The Effect of Coastline Concavity on Maximum Storm Surge Height along the US Gulf Coast

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https://doi.org/10.33697/ajur.2023.084

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ABSTRACT
Storm surge is the most dangerous component of landfalling tropical cyclones (TCs). The growing coastal population highlights the importance of research regarding the atmospheric and geographic factors influencing the maximum storm surge height (MSSH). To date, few studies have investigated the influence of coastline concavity. Here, we investigate the hypothesis that TCs making landfall on a concave coastline will have a higher MSSH than TCs making landfall on a convex coastline. The Colorado State University extended best track dataset includes the radius of 34 kt winds (R34), landfall minimum mean sea level pressure (MSLP), landfall maximum sustained winds, and forward speed of TCs. The storm surge database for the US Gulf Coast provides the location and MSSH for TCs impacting the U.S. Gulf Coast. From this, eleven TCs that meet specific criteria and represent the larger population of Atlantic TCs are selected. The adjusted degree of coastline concavity (ADoC) is calculated for each TC using the law of cosines and 50, 100, and 200 km radius buffers around the point of MSSH. A Mann Whitney *U* test does not indicate any significant differences between the mean MSSH of TCs making landfall on each coastline type. Additionally, results from a simple linear regression F-test suggest that none of the included parameters have a significant influence on MSSH despite the findings of previous research. Still, the Spearman's Rho correlation values suggest a weak positive relationship between the ADoC and MSSH. This relationship is significant at the 100 and 200 km buffers, which is consistent with the hypothesis. Results are limited by the small sample size. Future research should use a larger dataset and investigate how each individual storm characteristic affects MSSH.

KEYWORDS
Tropical Cyclones; Hurricanes; Storm Surge; Coastal Geography; Coastline Concavity; Gulf of Mexico; Law of Cosines

INTRODUCTION

With the increasing urbanization of coastal areas, the importance of local economies, and the growing number of people living near the ocean, research concerning coastal influences on storm surge is critical to developing effective coastal management, disaster preparedness, and resilience plans. The population density in counties along the U.S. Gulf Coast has grown by 32% since 1990.[1] Therefore, research focused on identifying locations of greater storm surge risk would allow emergency managers to formulate plans to expedite evacuation procedures for a growing population. For example, prior to the landfall of Hurricane Katrina (2005), many residents became stranded on evacuation routes due to the sheer number of people attempting to leave New Orleans at the same time.[2] This issue only contributed to the natural and social disaster that was Hurricane Katrina. Effective evacuation plans could streamline the evacuation process and decrease the amount of overcrowding on evacuation routes, allowing people to exit the area faster. Further knowledge of storm surge and the interactions between the coastline and maximum storm surge height (MSSH) has the potential to save lives.

Storm surge is often the most threatening and powerful component of landfalling tropical cyclones (TCs).[3] It can quickly reshape coastlines and destroy coastal habitats for both people and wildlife.[4] While TCs are ranked based on wind speed using the Saffir-Simpson Scale, storm surge is historically more destructive and deadly than wind. Storm surge height was once included in this scale but it was recently disassociated with the scale after events such as Hurricane Katrina (2005) and Hurricane Ike (2008) produced storm surges much higher than expected given the categorical rating of the storm at landfall.[4]

Numerous factors influence storm surge including the size and intensity (central barometric pressure) of a TC, the forward speed and angle at which the storm approaches the coastline, and the shape and size of the coastline and continental shelf.[5-10] The landfall maximum sustained winds, intensity, and size of a TC directly affect the storm surge height.[11] Sebastian *et al.* (2019) note that storm surge height on a concave coastline is dependent on the rate at which the water moves into the angled coast.[5] A fast-moving, intense TC with a high wind speed will result in a larger storm surge on open coasts due to a greater amount of water pushed into the coastline by the wind and forward motion of the TC. However, a slow-moving TC causes water to be pushed into an enclosed coast for a longer time, which can result in a larger storm surge in these areas.[12] Additionally, a larger TC will have a higher storm surge because strong winds are affecting a larger area of water, forcing a greater volume of water into the coast. The approach angle of a TC also impacts storm surge height. Winds perpendicular to the coast at landfall have the most effect on storm surge.[6] This means TCs approaching from the south or southeast are more likely to have a greater storm surge due only to the orientation of the winds to the coastline. Conversely, Rogers and Davis (1993) show that TCs approaching the northern Gulf coast from the southeast will likely weaken more quickly,[13] and therefore have a smaller storm surge. More recent research shows that TCs tend to intensify as they approach land under favorable environmental circumstances.[14, 15] Intensification near landfall could also contribute to a greater storm surge since more intense TCs tend to produce larger storm surges. Sebastian *et al*. (2019) argue that the storm surge will be higher on a concave coastline due to the "convergence of energy and accumulation of a large volume of water into the coast" and will peak before landfall.[5] For example, Hope *et al*. (2013) note that Hurricane Ike produced a maximum surge in Chambers County, Texas, due to the county's coastline shape, bathymetry, and approach angle of the storm.[6] The northwest approach track and great size of Hurricane Ike combined with the gentle sloping continental shelf and concave coastline of this part of the Texas coast contributed to the production of a storm surge higher than expected given a category 2 ranking at landfall.[6]

Despite the more well-understood relationships described above, the characteristics of a TC and coastline often interact with each other and affect the storm surge height. Rogers and Davis (1993) show that TCs approaching a concave coastline experience a lower land-to-water ratio and, therefore, a faster pressure rise and subsequent weakening.[13] This could possibly result in a smaller storm surge despite the concave shape of the coastline. More recent research by Hope et al. (2013) and Sebastian *et al*. (2019) suggests otherwise. Additionally, Lok (2021) show that smaller TCs are more likely to intensify near landfall, and a more intense storm can result in a greater storm surge.[14] The intensification of TCs near the coastline can be linked to enhanced coastal downwelling.[15] Coastal downwelling keeps ocean waters warm near the coastline, which enhances convection and drives intensification despite the interaction of vertical wind shear and dry air near landfall.[15] This suggests that other factors, such as the curvature of the coastline, may affect the storm surge height.

This research will address the following question: Is there a relationship between the shape of the coastline (concave, convex) and the maximum height of storm surge in those areas? If so, do concave coastlines experience a higher storm surge than convex coastlines? Due to the claim by Sebastian *et al*. (2019) that concave coastlines experience an accumulation of water and energy,[5] we expect that storms making landfall on a concave coastline will have a higher maximum surge height than storms making landfall on a convex coastline.

METHODS AND PROCEDURES

The SURGEDAT dataset for landfalling TCs along the United States Gulf Coast, provided by Needham and Keim (2012),[4] is the primary database in this study. This dataset provides the height of the maximum storm surge in meters and location of maximum storm surge in latitude/longitude coordinates via measurements taken inside flooded buildings to minimize the effect of waves. The astronomical tide level as well as the influence of waves is removed from the reported MSSH for all events included in Needham and Keim (2012).[4] The storm surge events in Needham and Keim (2012) also have an associated confidence level (1-5) based on the type and credibility of the source reporting the MSSH.[4] A confidence level of 1 corresponds to low confidence and is used for events where there is only one information source from within 50 km of the location of maximum storm surge or when there are significant contradictions between sources. Conversely, a confidence level of 5 means the MSSH is supported by at least two credible sources and multiple tide gauges in the surrounding area.[4] **Figure 1** shows the distribution of storm surge heights across the Gulf Coast for the eleven storms included in the study.

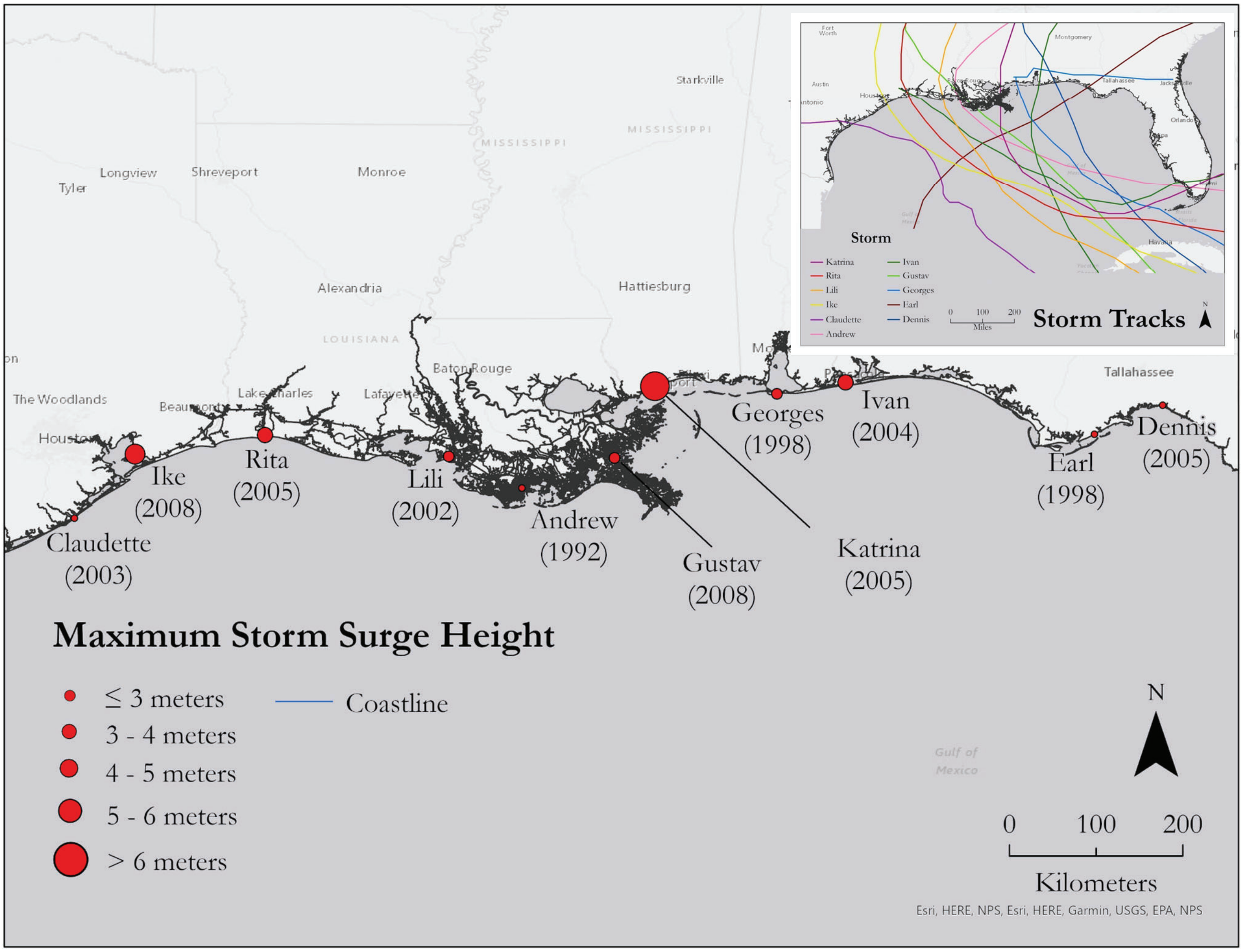

Figure 1. Geographical overview of the location and height of each maximum storm surge associated with the eleven TCs in this study. The inset shows the tracks of each TC.

This research focuses on TCs with a storm surge greater than 2 meters and a ranking of category 1 (64 knots) or higher on the Saffir-Simpson Hurricane Wind Scale. TCs in this study have landfall wind speeds between 75 and 125 knots, centered at 100 knots. Additionally, for a storm to be included in the analysis, it must meet the following criteria. First, the MSSH measurement must have a confidence level of 3 or higher (moderate to very high confidence). This means the MSSH must be validated by at least one credible source that is not contradicted by any other source.[4] Additionally, Drake (2012) classifies TCs with R34 measurements between 126 and 174 nautical miles as "medium" size. Therefore, TCs in this study must have an R34 measurement between 100 and 200 nautical miles with the distribution centered around 150 nautical miles.[16] Based on data from the HURDAT2 dataset, the average MSLP for TCs in the Atlantic basin occurring between 1988 and 2012 is 955 hPa.[17] The TCs in this study have an average landfall MSLP of 950 hPa. Based on data from the National Oceanic and Atmospheric Administration (NOAA), the forward speed of TCs between 5 and 30 degrees north latitude is between 10-14 mph.[18] The average forward speed for TCs in this study is 12 mph. Lastly, all TCs in this study make landfall along the northern Gulf coast so the angle of incidence with the coastline is visually between 60 to 120 degrees and all TCs have a northerly component to the forward motion. Specific measurement of the angle of approach is outside the scope of this research, which focuses on the coastline curvature, though it should be considered in future work.

The extended best track database, obtained from Colorado State University and described in Demuth (2006), is used to determine the landfall wind speed, pressure, and radius of 34-knot winds (R34) for each storm.[19] Additional specific statistics on individual storms are obtained from local National Weather Service websites and the National Hurricane Center website.[20-37] Since the sample of TCs in this research is centered around a medium size and average pressure and forward speed, these storms generally reflect the larger distribution of all hurricanes in the Atlantic basin. Summary statistics, including the mean and median for each storm attribute are shown in **Table 1**.

After selecting storms that meet the criteria listed above, we map the coordinates and determine the degree of concavity of the surrounding coastline. The NOAA Shoreline Website (NOAA 2000, 2008, 2013) provides the shapefile containing the coastline mapping data for the United States. The shoreline dataset is created using NOAA nautical charts and the mean high water tidal datum. The shapefile has an average scale of 1:70,000.[38] This file is clipped to focus only on the Gulf Coast and later to locations surrounding each maximum storm surge point.

In their research concerning the SURGEDAT database, Needham and Keim (2012) include tables with storm surge heights for numerous systems.[4] This database defines the spatial domain of this study as the United States Gulf Coast. The Gulf Coast provides a similar bathymetric profile at nearly all landfall locations,[6, 39, 40] thus eliminating one major influence on storm surge height and making it an ideal location to compare the storm surge height of different storms. The amount of available data included in this dataset and in the extended best track database restricts the temporal domain to events occurring between 1988 and 2012.[4, 19]

Storm Name	R34 (nautical miles)	Landfall Minimum MSLP (hPa)	Landfall Maximum Sustained Winds (kts)	Forward Speed (mph)
Andrew (1992)	125	937	125	16
Earl (1998)	103.75	985	80	10
Georges (1998)	121.25	961	95	7
Lili (2002)	157.5	957	105	15
Claudette (2003)	103.75	982	75	12
Ivan (2004)	187.5	931	110	12
Dennis (2005)	145	930	120	18
Rita (2005)	145	931	105	11
Gustav (2008)	180	954	95	16
Ike (2008)	190	952	95	10
Katrina (2005)	162.5	923	110	15
Mean	**144.26**	**949.15**	**100.26**	**12.49**
Median	**145.00**	**952.00**	**105.00**	**12.00**

Table 1. Characteristics of the storms used in this study.

After storms meeting all criteria are selected and mapped, we assign a value of concavity to the landfall area for each storm based on the section of coastline surrounding a maximum storm surge point. **Figure 2** explains the calculation of the degree of concavity at a 50 km radius around the point of maximum storm surge. After we map the location of each maximum storm surge, we create 50, 100, and 200 km buffers around each point of maximum storm surge.

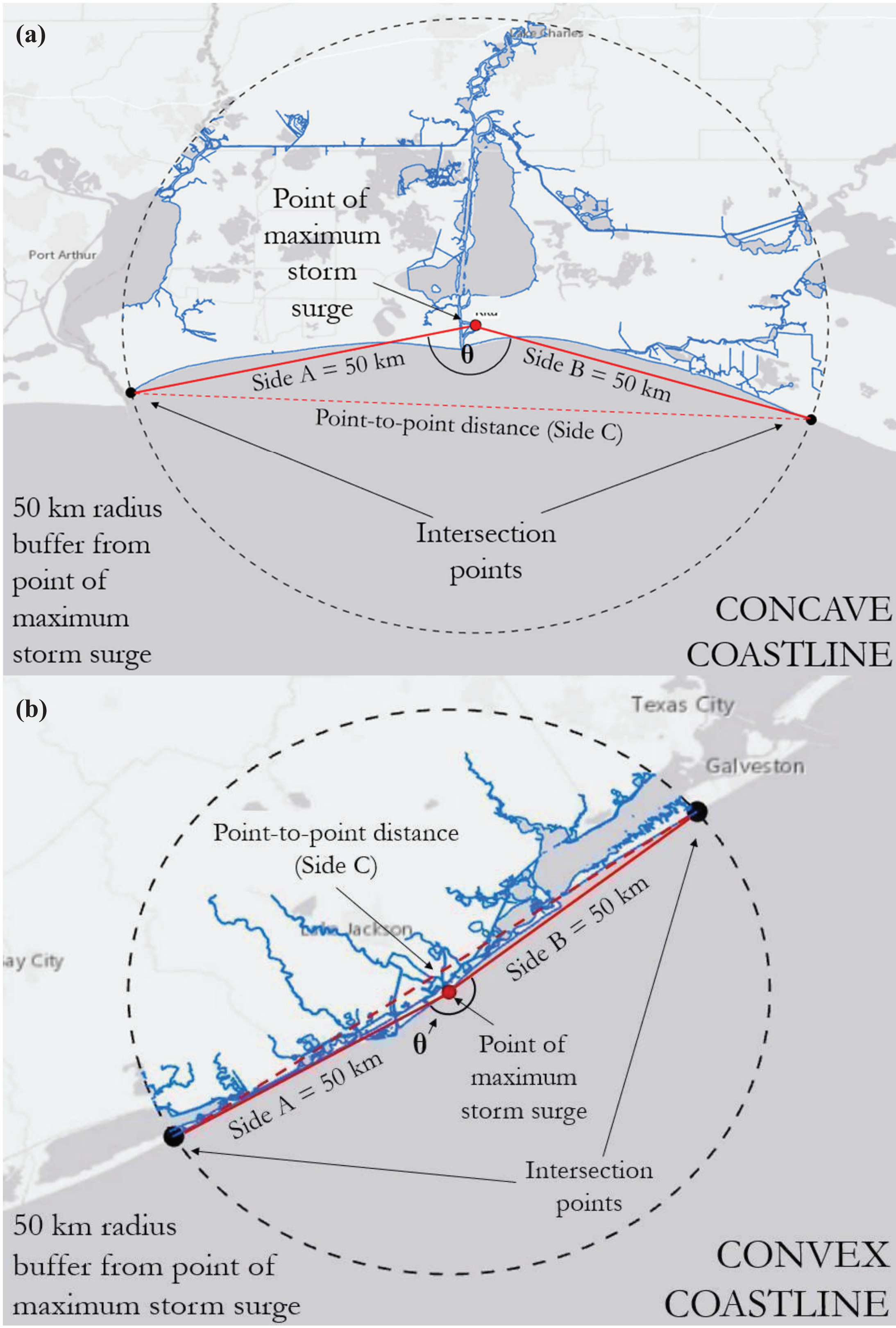

Figure 2. Calculation of the degree of concavity on a (a) concave and (b) convex coastline.

Next, we locate the intersections of this buffer with the coastline (**Figure 2**). To determine the degree of concavity, we calculate the straight-line distance between the intersection points (**Figure 2**). Then, the Law of Cosines is used to calculate the angle (θ_{rad}) between the coastline-buffer intersection points at radii of 50, 100, and 200 km. Sides A and B are equal to the size of the radius. For example, a radius of 50 km (100 km, 200 km) means sides A and B are equal to 50 km (100 km, 200 km). The point-to-point distance is represented by side C (**Table 2**). This process results in an angle measurement in radians (θ_{rad}), which is then converted to degrees (θ). Using this angle measurement in degrees, the adjusted degree of concavity (ADoC) is calculated using **Equation 1**:

$$\text{ADoC} = \frac{180-\theta}{180} \qquad \textbf{Equation 1.}$$

A coastline is concave if side C is located seaward of the point of maximum storm surge. In this situation, θ is less than 180 degrees and the ADoC is greater than zero. A coastline is convex if side C is located landward of the point of maximum storm surge. Here, θ is greater than 180 degrees and the ADoC is less than zero. A perfectly straight coastline has an angle of 180 degrees and an ADoC equal to zero. It is important to note that the coastline becomes more concave with larger buffer sizes due to the concave nature of the U.S. Gulf Coast. Additionally, some points of maximum storm surge are not located directly on the coastline since the original measurements were taken from inside flooded buildings.[4] This results in some error in calculating the ADoC because the location of the buffer-coastline intersection may cause the distance between intersection points to be slightly different than if the point of maximum storm surge were located directly on the coastline. In this study, the difference is less than 1% for MSSH points located on open coastlines but can range as high as 33% for MSSH points located near bays and deltas. In all cases, the category of concave or convex is unchanged. Another source of error could be due to the resolution of the NOAA shoreline dataset. Slight differences between this dataset and the actual coastline could affect the location of the intersection points, the length of side C, and therefore, the calculation of the ADoC.

In this study, the sample size is small, and the data are not normally distributed (see results), so non-parametric tests are necessary to evaluate the significance of the results. For all statistical tests, we use a 95% confidence level ($p < 0.05$) to determine the significance of the result. First, the Spearman's Rho is calculated to determine the correlation between MSSH and the ADoC for each buffer size. Second, a Mann Whitney *U* test is used to evaluate whether significant differences exist between MSSH associated with concave and convex coastlines. In general, the Mann Whitney *U* test determines if the samples come from different populations or if they are rooted in the same population. As a non-parametric test, the data do not have to be normally distributed since this test focuses on the rank of the data rather than the actual values. Still, this test has low power with small sample size and is only applicable when groups have four or more data points. In fact, it is impossible to achieve a statistically significant result ($p < 0.05$) with less than four samples in a group.[41] For this reason, the Mann Whitney *U* test is only used to compare the concave and convex groups at the 100 km buffer. Despite these limitations, the Mann Whitney *U* test is the best statistical test option to compare the data and serves as a model for future work that includes more cases. The null hypothesis (h0) is that there is no difference between the average storm surge height on a concave coastline and a convex coastline. The alternative hypothesis (h1) is that there is a difference between the average storm surge height on a concave coastline and a convex coastline.

Next, we perform a simple linear regression F-test. This test investigates the linear relationship between MSSH and each individual storm characteristic by comparing the sum of squares error of the full model to the sum of squares error of a reduced model. In the context of this research, the full model includes a linear relationship between an individual storm characteristic and the MSSH. Each reduced model contains only the y-intercept and residual error for that specific storm characteristic. There are no other variables in the reduced model suggesting no relationship, which is the null hypothesis. The F statistic tells us if the full model better explains any relationship (if it exists) between an individual storm characteristic and storm surge height. A large F-statistic with a significant ($p < 0.05$) result indicates that we should reject the null hypothesis for that individual storm characteristic and suggests that a specific variable has a significant influence on storm surge height.[42] Here, we investigate seven full models comparing, individually, the R34, landfall minimum MSLP, landfall maximum sustained winds, forward speed, ADoC at a 50 km radius, ADoC at a 100 km radius, and ADoC at a 200 km radius to the MSSH.

50 km Radius Buffer					
Hurricane	**MSSH (m)**	**Coastline Type**	**Side C**	**Angle (deg)**	**ADoC**
Ike	5.33	Concave	88.58	124.7	0.307
Ivan	4.57	Concave	99.72	171.4	0.047
Rita	4.57	Concave	96.53	149.7	0.168
Dennis	2.74	Concave	85.94	118.5	0.342
Earl	2.44	Convex	98.40	200.5	-0.114
Georges	3.63	Convex	98.03	202.8	-0.127
Gustav	3.96	Concave	57.07	69.6	0.613
Lili	3.75	Concave	86.75	120.3	0.331
Claudette	2.79	Convex	99.69	189.0	-0.050
Andrew	2.44	Concave	98.40	159.5	0.114
Katrina	8.47	Concave	97.78	155.8	0.134

100 km Radius Buffer					
Hurricane	**MSSH (m)**	**Coastline Type**	**Side C**	**Angle (deg)**	**ADoC**
Ike	5.33	Concave	188.07	140.2	0.221
Ivan	4.57	Convex	199.78	185.4	-0.030
Rita	4.57	Concave	192.93	149.4	0.170
Dennis	2.74	Concave	156.93	103.4	0.426
Earl	2.44	Convex	194.00	208.1	-0.156
Georges	3.63	Convex	197.31	198.8	-0.105
Gustav	3.96	Convex	190.61	215.3	-0.196
Lili	3.75	Concave	197.84	163.2	0.094
Claudette	2.79	Convex	199.06	191.1	-0.062
Andrew	2.44	Convex	194.33	207.4	-0.152
Katrina	8.47	Concave	153.03	99.8	0.445

200 km Radius Buffer					
Hurricane	**MSSH (m)**	**Coastline Type**	**Side C**	**Angle (deg)**	**ADoC**
Ike	5.33	Concave	377.36	141.3	0.215
Ivan	4.57	Concave	375.82	140.0	0.222
Rita	4.57	Concave	375.75	139.9	0.223
Dennis	2.74	Concave	372.08	136.9	0.239
Earl	2.44	Concave	399.97	178.6	0.008
Georges	3.63	Concave	387.48	151.3	0.160
Gustav	3.96	Convex	393.49	200.7	-0.115
Lili	3.75	Concave	399.22	172.9	0.040
Claudette	2.79	Concave	399.51	174.3	0.031
Andrew	2.44	Convex	361.05	231.0	-0.283
Katrina	8.47	Concave	372.20	137.0	0.239

Table 2. Calculation of the adjusted degree of concavity for each storm at a 50, 100, and 200 km radius.

RESULTS

Since storm surge height can be affected by the intensity, forward speed, size, and landfall wind speed, this study uses sample TCs with characteristics reflecting the larger population of TC landfall characteristics (**Table 1**). All TCs included have an average landfall wind speed of roughly 100 kts. These TCs have an average forward speed of 10.9 knots, an average landfall pressure of 949.2 hPa, and an average R34 of 144.3 nautical miles. The median values for each of these parameters are similar to the mean values (**Table 1**). The values for landfall maximum sustained winds are normally distributed (not shown); the values for R34, landfall minimum MSLP, and forward speed are not normally distributed. While the distributions of R34, landfall minimum MSLP, and forward speed values are not normal, the TCs selected still reflect a larger population of R34, landfall minimum MSLP, and forward speed values for TCs in the North Atlantic basin.[16-19]

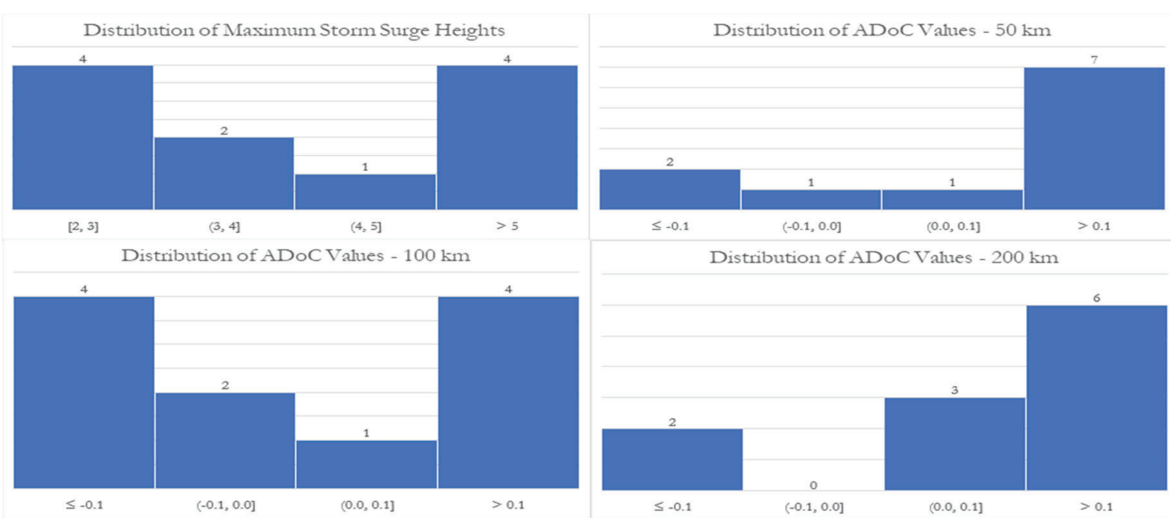

Figure 3. Histograms showing the distribution of storm surge heights (m) data and degrees of concavity.

Figure 3 shows the distribution of MSSH and ADoC at each buffer size. The ADoC values are not normally distributed, so non-parametric tests, such as Spearman's Rho and the Mann Whitney U test, are needed for analysis. Upon investigation, there is a slight correlation (r_s=0.292) between the ADoC and the MSSH on a 50 km radius buffer. The correlation increases to r_s =0.552 on a 100 km radius buffer and to r_s =0.525 on a 200 km radius buffer (**Table 3**). Using a 95% confidence level, the 100 and 200 km correlations are significant. **Figure 4** shows a visual representation of the relationship between MSSH and the ADoC at each buffer size. Just as the Spearman's Rho correlations indicate a weak relationship between variables, **Figure 4** suggests a slight positive relationship between the MSSH and the ADoC. Further, the relationship between these two variables strengthens as the buffer size increases, which is also supported by the significant relationships at the 100 and 200 km buffers. Given the numerous factors affecting storm surge height, a positive relationship for all three buffer sizes is notable, especially since the relationship is consistent with prior research suggesting higher storm surges along concave coastlines.[5]

Storm Name	Rank MSSH	Rank 50 km ADoC	Rank 100 km ADoC	Rank 200 km ADoC
Earl	1.5	2	2	3
Andrew	1.5	5	3	1
Dennis	3	10	10	11
Claudette	4	3	5	4
Georges	5	1	4	6
Lili	6	9	7	5
Gustav	7	11	1	2
Ivan	8.5	4	6	8
Rita	8.5	7	8	9
Ike	10	8	9	7
Katrina	11	6	11	10
Spearman's Rho (*p*-value)		**0.292 (0.192)**	**0.553 (0.039)**	**0.525 (0.049)**

Table 3. Ranked value for each variable used in the calculation of Spearman's Rho at each buffer size. The Spearman's Rho value is also shown with the corresponding *p*-value.

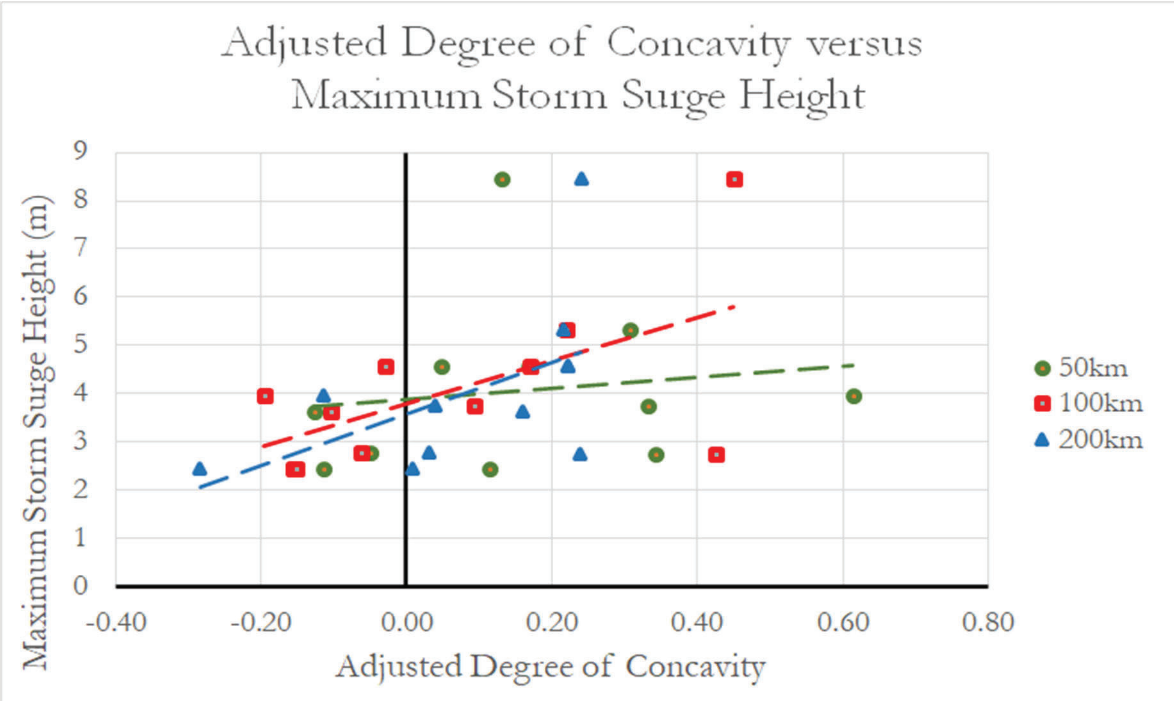

Figure 4. Scatter plot showing MSSH versus adjusted degree of concavity. Dashed lines indicate the approximate linear relationship for each buffer size.

Figure 5 compares the average MSSH for TCs making landfall on a concave coastline to the average MSSH of TCs making landfall on a convex coastline at each buffer size. Using the 50 km radius buffer, eight storms make landfall on a concave coastline, while three storms make landfall on a convex coastline. At a 100 km radius buffer five storms make landfall on a concave coastline and six storms make landfall on a convex coastline. Using the 200 km radius buffer, nine storms make landfall on a concave coastline while two storms make landfall on a convex coastline. For each buffer size, the average storm surge height on a concave coastline is higher than the average storm surge height on a convex coastline. The Mann Whitney *U* test is completed by comparing two groups (concave vs. convex coastlines) for the 100 km buffer only using a 95% confidence level. This test is not used to compare concave and convex groups at the 50 and 200 km buffers since there are less than four data points in a single group at each of these buffer sizes. The *p*-value (**Table 4**) does not indicate a statistically significant difference between the median height of maximum storm surge on a concave coastline and median height of maximum storm surge on a convex coastline at the 100 km buffer size. However, we must be cautious of these results due to the small sample size. Still, the results indicate that the null hypothesis may not be rejected and that storm surges in the two groups are statistically similar.

Buffer Size	*p*-value
100 km	0.118

Table 4. Mann Whitney *U* test *p*-values for each buffer size.

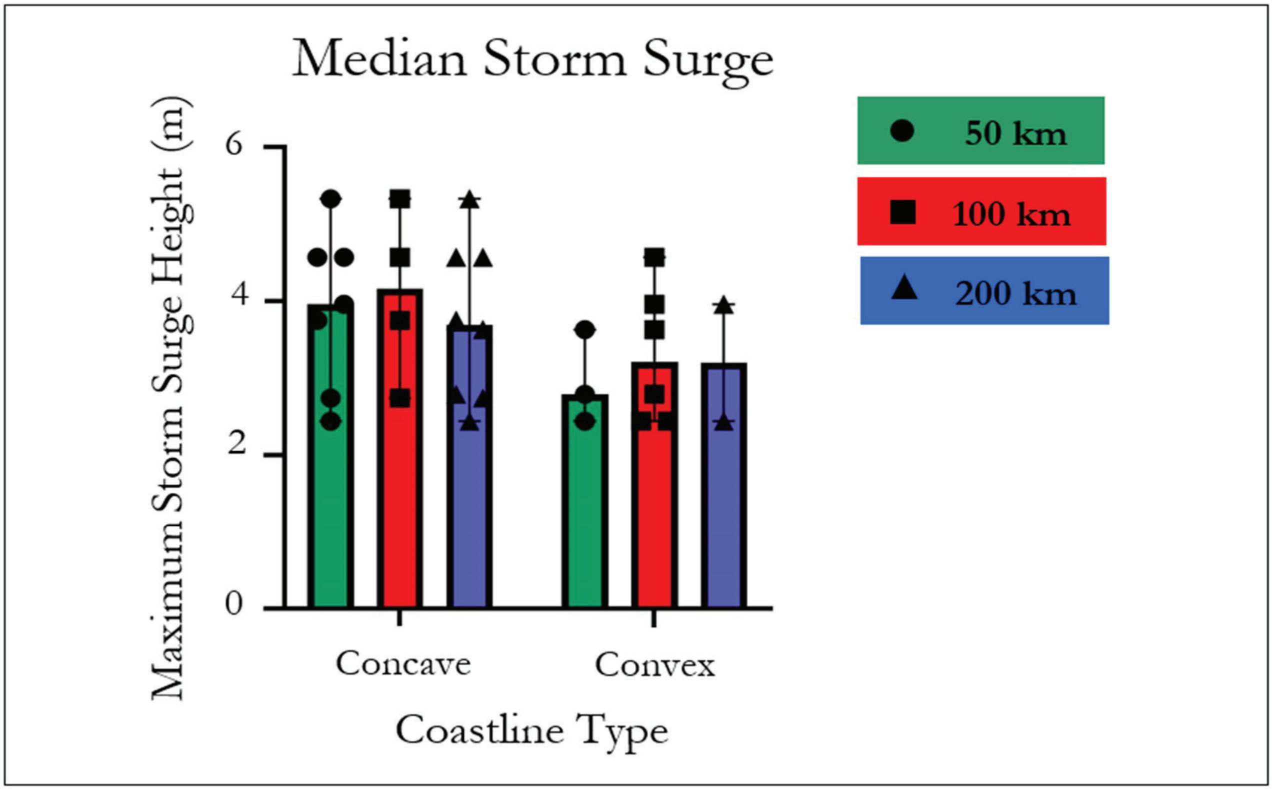

Figure 5: Comparison of the distributions of MSSH along a concave coastline and a convex coastline at each radius. The bar represents the median MSSH on each type of coastline. The whiskers represent the range. The points represent individual MSSH in the respective groups.

To investigate the relationship between MSSH and other individual storm characteristics, an F-test is performed (**Table 5**). First, to ensure linear relationships between all variables and the MSSH, we use a log transformation for the MSLP variable. All other variables have a near-linear relationship with MSSH and are not manipulated. For this sample, F-statistics indicate that there are no statistically significant influences on storm surge height at a 95 % confidence level (**Table 5**) despite the findings of previous research suggesting that R34, the landfall maximum sustained winds, landfall minimum MSLP, forward speed, all influence the MSSH.[5-15] For example, the explanatory power of the transformed landfall minimum MSLP [log (landfall minimum MSLP)] is not significant in this research, but previous studies show that MSLP does have a well-established relationship with storm surge height.[5, 7, 43, 44]. In this sample, multiple variables with established relationships with storm surge do not show significant linear relationships, which may be due to the small sample size. Therefore, we interpret these results cautiously and do not rule out the influence of any variable on the MSSH.

Despite the small sample size, we attempt to build a multiple linear regression model using forward stepwise regression since many of the variables achieve a 10% significance threshold ($p < 0.1$). This model tests if the variables included in Table 5 significantly predict the MSSH and uses the Akaike Information Criteria (AICc) stopping rule, similar to other studies in the atmospheric and climate science fields.[45, 46] The landfall maximum sustained winds, log (landfall minimum MSLP), R34, forward speed, and ADoC at each buffer size is considered in a single model. Using the AICc stopping rule, only the ADoC at the 100 km buffer is recommended for the model ($F = 4.777$; p-value = 0.057). This result implies that a simple linear regression model is the best linear model to predict MSSH and that additional variables do not explain enough additional variance to be included in the final model. However, as stated earlier, multiple variables with established relationships with MSSH are not included in the model, so results should be interpreted cautiously.

Parameter	F-Ratio (*p*-value)
Landfall Maximum Sustained Winds (kts)	0.246 (0.632)
log (Landfall Minimum MSLP (hPa))	3.433 (0.097))
R34 (nautical miles)	4.270 (0.069)
Forward Speed (mph)	0.037 (0.851)
ADoC - 50 km	0.216 (0.653))
ADoC - 100 km	4.777 (0.057)
ADoC - 200 km	3.492 (0.095)

Table 5. Simple linear regression F-ratio and corresponding *p*-value for each parameter, including the ADoC at each buffer size.

DISCUSSION

A handful of previous research studies address the many factors affecting storm surge height, but few studies have investigated the effect of coastline concavity, alone, on storm surge height. This study attempts to limit the influence of outlier storms by using a sample of TCs that generally reflects the larger population of Atlantic TCs in terms of intensity, size, landfall wind speed, and forward speed values. All TCs in this study make landfall along the US Gulf Coast, so the influence of the approach angle and the bathymetry of the continental shelf is also limited. Based on findings from previous research, it is hypothesized that landfalling TCs will have a higher MSSH on a concave coastline than similar landfalling TCs with MSSH on a convex coastline.

The Spearman's Rho values suggest a weak correlation between the MSSH and ADoC at the three radii used. Given the small sample size and considering the numerous factors affecting storm surge height, these correlations are a compelling result of this study, especially since the 100 and 200 km correlations are statistically significant. Additionally, a similar and increasingly positive trend with increasing buffer radius is an interesting result, further supporting the relationship (**Figure 5**). While the Mann Whitney *U* test does not suggest a statistically significant difference between the MSSH on a concave coastline and the MSSH on a convex coastline at the 100 km buffer, the sample size might be too small to detect any differences in the groups. Furthermore, acknowledging the numerous factors affecting storm surge height, it might be difficult to detect a clear relationship solely between the degree of coastline concavity and MSSH. Additionally, a forward stepwise regression suggests that only the ADoC at the 100 km buffer has significant explanatory power and is the only variable included in the final linear regression model. With a larger dataset, a multiple linear regression could be used with more confidence to evaluate whether coastline curvature can explain additional variation after other primary factors such as storm size are first considered.

Given the weak correlation between storm surge height and coastline curvature, it is interesting to note that, using a 50 km radius, the greatest storm surge observed on a convex coastline is greater than only two storm surges observed on a concave coastline. This trend is not as well pronounced with the 100 km or 200 km radius buffers (**Figure 5**). However, the median MSSH on convex coastlines is consistently smaller than the median MSSH on concave coastlines at each radius (**Figure 5**). These differences are small and not statistically significant based on a Mann Whitney *U* test. The small sample size could affect the outcome of the Mann Whitney *U* test. Nevertheless, combined with the increasing correlation between the ADoC and the MSSH as the buffer radius increases, which reaches significance at the 100 and 200 km buffers, these observations suggest the potential for even stronger results when a larger pool of storms is considered. Additionally, because the correlation between the ADoC and the MSSH increases and becomes significant with increasing buffer size (**Table 3, Figure 5**), a larger buffer zone size may be a more appropriate scale for assessing the influence of coastline shape. Future research should investigate the appropriate horizontal scale for assessing the influence of coastline curvature on storm surge.

There are limited studies investigating the effect of coastline concavity on MSSH, but the results of this study match the expectations set by the conclusions of Sebastian *et al.* (2019)[5] and Hope *et al.* (2013).[6] In their research, Sebastian *et al.* (2019) show that concave coastlines will likely experience a higher storm surge due to the concentration of water into the inward-sloping coast; the results of this study suggest similar findings in that most storm surges on a concave coastline are higher than the storm surges occurring on a convex coastline.[5] Additionally, Hope *et al.* (2013)[6] note that the concave coastline in Louisiana and Texas contributed to the higher storm surge in Hurricane Ike.[6] The results of this study provide further evidence that a positive relationship exists between coastline curvature and storm surge height, suggesting that concave coastlines may contribute to increased storm surge height.

The primary source of error in this study stems from the small sample size. In particular, the amount of data available in both databases used in this study restricts the temporal range from 1988-2012 and introduces further sources of error due to insufficient data available for meaningful statistical significance tests. Additionally, to limit the influence of the known factors affecting storm surge height, this study only includes storms with landfall characteristics that meet certain criteria and reflect a larger population of Atlantic TCs, which further limits the sample size. Due to the small sample size and non-normal distributions of variables, this study is limited in the statistical tests that can be used. For example, while the F-test did not identify any significant variables, we attempt to build a simple linear regression model, which only recommends the use of the ADoC at the 100 km buffer in the final model despite established relationships between MSSH and other variables. Furthermore, the Mann Whitney *U* test is only applicable at the 100 km buffer, and the results may not accurately reflect any true differences in the population due to the small sample size. As a result, there is an opportunity to conduct further research investigating the effect of coastline curvature when larger geographical and temporal scales are considered. Despite the limitations in the dataset, the approach used in this study may still be useful in future studies that seek to separate out the impact of a specific storm characteristic (*e.g.* intensity, wind speed, size, or forward speed) on MSSH. Changes in the coastline shape over time as the result of sea level rise and erosion/mitigation efforts and the influence of coastal waterways (rivers, bays, *etc.*) may also impact the degree of concavity and/or MSSH in an area.

An additional source of error stems from the location of MSSH with respect to the coastline. Some points of maximum storm surge are not located directly on the coast as these measurements were taken from inside flooded buildings.[4] Because the points of intersection between the coastline and each buffer are located directly on the coast, the distance of maximum storm surge from the coast has the potential to affect the angle measurement used in the calculation of the degree of concavity in this study, especially for the 50 km buffer. However, this error is generally small since the buildings are usually within 1 km of the coastline. To further minimize this effect, the 100 km and 200 km buffer zones are included. However, as the buffer zone is increased, the small inflections along each coastline are minimized and the degree of concavity of the entire section of coastline could be affected, resulting in an "average" degree of coastline concavity. More specifically, using a smaller buffer size allows small changes in the coastline shape to be better reflected in the ADoC calculation. For example, the 50 km buffer better captures the coastline shape of small bays or inlets around the point of maximum storm surge, which can affect storm surge height.[48,49] The larger buffer size (100 km or 200 km) covers areas of the coastline that may include bays or inlets but does not account for the coastline shape within these bays and inlets. In other words, a larger buffer does not capture these small features as well as a smaller buffer so the ADoC value becomes more of an "average" for the whole area. Idealized modeling studies could be used to eliminate this error by obtaining MSSH values directly at the coastline.

CONCLUSIONS

This research focuses on the effect of coastline concavity on MSSH along the Gulf Coast of the United States. More specifically, this research addresses the following questions: Is there a relationship between the shape of the coastline (concave, convex) and the maximum height of storm surge in those areas? If so, do concave coastlines experience a higher storm surge than convex coastlines? While there are few studies investigating the effect of coastline concavity on storm surge height, many studies state that storm surge height is influenced by a number of factors. The intensity (central barometric pressure) of a cyclone, forward speed and angle at which the storm approaches the coastline, and the shape and size of the coastline and continental shelf all influence storm surge height.[5-11] Many of these factors can also interact to influence storm surge height. Because of this, this study only uses TCs that meet certain criteria to more closely investigate the effect of coastline concavity on storm surge height. These criteria ensure these TCs represent the greater population of TCs with respect to size, intensity, landfall wind speed, and forward speed values. This study also focuses on the Gulf Coast of the United States to limit the influence of bathymetry and approach angle of TCs.

Results from a Mann Whitney *U* test did not indicate any significant difference between the storm surge heights of TCs making landfall on concave coastlines and the storm surge heights of TCs making landfall on convex coastlines at the 100 km buffer. This test was not applicable at the 50 and 200 km buffers due to the small number of samples in each group. The small sample size could limit the accuracy of this test at the 100 km buffer as well. Additionally, a simple linear regression F-test shows there are no significant influences of MSSH. This result is also likely due to the small sample size since many of these influences are nearly significant and previous research describes established relationships between storm size, storm speed, and storm intensity. For this reason, forward stepwise regression is used and shows that ADoC at the 100 km buffer is the dominant influence on MSSH. These results should be interpreted with caution due to the small sample size and absence of significant ($p < 0.05$) F-ratios prior to building the simple linear regression model. The Spearman's Rho correlation values suggest a weak positive relationship between the coastline concavity and the MSSH. This correlation is significant when considering concavity at larger horizontal scales (100 and 200 km). Additionally, storm surges on concave coastlines are consistently greater than storm surges on convex coastlines.

As mentioned above, a small dataset (n=11) marks the greatest limitation of this research. Expanding the spatial and temporal range of this research to include more TCs affecting the United States Gulf Coast and TCs impacting the southeast-Atlantic and northeast-Atlantic coastlines would add additional data to the analysis and possibly reveal additional significant relationships. Further research into the effect of individual storm characteristics on storm surge height would also provide more context and a better understanding of the potential impact of TCs on coastal communities. Lastly, this study is observation-based. Modeling studies and case studies would be helpful in isolating and identifying the influence of coastline curvature on storm surge height.

REFERENCES

1. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Storm Surge Overview, *https://www.nhc.noaa.gov/surge/* (Accessed Nov 2020)

2. Debrovo, A. (2008) *Hurricane Katrina - The One We Feared*, 14, Express Publishing, Harahan, LA.

3. Rappaport, E. N., 2014: Fatalities in the United States from Atlantic Tropical Cyclones: New Data and Interpretation. *Bulletin of the American Meteorological Society*, **95**, 341–346, *https://doi.org/10.1175/BAMS-D-12-00074.1.*

4. Needham H. F. and Keim B. D. (2012) A storm surge database for the US Gulf Coast, *Int J Climatol,* **32**, 2108-2123. *https://doi.org/10.1002/joc.2425*

5. Sebastian M., Behera M. R., and Murty P. L. N. (2019) Storm Surge Hydrodynamics at a Concave Coast due to varying approach angles of cyclone, *Ocean Eng,* **191**, 1-16. *https://doi.org/10.1016/j.oceaneng.2019.106437*

6. Hope, M. E., Westerink, J. J., Kennedy, A. B., Kerr, P. C., Dietrich, J. C., Dawson, C., Bender, C. J., Smith, J. M., Jensen, R. E., Zijlema, M., Holthuijsen, L. H., Luettich Jr., R.A., Powell, M. D., Cardone, V. J., Cox, A. T., Pourtaheri, H., Roberts, H. J., Atkinson, J. H., Tanaka, S., Westerink, H. J., Westerink, L. G. (2013) Hindcast and Validation of Hurricane Ike (2008) waves, forerunner, and storm surge, *J. Geophys. Res. Oceans,* **118**, 4424-4460. *https://doi.org/10.1002/jgrc.20314*

7. Resio, D. T. and Westerlink, J. J. (2008) Modeling the physics of storm surges, *Physics Today,* **61**, 33-38. *https://doi.org/10.1063/1.2982120https://doi.org/10.1063/1.2982120*

8. Irish, J. L., D. T. Resio, and J. J. Ratcliff, (2008) The Influence of Storm Size on Hurricane Surge. *Journal of Physical Oceanography*, **38**, 2003–2013, https://doi.org/10.1175/2008JPO3727.1.*https://doi.org/10.1175/2008JPO3727.1.*

9. Weisberg, R. H., and L. Zheng, (2006) Hurricane Storm Surge Simulations for Tampa Bay. *Estuaries and Coasts*, **29**, 899–913. *https://www.jstor.org/stable/4124819*

10. Zhang, C., and C. Li, (2019) Effects of hurricane forward speed and approach angle on storm surges: an idealized numerical experiment. *Acta Oceanol. Sin.*, **38**, 48–56, *https://doi.org/10.1007/s13131-018-1081-z.*

11. Longshore, D. (2008, 2000) *Encyclopedia of Hurricanes, Typhoons, and Cyclones* New Edition, 380-384, Checkmark Books, New York.

12. Islam, R., and H. Takagi, (2021) Statistical significance of tropical cyclone forward speed on storm surge generation: retrospective analysis of best track and tidal data in Japan. Georisk: *Assessment and Management of Risk for Engineered Systems and Geohazards* **15**, 247–257, https://doi.org/10.1080/17499518.2020.1756345.

13. Rogers R. F. and Davis R. E. (1993) The Effect of Coastline Curvature on the Weakening of Atlantic Tropical Cyclones, *Int J Climato,l* **13**, 287-299. *https://doi.org/10.1002/joc.3370130305*

14. *Lok, C. C. F., Chan, J. C. L., Toumi, R. (*2021*)* Tropical cyclones near landfall can induce their own intensification through feedbacks on radiative forcing, *Communications Earth and Environment,* **2:184***,* 1-10. *https://doi.org/10.1038/s43247-021-00259-8.*

15. Gramer, L. J., Zhang, J. A., Alaka, G. J., Hazelton, A., Gopalakrishnan, S. (2021) Coastal downwelling intensifies landfalling hurricanes, *Earth and Space Science Open Archive*, 1-21. *https://doi.org/10.1002/essoar.10508339.1*

16. Drake, L., 2012: Standardizing hurricane size descriptors for broadcast to the public. *40th Conference on Broadcast Meteorology, AMS https://ams.confex.com/ams/40BROADCAST/webprogram/Paper208126.html* (Accessed March 15, 2023).

17. Landsea, C. W., and J. L. Franklin, (2013) Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. *Monthly Weather Review*, **141**, 3576–3592, *https://doi.org/10.1175/MWR-D-12-00254.1.*

18. NOAA's Atlantic Oceanographic and Meteorological Laboratory, U.S. Department of Commerce. Hurricanes Frequently Asked Questions, *https://www.aoml.noaa.gov/hrd-faq/#avg-forward-speed*

19. Demuth, J., DeMaria, M., and Knaff, J.A. (2006) Improvement of advanced microwave sounder unit tropical cyclone intensity and size estimation algorithms, *J. Appl. Meteorol. Climatol.* **45**, 1573-1581.

20. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane IKE, *https://www.nhc.noaa.gov/archive/2008/al09/al092008.public_b.048.shtml?* (Accessed Nov 2020)

21. National Weather Service, NOAA. Hurricane Ike-September 2008, *https://www.weather.gov/hgx/projects_ike08* (Accessed Nov 2020)

22. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane IVAN, *https://www.nhc.noaa.gov/archive/2004/pub/al092004.public_a.055.shtml?* (Accessed Nov 2020)
23. National Weather Service, NOAA. Powerful Hurricane Ivan Slams the Central Gulf Coast, *https://www.weather.gov/mob/ivan*. (Accessed Nov 2020)
24. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane KATRINA. *https://www.nhc.noaa.gov/archive/2005/pub/al122005.public_a.026.shtml* (Accessed Feb 2023)
25. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane RITA, *https://www.nhc.noaa.gov/archive/2005/pub/al182005.public_a.026.shtml?* (Accessed Nov 2020)
26. National Weather Service, NOAA. Hurricane Rita - September 2005, *https://www.weather.gov/hgx/projects_rita05* (Accessed Nov 2020)
27. Earth Observatory, NASA. Hurricane Dennis, *https://earthobservatory.nasa.gov/images/15093/hurricane-dennis* (Accessed Nov 2020)
28. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane DENNIS, *https://www.nhc.noaa.gov/archive/2005/pub/al042005.public_a.025.shtml?* (Accessed Nov 2020)
29. National Weather Service, NOAA. Hurricane Dennis - September 2005, *https://www.weather.gov/mob/dennis* (Accessed Nov 2020)
30. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane EARL, *https://www.nhc.noaa.gov/archive/1998/archive/pub/PAAL0598.010* (Accessed Nov 2020)
31. National Weather Service, NOAA. Hurricane Earl - September 3, 1998, *https://www.weather.gov/mob/earl* (Accessed Nov 2020)
32. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane GEORGES, *https://www.nhc.noaa.gov/archive/1998/archive/pub/PBAL0798.050* (Accessed Nov 2020)
33. National Weather Service, NOAA. Hurricane Georges - September 28, 1998, *https://www.weather.gov/mob/georges* (Accessed Nov 2020)
34. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane GUSTAV, *https://www.nhc.noaa.gov/archive/2008/al07/al072008.public_a.031.shtml?* (Accessed Nov 2020)
35. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane LILI, *https://www.nhc.noaa.gov/archive/2002/pub/al132002.public_b.048.html* (Accessed Nov 2020)
36. National Hurricane Center and Central Pacific Hurricane Center, NOAA. Hurricane CLAUDETTE, *https://www.nhc.noaa.gov/archive/2002/pub/al132002.public_b.048.html* (Accessed Nov 2020)
37. Hurricanes: Science and Society, NSF and University of Rhode Island. 1992 – Hurricane Andrew, *http://www.hurricanescience.org/history/storms/1990s/andrew/* (Accessed Nov 2020)
38. NOAA Shoreline Website, NOAA. NOAA Medium Resolution Shoreline, *https://shoreline.noaa.gov/data/datasheets/medres.html* (Accessed Oct 2020)
39. Gulf of Mexico Bathymetry Contours, USGS. *https://pubs.usgs.gov/of/2000/of00-352/data/bathyc/browse/bathyc.gif* (Accessed July 2022)
40. Hamilton, P. (2006) Deep-Current Variability near the Sigsbee Escarpment in the Gulf of Mexico, *Journal of Physical Oceanography* **37**, 708-726. *https://doi.org/10.1175/JPO2998.1*
41. *GraphPad Prism 9 Statistics Guide - Interpreting results: Mann-Whitney test. https://www.graphpad.com/guides/prism/latest/statistics/how_the_mann-whitney_test_works.htm (Accessed April 17, 2023).*
42. Wilks, D. (2011) Forecast Verification in *Statistical Methods in the Atmospheric Sciences* (Dmowska, R., Hartmann, D., Rossby, H. T., Ed.) 2nd Ed., 255-332, Elsevier.
43. Klotzbach, P. J., Bell, M. M., Bowen, S. G., Gibney, E. J., Knapp, K. R., Schreck, C. J. (2020) Surface Pressure a More Skillful Predictor of Normalized Hurricane Damage than Maximum Sustained Wind. *Bulletin of the American Meteorological Society* **101**, E830–E846, *https://doi.org/10.1175/BAMS-D-19-0062.1*
44. Ditchek, S. D., T. C. Nelson, M. Rosenmayer, and K. L. Corbosiero, (2017) The Relationship between Tropical Cyclones at Genesis and Their Maximum Attained Intensity. *Journal of Climate*, **30**, 4897–4913, *https://doi.org/10.1175/JCLI-D-16-0554.1*
45. Soleimany, A., E. Solgi, K. Ashrafi, R. Jafari, and R. Grubliauskas, (2022) Temporal and spatial distribution mapping of particulate matter in southwest of Iran using remote sensing, GIS, and statistical techniques. *Air Qual Atmos Health*, **15**, 1057–1078, *https://doi.org/10.1007/s11869-022-01179-y*
46. Bloemendaal, N., Muis, S., Haarsma, R. J., Verlaan, M., Irazoqui Apecechea, M., de Moel, H., Ward, P. J., Aerts, J. C. J. H. (2019) Global modeling of tropical cyclone storm surges using high-resolution forecasts. *Clim Dyn* **52**, 5031-5044. *https://doi.org/10.1007/s00382-018-4430-x*
47. Mori, N., Kato, M., Kim, S., Mase, H., Shibutani, Y., Takemi, T., Tsuboki, K., Yasuda, T. (2014) Local amplification of storm surge by Super Typhoon Haiyan in Leyte Gulf. *Geophysical Research Letters* **41**, 5106-5113. *https://doi.org/10.1002/2014GL060689*

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PRESS SUMMARY

Storm surge is the most dangerous component of landfalling tropical cyclones. The growing coastal population highlights the importance of research regarding the atmospheric and geographic factors influencing storm surge height in these storms. This study uses a sample of tropical cyclones making landfall in the Gulf of Mexico that are representative of the larger population to isolate the effect of coastline shape on maximum storm surge height. A measure of coastline concavity is developed using geometry and 50, 100, and 200 km radius circles around the point of maximum storm surge. Statistical tests are used to look for relationships between the maximum storm surge height and the shape of the coastline. While there is only a small difference in the maximum storm surge height on the two coastline types, results suggest that storm surges occurring on an inward-sloping (concave) coastline tend to be greater than storm surges occurring on an outward-sloping (convex) coastline. The number of factors influencing maximum storm surge height makes it difficult to investigate the influence of the angle of the coastline on storm surge height. The results are limited by the small number of storms and the numerous factors influencing maximum storm surge height.