J12B.4 A LOOK AT TROPICAL STORM GASTON FLOODING IN VIRGINIA

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1. INTRODUCTION

Hurricane Gaston made landfall north of Charleston, SC on Sunday morning 29 August 2004. It weakened to a tropical depression as it moved north into North Carolina. Rainfall in North Carolina was generally in the 50 to 100 mm (2-4 inches) range. During the early morning of 30 August 2004, Gaston was losing strength and no flooding rain was anticipated for Virginia. Later, as the storm moved across southern and central Virginia, supercell thunderstorms developed evolving into a very heavy rain event for central Virginia. Gaston strengthened back to a tropical storm as it moved off the Delmarva coast early 31 August 2004. The maximum unofficial rainfall report was 324 mm (12.60 inches) recorded in the city of Richmond, VA (Fig. 1).

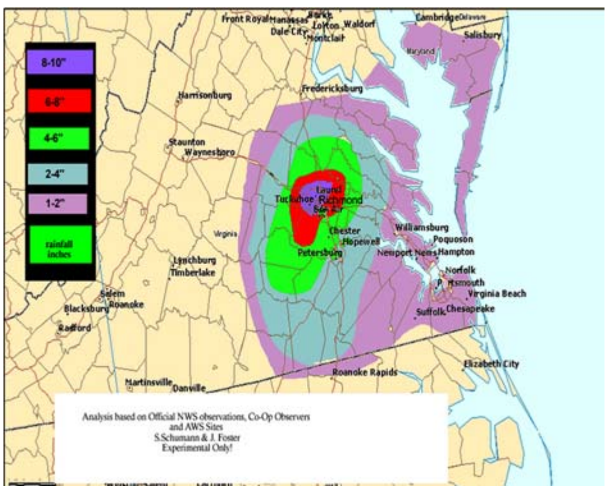

Figure 1. Observed storm total precipitation on 30 August 2004 from Gaston.

Substantial flash flooding occurred in many locations, most notably in the Central Virginia piedmont where numerous roads and bridges were washed out. The most severe flooding occurred in the Shockoe Bottom section in the city of Richmond, which is a low-lying downtown area known for its restaurants, bars and old tobacco warehouses converted into condominiums and apartments. (Fig. 2) Overall, the flooding was responsible for 8 fatalities and damage estimates were near $15 million. Federal disaster declarations were issued for several localities, with about 350 homes and more than 230 businesses either damaged or destroyed.

Figure 2. A portion of the flooded Shockoe Bottom section in Richmond, VA 30 August 2004.

Over half the deaths associated with tropical systems from 1970 to 1999 were caused by fresh water flooding per Rappaport (2000). The improved forecasting of these types of events with longer lead times should lessen future deaths. All Gaston's deaths in Virginia were from fresh water flooding. While flash flood warnings were issued more than 90 minutes before the most severe flooding, no long fused flash flood watches were issued to heighten public awareness of the potential for flash flooding. The deaths and lack of long lead time watches lead to an examination of Gaston to improve future forecasts.

This paper examines several model forecasts at various lead times for heavy rain potential before Gaston impacted the local area. The use of observational data is examined to determine what adjustments need to be made to improve short term forecasts. Forecast aids for determining potential flash flooding are developed from these examinations.

2. OBSERVATIONAL AND MODEL DATA BEFORE 12 UTC 30 August 2004

The forecast storm track by National Hurricane Center (NHC) slowed and turned the storm from a north to northeast motion moving across southeastern Virginia and off the Delmarva coast late on 30 August 2004. The Global Forecast System (GFS) model showed a similar storm track. The final observed storm track is shown in Fig 3.This storm track and storm motion are similar to tropical systems identified by Cline (2002), which

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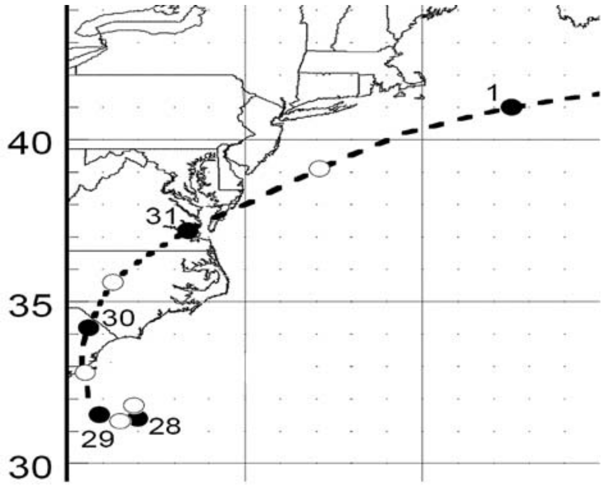

Figure 3. Final observed Gaston track from National Hurricane Center.

produced flooding rainfall. Pattern recognition developed from the climatology of tropical cyclone rains provides clues to the potential for heavier precipitation.

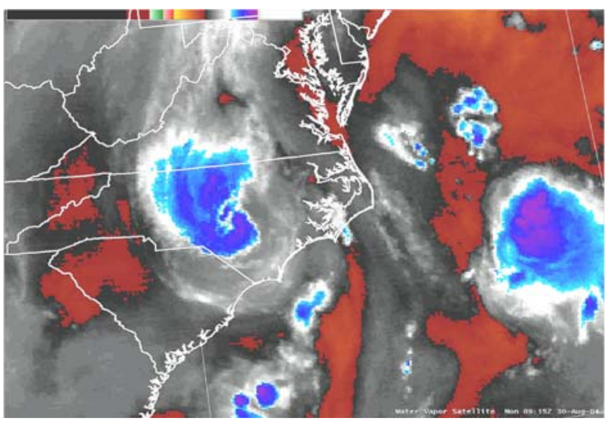

Figure 4. Water Vapor Satellite at 11 UTC 30 Aug 2004 with red showing drying.

A challenging forecast problem was how much moisture was available to Gaston for rain production as it approached Virginia. Water vapor satellite imagery (Fig. 4) showed some dry air wrapping into this system early on 30 Aug 2004. This dry air was observed in surface data also. National Weather Service Doppler radar was showing a gradual decrease in convection as the system approached southern Virginia early on 30 August 2004.

Satellite imagery (Fig. 4) showed the moisture plume originating over the very warm and moist Gulf Stream. Surface observations collaborated this with very high theta-e air indicated by surface observations southeast off the coast of North Carolina (Fig. 5). LaPenta et al. (1995) pointed out that one of the contributing factors to flooding over the Mid Atlantic is the availability of warm moist air from the Gulf Stream. The close proximity of the Gulf Stream allows this moist air to be quickly pulled into the system.

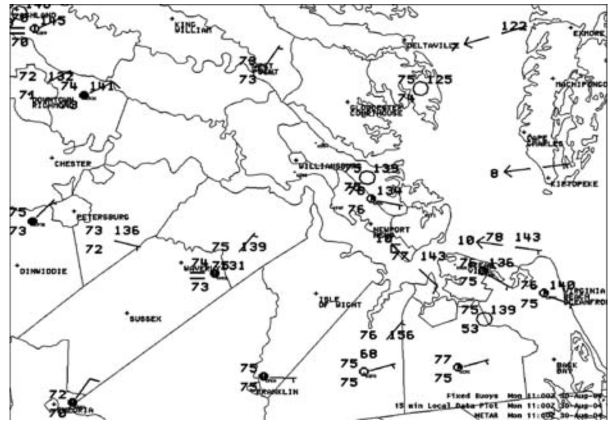

Figure 5. Surface observations 11 UTC 30 August 2004.

Both, the 00 UTC and 06 UTC North American Mesoscale model (NAM) kept the moisture well offshore. The GFS brought high moisture air, as depicted in the theta-e field (Fig. 6) well to the northeast of the center of Gaston. The local Workstation ETA (WsEta) was run on a 5 km grid. The 00 UTC run of the WsEta depicted high theta-e air near the storms center during the early afternoon and approaching the Richmond area by late afternoon and evening. The WsEta depiction was closer to the observed.

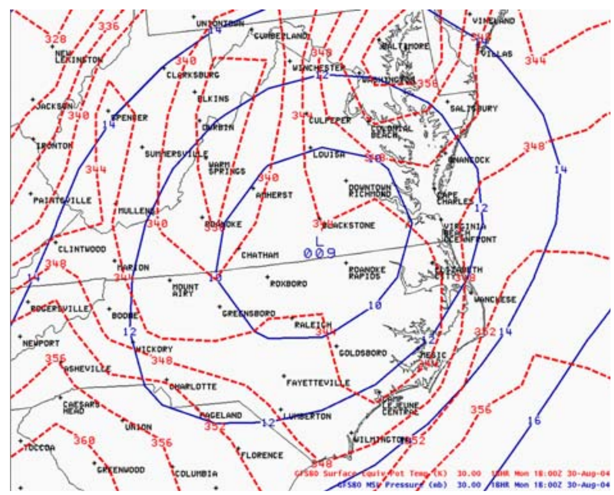

Figure 6. GFS 00 UTC forecast of MSL pressure (hPa; solid) and theta-e (F; dashed) valid 18 UTC 30 Aug 2004.

The Convective Available Potential Energy (CAPE) was minimal on both NAM and GFS while the WsEta showed much higher values between 2000 J kg^{-1} and 3000 J kg^{-1} (Fig. 7). The increase CAPE on the WsEta combined with strong wind shear indicated the potential for supercell thunderstorm development during the afternoon on 30 August 2004.

The NAM did not maintain a separate system at the surface (not shown). The GFS was much better in maintaining Gaston's strength and track through Virginia when compared to observations. For example, Fig. 6 shows the same strength for Gaston at 00 UTC 31 August 2004 as when Gaston was over North Carolina. This improved track and intensity forecast developed stronger vertical motion then the NAM.

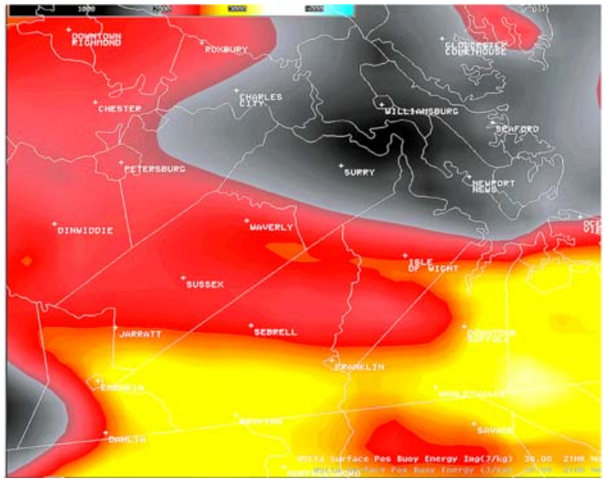

Figure 7. 00 UTC WsEta CAPE greater then 2000 J kg$^{-1;}$ in red to 3000 J kg^{-1} in yellow valid 18 UTC 30 Aug 2004.

Both the NAM and GFS had strong but weakening vertical motion (not shown) associated with the storm. The WsEta, however, developed a small jet at 250 hPa with the storm as it moved into Virginia during the afternoon (not shown). This contributed to increased upper level divergence near the Richmond area during the late afternoon.

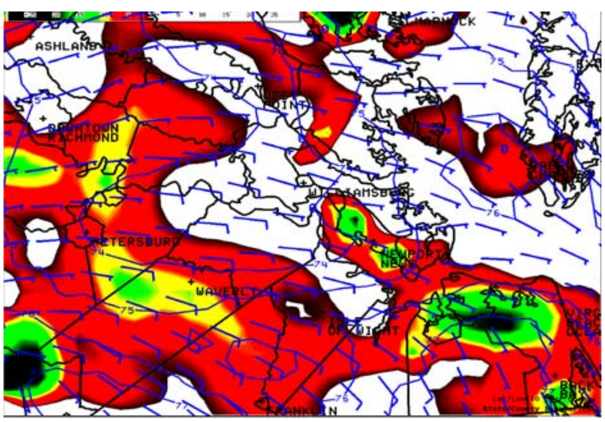

Figure 8. 00 UTC WsEta model run valid 21 UTC 30 August 2004 with surface winds and dewpoints (F; solid) and surface convergence shaded (10^{-5}s).

Colle (2003) showed through numerical simulations of Floyd, that the heaviest rain typically falls in a small area near mesoscale boundaries. The WsEta developed a surface boundary from Richmond to Virginia Beach along the James River, as depicted in Fig 8. The WsEta developed strong moisture convergence along this boundary. The divergence aloft coupled with the convergence near the surface provided for increased vertical motion along this boundary. This vertical motion and higher CAPE would imply the development of thunderstorms along this boundary and the motion would track these storms west toward Richmond. The boundary moved very little for several hours as forecasted by the WsEta.

3. OBSERVATIONAL AND MODEL DATA AFTER 12 UTC 30 AUGUST 2004

The 12 UTC NAM and GFS predicted 25 to 50 mm (1 to 2 inches) of precipitation from 12 UTC 30 August 2004 through 12 UTC 31 August 2004. The QPF forecast by both models was significantly under the observed rainfall with a large area of southern Virginia receiving an average of 50 to 100 mm (2 to 4 inches) of rainfall. Both the NAM and the GFS kept dewpoints in the low 70s with CAPE of only 500 J kg^{-1}. The 12 UTC WsEta showed potential for convection to develop. Figure 9 shows an area of strong surface convergence northwest of Richmond that remained here for several hours.

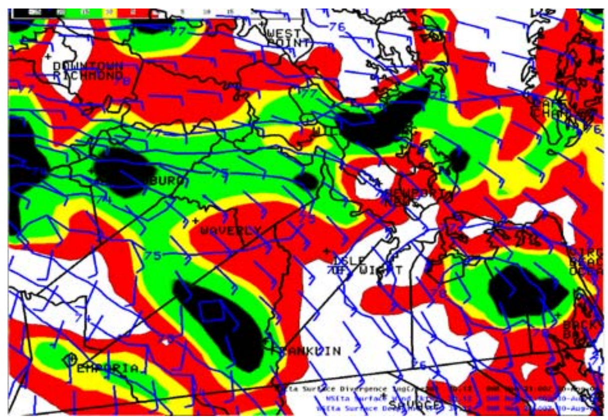

Figure 9. 12 UTC WsEta run valid 21 UTC 30 August 2004 with surface winds, dewpoints (F; solid) and surface convergence shaded (10^{-5}s).

The WsEta showed very high dewpoints in the mid to upper 70s combined with temperatures in the mid 80s to the northeast of Gaston at 21 UTC August 2004. These combined to produce CAPEs 3000 to 4000 J kg^{-1} from the WsEta. Figure 10 shows this band of very high CAPEs from near Virginia Beach and northwest to around Richmond.

The 12 UTC observational data showed potential for higher CAPE then the GFS and NAM forecasted. The 12 UTC RUC analyses show high theta-e air advecting into Gaston's circulation, with the 13 UTC visible satellite image (Fig. 11) showing some thinner clouds to the northeast of Gaston. The motions of the clouds on satellite showed the thicker cloudiness not arriving in the area from Virginia Beach to Richmond until late

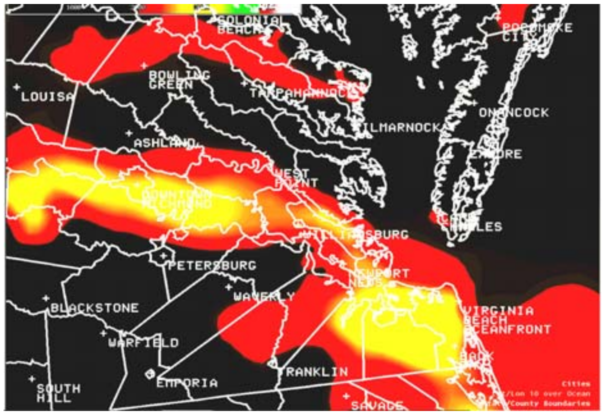

Figure 10. 12 UTC WsEta derived CAPE with shaded area greater then 2000 J kg^{-1} valid 21 UTC 30 August 2004.

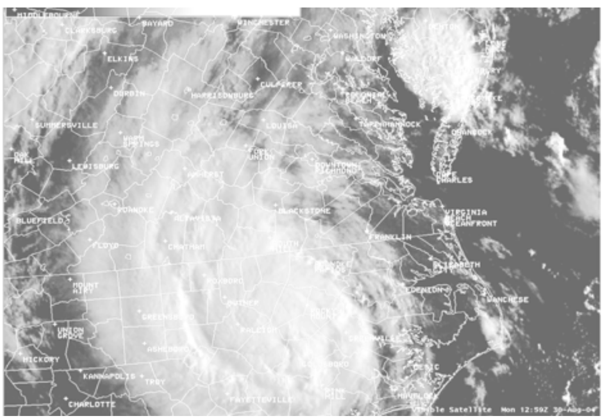

Figure 11. 13 UTC 30 August 2004 visible satellite.

morning. This allowed for greater insolation over this area through the morning giving higher temperatures. The 15 UTC RUC sounding for Newport News, shown in Fig. 12, is very moist and unstable. The wind profile shows both directional shear in the lowest levels and speed shear aloft supporting supercell development.

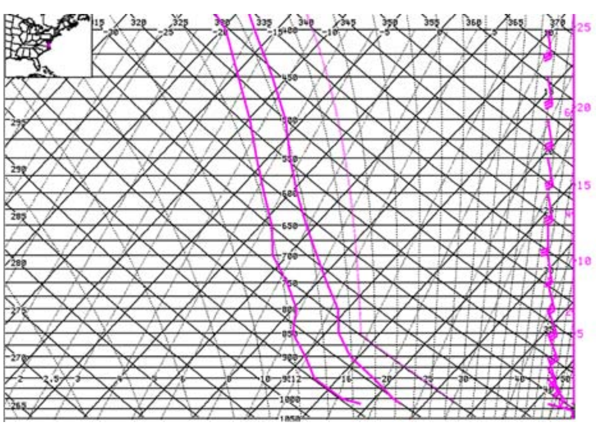

Figure 12. RUC sounding near Newport News,VA valid 15 UTC the area between the dotted line and temperature represents CAPE.

Developing convection is shown in Fig. 13, and stretches from near Hampton to Richmond along a surface boundary. This boundary is nearly stationary.

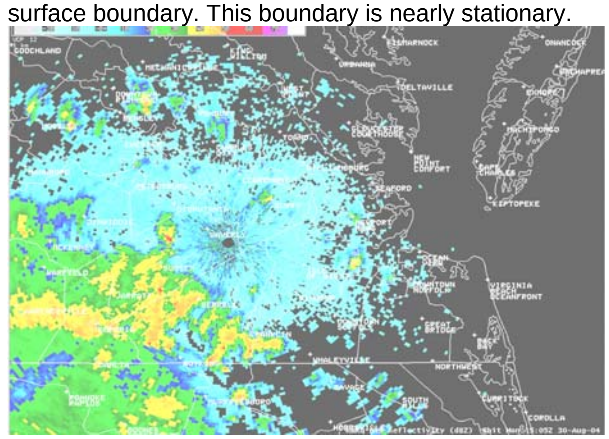

Figure 13. Wakefield WSR 88D 0.5 reflectivity at 15 UTC 30 August 2004.

The thunderstorms are moving northwest and slowing as they approach Richmond. The thunderstorms over the Richmond area showed rapidly cooling cloud top temperatures (Fig. 14). The coldest cloud tops have cooled to -70°C.

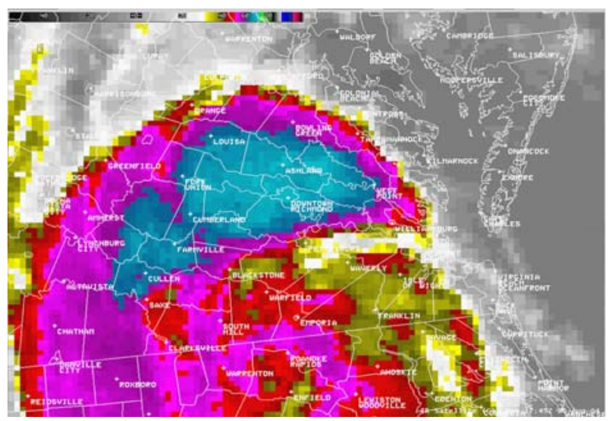

Figure 14. 18 UTC 30 August 2004 infrared satellite image.

As pointed out by Colle (2003), banding of heavy rainfall in inland tropical systems is related to thermal fields, wind and precipitation structures near the coastal zone. At 18 UTC, a boundary is evident in surface observations from near Virginia Beach northwest to Richmond (not shown). As shown in Fig. 15, very high dewpoint air in the mid to upper 70s, with Langley Air Force base reporting 79 °F, is located along a surface convergence area. This boundary remained stationary since 15 UTC. By 21 UTC this boundary rotated to the north, but the western end remained focused near Richmond. Figure 16 depicts the high CAPE values

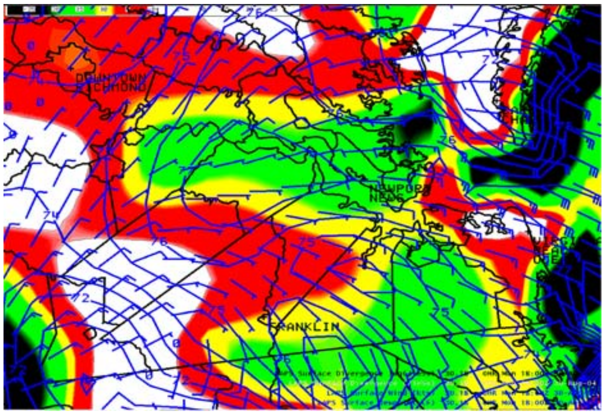

Figure 15. 18 UTC 30 August 2004 LAPS analysis surface winds, dewpoints (F; solid) and surface convergence shaded (10^{-5}s).

along this boundary. With southeast winds coming in from the Atlantic and across the mouth of the Chesapeake Bay, this wind flow is providing a connection to the abundant moisture near the Gulf Stream. This moisture is being drawn into this boundary.

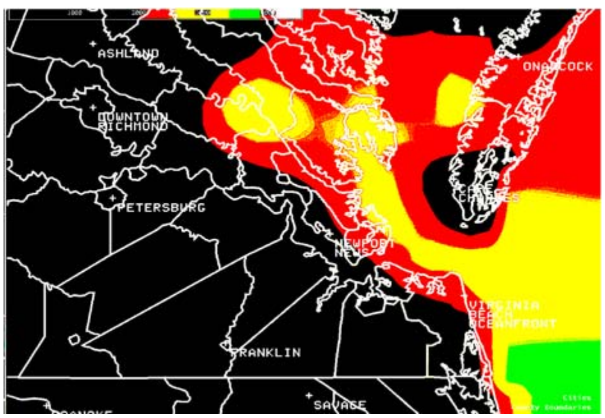

Figure 16. 21 UTC 30 August 2004 LAPS analysis of CAPE shaded area greater than 2000 J kg^{-1}.

The one hour rainfall as shown in Fig. 17 shows the heaviest rainfall in a curved area which is implying the turning of the thunderstorms from southeast motion to northeast motion. Where this turn occurs, the heaviest rainfall is occurring. This is centered over the Richmond area and remained here for several hours.

4. HYDROLOGIC CONSIDERATIONS

Several factors contributed to the substantial flooding in the Richmond metropolitan area. Despite no measurable precipitation in the preceding week, antecedent soil conditions remained relatively moist. This, in combination with the anticipated convective heavy rain bands normally associated with tropical system remnants, increased runoff potential. Urbanization was a tremendous factor as the heavy rainfall runoff from Gaston proved to be too much for the city of Richmond drainage system. The Wakefield, VA (KAKQ) 88D radar estimated one hour rainfall using the tropical Z/R relationship, and was only slightly below ground-truth observations. The Flash Flood Monitoring Program (FFMP) used in conjunction with the 88D proved to be an invaluable tool in detecting flash flooding in small basins. The digital precipitation array data was used by FFMP to plot curves of precipitation rate each volume scan. Figure 18 shows several peaks of greater than 3 inch per hour rainfall rates on the Shockoe Bottom sub basin.

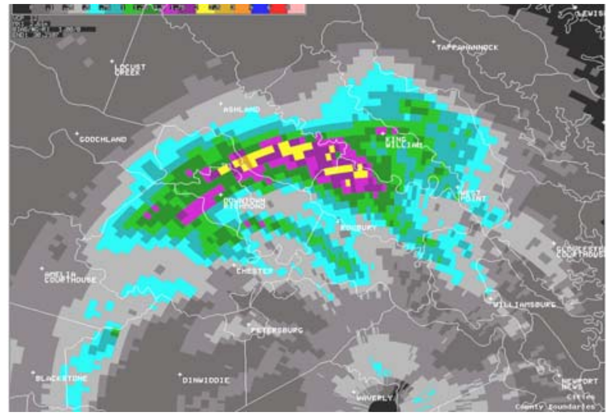

Figure 17. 21 UTC 30 August 2004 Wakefield radar (KAKQ) estimated one hour rainfall.

Since intense rainfall over a heavily urbanized basin typically results in very rapid and severe runoff at a lower flash flood guidance then non urban areas (Kelsch 2002), it was determined that for the sub-basin near Richmond flash flood guidance be lowered to near an inch per hour. Therefore the 2 to 3 inch per hour rate shown in Figure 18 greatly exceeded the one hour rainfall expected to produce flash flooding. The multiple peaks on the FFMP hourly precipitation rate display of over 1 inch per hour prompted the forecaster to issue a flash flood warning.

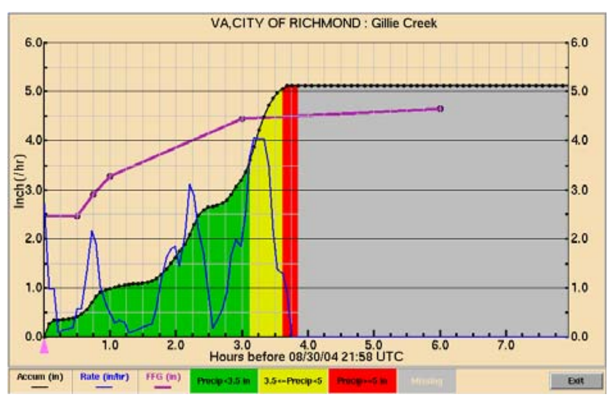

Figure 18. 2158 UTC 30 August 2004 FFMP graphic for a sub-basin near Shockoe Bottom in the city of Richmond.

5. CONCLUSIONS AND FORECASTERS AIDES

This study showed several key ingredients to be examined in the forecasting of potential flash flooding in tropical systems. Model QPF is typically one of the weaker forecast elements in numerical models and Gaston demonstrated this with poor forecasts of QPF by both the NAM and GFS over southeastern Virginia. The combined use of numerical model fields other than QPF and observations provides a means of looking for potential flash flood producing events.

Identifying the potential for flash flooding, due to tropical cyclones, starts with knowledge of pattern recognition. Examining the climatology of tropical systems' rainfall in relation to their synoptic patterns can help identify indicators for flash flooding. In particular, the track, including both speed and direction, for similar cases where flash flooding occurred were studied. In Gaston, the fact the system was slowing and turning indicated potential for flooding rainfall based on the climatology study of Cline (2002).

The amount of moisture is always an issue for flash flood forecasting in both tropical and non tropical systems. Gaston was showing signs of dry air coming into the system from the west as it moved across North Carolina. Assessing the progression of dry air is a key component in the process. The NAM and GFS models at both 00 UTC and 12 UTC kept the majority of the moisture just off the coast, which reduced the threat of flooding. The examination of surface and satellite data will show the location of moisture. The location and motion of this moisture should be compared with model forecast to determine if any adjustments to the moisture forecast of the model need to be made. As Gaston approached southern Virginia, high moisture was along and just off the coast early on 30 August 2004. The moisture can be observed by satellite and surface observations being pulled into the Gaston circulation.

Higher resolution models help with local topography issues, as well as show smaller scale atmospheric features. The WsEta with its higher resolution was able to capture that the moisture was forecasted to be incorporated into Gaston. It also showed stronger winds along the mouth of the Chesapeake Bay helping to channel this moisture to the west.

CAPE provides a measure of energy available to be released. Typically in tropical systems this value is relatively low around 500 J kg^{-1}. Substantially higher CAPEs would indicate the potential for stronger thunderstorms. The comparison of observational data to the WsEta forecast of Gaston CAPE revealed the good performance of the model. The WsEta developed CAPE over 2000 J kg^{-1}, which was observable on RUC and LAPs analysis soundings before the flooding rainfall developed near Richmond.

A location of enhanced lift such as small scale boundaries provided the focus necessary to produce flooding rainfall. The higher resolution on the WsEta developed a boundary, just not in the exact location. Observational data such as satellite visible imagery, surface observations, and radar can provide evidence of boundary location. Using the highest resolution LAPS analyses to show convergence can aid in the determination of the smaller scale boundaries. This evidence can provide a means to adjust forecasts to focus on these areas as the greatest potential for flooding rain.

Forecasters should use pattern recognition for determining potential flash flooding. Utilize surface observations, satellite imagery, and radar data, as well as RUC and LAPS analyses to compare parameters such as theta-e, moisture, CAPE and convergence with forecasts from models such as NAM, GFS and WsEta. Take advantage of the highest resolution models to look for small scale boundaries. By using local knowledge of topographic features make adjustments to flash flood guidance on the sub basin scale. Use appropriate tools such as FFMP to examine rainfall rates for flash flood potential. All these methods lead to improved situational awareness and early warnings in flash flood situations.

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