 UTC. (See Fig. 6 for the RUC sounding.)

6. CONCLUDING DISCUSSION

Thunderstorms in the mid-Atlantic region on 12 July 2004 produced both severe weather and record or near-record rainfall. A favorable synoptic-scale and mesoscale environment led to flash floods in several locations in Pennsylvania, New Jersey, and Delaware. However, with rainfall amounts measured up to 13 inches, the flash flooding in Burlington County in southern New Jersey was particularly severe, despite being an area not prone to flash floods.

The main focus of this paper was to show an example of different modes of convection occurring rather close to one another in space and time. Specifically, the afternoon thunderstorms over Delmarva were quite deep (50 kft) and produced both heavy rain and severe weather (tornadoes and wind damage), while the evening storms over New Jersey were relatively shallow (30 kft) and produced extremely heavy rain but no severe weather. The New Jersey storms were likely dominated by warm-cloud collision-coalescence processes, as evidenced by (1) low echo-centroids relative to the freezing level, (2) very limited cloud-to-ground lightning, and (3) an oceanic origin of the low-level inflow air into the storms.

From an operational forecast and warning standpoint, this event was handled fairly well overall. A flood watch for the area was issued around 400 am EDT that morning, and a multi-county flash flood warning was issued at 545 pm EDT, before the heaviest rain began. Although the KDIX radar rainfall estimates showed six to eight inches over much of central Burlington County (with a small ten inch maximum), it is very likely that these estimates are too low, given the report of 13 inches of rain in Tabernacle, New Jersey, and because the radar precipitation algorithm was using the standard Z-R relation ($Z = 300R^{1.4}$), which is not designed for warm-cloud rain processes. It would probably have been appropriate at some point in the late afternoon or early evening to change over to the “tropical” Z-R relation ($Z = 250R^{1.2}$), which would have yielded higher rainfall estimates and a stronger indication of the extreme nature of this event. It is, however, a significant challenge for operational meteorologists to recognize the changing character of convection in real time and adjust observing systems accordingly.

7. REFERENCES

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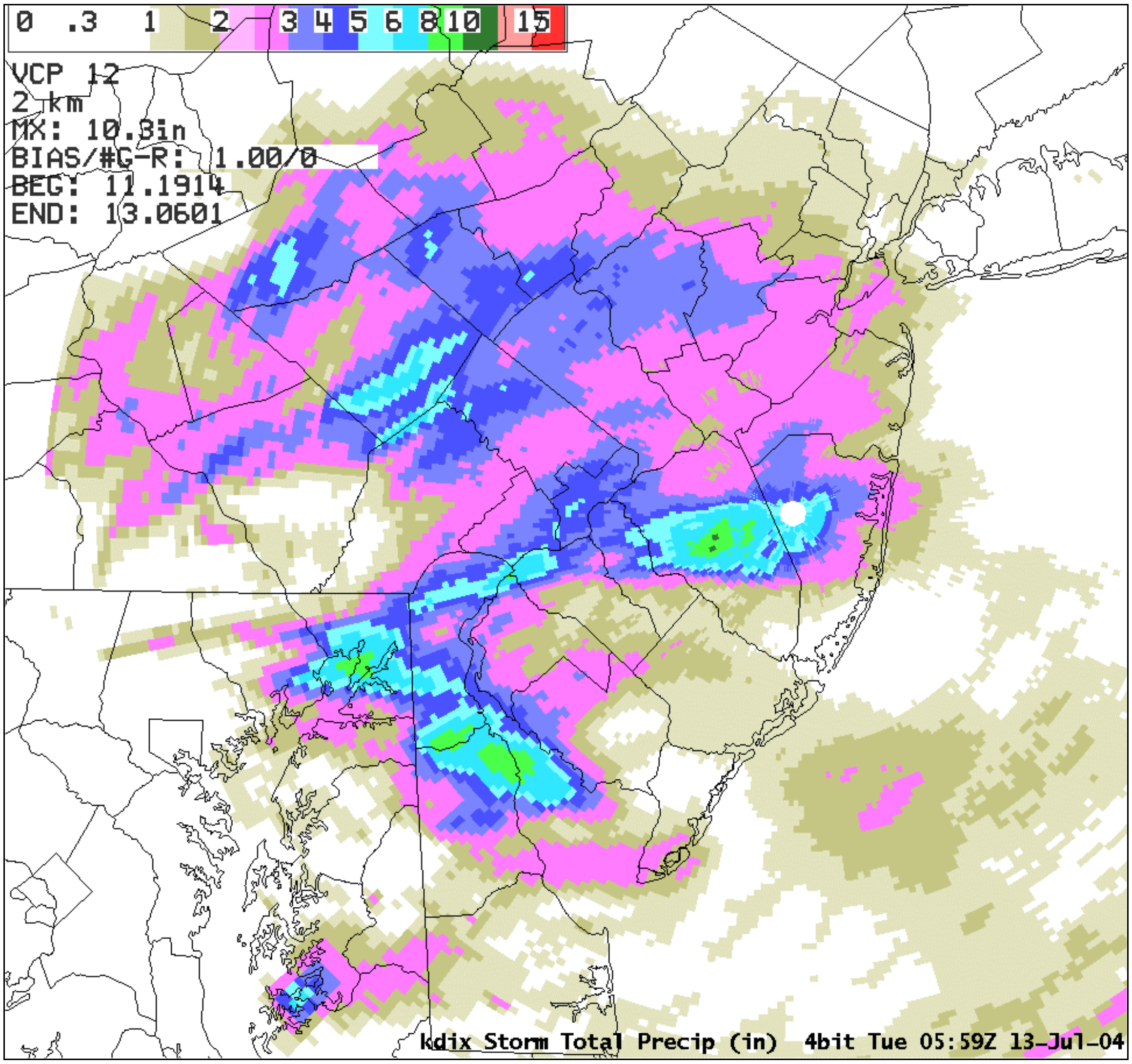

FIG 1. KDIX radar estimates of storm-total rainfall on 12 July, 2004, covering New Jersey, Delaware, and surrounding areas. A maximum of 10.3 inches (two dark green spots) is indicated over central Burlington County, NJ.

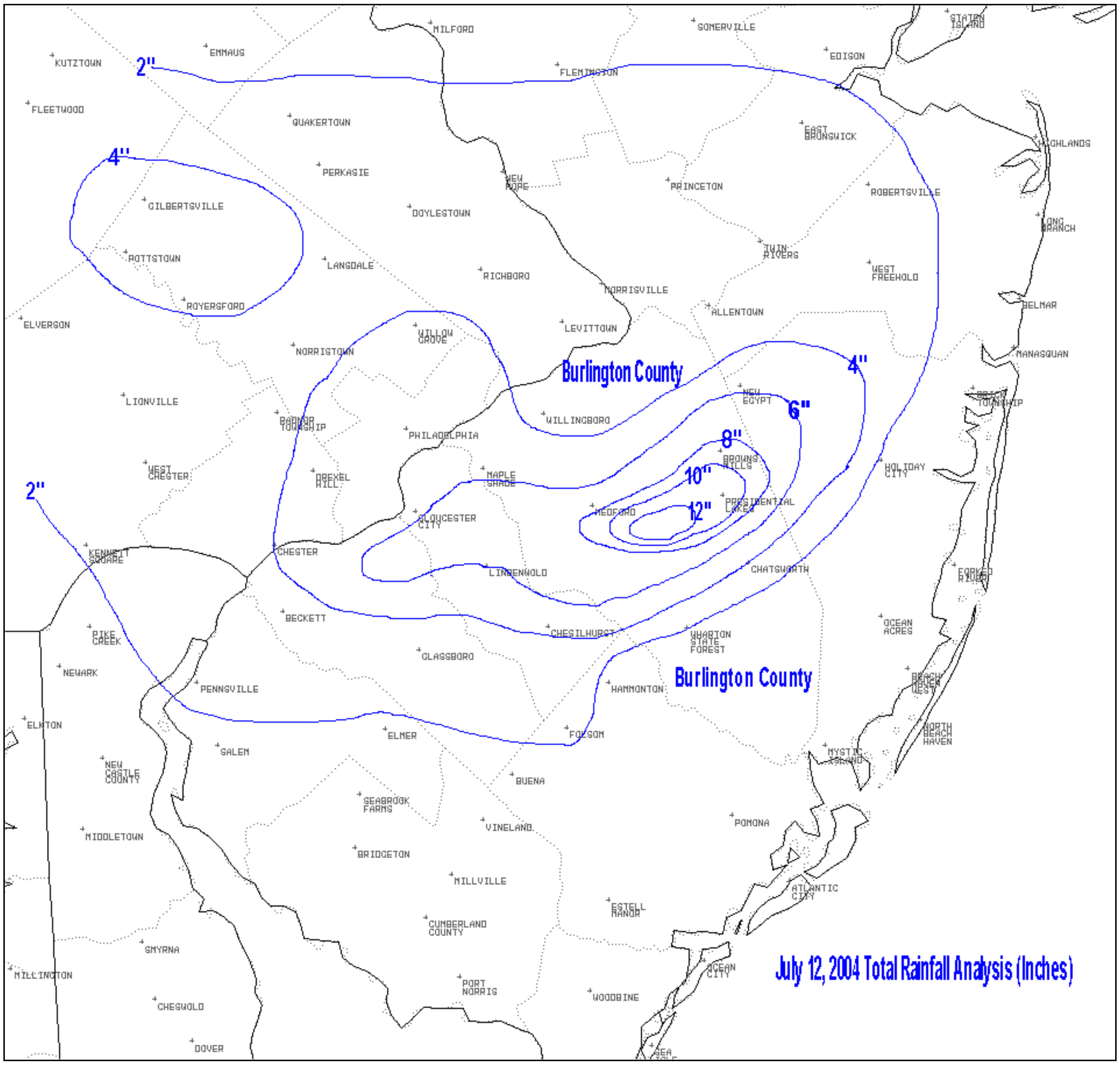

FIG 2. Analysis of storm-total rainfall on 12 July 2004, based on rain gage reports.

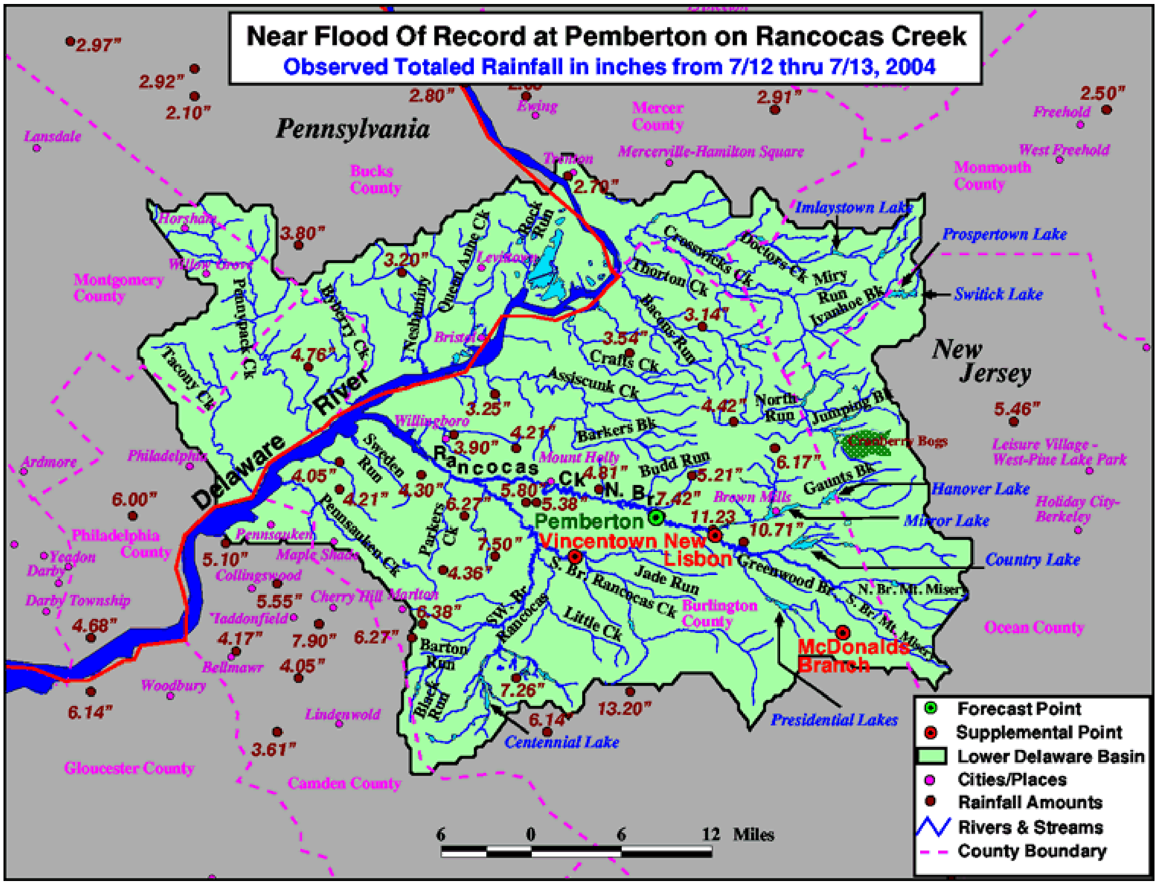

FIG 3. The lower Delaware River Basin and its tributaries, including the North, South and Southwest branches of the Rancocas Creek. Storm total rainfall amounts for 12 July 2004 are plotted in brown. (Map provided by MARFC).

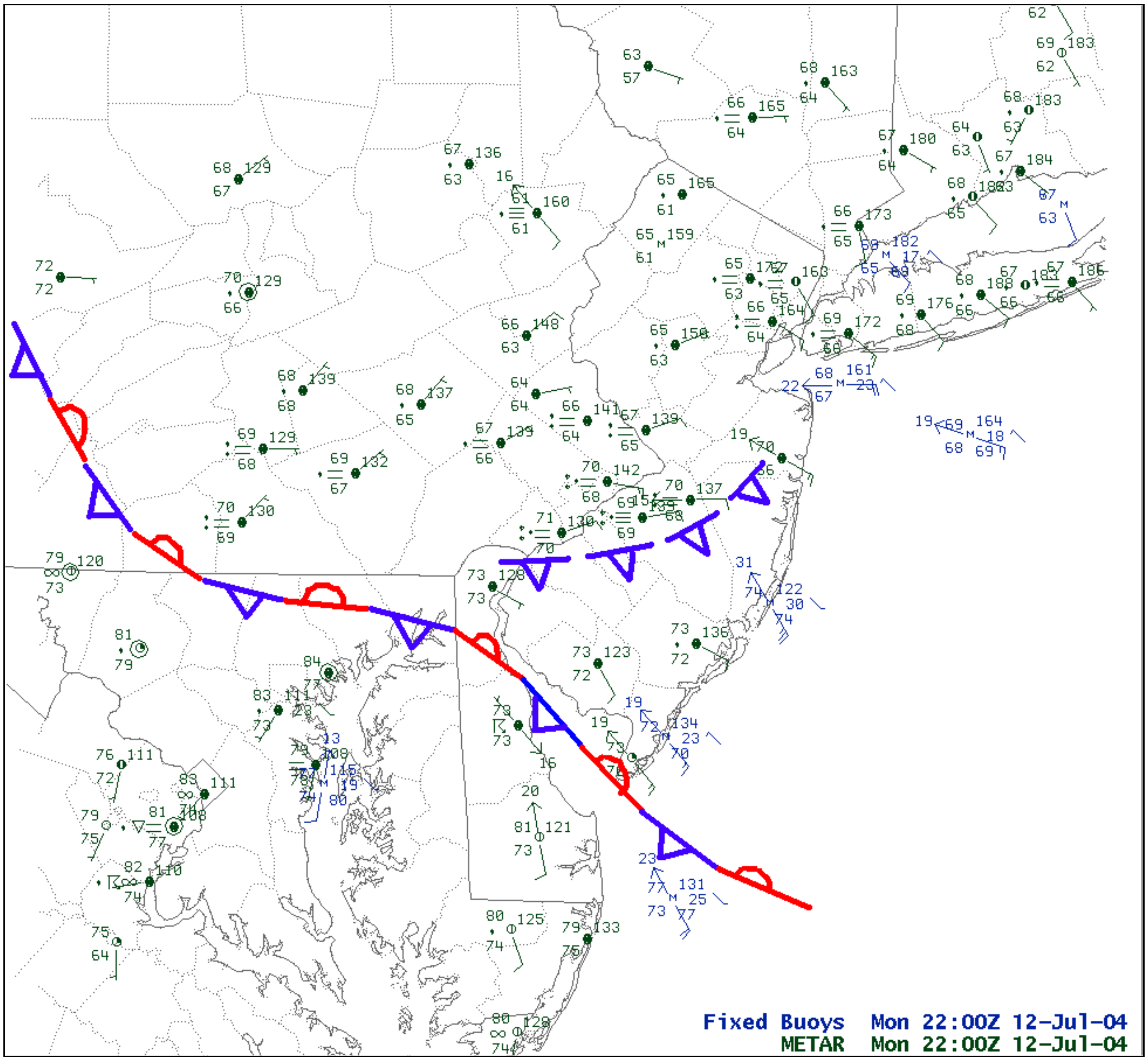

FIG 4. Surface observations and analyzed frontal boundaries over the study area at 2200 UTC on 12 July 2004.

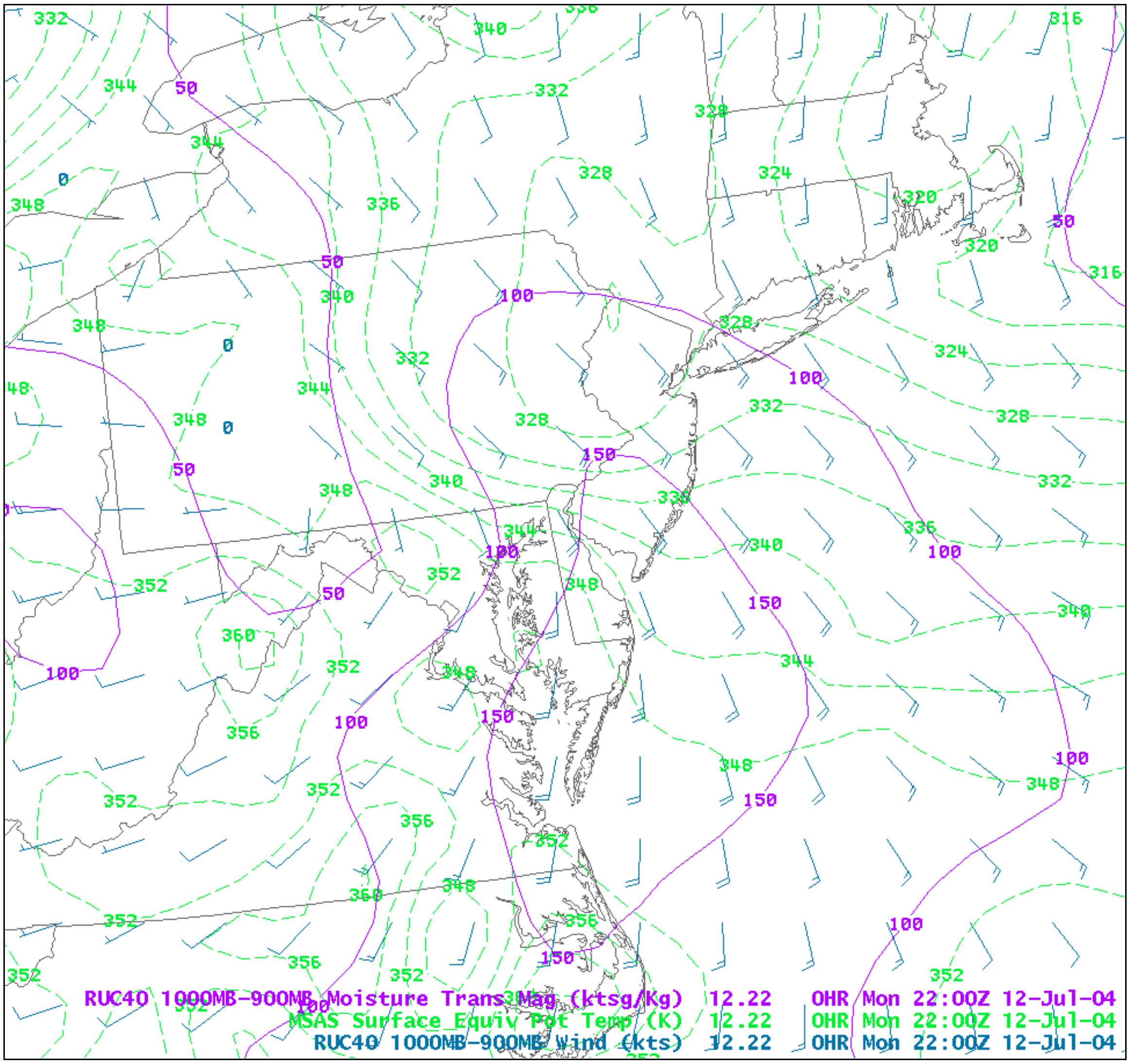

FIG 5. Low-level moisture and winds over the mid-Atlantic region at 2200 UTC on 12 July 2004. Blue wind barbs are analyzed winds in the lowest 100mb layer from the RUC model. Solid purple contours are the magnitude of lowest 100mb-layer moisture transport vectors (q***V***) from the RUC. Dashed green contours are surface theta-e from the MSAS.

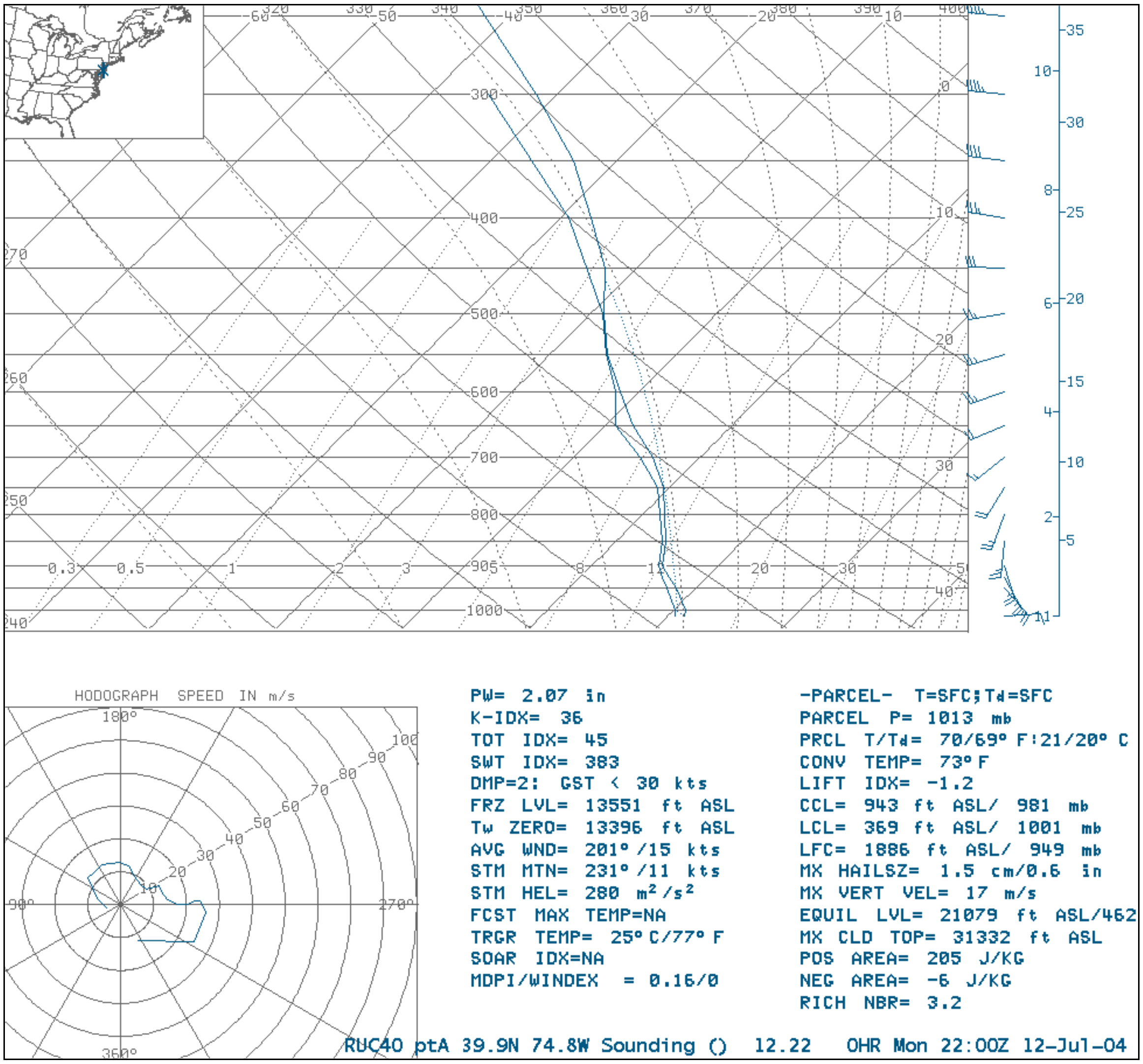

FIG 6. Sounding from the RUC 40km analysis, valid at 2200 UTC on 12 July 2004 over Burlington County, New Jersey.

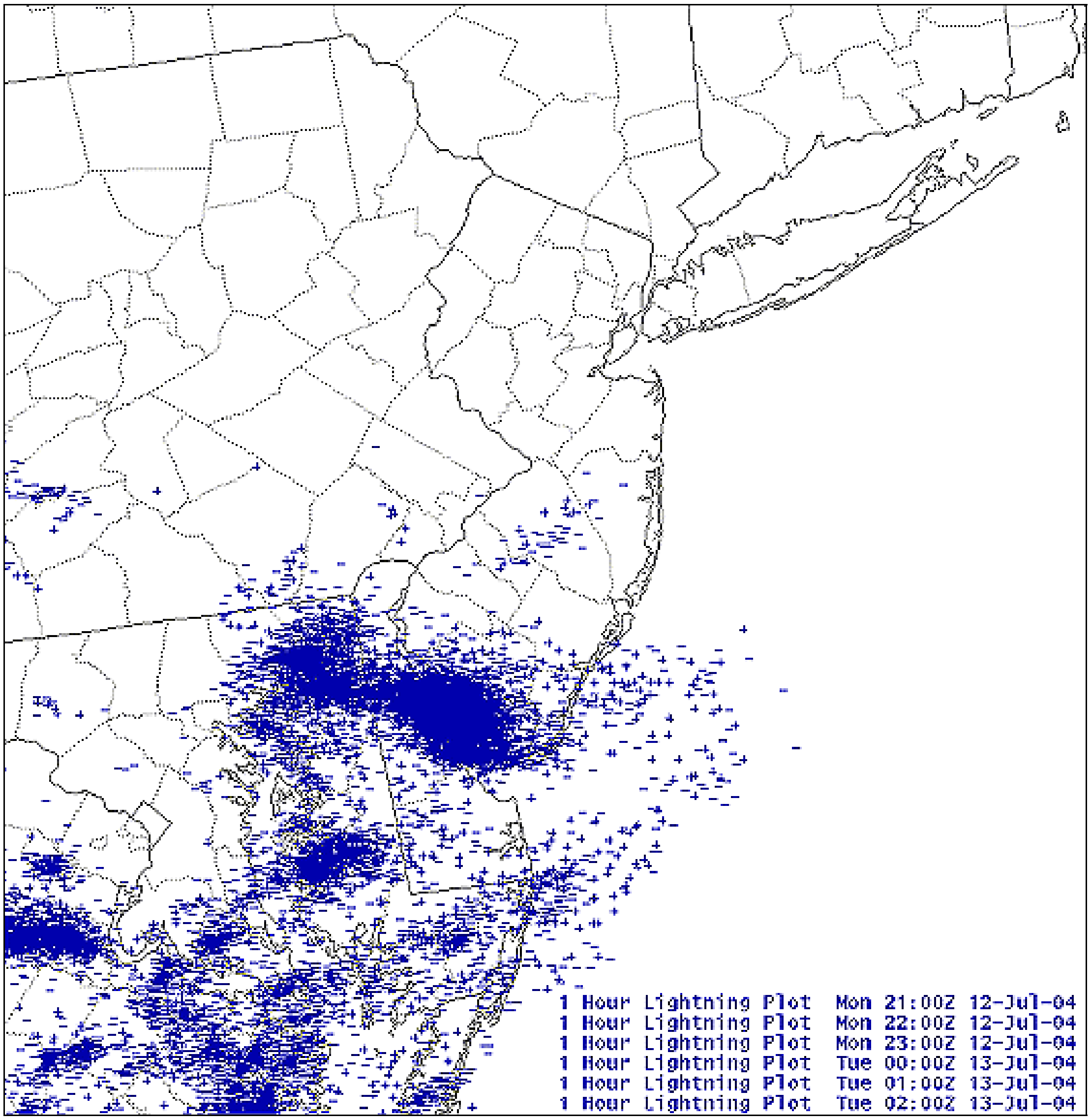

FIG 7. Total cloud-to-ground lightning flashes (positive and negative) over the study area between 2000 UTC on 12 July and 0200 UTC on 13 July 2004. This plot represents 15, 673 total lightning flashes in a six-hour period. Use of lightning data by the NWS is provided through a license agreement with Vaisala/GAI.