Development and Analysis of WSR-88D Hydrometeorological Algorithms

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1 Introduction

Analyses of WSR-88D hydrometeorological algorithms have focused on estimation of extreme rainfall from flash-flood producing storms. Of particular interest has been rainfall estimation at time scales between 5 and 6 minutes and at spatial scales from 1 - 100 km^2. The methodological approach has continued to focus on analyses of WSR-88D Level II data for *major* storms. We have continued work during the past year on storms in the Baltimore metropolitan region and in Puerto Rico. We have also included analyses of a series of flash-flood producing storms in the Philadelphia metropolitan region.

The principal results derived from these analyses are the following:

1. WSR-88D rainfall estimates can resolve the spatial and temporal distribution of flash-flood producing storms in urban catchments down to the finest time and space resolutions of the radar.

2. Flood response in urban catchments at 0.1 to 100 km^2 scale is strongly determined by the magnitude of rainfall rates at 1 - 15 minute time scale. Estimating extreme rainfall rates at these time and space scales is the central problem of urban flash flood forecasting.

3. Vertical motion plays a major role in determining the error characteristics of radar rainfall rate estimates for extreme rainfall rates.

4. Systematic overestimation of heavy rainfall events is characteristic of the tropical Z-R relationship in the Philadelphia metropolitan region. Underestimation of rainfall is typical of analyses based on the default Z-R relationship. The magnitudes of bias values using the tropical Z-R relationship were comparable for 4 events with widely differing storm characteristics (including remnant tropical cyclones); bias values ranged from 0.64 to 0.78 with an average value of 0.74. For the default Z-R relationship, bias values for the four events ranged from 1.32 to 1.53 with an average value of 1.40.

5. Multiplicative bias is the dominant control of differences in rainfall estimates between the default and tropical Z-R relationships.

6. The error characteristics of radar rainfall estimates for hurricanes exhibit systematic dependence on storm structure. In particular, there are pronounced contrasts between the eyewall, inner core rainbands and outer core rainbands, as identified by Molinari et al. [1999].

We elaborate on these conclusions below in discussions of each of the three major sections of the report. These sections deal with: 1) heavy rainfall events in the Baltimore metropolitan region, 2) heavy rainfall in the Philadelphia metropolitan region and 3) heavy rainfall from Hurricane Georges in Puerto Rico.

2 Analyses of Heavy Rainfall Events in the Baltimore Metropolitan Region

Analyses have been carried out for flash-flood producing storms in the Baltimore metropolitan region. In this section, results are summarized for storms that produced significant flooding in the Moores Run watershed, which is located in the northeastern corner of Baltimore City. The Moores Run watershed has two USGS stream gages, one which will be termed the "Radeke Avenue" gage and a second, which will be termed the "Moores Run tributary". The drainage basin above Radeke Avenue has a drainage area of 3.52 mi^2 and the drainage area above the tributary gage has a drainage area of 0.20 mi^2. The order of magnitude range in drainage areas covers the spatial scales of drainage basins that represent rapidly responding urban catchments.

Analyses are presented for 7 storms, which occurred on the following dates: 1) 13-14 June 2003, 2) 3 August 2002, 3) 6-7 July 2003, 4) 21 April 2000, 5) 14 July 2000, 6) 13 May 2000, and 7) 28 August 2000. The 13-14 June 2003 storm produced the record flood peak in Moores Run. The Moores Run stream gage at Radeke Avenue did not function during the event. The peak discharge based on high-water marks has been estimated to be approximately 23 $m^3\ s^{-1}\ km^{-2}$. The 13-14 June 2003 peak was approximately twice the magnitude of any other flood peak. Three storms have produced flood peaks with unit discharge values exceeding 11 $m^3\ s^{-1}\ km^{-2}$. Two of these storms are included among the storms analyzed for this report: the 3 August 2002 and 6-7 July 2003 storms. The third event occurred on 2 September 1998 (analyses have been initiated for this event using Sterling WSR-88D Level II data; rain gage and discharge data have not yet been obtained for this event). The 13-14 June 2003 storm also produced the record flood peak at the Moores Run tributary gaging station. The 3 August 2002, 6-7 July 2003, 2 September 1998 storms and 21 April 2002 storms are of comparable magnitude to one another, but have markedly smaller peak discharges than the 13-14 June 2003 event.

2.1 13-14 June 2003

Flash flooding occurred in Baltimore City during the evening of 13 June 2003 in response to a 45-minute period of rainfall beginning at approximately 2315 UTC. Record flooding occurred in Moores Run and major street flooding to the southwest of Moores Run resulted in property damage and successful rescue of residents caught in the flood.

The flood episode was initiated shortly after the merger of two storm elements around 2330 UTC (see Fig. 1 and the july1314.avi movie loop). Storm orientation resulted in an axis of peak rainfall accumulations (Fig. 2) extending from southwest of Moores Run through the Moores Run watershed and northeast into Baltimore

County. The rainfall accumulation map was derived from the Sterling WSR-88D Level II reflectivity observations using the default Z-R relationship and a 55 dBZ reflectivity threshold. No bias correction was applied. The 50 mm rainfall accumulation contour covered an area of approximately 15 km^2 and cut through the upper portion of the Moores Run watershed.

The Moores Run tributary gage is located in the southwestern portion of the basin. The basin boundary is shown in Fig. 2 and on other storm total maps in this section. The 40 mm rainfall contour cuts through the tributary basin. There is a sharp gradient in storm total accumulation over the lower portion of the Moores Run basin.

The Moores Run stream gage at Radeke Avenue did not function through the event. Based on high-water marks and an extended rating curve, initial estimates of the Radeke Avenue peak discharge are approximately 23 $m^3\ s^{-1}\ km^{-2}$. The Moores Run tributary gaging station produced a complete stage hydrograph for the event. The discharge hydrograph in Fig. 3 is truncated at 12 $m^3\ s^{-1}\ km^{-2}$, although the stage observations extend well above those associated with a discharge of this magnitude. Additional analyses are being carried out by the USGS to extend the rating curve. Preliminary analyses indicate that the peak discharge for the Moores Run tributary gage would approach the 23 $m^3\ s^{-1}\ km^{-2}$ similar to the Radeke Avenue site. The response time for the Moores Run Tributary station (Fig. 3) is approximately 10 minutes.

Rain gage observations were provided by the Baltimore City Department of Public Works for the event (Fig. 4). The rain gages are denoted "RG2" and "RG5". The RG2 gage is located in the upper Moores Run watershed and the RG5 gage is located just to the west of the basin.

The radar rainfall rate estimates at 5-minute time interval for the bin containing the RG2 gage agree quite well with the gage observations. The rain gage observations have a slightly larger peak 5 minute rainfall rate (145 $mm\ h^{-1}$) than the radar observations (120 $mm\ h^{-1}$). The storm total accumulation from the RG2 gage was 59.9 mm, less than 10 % more than the 55.1 mm accumulation from the radar rainfall estimates. The analyses for the RG5 gage are quite similar. The agreement between radar and rain gage estimates at 5-minute time interval is quite good. The storm total rainfall from the RG5 gage of 41.1 mm was only 5 % more than the radar rainfall accumulation from the gage.

Gage and radar analyses indicate that the storm contained a 10-15 minute period of extreme rainfall rates that was largely responsible for the extreme nature of flooding. The peak 5 minute rainfall rate from the RG2 gage decreases to only 140 $mm\ h^{-1}$ at 10 minute time interval and the 15 minute rainfall rate exceeded 120 $mm\ h^{-1}$.

2.2 3 August 2002

The 3 August 2002 storm was a severe thunderstorm (see Fig. 5 and movie loops of reflectivity and Doppler velocity from the BWI Terminal Doppler Weather Radar) that formed near the Maryland - Pennsylvania border and moved to the south through Baltimore County at approximately 40 $km\ h^{-1}$. Outflow boundaries from storms that had formed earlier to the east of Baltimore intersected the storm shortly before it reached Baltimore City (see TDWR movie loops, especially Doppler velocity loops).

Storm total rainfall estimates (Fig. 6) derived from Sterling reflectivity observations and using the default Z-R relationship have a maximum accumulation of more than 80 mm located on the western boundary of the Moores Run watershed. The storm total rainfall distribution reflects storm motion and intensification of the storm following interaction with outflow boundaries north of the Baltimore City line.

Unlike the 13-14 June 2003 radar rainfall estimates, the WSR-88D rainfall estimates are biased high compared to rain gage observations (Fig. 7). The rain gage data is from the Hazlewood Elementary School rain gage maintained by Baltimore City (data were provided by Rich Fulton). The Hazlewood gage is located just to the north of the Moores Run Tributary stream gage. It is located quite close to the maximum radar rainfall accumulation in Fig. 6. The peak rainfall rates from radar of 144 $mm\ h^{-1}$ are bounded by the reflectivity cap for the 15 minute period with peak rain rates. The Hazlewood rain gage has a peak 5-minute rain rate of 120 $mm\ h^{-1}$ and the 15 minute rain rate exceeds 100 mm h^{-1}.

The storm total accumulation for the Hazlewood rain gage (54.4 mm) was less than 60 % of the radar rainfall accumulation for the gage. The relatively large bias is consistent with the observation that the Moores Run and Moores Run tributary peak discharges were substantially smaller for the 3 August 2002 event than for the 13-14 June 2003 event.

The peak rainfall rates for the 3 August 2002 storm were slightly lower than those for the 13-14 June 2003 storm and the spatial extent of extreme rainfall rates was different for the two storms. Of particular importance is the sharp gradient in peak rainfall over the basin, with radar rainfall accumulations decreasing from 100 to 50 mm from west to east over the basin.

2.3 6-7 July 2003

The 6-7 July 2003 storm (Figs. 8 - 10) produced a flood peak in Moores Run that was comparable to the 3 August 2002 flood peak. Like the preceding storms, flash-flood producing rainfall was concentrated in a time period of 15-20 minutes, the storm total accumulations (Fig. 11) exhibited an elongated maximum that was centered over Moores Run, and peak rainfall rates at 5 - 15 minutes ranged from 100 to 150 $mm\ h^{-1}$.

The peak rainfall rates over Moores Run were concentrated around 0150 UTC. A distinctive feature of the July 2003 storm was that it appeared to exhibit vigorous growth coinciding with the time of maximum rainfall rates. A striking feature of the vertical profile of the storm (Fig. 10) was the growth of the 55-60 dBZ region in the upper portions of the cloud around 0150 UTC. In this respect, the storm contrasts with other storms producing extreme rainfall rates and flash flooding. As opposed to other events in which peak rainfall rates are associated with downdraft-dominated element of the convective cycle, the July 2003 storm produced peak rainfall rates at a time when the storm was updraft-dominated.

Even though the 6-7 July 2003 storm produced near-record flood peaks in Moores Run, the fraction of rainfall that was converted to runoff was relatively small. For the Moores Run Tributary station (Fig. 12) the basin-averaged rainfall was 46.4 mm and the runoff was 17.7 mm. Less than 40 % of the rainfall over the basin was converted to runoff. This feature is typical of flood response in Moores Run and other urban watersheds in the Baltimore Metropolitan region. Storage is an important element of basin response and constructed elements of the storage system, like detention basins, play a critical role in flash flood response.

Gage-radar intercomparisons for the 6-7 July 2003 storm (Fig. 13), like those for the 13-14 June 2003 storm, show excellent agreement between gage and radar rainfall estimates in the region of maximum rainfall. The Baltimore City "RG2" rain gage is located close to the maximum rainfall accumulation for the storm. As with the 13-14 June storm, peak rainfall rate estimates from radar are slightly lower than those from rain gages. Also, the time distribution is slightly broader for the radar rainfall estimates reflecting the differences in spatial sampling of the two sensors. Storm total rainfall from the RG2 gage of 39.9 mm is very close to the 40.7 mm radar rainfall accumulation.

Peak 5-minute rainfall rates exceeded 140 $mm\ h^{-1}$ and the 10 and 15 minute rainfall rates exceeded 100 $mm\ h^{-1}$.

2.4 21 April 2000

The 21 April 2000 event produced one of the largest flood peaks in the Moores Run Tributary basin. The Moores Run flood peak was produced by a rapidly moving storm element with a collapsing reflectivity profile (Figs. 14 and 15). The peak rainfall rates over Moores Run were concentrated in a 10 - 15 minute period centered around 2150 UTC on 21 April. During the time period between 2143 and 2203 UTC, the peak reflectivities for the storm at 4.5 km elevation decrease from 50 dBZ to 40 dBZ.

The rainfall distribution exhibited sharp gradients with peak accumulations of 45 mm in the lower portion of the Moores Run basin. As a consequence, the Moores Run tributary basin had a much larger unit discharge flood peak than the Radeke Avenue gaging station (Fig. 17). The storm total accumulation for the Moores Run tributary basin was 42 mm and the runoff was 11.0 mm. For the Radeke Avenue station the basin-averaged rainfall was 31.5 mm and the runoff was 5.0 mm.

2.5 14 July 2000

The 14 July 2000 storm produced the largest radar rainfall accumulations in Moores Run of any event that has been analyzed. The storm was a severe thunderstorm, embedded in a major convective outbreak (see Figs. 18 - 21 and july142000.avi movie loop). Reflectivity values exceeded 60 dBZ in the 9.5 km elevation CAPPI and surface reflectivities exceeded 65 dBZ.

Radar rainfall accumulations (Fig. 22) exceeded 100 mm and the peak accumulation of 250 mm was approximately 7 km southeast of the Moores Run watershed. Rainfall accumulations reflect the small net storm motion (Figs. 18 - 21 and july142000.avi movie loop) and extreme reflectivity values of the storm. Rainfall accumulations are quite sensitive to the reflectivity threshold. The rainfall analyses in Figs. 22 and 24 were based on a 55 dBZ threshold.

Despite the extreme rainfall accumulations, the 14 July 2000 storm produced flood peaks in Moores Run that were not only smaller than the 13-14 June 2003 record peak, but also smaller than the group of events clustered around the second largest peak (3 August 2002, 6-7 July 2003, 21 April 2000 and 2 September 1998). The peak discharge at the Moores Run Tributary location (Fig. 23) peaked at approximately 7 $m^3\ s^{-1}\ km^{-2}$, or 60 % of the 21 April 2000 peak (Fig. 17). The striking difference between the two events, is that the 14 July event exhibited a series of six peaks, corresponding to maxima in rainfall rate as reflected in the 5-minute Hazlewood rain gage observations. Although the 14 July 2000 storm did not produce comparable flood peaks to preceding events, it did produce near-record storm event runoff. The runoff from the Moores Run tributary gage of 28.6 mm more than doubled the runoff the 21 April 2000 storm.

The WSR-88D radar rainfall estimates produced a storm total accumulation of 128 mm at the Hazlewood gage location, where 75.7 mm of rain were recorded. From 2135 to 2205 the radar rainfall estimates are uniformly above 140 $mm\ h^{-1}$. During this period the Hazlewood rain gage observations range from 60 - 90 $mm\ h^{-1}$ in two distinct pulses of heavy rain. Hail contamination results in elevated rainfall rates and prevents discrimination of periods of lower rainfall rates.

The 14 July 2000 storm produced lower peak discharges in the Moores Run watershed than events with far lower storm total accumulations because of lower rainfall rates at 1 - 15 minute time scale. The storm illustrates the importance of temporal variability of rainfall rate at the 5-6 minute volume scan of the WSR-88D and accurate estimation of peak rainfall rates at these time scales.

2.6 13 May 2000

The 13 May 2000 flood in Moores Run was produced by a line of thunderstorms that moved rapidly over the region (Figs. 25 - 27 and may132000vert.avi movie loop). Vertical motion played an important role in the distribution of rainfall rates for the storm.

The evolution of the convective cell that passed over the Moores Run watershed exhibits a cycle of growth and decay. At 2336 UTC (Fig. 25), the storm has reached peak growth. Decreasing echo centroids and spread of high reflectivity to the rear of the storm is shown at 2346 UTC (Fig. 25). Growth of the low-level reflectivity maximum to the rear of the storm continued as the storm passed over Moores Run (Figs. 26 and 27). The movie loops, may132000vert.avi, illustrate a complete cycle of growth up the front side of the storm and decay to the rear of the storm for the cell to the north of the one that passed over Moores Run.

The storm total accumulation over the Moores Run watershed (Fig. 28) decreased from north to south over the basin with accumulations greater than 40 mm at the northern boundary decreasing to approximately 35 mm at the southern boundary of the basin. Rainfall was concentrated in a 10 - 15 minute time period centered at 2350 UTC (Figs. 25 - 27 and Fig. 29).

The timing of response of the Moores Run Tributary gage (Fig. 29) suggests that the time distribution of heavy rainfall from the WSR-88D rainfall estimates is too long. The rise and fall of the Moores Run Tributary hydrograph is contained within the time envelope of WSR-88D rainfall rate estimates which exceed 25 $mm\ h^{-1}$. Similar features were noted in comparing the WSR-88D rainfall rate estimates with the Hazlewood Elementary School rain gage observations for the 3 August 2002 storm (Fig. 7).

2.7 28 August 2000

The 28 August 2000 storm (Fig. 30) produced flood peaks in Moores Run that were comparable (or larger than) those from the 14 July 2000 storm. The surprising aspect of this observation is that storm total rainfall estimates for the 28 August storm (Fig. 31) were almost an order of magnitude smaller than those from the 14 July 2000 storm.

The storm was rapidly moving (approximately 60 $km\ h^{-1}$) and exhibited a pronounced Low Echo Centroid (LEC) structure. Peak reflectivity values ranged from 50 dBZ at the lowest elevation angle to less than 40 dBZ in the 4.5 km elevation CAPPI (Fig. 30).

The storm produced peak discharges at the Moores Run gaging stations that ranged from just under 4 $m^3\ s^{-1}\ km^{-2}$ at the Radeke Avenue gaging station to 5 $m^3\ s^{-1}\ km^{-2}$ at the Moores Run Tributary station. Runoff ratios (ratio of storm total runoff to storm total rainfall) for the event were approximately 60 %, much larger than for any other event. Peak WSR-88D rainfall rates reached only 30 $mm\ h^{-1}$. Comparing with response of the preceding events, the magnitudes of peak discharge in the Moores Run catchment suggest that peak rainfall rates approached 100 $mm\ h^{-1}$. This implies that the bias of WSR-88D rainfall rate estimates approached a factor of 3. This magnitude of bias would also place the runoff ratio for the Moores Run basin within the typical range of response for the catchment.

3 Analyses of Heavy Rainfall Events in the Philadelphia Metropolitan Region

Hydrometeorological analyses of rainfall and flood response are presented for three urbanizing drainage basins in the Philadelphia metropolitan: Wissahickon Creek, Pennypack Creek and the Little Neshaminy River. Analyses focus on four major flood events, the remnants of Tropical Storm Allison (16-17 June 2001), Hurricane Floyd (16-17 September 1999), the 16-17 October 1996 extratropical cyclone and the 19-20 January squall line event.

The largest flood peaks in the region were produced by Allison and Floyd and these peaks were much larger than preceding peaks in the region. For the Wissahickon Creek at 168 km^2 (USGS Gage ID 01474000), the flood peak from Allison nearly doubled the third largest flood peak, but was only 65 % of the flood peak magnitude from Hurricane Floyd in 1999. The difference between the peak magnitudes diminishes at the 106 km^2 scale of the USGS gaging station on Wissahickon Creek at Fort Washington. For Little Neshaminy Creek at 69.4 km^2, Allison produced a flood peak that was 25 % larger than the peak from Floyd. The USGS gaging station on Pennypack Creek malfunction during Allison, so direct comparisons of the two flood peaks is not possible. The headwaters of Pennypack Creek were the location of 8 flood fatalities from Allison.

The January 1996 storm (see jan191996.avi movie loop) produced record and near-record flooding in the Susquehanna and Delaware River basins (Barros and Kuligowski [1998]). Flooding resulted from a combination of snowmelt and anomalously high rainfall rates. Rainfall over the Philadelphia metropolitan region was associated principally with a pre-frontal squall line that moved rapidly over the region. The October 1996 storm (see oct191996.avi movie loop) also had an extensive history of flooding in the northeastern United States. The storm produced record rainfall and flooding in southeastern Maine. Storm total accumulations of more than 800 mm were reported in Maine and resulted in several dam failures. Hurricane Floyd (Atallah and Bosart [2003]) produced record flooding in North Carolina, eastern Pennsylvania and New Jersey. Tropical Storm Allison was most noted for flooding in Texas and Louisiana but 8 fatalities, numerous bridge failures and extensive property damage all occurred in a small section of the northeastern Philadelphia metropolitan region (see june162001.avi movie loop).

Rainfall analyses (Figs. 1 - 4) were performed for the 4 events using WSR-88D Level II reflectivity observations from the Fort Dix WSR-88D (brief gaps in the September 1999 storm were filled with Dover WSR-88D observations). Analyses were performed using the default Z-R relationship, $Z = 300 R^{1.4}$ and the tropical Z-R relationship $Z = 250 R^{1.2}$ Bias correction was carried out using rain gage data obtained from NCDC and from the NWS forecast office in Fort Dix.

Not surprisingly, there are large differences in storm total accumulations between the tropical and Z-R relationships. Peak rainfall accumulations for Allison of more than 600 mm are more than twice the peak accumulation values obtained from the default Z-R relationship (Fig. 4). There are, however, relatively small differences in rainfall accumulations for the bias-adjusted rainfall analyses. This implies that the differences in storm total rainfall for the four events is relatively insensitive to the exponent in the Z-R relationship.

Despite marked differences in storm properties, the multiplicative bias values estimated from gage-radar intercomparisons are quite similar. For the default Z-R relationship, bias values were 1.32 (October 1996), 1.35 (June 2001), 1.41 (September 1999) and 1.53 (January 1996). The average bias for the four events using the default Z-R relationship was 1.40. For the tropical Z-R relationship, the bias values were 0.64 (June 2001), 0.76 (October 1996), 0.77 (September 1999) and 0.78 (January 1996) for an average value of 0.74.

The hydrograph for the January 1996 flood in Wissahickon Creek (Fig. 5) began to rise approximately 10 hours prior to the onset of rainfall. Throughout the Susquehanna and Delaware River basins, anomalously rapid temperature increases and large antecedent snowpack resulted in a major contribution to flood response from snowmelt. For Wissahickon Creek, the estimated storm total rainfall was 34 mm and the runoff was 99 mm, resulting in a snowmelt contribution (assuming no infiltration) of 65 mm. For Pennypack Creek, the estimated storm total rainfall of 28 mm and storm runoff of 53 mm results in a snowmelt contribution of 25 mm. The peak response of the basin is controlled by the large rainfall rates associated with the rapidly moving squall line (Figs. 9 and 10).

The October 1996 flooding in the Philadelphia metropolitan region (Fig. 6) was produced by an 8-hour period of moderate rainfall rates (Fig. 11) punctuated by a brief period of elevated rainfall rates associated with a weak, embedded line of convection (Fig. 12). Flood peaks from the October 1996 storm in the Wissahickon and Pennypack basins were comparable to those from the January 1996 storm.

Hurricane Floyd produced record flooding in the Wissahickon and lower Pennypack Creek basins. Rainfall rates from Floyd were larger than those from the October 1996 storm, but much smaller than the peak rainfall rates from the Baltimore storms described above or the January 1996 and June 2001 storms. Extreme flooding was most pronounced at basin scales larger than 100 km^2. At smaller basin scales, the June 2001 produced much larger flood peaks than the September 1999 storm.

Record flooding in the upper Pennypack Creek, Little Neshaminy River and Sandy Run tributary of Wissahickon Creek was associated with the rainfall maximum inside the 200 mm storm total contours of the bias-adjusted rainfall analyses in Fig. 4. The remnants of Tropical Storm Allison were centered over Virginia during the period of peak rainfall. The rainfall distribution over the region (see Figs. 13 and 14 and june162001.avi movie loop) was characterized by multiple convective elements tracking over the region during a 12-hour time period (Fig. 8). Peak WSR-88D rainfall rates exceeded 100 $mm\ h^{-1}$.

4 Hydrometeorological Analyses of Hurricane Georges in Puerto Rico

The flood hydrology and hydrometeorology of Puerto Rico (see Fig. 1 for location map) are of special interest because of the high frequency of extreme "unit discharge" flood peaks relative to other locations in the United States (O'Connor and Costa [2003]). Tropical cyclones play a central role in the hydrology of extreme floods in Puerto Rico and many of the record flood peak measurements in Puerto Rico were associated with tropical cyclones, most notably Hurricane Donna (6 September 1960; see Barnes and Bogart [1961]), Hurricane Hortense (10 September 1996) and Hurricane Georges (21-22 September 1998).

In this section, hydrometeorological analyses of Hurricane Georges are presented, based on volume scan radar reflectivity observations from the San Juan WSR-88D radar and rain gage observations from the USGS rain gage network in Puerto Rico. The spatial distribution of extreme rainfall accumulations from Hurricane Georges is contrasted with the distribution of extreme rainfall rates. An important element of flood response is that the most exceptional flood peaks produced by Hurricane Georges were the product of extreme rainfall rates during a 30-45 minute period from a single element of eyewall convection. Orographic precipitation mechanisms play an important role in determining both the maximum rainfall accumulations from the storm (in the central mountain core of the island) and maximum rainfall rates from the storm (on the eastern portion of the island). Storm structure and motion play are important not only in determining the spatial and temporal variability of rainfall, but also in determining the error properties of radar rainfall estimates. Of particular importance are the contrasting properties of the inner core region, consisting of eyewall convection and inner core rainbands, and the outer rain band region of the storm (Molinari et al. [1999] and Cecil et al. [2002]).

Hurricane Georges moved from east to west over Puerto Rico at a speed of approximately 21 $km\ h^{-1}$ (see the movie loop georges.avi). The 190 km path over the island took 9 hours (from 2120 UTC on 21 September to 0620 UTC on 22 September) and the period of rainfall over the island was approximately 24 hours (from 1930 UTC on 21 September to 2000 UTC on 22 September). The eye of the storm passed directly over the island and storm motion oscillated slightly from northwest, as it reached the island, to west-southwest, as it exited the western end of the island. Storm speed did not vary markedly as the system passed over Puerto Rico. Hurricane Georges weakened as it made landfall, with minimum sea level pressure increasing from 970 to 978 hPa during passage over the island. Minimum sea level pressure decreased to 962 hPa with passage over the Mona Passage between Puerto Rico and Costa Rica. The low-reflectivity region of the eye was more than 1000 km^2 in size both on entering the island and after exiting the island (see georges.avi).

The structure of rainfall fields and the error characteristics of radar rainfall estimates for Hurricane Georges are examined in terms of the three regions of a hurricane identified by Molinari et al. [1999] (see also Cecil et al. [2002]): 1) the eyewall region, 2) the inner rainband region and 3) the outer rainband region (Figure 2). The eyewall is the region of precipitation surrounding the circulation center. It is approximately circular in form, but is not necessarily completely closed. The inner rainband region extends from the eyewall to approximately 100 km and is often bounded by a precipitation free area adjacent to prominent outer rain bands. The outer rainband region begins approximately 150 km from the cyclone center. Molinari et al. [1999] show large contrasts in convective intensity, as reflected in cloud-to-ground (CG) lightning strikes, between the inner core region, consisting of the eyewall and inner rainbands, and outer rainband region of hurricanes. The more convectively active outer rainbands contain the large majority of CG strikes.

Hurricane Georges, like many tropical cyclones, exhibited an asymmetric rainfall structure around the eye through much of the life cycle of the storm. At 1923 UTC (see georges.avi) on 21 September, the eye of Hurricane Georges, which was was approximately 1000 km^2 in area, was less than 50 km from the coastline. The onset of rainfall on the eastern portion of the island began at approximately 1930 UTC. At 1923 UTC, the reflectivity structure of the storm exhibited a pronounced asymmetry with more extensive development in the southern and eastern sectors of the storm This pattern of asymmetry persisted throughout much of the life cycle of the storm. Rain bands developed in the southeastern sector of the storm and passed from south to north over the island. Throughout the life cycle of Hurricane Georges over Puerto Rico, the “upslope” portion of the storm was located on the south (or southeast) side of the mountains.

The eye of Georges reached the eastern end of the island at 2117 UTC (see georges.avi) and was still structured as a near-circular, low-reflectivity region. A thin inner core rain band extended from north-to-south over the island, passing through the location of the San Juan WSR-88D radar. This band was responsible for the first pulse of high rainfall rates in the eastern and central portions of the island. During passage of Hurricane Georges over Puerto Rico, the eye region filled rapidly and eyewall convection was influenced by interactions with the complex terrain of the island for a discussion of orographic convection).

The largest rainfall rates from the storm occurred on the eastern portion of the island during a period of less than 1 hour, beginning at approximately 2345 UTC on 21 September. Eyewall convection intensified on its southern side as the eye passed over the eastern margin of the island, resulting in a high-reflectivity region along the southeastern and eastern portion of the island at 0000 UTC on September 22 (see georges.avi). Peak flood response in the eastern catchments of Puerto Rico was associated with this element of the storm. It produced the peak discharge for the Rio Grande de Loiza (see Figs. 13 and 14 and Fig. 1 for location) which exceeded the

United States flood peak envelope curve. The element of eyewall convection exhibited rotational signatures and its evolution is similar to the "eyewall mesovortex" described in Blackwell [2000] for Hurricane Danny.

The largest rainfall accumulations from the storm occurred in the central mountains of the island and the largest rainfall rates contributing to these peak accumulations were associated with eyewall convection and inner core rain bands (Figs. 2 d and e). During the period of peak rainfall rates over the central mountains, eyewall convection developed over ocean south of the island and wrapped up to the mountain barrier (see georges.avi).

Heavy rain fell over the western portion of Puerto Rico for 12 hours after the eye of the storm exited Puerto Rico at 0600 UTC (see georges.avi). At this time, north-south oriented rain bands were producing heavy rainfall (rain rates greater than 25 $mm\ h^{-1}$) over the island. Flood response in the western portion of the island (including the Arecibo and Tanama basins discussed in the following section) was due to rainband rainfall which developed in the southeastern sector of the storm and intensified over Puerto Rico in north-south oriented regions of embedded convection (Figs. 2 g and h).

The properties of radar rainfall estimates vary systematically with storm structure, as illustrated in the gage - radar rainfall analyses for the Rio Gurabo rain gage (Fig. 3). The most important element of these analyses is the overestimation of rain rate in the outer rain band region of the storm, using the tropical Z-R relationship. For the final period of heavy rainfall around 1200 UTC from outer rainbands, radar rainfall estimates for Rio Gurabo using the tropical Z-R equation are more than 50 % larger than rain gage observations. This feature is characteristic of gage-radar intercomparisons over much of the island. Overestimation of rainfall by the tropical Z-R relationship is consistent with the conclusions of Molinari et al. [1999] and Cecil et al. [2002] that the outer rainband region of hurricanes is the most convectively active portion of the hurricane. There is a pronounced underestimation of rain rates for the period of intense eyewall convection (Fig. 3). It is argued below, based on the evolution of vertical structure of this storm element, that vertical motion plays an important role in underestimation of rain rate for this element of the storm.

Storm total accumulation maps were developed from WSR-88D reflectivity observations. Rainfall maps were developed using the tropical Z-R relationship with a 52 dBZ reflectivity threshold (rainfall estimates were not overly sensitive to the reflectivity threshold, based on analyses using thresholds ranging from 50 - 55 dBZ). The largest rainfall accumulations for the storm were located along the high elevation regions of the island (Fig. 4; see Fig. 1 for location map with basin boundaries). The contours of maximum rainfall from the radar rainfall analyses are oriented from southwest to northeast over the Rio Saliente basin (Fig. 4), following the contours of the high elevation maxima of the region (Fig. 1). The gradients in rainfall accumulation from the center of the Rio Saliente basin are much sharper to the north, with storm total rainfall decreasing from a maximum of 720 mm to a minimum of 400 mm at the basin outlet. An elevated region of storm total rainfall exceeding 500 mm extends southward from the Rio Saliente basin. Analyses indicate a rainfall maximum extending southward from the highest elevation region of the island, with a sharp decrease in rainfall accumulation to the north of the mountain barrier.

For much of the storm life cycle, the vertical structure of reflectivity (Figs. 5 and 6) in the eyewall and inner rainband region of the storm was characterized by relatively weak convection in which peak reflectivities occurred close to the radar "bright band" (the region of elevated reflectivity associated with melting snow crystals below the 0 degree C level). The location of the bright band was approximately 4 km above ground level. Mean vertical profiles of reflectivity were constructed for a 30 km east-west cross-section located along the southern slopes of the island and a 30 km east-west cross-section located 40 km south of Puerto Rico over open ocean (Fig. 7). The mean reflectivity profiles are quite similar in the ice phase portion of the clouds above approximately 4 km. Below the 0 degree C level, there are sharp contrasts in the reflectivity profile with the lowest level reflectivity values over land nearly 1.5 dB higher than over open ocean. The vertical profiles are consistent with forced ascent over the upslope mountain barrier leading to high cloud water content. Orographic enhancement of precipitation over the upslope regions of the island resulted from scavenging of high cloud water and growth of precipitation to the ground surface. The sharp decrease in rainfall accumulation north of the mountain barrier is due to suppression of precipitation by downslope motion.

Storm total rainfall estimates for the Luquillo mountain region in northeastern Puerto Rico (Fig. 8) also exhibit the striking controls of orographic precipitation mechanisms. The axis of rainfall accumulations exceeding 400 mm contains the line of highest elevation in the Luquillo (note three peaks in Fig. 1). Rainfall accumulations contours from 200 - 400 mm northwest of the rainfall maximum are oriented southwest to northeast, roughly following the elevation contours. The 200 mm contour in the southwestern portion of the 900 km^2 region is contained within the low-elevation valley between Canovanas and Loiza. The major difference between rainfall accumulations in Canovanas and the central mountain basins was tied to the contributions from the period of intense eyewall convection around 0030 UTC.

The most striking aspect of Hurricane Georges was the development of deep convection in the eyewall over ocean after 2230 UTC (Figs. 9 and 10). Peak reflectivities exceeding 50 dBZ extended to 10 km AGL. Echo centroid elevation of this storm element decreased rapidly as it made landfall and passed over the eastern portion of the island. This period of decreasing echo centroid elevation was associated with the peak rainfall rates from the storm and record flooding in the Rio Grande de Loiza basin (Figs. 13 and 14).

The Rio Grande de Loiza peak (Fig. 14) discharge of 80 $m^3\ s^{-1}\ km^{-2}$ was not only the largest unit discharge flood peak for the event, but also exceeds the US envelope curve. Like the Rio Grande and Rio Canovanas peaks, the Rio Grande peak was associated with eyewall convection during the period between 2345 UTC and 0030 UTC. The most important element of the largest unit discharge flood peaks from Hurricane Georges was evolution of eyewall convection during this period.

The Rio Grande de Loiza peak unit discharge of 80 $m^3\ s^{-1}\ km^{-2}$ can be expressed as a discharge rate of 300 $mm\ h^{-1}$. There is no direct support for rainfall rates approaching this magnitude, either from rain gage or radar. The storm total runoff for the Rio Grande basin of 1450 mm is much larger than storm total rainfall analyses based on radar and rain gages (Fig. 13). Despite these observations, there are arguments to support the extreme nature of the Loiza peaks. The upper portion of the Loiza basin clearly received the heaviest rainfall from the eyewall convection. There were no rain gages in the upper portion of the Rio Grande, so there is no possibility for corroborating rain gage information. Radar rainfall estimates in the presence of strong downdrafts can severely underestimate rainfall rate. Inferences about the Loiza peak all turn on understanding the behavior of eyewall convection during the 45 minute period from 2345 to 0030.

Flood peak response to Hurricane Georges was not controlled by storm total accumulation but rather by peak rainfall rates. For the Loiza discharge observations, there are a sequence of peaks associated with rain bands from Hurricane Georges. The largest peak discharge was associated with extreme rain rates from eyewall convection and occurred early in the storm.

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