P1.14 THE SPATIAL PATTERNS OF RAINFALL PRODUCED BY HURRICANE IRENE (2011) AND OTHER TROPICAL CYCLONES WITH SIMILAR TRACKS

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1. INTRODUCTION

Hurricane Irene was one of the most damaging tropical cyclones of the 2011 Atlantic Basin tropical cyclone season. Although some damage did occur from high winds and storm surge, Irene produced record-breaking rainfall across several locations in the mid-Atlantic and northeastern U.S. The National Hurricane Center (NHC) tropical cyclone report (Avila and Cangialosi 2011) lists 399.8 mm (15.74 in) in Bayboro, North Carolina as the U.S. location receiving the highest rainfall. The Hydrometeorological Prediction Center (HPC) (http://www.hpc.ncep.noaa.gov/tropical/tropical_advisories.php?storm=IRENE&adnum=37&dt=2011082915&status=remnants) shows that locations in eight states received more than 254 mm (10 in) of rainfall. Half of the deaths in the U.S. attributed to Irene were due to fresh water flooding from the heavy rainfall (Avila and Cangialosi 2011).

Many tropical cyclones (TCs) tracking northward over the northeastern U.S. have produced heavy rainfall that caused flooding (e.g., Atallah and Bosart 2003; Atallah et al. 2007; Hart and Evans 2001; Konrad and Perry 2010). When passing through this region, TCs are typically becoming restructured by the process of an extratropical transition (ET) (Hart and Evans 2001). Interaction with strong westerlies associated with a middle latitude trough causes an increase in storm forward motion, vertical wind shear, and vorticity, and the environment surrounding the TC becomes baroclinic. The relatively cool and dry air encircles the TC from the southwest to southeast which helps to decrease precipitation in this section of the storm. However, isentropic uplift of the moist tropical air mass ahead of the storm center enhances precipitation (Atallah et al. 2007; Jones et al. 2003; Sinclair 2004). Interaction with topography such as that which occurs near the Appalachian Mountains can also enhance TC precipitation (Haggard et al. 1973; Sturdevant-Rees et al. 2001). In less than 24 hours, 200-300 mm of rain can fall from these transitioning systems (Jones et al. 2003), which can lead to flooding and associated damage to property and life.

This study utilizes a Geographic Information System (GIS) to characterize the spatial patterns of rainfall produced by Irene and to identify other TCs taking similar tracks over the U.S. The amounts and locations of the top 10% of rainfall totals are examined in relation to the storm track as well as latitude and longitude through the calculation of correlation coefficients. Comparisons of these values indicate which TCs produced a rainfall distribution most closely resembling that of Irene. Finally, a map is created that indicates the highest rainfall totals and the TC that produced that rainfall for the study region. The results of this study may aid rainfall forecasts for future TCs that are undergoing an ET over the northeastern U.S.

2. DATA AND METHODS

As trough interaction during the ET process helped to shape Irene's track, storms following a similar track would likely experience similar atmospheric conditions. Thus, the first task was to identify analog TCs that took a path similar to that of Irene over the U.S. Selecting tracks similar to that of Irene also controlled for effects of topography on rainfall enhancement as the Appalachian Mountains are located to the west of the storm track. Latitude and longitude coordinates from the six-hourly positions of Irene were entered into a GIS and points located 25 - 48° N were converted into a line feature. This line represents Irene's closest approach to and landfall within the U.S. when rainfall produced by

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the storm could be affecting the study area. This line was buffered by 200 km.

Tracks taken by prior-season TCs obtained from HURDAT were also imported into the GIS. The buffered track of Irene was used to clip the TC tracks from previous seasons and new attributes of track length and orientation were calculated for all tracks within the buffered region. Twenty-five TCs from previous seasons featuring a long track segment within the buffer having an orientation similar to that of Irene were identified.

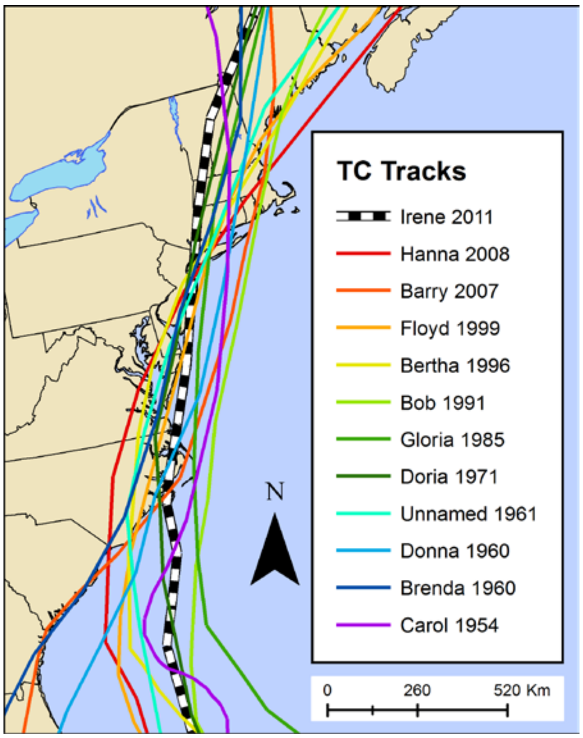

FIG. 1. Tracks of tropical cyclones occurring post-1948 passing nearest to the track of Hurricane Irene (2011).

The next step was to determine storm-total rainfall amounts for all TCs in the study. Daily rainfall totals were obtained from the National Centers for Environmental Prediction–Climate Prediction Center Unified Precipitation Dataset. These gridded data are available at a 0.25° spatial resolution beginning in 1948. Two main advantages of utilizing this dataset are 1) its complete spatial and temporal coverage over U.S. land areas beginning in 1948 and 2) that a uniform interpolation method and error corrections were applied to the entire dataset. The two main limitations of this dataset are that 1) rainfall totals are averaged over grid cells approximating 770 km^2 so that maximum point values where extreme rainfall occurs cannot be determined and 2) data are only available over land areas so that rainfall occurring offshore to the right of the storm track cannot be analyzed. Eleven of the 25 similar TC tracks occurred post-1948 resulting the analysis of 12 TCs total (Fig. 1).

The study region was defined by the U.S. border to the north and coastline to the east, and extended to south to 35° N and to 82° W in the west. There were 1460 grid cells in this region. Storm-total rainfall for all 12 TCs was calculated utilizing the cell statistics tool in ArcGIS. Daily rainfall totals were summed for each cell beginning on the day that was at least 24 hours prior to the storm's first landfall or point of closest approach to the North Carolina coastline and ending at least 24 hours after the storm left the U.S. Most rainfall totals accumulated over a five-day period. The distance and angle of each grid cell from the closest location along the storm track was calculated utilizing the near function. The highest 10% of rainfall totals for each storm that were left of the storm track were analyzed further to facilitate comparisons of the regions where the highest rainfall occurred. Measures of central tendency and dispersion were calculated and Spearman's rank correlations explored associations between the locations of high rainfall totals, distance to track, longitude, and latitude. Additionally, the highest rainfall accumulating at each cell in the study region, and the storm producing it was also determined.

3. RESULTS

3.1 The Rainfall of Irene (2011)

Hurricane Irene began to experience changes to its structure due to ET as early as August 26, when the NHC reported that its wind field had broadened. Forecast discussions over the next two days (http://www.nhc.noaa.gov/archive/2011/IRENE.shtml?) detailed an increase in forward velocity, southwesterly vertical wind shear, and dry air entrainment. Irene made landfall as a Category 1 hurricane at Cape Lookout, North Carolina on August 27 at 1200 UTC. Landfalls at 0935 UTC near Atlantic City, NJ and at 1300 ETC near Coney Island, NY occurred on August 28 while

Irene was a tropical storm (Avila and Cangialosi 2011). Near the time of landfall in North Carolina, forward velocity was estimated to be 6 ms^{-1}, and this increased to 10 ms^{-1} according to the last advisory issued 29 August at 0300 UTC. It should be noted that according to the HPC (http://www.hpc.ncep.noaa.gov/tropical/rain/irene2011.html) storm total rainfall was calculated for August 24-31. Surface analyses reveal that a stationary front was located near the Carolina coast on August 24 and precipitation did occur in association with this frontal boundary while the center of Irene was more than 1300 km away making landfall over the Bahamas as a major hurricane. Daily rainfall was summed over the period August 26 – August 30 for the current study. Thus, storm total rainfall values should be lower than those reported by the HPC.

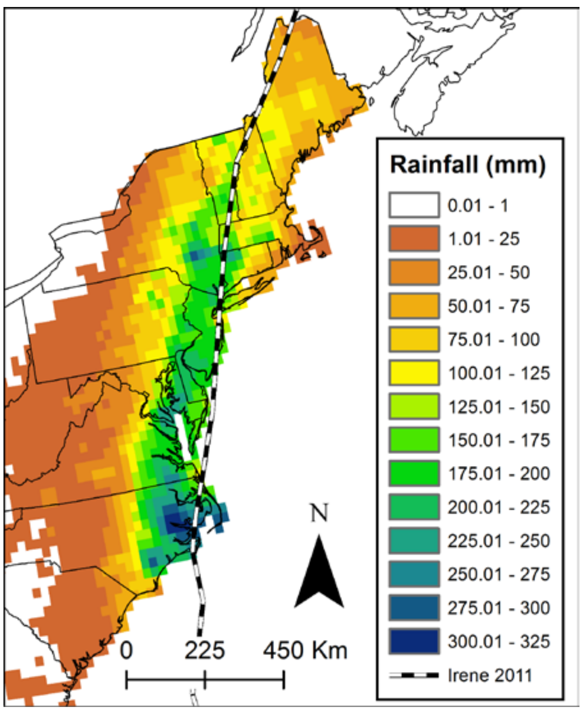

FIG. 2 Storm total rainfall for Hurricane Irene 2011.

The largest value of storm total rainfall was 324 mm (12.8 in) located near Washington NC, approximately 35 km from Bayboro where the maximum rainfall occurred according to the NHC and HPC. The top 10% of rainfall totals had a median of 208 mm with a range of 142 mm (Table 1). The highest rainfall amounts were near the point of the North Carolina landfall (Fig. 1), leading to a statistically significant negative correlation between latitude and rainfall totals (Table 2). However, 10 states including Vermont and Massachusetts, had at least one location receiving rainfall in the top 10% of highest values, so high rainfall totals were not strictly confined to North Carolina (Fig. 2). Rainfall totals exceeding 254 (125) mm occurred over approximately 2% (23%) of the study region. The Spearman's rank correlation coefficient calculated between the top 10% of rainfall totals and distance to track was not significant (Table 2), indicating that high rainfall was produced both near to and far from the storm track. Rainfall totals over 250 mm occurred from 2 – 220 km away from the storm track although the median distance for the top 10% was 79 km (Table 1). The non-significant correlation between distance of high rainfall from track and latitude (Table 2) indicates that the regions within Irene's rain field producing high rain rates were not expanding nor contracting as Irene tracked north.

Table 1: Statistics for storm total rainfall and distance to track for top 10% of rainfall totals left of track.

TC	Median Rainfall (mm)	Rain Range (mm)	Max. Rain (mm)	Medn Dist. Track (km)	Max. Dist. Trk. (km)
I2011	208	142	324	79	163
H2008	117	87	187	80	152
B2007	65	48	106	132	939
F1999	251	360	548	89	173
B1996	102	99	190	59	180
B1991	137	108	211	95	215
G1985	151	101	223	144	228
D1971	132	125	225	67	701
U1961	37	49	78	115	844
D1960	153	59	198	103	236
B1960	118	108	197	50	128
C1954	87	99	176	102	366

3.2 Comparisons of All Twelve Storms

The rainfall distribution most similar to that of Irene was produced by Hurricane Floyd (1999). When comparing the amount of the top 10% of rainfall totals over the study area for all 12 storms, Hurricane Floyd (1999) ranks first in terms of the median, maximum, and range of these high rainfall values, while Irene (2011) ranks second and Gloria (1985) is a distant third (Table 1). Despite having a relatively fast forward velocity of 10 ms^{-1} as it tracked over the study region, Floyd produced more than 300 mm of rainfall over an area measuring approximately 26,082 km^2. By comparison, the forward velocity of Irene ranged from 6-10 ms^{-1} as it tracked over land and it produced 300 mm+ of rainfall over only approximately 3,726 km^2 of the study area. As with Irene, Floyd's highest rainfall occurred near the location of its North Carolina landfall. Floyd and Irene were similar when comparing the median and maximum distance between the storm track and locations of the top 10% of rainfall totals on the left side of the storm track; only 10 km separated their values in both categories (Table 1). With a median distance to track of 80 km, Hanna (2008) was the most similar to Irene for this metric, but Hanna produced only half of the rainfall of Irene. Gloria (1985) and Barry (2007) had the largest median distances, both over 130 km, while Bertha (1996) and Brenda (1960) produced the smallest distances to track. Three TCs had at least one location receiving a top 10% rainfall total more than 700 km from the storm center. This result shows that high rainfall totals can occur at a large range of distances relative to the storm track as storms move across the northeastern U.S.

Table 2. Spearman's Rank correlation coefficients for the top 10% of rainfall totals left of track for each storm comparing rainfall amount, distance from the storm track, longitude, and latitude.

TC	Rain vs Dist.	Rain vs Long.	Rain vs Lat.	Dist. vs Lat.
I2011	-0.063	-0.373**	-0.506**	-0.154
H2008	0.072	0.048	0.052	0.098
B2007	-0.246**	0.383**	0.382**	-0.217**
F1999	-0.408**	-0.537**	-0.681**	0.293**
B1996	-0.190*	-0.172*	-0.192*	0.257**
B1991	-0.352**	0.089	-0.115	-0.040
G1985	0.133	-0.313**	-0.216**	0.420**
D1971	-0.324**	0.028	-0.078	0.000
U1961	0.234**	0.423**	0.493**	0.569**
D1960	-0.061	0.056	-0.001	0.098
B1960	-0.068	-0.521**	-0.622**	-0.230**
C1954	-0.255**	-0.288**	-0.417**	0.037

** significant at $\alpha = 0.01$; * significant at $\alpha = 0.05$

Not all TCs undergoing ET produce the same spatial patterns of rainfall as indicated by the difference in correlation coefficient values between rainfall totals, distance to track, latitude, and longitude (Table 2). As discussed previously, Irene (2011) had a nigh negative correlation with latitude meaning that the highest rainfall totals occurred in the southern part of the study region, and this relationship held for four of the other TCs in the study (Table 2).These same five TCs also exhibited high negative correlations between rainfall totals and longitude, indicating that the highest rainfall totals were located more towards the west rather than towards the east. The two TCs that produced lower rainfall totals had rainfall that increased, rather than decreased, towards the north and east. Higher rainfall totals were located close to the track for five of the TCs, while only the Unnamed storm of 1961 produced lower rainfall totals close to the track. High positive correlations indicated that the distance of high rainfall totals from the track increased towards the north, suggesting that the rain fields broadened over time in four TCs. Two storms had rain fields that contracted as they moved north.

Given that Hurricane Floyd produced the highest rainfall totals in the study that led to wide-spread flooding, especially in North Carolina (Lawrence et al. 2001), it is not surprising that of the 12 TCs, Floyd produced the highest rainfall over 24% of the study region (Fig. 3). Although Donna (1960) produced the highest rainfall over 16% of the study region, ranking it number two in this category, these were lower rainfall totals under 100 mm located in West Virginia and central Pennsylvania (Fig. 4). Irene (2011) produced the highest rainfall over 12% of the study region in many coastal locations as well as eastern New York and Vermont (Fig 3.) Overall, 14% of the study region including 10 states has received at least 200 mm of rainfall from a TC since 1948 (Fig. 4).

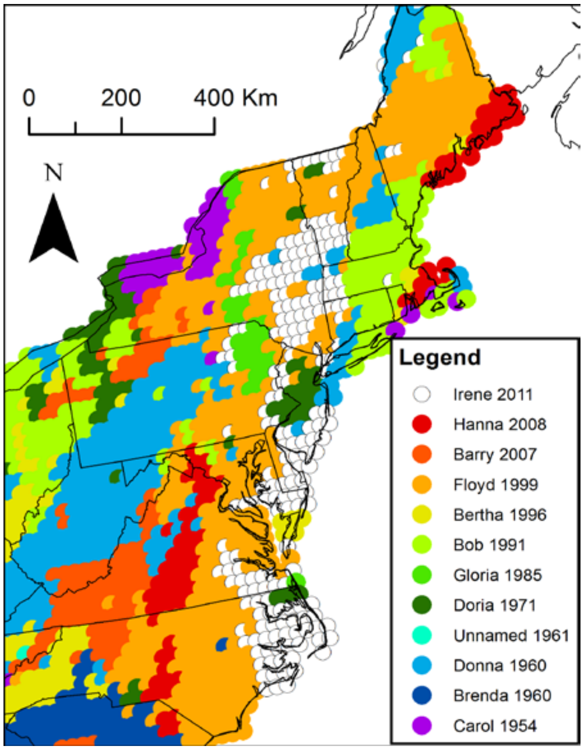

FIG 3. Tropical cyclone producing maximum storm total rainfall for each grid cell.

4. CONCLUSIONS AND FUTURE RESEARCH

According to the data analyzed in this study, Hurricane Irene (2011) produced at least 300 mm of rainfall in North Carolina and relatively high rainfall amounts in several other states as it tracked over the mid-Atlantic and northeastern U.S. The highest rainfall amounts over land areas occurred an average of 80 km to the left of the storm track. Since 1850, 25 TCs have taken tracks similar to that of Irene. For approximately 12% of the study region, Irene caused the highest TC-related rainfall totals of the 12 TCs for which rainfall distributions were analyzed. The TC with the most similar track and rainfall patterns to that of Irene was Floyd (1999). Floyd produced higher rainfall amounts overall, and produced the highest TC rainfall totals over 24% of the study region. Even though the twelve TCs took similar tracks, their spatial patterns of rainfall differed. Some TCs produced their highest rainfall totals in the southern and/or western part of the study region, and some produced higher rainfall values closer to the storm track. Other TCs featured a rain field that either broadened or became narrow through time. Thus, there is no one pattern that captured the majority of the variability in the rainfall patterns by these 12 TCs.

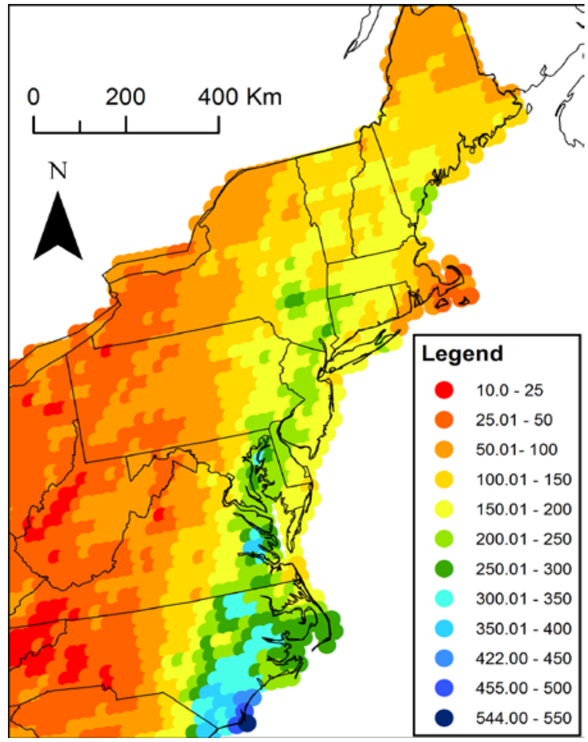

FIG. 4 Maximum storm total rainfall (mm) produced by a tropical cyclone included in the current study.

Future work utilizing the National Centers for Environmental Prediction–Climate Prediction Center Unified Precipitation Dataset to examine rainfall produced by all TCs since 1948 TCs will examine their contributions to the rainfall climatology and relationship to storm track as well as topographic features. Preliminary calculations show that Hurricane Irene contributed more than 50% of the August 2011 rainfall in the majority of grid cells located within 200 km of the storm track. In 2011, one location in eastern New York experienced its wettest August since 1948. Additionally, the analysis of Stage IV data during the passage of Irene, which combines data from radar and rain gauges, will better define the areas that received the highest rainfall totals from Irene as well as examine the rainfall it produced offshore.

5. ACKNOWLEDGEMENTS

University of Florida undergraduate students Britany Ziems (Environmental Science) and Donielle Rouse (Mechanical Engineering) assisted with the processing of rainfall data for some of the storms in the study. The work presented here was not funded but future work will be supported by a National Science Foundation CAREER Award: BCS-1053864.

6. REFERENCES

Atallah, E. H., and L. R. Bosart, 2003: The Extratropical Transition and Precipitation Distribution of Hurricane Floyd (1999). *Mon. Wea. Rev.*, **131,** 1063-1081.

Atallah, E. H., L. F. Bosart, and A. R. Aiyyer, 2007: Precipitation Distribution Associated with Landfalling Tropical Cyclones over the Eastern United States. *Mon. Wea. Rev.*, **135,** 2185-2206.

Avila, L., and J. Cangialosi, 2011: Tropical Cyclone Report Hurricane Irene (AL092011), http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf .

Haggard, W. H., T. H. Bilton, and H. L. Crutcher, 1973: Maximum Rainfall from Tropical Cyclone Systems which Cross the Appalachians. *J. Appl. Meteor.*, **12,** 50-61.

Hart, R. E., and J. L. Evans, 2001: A Climatology of the Extratropical Transition of Atlantic Tropical Cyclones. *J. Climate*, **14,** 546-564.

Jones, S. C., and Coauthors, 2003: The Extratropical Transition of Tropical Cyclones: Forecast Challenges, Current Understanding, and Future Directions. *Wea. Forecasting*, **18,** 1052-1092.

Konrad, C. E., and L. B. Perry, 2010: Relationships between Tropical Cyclones and Heavy Rainfall in the Carolina Region of the USA. *Int. J. Climatol.*, **30,** 522-534.

Lawrence, M. B., L. A. Avila, J. L. Beven, J. L. Franklin, J. L. Guiney, and R. J. Pasch, 2001: Atlantic Hurricane Season of 1999. *Mon. Wea. Rev.*, **129,** 3057-3084.

Sinclair, M. R., 2004: Extratropical Transition of Southwest Pacific Tropical Cyclones. Part II: Midlatitude Circulation Characteristics. *Mon. Wea. Rev.*, **132,** 2145-2168.

Sturdevant-Rees, P., J. A. Smith, J. Morrison, and M. L. Baeck, 2001: Tropical Storms and the Flood Hydrology of the Central Appalachians. *Water Resour. Res.*, **37,** 2143-2168.