Analysis of the Relationship between Flooding Potential of Landfalling Tropical Cyclones and their Size and Forward Speed

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Tropical cyclones striking land often bring heavy rainfall, which can last for a long duration and result in flooding events along the path of the storm. The size and forward speed of the storm has been shown to affect the amount of flooding caused. This study focuses on rainfall and related flood events caused by hurricanes Charley and Frances from the 2004 season. Both storms made landfall over Florida, but were of different intensities and sizes and took different trajectories after landfall. Instances of flooding events from the National Centers for Environmental Information Storm Events Database and flood warnings issued by the National Weather Service are used to identify possible flood locations. The locations are analyzed with actual rainfall totals and timing obtained from a database that combines radar estimates with rain gauge observations. Frances' larger size and slower speed was expected to cause more flooding. The results show that Frances had more flood events and warnings. Frances also had a significantly greater magnitude and duration of flooding in the tested areas. However, rainfall rates were not greater in flood warning areas during Frances, likely due to the tested events' proximity to center and Charley's greater intensity. The results of this study encourage future work to identify the relationship of tropical cyclone size and speed on flooding potential after landfall.

INTRODUCTION

Tropical cyclones are a grandiose force of nature that occur annually during summer and fall in the North Atlantic basin. Although they form and intensify over the ocean, they can also cross over land and cause much destruction through fast winds, storm surge, and heavy rainfall. During these destructive events that the preservation of life and property are of the utmost concern. A determining factor in the evacuation behaviors during hurricanes in the US is the intensity of the storm on the Saffir Simpson Hurricane wind scale (Whitehead et al. 2001). This scale uses wind speed to categorize hurricanes based on destructive potential (Lakshmi 2006). The categories range from a tropical depression up to a Category 5 hurricane. Since this scale only incorporates wind speed, it fails to evaluate all factors that lead to the destructive potential of a landfalling hurricane event. The potential for heavy rainfall is present regardless of a hurricane's wind speeds.

Factors such as size of the storm and its forward speed can play an important role in the potential for damange of these storms as they move over land (Rego and Chunyan 2009). Larger tropical cyclones can bring higher storm surge (Irish, Resio and Ratcliff 2003-2013) and more rainfall to a wider area (Matyas 2014). A tropical cyclone that moves quickly can produce a higher amount of wind-related damage and storm surge, but rainfall totals tend to be lower. Although rainfall from tropical cyclones is responsible for a high amount of deaths in the U.S. (Rappaport 2014), a study done in the aftermath of Hurricane Rita found that the relationship between risk perception of inland flooding and evacuation action was insignificant (Stein, Dueñas-Osorio and Subramanian 2010). Rather, evacuation potential has been found to be related to storm intensity (Whitehead et al. 2001).

In this study, the relationship among storm intensity, forward speed, size, and rainfall amounts will be examined using two storms from the 2004 hurricane season, Charley and Frances. Charley was a fast moving storm with Category 4 intensity and a smaller circulation. Frances was double the size of Charley and crossed the Florida coastline at Category 2 intensity, moving more slowly over land. These differences are shown below.

Table 1. Measurements of Charley and Frances

	Average Land Speed (km/h)	Time Over Land (hrs)	Radius of Outermost Closed Isobar (km)	Intensity at Landfall
Charley	39.1	17	185	Category 4
Frances	22.5	104	370	Category 2

This study will look at locations where flooding did occur, according to reports after the storm, or was forecast to occur according to the National Weather Service. Rainfall events will be analyzed in terms of their duration, magnitude, and rainfall rate. The differences in size and speed between these storms should result in Frances having produced more significant flooding events over land.

DATA AND METHODS

The first step was to determine where flood events occurred,. Polygons representing flood warnings issued by the National Weather Service were obtained from the Iowa Mesonet (IEM 2017) and used to identify the regions that received heavy rainfall. Since these polygons cover the entire country, the first task was to determine which had been triggered by the hurricanes. Polygons that bounded the regions receiving at least 12.5 mm of rainfall from each hurricane were used (Zhou and Matyas 2017). Both the flood warning polygons and hurricane rainfall polygons were imported into a Geographic Information System (GIS) and any flood warnings that fell outside of the rainfall boundary were removed from the study.

To further confirm that the flood warnings occurred while rainfall was being produced by the hurricane, a visual inspection was performed by examining the Wunderground hurricane database's satellite loops (Wunderground 2017) during the time when the warnings were occurring.Overall, 19 flood warnings were issued during the passage of Hurricane Charley, and 180 flood warnings were issued during the passage of Hurricane Frances. Regardless of whether a flood warning was issued, it was necessary to document where and when actual flood events occurred.

The NCEI Storm Events Database (NCEI 2017) houses information on inclement weather events taking place across the U.S. Spanning multiple decades and containing key information such as when, where, and what kind of event took place, this dataset was useful for identifying confirmed flood events. Using the timing and location of the storm's track, satellite imagery from the Wunderground hurricane archive, and descriptions of the events within the database, we identified 108 total flooding events that occurred due to each storm. Using the geographic coordinates representing the centroid of each event, all events were imported into the GIS and represented as points. To be sure that these events occurred within the region of rainfall produced by each storm, these points were also compared to the rainfall polygons developed by Zhou and Matyas (6). Eight flood events caused by rainfall during Hurricane Charley and 100 during Hurricane Frances were identified.

The main limitation of the Storm Events Database was that no reports were available for some areas which were known to have sustained damage from these storms. For example, in the immediate area around Punta Gorda, Florida where the strongest winds occurred during Charley's landfall, there were no events of any kind recorded, including those for wind damage. However, Punta Gorda is the location where the eye made landfall and the location of several damage reports from the storms including hospitals going out of service and roofs being torn off (Orlando Sentinel 2004). Thus, it was important to consider both the flood warnings and storm event reports since some flood reports are likely missing, and some flood events may not have received a warning.

Stage IV data (EOL 2017) were used to determine the rain rates that occurred in association with each storm. This dataset consists of gridded hourly rain rate values that were derived from ground-based weather radars and corrected using rain gauge observations. One advantage of using this dataset over other rainfall datasets is that it benefits from manual quality control measures implemented by river forecast centers before it becomes publicly available. The Stage IV data for the storms in this study were summed from the 12 hours prior and after each 6-hourly storm center location.

The Analysis Process

The next part of the analysis determined the timing of the flood warnings and events relative to the passage of the circulation center of each storm. The time of the 6 hourly track position was taken as a temporal center point. All warning and events from the storm were then assigned to a 6-hourly, center-track position. If the starting time of the event or warning fell within the three hours prior or the three hours after of a center point, they were grouped together irrespective of their location relative to the storm center. This allowed each 24-hour set of Stage IV data that were centered around the 6 hourly center-track positions to then be used to analyze events that began around that time.

Once storm events and warnings were assigned to their respective center points, the amount of rainfall per each hour in the 24-hour period surrounding the center location time to which they belonged was calculated. Within the GIS, each storm event point was assigned to the value of the rainfall grid cell in which it resided. The warning polygons were slightly more complex because they are an area instead of one single point in space that only overlapped a single pixel value. The average value of all pixels falling within the polygon as a whole was calculated to represent rainfall within the warning polygon. To facilitate a faster analysis, a python script was written to compile the data and export values to a spreadsheet. A model of this process is summarized by the flow chart in Figure 1.

Statistical Analysis

To determine the duration of each rainfall event, the number of hours that rainfall occurred out of the 24-hours analyzed was recorded. Rainfall totals for each event were created by adding all hourly values over the 24-hour period. The average rainfall rate was computed by averaging the rainfall experienced per hour over the 24-hours. Once these numbers had been created for all warnings and events, they were grouped based on whether they were caused by Charley or Frances.

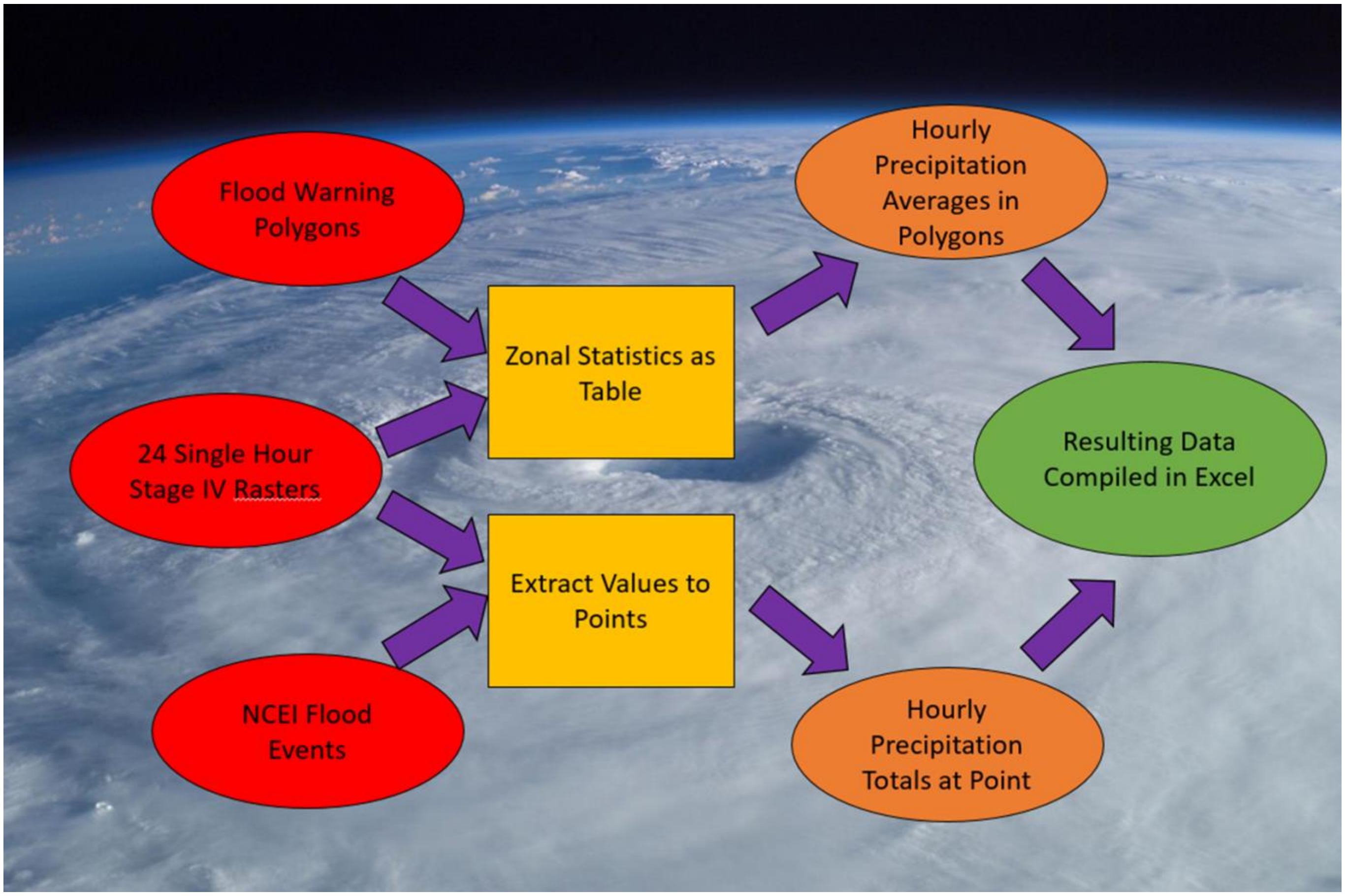

Figure 1. Schematic of the Analysis Process

These groups of data were then ready for statistical analysis. The magnitude, or rainfall totals, for all flood warnings grouped from each storm were tested against each other using a Wilcox Rank-Sum test. The significance level alpha was set to 0.05 and the means were tested for a statistically significant difference by setting the null hypothesis for the mean differences between the two groups to be zero. This same test was done for the duration and rainfall rate of flood warning areas. The statistical tests were then repeated for the NCEI events.

RESULTS AND DISCUSSION

The statistical analysis done on flood magnitude, duration, and precipitation rates showed a significant difference between the two hurricanes in all comparisons (Table 2). In the parameters of flood duration and magnitude, Frances had significantly more hours of reported rainfall in a 24-hour period and greater rainfall accumulation totals. This observed difference is in support of the hypothesis that Frances, as the slower and larger storm, would have a higher potential for flooding. Frances also had a greater rainfall rate at NCEI flood event locations. However, Charley had greater rainfall rates in the flood warning areas, which was likely due to the fact that Charley was a more intense storm than Frances. Precipitation rates have been linked to tropical cyclone intensity, especially in the core region of the storm (Knutson and Tuleya 2004). As shown in Figure 2, many of Charley's events and warnings were located closer to the center of the storm than those of Frances, possibly causing this difference in rainfall rates.

Table 2. Results of Statistical Comparisons

Comparison	Statistically Significant by Wilcox Rank-Sum? (α=0.05)	Charley Mean (millimeters)	Frances Mean (millimeters/hr)
Warning Rainfall Totals	✓	62.8	90.9
Warning Rainfall Duration	✓	12.7	20.2
Warning Rainfall Rate	✓	5.1	4.4
Event Rainfall Total	✓	52.6	95.4
Event Rainfall Duration	✓	8.8	18.2
Event Rainfall Rate	✓	5.7	6.2

Frances has a radius of outermost closed isobar at landfall that is double that Charley. Frances is also close to half the average land speed of Charley. A larger and more slowly-moving tropical cyclone should produce more rainfall over a larger area and the results show that Frances produced longer durations of rainfall and higher totals in both the warned areas and at the event locations. Frances also

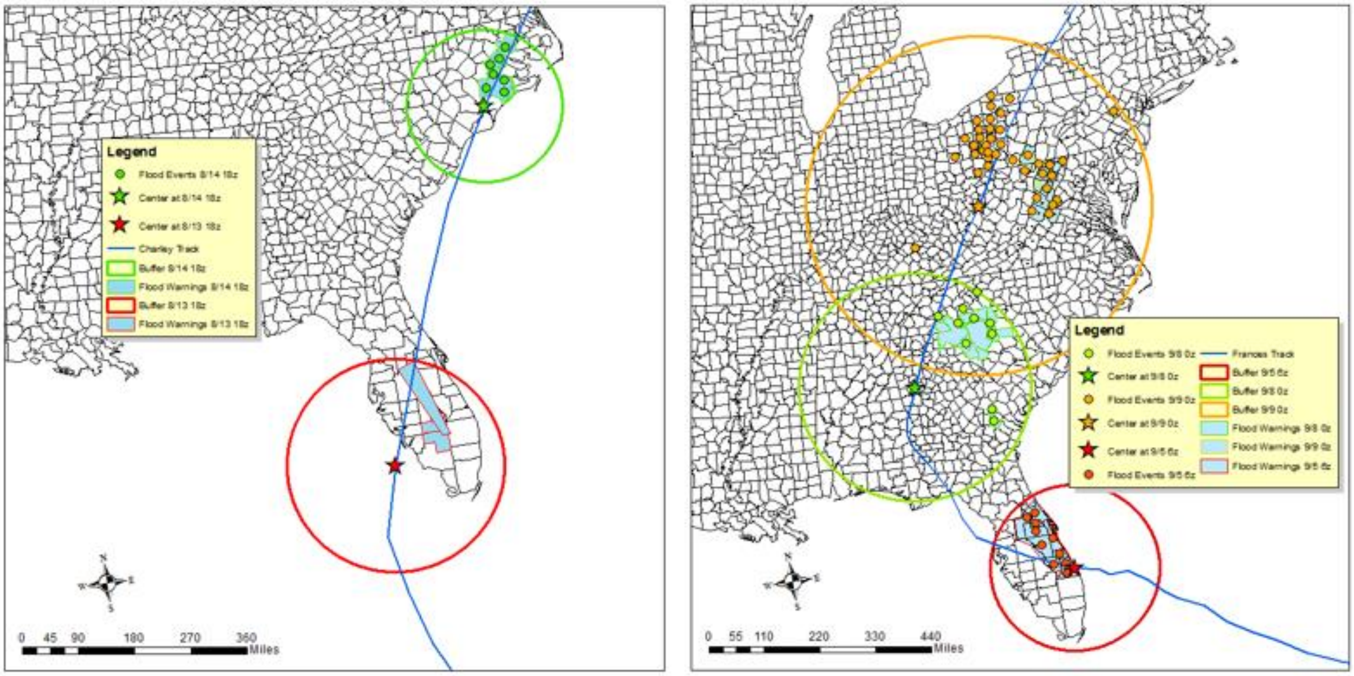

Figure 2. A few of the 6 hourly center locations and their related watches and warnings of Charley (left) and Frances (right)

produced more flood warnings and events than Charley. Distribution. Thus, the findings of this study support the hypothesized relationship and previous research on rainfall distributions in landfalling tropical cylones. These findings not only support the need for future research on other tropical cyclones, but can be used for emergency preparedness. A previous study showed inland flooding risk perception and evacuation behavior to not be strongly correlated. However, the researchers did find a positive correlation between local media and evacuation behavior (Stein, Dueñas-Osorio and Subramanian 2010). According to the results of the study, local media should work especially hard to warn people of the dangerous flooding that can occur as a large and slow-moving tropical cyclone moves inland.

CONCLUSION

This study sought to demonstrate the relationship between size and average forward speed of a landfalling hurricane to its flooding potential. A spatial analysis of rainfall, flood warnings, and reported flood events for hurricanes Charley and Frances were conducted using a GIS. Frances was a large and slow-moving storm that tracked inland. It produced more flood events and events had a longer duration and higher rainfall totals. However, average rain rates were higher for the events that occurred during Hurriane Charley, which could be due to the stronger winds in this storm converging more moisture to fall as precipitation.

There were limitations to the data being used in this study, the most notable being the omission of several areas from the Storm Events Database that should have experienced inclement weather events as a result of these storms. The averaging of rainfall within a warning polygon did not allow for the highest rain rates to be explored, which may have contributed most to the flood event. The fact that storm center positions are only available every six hours means that the precise location of the storm's center at time of event start or issuance of the warning cannot be determined.

The relationships between size, forward speed, and flooding potential should continue to be examined given the results of the current study. A large enough sample of storms exhibiting these relationships could be useful information to disseminate to the public with future storms, which could result in increasing public perception of hurricane flood risk and increasing evacuations for those in harm's way.

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