An Empirical Analysis on the Relationship between Tropical Cyclone Size and Storm Surge Heights along the U.S. Gulf Coast

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ABSTRACT: In the past decade, several large tropical cyclones have generated catastrophic storm surges along the U.S. Gulf and Atlantic Coasts. These storms include Hurricanes Katrina, Ike, Isaac, and Sandy. This study uses empirical analysis of tropical cyclone data and maximum storm surge observations to investigate the role of tropical cyclone size in storm surge generation. Storm surge data are provided by the Storm Surge Database (SURGEDAT), a global storm surge database, while a unique tropical cyclone size dataset built from nine different data sources provides the size of the radius of maximum winds (Rmax) and the radii of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds. Statistical analysis reveals an inverse correlation between storm surge magnitudes and Rmax sizes, while positive correlations exist between storm surge heights and the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds. Storm surge heights correlate best with the prelandfall radius of 93 km h^{-1} (50 kt) winds, with a Spearman correlation coefficient value of 0.82, significant at the 99.9% confidence level. Many historical examples support these statistical results. For example, the 1900 Galveston hurricane, the 1935 Labor Day hurricane, and Hurricane Camille all had small Rmax sizes but generated catastrophic

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surges. Hurricane Katrina provides an example of the importance of large wind fields, as hurricane-force winds extending 167 km [90 nautical miles (n mi)] from the center of circulation enabled this large storm to generate a higher storm surge level than Hurricane Camille along the same stretch of coast, even though Camille's prelandfall winds were slightly stronger than Katrina's. These results may be useful to the storm surge modeling community, as well as disaster science and emergency management professionals, who will benefit from better understanding the role of tropical cyclone size for storm surge generation.

KEYWORDS: Storm surge; Tropical cyclone; Natural hazards; Coastal flooding

1. Introduction

In the past decade, numerous tropical cyclones have generated destructive storm surges along the U.S. Atlantic and Gulf Coasts. While the maximum sustained wind speed of these storms differed considerably, large geographic cyclone size was a common feature among many of these high-profile storms. These disasters have made us reconsider how tropical cyclones generate storm surge.

In 2005, Hurricane Katrina generated a catastrophic storm surge that reached a maximum level of 8.47 m along the Mississippi coast (Knabb et al. 2011). This was the highest modern-day storm surge level in the United States (Needham and Keim 2012). This storm surge overwhelmed many levees in southeast Louisiana, which led to the flooding of approximately 80% of New Orleans (Kates et al. 2006). The $81 billion in damage from this storm (McTaggart-Cowan et al. 2008) ranks Katrina as the most costly natural disaster in U.S. history (Kessler et al. 2006). Katrina's large size contributed to this massive storm surge, enabling it to generate a higher storm surge than Hurricane Camille, even though Camille produced stronger winds when it struck the same area in 1969 (Irish et al. 2008).

Three years later, Hurricane Ike generated a 5.33-m surge in Chambers County, Texas (Berg 2010). This surge level surprised many people, because Ike approached the Texas coast as a category 2 hurricane on the Saffir–Simpson scale, with maximum sustained winds of 176 km h^{-1} (95 kt) (Berg 2010). At that time, the National Oceanic and Atmospheric Administration (NOAA) generalized category 2 hurricanes as having the potential to generate surge levels from 1.8 to 2.4 m (Irish et al. 2008). After Hurricane Ike, NOAA removed storm surge heights from the Saffir–Simpson scale, as it became apparent that maximum sustained wind speeds at landfall are not always a good indicator of surge potential. It is thought that Ike's large size contributed to this massive storm surge. As Ike approached the Texas coast, tropical storm–force winds extended as far as 296 km [160 nautical miles (n mi)] and hurricane-force winds extended as far as 204 (110 n mi) from the center of circulation (Demuth et al. 2006).

In 2012, Hurricane Isaac generated a large storm surge in southeast Louisiana and Mississippi. Storm tide levels exceeded 3 m in at least two Mississippi counties and four Louisiana parishes east of the Mississippi River (McCallum et al. 2012). In portions of Plaquemines Parish, Louisiana, storm tide levels exceeded 4.3 m (McCallum et al. 2012). Isaac's large size likely contributed to this massive coastal flooding event, as the storm became a hurricane just hours before landfall in southeast Louisiana (Berg 2013). Hurricane Isaac produced tropical storm–force winds up to 333 km (180 n mi) from the center of circulation for several days before making landfall and hurricane-force winds up to 111 km (60 n mi) from the center of circulation in the hours before landfall (Demuth et al. 2006). Also, the slow forward movement of Isaac may have also contributed to the large surge, as the duration of persistently strong winds was high in certain locations.

Two months after Isaac, Hurricane Sandy generated a destructive storm surge that flooded much of the U.S. Mid-Atlantic Coast, including portions of the greater New York City metropolitan area. The storm caused approximately $50 billion in economic losses and killed 147 people (Blake et al. 2012). Damage from Sandy's surge included more than $5 billion in losses to mass transit infrastructure (Bernstein 2013), as the storm surge inundated lower Manhattan and flooded the subway system. Sandy's large size likely contributed to its devastating storm surge. Several hours before landfall on the New Jersey coast, Sandy generated a massive wind field, with tropical storm–force winds extending 778 km (420 n mi) and hurricane-force winds extending 333 km (180 n mi) from the center of circulation (Demuth et al. 2006). From another perspective, the diameter of tropical storm–force winds was approximately 1519 km (820 n mi), which is greater than the driving distance from Atlanta to New York (Erdman 2012).

These surge events have attracted much attention, and several publications have now investigated the role of hurricane size for generating storm surge. For example, Irish et al. (Irish et al. 2008) found that hurricane size plays a key role for storm surge generation, particularly over mildly sloping bathymetry. They also estimate that differences in storm size may cause storm surge heights to vary as much as 30%. Nielsen (Nielsen 2009) stated that these observations are mimicked by a simple power fit and further investigated the role of storm size on surge height using 1D and 2D analyses.

Although these papers provided new insights into the influence of tropical cyclone size on storm surge generation, the approach of these analyses relied heavily on modeling. A thorough literature review on this topic reveals that no studies have relied on empirical analysis to investigate this topic. As such, this paper investigates the role of tropical cyclone size for generating storm surges along the U.S. Gulf Coast by 1) building a comprehensive tropical cyclone size data set; 2) correlating various tropical cyclone size parameters with observed storm surge heights; and 3) investigating relationships between tropical cyclone size and maximum sustained wind speeds.

2. Data

2.1. Storm surge data

Storm surge data are provided by the Storm Surge Database (SURGEDAT), a global surge database that provides more than 7600 high-water marks from storm surge events in the United States since 1880 (Needham and Keim 2012; Needham et al. 2013). We chose the U.S. Gulf Coast as the geographic region for this analysis based on the excellent quality of surge data provided by SURGEDAT for this region. The database provides the location and height of peak storm surge for 191 surge events along this coastline since 1880, as well as widespread coverage of observations for 110 individual Gulf Coast storms, supported by approximately

5200 high-water marks. An updated surge dataset is available for download online (at http://surge.srcc.lsu.edu).

2.2. Tropical cyclone wind and position data

Tropical cyclone wind and position data are provided by Elsner and Jagger (Elsner and Jagger 2013). This dataset provides hourly information on tropical cyclone maximum sustained winds, forward speed, direction, and position. The authors utilized spline interpolation to provide nonlinear tropical cyclone data from 6-h observations provided by the Hurricane Database (HURDAT; AOML 2006).

2.3. Tropical cyclone size data

A thorough literature review reveals that many sources provide tropical cyclone size data. These sources provide a variety of temporal coverage, hurricane size parameters, and units of measurement. The most common measurement type is radius of maximum wind (Rmax), which measures the distance from the center of the hurricane eye to the peak wind speed, usually observed in the eyewall. Distances are usually provided in nautical miles, although some sources list distances in kilometers.

The Atlantic Oceanographic and Meteorological Laboratory (AOML) HURDAT reanalysis project provides four datasets that include hurricane size information. These data provide a comprehensive reanalysis of hurricane characteristics, including the radius of maximum winds. AOML provides data for the years 1851–1910 (Landsea et al. 2003), 1911–20 (Landsea et al. 2007), 1921–30 (Landsea et al. 2011), and 1944–53 (Hagen et al. 2012).

Various other sources provide hurricane size data, which are listed as radius of maximum wind. Simpson and Riehl (Simpson and Riehl 1981) provide data for 59 hurricanes from 1893 to 1979, Ho et al. (Ho et al. 1975) provide data from 1900 to 1969, and Irish et al. (Irish et al. 2008) provide data for 22 selected hurricanes from 1941 to 2005. All of these sources only provide the distance of Rmax. Powell and Reinhold (Powell and Reinhold 2007) provide storm size data for 18 hurricane landfalls in the United States from 1989 to 2005, as well as Hurricane Camille, in 1969. Data are provided as Rmax, as well as radius of 34-, 50-, and 64-kt winds, all listed in kilometers. Demuth et al. (Demuth et al. 2006) provide hurricane size data in 6-h intervals for tropical systems from 1988 to the present, which are listed as Rmax; eye diameter; radius of the outer closed isobar; and radii of 34-, 50-, and 64-kt winds, all in nautical miles. Although this source was originally published in 2006, the website associated with this publication is updated annually. This is the only source that provides hurricane size data in various time intervals, providing insight into the variation of hurricane size over time for specific storms.

3. Methods

The first step in this analysis involved creating a comprehensive tropical cyclone size dataset because each of the (nine) size sources provides data for a select period of time, but no source provides a comprehensive archive of complete size data. We archived the size of Rmax, as this measurement type is the most common in

Table 1. Landfall/surge event types that were removed from analysis in Needham and Keim (Needham and Keim 2014). A total of 72 events were removed from the analysis.

Event type	No. of events	Example storm (year)
Storm tracks closest to location of peak surge 4 h or more after COO	22	Tropical Storm Matthew (2004)
Peak surge located to the left of landfall	17	Unnamed (1916)
Landfall location far from location of peak surge	24	Gilbert (1988)
Tropical cyclone moving offshore as it generates peak surge	9	Unnamed (1947)

historical literature, as well as the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds, even though these data are only available since 1988.

As this paper investigates the role of tropical cyclone size for generating storm surge, it is only necessary to archive size data for storms with useable storm surge data. Although SURGEDAT provides peak storm surge data for 191 events along the U.S. Gulf Coast since 1880, it is not necessary to obtain size data for all of these events because only surge events that are identified near the location of a tropical cyclone landfall will be used in this study. This methodology follows the approach used by Needham and Keim (Needham and Keim 2014), as they created a landfall classification system that categorized surge events into 14 categories, depending on the relationship between the tropical cyclone track and peak surge location. Of the 189 surge events analyzed between 1880 and 2011, 117 provided useable data in which a peak storm surge position was located near a landfalling tropical cyclone, while 72 events were removed from the analysis, because of disconnects in time and space of the storm track and the surge event. A list of the event types that were removed from this analysis are provided in Table 1.

This landfall classification system defined the landfall location as the closest offshore observation (COO), which was the offshore tropical cyclone position closest to the location of peak storm surge. However, 22 tropical cyclones were removed because 4 h or more passed between the time of COO and the time when the tropical cyclone actually tracked closest to the location of peak surge. In these cases, the tropical cyclone tracked inland toward the location of peak surge for at least 4 h after COO, which means the storm conditions near the location of peak surge may have differed considerably from the conditions when the cyclone made landfall. In many of these cases, the peak surge occurred on a bay, enabling the storm track to make its closest approach to the location of peak surge while the storm was located inland for several hours. Peak surge events that were located to the "left" of tropical cyclone tracks were also removed from this analysis. These 17 events were excluded from the study because peak surge heights usually occur to the "right" of tropical cyclone tracks in the Northern Hemisphere, so it is possible that SURGEDAT is missing the actual location and height of peak surge for these events or extreme extenuating circumstances prevailed in the storm track and/or the coastal geomorphology. Tropical cyclones that tracked too far away from the location of peak surge were also excluded from this analysis. The 24 events that fall into this category often include tropical cyclones that made landfall far south of the Texas–Mexico border but still produced a surge observation in south Texas, as well as tropical cyclones that track well south of the Florida Keys, but still generate elevated seas along the island chain. Tropical cyclones that made landfall more than 159 km (86 n mi) from the location of peak surge were removed from this analysis, as this distance represents the average extent of tropical storm–force winds in category 1 and category 2 hurricanes (Keim et al. 2007). The final event type that was removed from this analysis included cyclones that generated a peak surge along the west coast of Florida as they tracked westward off the peninsula. These nine events were removed because the tropical cyclones were not making landfall but moving from land to water as they generated a storm surge event.

Although the landfall classification system adds some complexity, it improves the analysis by providing a consistent method for determining landfall while removing missing or inaccurate surge data. The tropical cyclone size analysis will identify size data for as many of the 117 useable surge events as possible, as well as Tropical Storm Debby and Hurricane Isaac, which both occurred in 2012 and were not included in the previous analysis.

Tropical cyclone size data were provided as a measure of Rmax size for 83 of these 119 surge events. Most sources provided one Rmax size per tropical cyclone; however, Demuth et al. (Demuth et al. 2006) provided values at 6-h intervals for 31 out of 33 tropical cyclones since 1988. This source was missing Rmax data for Hurricanes Chantal and Jerry, which both produced peak surge observations in Texas in 1989. For cases in which Rmax sizes changed as a tropical cyclone approached the coast, the Rmax size at 18 h before landfall was utilized to represent the storm characteristics as the cyclone approached the coast. This specific time interval was determined because Needham and Keim (Needham and Keim 2014) found that surge heights correlate best with wind speeds 18 h before landfall.

Demuth et al. (Demuth et al. 2006) also provided the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds for tropical cyclones from 1988 to 2012. These distances were archived at landfall and 18 h before landfall. This source provided distance in nautical miles to the northeast, southeast, southwest, and northwest of the storm center. We chose the nautical miles greatest distance and employed interpolation techniques if the time of landfall fell between 6-h observations. Following the methodology established by Needham and Keim (Needham and Keim 2014), we did not archive data if the tropical cyclone was not centered over the Gulf of Mexico or approaching the Florida Keys from the Atlantic. As such, size observations were not archived for Hurricane Charley at 18 h before landfall, as this storm was centered in the Caribbean Sea, south of Cuba, at this time. The Rmax size of Charley consistently remained at 19 km (10 n mi) from this time until it crossed Cuba and made landfall in Florida, so we used the Rmax size from the Florida landfall. Although Powell and Reinhold (Powell and Reinhold 2007) also provided the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) wind fields for Hurricane Camille, these data were not utilized because they relied heavily on modeling, while this paper relies on empirical observations.

After building this tropical cyclone size dataset, we identified the largest and smallest tropical cyclones, as well as the average size of these storms. We also analyzed the correlation between various tropical cyclone size parameters, as well as the relationship between those parameters and storm surge heights.

4. Results

4.1. Analysis of Rmax size for storm surge generation

The average Rmax size of the 83 events was 48.3 km (26.08 n mi). The 31 Rmax sizes provided by Demuth et al. (Demuth et al. 2006) show some change in size as tropical cyclones approach the coast. At landfall, the average Rmax size of these events was 61.41 km (33.16 n mi), while the average size at 18 h before landfall was 67.1 km (36.23 n mi). These results may indicate that Rmax sizes tend to decrease as a tropical cyclone approaches the coast; however, these values were only calculated for a subset of storms for which we have accurate storm surge data and may not represent patterns found in more extensive analyses. It is unclear why the average size of the storms provided by Demuth et al. (Demuth et al. 2006) is noticeably larger than the average size for the entire dataset. While changes in detection methodologies are a possible explanation, it is also noteworthy that many of the smallest tropical cyclones, like Hurricane Camille and the 1935 Labor Day hurricane, occurred before 1988, so they are not included in the data provided by Demuth et al. (Demuth et al. 2006).

The three storms with the largest Rmax sizes were tropical storms that produced peak surge heights along the west coast of Florida. Tropical Storm Josephine had an Rmax size of 167 km (90 n mi) in 1996, the Rmax size for Tropical Storm Keith in 1988 was 141 km (76 n mi), and Tropical Storm Debby's Rmax size was 139 km (75 n mi) in 2012.

The storms with the smallest Rmax sizes were intense tropical cyclones that made landfall as major hurricanes. The Rmax size of Hurricane Dennis in 2005 was 9 km (5 n mi), the 1935 Labor Day hurricane had an Rmax size of 11 km (6 n mi), and Hurricane Camille had an Rmax size of 15 km (8 n mi) in 1969. The 1935 Labor Day hurricane and Hurricane Camille both made landfall as category 5 hurricanes.

The pattern shown in these events reveals an inverse relationship between Rmax sizes and maximum sustained wind speeds. The storms with the largest Rmax sizes tend to be less intense, while the most intense tropical cyclones that have struck the United States tended to have small Rmax sizes. This observation is supported statistically, as the Pearson correlation of Rmax sizes and maximum sustained wind speeds 18 h before landfall is inverse. The r value of this correlation is 0.46 and the correlation is significant at the 99.9% confidence interval.

The inverse relationship between Rmax sizes and maximum sustained wind speeds raises an interesting question related to storm surge generation. If tropical cyclone size, defined as the Rmax size, relates inversely with maximum sustained wind speeds, which of these two parameters correlates better with storm surge heights? Statistical analysis of these variables reveals that storm surge magnitudes correlate inversely with Rmax sizes, with a Pearson correlation r value of 0.0902, significant at the 99% confidence level (Figure 1). These results indicate tropical cyclones with small Rmax sizes often produce larger storm surge magnitudes than tropical cyclones with large Rmax sizes. However, a Pearson correlation test shows that storm surge heights correlate positively with maximum sustained winds 18 h before landfall for these 83 tropical cyclones, producing an r^2 value of 0.62, significant at the 99.9% confidence level. These values are comparative to results provided by Needham and Keim (Needham and Keim 2014), who found the

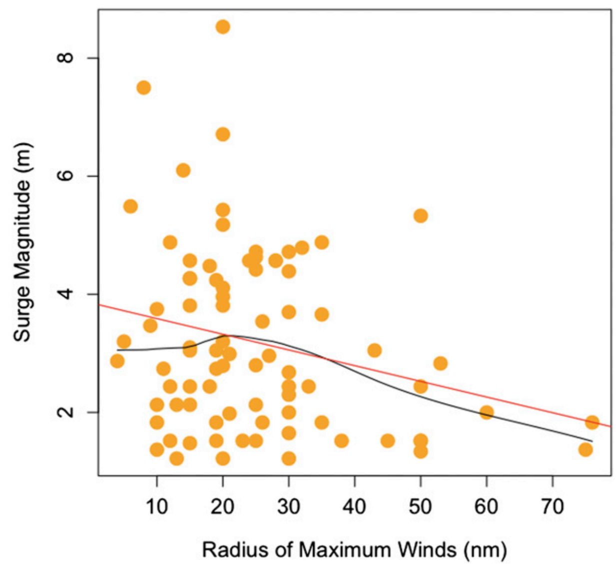

Figure 1. LOESS (black line) and linear (red line) regression models for the relationship between surge heights and the radius of maximum winds (nm). Orange circles depict observed events.

relationship between storm surge heights and prelandfall winds produces *r* values of 0.60 for 117 events from 1880 to 2011 and 0.66 for 63 events from 1960 to 2011.

Although it may seem counterintuitive that tropical cyclones with larger Rmax sizes tend to generate smaller storm surges, historical examples support these results. For example, the three tropical cyclones with the largest Rmax sizes, tropical storms Josephine, Keith, and Debby, generated an average surge height of 2.01 m, while the three tropical cyclones with the smallest Rmax sizes, Hurricane Dennis, the 1935 Labor Day hurricane, and Hurricane Camille, generated an average surge magnitude of 5.40 m.

A comparison between the 1900 Galveston hurricane and Hurricane Ike in 2008 provides a helpful comparison, because both storms tracked across the Gulf of Mexico from southeast to northwest and made landfall on Galveston Island, Texas. The 1900 Galveston hurricane was a small storm, with a radius of maximum winds of 26 km (14 n mi) (Ho et al. 1975; Simpson and Riehl 1981; Landsea et al. 2003), while Hurricane Ike was larger. The radius of maximum winds for Hurricane Ike was 92 km (50 n mi) at 18 h before landfall and 56 km (30 n mi) at landfall (Demuth et al. 2006). Although Ike was a larger storm, it generated a peak surge level of 5.33 m in Chambers County, Texas (Berg 2010), while the 1900 Galveston hurricane generated a peak surge of 6.1 m (Garriott 1900), which devastated Galveston Island.

The storm surge history of the Florida Keys provides further evidence for the inverse relationship between surge magnitudes and Rmax sizes. We have listed the surge magnitude, Rmax size, and wind speed 18 h before landfall for the 13 Florida Keys surge events analyzed in this study (Table 2). This region is chosen because this island chain has relatively consistent bathymetry, without the presence of large bays or sounds, which enhance surge heights (Needham and Keim 2011).

Table 2. Comparison of storm surge heights, hurricane size, and maximum sustained wind speed at 18 h before landfall for the 13 Florida Keys surge events analyzed in this study. Data are compiled from Ho et al. (Ho et al. 1975), Landsea et al. (Landsea et al. 2003; Landsea et al. 2007; Landsea et al. 2011), Demuth et al. (Demuth et al. 2006), and Hagen et al. (Hagen et al. 2012).

Storm name	Year	Peak surge location	Surge height (m)	Rmax in km (nm)	18 h wind in km h^{-1} (kt)	Surge rank	Wind rank	Size rank
Unnamed	1910	Key West	4.57	52 (28)	237 (128)	2	2	4
Unnamed	1919	Cow Key	4.27	28 (15)	209 (113)	3	4	9
Unnamed	1929	Key Largo	2.68	56 (30)	198 (107)	6	6	1
Labor Day	1935	Lower Matecumbe	5.49	11 (6)	219 (118)	1	3	12
Unnamed	1948	Key West	1.83	19 (10)	Outside GOM	8	—	10
Donna	1960	Upper Matecumbe	4.11	37 (20)	239 (129)	4	1	6
Isbell	1964	Key West	1.37	19 (10)	Outside GOM	11	—	10
Betsy	1965	North Key Largo	2.74	35 (19)	204 (110)	5	5	7
Inez	1966	Big Pine Key	1.52	35 (19)	139 (75)	9	8	7
Floyd	1987	Lower and Middle Keys	1.22	No data	Outside GOM	12	—	No data
Gordon	1994	Upper Florida Keys	1.22	56 (30)	83 (45)	12	10	1
Georges	1998	Florida Keys	2.3	56 (30)	144 (78)	7	7	1
Rita	2005	Key West	1.52	46 (25)	109 (59)	9	9	5

The four hurricanes with the strongest prelandfall winds in this region generated the four largest surge events, although not in rank order. However, the hurricanes with the four largest Rmax sizes generated the 6th, 7th, 9th, and 12th largest surges. The 1935 Labor Day hurricane was the smallest storm in this archive, but it produced the largest modern-day surge height in the Florida Keys. Although the radius of maximum winds for this event was only 11 km (6 n mi) (Ho et al. 1975), this storm generated a massive 5.49-m surge (Knowles 2009, Chart File 3-16-10,409.), which was the sixth highest surge event in magnitude along the U.S. Gulf Coast in the past 132 years, according to the SURGEDAT database. This storm was a category 4 hurricane, with maximum sustained winds of 218 km h^{-1} (118 kt), 18 h before landfall. It further intensified into the first category 5 hurricane to make landfall in the United States (National Weather Service 2010).

4.2. Analysis of wind swath size for storm surge generation

Demuth et al. (Demuth et al. 2006) provided wind swath data for tropical cyclones that impacted the U.S. Gulf Coast since 1988. These data are provided as radial distances of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds. SURGEDAT provided surge data for 33 storm surges located near landfalling tropical cyclones during this time period, making them suitable for analysis.

The size of each of these wind swaths was recorded at landfall and 18 h before landfall. At landfall, 31 observations were provided for radius of 63 km h^{-1} (34 kt) winds, 32 observations were provided for radius of 93 km h^{-1} (50 kt) winds, and 29 observations were available for radius of 119 km h^{-1} (64 kt) winds (Table 3). Missing data explain why 33 observations are unavailable for each of these time periods. At 18 h before landfall, 31 observations were available for 63 km h^{-1}

Table 3. Spearman rank order correlations measuring the relationship between storm surge heights and radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds.

Radius measure	63 km h^{-1} (34 kt) winds at landfall	63 km h^{-1} (34 kt) winds at landfall − 18 h	93 km h^{-1} (50 kt) winds at landfall	93 km h^{-1} (50 kt) winds at landfall −18 h	119 km h^{-1} (64 kt) winds at landfall	119 km h^{-1} (64 kt) winds at landfall − 18 h
No. of observations	31	31	32	30	29	30
R value	0.6874	0.6069	0.7634	0.8158	0.7388	0.7935
P value	0.0000	0.0004	0.0000	0.0000	0.0000	0.0000

(34 kt) winds and 30 observations were available for both 93 (50 kt) and 119 km h^{-1} (64 kt) winds (Table 3). Missing data account for some of the data loss; however, we intentionally excluded data from Hurricane Charley at 18 h before landfall, because the storm was centered in the Caribbean Sea, south of Cuba, at this time.

For observations 18 h before landfall, the average extent of 63 km h^{-1} (34 kt) winds was 278.5 km (150.4 n mi), the maximum radius was 463 km (250 n mi) in Hurricane Ivan in 2004, and the minimum distance was 74 km (40 n mi) in Tropical Storm Humberto in 2007. The average size of 93 km h^{-1} (50 kt) winds was 166 km (89.9 n mi), the maximum size was 278 km (150 n mi) in Hurricane Ike in 2008, and the minimum distance was 0 km (0 n mi), which occurred for six tropical cyclones that did not reach this intensity. The average value was computed for the 24 events that generated winds of at least 93 km h^{-1} (50 kt). The average radius of 119 km h^{-1} (64 kt) winds among the 16 storms that generated hurricane-force winds was 113 km (60.8 nm). The greatest extent was 217 km (117 nm) in Hurricane Opal in 1995, and the smallest was 0 km (0 nm), which occurred in 14 tropical cyclones that did not reach hurricane-force winds.

Statistical analysis determined positive correlations between storm surge heights and the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds (Table 3). We used Spearman rank order correlations for these tests because of data constraints, as the value of some radii were listed as zero, such as the radius of 119 km h^{-1} (64 kt) winds if the tropical cyclone was below the intensity of a hurricane. Correlation tests found the radius of 93 km h^{-1} (50 kt) winds 18 h before landfall produced the best correlation with surge heights ($r = 0.82$; $p < 0.01$). We used linear and local regression (LOESS) to depict this relationship graphically in Figure 2. The radius of 34-kt winds 18 h before landfall produced the least optimal correlation ($r = 0.61$; $p < 0.01$).

The Rmax sizes were inversely related to the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds (Table 4). These results suggest that tropical cyclones with more compact eyewalls tend to cover larger areas with strong winds. This is logical when considering that storm surge magnitudes relate positively with the size of wind fields but negatively with Rmax sizes. The relationship between Rmax sizes and the size of the wind fields became increasingly inverse for stronger wind speeds. Also, this negative correlation was greater at 18 h before landfall than at landfall for the area of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds. However, these results were only significant above the 90% confidence level for the relationship between Rmax sizes and 119 km h^{-1} (64 kt) winds at landfall and 18 h

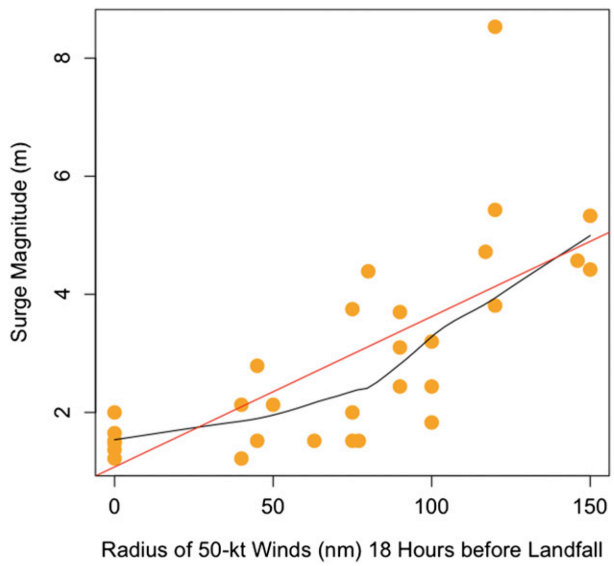

Figure 2. LOESS (black line) and linear (red line) regression models for the relationship between surge heights and radius of 93 km h^{-1} (50 kt) winds (nm) at 18 h before landfall. Orange circles depict observed events.

before landfall. Hurricanes Katrina and Rita are examples of such storms. Both of these hurricanes had Rmax sizes of 37 km (20 nm), which is smaller than the average distance for the 83 storms with Rmax data; however, the radius of 119 km h^{-1} (64 kt) winds for both of these hurricanes ranked in the top five and both cyclones generated catastrophic storm surges along the northern Gulf Coast.

Many tropical cyclones in the past several decades reveal the importance of wind swath area for generating storm surges. For example, the tropical cyclones with the six largest radii of 119 km h^{-1} (64 kt) winds produced the six largest storm surges, although not in rank order. However, relatively low-magnitude storm surges were generated by the 14 tropical cyclones with no radius of 119 km h^{-1} (64 kt) winds at 18 h before landfall. These events were all tropical storms, with wind intensity less than hurricane force. From another perspective, 75% (12 of 16) of the tropical cyclones with nonzero radii of 119 km h^{-1} (64 kt) winds at 18 h before landfall

Table 4. Correlation between Rmax sizes and the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds. All of these correlations are inverse, meaning that there is a negative relationship between the variables.

Radius measure	63 km h^{-1} (34 kt) winds at landfall	63 km h^{-1} (34 kt) winds at landfall − 18 h	93 km h^{-1} (50 kt) winds at landfall	93 km h^{-1} (50 kt) winds at landfall − 18 h	119 km h^{-1} (64 kt) winds at landfall	119 km h^{-1} (64 kt) winds at landfall − 18 h
R value for Rmax vs swath size	−0.0458	−0.1868	−0.1208	−0.2247	−0.3306	−0.4274
P value	0.8088	0.3294	0.5233	0.2486	0.0804	0.0242

generated surge heights of at least 3 m, while none of the 14 storms with a zero value for the radius of 119 km h^{-1} (64 kt) winds generated a surge exceeding 3 m.

5. Discussion

This analysis reveals that we must be careful how we define tropical cyclone size when considering its role in storm surge generation. The size of Rmax correlates inversely with surge height, while the radii of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds correlate positively with surge magnitudes, indicating that surge potential is increased in tropical cyclones with small Rmax sizes or large swaths of strong winds. However, observations from some storms may appear to contradict these results. For example, Hurricane Katrina generated a larger storm surge than Hurricane Camille, although Camille had a smaller Rmax size. However, the swath size of Katrina's wind field was larger than the area covered by Hurricane Camille. It should also be noted that Katrina's maximum sustained winds were comparable to Camille's at 18 h before landfall; the difference in wind speeds was only about 20 km h^{-1} (11 kt). Such comparisons may reveal that the larger of two tropical cyclones with comparable prelandfall wind speeds may generate the higher storm surge, while the stronger of two cyclones with comparable sizes may generate the larger surge.

We should use caution not to overestimate the role of tropical cyclone size. The comparison between Katrina and Camille may tempt us to do so, as Katrina is often referred to as a category 3 hurricane that generated a higher storm surge than a category 5 hurricane along the same stretch of coastline. As bathymetry and geomorphology were relatively constant for these two storms, we may overemphasize the importance of tropical cyclone size if we do not consider that Katrina's prelandfall wind speeds were also intense and surge heights correlate better with prelandfall winds than wind speeds at landfall (Jordan and Clayson 2008; Needham and Keim 2014).

Our analysis also further expands understanding of the importance of prelandfall tropical cyclone characteristics for storm surge generation. Storm surge magnitudes correlated best with the radii of 93 (50 kt) and 119 km h^{-1} (64 kt) winds at 18 h before landfall, and these correlations were noticeably higher than the radii of those same wind fields at landfall. These results help us understand that maximum sustained winds are not the only tropical cyclone parameter that correlates better with surge heights before striking the coast than at landfall. The role of prelandfall tropical cyclone size, particularly the area of 93 (50 kt) or 119 km h^{-1} (64 kt) winds, appears to be comparable to the role of prelandfall winds for storm surge generation. The r values for the correlation of surge and prelandfall winds were 0.7754 ($r^2 = 0.60$) in 117 wind–surge events since 1880 and 0.81 ($r^2 = 0.66$) in 63 wind–surge events since 1960 (Needham and Keim 2014).

Our study utilized peak storm surge heights and did not consider the full extent of storm surge inundation along a coastline. While small, intense tropical cyclones have sometimes generated high surge magnitudes, larger cyclones tend to inundate larger expanses of coastline. For example, although the 1900 Galveston hurricane generated a higher peak surge than Hurricane Ike in 2008, Hurricane Ike's surge likely inundated a longer stretch of coastline (Needham and Keim 2011). Although

Ike made landfall near Galveston, Texas, the storm produced a storm tide of 3.32 m south of New Orleans, in Plaquemines Parish, Louisiana (Federal Emergency Management Agency 2009), more than 463 km (250 n mi) east of Ike's landfall location. A thorough literature review does not provide any coastal flooding observations that far east from the 1900 Galveston hurricane. Therefore, it appears as though Ike's massive size generated higher surge levels than the 1900 Galveston hurricane outside the zone of peak surge. This comparison may provide an important insight into this study. While small, intense tropical cyclones sometimes generate high-magnitude storm surges, the extent of inundation along the coastline may be less than the surges produced by larger, less intense cyclones.

6. Summary and conclusions

This study provides the first empirical analysis on the relationship between tropical cyclone size and storm surge heights. Storm surge is provided from SURGEDAT, tropical cyclone position and intensity data are provided by Elsner and Jagger (Elsner and Jagger 2013), and a tropical cyclone size dataset is built from nine separate sources. Tropical cyclone size data were archived as the size of the radius of maximum winds (Rmax), as well as the radius of 63 (34 kt), 93 (50 kt), and 119 km h^{-1} (64 kt) winds.

Rmax sizes correlated inversely with storm surge heights, prelandfall wind speeds, and the size of wind swaths. Historical examples support this statistical analysis. For example, the cyclones with the three largest Rmax sizes were all tropical storms that did not reach hurricane intensity and generated average surge levels of approximately 2 m. However, the tropical cyclones with the three smallest Rmax sizes were all major hurricanes that generated large surges, averaging 5.4 m. The 1900 Galveston hurricane, the 1935 Labor Day hurricane, and Hurricane Camille all had small Rmax sizes but generated catastrophic storm surges.

Conversely, the size of tropical cyclone wind swaths correlated positively with surge heights. Storm surge magnitudes correlated best with the radius of 93 km h^{-1} (50 kt) winds at 18 h before landfall, when the Spearman correlation coefficient reached 0.8158, followed by the radius of 119 km h^{-1} (64 kt) winds at 18 h before landfall. These results indicate that storm surge magnitudes relate to the prelandfall size of tropical cyclone wind swaths about as well they do to the strength of prelandfall winds. This study also reveals that storms with compact eyewalls and large wind fields tend to generate larger storm surges.

Such results may be helpful to the storm surge modeling community, as scientists are currently reevaluating the role of various tropical cyclone parameters for storm surge generation. These results may also be important for the emergency management and disaster science community for better understanding surge potential in specific types of storms. As many of the recently destructive storm surges were generated by large tropical cyclones, it is important to realize that storms such as the 1900 Galveston hurricane, the 1935 Labor Day hurricane, and Hurricane Camille all generated catastrophic storm surges, even though they were all small storms, at least in regards to the Rmax size. Coastal stakeholders should take the utmost precautions for such events, as well as tropical cyclones with large prelandfall radii of 93 (50 kt) or 119 km h^{-1} (64 kt) winds, which tend to consistently generate large surge events.

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