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A CLIMATOLOGICAL ANALYSIS OF THE EXTENT OF RAINFALL PRODUCED OVER THE U.S. BY ATLANTIC BASIN TROPICAL CYCLONES

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1. INTRODUCTION

In the U.S., rainfall associated with tropical cyclones (TCs) has caused significant impacts. Flooding from TCs has caused numerous fatalities and economic losses (Rappaport 2000; Czajkowski et al. 2011; Rappaport 2014). On the other hand, TC rainfall can have a positive hydro-climatic influence on the ecological system when alleviating drought conditions (Sugg 1968; Maxwell et al. 2012; Brun and Barros 2014). To better understand the inland impact of tropical cyclone precipitation (TCP), it is important to know the extent of TCP produced during each event where the extent is defined as the area receiving rainfall greater than a certain threshold (Rezapour and Baldock 2014). Producing a spatial climatology from these rainfall swaths provides a measure of how far from the storm track TCP can extend on average, and facilitates the identification of locations that receive TCP.

Many studies separate TCP from rainfall generated by other weather systems by searching a uniform radius and attribute all rainfall within this radius to the TC. The most common span is 500- to 600-km from the storm track (Lonfat et al. 2004; Larson et al. 2005; Lonfat et al. 2007b; Kunkel et al. 2010; Nogueira and Keim 2010; Villarini et al. 2011; Prat and Nelson 2012; Hernández-Ayala and Matyas 2016). Yet rainfall patterns in landfalling TCs do vary among individual storms (Konrad et al. 2002; Matyas 2006; Chen et al. 2010; Matyas 2010b, 2010a). Thus, applying a uniform search radius may underestimate or overestimate TCP area. To account for variations in TC size, Zhu and Quiring (2013) used moving buffers representing the radius of the outermost closed isobar, but we are not aware of a study that extracts TCP utilizing a method that defines the outermost boundary, or rainfall swath. Developing such a technique should improve accuracy when measuring TCP extent.

Although the amount and contribution of TCP have been documented over regional scales (Knight and Davis 2007; Konrad and Perry 2010; Nogueira and Keim 2010; Zhu and Quiring 2013; Zhu et al. 2013) there is a need to construct a spatial climatology based on actual TCP swaths using long-term surface-based observations. After landfall, rainfall may decrease due to a decrease in latent heat flux (Kimball 2008), while TCP can be enhanced and/or be redistributed asymmetrically about the storm track under certain conditions (Konrad et al. 2002; Lonfat et al. 2007b; Matyas 2007, 2008; Konrad and Perry 2009; Zick and Matyas 2016). When TCs move into the middle latitudes, they can be restructured into extratropical cyclones. As the extratropical transition (ET) proceeds, rainfall regions become more dispersed, with a shift of heavy rainfall to the left (north or northwest) of track (Jones et al. 2003; Atallah et al. 2007; Matyas 2010b; Zick and Matyas 2016). Although some studies have explored the impacts of environmental conditions on storm structure and the resulting rain rate, magnitude, and areal coverage (Lonfat et al. 2007a; Konrad and Perry 2009; Matyas 2013; Matyas 2014) a need still exists to analyze TCP events from a longer record to determine which aspects of a TC are associated with rainfall swaths that expand as they pass over the U.S.

TC wind and rain hazards can occur far inland and cover large areas (Kaplan and DeMaria 1995; Lonfat et al. 2007a; Villarini et al. 2014). Two previous studies estimated the cumulative frequency or return interval of wind events associated with TCs. Zandbergen (2009) examined the inland exposure of U.S. counties to tropical storm- and hurricane- force winds by using symmetric, uniform distance buffers along the track. Kruk et al. (2010) used asymmetric wind swaths according to the average size of TC wind fields to calculate return intervals for inland

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TC wind events over the eastern U.S. Yet we are not aware of a study employing similar methods to measure TCP return intervals.

Previous research has measured the extent of TC rain fields utilizing remotely-sensed data with a high spatial and temporal resolution. Matyas (2010a) used reflectivity values obtained from ground-based radars to define the edges of the rain fields of 31 hurricanes at the time of landfall. The average extent was 223 km, however variations were large when comparing across storms and on the right and left sides of the storm track. Other key findings were that moisture and vertical wind shear were key predictors of rain field extent and that the rain fields frequently extended beyond the radius of gale-force winds in the forward quadrants. Guo and Matyas (2016) examined rainfall from a satellite-based dataset and compared the extent of 5 mm hr^{-1} rain rates with the radius of gale-force winds. The rain fields exhibited variations in extent over the diurnal cycle, and the extent of wind and rain fields were not always strongly correlated, especially on the west sides of TCs over the Gulf of Mexico. Although these datasets allowed rainfall to be detected over land and water, the main drawback is that the availability of data limits the number of years and hence the number of storms that can be included in the study.

The goal of the current study is to construct a spatial climatology of TCP extent over the eastern U.S. We first describe a Geographic Information System (GIS)-based method to delineate and measure the outermost extent of TC rainfall. Next, we examine the trend of rainfall extent to the left of track and explore TC attributes related to these trends. After we describe the return interval and cumulative frequency for receipt of TCP, we finally compare the rainfall swaths developed in this study to wind swaths constructed as detailed by Kruk et al. (2010) to determine the frequency with which locations receive either condition produced by TCs. This analysis allows for an improved picture of inland hazards posed by TCs from a climatological perspective.

2. DATA AND METHODS

Daily precipitation totals were obtained from the U.S. Unified Precipitation Data (UPD) from NOAA Climate Prediction Center (CPC) where data are available since 1948 (Higgins et al. 2007). The gridded precipitation values are interpolated onto a 0.25° by 0.25° grid (Higgins et al. 2007; Higgins and Kousky 2013). This dataset offers complete spatial and temporal coverage of observational data over U.S. land areas and includes a uniform interpolation method and error corrections (Atallah et al. 2007; Corbosiero et al. 2009; Higgins and Kousky 2013). According to Atallah et al. (2007), the spatial distribution of the storm-total precipitation approximating 25.4 mm is well replicated for most TCs.

The TC tracks were obtained from International Best Track Archive for Climate Stewardship (IBTrACS), which provides TC center locations and storm intensity every 6 hours at the standard synoptic times each day (Knapp et al. 2010). To explore TCP patterns over land, we included all 257 TCs producing rainfall over the U.S. Gulf and East Coasts during 1948-2014. Previous research (Jones et al. 2003; Nogueira and Keim 2010; Matyas 2014) determined that land areas can receive heavy rainfall from TCs prior to the circulation center's landfall. As our goal was to include all rainfall from the 257 TCs, the analysis began on the day when the TC first passed within 550 km of the U.S. coastline and ended on the day it moved beyond 550 km of the U.S. or dissipated over the U.S.

Daily precipitation values from UPD are accumulated at 1200 UTC. To match 6-hourly TC positions with daily precipitation, TC observations from 1200 UTC -1200 UTC were used to determine daily storm motion. Then, a value of 12.5 -mm per day was used to define precipitation regions as it falls within the most accurate range (10-30 mm per day) of UPD (Ensor and Robeson 2008), and has been used to identify moderately heavy rainfall from TCs or other weather systems (Konrad et al. 2002; Groisman et al. 2012). We first developed python-based scripts to generate all 12.5 -mm/day contours and convert them to polygons (Fig. 1a). The second step was to identify TC precipitation features. After locating the centroid of each polygon, its distance from the nearest point along the storm track was measured. Polygons were retained if their centroids were less than 550 km from the storm track. This method, also utilized by Jiang et al. (2011), ensures that rainfall is included if it occurs more than 550 km from the storm track so long as the centroid of the rainfall region falls within 550 km of the storm track. Isolated regions with areas less than four UPD pixels in size (~> 3,360 sq km) were excluded. Finally, all daily TCP features (Fig. 1b) were merged to generate storm-total rainfall regions, or rain swaths.

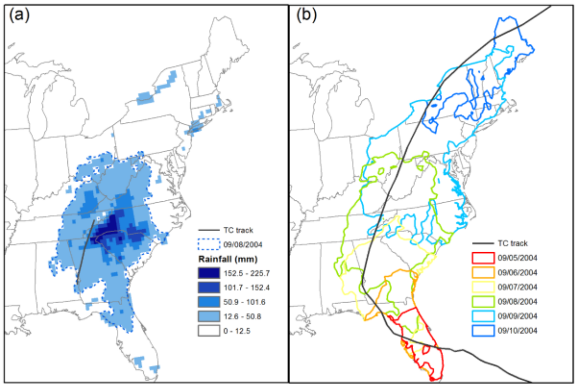

Fig. 1. Rainfall analysis for Frances (2004) showing (a) daily rainfall accumulation, and (b) extracting and merging polygons from all days that the TC tracked through the study area.

We next measured the widths of the precipitation features. Using GIS, every 10 km along the track, a straight line was drawn perpendicular to the track until it intersected with the TCP polygon edge. If the points of intersection between the lines and the edges of swaths were located on the U.S. border or coastline, these lines were discarded as it is unknown how far the swath extends beyond the edge of the rainfall dataset (Fig. 2a). The lengths of the remaining lines were calculated to get the width of rainfall extent. Finally, we calculated the average width and changes of width on the right and left sides of the track.

To compare the extent of rainfall with TC wind, we also generated wind swaths for all TCs. The distances that we employed were taken from the work of Kruk et al. (2010). They divided TCs into six categories according to intensity based on the Saffir-Simpson Scale: post-tropical (PT) for storms completing an extratropical transition, tropical storm (TS), Category 1 Hurricane, Category 2 Hurricane, Category 3 Hurricane, and Category 4-5 Hurricane. For each category, overland average distances in each of four quadrants (northeast, northwest, southeast, and southwest) for each wind intensity threshold were calculated using the extended best-track dataset available from 1988-2008. In the current study, we constructed the wind swaths for our 257 TCs using the distance parameters for 17-m s^{-1} wind reported by Kruk et al. (2010) (Table 1) (Fig. 2b).

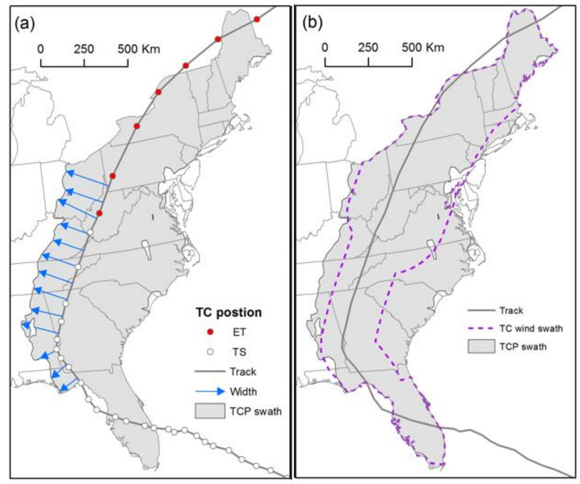

Fig. 2. Analysis for Frances (2004) showing (a) measuring rainfall swath extent, and (b) modeling the extent of gale-force winds.

Table 1. Averages of radii for 17-ms^{-1} wind (unit: km) (Kruk et al., 2010).

Category	PT	TS	Cat 1	Cat 2	Cat 3	Cat 4-5
Left radius	217	121	148	211	221	208
Right radius	357	186	240	300	328	268

Last, we produced a series of maps with frequency distribution for overland locations impacted by wind and rainfall associated with TCs. The frequency was summarized in county units, since many tasks including hazard preparation and planning, loss estimation, risk analysis, mitigation, and response to TCs are handled at the county level (Zandbergen 2009; Czajkowski et al. 2011; Esnard et al. 2011). To further estimate how frequently a particular location was impacted by TCP events, we calculated return intervals, which are defined as the ratio of study period (e.g. 67 years) over frequency count.

3. SPATIAL CHARACTERISTICS OF TCP REGIONS OVER LAND

In this section, the spatial characteristics of storm-total TCP regions of 257 TCs making landfalls over eastern U.S. during 1948-2014 are summarized. Previous studies suggested different TCs striking the same stretch of coastline tend to approach along a similar path, and should encounter similar synoptic-scale environments while moving inland (Jagger and Elsner 2012). Thus, we categorized the TCs landfalls into three regions including the Gulf Coast from Texas to Alabama, Florida, and the East Coast from Georgia to Maine (Jagger and Elsner 2006; Jagger and Elsner 2012) (Fig. 3). TCs in the Gulf Coast category should move poleward and interact with the relatively dry environment of the mid-U.S. if they do not dissipate shortly after landfall. Many TCs making landfall over Florida spend a short amount of time over land. For both Florida and East Coast tracks, only the left side width is examined since most TCs track near to the coastline.

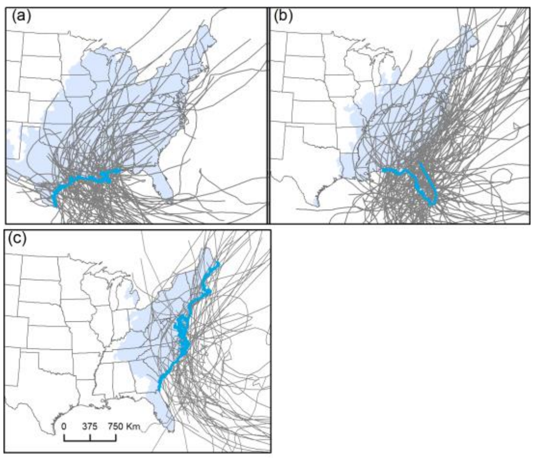

Fig. 3 Tracks and locations receiving rainfall (shaded) from TCs making landfall over the (a) Gulf Coast, (b) state of Florida, and (c) East Coast.

A total of 104 TCs made landfall from Texas to Alabama (Fig. 3a), and they have the longest period over land averaging 2.1 days. Precipitation associated with these TCs influences the largest geographic region, with a total area of 39.86× 10^5 km^2, which covers almost the entire eastern two-thirds of the U.S. The average left extent of TCP swaths is about 196 km among 76 TCs whose left extents could be measured, which is the smallest width among the three groups. The right sides of these TCs extend about 295 km from the track on average. We further divided TCs according to the time spent over land (Table 2). The left extent increases with period length over land, while the right extent shows a decline for TCs spending longer than 3 days over land. This result generally agrees with the previous research that as TCs make landfall over Gulf Coast and move inland, the rainfall pattern becomes more asymmetric with expanding left/forward side of outer edge of rainfall and diminished rainfall on the right/ rear side due to the ET process and/or dry air intrusion in this region (Zick and Matyas, 2016).

Table 2. Spatial characteristics of TCP swaths for Gulf Coast landfalls (km).

Storm-total period	Width	N	Avg.	Std. Dev.	Percentile		
					25	50	75
< 1 day	Left	12	144	130	33	95	274
	Right	9	269	165	70	329	377
1-3 days	Left	41	189	120	98	165	263
	Right	42	316	186	197	306	398
> 3 days	Left	23	236	173	120	204	298
	Right	21	264	115	154	272	376

For TCs making landfall over the Florida panhandle, most of them approach from the south or southwest, while TCs cross the peninsula from the west or east (Fig. 3b). The average period over land is about 1.5 days in this group. The average and median values of left extent are 233 km and 209 km respectively (Table 3), which is the largest left extent among the three groups. When comparing TCs with periods between 1- 3 days and greater than 3 days over land, the left extent also increased with the period over land.

Table 3. Spatial characteristics of TCP swaths for Florida landfalls (km).

Storm-total period	Width	N	Avg.	Std. Dev.	Percentile		
					25	50	75
< 1 day	Left	34	241	126	149	231	322
1-3 days	Left	24	217	99	147	188	257
> 3 days	Left	17	241	72	190	222	282

There were 53 TCs that made landfall over the East Coast region (Fig. 3c). The average period over land of 1.1 days is the shortest compared to the other two groups. Yet the average and median values of left extent of rainfall swaths (Table 4) are comparable to those from the Florida region, and larger than those from the Gulf Coast region. Many TCs in this region are undergoing ET which is known to increase the areal coverage of rainfall ahead of the storm center (e.g., Atallah et al., 2007; Matyas, 2010). This fact supports the need to include data from the period prior to landfall in construction of storm-total rainfall maps. The average left extent of TCP swath also increases for longer periods over land as in the other two regions.

Table 4. Spatial characteristics of TCP swaths for East Coast landfalls (km).

Storm-total period	Width	N	Avg.	Std. Dev.	Percentile		
					25	50	75
< 1 day	Left	46	228	90	174	223	277
>1 day	Left	21	238	75	182	1222	297

4. CHANGE OF LEFT WIDTH OF TCP SWATH ALONG TRACKS

The left sides of rainfall swaths tend to be wider as TCs spend more time over land. Thus, we tested for trends in the expansion or contraction of the left side for TCs that spent at least 1.5 days over land with a swath length more than 500 km. Eighty-eight TCs met these criteria. The width data were smoothed with a moving average window of 100 km based on width measurements taken every 10 km. A set of simple trend analyses were utilized. First, a linear regression tested the overall trend for the entire swath, and then the slope and coefficient of determination (R^2) were examined. As values of R^2 greater than 0.3 are statistically significant at the 0.05 level, TCs meeting this criterion were deemed to have a significant linear change in width. If the value of R^2 is smaller than 0.3, a joinpoint regression analysis was run to determine where a change of trend occurs and the slope of each segment. The results of these two tests allow us to place TCs into one of four classes for increasing (Group I), decreasing (Group II), increasing-decreasing (Group III), and decreasing-increasing (Group IV) trends (Fig. 4).

Table 5 summarizes the changes in left extent for TCs in the four groups. The change magnitude was calculated by subtracting the first width measurement from the last width measurement of a segment with a significant trend. Group I includes 40 TCs and the average and median magnitudes of increase in left width are about 210 km and 190 km, respectively, with a standard deviation of 121 km. Group II includes 18 TCs with decreasing trends of left side, with average (median) decrease magnitude of left width approximating 98 (81) km, and a standard deviation of 64 km. Cases in Groups III and IV have significant changes in the trend of left width. Group III includes 15 TCs with decreasing left width during the first segment and increasing left widths during the second segment. The total change in width of this group is positive for 13 out of 15 TCs, with an average (median) value of 63 (55) km, indicating that the overall trend of this group is increasing. Group IV includes 12 TCs with increasing left width first followed by decreasing left widths, which is the smallest group. The total change over land in width of this group is negative for 10 out of 12 TCs, with an average value of 37 km and a median value of 19 km, which means the overall trend of this group is decreasing. In summation, Groups I and III (II and IV) feature left widths that are increasing (decreasing) overall.

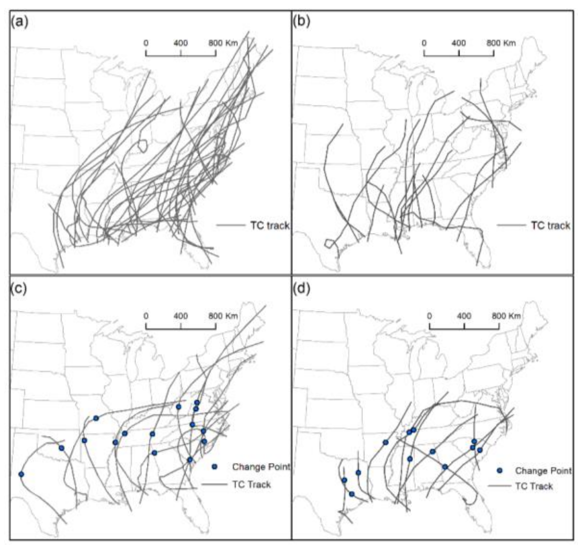

Figure 4. TC tracks and change points in: (a) Group I with increasing trend, (b) Group II with decreasing trend, (c) Group III with increasing-decreasing trend, (d) Group IV with decreasing-increasing trend

Next, multiple Chi-square tests were performed to determine which TC attributes are associated with expansion and contraction of rain fields. To fulfill the frequency requirements of the tests, we combined Group I and III and Group II and IV. First, TCs were divided into tropical depressions (TD), tropical storms (TS), and hurricanes (HU) according to intensity at the best track position immediately prior to landfall, as Konrad and Perry (2010) found a positive correlation between intensity and rainfall pattern over land. As TCs move inland, they might re-intensify due to the ET process, approaching coastline, or favorable surface conditions (Klein et al. 2000; Andersen and Shepherd 2013). Those TCs which experienced reintensification over land were expected to have increasing left widths due to their structures becoming more symmetrical as moisture is advected to the left side.

Table 5. Number of TCs in each group and mean and median change in width of left side (km). Negative values indicate decreasing width.

	Group I		Group II		Group III		Group IV	
Number of TCs	40		18		15		12	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median
Total change	212	190	-98	-81	63	55	-37	-19
Increasing segment	/	/	/	/	134	106	96	97
Decreasing segment	/	/	/	/	-73	-66	-133	-127

Furthermore, there are two main outcomes for TCs moving inland: they may cease to exist over land, or move back over the ocean. In both cases, TCs may also undergo ET. We further examined these three situations' impact on TCP size change individually. TCs that move back over the ocean may advect increasing amounts of low-level moisture into their circulation, leading to an increase in extent (Matyas, 2007). As Matyas (2014) found that going through ET was associated with the largest rain field areas, we expect that TCs experiencing ET may expand their rainfall swaths left of the track. The TCs that cease to exist over land might encounter different situations: increasing left width for TCs that merged with or were absorbed by a front, or decreasing left width for TCs that dissipated/became a remnant low. The demise-type information was extracted from National Hurricane Center's (NHC) storm reports for TCs available beginning in 1995 (http://www.nhc.noaa.gov/data/tcr/), and preliminary TC reports and annual reports from NHC for earlier TCs. The demise of the TC is noted in the storm reports at the last synoptic time that the TC center position is available. Only 9% of TCs after 1995 were identified as being absorbed by or merging with fronts. For TCs prior to 1995, we classified them as dissipating over land if they did not complete an ET and the report does not mention that synoptic-scale influences played a role in weakening the storm post-landfall.

All four Chi-square tests yielded statistically significant results with a 95% confidence level (Table 6). Two thirds of TCs in Groups I and III were hurricanes immediately prior to landfall, while 60% of TCs in Groups II and IV were tropical storms or tropical depressions. TCs that experienced re-intensification also showed higher probability to expand their left width. These results generally agree with Konrad and Perry (2009), which found that TCs with lowest rainfall and smaller size over land were tropical storms immediately prior to landfall, and rainfall of these events is mainly located on the right side of system. They explained these results by using conclusions from Matyas (2007) that weaker TC wind circulations advect less moisture towards the left or continental side of the cyclone.

Table 6. Results of Chi-Square tests to determine attributes associated with changing width of the left side of rainfall swaths.

Attributes	$\chi 2$	*p*-value	Sub-category	Count	
Landfall intensity	5.914	0.015		I and III	II and IV
			TD and TS	18	18
			HU	37	12
Re-intensify over land	8.910	0.003	True	25	4
			False	30	26
Moved back over ocean	5.559	0.018	True	23	5
			False	32	25
Dissipated over U.S.	11.814	0.001	True	11	17
			False	44	13
Completed extratropical transition	5.686	0.017	True	35	11
			False	20	19

Rainfall swath size tends to increase for TCs that move back over the ocean, as most TCs in Groups I and III also re-intensify as they approach the coastline. TCs that dissipated over land show more probability to have a decreasing trend in rainfall size. The results show that 17 out of 30 TCs in Group II and IV dissipated over land, and several TCs in this situation have very little rainfall during the end of the storm period. We also found 11 TCs that dissipated over land yet had expanded their rainfall on the left side. Their expansion is most likely due to intersecting with fronts, approaching the coast, or reintensification over anomalously moist soil conditions (e.g. Tropical Storm Erin in 2007) (Arndt et al. 2009). Last, TCs undergoing ET are also more likely to have an expanding rainfall swath on their left side. This result generally agrees with previous studies which suggested that these TCs will produce an asymmetric rainfall pattern as their rain fields expand on the left side of the storm and diminish on the right side (e.g., Jones et al., 2003; Atallah et al., 2007, Zick and Matyas, 2016).

5. RETURN INTERVALS OF TC RAINFALL AND WIND EVENTS

By examining all rain and wind swaths associated with TCs during 1948 to 2014, we provide a climatological view of the areas of eastern U.S. that have been most affected by TCs. We found that 2435 counties in 25 states, covering 54 % of the CONUS, have been affected by TCP at least once during the study period (Figure 5(a)). The return interval of TCP events ranges from one event every 0.61 to 67 years, the duration of the study period (Fig. 5a). The distribution of TCP recurrence intervals shows a gradual decrease from southeastern coastal areas to inland areas. However, a prominent precipitation gradient becomes evident along the Appalachian Mountains, where strong orographic enhancement of precipitation often occurs on the windward southeastern slopes, while valleys to the northwest often experience sinking air not conducive to heavy rainfall (Knight and Davis, 2007; Konrad and Perry, 2010). An expansive and continuous region from coastal Texas extending northeastern to Vermont and Maine averages at least one TCP event every one to three years. Our results generally agree with spatial patterns of annual heavy TCP over the southeastern U.S. reported by previous studies (Knight and Davis, 2007; Konrad and Perry, 2010) and clearly show the regions at a higher risk of receiving TCP with recurrence of one year and 1-3 years over entire eastern U.S., especially over areas more than 100 km from the coastline and in the northeastern states.

When examining the wind swath data, 278 fewer counties receive one wind event per year as compared to those receiving one rainfall event per year (Fig. 5b). The regions with return intervals between 1 to 3 years also show a large difference in coverage. The wind events are mainly confined to the coastal states while rain events with similar return intervals extend west into Ohio and include all of Kentucky and Tennessee. Only 147 counties have received more wind events than rain events (Fig. 5c) and these are located in the western portion of the study region and in coastal Texas. The likely reason for wind events to have occurred more frequently than rain events is that in these areas, rain field size tends to be smaller due to dry environmental conditions, especially on the left side of the storm. Also, the wind radii distances are calculated using historical averages rather than actual wind measurements, so that TC wind circulations could be smaller in these areas, but this size difference cannot be utilized. For most regions, the rainfall occurrence is much more frequent than that for 17 ms^{-1} winds. The largest differences occur within Florida and regions east of the Appalachian Mountains, which again suggests that increased moisture availability near the coast and orographic enhancement of precipitation are associated with larger rain field swaths.

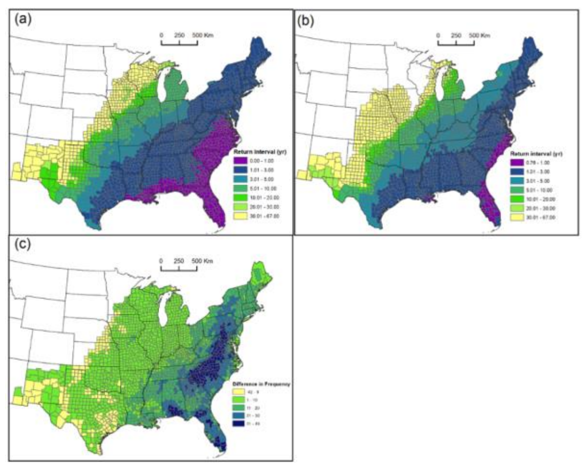

Figure 5. Counties with (a) return interval of TCP events, (b) return interval of TC wind events, and (c) difference in cumulative frequency of rainfall and wind events.

6. CONCLUSIONS

This study addressed the need for a detailed climatology of the spatial characteristics of storm-total rainfall swaths from North Atlantic Basin TCs over the eastern U.S. In this study, a GIS-based method was developed to delineate rainfall swaths of 257 U.S. landfalling TCs during 1948 to 2014, and then calculate their width over land. This method improved upon previous research by extracting a more precise spatial pattern of TCP over land and measured the widths of rainfall on each side of the track. Statistical tests revealed differences in conditions associated with trends in the width of the swath on the left side of the track. Last, the return intervals and frequencies of rainfall and wind events associated with TCs were examined at the county level.

The average left width of a TCP swath ranges from 196 km in TCs making landfall along the Gulf Coast to 233 km for those making landfall over Florida. The average right width of rainfall swaths of TCs making landfalls over Gulf Coast is about 295 km. These statistics support the findings of Matyas (2010) and should be useful for hydroclimatologists calculating the contribution of TCP to a regional water budget (e.g., Knight and Davis, 2007) and serve as a baseline for atmospheric scientists examining rainfall from TCs under future climate scenarios (Wright et al. 2015). Despite the tendency for TC wind fields to decrease in size after landfall, we found that 70 out of 85 TCs have rain swaths that expand in width on the left side at some point while over land. The TCs exhibiting this expansion had attributes of being hurricanes at landfall, re-intensifying over land, undergoing ET, and/or maintaining a position near the coastline rather than tracking far inland. Thus, people located to the left of the projected storm track should monitor conditions closely as they may receive TCP even if located 100-200 km away from the storm center.

Last, we compared return intervals for rainfall and wind events from TCs at the county level. Most counties over the eastern U.S. are exposed more to rainfall than to wind from TCs, especially regions east of the Appalachian Mountains, where the rainfall frequency can be 1.6 to 2.9 times the wind frequency. The previous studies suggested that the wind intensity will decay and extent will decrease after landfall, especially on the left side of the track, while during ET process, the wind field will expand again on the right side (Kruk et al., 2010). The rainfall swaths are more likely expand on the left side in this region due to ET and high moisture availability from the ocean. It should be noted that the rainfall swaths were constructed based on a moderately heavy rainfall threshold (Groisman et al., 2012). The regions within these TCP swaths could be viewed as being at risk of flooding as a TC approaches, however the actual magnitude of the hazard will vary according to many conditions such as rainfall intensity, storm duration, surface slope, and whether soils are saturated (Villarini et al., 2011, Rezapour and Baldock, 2014; Villarini et al., 2014).

The TCP swaths data derived in this study are valuable to various aspects of society. The climatology of the frequency of storm-total rainfall from TCs may be useful to landuse planners when considering the potential flooding regions. From a hazard perspective, a combined dataset of TC rainfall and wind swaths could be input into models like FEMA's HAZUS, which will help government officials identify broad areas that are exposed to these conditions. A detailed analysis of the exposure of the population, urbanized areas, and the ecological system to TC conditions is necessary to evaluate the possible impact and risk of TCs. These swaths can also be useful in the analog approach to forecasting as TCs with similar trajectories might encounter similar synoptic environmental conditions and produce similar rainfall patterns. As such, we are making shapefiles of all 257 rainfall swaths available online (https://hurricane.geog.ufl.edu/).

Results in this study are subject to a few uncertainties. First, by examining rainfall regions greater than 12.5mm-day, we focused on the edge of the rainfall swath to determine which areas were impacted by TCP. To fully investigate rainfall impact, spatial analysis should be performed on precipitation datasets such as the Stage IV analysis that provides rain gauge-corrected radar estimates (Villarini et al., 2011) that do not smooth the extreme values that are needed to examine heavy rainfall impacts over land. Second, due to data limitations, we only measure the rainfall over land, which does not offer information about entire extent of the storm, especially to the right side of the TC center. Observations taken from satellites (e.g. Tropical Rainfall Measuring Mission (TRMM) (Huffman et al. 2007) offer full spatial coverage in the tropics and subtropics to examine TC characteristics such as rain field size, extent, and location relative to the track. Also, this study investigated the associations between several TC attributes and change in rainfall width. Although data span a shorter period and display some inconsistencies in representing TCs over the long-term (Zick and Matyas 2015a, 2015b), the North American Regional Reanalysis dataset has a similar spatial resolution to the TRMM dataset and could be employed to investigate synoptic-scale conditions (e.g. total precipitable water, vertical wind shear, temperature and moisture gradients associated with frontal boundaries) that may contribute to rain field expansion after landfall.

7. ACKNOWLEDGEMENTS

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