

**Heavy Rains Across The Mid-Atlantic and Northeast
September 29 – October 2, 2010
By: Rich Otto, HPC Meteorologist**

Introduction

From September 29th to October 1st, 2010, a historic, widespread heavy rain event occurred along the east coast of the United States, producing numerous single and multiple day record rainfall amounts, with one all time one day rainfall record (see Table 1). The combination of a strong upper level low, slow moving frontal boundary, anomalously high precipitable water values and a series of low pressure waves riding along the front contributed to the heavy rain. There were two periods of heavy rain, with the second being aided by the remnants of Tropical Storm (TS) Nicole which reached the coast of the Carolinas Thursday evening (0000 UTC Oct. 1). Widespread gale and storm force winds were also reported with this system along the Mid-Atlantic coast.

Storm total precipitation from the evening of September 28th though the morning of October 2nd displayed a widespread swath of 3 to 6 inches of rain from eastern North Carolina northward into upstate New York and Vermont (see Fig. 1). Within this axis of rainfall was an even more impressive axis of 6 to 10 inches plus from near Wilmington, NC northward through the western shore of the Chesapeake Bay. The greatest reported storm total rainfall from this event was reported 3.3 miles northwest of Swansboro, NC with 17.84 inches over a 3 day period from September 28th to October 1st.

Record 24hr Maximum Rainfall in inches (midnight to midnight)							
Sep. 29		Sep. 30		Oct. 1		Oct. 2	
Richmond, VA	2.25	New Bern, NC	8.93	Philadelphia, PA	3.00	Windsor Locks, CT	2.26
		Elizabeth City, NC	5.86	Allentown, PA	2.35	Worcester, MA	2.29
		Norfolk, VA	7.85	Wilmington, DE	3.26		
		Richmond, VA	3.69	Trenton, NJ	2.71		
		Lynchburg, VA	2.89	Newark, NJ	2.36		
		Washington Dulles, DC	4.74	Albany, NY	3.04		
		Washington Nat'l, DC	4.66	LaGuardia, NY	2.24		
		Baltimore Int'l Apt, MD	6.02*	Kennedy, NY	2.02		
		Allentown, PA	5.73	Worcester, MA	2.19		
		Williamsport, PA	3.91	Hartford, CT	2.15		
		Scranton/Wilkes-Barre Apt., PA	3.69	Caribou, ME	1.20		
		Harrisburg, PA	3.22				
		Philadelphia, PA	2.41				
		Wilmington, DE	4.32				
		Newark, NJ	1.21				
		Binghamton, NY	4.24**				
		Massena, NY	3.41				
		Watertown, NY	2.90				
		Albany, NY	2.68				
		Syracuse, NY	2.66				
		Montpelier, VT	1.19				

* second highest calendar day on record at BWI, highest daily rainfall total recorded in the month of Sep. (records go back to 1871)
 ** breaks the all time record for rainfall on any calendar day at Binghamton regional airport (records go back to 1951)

Table 1: 24hr record rainfall reports associated with the event

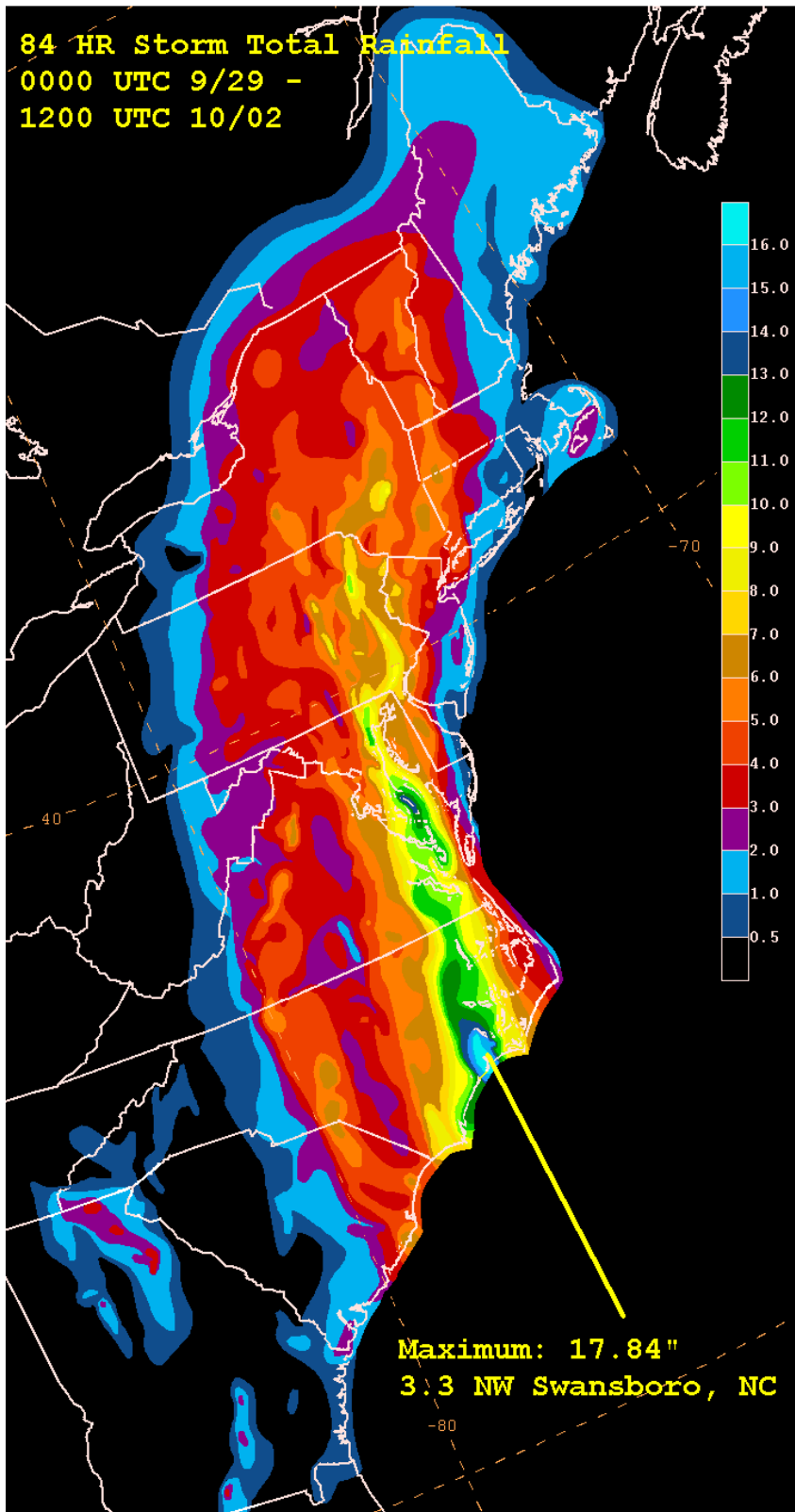


Figure 1: Storm total rainfall from 00Z Sep. 29 – 12Z Oct. 2, 2010. (note: some rainfall from North Carolina southward, includes up to an inch of rain for the 12 hrs preceding 00Z Sep. 29)

Some other noteworthy rainfall totals from the event included 17.30 inches in Cedar Point, NC, 12.90 inches three miles northeast of Jacksonville, NC, 12.53 inches three miles northwest of Newport News, VA, and 13.48 inches in Solomons, MD. Given the extreme rainfall, and some locations receiving a majority of the storm total rain over a short period of time, flood watches and warnings were issued concurrent with flooding observed up and down the east coast (see effects Fig. 2). However, the flooding could have been much worse. Antecedent conditions leading up to the heavy rain event were very dry, with many locations in the east experiencing below average rainfall and drought conditions (Figs. 3A,B).



Figure 2: Photos taken of flooded roadways which were observed throughout the eastern United States. Fig. 2A: Annapolis, MD (courtesy: <http://bluecrabyoyophotography.com>) Fig. 2B: Jacksonville, NC (courtesy: <http://www2.wnct.com>) Fig 2C: Phoenicia, NY (courtesy: <http://woodlandvalleyview.blogspot.com>).

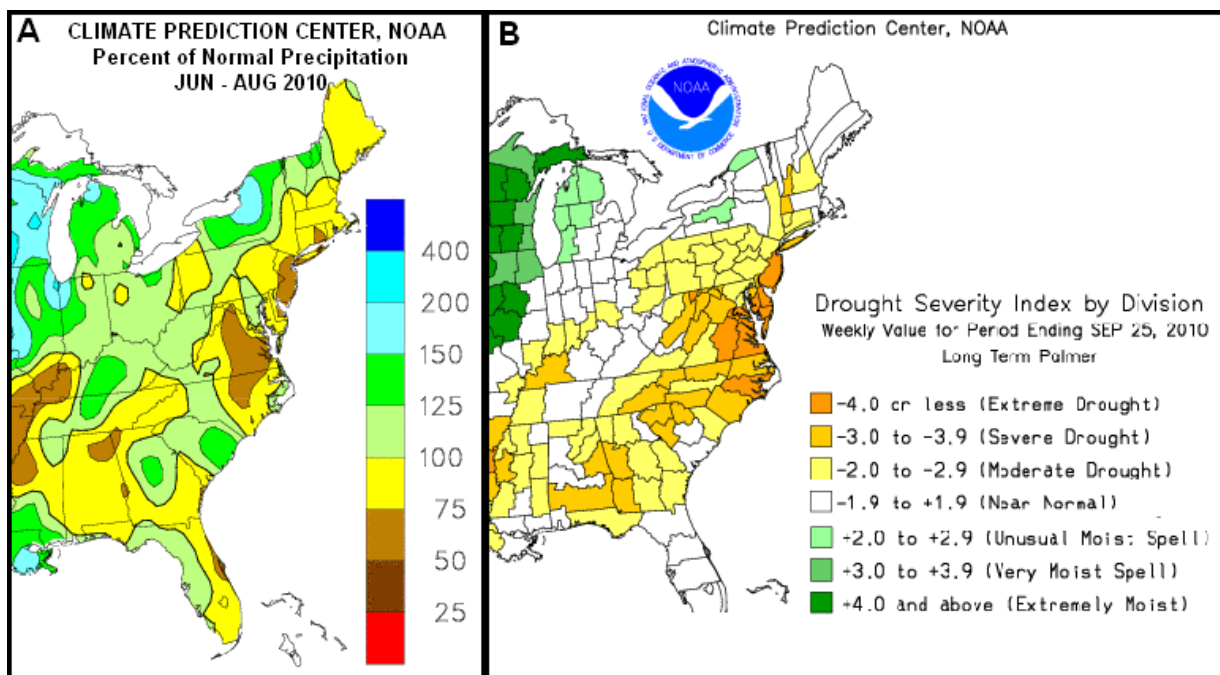


Figure 3: (A) Percent of normal precipitation from Jun. to Aug. 2010, indicating drier than normal conditions leading up to the heavy rain event. (B) Drought Severity Index just prior to the event, highlighting drought conditions over many of the areas that saw heavy rain.

In addition to the heavy rain experienced between September 29th and October 1st, heavy rain was observed over portions of the Carolinas from September 26th - 29th. This led to 3, 4 and 5 day rainfall records for portions of North Carolina, exceeding 20 inches in the southeastern

portion of the state. However, since those rains were not connected with the September 29th to October 1st storm system, their details will not be discussed in this report.

Synoptic Evolution

There is some discussion in the meteorological community as to whether this event actually qualified as a predecessor rain event (PRE). To qualify as a PRE event, a coherent mesoscale region of heavy rain, ≥ 4 in. (24 hr^{-1}), must occur approximately 600 mi. poleward of a recurving tropical cyclone (TC), 24 – 36 hr in advance of the main rain shield associated with the TC (Galarneau Jr. et al. 2010). In this case, a clear break did not exist between the rain associated with the synoptic scale storm system and the rain tied to the remnants of TS Nicole. Also, given the magnitude of moisture already in place along the east coast before the arrival of the tropical cyclone remnants, there is a question as to how much moisture augmentation was generated by the remnants of TS Nicole.

More generally, the event shares many characteristics with a Maddox “Synoptic” type flood event (Maddox 1979), including a stalled frontal boundary, upper-trough to the west of the front, and a deep plume of moisture ahead of the front. Rainfall associated with the event began around 0000 UTC on Sep. 29th, when a southern stream mid to upper level trough started to close off over the Tennessee valley (see Fig. 4). The western portion of a large blocking ridge is also seen in the western Atlantic at this time which helped to keep an extended period of deep southerly flow located along the east coast throughout the event. At the surface (Fig. 5), a stationary front was located from just off of the southeast coast, southwestward into the eastern Gulf of Mexico, separating an already high axis of precipitable water to its east from a relatively dry airmass to the west of the boundary (Fig. 6).

Over the next 24 hours, ending 0000 UTC on Sep. 30th, the mid-level low completely closes off from the northern stream trough and slowly drifts south across the Tennessee valley. The frontal boundary located just off the southeast coast remains in roughly the same location however the 850 mb flow backs from south to southeast while increasing in magnitude to 40 kt just off the coast of the Carolinas. The associated increase in warm air advection supported increased rainfall coverage and intensity along the southern Mid-Atlantic coast through 0000 UTC on Sep. 30th and the moisture advection shifted the deep plume of tropical moisture westward over land.

During the day on Thursday (Sep. 30), the closed low slowly tracks from the Tennessee valley to the Piedmont of North and South Carolina while a subtle shortwave trough on the east side of the closed low allows a surface low along the front and a swath of moderate to heavy rain to follow a similar path up the east coast, tracking into northern New York by 0000 UTC on Oct. 1st. The northern nose of the moisture plume is also brought northward through New York state with observed precipitable water values exceeding 2 inches at Albany, NY at 0000 UTC on Oct. 1st. At the same time, a surface low tied to the upper level remnants of TS Nicole tracked northward, reaching eastern North Carolina around 0000 UTC on Oct. 1st, which will bring the second wave of heavy rain for the event. Also of note during this time frame is a strong upper level jet at 300mb exceeding 100 kt (not shown) extending from the Carolinas into southeast Ontario, whose right entrance region provided added lift through a region synoptic scale upper divergence along the Mid-Atlantic coast.

Finally, between 0000 UTC on Oct. 1st and Oct. 2nd, the closed low over the Carolina Piedmont weakens into an open wave as it moves to a location just off the Mid-Atlantic coast, at the same time merging with the upper level remnants of TS Nicole. The surface low over eastern North

Carolina at 0000 UTC on Oct. 1st is accompanied by a second round of heavy rain which is observed to track from eastern North Carolina Thursday night into New England on Friday, Oct. 1st. At the same time, a cold front extending south of the low swings eastward, sharply reducing available moisture in the Mid-Atlantic, eventually ending the heavy rain event by 12Z on Oct. 2nd. Although heavy rain was observed in New England, especially over western portions of the region, the magnitude was far less that what was seen from New York, southward along the Mid-Atlantic coast due to weakening dynamics aloft along with a shorter duration of heavy rain.

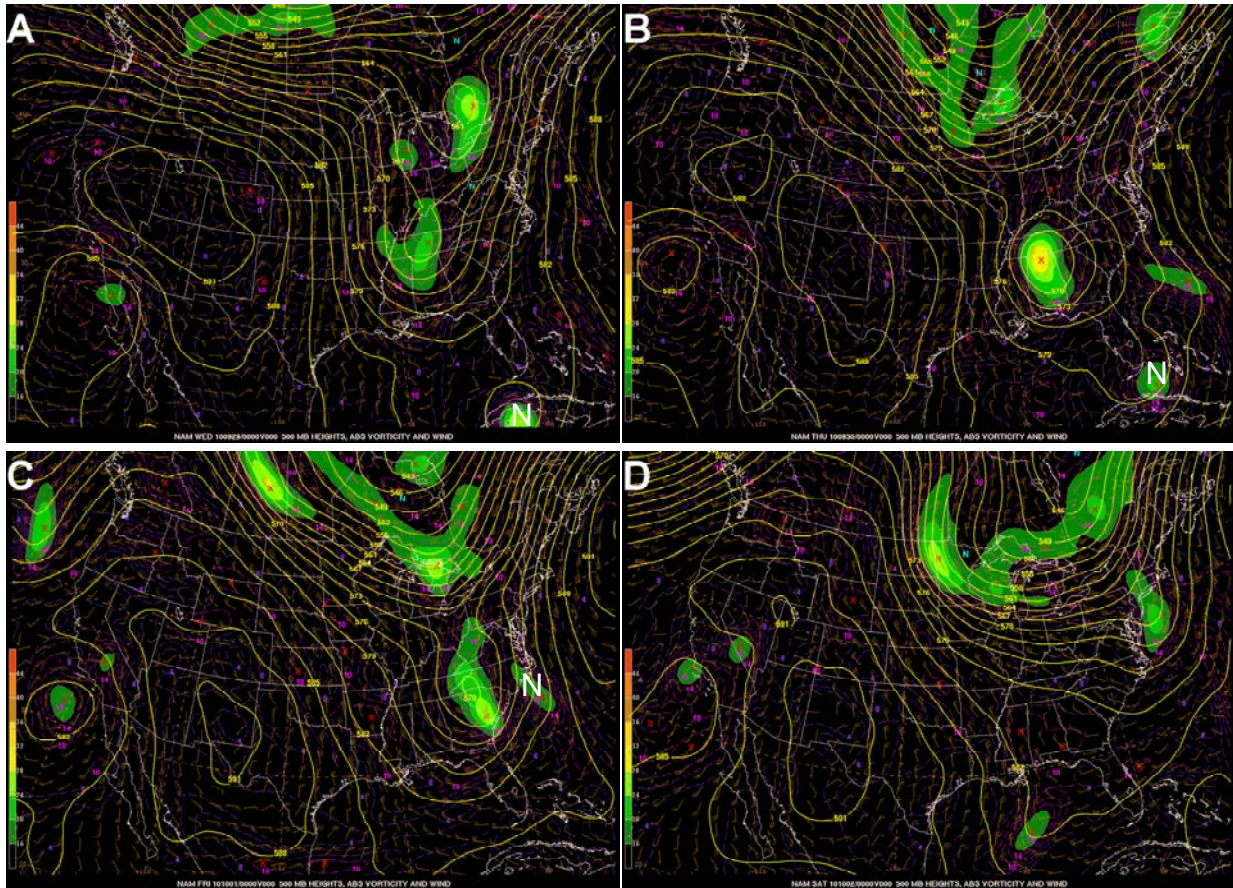


Figure 4: NAM analyses of 500 mb heights, vorticity and wind (knots) in 24 hr time increments; valid (A) 0000 UTC 9/29, (B) 9/30, (C) 10/1, (D) 10/2. The 500 mb vorticity maxima associated with TS Nicole is labeled "N" in (A), (B), and (C). Images courtesy – Hydrometeorological Prediction Center

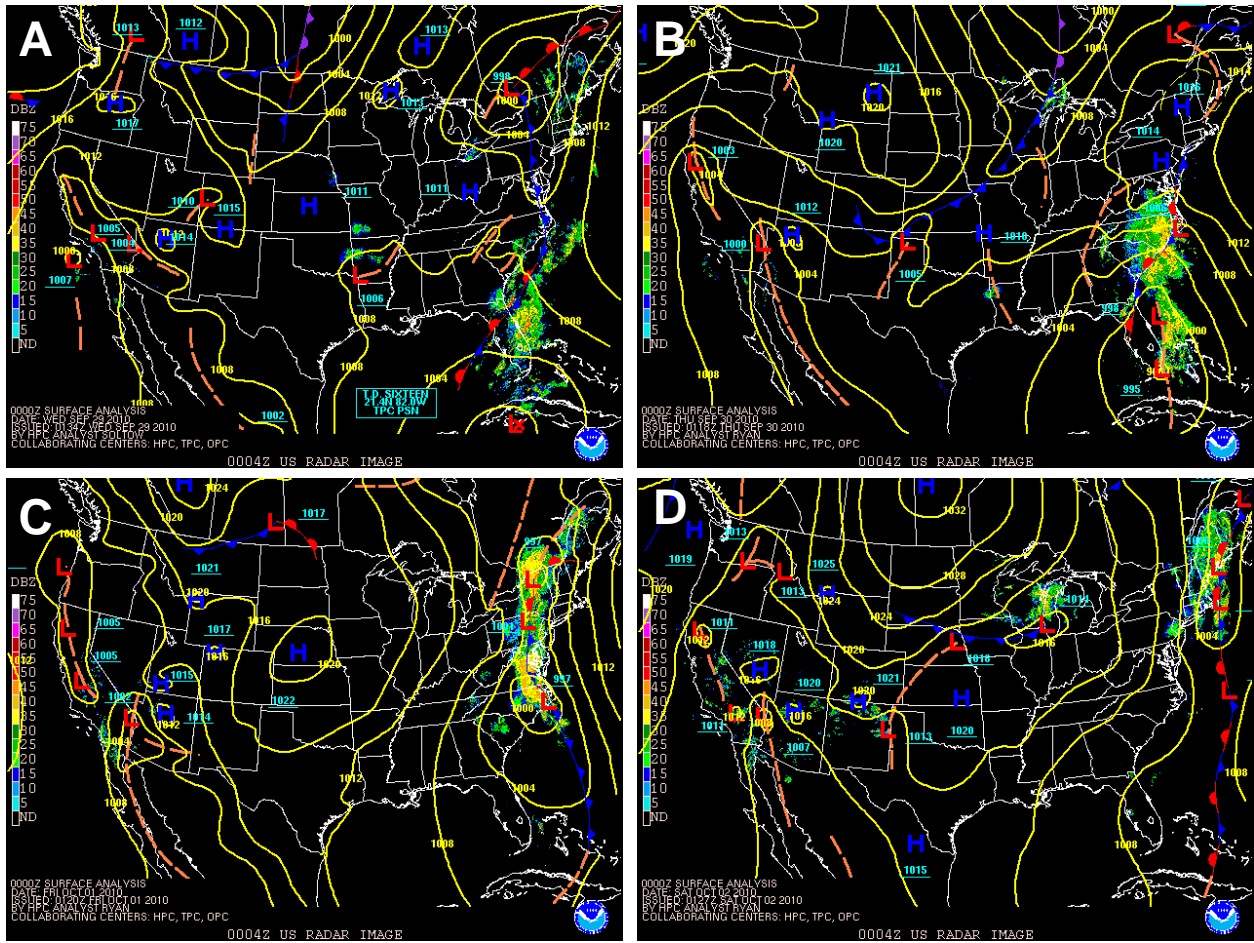


Figure 5: HPC surface analysis / radar composite overlay every 24 hr; valid 0000 UTC (A) 9/29, (B) 9/30, (C) 10/1, and (D) 10/2). Images courtesy – Hydrometeorological Prediction Center

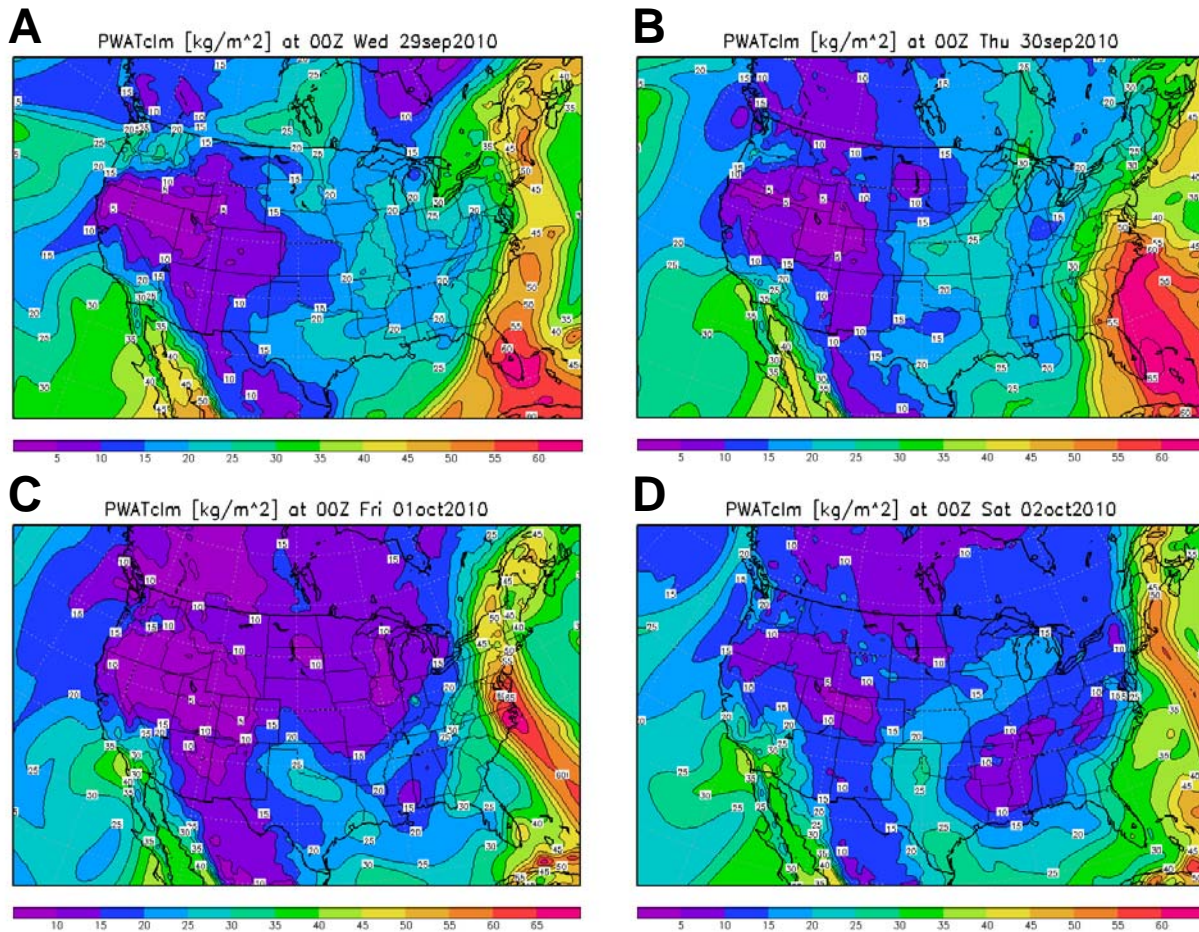


Figure 6: Precipitable water analyses in millimeters every 24hr valid 0000 UTC (A) 9/29, (B) 9/30, (C) 10/1, (D) 10/2. Images courtesy – National Climatic Data Center.

Mesoscale Features

There were several mesoscale features embedded within the larger synoptic scale event which played a large role in which areas received the greatest rainfall totals. These smaller temporal and spatial elements resulted in bands of heavy rain on the order of 10 to 20 miles wide which produced 1 to 3 inch per hour rainfall rates over roughly the same locations.

One such instance occurred along the western shore of the Chesapeake Bay in Maryland between 0600 and 1800 UTC on Thursday, Sep. 30th. After a short break in rain over the area around 2100 UTC on Wednesday, Sep. 29th, a surge of moderate and heavy rain approached from the south. The surge was likely tied to a number of factors discussed below.

First, a rapid increase in wind speed was observed at 850 mb between 0000 UTC Sep. 30th and 1200 UTC Sep. 30th where winds veered from roughly 20 kt from the southeast to the south at near 60 kt. This increase in low level wind speed was concurrent with a surge of high precipitable water which translated into a maximum of 850 mb moisture transport across the Chesapeake Bay region (see Figure 7). In addition, a strong warm front lay oriented southwest to northeast across the Chesapeake Bay at 0600 UTC which moved into central Maryland at 1200 UTC and central Pennsylvania at 1800 UTC. Figure 8 shows the position of the warm front at 1200 UTC along with a RUC short term forecast of frontogenesis at 850 mb. Due to the

increase in magnitude of the 850 mb wind which similarly increased frontogenesis at this level, a thermally direct circulation was enhanced with vertical motion positioned on the warm side of the front over the area of interest.

As the warm front lifted north along with a broad region of overrunning precipitation into Pennsylvania and New York, a relatively narrow south to north oriented band of moderate to heavy rain remained in the vicinity of the Chesapeake Bay through 1800 UTC (see Figure 9). During this timeframe, individual cells continued to train over roughly the same locations owing to deep southerly mean flow combined with an almost equally fast upwind propagation component to the cells (see Figure 10). Veering winds were present in the surface to 850 mb layer in both the Sterling and Wallops Island soundings from 1200 UTC, indicative of warm air advection. Also present is a layer of low to mid-level instability at Wallops Island, which likely spread northward through 1800 UTC. Both the weak instability and warm air advection were likely contributors to ongoing rain during this time frame. The height of the freezing level is also evident on both soundings (despite their opposite locations with respect the warm front), with the 0 C isotherm located near 600 mb, translating to a warm layer depth of roughly 13000 ft. Such a deep layer above freezing suggests warm rain processes are likely, leading to intense rainfall rates at the surface. Intense rainfall was indeed observed as confirmed by 12 hr rain gauge reports ending at 1800 UTC Sep. 30, for Patuxent River Naval Air Station, MD with 7.93 inches and Annapolis, MD with 7.47 inches.

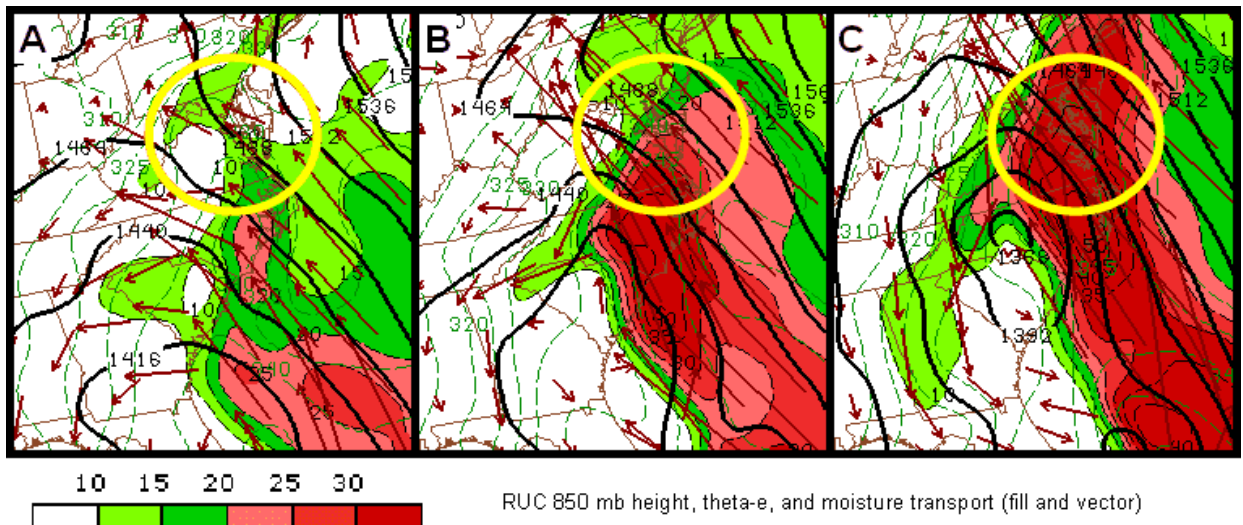


Figure 7: 1 hr forecasts from the RUC displaying 850 mb height, theta-e and moisture transport valid (A) 0000 UTC 9/30, (B) 0600 UTC 9/30, and (C) 1200 UTC 9/30. Region of interest is circled in yellow. Images courtesy – Storm Prediction Center.

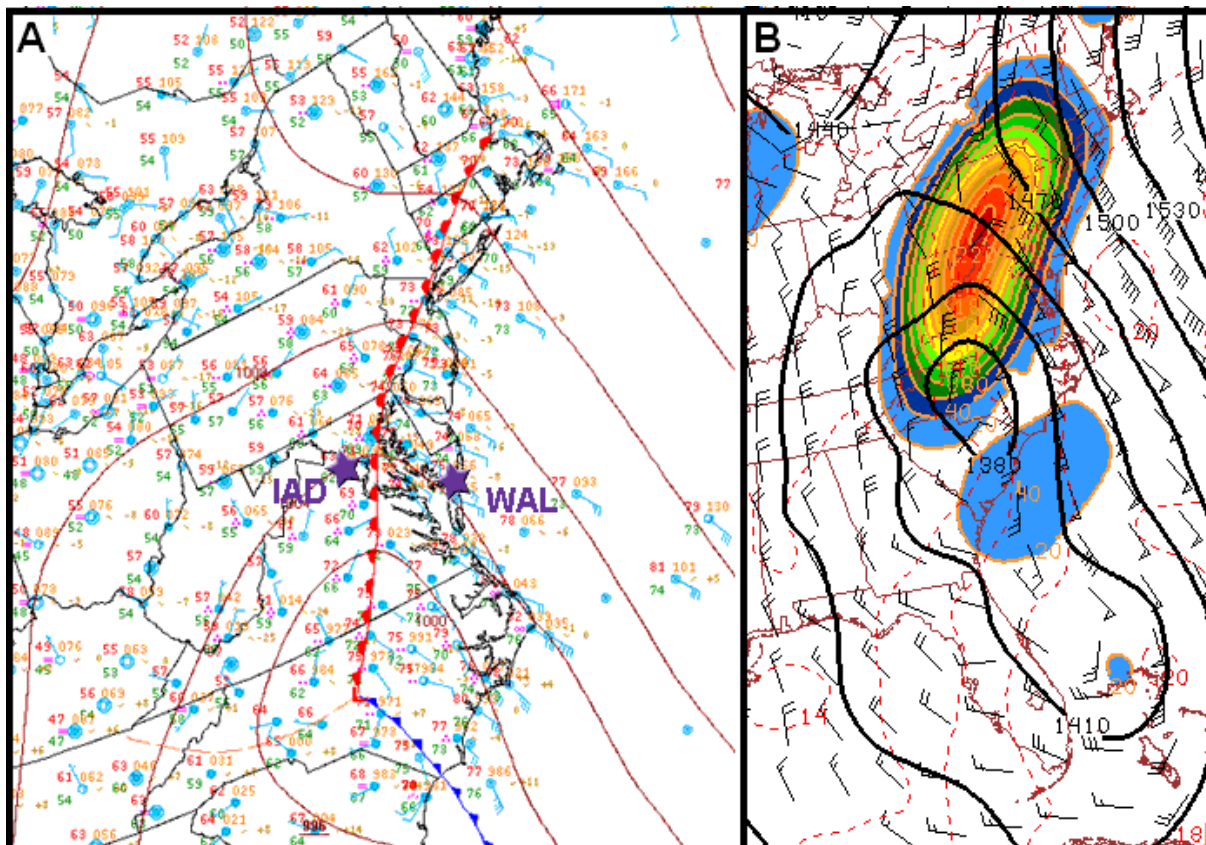


Figure 8: Valid time is 1200 UTC 9/30 displaying the HPC surface analysis (Fig. 8A) and a 1 hr forecast from the RUC displaying 850 mb height, temperature, wind and Petterssen frontogenesis (Fig. 8B). Images courtesy – Hydrometeorological Prediction Center and Storm Prediction Center

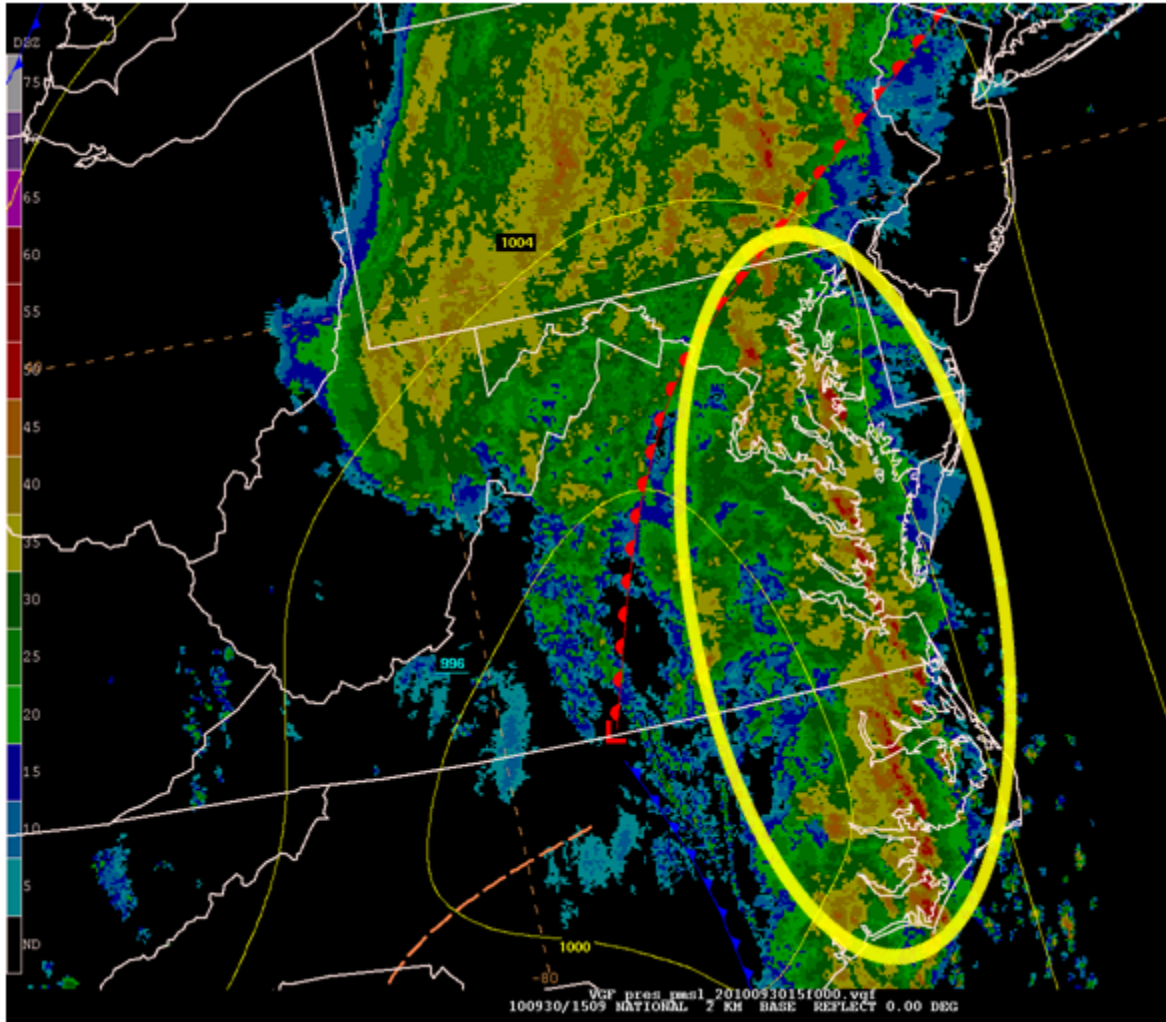


Figure 9: 1509 UTC Base Reflectivity overlaid with 1500 UTC HPC surface analysis, valid 09/30. Circled area highlights narrow but intense rain bands producing 1 to 3 inches of rain per hour. Image courtesy – Hydrometeorological Prediction Center.

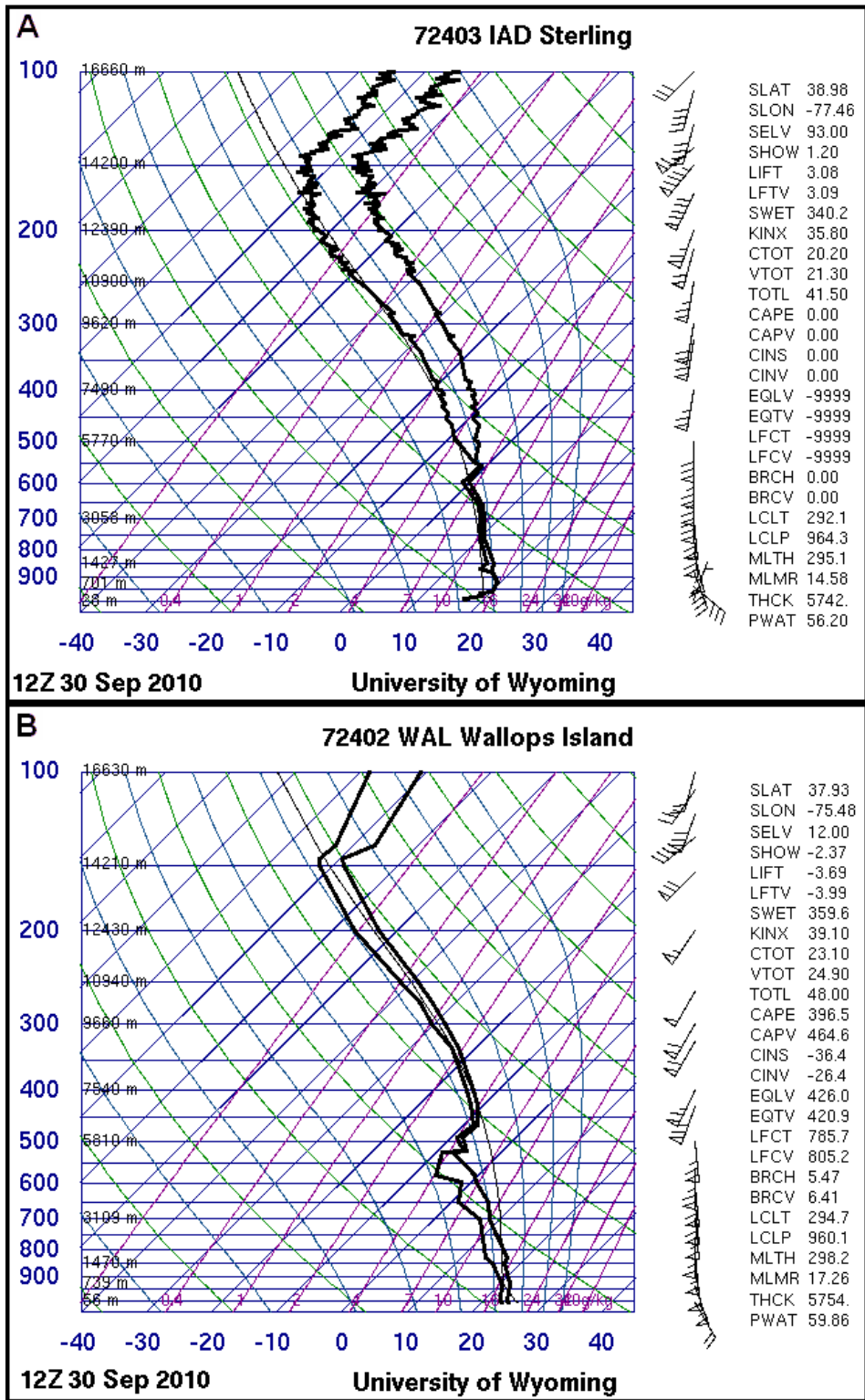


Figure 10: Skew-T soundings valid 1200 UTC 9/30 for Sterling, VA (Fig. 9A) and Wallops Island, VA (Fig. 9B). Reference Fig. 8 for a map of station locations. Images courtesy – University of Wyoming <http://weather.uwyo.edu/upperair/sounding.html>

Similar processes over eastern Maryland as noted above also occurred along the North Carolina coastline between Wilmington and Hatteras earlier in the event, coupled with previous

overrunning rain prior to 1200 UTC on the 29th. Although rain echoes were not as organized in terms of being uninterrupted as observed in eastern Maryland, periods of training cells, containing moderate and heavy rain, were observed along a relatively narrow axis within deep southerly flow between 1200 UTC on Sep 29th and 1800 UTC on Sep. 30th.

Shortly before 0000 UTC on Oct. 1st, a 996 mb surface low associated with the remnants of TS Nicole made landfall along the central North Carolina coast along with a second round of heavy rain. Gauge adjusted radar estimated rainfall indicates an additional 2 to 6 inches of rain fell along the southeastern North Carolina coast between 1800 UTC Sep. 30 and 0600 UTC Oct. 1 in direct association with the surface low and second wave of heavy precipitation (see Figure 11). As this area of precipitation tracked to the north, it is estimated that an additional 1 to 3 inches fell from eastern Virginia into eastern upstate New York.

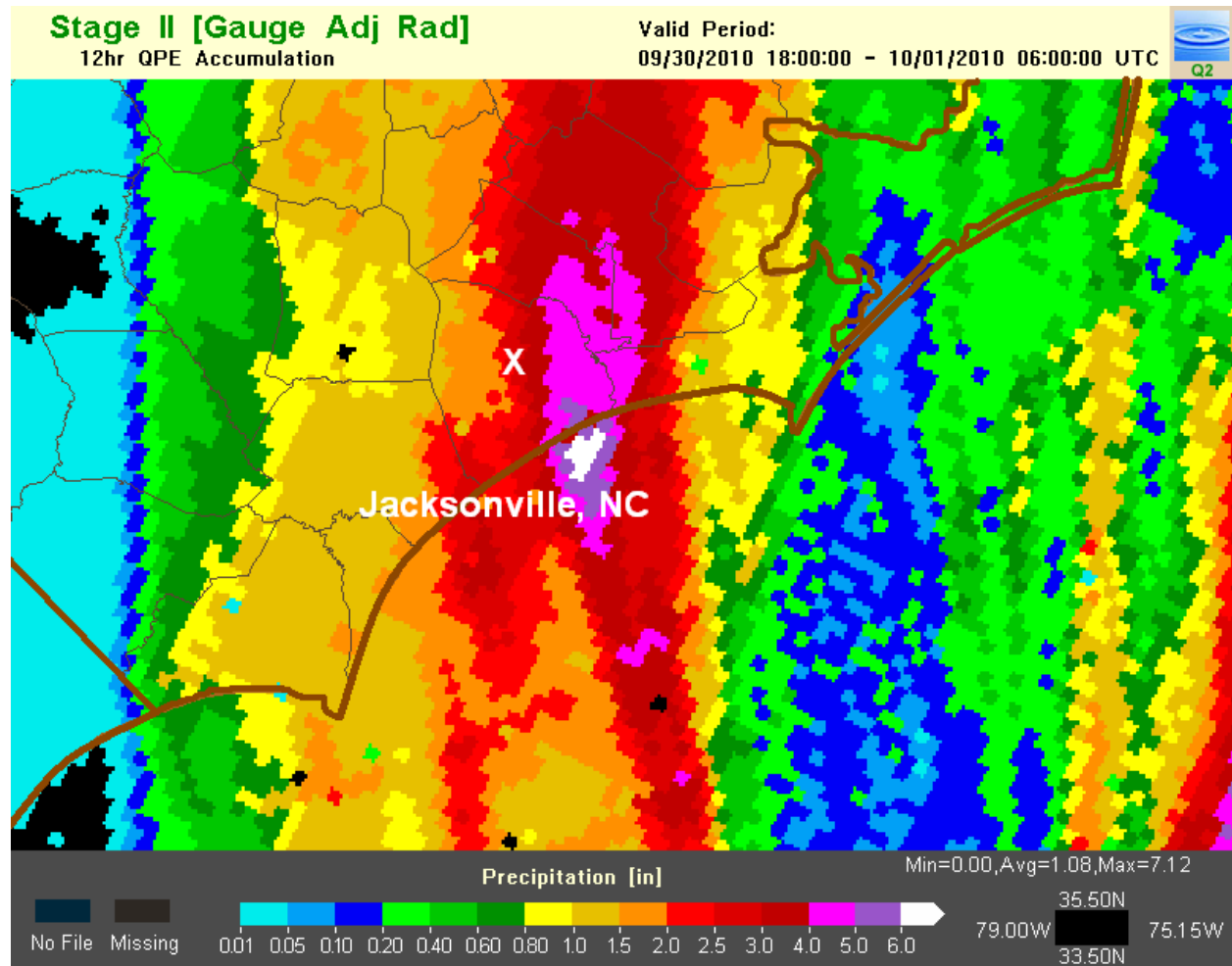


Figure 11: 12 hr period of radar estimated rain with adjustments toward gauge data over southeast North Carolina, valid 0600 UTC Oct. 1. Image courtesy – <http://nmq.ou.edu>

Conclusion

Over an 84hr period between 0000 UTC on Sep. 30th and 1200 UTC on Oct. 2nd, a widespread heavy rain event occurred from the southeast coast of the U.S. into New England producing a widespread axis of 3 to 6 inches spanning 800 miles in length. Within this broader axis was a narrower, but still impressive, 400 mile long axis of rainfall exceeding 8 inches between

southeast North Carolina and northern Maryland. Storm total rainfall of 10 to 20 inches was seen in North Carolina, Virginia and Maryland breaking many long-standing records and bringing September rainfall from one of the driest on record to one of the wettest for cities such as Wilmington, NC. Widespread rainfall of this magnitude hasn't been observed since excessive rains fell in connection with TC Floyd of 1999.

Despite antecedent conditions of below normal precipitation along the eastern U.S., this amount of rainfall over a short period of time resulted in widespread rural and urban flooding combined with river levels overflowing their banks. Flooding waters onto highways and rural roads combined with strong winds led to countless high water rescues and dollars of property damage from the Southeast to the Northeast.

The event shared characteristics of a Maddox synoptic flood type, occurring ahead of a deep upper level trough over the Ohio Valley and Southeast, with a blocking mid and upper level ridge located in the western Atlantic. The configuration allowed waves of low pressure to move along the stalled NE-SW oriented front within a moisture rich environment. Precipitable water values of 2 to 2.5 inches, which corresponded to standardized anomalies of +3 to +4 above the mean, combined with 850 mb v-wind anomalies exceeding 5 standard deviations above the mean were observed along the Mid-Atlantic coast.

The remnant moisture and energy from TS Nicole made landfall along the North Carolina coast during the afternoon of Sep. 30 bringing an additional round of heavy rain to the east coast. The entire event came to an end as the associated upper level trough along the east coast exited into the Atlantic late in the day on Oct. 1st (Friday night).

References

Galarneau Jr., T. J., L. F. Bosart, R. S. Schumacher, 2010: Predecessor rain events ahead of tropical cyclones. *Mon. Wea. Rev.*, **138**, 3272-3297.

Maddox, R. A., C. F. Chappell and L. R. Hoxit, 1979: Synoptic and meso-alpha aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60**, 115-123.