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B5.2 The Historic Heavy Rainfall and Flooding Events of 7-8 September 2011 across the Mid-Atlantic and Northeastern States

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ABSTRACT

The combined effects of Tropical Storm Lee and Hurricane Katia resulted in excessive rainfall across Maryland, Pennsylvania, and New York State on 7-8 September, 2011. Lee's plume of moisture spread northward across the Eastern United States from 5-8 September, while its remnant circulation slowly decayed. Although heavy rainfall affected a wide region, it became particularly concentrated on 7-8 September. Further analyses revealed a complicated pattern and moisture contributions from multiple sources, including distant Hurricane Katia. Given the infusion of moisture from Katia, and the influence of this system on the overall large-scale pattern, this case is considered to be a Predecessor Rainfall Event (PRE).

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1. Introduction

A rainfall event of historic proportions impacted sections of the Eastern United States in early September 2011. Although a broad region was affected from 4-8 Sep, the most intense rain fell within a narrow south to north band (Fig.1, labeled PRE#1) on 7-8 Sep, extending mainly from Central and Eastern Pennsylvania, up into Central New York (Fig. A secondary heavy rain band (Fig. 1, 1). PRE#2) impacted areas labeled from Delaware, northward through New Jersey, and into Connecticut. This paper will focus primarily on the evolution of PRE#1.



Figure 1. One day observed precipitation analysis, derived from the NWS Advanced Hydrologic Prediction Service (AHPS) web site, valid from 1200 UTC, 7 September to 1200 UTC, 8 September 2011.

The aforementioned bands of excessive rainfall resulted from synoptic interactions between the remnants of Tropical Storm Lee in the Ohio Valley, a stationary frontal zone along the Eastern Seaboard, and Hurricane Katia well off the Mid-Atlantic coast. The juxtaposition of these systems is shown in Fig. 2.



Figure 2. Mean sea-level pressure and radar surface analyses from the NOAA/NWS Hydrometeorological Prediction Center (HPC), valid at 0600 UTC, 8 September 2011.

Given the role of Hurricane Katia in this event, and its large separation distance from the prime regions of heavy rainfall across the Mid-Atlantic and Northeastern states, this case is considered to be a Predecessor Rainfall Event (PRE). PRE are coherent areas of heavy rainfall that are well removed from a tropical cyclone's main precipitation shield, yet are still indirectly tied to the existence of the tropical system (Cote 2007 and Moore 2010). In order for an event to be considered a PRE, the following criteria need to be satisfied: 1) At least 4" (100 mm) of rain must fall within the PRE centroid in 24 h or less, with accompanying radar reflectivity values of at least 35 dBz for 6 h or more, 2) Although there is no objective separation distance requirement, there must be a clear separation on radar imagery between the PRE and the main tropical cyclone precipitation shield, and 3) Deep tropical moisture, directly associated with the parent tropical cyclone, must be advected away from the tropical system and into the PRE region (Cote 2007; Galarneau et al. 2010; and Moore 2010).

Katia's presence had a significant impact on the amplification of an uppertropospheric ridge over the Western Atlantic, and also associated upper-tropospheric jet intensification upstream. Additionally, a tongue of tropical moisture was transported from the vicinity of Katia into the Northeastern United States, further enhancing an air mass that was present over the region with high water vapor content. These factors will be discussed in greater detail in Section 3. Towards the end of Section 3, comparisons will also be made to an analog case (11-12 Sep 2008 over the Southern Plains), indirectly tied to both Hurricane Ike and Tropical Storm Lowell (Bosart et al. 2012).

2. Data Collection and Methods

Total rainfall for the 7-8 Sep 2011 event, as well as monthly rainfall departures from normal, was derived from the NWS Advanced Hydrologic Prediction Service (AHPS) web site (www.weather.gov/precip; Fig. 1). Surface and radar analyses for each derived from case were the NWS Hydrometeorological Prediction Center (HPC) web site (www.hpc.ncep.noaa.gov/html/sfc_archive.sht ml; Fig. 2). Upper-air analyses for the 7-8 Sep 2011 (Fig. 4) case were derived from the NWS Storm Prediction Center (SPC) web site (www.spc.noaa.gov).

The NWS Advanced Weather and Information Processing System (AWIPS) Warning Event Simulator (WES) was used to construct images, featuring various satellite products, as well as initialized numerical weather prediction (NWP) fields (Figs. 5 and 6).

Trajectory analyses were derived from the Air Resources Laboratory web site (www.ready.arl.noaa.gov/HYSPLIT traj.php), utilizing the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Fig. 7).

3. Analysis and Discussion

a. Synoptic Setting

Antecedent conditions were already quite wet over the Eastern United States going into September, 2011, owing to well above normal rainfall during the preceding summer months (Fig. 3). This helped set the stage for the record flood event that was to follow.

At around 0000 UTC, 4 Sep, Tropical Storm Lee made landfall along the Louisiana coast. Over the next several days (4-8 Sep), as Lee's lower-tropospheric circulation transitioned to a Tropical Depression, and then an extratropical low, it tracked slowly northeastward through the Deep South and Tennessee Valley, eventually reaching the Ohio Valley by 7-8 September (Lee's track not shown). During the same time frame (4-8 Hurricane September), Katia lumbered northwestward over the Atlantic Ocean, tracking well north of the Caribbean Islands, but also well to the south and west of Bermuda (Katia's track also not shown). Katia peaked in intensity on 6 Sep, briefly reaching Major Hurricane status (Category 3 on the Saffir-Simpson Scale). In the meantime, between the two tropical systems, a surface frontal boundary had become nearly stationary along the East Coast, extending from Southern New England down to the Carolinas (refer to Fig. 2 for frontal position).



Figure 3. Monthly Percent of Normal Precipitation for August, 2011, derived from the NWS AHPS web site.

b. Upper-tropospheric jet modification

In the upper-troposphere (200-250 hPa), a well defined short-wave in the northern stream extended from near Hudson's Bay southward to the Western Great Lakes

region on 5 Sep, with a speed maximum of around 100 kt on the forward side of the trough axis (Fig. 4a). From 5-7 Sep, the largescale flow pattern underwent significant amplification, with the above mentioned short-wave only slowly progressing eastward, the remnant circulation of Lee shifting into the Lower Ohio Valley, and a substantial uppertropospheric ridge building in the Western Atlantic, just offshore from New England and the Canadian Maritime Provinces (Fig. 4b). In response to this synoptic set-up, the uppertropospheric jet streak increased to 150+ kt, with a well-developed jet entrance region and diffluent wind flow pattern forming southward through the Northeastern and Mid-Atlantic states, thus promoting enhanced large-scale ascent over this region.



Figure 4. a) 250 hPa analysis (streamlines (black contours) and wind speeds (shaded)) for 0000 UTC, 5 September 2011, as derived from the NWS SPC web site, and b) Same as in Fig. 4a, except for 1200 UTC, 7 September 2011.

The presence of Hurricane Katia downstream was quite influential in the amplification process of the Western Atlantic ridge, due to its warm asymmetric outflow. As shown in Figs. 4 and 5, notable 250-200 hPa warming/height rises over the Western Atlantic, New England, and Southeastern Canada from 5-7 Sep, induced strong negative potential vorticity advection just upstream. When combined with the gradual approach from the west of a short-wave trough and corresponding potential vorticity maximum, the potential vorticity gradient became rather tight over Quebec and Southeastern Ontario; and hence the rapid increase in uppertropospheric winds (Brennan et al. 2008; Figs. 4 and 5). The effect that tropical cyclones can have on jet structure, due to diabatic warming from their mid to upper-tropospheric outflow, has been well documented (Atallah and Bosart 2003; Colle et al. 2003; Farfán and Fogel 2007; and Galarneau et al. 2010).



Figure 5. Initialized 200 hPa heights (green contours), potential vorticity (PVU, dashed tan contours), and potential vorticity advection (negative values shaded) from the Rapid Update Cycle (RUC) model, valid at 0600 UTC, 7 September 2011.

c. Moisture trajectories into the PRE region

As mentioned earlier, by 7 September 2011, strong upper-tropospheric diffluence

had developed within the jet entrance region, from Virginia northward into New York State. The lower-tropospheric branch of the resultant thermally direct circulation (Nicosia and Grumm 1999) promoted a strong south to southeasterly fetch and enhanced frontogenesis in the 925-850 hPa layer (not shown), especially over Pennsylvania and Central New York.

The long southeasterly fetch was key to advecting tropical moisture from the Western Atlantic into the Eastern United States. As shown in Figure 6, two air streams with very high water content (each with precipitable water values exceeding 50 mm) converged along the Eastern Seaboard. The western-most air stream, extending from Florida northward up the East Coast, represented a combination of moisture plumes originating from the tropical Atlantic and Gulf of Mexico. This particular air stream was also closely tied to the circulation of former Tropical Storm Lee. The eastern-most air stream, extending from southeast to northwest over the Atlantic, was closely tied to Hurricane Katia.



Figure 6. Blended (combination of Advanced Microwave Sounding Unit (AMSU) and Special Sensor Microwave/Imager (SSM/I) polar-orbiting platforms) Total Precipitable Water (TPW, shaded values) satellite imagery, from 2343 UTC, 7 September 2011.

As indicated from backwards trajectories (Fig. 7) ending at Binghamton, NY (KBGM) at 0000 UTC, 8 September 2011; with several points along the trajectory lines superimposed on Blended Total Precipitable Water (TPW) satellite imagery (Figs. 8a and 8b), varied moisture sources contributed to this excessive rainfall event. In the 1-3 km above ground level (agl) layer at KBGM, the primary moisture contributions originated from the Western Atlantic, closely following the leading edge of Hurricane Katia's moisture plume over time. In the midtroposphere at KBGM (near 6 km agl), the main influx of high water vapor content air originated from the Gulf of Mexico and the Southeastern United States, closely following the moisture plume associated with Tropical Cyclone Lee. These trajectories implied that the far western edge of Hurricane Katia's moisture stream may have been entrained into the heavier rain bands impacting the region, merging with the already present high precipitable water air mass tied to the remnants of Tropical Storm Lee, from late on 7 Sep into the early morning hours of 8 Sep. Prior research (Schumacher et. al, 2011 and Schumacher and Galarneau 2012) has shown that the infusion of tropical cyclone- related moisture has increased atmospheric water vapor content by as much as 20 mm in other



Figure 7. Backwards air parcel trajectories, ending at 0000 UTC, 8 Sep 2011 at Binghamton, NY (KBGM), utilizing the HYSPLIT model. These trajectories terminated at three different vertical levels (1500 m agl (red trace), 3000 m agl (blue trace), and 6000 m agl (green trace)).



Figure 8. a) Blended TPW satellite imagery (same as in Fig. 5), valid at 0642 UTC, 7 Sep 2011, and b) Same as in Fig. 7a, except valid at 0605 UTC, 6 Sep 2011. The red circles represent the approximate locations of the 1500 m air parcel along its trajectory (from Fig. 6) at each time; while the green circles represent the approximate locations of the 6000 m air parcel at each time.

d. Categorizing the 7-8 Sep 2011 PRE

PRE were first catalogued and categorized by Cote (2007). PRE were separated by the paths/approximate landfall locations of their parent Atlantic Basin tropical cyclones. The initial database consisted of 47 separate PRE over an 8-year period from 1998 through 2006 (Cote 2007). In Galarneau et al. (2010), the PRE database was expanded temporally from 1995 through 2008, with the main mode of categorization

being curvature of the upper-tropospheric jet segments most closely associated with individual PRE. In Moore (2010), the PRE database was once again expanded (56 separate PRE over a 22-year period from 1988 2010). Different categories were to constructed with consideration given to the entire synoptic back-drop that the PRE were embedded within. These categories are: 1) Jet in Ridge PRE (Fig. 9a), 2) Southwesterly Jet PRE (Fig. 9b), and 3) Downstream Confluence PRE (Fig. 9c; Moore 2010). Given the anticyclonically curved nature of the upper-tropospheric jet (Fig. 4b), as well as the relatively large separation distance between Hurricane Katia and the PRE region (Fig. 2; especially as compared to typical Southwesterly Jet and Downstream Confluence PRE separation distances), the 7-8 September 2011 case most closely resembled a Jet in Ridge PRE.



Figure 9. A pictorial representation of the three different PRE classes, focusing on the overall uppertropospheric synoptic pattern (adopted from Fig. 2.1 in Moore 2010). The red shaded areas represent uppertropospheric jet maxima. Black contours depict uppertropospheric streamlines. Green stars show typical PRE regions for each category, while approximate tropical cyclone locations are portrayed using standard symbols.

e. Brief analog comparison to the 11-12 Sep 2008 PRE

In mid-September, 2008, multiple PRE (connected with Hurricane Ike and Tropical Storm Lowell) impacted a broad area of the Central United States, from the Southern Plains northeastward to the Lower Great Lakes region, with rainfall amounts of 6-12" (150-300 mm)/24 h common, with several new daily rainfall records set across the region (Bosart et. al, 2012). For this manuscript, we'll focus on the PRE which took place from portions of Central Oklahoma into Southeastern Kansas.

A nearly stationary band of rainfall intensified in the 12-18z time frame on 11 Sep 2008, from the Texas Panhandle, across Oklahoma, and into Southeastern Kansas and Western Missouri. By the time heavier rainfall began to shift northeastward on 12 Sep, locally in excess of 10" (250 mm) had fallen in portions of Oklahoma and Kansas. Excessive rainfall was the result of moist tropical air streams (associated with both Hurricane Ike in the Gulf of Mexico and Tropical Cyclone Lowell in the Gulf of California, Fig. 10) converging over the Southern Plains, combined with a slow moving frontal boundary over West Texas, the Oklahoma Panhandle, and Western Kansas. The juxtaposition of these systems, combined with a radar snapshot, is shown in Fig. 11.



Figure 10. Geostationary Orbiting Environmental Satellite (GOES) Water Vapor imagery, valid at approximately 0700 UTC, 12 September 2008. Annotations have been made for the PRE region location (black ellipse), approximate moisture paths between respective tropical cyclones and the PRE region (black arrows), as well as approximate positions-of both Hurricane Ike and Tropical Storm Lowell (using conventional symbols).



Figure 11. Mean sea-level pressure and radar analyses from the NWS HPC, valid at 0300 UTC, 12 September 2008.

Backwards parcel trajectories (Fig. 12), ending at Wichita, KS (WICT) at 0300 UTC, 12 Sep, illustrated the dual moisture contributions from Atlantic Basin Tropical Cyclone Ike and Eastern Pacific Tropical Cyclone Lowell (please refer to Figs. 10 and 11 for a frame of reference, regarding the positions/tracks of Tropical Cyclones Ike and Lowell). In the lower-troposphere (1-3 km agl layer), air parcels had their origins in the Gulf of Mexico, squarely within Hurricane Ike's large moisture shield. Meanwhile, in the midtroposphere (6-9 km agl), air parcels had their origins along the Pacific coast of Mexico, and closely aligned themselves with Tropical Storm Lowell's stream of moisture over time.

4. Conclusions

A case study of the 7-8 September 2011 excessive rainfall/flooding event across the Mid-Atlantic and Northeastern States was performed. The following were key findings:

Due to the combined effects of Tropical Storm Lee and distant Hurricane Katia, this case was considered a PRE. These specific effects will be briefly outlined below.

Two very high water vapor content air streams (one associated with the remnants of Tropical Cyclone Lee and one associated with Tropical Cyclone Katia) converged over the PRE region.



Figure 12. Backwards air parcel trajectories, ending at 0300 UTC, 12 September 2008 at Wichita, KS (KICT), utilizing the HYSPLIT model. These trajectories terminated at three different vertical levels (1500 m agl (red trace), 3000 m agl (blue trace), and 9000 m agl (green trace)).

- Hurricane Katia had a significant impact on the overall synoptic pattern in the following ways, which led to sustained heavy rainfall:

1) An upper-tropospheric jet maximum markedly intensified north of the PRE region, induced from a tightened uppertropospheric potential vorticity gradient (the result of negative potential vorticity advection north of Katia (height rises from its warm outflow)), plus an approaching short-wave and potential vorticity maximum from the west.

2) Enhanced lower-tropospheric frontogenesis, within the entrance region of the aforementioned jet maximum, resulted in a nearly stationary zone of strong forced ascent.

3) The blocking Western Atlantic ridge and highly amplified state of the largescale pattern, led to a very slow east to west progression of systems (including the band of excessive rainfall under study). The 7-8 Sep 2011 PRE bore several synoptic-scale similarities to a series of PRE which impacted the Central United States from 11-13 Sep 2008.

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